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# Flash floods and landslides in the city of Recife, Northeast Brazil after heavy rain on May 25–28, 2022: Causes, impacts, and disaster preparedness

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ABSTRACT

From late May to early June 2022, 130 people died in catastrophic landslides and flash flood events triggered by exceptionally heavy rains in the states of Pernambuco, Alagoas, and Paraíba, along the coast of Northeast Brazil. Total rainfall in the city of Recife on May 25–30 was 551 mm, 140 mm higher than the average of the month of May. Rain was heaviest on May 25 and 28, with 100–200 mm and 151–250 mm, respectively. This coincided with easterly wave disturbances. May 28 saw the most rain, due to a significant cold front. Fourteen municipalities in the metropolitan region of Recife declared a state of emergency. According to the Civil Defense of Pernambuco state, the rain impacted 130,000 people there. Most of the heavy precipitation fell over areas with medium to very high geological vulnerability to landslides and extreme hydrological events. The loss of life and substantial economic impacts in Recife caused by the heavy precipitation of May 2022 and the disasters induced by it show that this city, like many others around the world, has limited capacity to cope with climate extremes. Urbanization has increased population density occupying hills and slopes of the city, contributing to the problem. To reduce the impact of such disasters, residents must be made aware of the risks of climate-related events, and they must be encouraged to heed alerts warning of natural disasters issued by state and federal institutions. Efficient monitoring of risk is also needed. Risk management will be viable only when everyone participates, which requires education and cultural change.

## 1. Introduction

Brazil has an estimated 3,000 km$^2$ of areas at risk for prevailing climate-related disasters. These areas were recently determined to have high and very high risk of landslides, floods, and flash floods. At least 825 municipalities are critically vulnerable to disasters (Alvalá et al., 2019; Assis Dias et al., 2020). Of the 8,266,566 people most at risk, around 75% are in areas susceptible to landslides or combined landslides and floods (Alvalá et al., 2019; Zachariah et al., 2022). This population faces considerable vulnerability (IBGE 2010). Recurring events in recent years underscore how urgent it is to mitigate the disaster risk (UN Office for Disaster Risk Reduction, 2019a, b).

Between January 1, 2013, and April 5, 2022, natural disasters caused US$ 67 billion in damages throughout Brazil (CNM 2022). From January to July 2022 alone, landslides, flash floods, and floods triggered by heavy precipitation events have left hundreds dead and missing in Brazil. The National Confederation of Municipalities (CNM 2022) estimates 503 deaths due to disasters related to heavy precipitation as of July 4, 2022. This is higher than the 290 deaths in all of 2021. From 2014 to 2018, fewer than 100 fatalities were caused by disasters triggered by heavy precipitation annually. After 2019, this number jumped to over 200 per year, with 2022 being the worst yet (as of July).

The city of Recife, capital of the state of Pernambuco, and 13 other municipalities, comprise the metropolitan region of Recife (MRR). Together, they form the fifth-largest population center in Brazil (Fig. 1). The MRR has an estimated population of 4,047,088 in 2020 (IBGE and CEMADEN, 2018), spread over a territory of 2,774 km$^2$. The population density is high, at 1,459 inhabitants/km$^2$ (https://www.citypopulation.

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de/en/brazil/metro/RM0003_recife/, last accessed on August 1, 2022).

Geographically, Recife is a coastal city, about 2.5–5 m above sea level, in a region comprised of the Atlantic Rainforest Biome. The geography is characterized by its low elevation, the influence of tides, and a water table very close to the surface. Recife has undergone a process of urban densification and verticalization, occupying areas of banks and hills, and channeling rivers. Together, these elements hinder adequate municipal drainage – which becomes even more problematic with heavy rains in a short amount of time. Floods, flash floods, and landslides then impact Recife's population negatively and severely, causing deaths, temporary eviction from homes, damaged physical infrastructure, disrupted urban mobility, and diseases linked to contaminated water (ICLEI, 2020).

According to data from Recife's Drainage Master Plan (ICLEI, 2020), the city has 159 critical points of flooding, and 52% of its population lives in areas that often flood on rainy days. Of all existing channels in the city, 42% remain in a natural state, but most have had their banks occupied by irregular constructions. The Municipal Plan of Risk Reduction (ICLEI, 2020) maps more than 670 risk areas in the city. This plan proposes to reduce these areas as much as possible in sectors with a very high risk of landslides and floods. The city's poorest live on riverbanks and alongside canals. While heavy rainfall can trigger natural disasters, this driver is not the sole reason for them. A high population density lives in poorly built housing, in areas of risk, and this is also a key part of the problem (Assis Dias et al., 2020).

Between the last week of May and early June 2022, 130 people died in landslides and flash floods in the states of Pernambuco, Alagoas, and Paraíba, all located along the coast of Northeast Brazil (ENEB). Exceptionally heavy rains in the area, combined with inadequate protective measures, caused these tragedies. As reported in the news and by meteorological agencies of Brazil and Pernambuco itself, in less than 24 h on May 27 and 28, the MRR received more than 70% of the rain that usually falls in all of May. Ordinarily, May is the third-rainiest month, with an average of 311.8 mm (INMET). The impact of this heavy rain

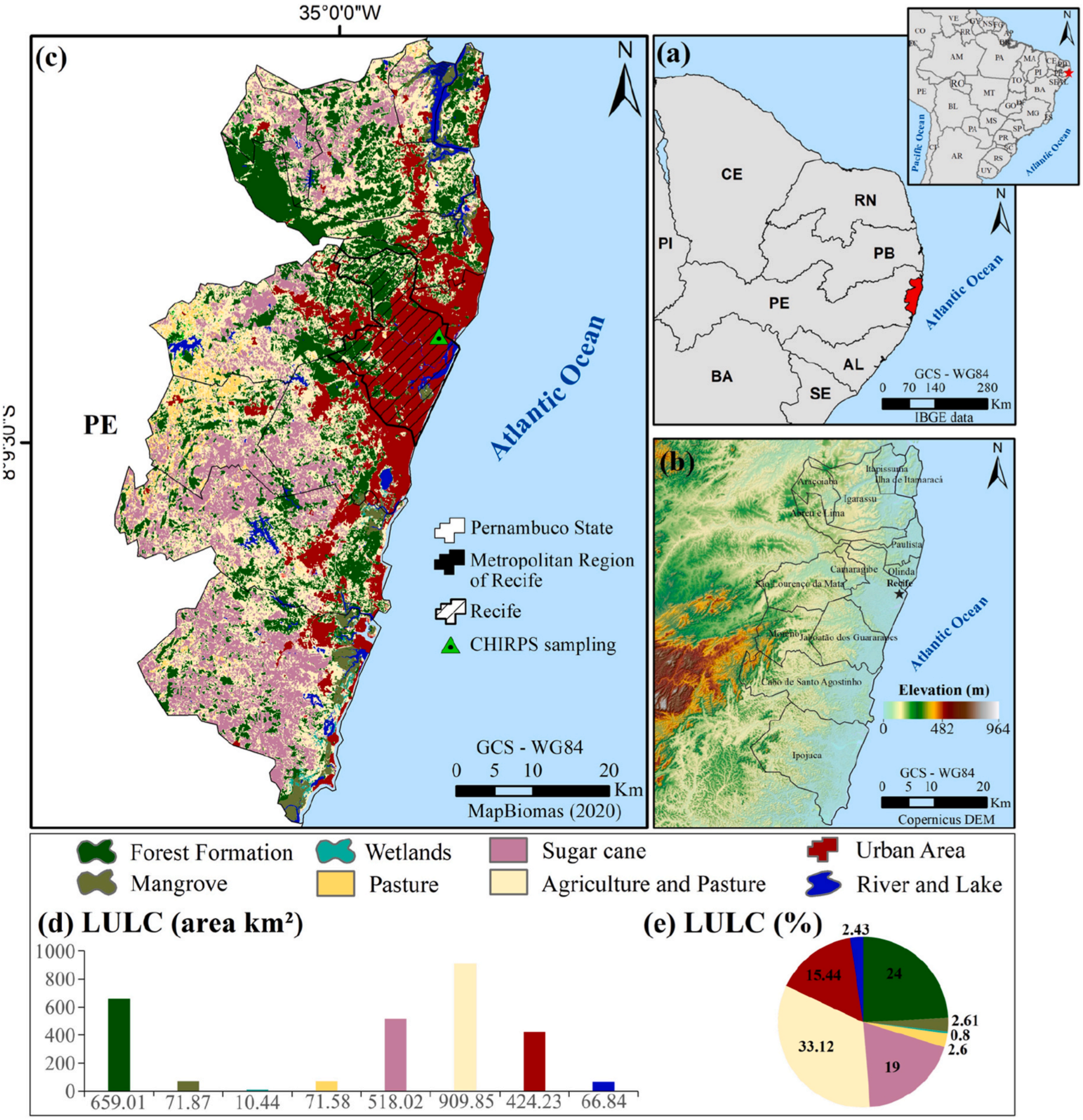

**Fig. 1.** (a) Location of study site in Brazil; (b) digital elevation model for the study area; (c) land use and land cover for the metropolitan region of Recife (Pernambuco State, Brazil) and the CHIRPS sampling spot used to extract rainfall data from 1981 to May 2022; (d) land use and land cover (LULC) area in km$^2$; and (e) LULC in %.

was catastrophic. It was Recife's worst natural disaster since 1966, when 175 people died (Almeida da Silva and Mandú, 2020). This extreme rainfall accumulation followed a week of very heavy rain that intensified on May 25 and 28 over several parts of ENEB, including the states of Pernambuco, Sergipe, Alagoas, Rio Grande do Norte, and Paraíba. The results were landslides and widespread floods across these regions.

These events displaced 39,285 people in Alagoas, and 4,200 people across 24 municipalities in Pernambuco, as reported by the state and federal Civil Defense (Flood List- https://floodlist.com/america/brazil-floods-july-2022-alagoas-pernambuco-riograndedonorte, last accessed on August 1, 2022). The densely populated MRR was hit particularly hard, with impacts mostly in vulnerable areas near hillsides. Outside of the urban center, another 80 municipalities across Pernambuco and Alagoas declared a state of emergency. As we investigate in later sections, the total rainfall in Recife over only five days was 551 mm (May 25–30), 140 mm above May's monthly climatology. In northern Pernambuco and Paraiba states, floods were also reported. In Alagoas, authorities declared a state of emergency after recording the highest rainfall totals since 1935, when rainfall monitoring began.

The Brazilian Panel on Climate Change (PBMC, 2016) ranks Recife in 16th place, of all the cities in the world most vulnerable to climate change. Considering these concerns, this study has several objectives. We describe the rainfall climatology of ENEB and rigorously analyze meteorological drivers that caused May's long and intense rains. The Easterly Wave Disturbances (EWD) events in the last week of May 2022 in Recife are particularly important. We map the extreme precipitation events and the areas affected in high resolution. These maps of landslides and floods show that the highest number of deaths occurred on hillsides. The maps indicate tendencies in heavy precipitation, and how the events of 2022 compared to historical records. We simulate and map the inundations in the study area resulting from the heavy precipitation events of May 23–29, 2022. We question why more than a hundred people died, despite precise early warnings of the risk of severe natural disasters having been issued prior to May 25. Did the population or municipal governments fail to perceive the risk of natural disasters? Is this why residents in areas of risk ignored the alerts? In practice, correcting the strategy used to prepare for disaster will require an in-loco investigation involving civil defense, communities, and local governments. This is a matter of ongoing work.

## 2. Data and methodology

The study uses a wide range of data sources, from observational (rainfall data from various networks) as well as gridded data sets; NCEP-NCAR reanalysis for atmospheric circulation fields; indices of rainfall extremes; and sea surface temperatures (SST and GOES-18 imagery) to observe the propagation of easterly wave disturbances (EWD) during the rainfall event.

As auxiliary information, and for qualitative analysis that corroborates the impacts of observed rainfall extremes on floods and landslides, we include information from the newspapers on the web and other social media. In addition, we include information from the website of Flood List (https://floodlist.com); this site provides updated flood-related information worldwide. Its information is drawn from government and international agencies, describing the magnitude of disasters, geographical coverage, and impact information, as well as damages and casualties. We also review the weather reports from the National Institute for Meteorology of Brazil (INMET), Pernambuco's Water and Climate Agency (APAC), Brazil's National Institute for Space Research (INPE), the National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN), and the National Center for Risk and Disaster Management (CENAD), for the month of May 2022 to check on station rainfall amounts and related weather patterns.

### 2.1. Precipitation data

Station rainfall data comes from various sources: INMET, APAC, and INPE. For studies on rainfall extremes, we use the Recife-INMET and Recife-APAC stations. While the former has data up to 2020, the later shows data up to July 2022.

Additional data comes from the CEMADEN Environmental Observational Network. Among other facilities, this network includes 3,500 telemetric rain gauges, and 301 hydrological stations equipped with pluviometers, water level sensors, and cameras for all Brazil. CEMADEN designed its observational network specifically to monitor conditions in areas of risk. This is quite different from conventional observational meteorological networks for weather and hydrological monitoring. Most of CEMADEN's rain gauges are located directly in areas of risk, in the vicinity of unstable slopes or in critical watersheds for flash floods. This dataset is available from 2013 onward. However, due to maintenance and logistical problems, there are some observational gaps. This data is freely available from http://www2.cemaden.gov.br/mapainterativo and additional information on the CEMADEN network is provided by Marchezini et al. (2020) and Espinoza et al. (2021).

For more comprehensive analysis of rainfall trends in the state of Pernambuco, we use the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset (Funk et al., 2015). CHIRPS is a rainfall product available at daily to annual time scales with a spatial resolution of 0.05°x0.05°, covering 1981 to the present. The dataset 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/. Studies of other regions in Brazil have applied the CHIRPS-2.0 dataset (Marengo et al., 2021, and references quoted therein).

### 2.2. Atmospheric circulation and SST fields

We explore upper and low-level circulation changes in South America that lead to the occurrence of Easterly Wave Disturbances (EWD) and heavy precipitation on the eastern coast of Northeast Brazil. We focus on the last week of May 2022, when EWDs occurred, and when heavy precipitation hit the Recife metropolitan region (MRR) and nearby cities. We analyze the period of May 25–28, 2022 for 850- and 500-hPa vertical-velocity anomalies, and May 25 and 28 for 500- and 850-hPa zonal-wind and specific-humidity anomalies. We select these parameters to observe lower- and middle-level circulation and moisture transport along ENEB. All atmospheric fields are from the NCEP/NCAR reanalysis. We calculate anomalies relative to the 1981–2010 long-term mean. Sea surface temperature (SST) data is from the NOAA website: https://psl.noaa.gov.

### 2.3. Other datasets

To see the development of convection during EWDs, we use infrared (IR) images from GOES-16 for May 23 to 28, 2022 at 900 UTC from CPTEC/INPE. The weather map for May 23 is from the National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce, 2015): NCEP GFS 0.25.

### 2.4. Indices of rainfall extremes and test of significance

We use the rainfall indices for extremes developed Frich et al. (2002): R10, R50, R100, and R200. These represent the number of days each year with rainfall above 10, 50, 100, and 200 mm R5xday represents the maximum consecutive 5-day precipitation measured each year, an amount that could lead to flooding and landslides. We calculate these indices using CHIRPS data for 1981–2022, along with data from the Recife-INMET (1934–2020) and the Recife-APAC (2017–2022) weather stations. We use the Mann-Kendall (MK) nonparametric trend test

(Mann, 1945; Kendall, 1975; Yue et al., 2002) to identify statistical significance in the indices of rainfall extremes.

### 2.5. Flood inundation modeling

We simulate the flood events of May 24, 25, 26, 27, and 28, 2022 using Brunner's (2016) HEC-RAS 2D model. We analyze daily rainfall data covering 1981 to May 2022 from CHIRPS (Funk et al., 2015) using a box and whisker plot to calibrate the model. HEC-RAS 2D has been used worldwide (e.g., Costabile et al., 2021). The Manning coefficient, n, is obtained using the land use and land cover (LULC) data and the n table from Chow (1959). The LULC comes from MapBiomas for 2020 (https://mapbiomas.org/en?cama_set_language=en). The digital elevation model (DEM) is from ALOS PALSAR available at the Alaska Satellite Facility (ASF). We resample ALOS/PALSAR images from 30 m to 12.5 m pixel size with orthometric altitude (EGM96 geoid model) before converting them to a geometrical (ellipsoidal). The main limitation of this study's model parametrization is the lack of sea-level data to calibrate it. Hence, the model does not take into consideration the tide effect during the flash flood.

## 3. Rainfall in Eastern Northeast Brazil (ENEB)

### 3.1. Climatology

The city of Recife, located in ENEB, is susceptible to extreme precipitation events. Intense rainfall episodes have been recorded prior to its current high annual average (Wanderley et al., 2021). The most rain ever recorded was 335.8 mm on August 8, 1970. Out of several rainfall-driving systems, we highlight the Intertropical Convergence Zone (ITCZ), EWDs, and coastal breezes (Kousky, 1980; Reboita et al., 2010; Gomes et al., 2019). Of all capital cities of Northeast Brazil, Sousa

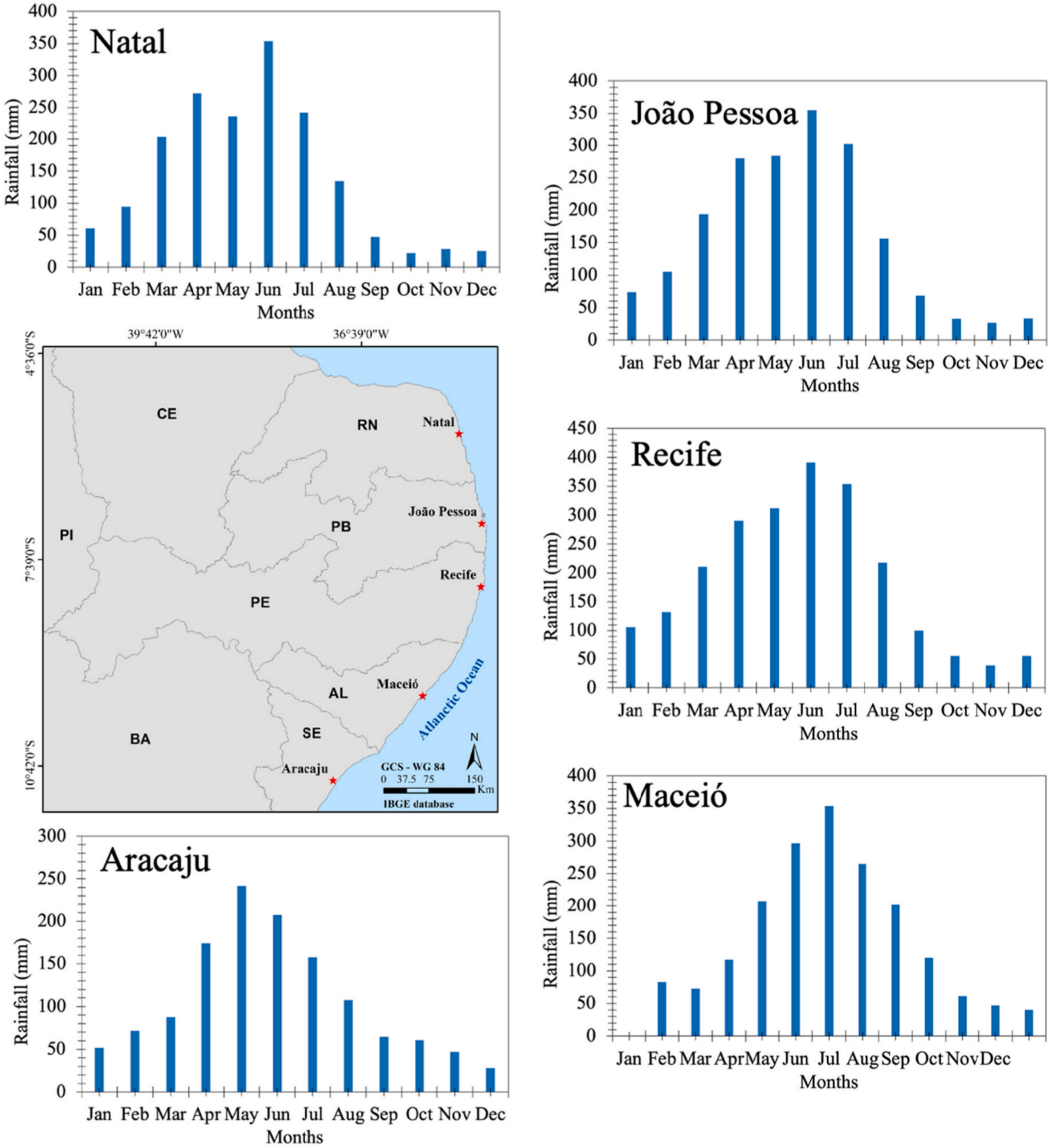

**Fig. 2.** Climatology of 1981–2010 average monthly rainfall in meteorological stations in ENEB: Aracaju-State of Sergipe, Natal-State of Rio Grande do Norte, Recife-State of Pernambuco, Maceió-State of Alagoas, Joao Pessoa-State of Paraíba; source: Brazilian Institute for Meteorology (INMET).

et al. (2016) note that Recife has had the most significant high daily rainfall events for the return time of 50 years (203.8 mm) and 100 years (224.5 mm).

The rainy season in Recife and other cities in ENEB starts in April and ends in August (Fig. 2), with peaks in June. The region receives 2,263 mm/year (long-term mean 1981–2010). In recent years, extreme rainfall events over the eastern coast of Northeast Brazil has caused deaths and homelessness, as along with other social and economic costs to the region (Ávila et al., 2017; Comin et al., 2021). Extreme events are often seen when several atmospheric systems interact. Among them, EWDs occasionally cause heavy rains in this region (Neves et al., 2016). Ferreira et al. (1990) identify EWDs in the wind field, which propagates westward over the tropical South Atlantic Ocean during the austral autumn and winter, presenting wave configurations in the wind and pressure fields.

Low-level convergence increases when these disturbances interact with local circulations, causing intense rainfall on the eastern and northern Northeast Brazil coasts. EWDs' outpouring of rain also increases as they move over warmer waters off the western tropical Atlantic near the coast of ENEB, particularly for SSTs higher than 27 °C. EWDs often drive the high levels of rainfall that result in flash floods, landslides, and other environmental problems (Gomes et al., 2015), as was the case in Recife in May 2022 and Maceió in June 2010. The Atlantic Ocean warmer than normal over a wide area also produce temperature increase in the lower atmospheric layers. This effect allows both greater evaporation from the ocean and, particularly, retention of a greater amount of moisture in the lower the atmosphere, which is then transported to the continent by southeasterly winds, favoring the development of convection and intense rainfall.

In the first half of the last century, the literature already documented the presence of cloud clusters in the tropical atmosphere moving from east to west, including in the South Atlantic (Berry et al., 1945). Later studies specific to the South Atlantic associated such cloud clusters with EWD and revealed their relationship with high-rainfall episodes during the rainy season in eastern NEB (Wallace, 1970; Wallace and Chang, 1972; Yamazaki and Rao, 1977).

Pontes da Silva (2011) and Gomes et al. (2019) use the ERA-Interim reanalysis for 1989–2010 to identify an annual average of 23 EWDs reaching the coast of ENEB, with small interannual variability. The precipitation composition indicates that the EWDs account for 60–70% of total rainfall during the rainy season in ENEB. On average, EWDs' lifetime is 4–6 days, wavelength is 4307 km, and phase velocity is 9.5 m $s^{-1}$. According to these authors, EWDs can originate from the association with four distinct types of atmospheric systems: cold fronts, convective conglomerates from the west coast of Africa, ITCZ, and high-level cyclonic vortices. The annual occurrence of EWDs seems to be lower (higher) during El Niño (La Niña). EWDs are more active in the months of the rainy season. Their composite analysis indicates strong relative vorticity and divergence anomalies at low levels, as well as in the vertical profiles of relative humidity and vertical velocity (omega). In May 2022, two EWD episodes occurred, on May 25 and 28 (CEMADEN, INMET). According to APAC, EWDs were observed on June 1, 4, 7, 12, 16, and 23.

## 4. Intense rainfall in the last week of May 2022 in the MRR: Results and discussion

### 4.1. Rainfall on the coast of ENEB in May 2022

Between the last week of May and early June 2022, landslides and flash floods triggered by intense rainfall also affected Recife and the neighboring states of Alagoas, and Paraíba, all located along the coast of Northeast Brazil (ENEB). Fig. 3 shows intense rainfall during May 23–28, more intense on May 23 and 28, over the states of Alagoas, Paraiba and Pernambuco. According to INMET, May 2022 was the rainiest May since the beginning of records in 1961, with 714 mm (climatology of 287.7 mm) in João Pessoa, the capital of the state of Paraíba. The previous record was in May 1964, with 701.6 mm. In Recife, it rained 783.6 mm in May 2022, and in Maceió, 579 mm (climatology of 276.3 mm). During the EWD episodes, on May 25, rainfall was about 180 mm above normal over Alagoas and Pernambuco on May 28 rainfall was 120 above normal over Pernambuco and Paraiba.

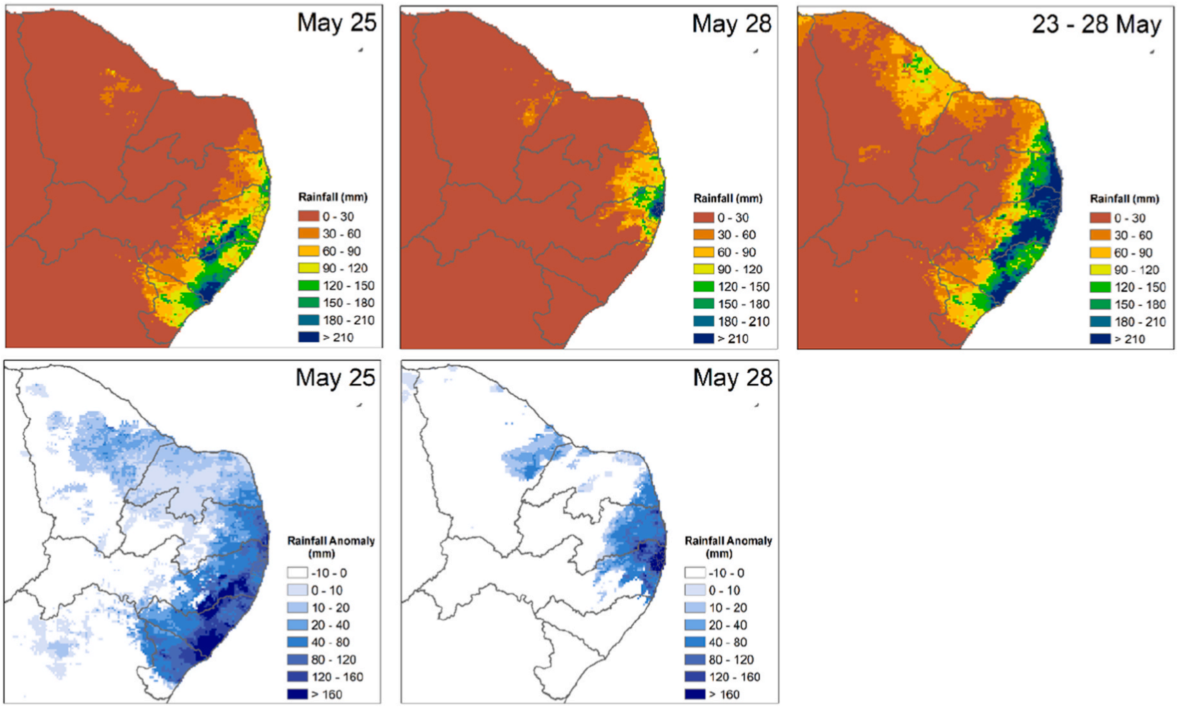

**Fig. 3.** Observed rainfall on May 25 and 28, and accumulated rainfall for May 23–28 (top row), and rainfall anomalies for May 25 and 28 (bottom row), in mm, for the ENEB region. Source of data: CHIRPS.

INMET and APAC reported during the last week of May 2022 the heavy rainfall that affected the coast of ENEB. As of May 27, 2022, some areas of the state, including Ipojuca, São Benedito do Sul, Belém de Maria, and Martial had already seen twice their monthly average rainfall totals. From May 1–28, 2022, the MRR registered these totals: Corrego Jenipapo, 487.8 mm; Ibura, 430.2 mm; Alto Mandu, 519.6 mm; Dois Irmãos, 486.6 mm; Recife/APAC, 414.7 mm; Porto, 419.8 mm; Morro da Conceição, 428.4 mm; Jaboatão dos Guararapes/Alto Vento, 476 mm; and Jaboatão dos Guararapes/Curado, 472.6 mm (CEMADEN).

In northern Alagoas state, at the border of Pernambuco, the municipality of Jacuípe had flooding, as levels of the Jacuípe River rose. On May 25, the river stood at 5.11 m, below the flood triggering level of 5.3 m but still rising. Authorities of the state of Paraíba reported that the dam of the Tanques Reservoir broke in Pocinhos on May 25, after continued heavy rain. Local authorities reported six houses severely damaged or destroyed, four people injured, and roads flooded in Jaboatão dos Guararapes, south of Recife, on May 25. A total of 14 municipalities declared a state of emergency: Recife, Olinda, Jaboatão dos Guararapes, São José da Coroa Grande, Moreno, Nazaré da Mata, Macaparana, Cabo de Santo Agostinho, São Vicente Férrer, Paudalho, Paulista, Goiana, Timbaúba, and Camaragibe. The Civil Defense of Pernambuco counted 119,223 people impacted in the state. Meanwhile, in neighboring Alagoas, the Civil Defense reported 2,102 people evacuated from their homes and moved to relief camps, and another 8,017 sheltered with relatives or friends.

From May 23 to 28, 2022, a considerable accumulation of more than 500 mm was recorded in the city of Recife, culminating in the natural disaster addressed in the present study (Fig. 4). This rain, however, was heavier on May 25 and 28, consistent with the occurrence of EWDs on those days, with a significant contribution from the cold front associated with the cold air incursion on May 28, 2022.

Olinda and Recife suffered from flooding where the Tejipió river broke its banks, and heavy rain continued afterwards, particularly in MRR. As of May 25, Civil Defense had reported damage caused by floods and landslides in eight municipalities in the state of Pernambuco. The state of Alagoas reported more than 250 mm of rain in 24 h on May 24, the average amount seen in the entire month of May. Among the municipalities most affected is Penedo, where authorities declared a state of emergency after recording the highest rainfall since 1935, when monitoring began. From late May 24 to May 25, the area received 260 mm of rain.

### 4.2. *High-resolution mapping of intense precipitation events in Recife and areas at risk for disasters*

Recife, like other cities in Brazil and around the world, has experienced rapid growth in urban vulnerability and exposure. Settlements have proliferated in areas with limited adaptive capacity – especially unplanned and informal settlements. The MRR shows 1,802 areas at risk for natural disasters associated to heavy rainfall, in 12 municipalities. In total, CEMADEN monitors 333 municipalities in Northeast Brazil. This region has 294 municipalities, with 638,872 of their residents exposed to such risks. Around 80% of those live in areas with a high or very high risk of landslides (Assis Dias et al., 2020). The flooding and landslides that severely impacted these areas were a direct consequence of extremely heavy rainfall in the week of May 23 and continuing into June.

State and federal meteorological agencies reported that heavy precipitation caused flooding and wind damage in parts of Pernambuco state on May 23, 2022. At a more regional ENEB scale, Fig. 5 shows daily rainfall from May 1 to Jun 21, in stations from the CEMADEN network in MRR. As indicated by the arrows, the highest amount of rain fell in Recife and Maceió during the EWD events of May 25 and 28. Both events affected Recife, with the first having the biggest effect on Maceió. The municipality of Maceió reported that from late May 24 to May 25, the area received 260 mm of rain, higher than the previous record of 200 mm, in 1945.

Fig. 6 shows rainfall on May 25 and 28 (and anomalies) and accumulated rainfall from May 23–28th, 2022. The regions most affected in both episodes were the southern part of Recife and the northern part of the municipality of Jaboatão dos Guararapes, which had more than 200 mm above average. Between May 24 and 29, accumulated rainfall was 482 mm in São Lourenço da Mata, 467 mm in Recife, 462 mm in Jaboatão dos Guararapes, 448 mm in Olinda, and 429 mm in Camaragibe, all municipalities in the greater Recife metropolitan area. For the municipality of Recife, the regions most vulnerable to landslides and hydrological events near Olinda to the north and Jaboatão dos Guararapes to the south (Assis Dias et al., 2020) are also those with the highest poverty rate and population density (Souza et al., 2014). The municipality ranks third among MRR's most critical, in terms of its number of landslides.

The maps in Fig. 7 show the accumulated rainfall for May 25 and 28 for the MRR (dataset from weather stations). Red circles show areas with medium to very high geological vulnerability to landslides and extreme hydrological events, following Assis Dias et al. (2020). Large amounts of rain fell in areas with high geological risk: 100–200 mm on May 25 and 151–250 mm on May 28.

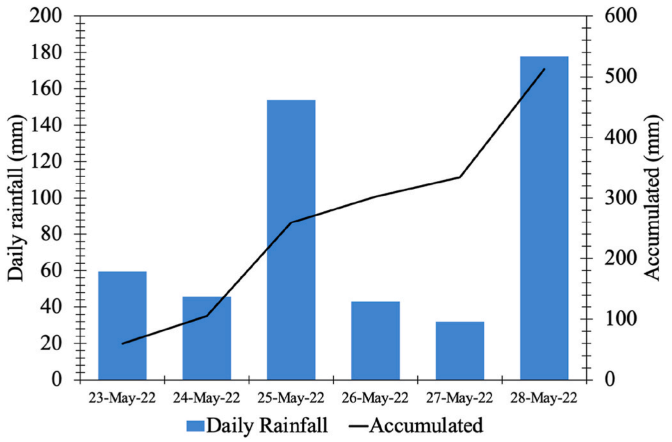

**Fig. 4.** Daily and accumulated rainfall (mm) from May 23 to 28 at the Córrego Jenipapo meteorological station in Recife (Source: CEMADEN).

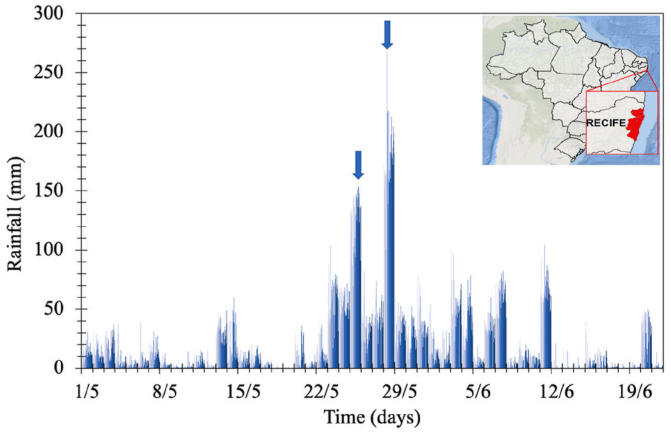

**Fig. 5.** Daily rainfall in the Metropolitan Region of Recife for May and June (up to June 21), 2022 from CEMADEN rainfall gauges. Map inset in upper right corner shows location of region. Arrows indicate the EWDs on May 25 and 28. (Source: CEMADEN's environmental network).

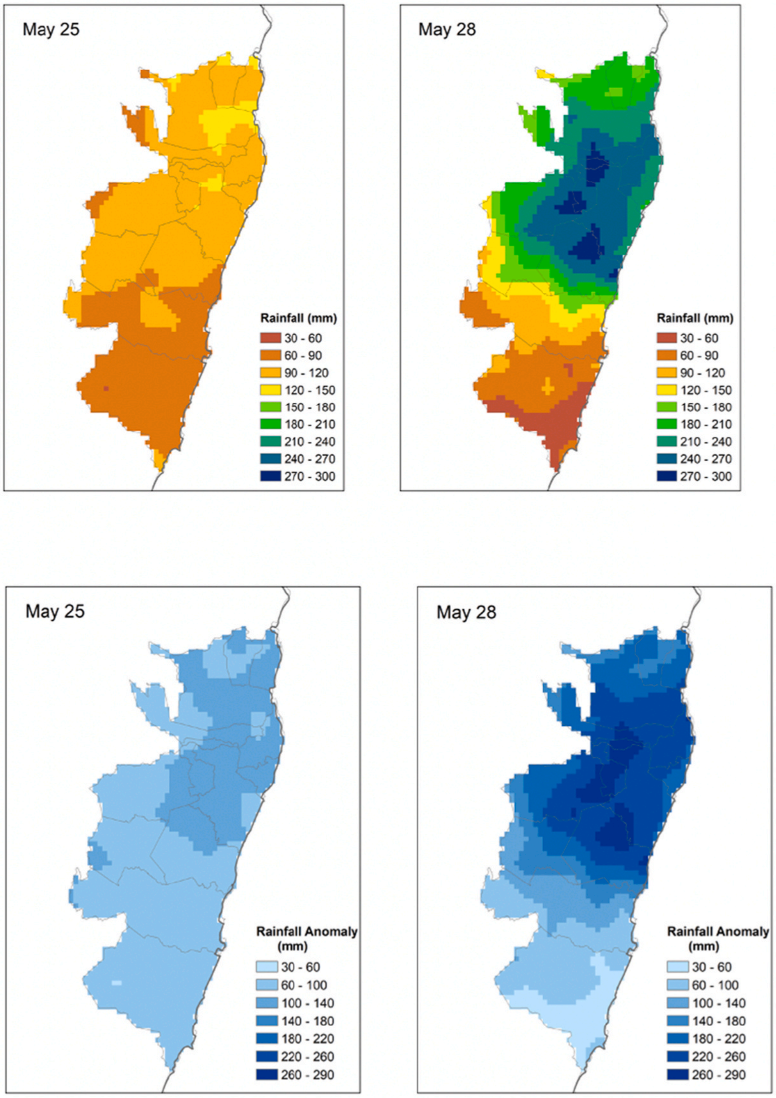

**Fig. 6.** Observed rainfall on May 25 and 28, and accumulated rainfall for May 23–28 (top row), and rainfall anomalies for May 25 and 28 (Sidebottom row), in mm, for the Recife metropolitan area. Source of data: CHIRPS.

### *4.3. Atmospheric circulation fields*

Fig. 8 shows satellite images of the infrared channel for May 23 to 28, 2022. On May 25 and 28, the lower temperatures represent intense convective activity over coastal ENEB, indicative of EWD events. The sequence of images reveals clusters of shallow clouds over the Atlantic Ocean that propagate from east to west and develop vertically as they approach the coast of ENEB due to the observed warm sea surface temperature (SST).

For this same area, Fig. 9 (left and right) shows an abnormally intense upward motion at low (850 hPa) and medium (500 hPa) levels. These features indicate a vigorous and deep convective activity and intense rainfall accumulation, compatible with EWDs (Gomes et al., 2019).

In ENEB on May 25 and 28, the days with EWD, Fig. 10 shows the intense easterly flow at lower and medium levels with the high moisture content. May 25 shows intense easterly flow up to 500 hPa from the tropical Atlantic into Northeast Brazil with higher moisture content along the ENEB coast. On May 28, despite more intense easterly flow, higher moisture content is mainly concentrated along 13$^{o}$S.

Analysis of previous meteorological conditions suggests that two cold fronts contributed to Recife's extreme rainfall from May 23 to 28, 2022. Measurements of atmospheric pressure fields at sea level, wind, vorticity, and divergence in different levels of the atmosphere (1000, 925, 850, 700 and 500 hPa), from May 15 to 29 generated by the United States weather forecast system (Global Forecast System - GFS) and synoptic charts of the Brazilian Navy (Marinha do Brasil, 2022a) show perturbations associated with EWDs on May 25 and 28. Fig. 10 shows sea level pressure and wind field vorticity on May 23 at 700 hPa. A positive vorticity line (representing an anticyclonic/counterclockwise wind rotation, red band inside the green circle reaching the coast) east of the NEB, aligns with an extensive positive vorticity band (indicated by the yellow line) that extends to near a low-pressure center (indicated by the letter "B" in red). This extensive band is associated with the remnants of a cold front, and its respective low pressure. Fig. 11 also highlights other disturbances (black ellipse) over the ocean, along the coast of ENEB. These propagated eastward, reaching the coast of ENEB from May 23–28 (figures not shown).

The Hovmöller diagram of vertical velocity (omega) at the 850 hPa level (Fig. 12a) reveals the eastward propagation of the upward vertical motion towards the ENEB coast. The rising motion (blue) moves from about 20$^{o}$W to Recife precisely on May 25 and 28, the same days that the

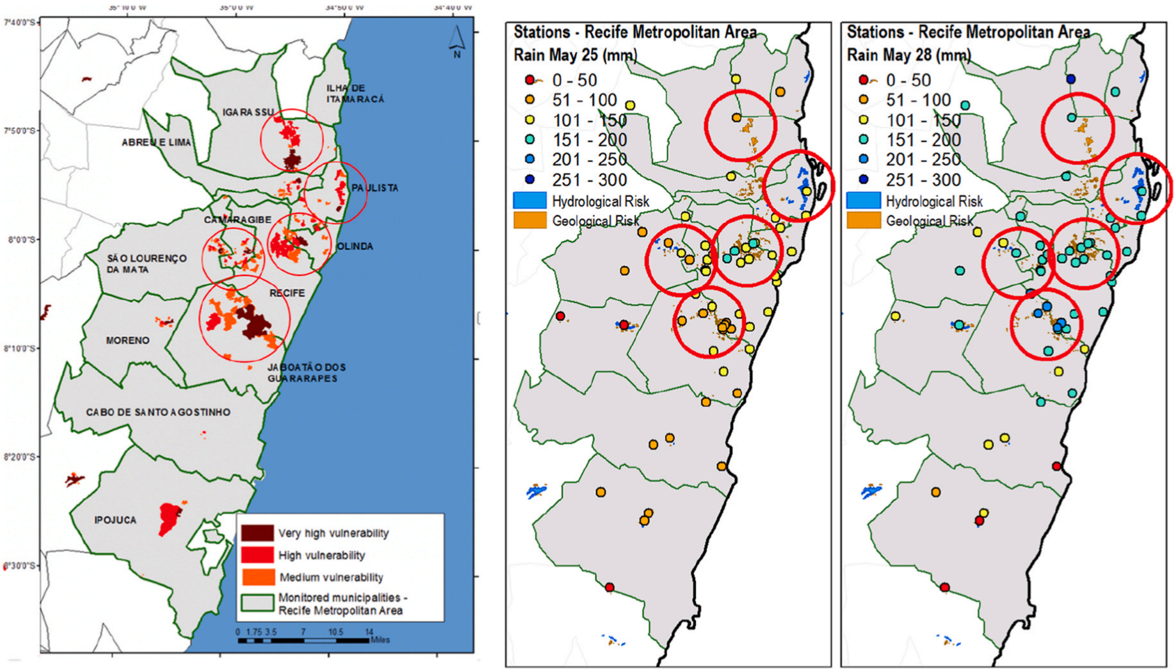

**Fig. 7.** Areas of the metropolitan region of Recife showing monitored by CEMADEN (gray color) and levels of vulnerability to landslides and hydrological events, summarized by red circles (left) [Assis Dias et al. (2020)]. Accumulated rainfall (in mm) for the May 25 and 28, 2022 EWDs in this area (center and right). Rainfall color scale is shown in the upper left of last two maps. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

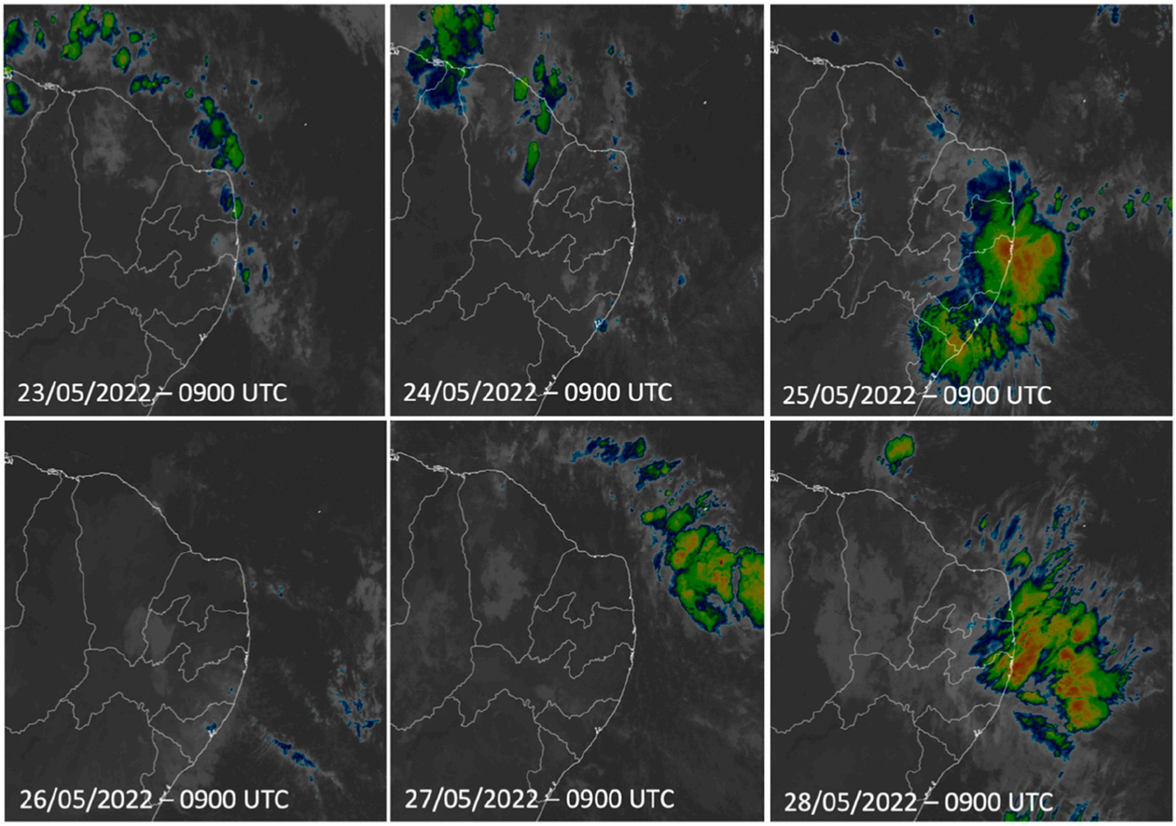

**Fig. 8.** Infrared (IR) images from GOES-16 for May 23 to 28, 2022 for ENEB at 900 UTC for Northeast Brazil (Source: CPTEC/INPE).

EWD and the highest volumes of rain occurred. This propagation also appears at other levels, and it reveals the origin of the disturbance at low levels and the vertical development to higher levels as convection deepens. The phase velocity is 10 m/s for the wave that reached Recife on May 25. Gomes et al. (2019), Pontes da Silva (2011), Diedhiou et al. (2010), Yamazaki and Rao (1977), and others find similar phase

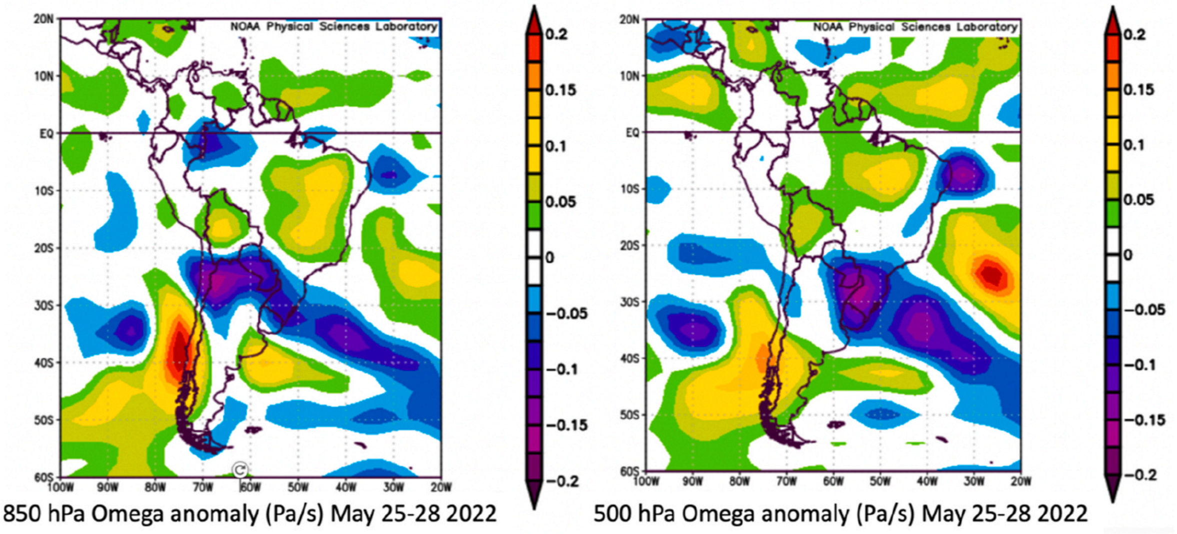

**Fig. 9.** 850 and 500 hPa Ω (Pa/s) anomaly for May 25–28, 2022 in South America, relative to 1981–2010. Color scale is on the right side of each panel. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

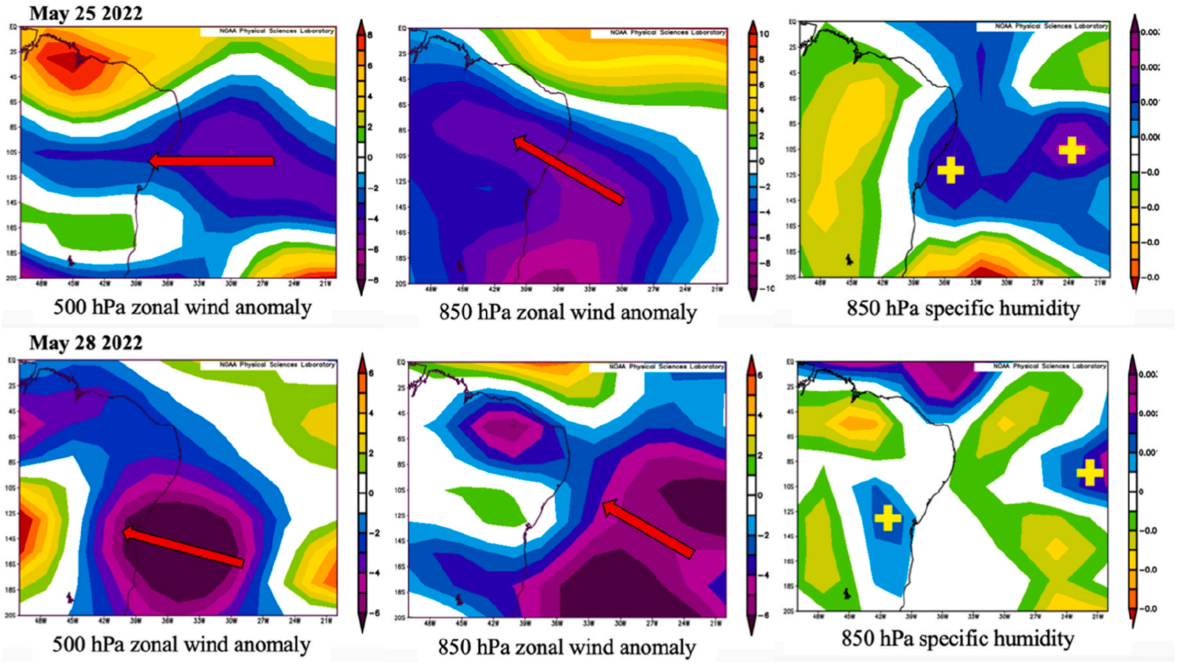

**Fig. 10.** 850 and 500 hPa zonal wind and 850 hPa specific humidity anomaly for May 25 (upper panel) and May 28 (lower panel), 2022 in Northeast Brazil, relative to 1981–2010. Color scale is on the right side of each panel. Arrows indicate easterly flow and "+" shows regions with higher moisture content. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

velocity. On the other hand, the disturbance that hit Recife on May 28 had a mean phase velocity of approximately 4.3 m/s (20° longitude in 6 days). This speed is below the 6–14 m/s found in the literature (Gomes et al., 2019). The propagation speed of the disturbance that arrived in Recife on May 28 is not constant. It is lowest between May 26 and 27 (approximately 2.6 m/s) and highest between May 27 and 28 (approximately 9 m/s). The fact that the upward motion intensifies when it arrives at the coast may be an effect of the increase in convergence at low levels (due to breeze circulation and friction on the surface of the continent).

The Hovmöller figure of SST (Fig. 12b) shows that convection growth appears to be related to the SST values in the Atlantic Ocean, with a greater flow of vapor to the lower layers of the atmosphere along the coast of ENEB. Through the vertical gradient of potential equivalent adiabatic temperature, the flow increases thermodynamic instability, and therefore the potential for precipitation. Convection is particularly strong when it passes over water above 28.5 °C. The TSM anomalies were not statistically significant (below 1 °C), and this may not relate to onset nor to development of convection. The emergence appears to be exclusively atmospheric. Analysis shows that EWDs did not appear in the $20^{0}$ W of the Hovmöller. They appeared to the southeast, with an origin that seems unrelated to intense SST anomalies. EWDs have increased convection as they enter a region with warmer waters, with SST above 28.5 °C.

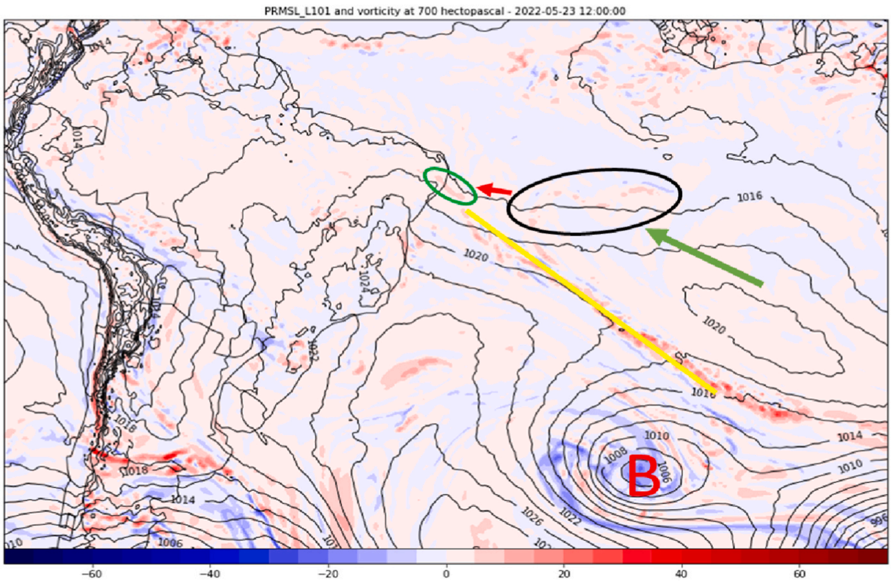

**Fig. 11.** Mean sea level pressure (black lines) and relative vorticity at 700 hPa level (shaded - multiplied by $10^5$), on May 23, 2022 at 1200 UTC. The green arrow indicates the trajectory of low-pressure disturbances. The red arrow indicates the direction of propagation. The black and green ellipses, and the yellow line, indicate the presence of disturbances. The letter "B" in red indicates the position of the low-pressure center. Source: National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce, 2015): NCEP GFS 0.25 Degree Global Forecast Grids Historical Archive. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory, Boulder, CO [Available online at https://doi.org/10.5065/D65D8PWK.]. Accessed 10 Jul 2022

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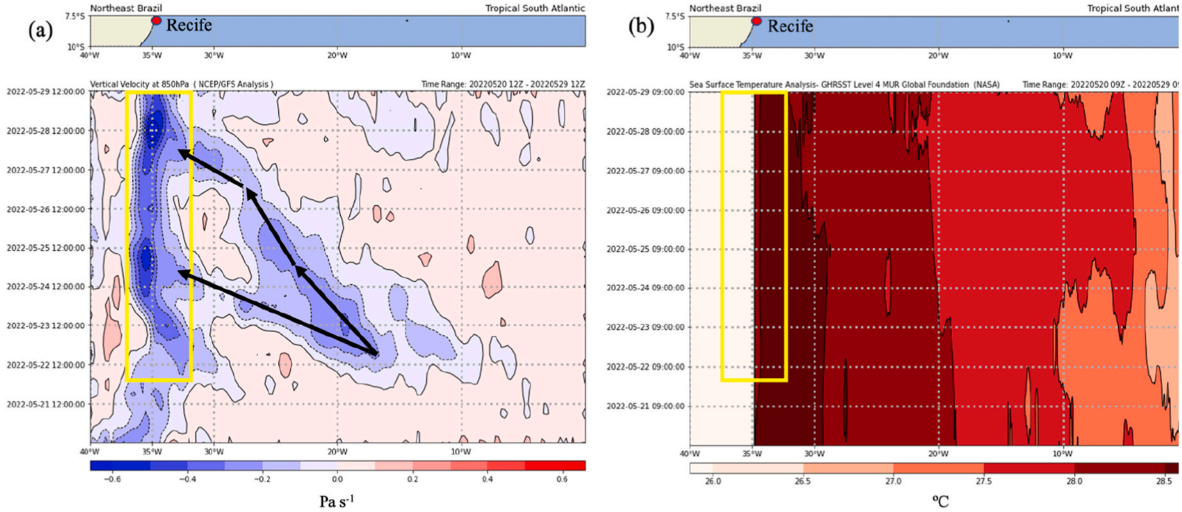

**Fig. 12.** a) Hovmöller diagram of vertical velocity (omega) at the 850 hPa level; blue colors show rising motion and arrows represent the movement of the EWD episodes of May 25 and 28. b) Hovmöller diagram of SST. Both figures are for May 21 to 29 between 0° and 40° W covering the Atlantic and the coast of Recife. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

### 4.4. *Rainfall extreme tendencies*

As seen in previous sections, rainfall in the 2022 rainy season (until June) was well above average, higher than in 2020 or 2021, in the Recife meteorological station from APAC. Our analysis extends to the end of July 2022. Rainfall volumes for May and June 2022 are high (Fig. 13a, c), compared to 2020 and 2021, and to the climatology. The tendency detected at INMET's Recife meteorological station from 1969 to 2020 shows non-statistically significant downward trends in the number of days with 20 mm in 52 years. The previous record was on August 11, 1970, with 336.7 mm. The number of days with daily rainfall totals of and above 50 and 100 mm does not change over the decades (Fig. 12b).

In 2022, the rainy season from April–July accumulated 1612 mm of rain, beating the 1981–2010 climatology of 1347.1 mm. For 2020, 2021, and 2022, the Recife APAC meteorological station shows an increase in the number of days with daily rainfall totals above 20 and 50 mm, and three days with rainfall above 100 mm in 2021 and 2022. Fig. 12d does not show days with rainfall of 200 mm or above for the Recife APAC Station. However, stations from CEMADEN's networks show that on May 28, three fluviometric stations in Jaguatão dos Guararapes showed daily rainfall of 216.1, 217.6, and 217.6 mm, and another four in the city of Recife showed 197.8, 212.8, 204.6, and 198.9 mm. Since these stations have few years of data, we cannot perform any trend analysis, nor compare with previous decades. On May 25, no occurrences of precipitation above 200 mm were detected in the MRR, but 36 stations from the CEMADEN network measured precipitation between 100 and 150 mm on that day.

We use the RX5day, R50, and R100 mm indices. We also analyze the trend of extreme rainfall in the study region at a 5% significant level. We calculate the anomalies of R50 and R100 related to the 2022 extreme events, considering historical rainfall data. Fig. 14a–d shows the monthly trends of total rainfall for the rainy months of ENEB. June showed the most extensive area with a significantly increasing rainfall trend, especially in the states of Pernambuco and Alagoas. Also, the maximum five consecutive days of total precipitation (RX5 day) has been increasing in the region (Fig. 14e) for the last 40 years. The extreme

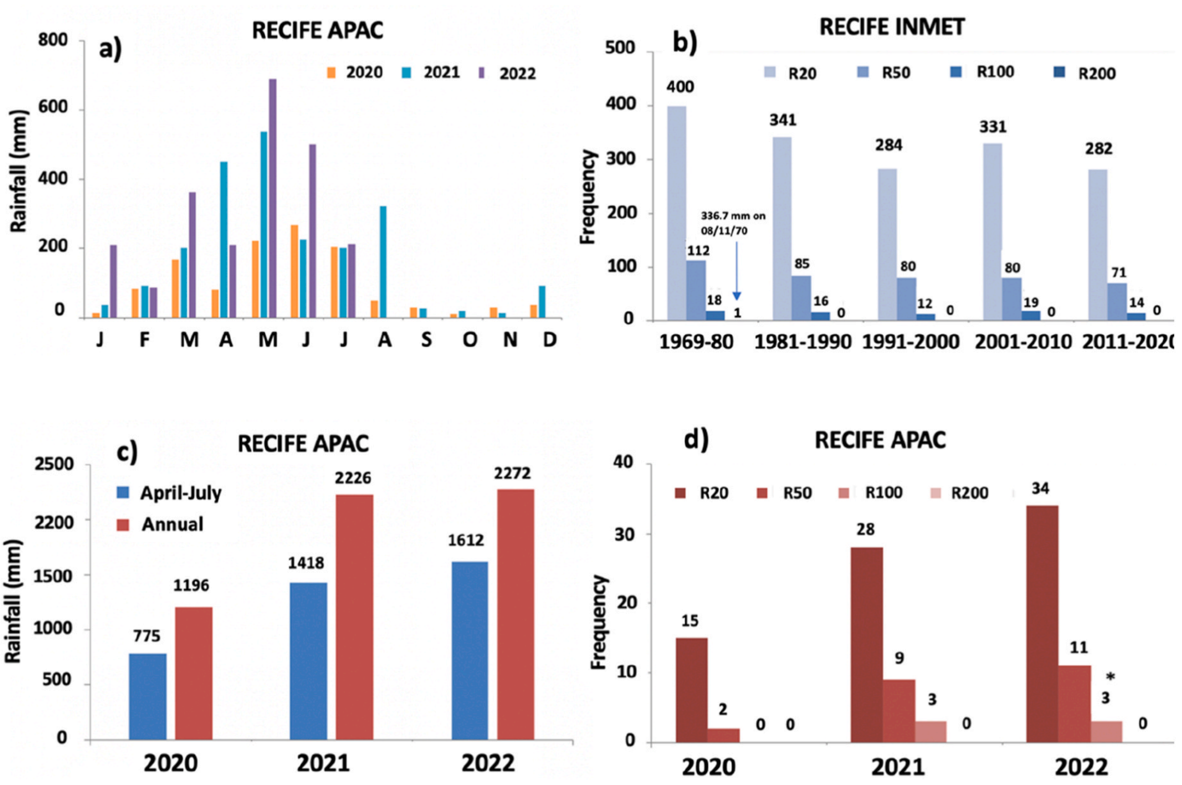

**Fig. 13.** a) Monthly rainfall for the Recife APAC meteorological station for 2020, 2021, and 2022 (until July 2022); b) Number of days with daily rainfall totals equal to or above 20, 50, 100, and 200 mm at the decadal level for Recife INMET meteorological station from 1969 to 2020; c) Accumulated total and rainy season (April–July) rainfall for 2020, 2021, and 2022 (until July 2022) for the Recife APAC meteorological station; d) Number of days with rainfall equal to or above 20, 50, 100, and 200 mm for the Recife APAC meteorological station for 2020, 2021, and 2022 (until July 2022). Recife INMET meteorological station (8.05°S, 34.95°W), Recife APAC (8.04°S, 34.87°W).

rainfall event of 2022 contributed to a positive anomaly in the annual count of days with rainfall exceeding 50 and 100 mm (R50 and R100). Alagoas and Sergipe had 2–4 days of rainfall exceeding 50 mm than usual. On the other hand, the trends analysis considering R50 and R100 indices does not indicate an increasing tendency in the last 40 years (not shown).

The RX5 day represents the intensity (mm/day) of rainfall while the R50 and R100 indices represent the frequency (number of cases) of events over predefined defined thresholds (50 mm or 100 mm). Thus, trend analyzes in Fig. 13 show that although there is no evidence that the frequency of heavy rainfall events has increased in the ENEB, there are signs that events have become more intense (greater volume of rain accumulated in a short time), indicating that although random, the events may be becoming more destructive, especially if it occurs in densely populated regions (as the 2022 event in Recife).

### 4.5. *Flood inundation mapping*

Intense rainfall in MRR in May 2022 increased the chance of floods when accompanied by (a) larger astronomical tide (spring tide); or (b) positive weather tide. The two cases may have contributed to the May 28, 2022, flooding, especially. The astronomical tide table shows a higher tidal range on May 28, 2022, consistent with the “new moon” of May 30, 2022 (Marinha do Brasil, 2022b). The tide heights measured at Recife Port (8° 3′ 4″ S, 34° 52′ 0.998″ W) on May 28 were 2.1 m (0200 a.m.), 0.4 m (0845 a.m.), 2.2 m (0247 p.m.), and 0.4 m (0900 p.m.). Signs also point to a contribution from the meteorological tide: strong southeasterly winds blew on the coast of NEB on those days (with the second cold front contributing), which may have caused the “piling up” of water on the coast, causing sea level rise, adding to the tidal height (Ekman transport). Higher sea levels cause rainwater to flow more slowly, increasing the magnitude of the flood.

Annual rainfall data (Fig. 15a) shows an average value from 1981 to May 2022 of 187.2 mm, with a minimum and maximum of 15.6 and 1,237.8 mm, respectively. The highest rainfall occurred in 1994, and the lowest in 1995. The highest average rainfall (293.0 mm) occurred in 1986. The minimum, maximum, and average rainfall from January to May 2022 were 41.6, 625, and 247.2 mm, respectively. The average rainfall of 2022 was higher than the average for the analyzed time series.

Taking only the month of May of each year analyzed (Fig. 15b), the average rainfall was 11 mm, almost 17 times lower than the annual average. For example, the minimum and maximum rainfall observed were 3.84 (May 2001) and 266.9 mm (May 2022), respectively. The average rainfall in May 2022 was 20.2 mm, twice as high as the average of the entire period. Based on the rainfall time series, we simulated spatial and temporal variation of the flood inundation in the study area for the following days: May 24, 25, 26, 27, and 28, 2022 using the HEC-RAS 2D model (Fig. 16). Results show a water depth (or water height, m) ranging from 0 to 5 m. The reference for the water depth (or water height, m) was the DEM used in the simulation. The water height followed the rainfall rhythm for those days. The maximum flood inundation occurred on May 28, 2022. Recife’s simulated area of flooding in May 2022 includes the following totals: 15.27 (May 24), 40.37 (May 25) 26.01 (May 26), 20.43 (May 27), and 40.65 km$^2$ (May 28).

Neves and Muehe (1995), using data from tide gauge measurements obtained between 1946 and 1988, indicate a high relative rise in sea level of 5.6 mm/year. These authors simulate the potential impact of 1 m of sea level rise. Their results show that 60% of the impacted area would be mangroves, but the entire business district would be directly affected. As highlighted by Olbert et al. (2017) coastal flooding occurs when high water levels due to tides and storm surges takes place in low-lying coastal areas, in combination with waves. Sa’adi et al. (2022) studied

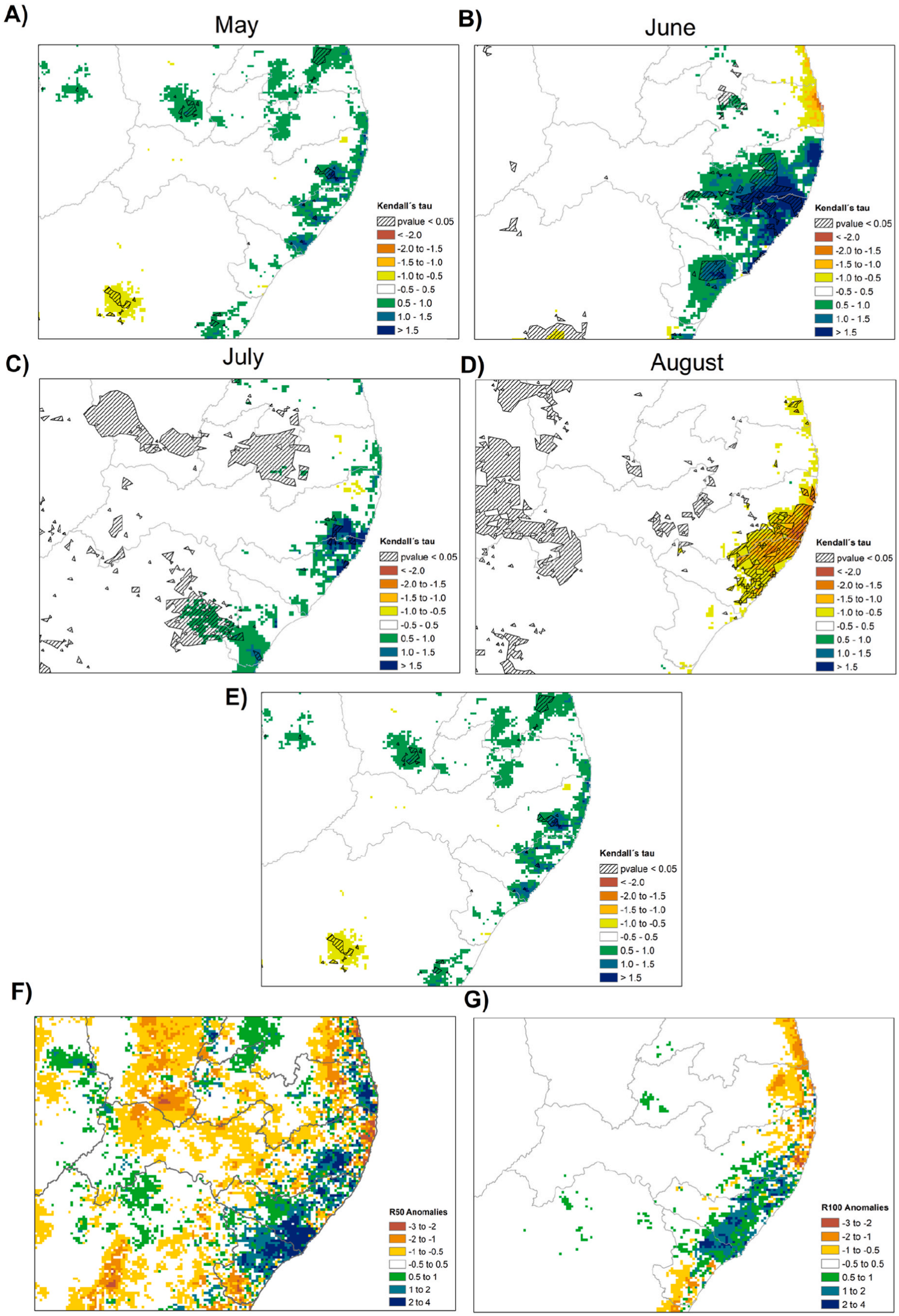

**Fig. 14.** Pixel-wise Mann–Kendall trends for total monthly rainfall for (A) May, (B) June, (C) July, (D) August, and (E) Rx5day from 1981 to 2022. Positive values represent increasing trends, and hatched areas indicate trends significant at a 5% confidence level. Anomalies of (F) R50 and (G) R100 for 2022, in number of days.

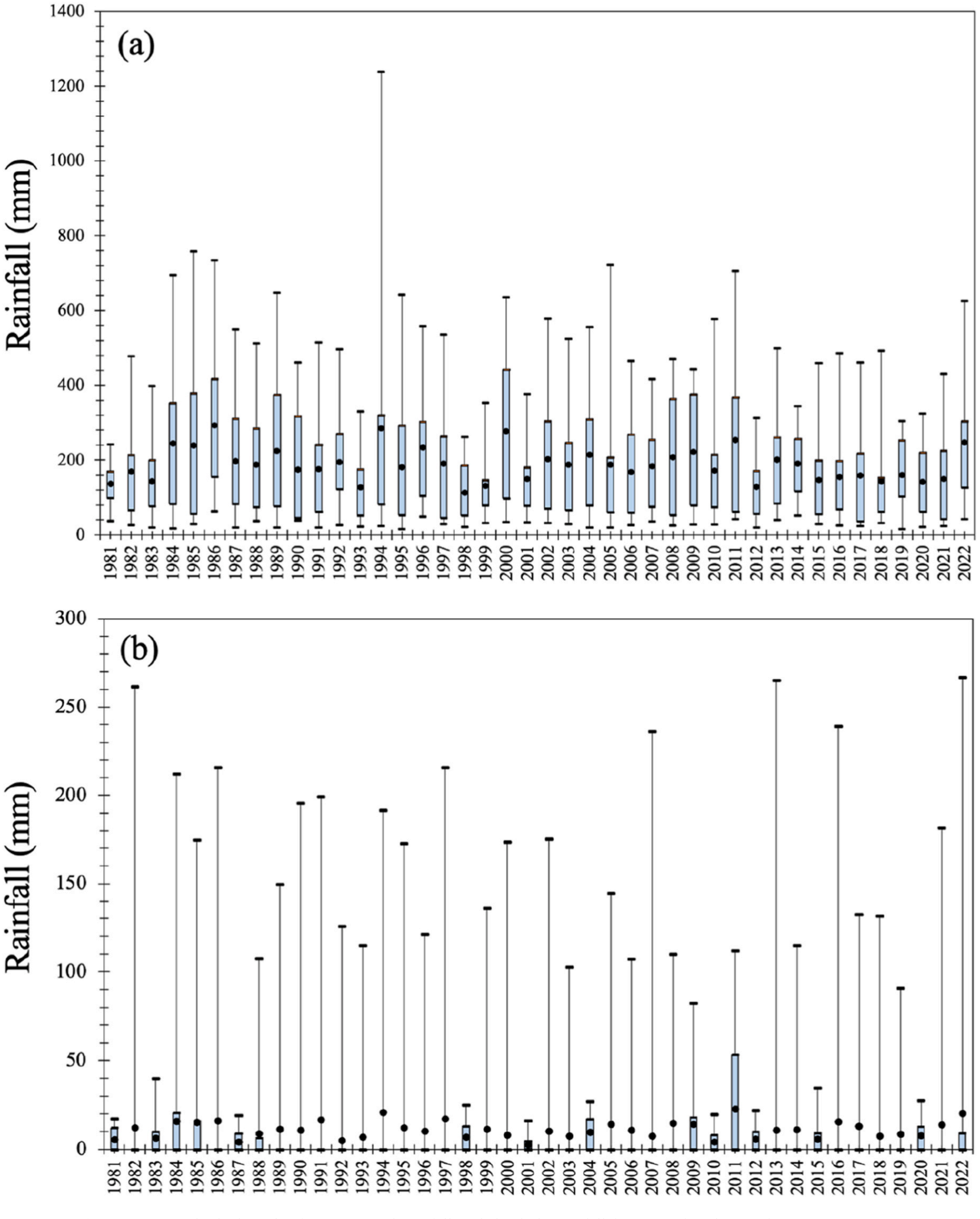

**Fig. 15.** Box and whisker plot for (a) annual rainfall and (b) daily rainfall for May of each year from 1981 to 2022.

the effect of the tide on flood modeling in Tinggi, Malaysia and found a 43% lower than the observed data of flood depth when tidal effect was not considered and an average similarity of 91.4% when considered. On the other hand, Yonehara and Kawasaki (2020) analyzed the effect of tidal effect on flood inundation in a low-lying river basin and found that depending on the location of the study site the rainfall contribution to flood occurs was far important then the tide influences. The influence of tide will be stronger near the coastal zone and weaker into the urban zone.

From the flood inundation simulations, we estimate the area (%) affected by flash flooding in each LULC class on May 25, 26, 27, and 28, 2022 (Fig. 17). Classifications are based on the following water depths: 0, 1.25, 2.5, 3.75, and 5 m. On May 24, 54.84 mm of rain fell; the following day, 109.68 mm (see Fig. 1 for location data supplied by CHIRPS). Fig. 16a shows which areas were affected by flooding in each LULC class on May 25. On this day, 7.41% of agriculture and pasture had water at 0 m and 5.44% by 1.25 m. Forested land was covered 3.65% at 1.25 m. Urban areas had 4.4% with 1.25 m. On May 26 (with no rain, Fig. 17b), water at least 1.25 m deep reached 3.42%; May 27 (with no rain, Fig. 17c) saw 4.94% of urban area was at the same level (0 m), and 2.3% at 1.25 m of water. On May 28 (with rain of 266.95 mm, Fig. 17d), the urban area suffered flooding of 11.05%, 5.03%, 1.25%, 0.12%, and

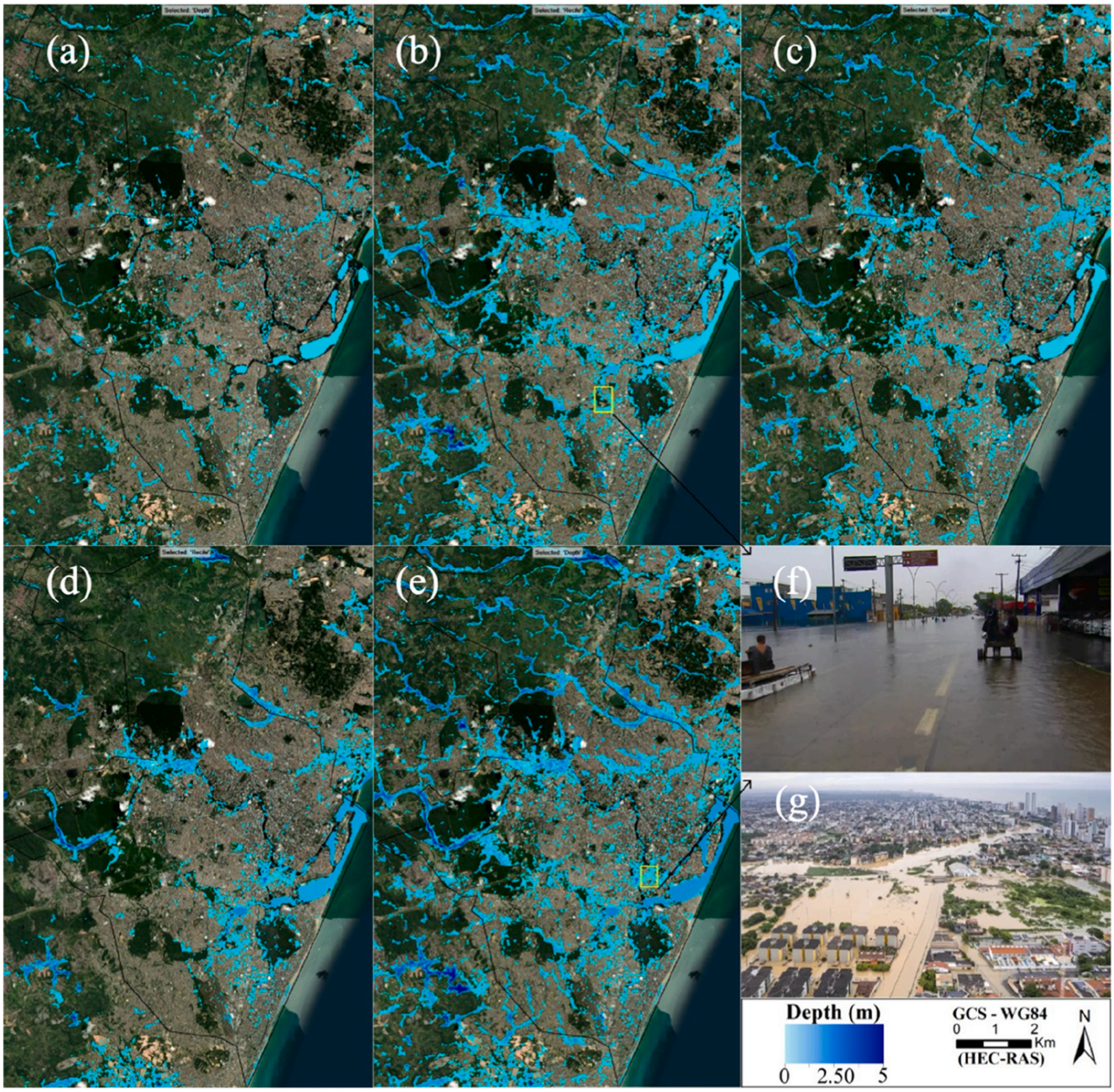

**Fig. 16.** Spatial and temporal flood inundation simulation in the study area. (a) May 24, (b) May 25, (c) May 26, (d) May 27, and (e) May 28, 2022. (e) Flood inundation occurred on May 25, 2022, Avenida Recife, Ipsep (Source: G1). (f) Flood inundation occurred on May 28, 2022, Adelmar da Costa Carvalho Stadium, Ilha do Retiro (Source: CNN Brazil).

0.01% for 0, 1.25, 2.5, 3.75, and 5 m, respectively. Rivers and lakes overflowed, with levels 2.5 m over their banks in 54% of their area.

### *4.6. Disaster risk in MRR: What happened in the last week of May 2022?*

The tragedy in the Recife metropolitan region (MRR) in May 2022 claimed more than 100 lives. The area has experienced repeated flooding in the past. The 1966 floods caused more deaths, and more people affected overall. In 1975, the flooding was more chaotic, caused more damage, and inundated MRR completely. The floods of 1966 and 1975 happened in a period when the population of Recife was considerably smaller. From 1940s to 1950s, Recife had its first major demographic expansion, growing from 200,00 to 500,000 inhabitants. The population continued to grow from 524,000 to 1.4 million inhabitants between 1950 and 2000. Urbanization occurred more by densification than by spreading (Leão et al., 2021). The population grew from 1,006, 000 inhabitants in 1966 to 1,249,841 inhabitants in 1975, according to the Anuário Estatístico do Brasil – 1966, and Anuário Estatístico do Brasil – 1975 (IBGE 1966, 1975). In 2021, the estimated population of Recife was 1,661,017 inhabitants. In 1966 and 1975, the deaths during floods were mostly linked to drowning. In contrast, many flood-related deaths in May 2022 were due to landslides. The increased population density occupying hills and slopes of the city contributed to this problem. Possible solutions in the medium and long term include improving drainage in sloped areas.

More than half of Recife's population lives in highly vulnerable areas (Assis Dias et al., 2020). As in other disasters in Brazil (Marengo and Alves, 2012; Marengo et al., 2021; Alcântara et al., 2022), heavy precipitation events trigger natural disasters, with floods— and particularly landslides— disproportionately affecting vulnerable communities. Low-income neighborhoods located in vulnerable and exposed areas in capital cities and rural areas are devastated. Thus, the impacts of such disasters are exacerbated by the pre-existing structural vulnerability in the region. This indicates a need to review the protocols for disaster risk reduction and disaster management. Warnings of extreme weather-related natural disasters and risk alerts must be stronger. When such warnings are made, anticipatory action to protect people and critical structure must be taken. For example, the intense rainfall and

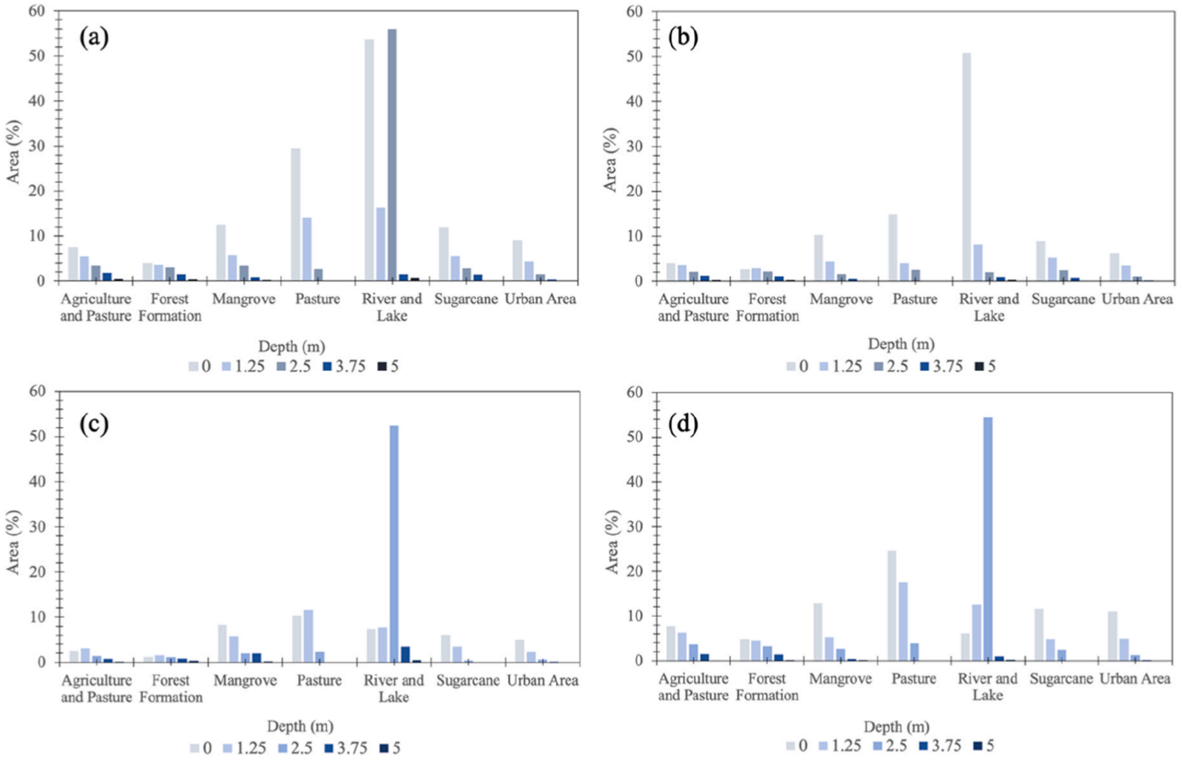

**Fig. 17.** Flood inundation depth (m) in each LULC on (a) May 25, (b) May 26, (c) May 27, and (d) May 28, 2022.

floods in Bahia and Minas Gerais in Brazil during the last week of December 2021 were adequately monitored, and early warnings issued by CEMADEN helped minimize related damage and protect human lives and property (Marengo et al., 2021; WMO, 2018).

Increased vulnerability of the local population to these hazards arises from unplanned and informal urbanization in flood-prone areas and steep hillsides. Socioeconomic, demographic, and governance factors will likely mediate long-term impacts and recovery. In May 2022, weather forecasts and warnings were issued by meteorological agencies (INMET, INPE, APAC). However, they underestimated the quantity of rain expected in MRR. A similar situation had been observed in the heavy rainfall and related disasters triggered by such rainfall extremes in Petropolis in February 2022 (Alcântara et al., 2022). While meteorological services issue forecasts for extreme weather, these do not represent forecasts or early warnings of risk of climate-related natural disasters.

Worldwide, some progress has been made in implementing multi-hazard early warning systems (MHEWS). As defined by the World Meteorological Organization (WMO) (WMO, 2018), these centers monitor meteorological and vulnerability/exposure conditions that may lead to disasters. They can issue risk alerts for natural disasters at the municipal level. Early warning is essential for disaster risk reduction. It can prevent loss of life and reduce the economic and material impacts of hazardous events. To be effective, early warning systems must actively involve the people and communities at risk from hazards. The public must be educated and aware of risks, receive messages and warnings efficiently, and remain constantly prepared to take early action.

In Brazil, the National Center for Monitoring and Early Warning of Natural Disasters from the Ministry of Science, Technology, and Innovation (CEMADEN) is closest thing to an MHEWS center. This federal institution is responsible for monitoring and issuing early warnings and alerts at various levels of risk of landslides, floods, and flash floods (CEMADEN-www.cemaden.go.br, Assis Dias et al., 2020). These alerts are delivered in real-time to the Civil Defense Executive Secretary (SEDEC) and CENAD from the Ministry of Regional Development. After assessing the disaster risk alerts information received by CEMADEN and weather forecasts from state and federal meteorological agencies, CENAD delivers alerts of disaster risk to civil defense offices and municipalities. Based on these alerts, municipalities inform the population about possible upcoming events by mobile phone (SMS), radio, TV, or even by deploying vehicles equipped with loudspeakers. CEMADEN was created in 2011 and monitors 1,038 Brazilian municipalities. These cities and towns are prioritized due to their history of disasters and high concentrations of vulnerable residents in high-risk areas. So, while CEMADEN works with disaster risk reduction, the civil defense works with disaster management.

In advance of the event on May 25, 2022, CEMADEN issued alerts of the risk of hydrological events for MRR (bulletin 1938/22) at the moderate level at 16:01 LST on May 23, and for the risk of landslides (bulletin 1941/22) at the moderate level at 16:23 LST. At 20:25 LST, the landslide alert was upgraded to high level, and later, at 20:25 LST, it was further upgraded to very high. The same 1941/22 bulletin upgraded the alert for landslides predicted for May 28 to very high at 06:13 LST. The alert in bulletin 193/22 for hydrological risk for May 25 was updated to high at 05:08 LST and then to very high at 13:31 LST. Figs. 5 and 7 show the rain continuing unabated after May 23. Bulletins 1938/22 and 1941/22 can be obtained at CEMADEN (www.cemaden.gov.br).

Despite the meteorological predictions and alerts of the risk of disaster, the population and government appear to not have been convinced to take actions that could potentially have saved lives. Meteorological centers cannot predict vulnerability and exposure, since these depend on several non-environmental factors, such as communication, governance, and cultural attitudes towards messages from scientific agencies. Other additional barriers can interfere with the decision-making process needed to implement a disaster risk alert. Regarding communication, the target population may not understand the nature of the alerts, or the technical language they sometimes use. For example, news media reported that people evacuated by the civil defense were reluctant to leave their residences. Some were afraid of looting. Others returned home to retrieve forgotten documents or pets.

These errors left some people in vulnerable areas when disaster hit and killed them. These failures highlight the need to improve how alerts are issued and communicated to the affected population. The combination of increasing frequent extreme events and a population living in areas or risk that may be inattentive to alerts is lethal. It results in more deaths from climate-related disasters. Research involving those who work with the physical aspects of disasters and social scientists is required to improve disaster risk reduction.

## 5. Conclusions and recommendations

The heavy precipitation events in 2022 prove just how vulnerable Recife and the other districts in MRR are to extremes of climate variability. The likelihood of more extreme events due to climate change cannot be ignored. On May 28, 2022, almost 17% of the entire urban area of Recife was hit by inundations. Water approximately 5 m deep covered 0.01% of the city (according to the digital elevation model). World Weather Attribution (Zachariah et al., 2022) notes that although these heavy-precipitation events are atypical in ENEB, they are now more likely to happen, in a climate warmed by human activity. Since both events broke all previous records, it is impossible to quantify how much more likely climate change has made them. The warming of the planet has increased the intensity of rainfall. Rainfall events as rare as these, had they occurred in a climate 1.2 °C cooler, would likely have been approximately one-fifth less intense (Zachariah et al., 2022).

To reduce adverse impacts of climate-related disasters, support resource management decisions, and improve outcomes requires climate services, end-to-end early-warning systems, and sustainable investments. The systems in place are not yet adequate.

Therefore, more investments—and more precisely targeted investments—in climate services are needed to strengthen early-warning systems and decision support for adaptation in climate-sensitive areas. In addition, it is essential to educate the population and governments about the deadly risks of climate-related disasters, and to reinforce public perception of the need to react to alerts and warnings of natural disasters issued by the state or federal institutions. A well-implemented plan, developed in co-production between the academic, public, and private sectors, and with local and state governments, will certainly improve disaster risk management. These actions must join the efficient monitoring of the risk of disasters induced by heavy rainfall to reduce this risk. In the end, well-coordinated initiatives aim to support municipal governments in protecting critical urban infrastructure and vulnerable populations from natural disasters caused by extreme weather events. Since extreme rainfall has become more intense and frequent across the globe, and populations are increasingly vulnerable, the risk of disaster only rises (IPCC, 2021, 2022).

Municipalities need to create an infrastructure of material, financial and human resources. Workers must be informed, motivated, trained, qualified, and guided to carry out civil defense actions on a full-time basis, since disaster can happen any day or time (CNM 2022). These actions require a great deal of preparation from local management. Adequate support and integration with the other entities of the Federation are necessary to maintain the actions at the local level. The many municipal civil defense protection competencies require uninterrupted technical and financial support from federal and state governments to strengthen them.

In practice, risk reduction must work together with risk management, starting with prevention and mitigation. Optimizing the preparation and response actions of the municipal civil defense and protection systems to disasters at the local level is possible. However, risk management will only be viable when everyone participates, which requires cultural change. The entire population, young and old alike, must understand the risks posed by those natural disasters, and remain vigilant and attentive to the alerts that may be disseminated, for a true collaboration in reducing these risks.

## CRediT author statement

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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