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Heavy rainfall associated with floods in southeastern Brazil in November–December 2021

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Abstract
In southeast Brazil, heavy precipitation events during the summer trigger floods. These disasters are responsible for most loss of lives. In November and December 2021, the northern area of Minas Gerais and the southern part of Bahia were affected by periods of very heavy rain and intense floods. Heavy precipitation contributed to unusually high soil saturation that favored floods that claimed lives. Estimated losses totaled about $3.1 billion U.S. dollars from November to December 2021. Therefore, this study: 1. evaluates the meteorological conditions in November–December 2021, in particular from December 22 to 29, when it rained up to 300 mm above average in this region, 2. analyzes the floods, exacerbated by extreme rainfall events earlier in November and December, and 3. discusses monitoring and issuing risk alerts of these disasters by government agencies that helped minimize damage and property loss and reduce fatalities.

Keywords Natural hazards · Heavy rainfall · Floods · Disaster risk reduction

1 Introduction

Climate-related disasters and hazards, such as droughts, floods, landslides, and storms, are natural events in long-term weather cycles that climate change may affect (Azadi et al. 2022). Record-breaking rainfall extremes have increased worldwide in the last decade, of which some are likely to be a consequence of climate change (Robinson et al. 2021). Population clustering in susceptible to floods areas and unsustainable land use in urban and rural regions have also heightened our vulnerability to natural disasters. Overall, in the past two decades, an average of nearly 200 million people were affected by climate-related disasters worldwide every year. On average, such disasters caused nearly 60,000 deaths annually from 2000 to 2019 (CRED 2020; UNDRR 2020).

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Globally, floods are the most common type of disaster. They account for 44% of total events between 2000 and 2019. Floods have affected more people than any other type of disaster in the twenty-first century. In 2018, 3.9 billion people were affected by natural disasters (CRED 2018, 2020; CRED and UNDRR 2020). That year alone witnessed 127 unprecedented flood events (CRED 2019).

Natural disasters exacerbate preexisting socioeconomic crises and disrupt the course of people's lives. Disasters especially threaten those segments of the population that are already most vulnerable and susceptible to hazards. These are people with limited capacity to cope with such harm. Brazil is no exception. Its 2010 census reveals that 84% of Brazilians live in cities and urban agglomerates (IBGE 2018). Urbanization has occurred at a chaotic and unplanned pace (Young et al. 2019). The outcome of the combination of misdirected urban land use policy and an increasing frequency of weather extremes could not be worse.

The increase in meteorological hazards, combined with a larger population living in high-risk areas, triggers disasters such as landslides and floods (Espinoza et al. 2021; Marengo et al. 2021; IPCC 2021). Year after year, disasters affect Brazil's cities, hitting thousands of people and wreaking social and economic damage (Bouwer 2019; CEPED 2013).

For this reason, attributing natural disasters only to climate and weather extremes can be misleading. More accurately, extreme events interact with preexisting fragility and inequality on the ground to create disasters (Lahsen and Ribot 2021). More than 95% of disasters in Brazil are weather or climate related (CEPED 2013). Over 5 million people, mostly poor and vulnerable, live in urban and rural areas with high population density, and hundreds of thousands of households sit precariously on unstable slopes (Avila et al. 2016).

Flash floods, floods, and landslides represent 70% of natural disasters nationally and 90% of those in southeast Brazil. This region includes the states of São Paulo, Rio de Janeiro, Minas Gerais, and Espírito Santo. With its high population, the Southeast also suffers the highest total mortality rates from natural disasters. The metropolitan regions of São Paulo and Rio de Janeiro are the largest cities in Brazil. Southeastern South America has seen an increase in total annual rainfall and frequency of extreme rain events (Skanski et al. 2013; Donat et al. 2013, and references quoted therein). In fact, from 2015 to 2019, the states in southeastern Brazil experienced 1373 extreme rainfall events (with precipitation above 50 mm/hour). Of these, 730 occurred in the state of São Paulo (EM-DAT 2019). With vulnerable populations living in exposed areas, heavy rainfall and high population density trigger disasters, resulting in fatalities and displacing people (Ramires and Mello-Thery 2018; Marengo et al. 2020).

Brazil's National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN) has overseen monitoring and issuing warnings of the risk of landslides, flash floods, and floods since 2011. CEMADEN monitors 1038 municipalities of a total of 5570 municipalities in Brazil. It relies on history and knowledge of exposed social systems, especially their vulnerability to heavy rainfall (Alvalá et al. 2019).

Southeast Brazil experiences frequent extreme precipitation events, leading to the cascading effects of flooding and landslides, population displacement, homelessness, and financial loss. For example, in January 2011, heavy rainfall sparked flash flooding and mudslides across the highlands of Rio de Janeiro, devastating mountain towns. According to official Brazilian sources, these floods and landslides claimed the lives of 918 people and left 99 missing and 35,000 homeless. It was the worst natural disaster in Brazil's history and became a driving motivation leading to the creation of CEMADEN that year. In that January 2011, the region had 460 mm of rain, in contrast to its January climatology of about 230 mm. In the highlands of Rio de Janeiro, 86–160 mm of rain fell from January 1–7 and about 300 mm from January 11–17 (Marengo and Alves 2012).

During the summer of 2020, several episodes of intense rainfall produced damages and fatalities in Belo Horizonte, São Paulo, Vitoria, and Rio de Janeiro (CEMADEN-www.cemaden.gov.br). On January 8–9, 2020, heavy rain affected the city of São Paulo, triggering landslides and flash floods. On January 23–25, 2020, heavy precipitation occurred in the city of Belo Horizonte, the capital of the state of Minas Gerais. Flooding and landslides left extensive material and human damage and exorbitant economic losses. The event broke records: 320.9 mm of precipitation accumulated in Belo Horizonte within 72 h, equal to approximately 97% of its January climatology (329.1 mm) (Dalagnol et al. 2021).

From November through December 2021, heavy rainfall affected the southern region of the state of Bahia (SBA) and the northern section of the state of Minas Gerais (NMG). It caused widespread floods, yet resulted in a relatively low number of casualties, given the events' intensity. National and international agencies reported the flood events in this region, with some rainfall records (WMO 2022). According to a report from the European Commission (2022), heavy rainfall caused significant flooding and river overflow starting in November 2021. In Bahia, 17 municipalities reported a state of emergency due to a dam collapse, followed by flooding that began on December 23. SBA and NMG suffered from the floods: Houses, schools, hospitals, and other infrastructure were damaged and destroyed, along with other losses and fatalities.

This paper comprehensively analyzes the meteorological and hydrological features observed during the November–December 2021 heavy rains that affected susceptible to floods areas of SBA and NMG. New historical rainfall records were set during those two months, and they were intense enough to trigger floods. We also investigate the meteorological conditions that resulted from those rainfall extremes, the hydrological impacts in the region, and trends in rainfall extremes. These are indicators of increasing climate risk that could lead to even more natural disasters in susceptible to floods areas of SBA and NMG in the future. We rely mainly on rainfall data and meteorological reports provided by the National Institute for Space Research (INPE), CEMADEN, and the National Institute for Meteorology (INMET), along with hydrology records from the ANA station network documenting periods of heavy rainfall in November and December 2021. We also use data from agencies such as the National Oceanic and Atmospheric Administration (NOAA), sites such as Relief Web and Flood List, and press agencies as auxiliary information (see the next section). Lastly, we discuss monitoring of conditions ladings to floods on that period, and the issuing of flood risk alerts by CEMADEN, that helped minimize damage and property loss and the number of lives lost due to the floods.

2 Data and methodology

The region impacted includes 574 municipalities, as reported by the Civil Defense of the states of Minas Gerais (http://www.defesacivil.mg.gov.br/boletim-diario) and Bahia (http://www.defesacivil.ba.gov.br/municipios-em-situacao-de-emergencia-chuvas/).

2.1 Atmospheric circulation

We explore changes in upper- and low-level circulation, convection, and moisture fields that led to anomalous wet conditions, particularly during the wettest period in the last week of December 2021, when total rainfall reached values up to 300% above average. For comparisons, similar analyses were performed for other wet episodes in November–December 2021 (see Supplementary Material Fig. S1). We investigate upper-, middle-, and low-level atmospheric fields, OLR, precipitable water, and soil moisture fraction (0–10 cm). All atmospheric fields come from NCEP/NCAR reanalysis; anomalies are relative to the 1981–2010 long-term mean. These datasets are available from the NOAA website: https://psl.noaa.gov/site_index.html.

2.2 Rainfall

For southern Bahia and northern Minas Gerais, precipitation datasets from INMET have good quality and long-term coverage. However, the spatial coverage is sparse, making global datasets such as the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS-Funk et al. 2015) the best available alternative to estimate spatially distributed precipitation in these regions. CHIRPS is a rainfall product available at daily to annual time scales, with a spatial resolution of 0.05°×0.05°, which contains data from 1981 onwards. The dataset also includes satellite imagery and rain gauge data to create gridded rainfall time series. The new dataset of CHIRPS version 2.0 has stations worldwide, including more than 11,000 in Brazil alone. This new dataset is available at https://data.chc.ucsb.edu/products/CHIRPS-2.0/. The CHIRPS-2.0 dataset has been applied in studies of several regions in Brazil (Marengo et al. 2021; Baez-Villanueva et al. 2017; Beck et al. 2017; Paredes-Trejo et al. 2017; Paca et al. 2020; Cuartas et al. 2022). CHIRPS-2.0 has been validated worldwide, including in Brazil (Baez-Villanueva et al. 2017; Paredes-Trejo et al. 2017; Paca et al. 2020; Cavalcante et al. 2020). Beck et al. (2017) CHIRPS-2.0 performs better than other gridded precipitation datasets in Brazil as shown in evaluate of its accuracy.

Records from INMET, INPE, and CEMADEN identify periods of heavy rainfall in November and December 2021. We use daily rainfall data from INMET stations in SBA and NMG to identify trends in heavy precipitation events to 2021. These data on rain accumulation in wet periods indicates trends in the number of days with rainfall above certain thresholds (50, 100, and 200 mm) and RX5day (rainfall accumulated in 5 days that can trigger flash floods). We also review weather reports from INMET for November and December 2021 (https://portal.inmet.gov.br/noticias/an%C3%A1lise-das-chuvas-na-bahia-minas-gerais-e-espir%C3%ADto-santo-em-dezembro-de-2021, last accessed on January 21, 2022) for station rainfall amounts and related weather patterns.

A new dataset comes from stations in CEMADEN's Environmental Observational Network. This network consists of nine dual-polarization S-Band weather radars, 3500 telemetric rain gauges, 301 hydrological stations equipped with pluviometers, water-level sensors, and cameras, 130 geotechnical stations with soil moisture sensors for different depths, and 595 automatic weather stations equipped with soil moisture sensors. All data from this network are reported every 10 min for Brazil's entire territory. In this study, we use the stations located in SBA and NMG. The sensors are deployed in previously mapped critical susceptible to floods areas, due to their history of natural disasters triggered by insufficient (drought) or excessive (flood, flash flood, landslides) water. We must stress that CEMADEN's observational network monitors conditions in high-risk areas. This differs from conventional observational meteorological and hydrological monitoring. For example, most of CEMADEN's rain gauges are located directly in risk areas, near unstable slopes or critical watersheds for flash floods. This dataset has been available since 2013, but some observational gaps exist due to maintenance and logistical problems. The data are freely available from http://www2.cemaden.gov.br/mapainterativo (Marchezini et al. 2020).

As auxiliary information, and for qualitative analysis to corroborate the impact of observed rainfall extremes on floods, we include information from national and international agencies and press reports on the internet and social media. We also include information from the websites Relief Web (https://reliefweb.int/disaster/fl-2021-000204-bra) and Flood List (https://floodlist.com). These sites provide updated flood-related information worldwide. They draw information from government and international agencies to describe the magnitude of disasters, geographical coverage, impact information, damages, and casualties.

2.3 Hydrological information

River level data are from Brazil's National Water and Sanitation Agency (ANA) through the National Hydro-meteorological Network (http://www.snirh.gov.br/hidrotelemetria/Mapa.aspx#). This provides real-time information (measured every 15–30 min). We choose six hydrological stations in Bahia and Minas Gerais (Table 1): Itajuípe, Mascote, Itapetinga, and PCH Colino1 (state of Bahia), and São Pedro do Pampã and UHE Itapebi (state of Minas Gerais). The daily time series of these stations come from the Hidroweb ANA system (https://www.snirh.gov.br/hidroweb/serieshistoricas).

Table 1 Description of hydrological stations

Station	River	Lat	Long	Responsible	Operator
Itajuípe	Almada	− 14.6744	− 39.3769	INEMA	
Itapetinga	Catole Grande	− 15.2414	− 40.2333	ANA	CPRM
Mascote	Pardo	− 15.5686	− 39.3044	ANA	CPRM
PCH Colino 1*	Jucuruçu	− 17.3203	− 40.6764	ESPRA	ESPRA
São Pedro do Pampã	Pampã	− 17.0822	− 40.0772	ANA	CPRM
UHE Itapebi**	Jequitinhonha	− 16.4222	− 41.0331	Itapebi Energy Company S.A	

Sources of data Institute of Environment and Water Resources (INEMA) of Bahia, National Water and Sanitation Agency (ANA), Brazilian Geological Service (CPRM), Serra da Plata Energy Company S.A. (ESPRA)

*PCH pequenas centrais hidroeletricas—small hydroelectric power plants

**UHE usinas de geração de energia—hydropower generation power plants

2.4 Trends in rainfall extremes

Historical daily rainfall data from 1980 to 2021 come from INMET. The five stations selected are distributed over the area of heavy rainfall in December 2021 in Bahia and Minas Gerais: Caravelas, Guaratinga, and Lençóis (Bahia), and Salinas and Pedra Azul (Minas Gerais). In addition, data from CHIRPS fill in the gaps in rainfall measurements, with a high resolution (0.05°) from 1981 onwards (Funk et al. 2015).

The extreme rainfall events in this study are characterized by indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI). These indices, based on daily rainfall values, use climatic extremes, such as frequency and intensity, to verify changes in local, regional, and even global weather and climate patterns (Frich et al. 2002; Peterson and Manton 2008; Zhang et al. 2011). Therefore, we choose the indices considered in the present study based on the extremes of rainfall in the study area (Table 2).

We use the ClimPACT2 software (Alexander and Herold 2016) to calculate the indices based on the RClimDex software (Zhang and Yang 2004), a code in the R language provided by ETCCDI. For all indices, the software provides an annual linear trend, standard error of estimates, and the trend's statistical significance level (*p*-value). The present study's trend is significant, at a level of 95% ($p \leq 0.05$). We use daily data from five INMET stations to calculate the indices. In addition, CHIRPS data help to identify rainfall anomalies in Bahia and Minas Gerais.

3 Description of heavy rainfall and hydrological disasters in southern Bahia (SBA) and northern Minas Gerais (NMG) from November to December 2021

This section describes the atmospheric circulation patterns leading to rainfall and hydrological extremes in the region on that period. From November 2021, heavy rains and subsequent floods affected SBA and NMG. On a more regional scale, Fig. 1 shows daily rainfall from November 1 to 30, 2021, for SBA (a) and NMG (b), and from December 1 to 31, 2021, for SBA (c) and (d) at stations in CEMADEN's network. The map at the top of the figure shows the stations used in the study (light blue color) while the red areas show regions that are susceptible to floods. These extreme rainfall events caused floods in SBA and NMG in November and December 2021. The hazard patterns (heavy rain) triggered disasters (flash floods) that affected vulnerable people living in exposed susceptible to flood areas and had severe impacts (deaths, economic losses, damages, displaced people). In the days before the disaster, government agencies issued forecasts for heavy rainfall and risk alerts for floods.

Table 2 Description of ETCCDI extreme rainfall indices used in this study

Index (units)	Definition
PRCPTOT (mm)	Annual total rainfall from wet days (wet day = rainfall rate ≥ 1 mm)
RX5day (mm)	Annual maximum consecutive 5-days rainfall
R10mm (days)	Number of days per year with rainfall ≥ 10 mm
R20mm (days)	Number of days per year with rainfall ≥ 20 mm
R50mm (days)	Number of days per year with rainfall ≥ 50 mm

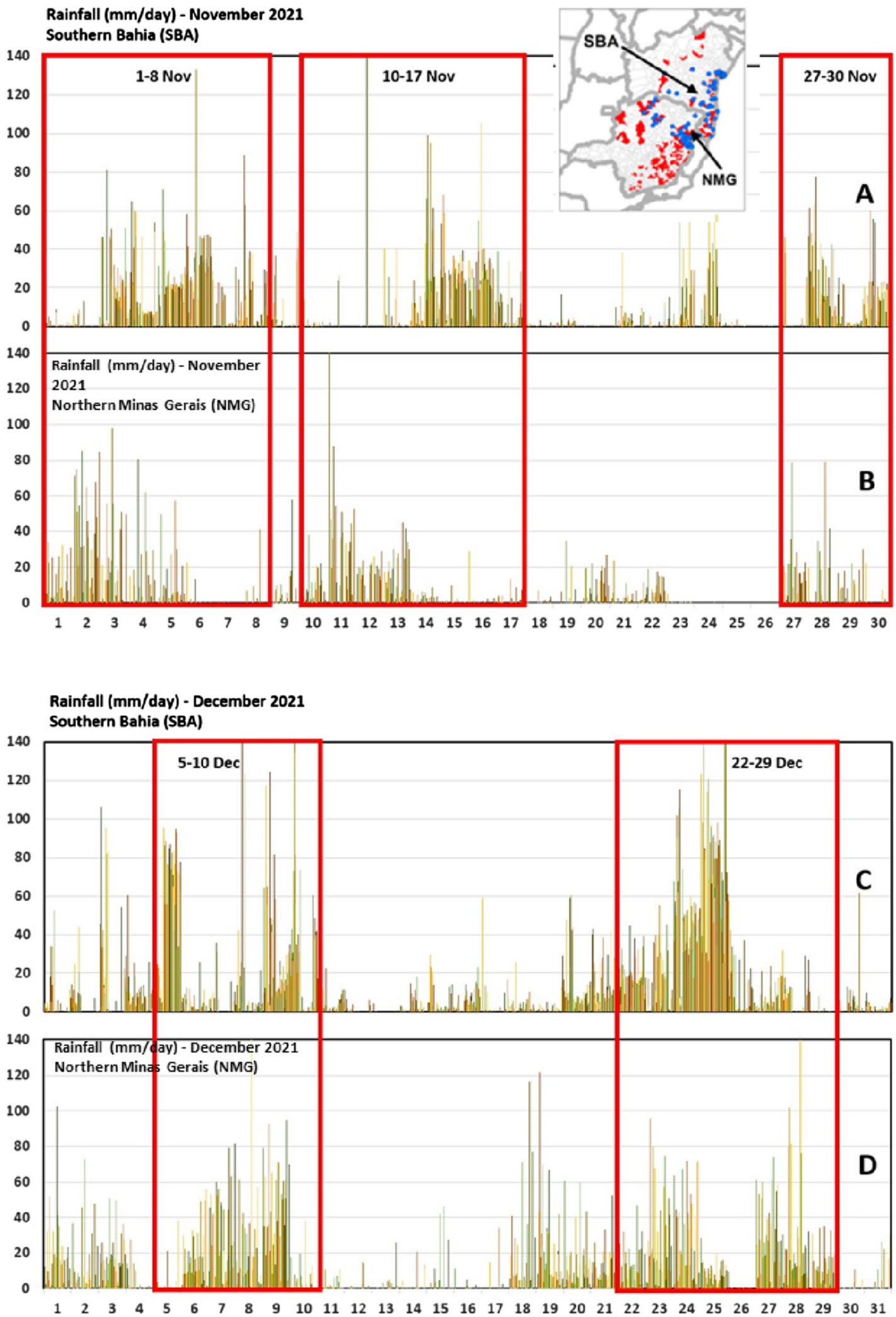


Fig. 1 Time series of daily rainfall in November 2021 for stations located in southern Bahia (**a**) and northern Minas Gerais States (**b**) for November 2021, and a similar arrangement is shown in (**c**) and (**d**) for December 2021. Wet periods are identified by red squares in both regions and months. The map on the upper sideshow in light blue color the location of the stations from the CEMADEN Network in the states of Bahia and Minas Gerais used for the time series. *Sources of data* CEMADEN Network

3.1 Atmospheric circulation during the wet period of December 22–29

To analyze the general context in which the episodes of heavy rain occurred, Fig. 2a, b shows wind anomalies at low (850-hPa) and high (200-hPa) atmospheric levels for the November–December 2021 period. A clear barotropic situation marked the dominant circulation during these two months since the anomalies show a distinct vertical coherence throughout the troposphere. This characteristic determined an almost stationary behavior of systems involved, consistent with a blocking situation, which justifies the persistence of rainfall patterns over two months.

A strong cyclonic anomaly dominated the atmospheric circulation over the Atlantic Ocean to the north of an anomalous anticyclone located over higher latitudes. Thus, the easterly anomalies observed south of the cyclonic anomaly, i.e., at medium and subtropical attitudes, were consistent with decreased baroclinic activity associated with rain-producing systems. On the other hand, the increase in westerlies to the north of 25°S, consistent with the strengthening of the subtropical jet, supported the activity of rainy systems, such as cold fronts and SACZ, over the states of Bahia and Minas Gerais.

In both NMG and SBA, the wettest period was December 22–29 (see Sect. 3.2). In NMG, December 27–29 was also very wet (Fig. 1). These were the periods, according to local media and relief agencies, when floods took the most lives. The circulation fields from Fig. 3a–f show the wettest period December 22–26, as anomalies compared to the mean of the whole month. The figure shows a meteorological situation that promoted intense convection and upward vertical motion moisture convergence along the South Atlantic Convergence Zone SACZ (see Sect. 3.2), in a moister atmosphere with a large amount of precipitable water over regions with saturated soil.

In terms of atmospheric dynamics, the overall meteorological situation was embedded in a barotropic pattern. This included a wide, warm anticyclonic circulation over southern South America and cyclonic circulation over southeastern South America and the region under study (Fig. 3a, d, e). An almost vertical structure occurred at high latitudes, while an

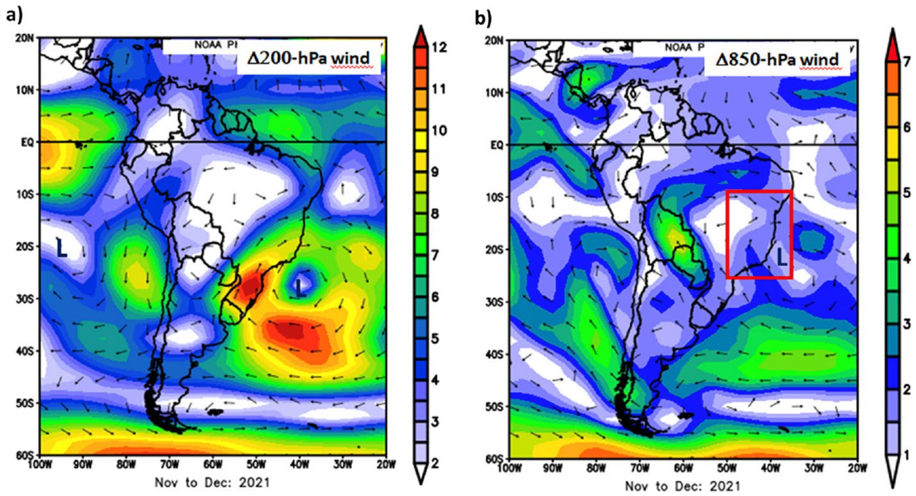


Fig. 2 Upper and low-level circulation field anomalies for the mean of November and December 2021 in South America. **a** 200 hPa winds (m/s), **b**) 850 hPa winds (m/s). Anomalies are relative to 1981–2010. *Sources of data* NOAA

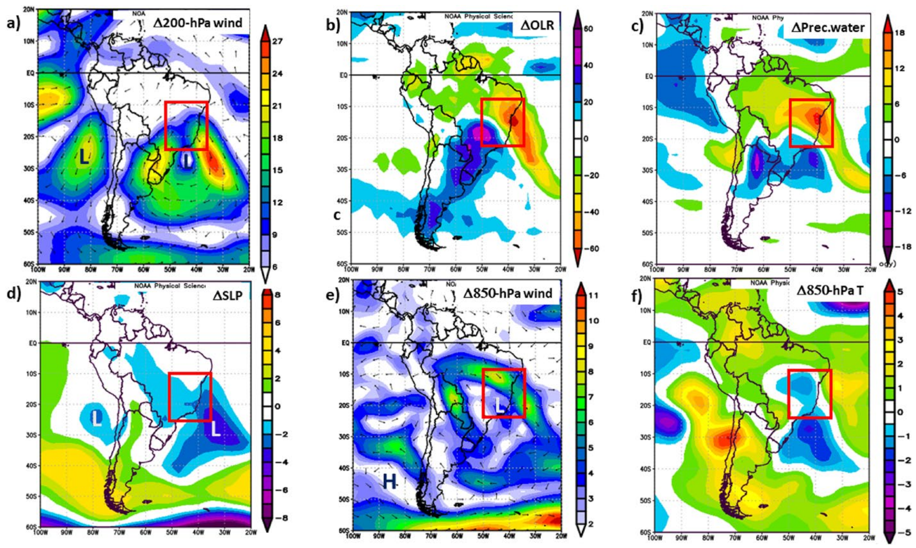


Fig. 3 Upper, middle and low-level circulation field anomalies for December 22–29, 2021 in South America. **a** 200-hPa winds (m/s), **b** OLR (W/m^2), **c** precipitable water (kg/m^2), **d** SLP (hPa), **e** 850 hPa winds (m/s), **f** air temperature 850 hPa (K), Anomalies are relative to 1981–2010. *Sources of data* NOAA

intense cold cyclone hovered over the Atlantic Ocean, east of southern Brazil (Fig. 3f). The barotropic structure of this cyclone is also apparent, since it extended from the surface all the way up to high tropospheric levels (Fig. 3a). Due to the barotropic nature of the general situation, different forcings acted together for several days, yielding significant humidity anomalies allied to continuous vertical movement, and large areas of low-level convergence. These factors are a fundamental cause of persistent and abundant precipitation. In addition, low-level 850-hPa circulation (Fig. 3e) northwesterly wind anomalies allowed persistent anomalous moisture transport from the Amazon to the region of interest. This flow contributed to strong precipitable water anomalies (Fig. 3c), upward motion, strong convection (Fig. 2b), and heavy rainfall in the region, leading to wet soil (not shown).

Because the 2020–2021 austral summer was affected by the La Niña phenomenon, rainfall over the Amazon was higher than expected, probably producing higher moisture transport to eastern Brazil than during average conditions. Low-level convergence and increased precipitable water associated with the cyclone triggered the intense and persistent rainfall. This situation was reinforced by the proximity of the mid-level trough axis. However, the stationary character of the cyclone did not allow a strong advection of cyclonic vorticity. Instead, it combined with warm and humid air on the surface over the impacted area, to facilitate the convective ascent of the air (Fig. 3b, f).

Figure 4a shows a Wave 4 pattern at the upper and middle levels (as shown by the 200-hPa and 500-hPa and wind anomalies at midlatitudes), frequently associated with blocking. Figure 2 indicates that the rain in BA-MG on December 22–29 was not a local event, but part of a global circulation pattern. The trough and the jet at high levels are evident. This is another factor contributing to lifting the air and the subsequent increase in convection and rainfall, due to increased low-level moisture transport into the region in December 2021. This configuration of the subtropical upper-level jet could compound the SACZ stationarity and the occurrence of anomalous precipitation over southeastern South America

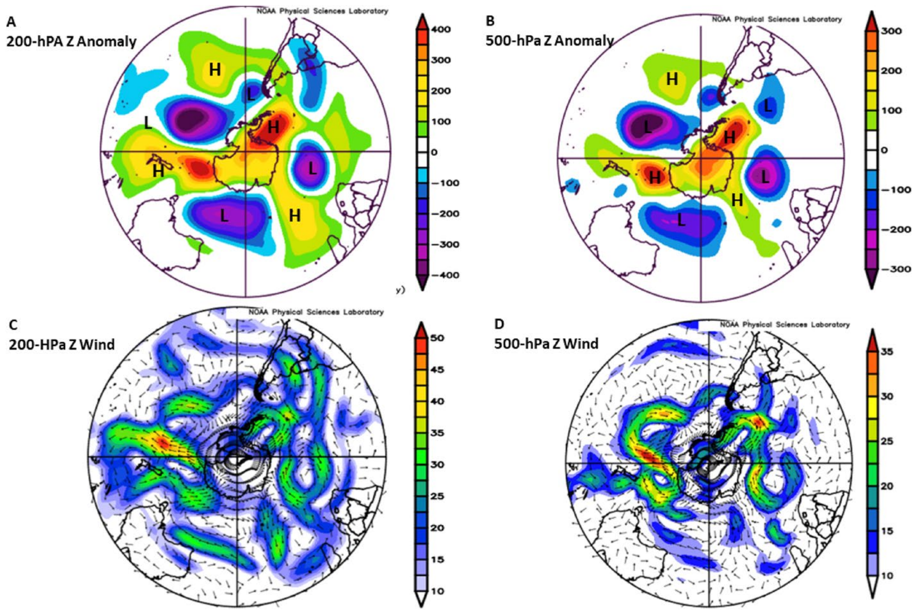


Fig. 4 Upper and mid-level circulation field anomalies for December 22–29, 2021, in the southern hemisphere. **a** 200-hPa geopotential height (m), **b** 500-hPa height (m), **c** 200-hPa winds (m/s), **d** 200-hPa winds (m/s). Anomalies are relative to 1981–2010, *Sources of data* NOAA

(Baez-Villanueva et al. 2017; Carvalho et al. 2002). Mid-latitude westerly winds turned to easterly winds at 40–50° S and 60–40°W (Fig. 3f), a typical signature of atmospheric blocking (Trenberth 1985). This pattern supported the stationarity of the atmospheric pattern that fed the SACZ structure. Remarkably, there is a persistent low-pressure anomaly off the southeastern Brazilian coast (Fig. 3e). As shows in Sect. 3.2, due to the presence of the SACZ, the states of Bahia and Minas Gerais experienced heavy rainfall starting in November and December 2021.

In sum, during December 22–29 two cutoff upper-level low-pressure systems have formed to the north of a high-pressure blocking system stretched west-to-east across southern portions of South America. One low is southeast of Brazil and is causing historic rainfall across Brazil. A second upper low is off South America's West Coast, causing the heavy rain pattern to arc westward.

3.2 Rainfall

This subsection describes the rainfall in Brazil in November and December 2021. Heavy rainfall episodes started in November 2021. The summer season, from December to February, is generally considered the rainy season, when most rain-related disasters occur in the country. Because of the SACZ, the states of Bahia and Minas Gerais experienced heavy rainfall starting in early November 2021. The SACZ is the main system that causes intense rainfall in the region and is one of the atmospheric system components of the South American Monsoon System. The SACZ is a convective band that extends northwest–southeast from the Amazon Basin to the subtropical South Atlantic Ocean, identifiable by persistent cloudiness and frequently configured in the austral summertime (Carvalho et al. 2004 and references therein).

The propagation of mid-latitude wave trains east of South America modifies circulation and moisture transport in the tropics and subtropics from the Amazon region by the South American low-level jet (LLJ) east of the Andes (Carvalho et al. 2004; Marengo et al. 2004). The regional distribution of extreme precipitation depends on the position and intensity of the convection along the SACZ (Carvalho et al. 2002). In addition, the north–south Atlantic SST gradient influences SACZ, LLJ, and continental rainfall (Kitoh et al. 2020). This meteorological situation is likely associated with a Madden–Julian Oscillation (MJO) that modulates SACZ intensity (Kitoh et al. 2020).

Rainfall patterns in NMG and SBA are shown in Fig. 1. SBA's heavy rainfall events in November and December 2021 had atypical timing and intensity. Figure 5 shows the climatology of rainfall (1981–2010) in the states of Bahia and Minas Gerais for November and December (a, b), the accumulated rainfall in November and December 2021 (c, d), and the respective anomalies (e, f). The region under study is located inside the red box at the top of the panel (to identify the region on the map of Brazil, shown in more detail in Fig. 5e–f. Figure 5a, b shows that over the SBA-NMG region. November and December climatology is between 150 and 200 mm/month. In December 2021, it rained more than 3000 mm, and rainfall anomalies show more than 200 mm above average (Fig. 5c, d), indicating that rainfall was several times above normal. Given this, the study region is defined and shown in the red boxes in Fig. 5e, f, and further analyses focus on that region for stations in SBA and NMG that surpassed 200 mm in December 2021.

According to INPE (technical bulletins available from http://tempo.cptec.inpe.br/boletimtecnico/pt, with a choice of month and date), from November 1 to 8, SACZ episodes were detected in SBA. Again, from November 10 to 17, SACZ affected not only this same region, but also the state of Espirito Santo. One more SACZ episode on November 27–30, 2021, affected Bahia, Espirito Santo, and Rio de Janeiro. Red boxes indicate these episodes in Fig. 1. According to INMET and CEMADEN (https://www.gov.br/cemaden/pt-br/assuntos/monitoramento/boletim-de-impactos/boletim-de-impactos-de-extremos-de-origem-hidro-geo-climatico-em-atividades-estrategicas-para-o-brasil-2013-14-01-2022-ano-5-no-38, last accessed on September 29, 2022), in December 2021, three SACZ episodes (December 1–4, 7–11, and 23–27) affected the region between SBA and NMG. Finally, on December 7, storms caused by the passage of a subtropical cyclone formed near the coast of Rio de Janeiro. These, combined with moisture convergence and the SACZ, produced heavy precipitation that affected several cities in SBA.

For an example of an individual station, in Itamaraju (17° 02′ S; 39° 03′ W), according to CEMADEN, it rained 769.8 mm in December 2021 (climatology of 148 mm). The previous record was in December 1989, when abundant rainfall caused overflowing rivers and flooding, and closed highways, including the BR 101. At that time, 2 people died, 267 were injured, 6371 were left homeless, and 15,199 were displaced. In total, 220,297 people were affected by the floods. In that month, it rained 400 mm (240% above normal) in Vitoria da Conquista; 504.6 mm in Caravelas (260% above normal); 421.9 mm in Cruz das Almas (3167% above normal); 248.7 mm in Jacobina (218% above normal); 648 mm in Lencois (460% above normal); 223.2 mm in Morro do Chapeu (212% above normal); and 387.9 mm in Salvador-Ondina (512% above normal), according to information provided by INMET.

According to the Institute for the Environment and Water Resources of the state of Bahia (INEMA-www.inema.ba.gov.br), on December 23–27, it rained 215 mm in Valença (13° 22′ S; 39° 04′ W, climatology of 64.9 mm); 209 mm in Ilheus (14° 47′ S; 39° 02′ W,

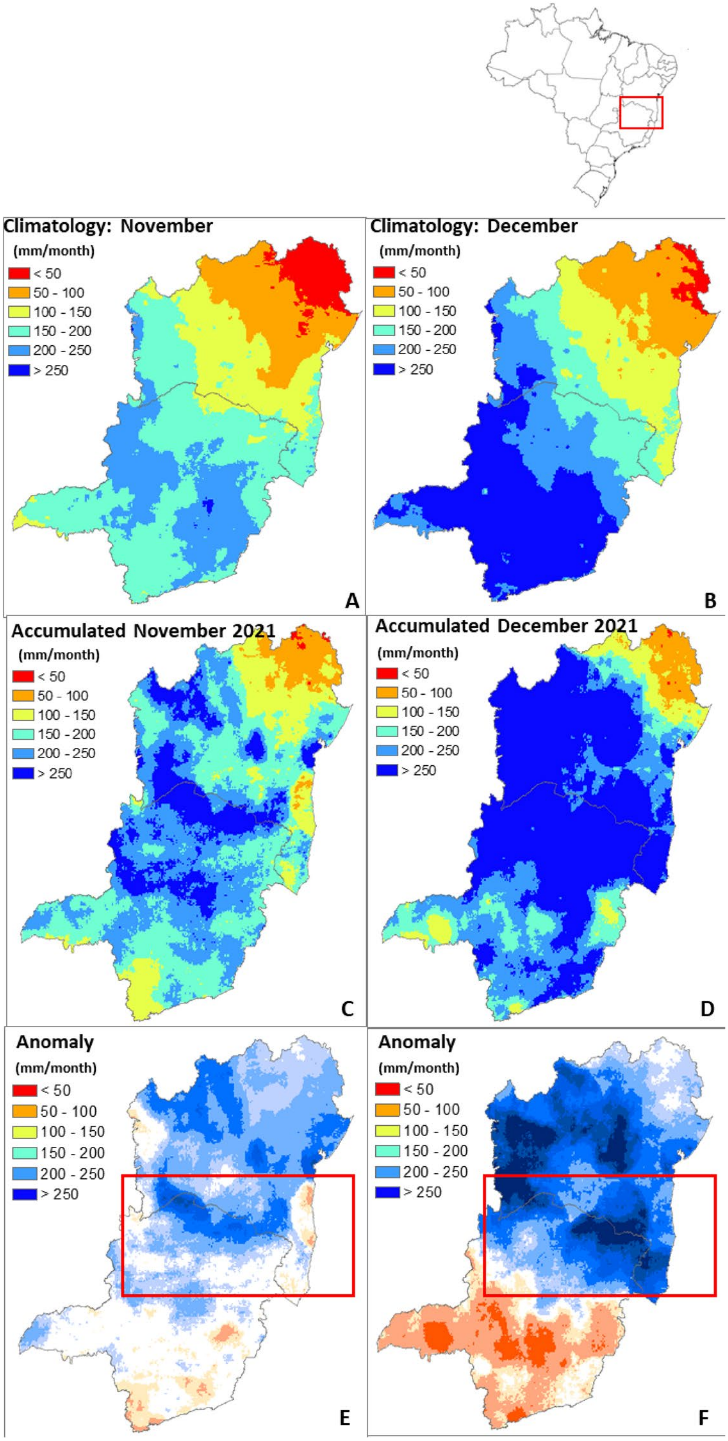
Fig. 5 Rainfall in the States of Bahia and Minas Gerais in southeast Brazil. **a** Climatology for November, **b** Climatology for December, **c** Accumulated rainfall in November 2021, **d**) Accumulated rainfall in December 2021, **e** Rainfall anomaly for November 2021, **f** Rainfall anomaly for December 2021. Units in mm/month. The color scale is shown on the upper left side of each panel. Anomalies are relative to 1981–2010. The area of interest covering the southern part of the state of Bahia and the northern region of Minas Gerais is shown inside the red square in the map of Brazil in the upper-level and in figures e and f. *Sources of data* CHIRPS

climatology of 122.8 mm); and 188 mm in Salvador (climatology of 58.1 mm), all located in SBA.

In Salvador, the capital of Bahia, it rained 175.65 mm from December 1–10. The climatology is 58.1 mm. On December 13, according to the site *Noticias Agricolas* (www.noticiasagricolas.com.br/noticias/soja/304834-excesso-de-chuvas-atinge-lavouras-de-soja-na-Bahia-com-alagamentos-e-plantas-mortas.html#.YfE7NWBvBI, last accessed on March 1, 2022), the excessive rainfall affected soybean fields in the state of BA with floods. The waterlogged soil killed the plants. While the planting for 2021/2022 benefited from early rainfall in October, rainfall increased and triggered floods. The rains persisted in significant volumes. On December 15, another SACZ episode produced high accumulated rainfall values. On that day, 86.2 mm of rain fell in Vitoria da Conquista (14° 51′ S; 40° 50′ W), 70.8 mm in Salvador (12° 58′ S; 38° 28′ W), and 57.0 mm in Cruz das Almas (12° 39′ S; 39° 07′ W) in SBA.

The meteorological pattern that characterized the wettest period of December 22–29 consisted of atmospheric trough episodes on the coast of the state of Bahia, moisture convergence in the middle and lower layers, and moisture transport coming from Amazonia. Evaporation arose from a warmer tropical South Atlantic off the coast of the state of Bahia (around 2–2.5 °C warmer than average since November 2021). The horizontal SST gradient between the ocean and SAB induced the cold fronts to remain stationary for a few days over the region. All these conditions, including the SACZ and moisture from Amazonia, produced more rainfall in SBA and NMG. At intraseasonal time scales, according to NOAA (www.cpc.ncep.noaa.gov/products/precip/CWlink/ghazards/ARCHIVE/PDF/20211207_ghazard.pdf, last accessed on September 30, 2022), the MJO strengthened during late November and early December 2021, and forecasts for December 15–21 showed moderate confidence for weekly total rainfall in the upper third of the historical range from central Amazonia to southeast Brazil, including SBA and NMG. At interannual time scales, 2021 was also a La Niña year that started in 2020 and continued in 2022 (https://www.noaa.gov/news/double-dip-la-nina-emerges, last accessed on September 29, 2022).

As a result, by December 26, greater daily rainfall totals were detected in locations in SBA: 127.6 mm in Itiruçu (13° 31′ S; 40° 09′ W), 77.6 mm in Barreiras (12° 09′ S; 44° 59′ W), 66.8 mm in Guanambi (14° 12′ S; 42° 46′ W), 63.8 mm in Salvador, and 58.6 mm in Ilhéus. By December 27, in Itabuna, in SBA, the Cachoeira river that crosses the city rose by about 10 m. Bridges closed, energy was shut down, and the isolated population had to be rescued by helicopter (*SBT News 2021*-www.sbtnews.com.br/noticia/primeiro-impacto/191765-chuvas-na-Bahia-Rio-em-Itabuna-sobe-quase-10-metros, last accessed on January 27, 2022). During that period, heavy rainfall claimed victims across the state. The level of several rivers rose, bursting two dams near the municipalities of Vitoria da Conquista and Jussiape in Bahia (https://reliefweb.int/report/brazil/acaps-briefing-note-brazil-floods-bahia-and-minas-gerais-07-february-2022, last accessed on September 30, 2022). Rescue and relief operations proved to be highly complex and time-consuming, due to flooding on roads and the continuing rains in the region.


Climatology: November
(mm/month)
< 50
50 - 100
100 - 150
150 - 200
200 - 250
> 250
A
Climatology: December
(mm/month)
< 50
50 - 100
100 - 150
150 - 200
200 - 250
> 250
B
Accumulated November 2021
(mm/month)
< 50
50 - 100
100 - 150
150 - 200
200 - 250
> 250
C
Accumulated December 2021
(mm/month)
< 50
50 - 100
100 - 150
150 - 200
200 - 250
> 250
D
Anomaly
(mm/month)
< 50
50 - 100
100 - 150
150 - 200
200 - 250
> 250
E
Anomaly
(mm/month)
< 50
50 - 100
100 - 150
150 - 200
200 - 250
> 250
F

In sum, the higher-than-normal rainfall in the first two periods of November 2021 started in NMG and later moved to SBA, particularly from November 10–17. On November 10–13, intense rainfall affected NMG, and from 14 to 17, it migrated SBA with almost the same intensity. CPTEC/INPE and INMET (CPTEC INPE 2022; INMET 2021) identify episodes of SACZ from November 2 to 7, 12 to 15, and 20 to 23, 2021, and from December 7 to 11 and 22 to 29, 2021. In the third period, the two regions experienced heavy rainfall almost simultaneously, although it was less heavy than in the other periods. However, the impacts were much greater because of the wet soil, due to the heavy rainfall in previous periods in November and early to mid-December.

Based on these criteria, we select some periods with intense rainfall in the region for detailed analysis of rainfall distribution: November 1–8, 10–17, and 27–30, 2021, and December 7–11 and 22–29, 2021. The SACZ was present during some days in all those periods. Figure 1 shows the relevant data from the CEMADEN network. Figure 5 shows accumulated rainfall in these periods (Fig. 6a–c, e, f), as well as the monthly accumulation in November and December 2021 (Fig. 6d, g). The dots represent the location of the CEMADEN stations. Heavy rainfall and flooding in early and mid-November affected 471,009 people across 116 municipalities. Around 100 municipalities declared a state of emergency (Fig. 6a). December 22–29 had accumulated rainfall between 300 and 500 mm at some stations. Floods triggered by heavy rainfall caused fatalities. Further heavy rain fell in the state starting December 23, 2021. INMET shows 87.4 mm of rain in 24 h in the city of Barreiras on December 23 and 117.9 mm in Caravelas (17° 45′ S; 39° 15′ W) on December 24. Vitória da Conquista saw 89.8 mm in 24 h, while Itiruçu recorded 127.6 mm in 24 h on December 26, all located in SBA.

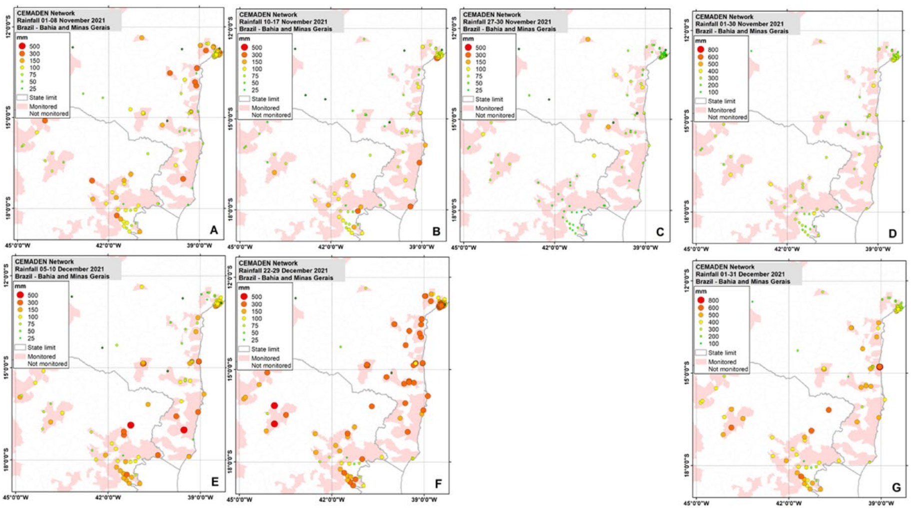


Fig. 6 Accumulated rainfall for southern Bahia and northern Minas Gerais during wet periods identified in Fig. 2 for November (**a**, **b**, **c**) and December (**e**, **f**) in mm. Figures d and g show the monthly rainfall accumulated for November and December 2021, respectively. Units are in mm. The period and color scale appears at the top left side of each panel. *Sources of data* CEMADEN network

3.3 Hydrological features

Figure 7 shows river level variations from October 15, 2021, to January 10, 2022. Although this period represents only part of the rainy season in SBA and NMG, the sequence of extreme rainfall events that started in November 2021 led to rapid soil saturation. Therefore, when the heaviest rains fell in December 2021, most of the water became direct surface runoff, quickly reaching the rivers in the region. The significant rise in river levels caused them to overflow. The maximum peak level observed during December 22–29 was 0.60 m at Itajuípe, 10.03 m at Mascote, 7.88 m at Itapetinga, and 8.61 m at the UHE Itapebi. As a result, the levels at Itajuípe (Almada River), Itapetinga (Carole Grande River), and Mascote (Pardo River) increased by 5.13, 5.45, and 7.95 m from their historical December mean (0.91, 2.43, and 2.08 m, respectively). At São Pedro da Pampã station (Pampã River), the maximum peaks on December 7–11 and 22–29 were 3.98 and 3.90 m, respectively: 2.60 and 24.54 m above the mean level for December. For the Jucuruçu River, the maximum level of 6.42 m on December 7–11 was registered at PCH Colino1 station. These values represent an increase of 4.62 m

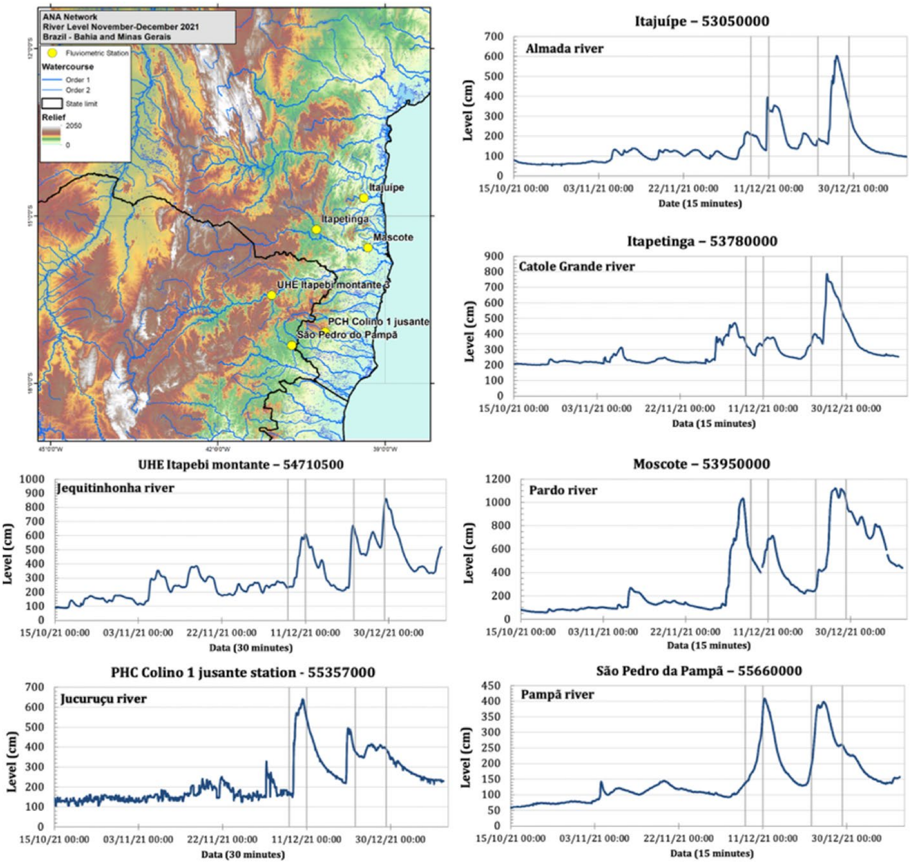


Fig. 7 Hydrological stations location and time series of river levels (cm) from October 15, 2021, to January 10, 2022. The data were registered every 15 and 30 min. *Sources of data* Table 1

from the December mean of 1.80 m for 2015–2019. Unfortunately, no historical data are available for the UHE Itapebi station.

The maximum river levels in December 2021 were higher than any previously recorded for the stations of Itajuípe (1980–2018), Itapetinga (1980–2020), and PCH Colino1 (2015–2019). These correspond to anomalous river rises of 0.94 m, 2.36 m, and 2.05 m, respectively. These observations suggest that the events in the evaluated period set a new historical maximum value. On the other hand, at Mascote and São Pedro do Pampã stations, the peak levels in December 2021 were below the maximum historical value (11.00 m on March 24, 1997, and 4.38 m on November 13, 2006, respectively). The Bahia state government reported on December 29 that 629,398 people had been affected by floods, with 91,258 displaced. Over 430 people had suffered injuries. (https://floodlist.com/america/brazil-floods-bahia-december-2021-update, last accessed on September 28, 2022).

3.4 Trends in monthly and daily precipitation extremes

Figure 8 compares mean monthly rainfall from 1981 to 2010 and rainfall for 2021 from the 5 INMET stations in SBA and NMG. In December 2021, rainfall was well above normal in all stations listed in Table 3 (for SBA). Table 3 shows average values from December 1981–2010 of 149.1, 165.4, 149.4, 191.6, and 192.0 mm, with overestimated rainfall amounts compared to December 2021, of 353.1, 255.2, 498.0, 533.4, and 301.9 mm, at Caravelas, Guaratinga, Lençóis, Pedra Azul, and Salinas, respectively. In 2021, these values represented an increase more than 250% over the long-term average

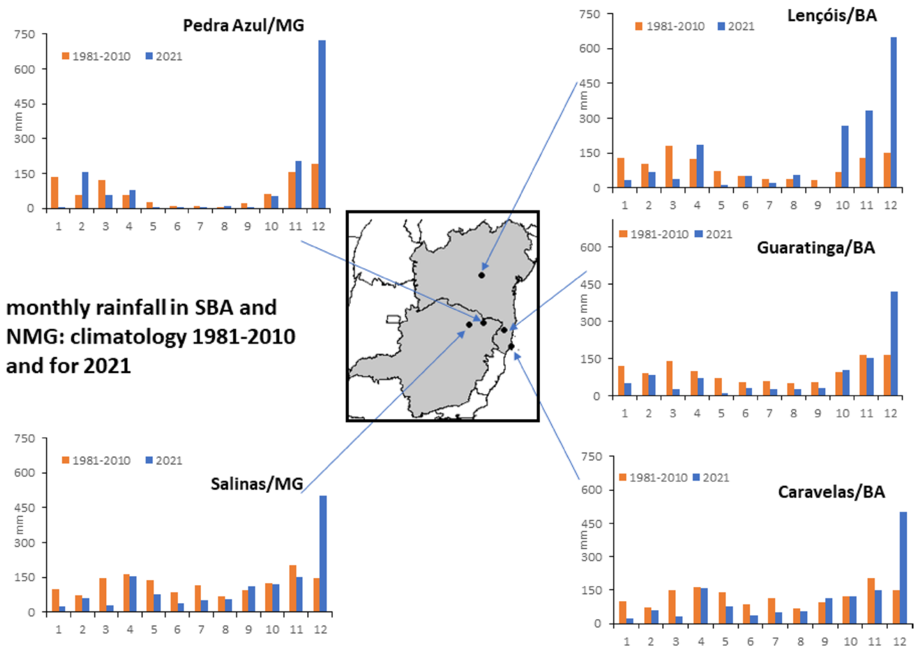


Fig. 8 Monthly rainfall for 1981–2010 climatology (orange bars) and 2021 (blue bars) for the 5 rainfall stations in southern Bahia and northern Minas Gerais used in this study. Units are in mm/month. *Sources of data* INMET

Table 3 December rainfall averages and 2021 values for stations shown in Fig. 8

Station/period	1981–2010 (mm)	2021 (mm)	Deviation (mm)	Deviation (%)
Caravelas	149.1	502.2	353.1	337
Guaratinga	165.4	420.6	255.2	254
Lençóis	149.4	684.4	498.0	433
Pedra Azul	191.6	725.0	533.4	378
Salinas	192.0	493.9	301.9	257

Deviation from long-term (1981–2010) levels for stations in SBA and NMG (source INMET)

(1981–2010), reaching an extreme 433% at Lençóis. In other stations not depicted in Fig. 8, but located in SBA, 400 mm (240% above normal) of rain fell in Vitoria da Conquista; 504.6 mm in Caravelas (260% above normal); 421.9 mm in Cruz das Almas (316% above normal); 248.7 mm in Jacobina (218% above normal); 223.2 mm in Morro do Chapeu (212% above normal); and 387.9 mm in Salvador-Ondina (512% above normal).

In SBA, in Lençóis, December 2021 was the wettest month ever. The previous record had been from 1989, with 564.5 mm of rain. Rain at other INMET stations in December 2021 is not listed in Table 3: 421.4 mm in Barreiras in 2021 (previous records are 684.4 mm in 1989 and 442 mm in 1985); 449 mm in Correntina in 2021 (the record is 787.4 mm in 1989); 421.9 mm in Guaratinga in 2021 (the record is 489.6 mm in 1989); 319.6 mm in Bom Jesus da Lapa in 2021 (the record is 612 mm in 1989; and 414.4 mm in 1985); and 447.8 mm in Vitoria da Conquista (the record is 447.8 mm in 1989).

Figure 9 shows the time series of annual total rainfall (PRCPTOT) and annual maximum consecutive 5-days rainfall (RX5day). Figure 9 shows the time series of the number of days with rainfall above 10 mm (R10mm), 20 mm (R20mm), and 50 mm (R50) during 1980–2021. While neither figure shows a clear trend in the time series of these rainfall indices, December 2021 appears extremely high relative to 1980–2021 values, particularly for R10 and R20. It may be comparable to 1989 (as explained in previous sections). This shows a large interannual variability of rainfall in the region.

Table 4 shows that only the R10mm index featured a significant trend at a 95% level in the stations evaluated in the present study. The annual total rainfall (PRCPTOT) tends to decrease by − 4.569 mm, − 5.905 mm, − 3.454 mm, − 0.429 mm, and − 2.012 mm per year at Caravelas, Guaratinga, Lençóis, Pedra Azul, and Salinas, respectively. The indices that represent the annual maximum consecutive 5-days rainfall (RX5day) also show a tendency to decrease by − 0.301 mm, − 0.191 mm, and − 0.088 mm at Caravelas, Guaratinga, and Lençóis, but to increase by 0.988 mm and 0.262 mm per year at Pedra Azul e Salinas, respectively. The indices representing the wet days, R10mm, R20mm, and R50mm, show an overall negative trend for the number of days with rainfall amounts above 10, 20, and 50 mm, except Salinas for R20mm, and Caravelas, Pedra Azul and Salinas for R50mm. Figure 9 shows that December 2021 was extremely high, despite the negative trends.

Figure 10a shows an increase in the RX5day index in SBA, NMG, and the west side of the state of Bahia. However, these changes do not reach significance (Fig. 10b). These anomalies are driven by the extreme rainfall events observed in December 2021. In the rest of Minas Gerais, a negative trend in RX5day reaches statistical significance, particularly near the Cantareira System, that provides water for São Paulo. This system of reservoirs is in the southern part of the state of Minas Gerais, on the border with the State of Sao Paulo.

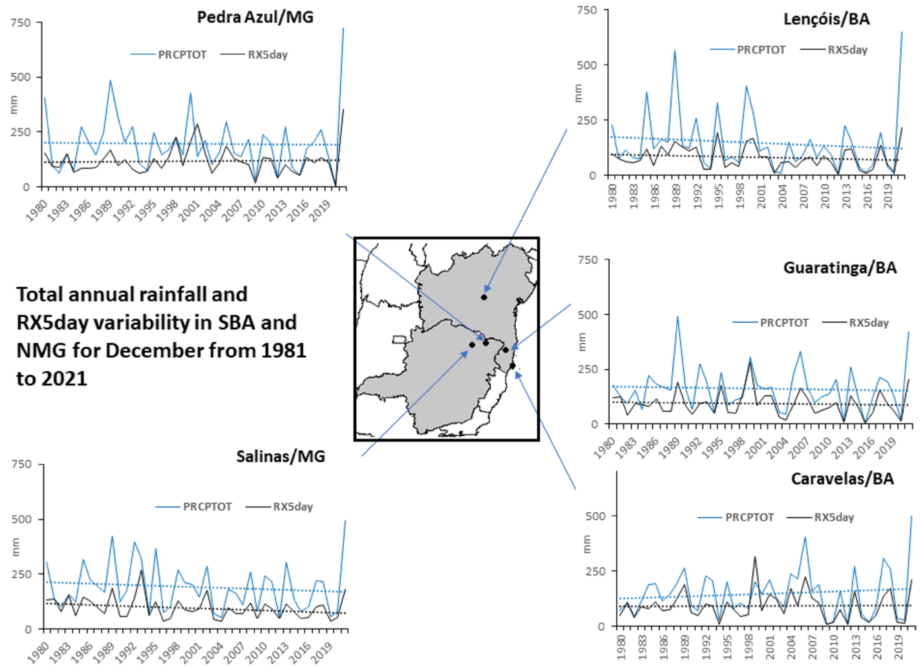


Fig. 9 Time series of annual total rainfall (PRCPTOT-blue line) and annual maximum consecutive 5-days rainfall (RX5day-black line) for 1981–2021 for the 5 INMET rainfall stations in southern Bahia and northern Minas Gerais used in this study. Broken lines represent the linear trends. Units are in mm/month. *Sources of data* INMET

Table 4 Trends of ETCCDI extreme rainfall indices for the stations analyzed

Index (units)	Caravelas	Guaratinga	Lençóis	Pedra Azul	Salinas
PRCPTOT (mm)	−4.569	−5.905	−3.454	−0.429	−2.012
RX5day (mm)	−0.301	−0.191	−0.088	0.988	0.262
R10mm (days)	−0.332*	−0.248	−0.146	−0.056	−0.085
R20mm (days)	−0.142	−0.113	−0.045	−0.021	0.021
R50mm (days)	0.033	−0.020	−0.025	0.034	0.011

*Significant at 95% level ($p \leq 0.05$)

While SBA and NMG had more days with rainfall above 20 mm and 50 mm in December 2021 (Fig. 11c, e), in the long term, the observed trends have negative tendencies in both states (Fig. 11d, f) in the SBA and all the state of Minas Gerais. This confirms previous analyses with no clear trend in the rainfall total and extremes in SBA and NMG. However, December 2021 was extremely high, compared with 1980–2021, as shown by rainfall anomalies from the stations from INMET and CEMADEN and at the regional level from the CHIRPS dataset. The positive R20 and R50 anomalies in SBA and NMG and the weak positive trends in these areas suggest that these trends forced the extreme rainfall in December 2021.

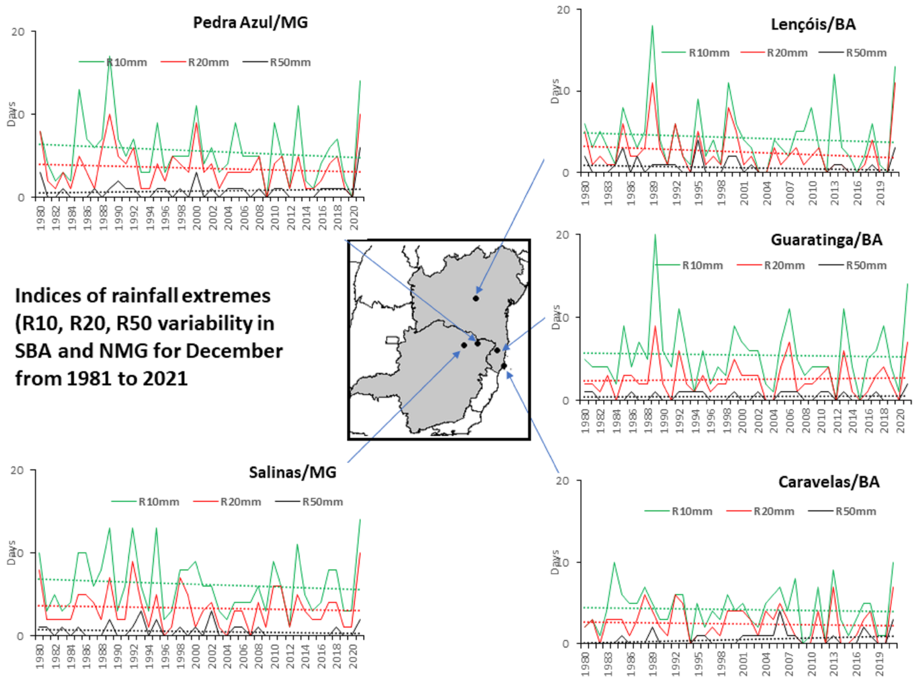


Fig. 10 Similar to Fig. 9, but for the number of days with rainfall above 10 mm (R10mm-green line), 20 mm (R20mm-red line), and 50 mm (R50mm-black line)

4 Discussion

Although rainfall alternated between SBA and NMG in November and December, 2021, the heaviest rain fell in SBA and NMG during the last week of December. Unfortunately, soil saturation from previous intense rainfall events caused disasters. Floods left fatalities and substantial economic damage in the region. Rainfall in SBA and NMG in December 2021 was between 250 and 430% above the 1981–2010 climatology. In SBA, it rained more than five times the average for this time of year.

The weather-related patterns that triggered floods reported in the previous paragraphs were associated with the action of the summertime SACZ and moisture transport coming from Amazonia. The SACZ during the wettest period between December 22 and 29 was anomalously northward, located over SBA and NMG. The meteorological situation favored intense convection, upward vertical motion, and moisture convergence along the SACZ in a moister atmosphere with extensive precipitable water and saturated soil contents. Due to the barotropic nature of the regional atmospheric circulation, different forcings acted for several days, yielding significant humidity anomalies allied to constant vertical movement and large areas of low-level convergence. The upper and middle atmospheric circulation favored blocking, and the configuration of the subtropical upper-level jet may have led to the SACZ's stationarity and the anomalous precipitation over SBA and NMG. The MJO also enhanced moisture convergence in the region in a climate scenario governed by La Niña.

Fig. 11 Spatial distribution of RX5day (**a**), R20 (**b**), and R50 (**c**) anomalies for December 2021; Spatial ▶ distribution of Sen's slope coefficients of linear trends and their significance for (**d**) RX5day, (**e**) R20, and (**f**) R50 for December over the period 1981–2021. Cross-hatching shows areas with significant trends at 95%. *Sources of data* CHIRPS

According to local media and state agencies, floods damaged and destroyed houses, schools, hospitals, and other infrastructure in November and December 2021 in the southern region of Bahia and the northern part of the State of Minas Gerais. State agencies' preliminary reports indicate that at least 33 people died: 27 in Bahia (Governo do Estado de Bahia 2022) and 6 in Minas Gerais (Civil Defense of the State of Minas Gerais 2022). The casualties resulted from floods, particularly in the last week of December (Civil Defense of the State of Minas Gerais 2022). Furthermore, sanitary conditions were severely compromised with concomitant risk of disease outbreaks. Schools were used as shelters, jeopardizing safe return to education. In addition, mental health and child protection among children and adolescents may have suffered (Web Relief 2022; UNICEF 2022). Data from the National Committee of Municipalities CNM (2022) show estimated losses due to disasters in Bahia and Minas Gerais from October 1, 2021, to January 17, 2022, on the order of $15.4 billion Brazilian Reais (about $3.1 billion).

Hydrological records show anomalously high river levels, particularly between December 22 and 29, with average increases of 900 and 708 cm at some stations, compared to the level on November 1, 2021, before the extreme rain events. The heavy rains in December 2021 turned into a direct surface runoff, quickly reaching the rivers in the region. The resulting soil saturation and significantly higher levels caused them to overflow. From December 17, 2021, five days before the start of the heavy rain events that triggered the floods, first contacts (by e-mail, phone calls, WhatsApp, and social media) between the region, the municipal offices of the Civil Defense, and CEMADEN were made, regarding the risk of hydrological disaster due to the dangerously high amount of rain in SBA.

CEMADEN, with the help of other federal agencies such as INMET, INPE, and the Brazilian Geological Survey (CPRM), identified high and very high hydrological risks (of floods in the region). At that moment, daily bulletins of hydrological risk were submitted to CENAD, which communicated this forecast to the civil, municipal, and state police and emergency services. Figure 12 shows that from December 20, the Risk Forecast Bulletin issued by CEMADEN indicated a moderate risk for locations in SBA until December 22. By December 23, the area with high-risk alert extended to NMG and the state of Espírito Santo. A forecast of high risk for floods in SBA and NMG appeared on December 24, and by December 25, the high-risk area extended to large parts of SBA and NMG, and it remained in SBA until December 30. These bulletins are available daily on CEMADEN's website (https://www.gov.br/cemaden/pt-br/assuntos/riscos-geo-hidrologicos/30-12-2021-previsao-de-riscos-geo-hidrologicos, last accessed on September 30, 2022. This bulletin is for December 30, 2021. For previous bulletins, the date is formatted day-month-year. So 30-12-2021 is for December 31, 2021.

In December 2021, rainfall was monitored at the municipal level. The high amounts predictably led to flooding. As seen in previous sections, on December 24 it rained more than 110 mm in several locations in SBA. Total rainfall at the state capital Salvador exceeded 250 mm, five times the historic average. Floods were reported there on Christmas Eve. A total of 92 hydrological alerts for SBA and NMG were issued by CEMADEN, 24 h in advance from December 22 to 29. In fact, 45 occurrences of floods were reported in municipalities in SBA and NMG during that period. The high risk of flood in SBA and NMG

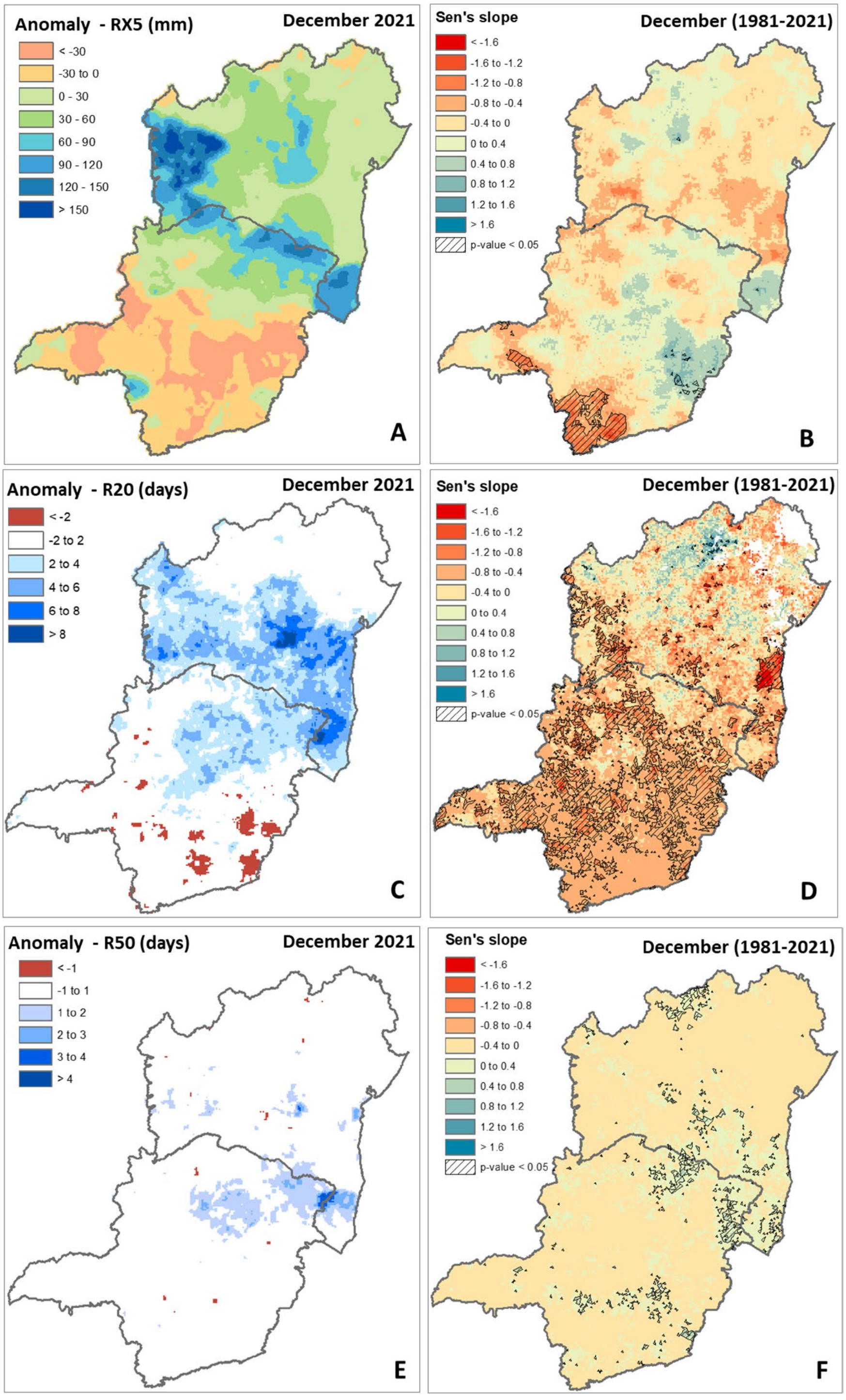

Anomaly - RX5 (mm)
December 2021
< -30
-30 to 0
0 - 30
30 - 60
60 - 90
90 - 120
120 - 150
> 150
A
Sen's slope
December (1981-2021)
< -1.6
-1.6 to -1.2
-1.2 to -0.8
-0.8 to -0.4
-0.4 to 0
0 to 0.4
0.4 to 0.8
0.8 to 1.2
1.2 to 1.6
> 1.6
p-value < 0.05
B
Anomaly - R20 (days)
December 2021
< -2
-2 to 2
2 to 4
4 to 6
6 to 8
> 8
C
Sen's slope
December (1981-2021)
< -1.6
-1.6 to -1.2
-1.2 to -0.8
-0.8 to -0.4
-0.4 to 0
0 to 0.4
0.4 to 0.8
0.8 to 1.2
1.2 to 1.6
> 1.6
p-value < 0.05
D
Anomaly - R50 (days)
December 2021
< -1
-1 to 1
1 to 2
2 to 3
3 to 4
> 4
E
Sen's slope
December (1981-2021)
< -1.6
-1.6 to -1.2
-1.2 to -0.8
-0.8 to -0.4
-0.4 to 0
0 to 0.4
0.4 to 0.8
0.8 to 1.2
1.2 to 1.6
> 1.6
p-value < 0.05
F

Fig. 12 Daily forecasts of hydrological risk (floods) issued by CEMADEN valid from December 20 to 31 ▶ 2021 (**a** to **l**). The forecasts are issued 24 h in advance. The levels of risk are indicated by the color scale inside each panel. In Panel **a** the letters MG and BA indicated the location of the States of Minas Gerais and Bahia, respectively. Black circles indicate the affected region. Source: CEMADEN

was concentrated on December 24 and 25. CEMADEN's monitoring provided a better picture of the meteorological and hydrological situation, so extreme heavy rainfall could be identified and monitored. As a result, the high risk of flooding was better predicted. The population was warned, so minimal damage and a relatively low number of fatalities were reported. Indeed, less than 4% of the number of people died this time, compared to those who perished in the flash floods and landslides in the highlands of Rio de Janeiro in January 2011.

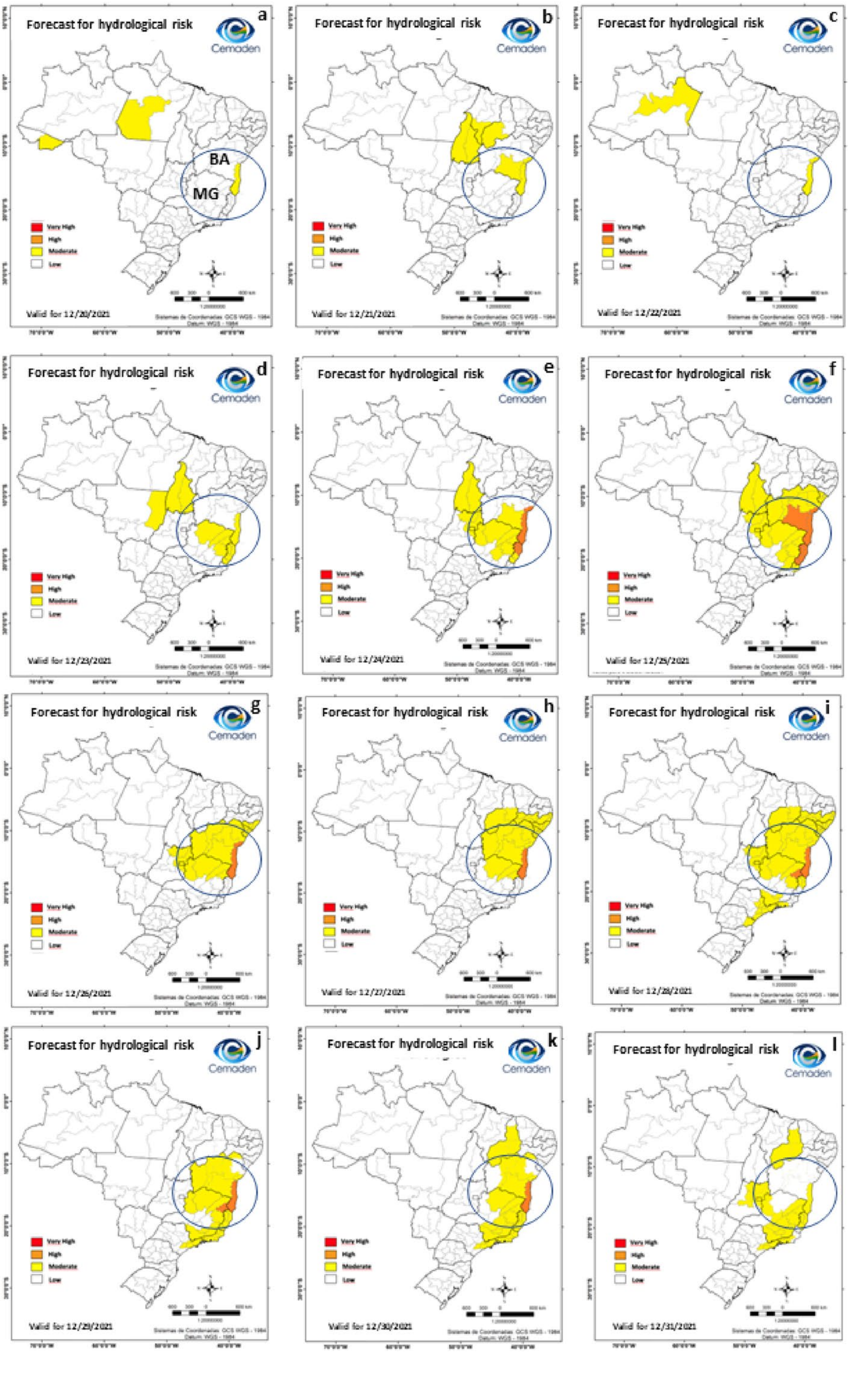
5 Conclusions and recommendations

It is well established that many factors cause disasters, even when the weather plays a role (Ribot 2014; Reuters 2022). It is essential to understand the conditions and trigger factors in areas affected by disasters of geo-hydro-meteorological nature, because the main hazards are meteorological in nature (heavy rainfall). These disasters threaten the life and property of people living in areas of cities susceptible to floods. The floods that happened in the states of Bahia and Minas Gerais in December 2021 affected more rural towns and cities that, in recent history, were not prepared to deal with this kind of disaster.

Extreme rainfall frequently occurs in this region during the wet summer season every year. These events can affect thousands of residents and cause financial losses through the cascading effects of flooding and landslides. For example, the heavy rainfall in southern Bahia and northern Minas Gerais on December 22–29, 2021, led to floods that took the lives of 33 people. In one location, 500 mm of rain fell in just 48 h. In some parts of SBA and NMG, monthly rainfall in December 2021 was between 250 and 430% above average. On December 28, 2021, the government of Bahia reported that 471,009 people had been affected by the heavy, persistent rainfall of the previous 30 days. Of those, 62,796 people were displaced from their homes. The heavy rainfall triggered extreme flooding, led to the collapse of two dams, and caused costly economic losses.

Rainfall totals in November and December 2021 were considerable. Their impacts in Minas Gerais and Bahia highlight the preexisting conditions of vulnerability related to socioeconomic, structural, and institutional aspects. Housing and infrastructure on the floodplains reveal how exposed people and assets are. Areas affected include both formal and non-formal occupations, authorized by the local governments. The rain severely affected rural areas, especially small producers and traditional populations. These groups highly depend on their agricultural production and small animals, which were destroyed during the floods. In addition to the destruction of plantations, many houses were also affected. Many do not have a financial reserve to purchase new inputs, so they depend on help from state and federal governments.

Tragedies such as floods and landslides are recurrent during the summertime rainy season in southeast Brazil. This highlights the need to improve the ability to monitor not only the meteorological situation, but also to monitor, predict, and issue risk alerts for these disasters in advance. This can minimize related damage and protect human life and property.


a
Forecast for hydrological risk
Cemaden
BA
MG
Very High
High
Moderate
Low
Valid for 12/20/2021
b
Forecast for hydrological risk
Cemaden
Valid for 12/21/2021
c
Forecast for hydrological risk
Cemaden
Valid for 12/22/2021
d
Forecast for hydrological risk
Cemaden
Valid for 12/23/2021
e
Forecast for hydrological risk
Cemaden
Valid for 12/24/2021
f
Forecast for hydrological risk
Cemaden
Valid for 12/25/2021
g
Forecast for hydrological risk
Cemaden
Valid for 12/26/2021
h
Forecast for hydrological risk
Cemaden
Valid for 12/27/2021
i
Forecast for hydrological risk
Cemaden
Valid for 12/28/2021
j
Forecast for hydrological risk
Cemaden
Valid for 12/29/2021
k
Forecast for hydrological risk
Cemaden
Valid for 12/30/2021
l
Forecast for hydrological risk
Cemaden
Valid for 12/31/2021

One encouraging aspect of December 2021 is the relatively low number of deaths caused by these disasters triggered by heavy precipitation concentrated in just a few days. For example, in January 2011, in the highlands of Rio de Janeiro, it rained 460 mm (climatology for January: 230 mm). In the city of Nova Friburgo that month, it rained 280 mm in only 48 h. The heavy rainfall sparked flash flooding and mudslides across the highlands, devastating mountain towns. Floods and landslides claimed the lives of 916 people and left 35,000 people homeless. The recent situation shows that compared to January 2011 in Rio de Janeiro, although the amount of rain in Minas Gerais and Bahia was much higher, the death toll was lower.

This fact could be attributed partly to the accuracy of weather forecasts. The intense SACZ days that occurred in advance of the rain was a sign of the rain to come, since the SACZ was the leading cause of heavy rainfall during those periods. This system is typical of austral summer in the region. Furthermore, the intense rainfall and floods in Bahia and Minas Gerais in Brazil during the last week of December 2021 were adequately monitored, and alerts issued by CEMADEN to the Civil Defense helped minimize related damage and protect human life and property. As a result, the loss of life in this disaster was lower than in previous disasters, despite higher accumulated rainfall. The reality in 2011 was tragically different.

The WMO (2022) advises that South America is among the regions with the greatest documented need for strengthening early warning systems. Multi-hazard early warning systems (MHEWS), such as CEMADEN, are essential for effective adaptation in areas at risk from weather, water, and climate extremes. In Brazil, disaster risk reduction must be considered an essential aspect of disaster governance strategies. Certain actions must be considered: (a) to improve strategic planning focused on mitigation and adaptation; (b) to maintain and expand monitoring systems such as those of CEMADEN; (c) to include tens of thousands of new risk areas in heavy densely populated regions; (d) to continually improve computer models; (e) to advance with quality research on natural hazards that can potentially trigger disasters; and (f) to cultivate the understanding among the population and local governments that disasters may occur with heavy rainfall in susceptible to floods areas, and that people can be harmed or even killed.

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Author contributions JM, MS, AC, APC, SS, RA, OMCS, and JE conceived and wrote the paper. DGF, FB, AR, VS, GD, TR helped in the gathering and data analysis as well as in the interpretation of maps and diagrams.

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Data availability Datasets, weather reports, rainfall records, and global reanalyses can be found in these public archives: CEMADEN: www.cemaden.gov.br and http://www2.cemaden.gov.br/mapainterativo; ANA: www.snirh.gov.br/hidrotelemetria/Mapa.aspx# and www.snirh.gov.br/hidroweb/serieshistoricas; INMET: www.inmet.gov.br and portal.inmet.gov.br/informativos#; CHIRPS: http://data.chc.ucsb.edu/products/CHIRPS-2.0/; NOAA: psl.noaa.gov/siteindex.html. Official statistics of damages and impacts are found on the sites of the Civil Defense of the States of Minas Gerais (www.defesacivil.mg.gov.br/boletim-diario) and Bahia (www.defesacivil.ba.gov.br/municipios-em-situacao-de-emergencia-chuvas/).

Declarations

Conflict of interest The authors declare no competing interests.

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