RESEARCH

Analysis of extreme rainfall and landslides in the metropolitan region of the Paraiba do Sul River Valley and North Coast of Sao Paulo, Brazil

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Abstract

The impact of hydrological and geological disasters has resulted in significant social, economic, and human losses, which added climate change impacts, and such events have become more frequent and intense. Therefore, our objective is to analyze the extreme rainfall (trends) in the Metropolitan Region of the Paraiba do Sul Valley and North Coast of Sao Paulo (RMVPLN). This analysis will support the most affected areas by landslides identification, which mainly impact roads and their population. In addition, evaluate the atmosphere conditions that supported these extreme rainfall events. To achieve our objectives, we have surveyed historical landslide data reported by the Brazilian government and information related by press and media. The precipitation evaluation used CHIRPS v.2 data and ETCCDI indices and the vertically integrated moisture flow and wind speed were calculated by ERA5 reanalysis. Our results show that the frequency and intensity of rainfall indicators such as seasonal PRCPTOT, R20mm, R30mm, and SDII have increased, particularly in the coastal and mountainous regions of São Paulo. This is due to positive anomalies of moisture transport and an increase of ocean winds influenced by the intense South Atlantic Subtropical Anticyclone (SASA). The region with the highest susceptibility to landslides triggered by extreme rainfall is the one that combines deforested areas, high slope topography, and excessive anthropic intervention. The presence of mountainous regions increases the risk of landslides, which can damage local infrastructure and expose the vulnerability of populations in these risk areas.

1 Introduction

The two most economically important Brazilian cities are São Paulo (SP) and Rio de Janeiro (RJ), which are in the Southeast region. Their estimated population in 2021 is around 12,396,372 and 6,775,561 inhabitants for SP and RJ, respectively (IBGE 2023). Between these two cities is

located the Metropolitan Region of the Paraiba Valley. This region is the natural connection between SP and RJ and both cities are connected by Dutra Highway, which crosses the Paraiba do Sul River Valley. While the North Coast of Sao Paulo is not located here, we decided to include it in our analysis due to its elevated risk of extreme rainfall-triggered disasters. We refer to these regions as RMVPLN (in Portuguese). The RMVPLN shows a population of 2,506,181 inhabitants, and an urbanization rate of 94.8% (Waldvogel et al. 2021).

From the 1950s onwards, there was an option to adopt road transport in Brazil (Barat 1978), which should not occur in a country of continental dimensions. In this same period, there was an intense process of urbanization in urban centers (Santos 2008; Baer 2002), a period called the "rural exodus." Such fluxes occurred from medium-sized cities to state and federal capitals (Ricci 2006; Alves et al. 2011) without planning of the governments. Associated with the lack of environmental and urban planning (Rolnik 2011), these have resulted in disorderly urban expansion and occupation of risk areas (Mendes et al. 2018a). These are reflected in the installation of highways in areas of high

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slope topography without proper planning, making them vulnerable to hydro-geo-meteorological origin disasters, mainly landslides (Marengo et al. 2021).

According to the Brazilian Atlas of Natural Disasters (UFSC-CEPED 2013) and the S2ID System (BRASIL 2023), the RMVPLN area is highly susceptible to extreme rainfall disasters. Specifically, landslides occur with great frequency in the mountainous regions of RMVPLN (Almeida et al. 2016), as evidenced by past events such as those in 1967 in the municipality of Caraguatatuba, 2000 in Campos do Jordao, and 2023 in São Sebastiao (Mendes et al. 2018a; Dias et al. 2021; Vieira et al. 2023). These landslides can cause significant economic, social, and human losses. Additionally, extreme rainfall also leads to floods and flash floods, as seen in the 2010 event in São Luiz do Paraitinga (Santos 2016), which had a strong impact on the municipality.

Recent studies have identified a concerning trend of increasingly extreme rainfall events, in the Brazilian Southeast and South, including the State of Sao Paulo (IPCC 2022, 2021; Dunn et al. 2020; Donat et al. 2016). This could potentially lead to an increase in water-related disasters in these regions. The RMVPLN, which is characterized by its coastal plains, plateaus, steep slopes, and valleys (Ross and Moroz 1996), has further exacerbated the situation due to disordered urbanization, unplanned and irregular neighborhoods, and excessive cuts and embankments for urban infrastructure and highways (Mendes et al. 2018b; Oliveira-Folharini et al. 2018; Vieira et al. 2018). As a result, the population in these areas is at a higher risk of vulnerability and exposure. The changes in rainfall and temperature, supported by physical climate changes, provide further evidence of the possible occurrence of disasters. Studies have also shown a significant increase in rainfall above 10 mm/day (R10mm) in Southeastern South America over the past 40 years, with negative trends of consecutive dry days (CDD) in south-central Brazil (Marengo et al. 2010; Avila-Diaz et al. 2022).

Over the past six decades, there has been a noteworthy rise in intense rainfall in the Southern regions of Brazil. This increase is evident in the total annual precipitation (PRCP-TOT) and the maximum annual daily rainfall (Rx1day), as highlighted by Donat et al. (2016). According to Dunn et al. (2020), even though global changes in R10mm rainfall have been minimal, there have been substantial regional surges, especially in South America, the Andes, and the western Amazon region. Additionally, there has been an increase in very wet days (R95p), and the intensity of Rx1day has increased by 2 mm per decade in Southern South America.

The Metropolitan Region of Rio de Janeiro has been grappling with the impact of extreme rainfall for quite some time. According to Dereczynski et al. (2017), the region experiences an average of 1.3 floods and landslides per year, predominantly during summer and autumn. Recent research

conducted by Regueira and Wanderley (2022) has revealed that both Rx1day and Rx5day rainfall have risen in Rio de Janeiro state, which has been linked to floods and landslides. Furthermore, Zilli et al. (2017) found that total rainfall, daily rainfall average, maximum daily rainfall per season, and rainfall exceeding the 95th percentile have all increased in the state of São Paulo, as confirmed by Machado et al. (2021). Marengo et al. (2020a) also found that rainfall frequency and intensity have increased noticeably in São Paulo, with the number of days with rainfall exceeding 80 and 100 mm in the Metropolitan Region of São Paulo being higher in the last two decades than in the 1960s.

When analyzing changes in extreme rainfall in São Paulo, Silva Dias et al. (2013) noted that local anthropogenic forcings may lead to extreme events such as heat islands and the impacts of atmospheric pollution. On the other hand, Zilli et al. (2017) showed the relationship between changes in extreme rainfall and displacements of the SACZ in Southeastern Brazil, suggesting the observed changes are atmospheric responses to radiative forcing, a consequence of global warming.

Finally, in this scenario of evident changes in rainfall, this study aims to:

i)   Identify the areas of highways most susceptible to landslides and their surroundings
ii) Analyze recent changes in rainfall
iii) Analyze the atmospheric circulation that causes rainy years and respective extreme rainfall

It is important to note that the relationship between extreme rainfall and landslides is not straightforward and is dependent on various non-environmental factors. As a result, we will also examine the conditions of different elements that trigger landslides, such as the occupation of terrain with high slopes, deforestation for the installation of urban infrastructure and highways, and disorderly occupation of urban areas in the RMVPLN. However, it is essential to clarify that our work is not intended to attribute changes in the frequency of landslides to changes in the vulnerability of the local population or exposure to the regions they live. Our study is limited to assessing the natural hazard component of landslides.

2 Materials and methods

2.1 Study area

This study was conducted in the RMVPLN, located in the Southeast region of Brazil, encompassing 39 municipalities within the state of São Paulo (São Paulo 2012). The study area itself is a sizable 16,170 km^2 and is primarily located in

the Paraiba do Sul hydrographic basin. Within this region, the Paraiba do Sul River serves as the primary river, formed by the convergence of the Paraitinga and Paraibuna Rivers (Marengo and Alves 2005). The RMVPLN (Fig. 1) can be separated into four distinct zones: (i) Serra da Mantiqueira Mountain; (ii) Paraiba Valley; (iii) North Coast; (iv) Serra do Mar and Bocaina Mountains.

The highways analyzed here may be vulnerable to disasters triggered by extreme rainfall and affect the local population. Among the key highways, we targeted the landslides that interrupted the operation of transport infrastructures between January 1, 1991, and December 31, 2022.

The climate of RMVPLN is Cwd in the Koppen classification system (Ovalle et al. 2013; Guedes et al. 2020), and strongly influenced by the South America Monsoon System (SAMS), Orographic Rainfall (OR), Frontal System (FC), and South Atlantic Convergence Zone (SACZ) (Carvalho et al. 2004; Lima and Satyamurty 2010; Milanesi and Galvani 2011; Cavalcanti 2012; Boers et al. 2013; Grimm 2019; Ferreira and Reboita 2022). These attributes contribute to a great ratio of precipitation, being specially concentrated (frequency and intensity)

in the coastal (North Coast) and mountain areas (Serra da Mantiqueira, Mar and Bocaina). This extreme rainfall exposes the local population to risk of disasters, such as landslides, flood, and flash floods (Mendes and Valério Filho 2015). The research methodology is illustrated in Fig. 2.

2.2 Landslide survey, georeferencing, and land use and land cover

This study provides a comprehensive overview of the landslides that occurred in the RMVPLN region between 1991 and 2022. Our research draws upon a variety of sources, including the Brazilian Atlas of Natural Disasters spanning from 1991 to 2012, the Integrated Disaster Information System S2iD covering the entire study period, and reports from reputable press and media outlets such as newspapers and websites. Furthermore, we cross-referenced the events with the digitized historical collection of "O Estado de São Paulo" newspaper, accessible via https://acervo.estadao.com.br/procura/, and georeferenced them in the QGIS 3.16 Software database to ensure the accuracy of our findings,
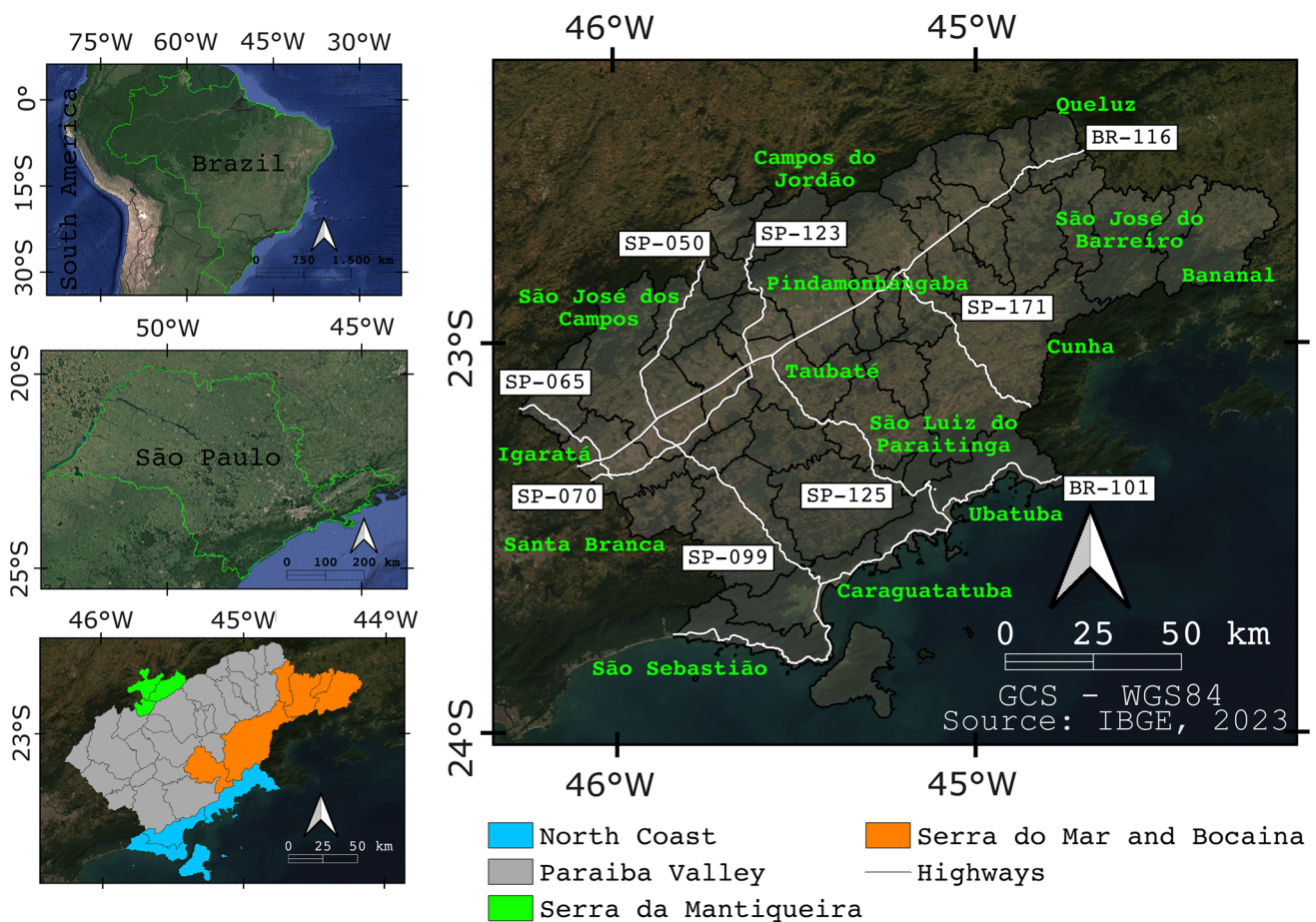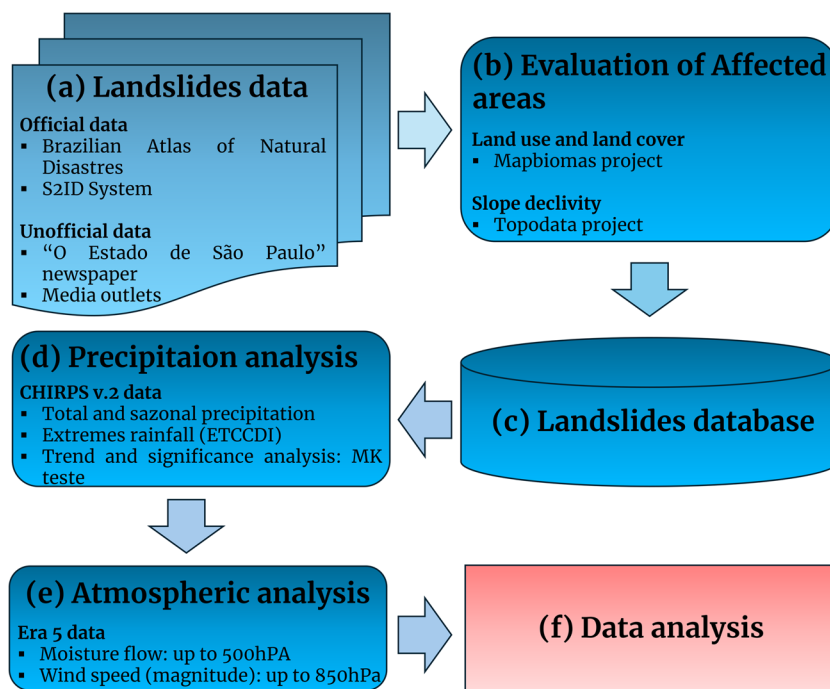

Fig. 1 Geographic regions of the RMVPLN

Fig. 2 Steps followed in this research. Indicators (**a**)–(**f**) represents the sequential methodology flow

particularly concerning landslides in regional highways. We decided to focus on the period from 1991 onwards because the Brazilian government only started compiling official reports on landslides from this date onwards, which can be found in both the Brazilian Atlas of Natural Disasters and the S2ID System.

To evaluate the areas affected by landslides and identify changes in land use and cover, we turned to the Mapbiomas project database, accessible at https://mapbiomas.org/. This project uses Landsat satellite data to generate land use information, covering the period between 1985 and 2021 in the 7.0 collection (Neves et al. 2020; Souza et al. 2020; Rosan et al. 2021). Moreover, we employed the digital elevation model from the Topodata Project to identify the slope of the affected areas. This information is available at http://www.dsr.inpe.br/topodata/, with a spatial resolution of 30×30 m per pixel (Valeriano and Rossetti 2012) .

2.3 Precipitation data

In this study, we utilized CHIRPS v.2 as our source of precipitation data. CHIRPS v.2 estimates rainfall for a given location based on satellite observations and rain gauges, designed to monitor agricultural droughts and global environmental changes, as well as analyze climate extremes in a historical context.

The process of building the precipitation estimate is broken down into three main components: CHPclim, CHIRP, and the merging of data from stations worldwide. The horizontal resolution of the precipitation data is $0.05 \times 0.05°$,

with each pixel measuring 25 km^2 (5×5 km) (FUNK et al. 2015). Daily rainfall data from January 1, 1981, to December 31, 2022, was specifically selected for this study in order to understand the spatial distribution of rainfall in the RMVPLN, classify its extremes, and observe possible trends of changes in its distribution.

To ensure the accuracy of CHIRPS v.2 rainfall data, studies have been conducted in Brazil, comparing rainfall estimates with gauges data from INMET (Brazilian National Institute of Meteorology). These studies have found an excellent correlation between CHIRPS v.2 rainfall and gauges data, with one study showing a correlation coefficient (R 0.94) for the Atlantic Forest biome in Northeastern Brazil (Paredes-Trejo et al. 2017). According to Paca et al. (2020), CHIRPS v.2 precipitation data is suitable for examining rainfall variability in the Amazon River basin and has advantages over other precipitation products.

When it comes to validating precipitation data from CHRIPS v.2 in neighboring areas of the RMVPLN, we have seen positive results compared to other models and satellite-based rainfall. A study conducted in São Paulo state by Ramos Filho et al. (2022) validated rainfall data that combined gauge and satellite, and CHIRPS v.2 was discovered to have a higher KGE value for extreme precipitation in daily, 5-day, and 10-day periods compared to the MSWEP 2.2 and IMERG-F. We also observed good results in comparing daily precipitation data from CHIRPS v.2 and TRMM with the INMET station in the south of Minas Gerais state, which included data of the municipality of Campos do Jordão/SP in the analysis. In this case, the correlation coefficient (*R*)

and determination (R^2) were 0.96 and 0.92, respectively (Nogueira et al. 2018). Additionally, CHIRPS v.2 boasts better spatial resolution than TRMM. Given that gauge stations data in the RMVPLN frequently have numerous failed records and varying periods of observation, CHIRPS v.2 data provides the best alternative for analyzing extreme rainfall in the region. The CHIRPS v.2 rainfall data used in this study is available for download at https://data.chc.ucsb.edu/products/CHIRPS-2.0/.

As part of our research, we carefully examined the patterns and statistical significance of PRCPTOT (total precipitation — TR) across two distinct seasons: the rainy season (RS) from October to March and the summer season (SS) from December to February. Furthermore, we utilized ETCCDI indices to determine extreme rainfall indicators.

2.4 Expert Team on Climate Change Detection and Index (ETCCDI)

To identify the most intense rainfall events that impact highways, we employed the ETCCDI indices. These indices were established by the Expert Team on Climate Change Detection and Index in 1998 and play a vital role in understanding extreme weather patterns (Alexander et al. 2019). For this study, we utilized the ClimPACT v.3 Software that processes data using the R language (Alexander and Herold 2016) to compute the indices.

The ETCCDI indices play a crucial role in climate analysis and research. They are extensively used to identify changes in various climatic variables, such as precipitation, extreme rainfall, temperature, and heat waves. By measuring and analyzing these indices, it is possible to better understand the complex patterns of climate change and their impacts on the environment and society (Zwiers et al. 2013; Thibeault and Seth 2014; Turco et al. 2014; Gebrechorkos et al. 2019; Cooley and Chang 2021). Our research objectives were accomplished by selecting nine indices (refer to Table 1 for further details).

The ETCCDI indices were calculated using daily rainfall data from two periods: (i) 1981–2022 to identify rainfall extremes, observe trends (climatology), and determine statistical significance using the Mann-Kendal method; and (ii) 2002–2022 minus 1981–2001 (anomalies) to observe recent changes in the distribution of extreme rainfall. After careful analysis of the terrain, we have identified nine regions within the RMVPLN that are particularly susceptible to landslides (São Sebastião, Caraguatatuba, Ubatuba, Taubaté, Campos do Jordão, São José dos Campos, São Luiz do Paraitinga, Cunha, and Queluz) and calculate extreme rainfall using ETCCDI indices. Additionally, we have pinpointed seven key locations (as listed in Table 2) to ensure that our analysis of extreme rainfall indicators is consistent and our findings are applicable throughout the area (Ubatuba II, Santa Branca, Igaratá, Aparecida, Pindamonhangaba, São José do Barreiro, and Bananal).

Both precipitation and extreme rainfall maps were produced using the WGS-84 Geographic Coordinate System and the cartographic base of the Brazilian Institute of Geography and Statistics (IBGE), which is available at https://www.ibge.gov.br/geociencias/downloads-geociencias.html.

2.5 Rainfall thresholds for triggering landslides

This study delves into the crucial rainfall thresholds that can induce landslides in the RMVPLN region. These thresholds consider the accumulation of rainfall over 24 h (Rx1day) and 72 h (Rx3day). Tatizana et al. (1987a, b) were pioneers in researching the Serra do Mar Mountains, leading to the creation of equations that factored in the area's fundamental characteristics and hourly rainfall data from rain gauges related to landslide onset.

Santoro et al. (2010) later updated these equations, achieving better outcomes with rainfall accumulation over 72 h, which have effectively been used in neighboring regions, as well as in Minas Gerais, Rio de Janeiro, and São Paulo states, all with similar topography (Parizzi et al.

Table 1 ETCCDI index definitions and rainfall analysis positions

	Index	Definition	Units
ETCCDI indices	PRCPTOT	Annual total precipitation on rainy days	mm
	Rx1day	Maximum precipitation in 1 day	mm
	Rx3day	Maximum precipitation on 3 consecutive days	mm
	R10mm	Number of days that precipitation ≥ 10 mm	day
	R20mm	Number of days that precipitation ≥ 20 mm	day
	R30mm	Number of days that precipitation ≥ 30 mm	day
	R95p	Total annual precipitation with RR percentile > 95th percentile	mm
	R99p	Total annual precipitation with RR percentile > 99th percentile	mm
	SDII	Total annual precipitation divided by the number of wet days ≥ 1.0 mm	mm/day

Source: Frich et al. (2002), Alexander (2016)

Table 2 Detailing of extreme rainfall analysis positions

Region	Municipality	Latitude	Longitude	Altitude (m)
North Coast	São Sebastião	−23.765	−45.410	19.2
	Caragutatuba	−23.598	−45.440	220.1
	Ubatuba	−23.410	−45.111	21.8
	Ubatuba II	−23.282	−44.845	417.0
Serra do Mar and Bocaina	São Luiz do Paraitinga	−23.252	−45.293	784.2
	Cunha	−23.108	−44.924	1005.7
	São José do Barreiro	−22.766	−44.640	1644.0
	Bananal	−22.712	−44.354	540.3
West of RMVPLN and Serra da Mantiqueira	Igaratá	−23.161	−46.101	621.5
	São José dos Campos	−12.072	−45.920	572.2
	Campos do Jordão	−22.769	−45.614	1665.8
	Pindamonhangaba	−22.743	−45.434	1206.0
Paraiba Valley	Santa Branca	−23.384	−45.775	734.9
	Taubaté	−23.027	−45.543	594.7
	Aparecida	−22.875	−45.245	635.0
	Queluz	−22.564	−44.845	525.1

2010; Mendes et al. 2015; Molina et al. 2015; Oliveira et al. 2016; Metodiev et al. 2018; São Paulo 2022). Based on these studies, we adopted the rainfall thresholds for the possibility of triggering a landslide (Rx1day and Rx3day): (i) North Coast — 40 mm/24 h and 100 mm/72; (ii) Paraiba Valley — 40 mm/24 h and 80 mm/72 h in; (iii) Serra da Mantiqueira — 40 mm/24 h and 60 mm/72 h; and (iv) Serra do Mar and Bocaina — 40 mm/24 h and 80 mm/72 h.

It is worth noting that the RMVPLN region employs the Rx1day and Rx3day indicators to identify specific levels of rainfall that trigger civil defense observation and precautionary measures. These measures are meticulously planned and executed by the Preventive Plan of Civil Defense of the State of São Paulo (São Paulo 1997). Furthermore, in the event of extreme rainfall, the National Center for Monitoring and Alerts of Natural Disasters (CEMADEN) issues alerts that can prompt civil defense activities aimed at mitigating the impact of landslides (Macedo et al. 2020).

We utilized estimated rainfall data from CHIRPS v.2, widely employed around the world to identify clusters of landslides from 1988 to 2018 (Benz and Blum 2019). In Taiwan, it was used to evaluate the potential relationship between rainfall and landslides (Hölbling et al. 2020), and in Colombia, it was used to establish thresholds that could trigger landslides (Cullen et al. 2022).

2.6 Assessing rainfall trends and extremes

In this research, we used the non-parametric Mann–Kendall (MK) test (Mann 1945; Kendall 1975) to evaluate the trends in rainfall and its extremes. The MK test analyzes the data sample by comparing each value to subsequent data, with positive values indicating an upward trend and negative values indicating a downward trend in the data, obtained from S (Wilks 2011):

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

where:

$$\text{sgn} = \begin{cases} 1, \text{if}\,(x_j - x_i) > 0 \\ 0, \text{if}\,(x_j - x_i) = 0 \\ -1, \text{if}\,(x_j - x_i) < 0 \end{cases}$$

In cases where $n > 10$ (n is the number of data points), the variance (V) is calculated from the Gaussian distribution with zero mean:

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

And the statistical significance of the data is obtained by Z:

$$z = \begin{cases} \frac{(S-1)}{\sqrt{\text{Var}(S)}}, S > 0 \\ \frac{(S+1)}{\sqrt{\text{Var}(S)}}, S < 0 \end{cases}$$

2.7 Vertically integrated moisture flow and wind magnitude

The relationship between atmospheric circulation and precipitation patterns in the RMVPLN was evaluated through ERA5 reanalysis ERA5 (https://cds.climate.copernicus.

eu). The vertically integrated moisture flow (surface up to 500 hPa) was applied to identify possible anomalies in the Amazonian moisture transport in the austral summer (DJF) (Ruv Lemes et al. 2023). The climatological reference period was considered 1979/2022, without considering the set years/events. In addition, the evaluations were also based on wet (09/2010, 12/2013, and 22/2023), normal (10/2011), and dry (11/2012 and 13/2014) years in the RMVPLN, regarding the climatology of the period 1981/2022 and classified by the Quantis Techniques (Pinkayan 1966).

Finally, the wind speed (magnitude) in 850 hPa was also evaluated to identify some possible changes in the South Atlantic Subtropical Anticyclone (SASA) (Reboita et al. 2019) during austral summer. Such evaluations have great importance to evaluate not only the influence of climatological position, which can provoke drought events (Coelho et al. 2016) but also affects the water input in South America (Marengo et al. 2020b). The integrated moisture flux is calculated by the following equations (Ruv Lemes et al. 2023):

$$Qu = \frac{1}{g} \int_{pt}^{po} qudp$$
$$Qv = \frac{1}{g} \int_{pt}^{po} qudv$$

where Qu represents the zonal and Qv the meridional component of wind, pt represents the pressure in the upper 500 hPa, and po represents surface pressure. The moisture transport anomaly was calculated using the following equation (Ruv Lemes et al. 2020):

$$\sqrt{u \cdot u + v \cdot v}$$

where u is the zonal component of the wind and v is the meridional component.

3 Results and discussions

3.1 Historical of landslides in the RMVPLN

Between 1991 and 2022, approximately 84 landslides caused disruptions on highways in the RMVPLN (UFSC-CEPED 2013; Brasil 2023). These landslides were mostly found on highways located in the Serra do Mar, Serra da Mantiqueira, and the North Coast. The recurrence of landslides was observed in regions with high slopes, intense rainfall, and topographic similarity. These factors, both natural and anthropic (IPT 2007), increased the vulnerability of transport infrastructures and the local population living around these highways.

The analysis of land use and cover data (Mapbiomas 2023) showed that landslides predominantly occurred in regions with pastures and without native vegetation in Paraiba Valley and Serra da Mantiqueira (Camarinha et al.

2014). In Serra do Mar, landslides occurred in areas with native vegetation, but with a topography of high slope and winding roads (Manning et al. 2008), while on the North Coast, landslides were related to high slope topography, extreme rainfall, and native vegetation close to urban infrastructures (Alcântara et al. 2022).

The North Coast region has a concerning history of grappling with landslide issues that are often triggered by heavy rainfall. A tragic example of this occurred in March of 1967 when Caraguatatuba was hit with severe floods and landslides following 3 days of incessant rain. This event resulted in the loss of over 400 lives and destroyed access roads to the city (Folha de São Paulo 1967; Ploey and Cruz 1979). Sadly, this kind of devastation was repeated in February of 2023 in São Sebastiao when a series of landslides and debris flows decimated entire neighborhoods, caused significant economic losses, and resulted in the loss of 65 lives. In this instance, over 600 mm of rainfall was recorded (Costa 2023).

Landslides may affect multiple sectors of society and the RMVPLN population, which has emphasis on the North Coast and Serra da Mantiqueira cities developing tourism activities (Silva et al. 2017; Santos et al. 2018; Pinheiro et al. 2019). These landslide events may not only disrupt the traffic among regional highways (Teodoro et al. 2021) but also result in fatalities for those who live in steep terrain areas (Camarinha et al. 2014). The economy is directly impacted through these traffic interruptions in RMVPLN, which may generate equivalent costs around US$1279.29 per m^2 (relative to 2019). The reconstruction of houses and other improvements might also be expensive, reaching up to US$357.35 per m^2. These costs harm the population, who already present a high vulnerability level facing extreme precipitation events (Batista et al. 2019).

Of the 84 recorded landslide events, 48.8% occurred in forested areas, 46.4% occurred in agricultural areas/pastures, and only 4.7% occurred in non-vegetated/urbanized regions. The slope and distribution of landslides by land use and cover can be seen in Table 3 and Fig. 3.

3.2 Precipitation

3.2.1 Climatological evaluation (1981–2022)

The RMVPLN region exhibits variations in precipitation levels, as indicated by PRCPTOT, which are influenced by differences in topography. The average rainfall in this region ranges from 1206.0 to 2132.5 mm/year between the years 1981 and 2022. The rainy season in this region typically occurs between October and March, with the heaviest rainfall recorded between December and February, a phenomenon that is attributed to the South American Monsoon System, South Atlantic Convergence Zone (SACZ), Frontal

Table 3 Occurrences of landslides in the RMVPLN

	Municipalities	Landslides (%)	Municipalities	Landslides (%)	
Municipalities	Guaratingueta	1 (1.2)	Cunha	3 (3.6)	
	Campos do Jordao	1 (1.2)	Lavrinhas	3 (3.6)	
	Jambeiro	1 (1.2)	Queluz	3 (3.6)	
	Pindamonhangaba	1 (1.2)	Paraibuna	4 (4.8)	
	Natividade da Serra	2 (2.4)	São Jose dos Campos	6 (7.2)	
	Jacarei	2 (2.4)	São Luiz do Paraitinga	8 (9.5)	
	Monteiro Lobato	2 (2.4)	São Sebastiao	8 (9.5)	
	Santo Antônio do Pinhal	2 (2.4)	Ubatuba	10 (11.9)	
	Taubate	2 (2.4)	Caraguatatuba	25 (29.8)	
Highways	Highways	Landslides (%)	Highways	Landslides (%)	
	(SP-123)	3 (3.6)	(BR-101)	13 (15.5)	
	(SP-171)	4 (4.8)	(SP-125)	17 (20.2)	
	(SP-050)	8 (9.5)	(SP-099)	29 (34.5)	
	(BR-116)	10 (11.9)			
	Highways	Agriculture/pasture (%)	Non-vegetated area/urbanization (%)	Forest/native vegetation (%)	Total (%)
Land use and cover	(BR-101)	3 (23.0%)	2 (15.3%)	8 (61.5%)	13 (100%)
	(BR-116)	9 (90%)	1 (10%)	0 (0%)	10 (100%)
	(SP-050)	8 (100%)	0 (0%)	0 (0%)	8 (100%)
	(SP-099)	5 (17.2%)	1 (3.5%)	23 (79.3%)	29 (100%)
	(SP-123)	1 (33.3%)	0 (0%)	2 (66.4%)	3 (100%)
	(SP-125)	9 (53.0%)	0 (0%)	8 (47.0%)	17 (100%)
	(SP-171)	4 (100%)	0 (0%)	0 (0%)	4 (100%)
	Total	39 (46.4%)	4 (4.7%)	41 (48.8%)	84 (100%)

Systems (FS), and South Atlantic Sea Surface Temperature (Carvalho et al. 2002; Gan et al. 2009; Lima et al. 2010; Machado et al. 2021).

The North Coast of the region typically records the highest levels of precipitation, ranging from 1675.3 to 2132.5 mm/year, as depicted by the dark blue color in Fig. 4. This finding is consistent with Silva and Simões' (2014) earlier findings on rainfall in the same region. The high levels of precipitation in this area result from atmospheric circulation characteristics where the Serra do Mar Mountains obstruct moisture incursion from the South Atlantic Ocean and induce ascending movements that generate large volumes of precipitation (Nunes et al. 2009).

The North Coast of the region records very wet years, including 1983, 1985/1986, 1996, 2010, 2015/2017, and 2022/2023, which are influenced by SACZ intensification, anomalies in the Atlantic Ocean SST, or even ENOS (Liebmann et al. 2001; Castellano and Nunes 2010; Sobral et al. 2020). After 2010, there has been an increased alternation between rainy years and below-average rainfall in the period 1981/2022.

The Serra do Mar and Serra da Bocaina Mountains also record significant precipitation levels ranging from 1533.1 to 1827.1 mm/year. In this area, high-intensity precipitation occurs, associated with different atmospheric systems such as SACZ, Cold Fronts, and Cyclonic Vortices (Horta and Neves 2019). Fog, low-intensity rainfall, and drizzle are also common (Arcova et al. 2019). The western and northern part of the Paraiba Valley, where the Serra da Mantiqueira is located, records an average precipitation of 1496.7 to 2071.0 mm/year. Due to its high altitude, this region experiences orographic precipitation (Cândido and Nunes 2008; Oliveira and Galvani 2015). The climatology of the Paraiba Valley is compatible with those obtained by Brasiliense et al. (2020).

Precipitation in the Paraiba Valley ranges from 1206.3 to 1497.8 mm/year (light blue in Fig. 4). Rainfall gradually increases towards the eastern part of the Paraiba Valley, with the wet season typically starting at the end of September (Fisch 1999; Villaron and Fisch 2013). This phenomenon is facilitated by atmospheric heating, which causes natural convection and convective rainfall (Dufek and Ambrizzi 2005) and ends at the beginning of April. According to research conducted by Cai et al. (2020), the El Niño Southern Oscillation (ENSO) has been observed to cause droughts in the northern region of Brazil, while resulting in floods in the southern region. However, studies by Fisch and Valério (2005) and Carvalho and Jones (2009) show that there is no significant impact on the levels of rainfall in the Paraíba Valley and the state of São Paulo, respectively. Figure 4
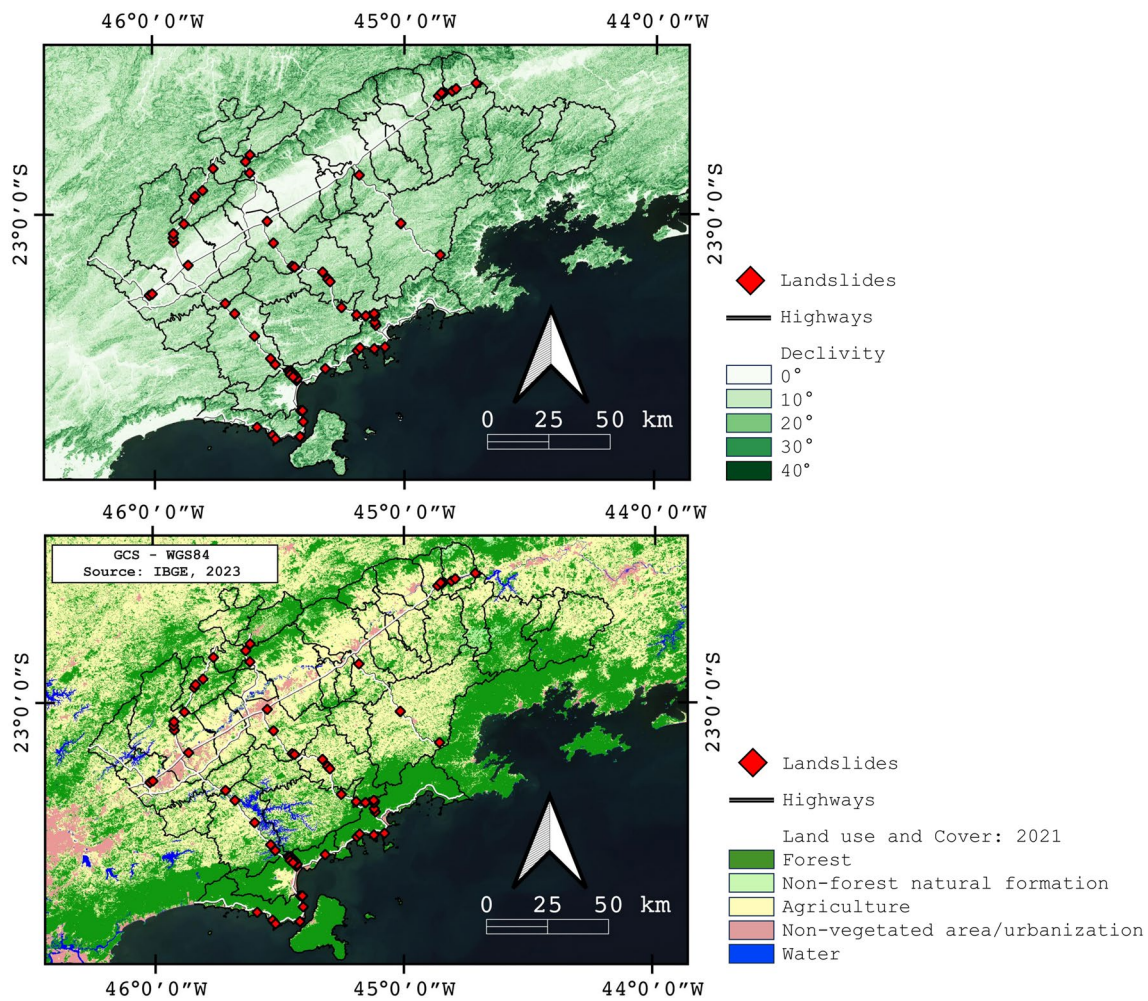
Fig. 3 Location of landslide by declivity and land use and cover

illustrates the distribution of precipitation in the RMVPLN between the years 1981 and 2022.

3.2.2 Extreme rainfall (1981–2022)

The distribution of extreme rainfall indicators in the RMV-PLN is characterized by frequent and intense rainfall in the North Coast and Serra do Mar, Mantiqueira, and Bocaina Mountains. These regions are influenced by orographic precipitation, as well as the position of the South Atlantic Subtropical Anticyclone (SASA) and the SACZ. The Paraiba Valley, on the other hand, experiences the lowest extreme rainfall in the RMVPLN when compared to coastal and mountainous regions.

The North Coast, Serra do Mar, and Bocaina receive most of the R10mm rainfall, up to 73 days, indicating that high altitudes and orographic rainfall play a crucial role in the high incidence of this type of precipitation in areas with similar topography (Obregón et al. 2014). The R20mm (up

to 42 days) and R30mm rainfall (up to 25 days) follow the same spatial pattern as the R10mm. These findings are consistent with the positive trends of R20mm to RMVPLN, as reported by Dufek and Ambrizzi (2008), when evaluating precipitation variability in the state of São Paulo.

The intense rainfall (R95p) ranges between 185.4 and 357.4 mm/year, while the extremely intense rainfall (R99p) ranges between 51.3 and 102.2 mm/year, with more intensity on the North Coast and mountainous regions (R95p range between 265.5 and 357.4 mm/year and R99p range between 76.1 and 102.2 mm/year). The concentration of P95p and R99p rainfall in the coastal areas of the state of São Paulo (here represented by the North Coast) and in the mountainous regions of the RMVPLN is compatible with the results obtained by Liebmann et al. (2001), which linked South Atlantic Convergence Zone (SACZ) episodes with extreme rainfall events. The heavy rainfall often triggers landslides, resulting in fatalities, as reported in Seluchi and Chou's (2009) study on the southeastern region of Brazil.
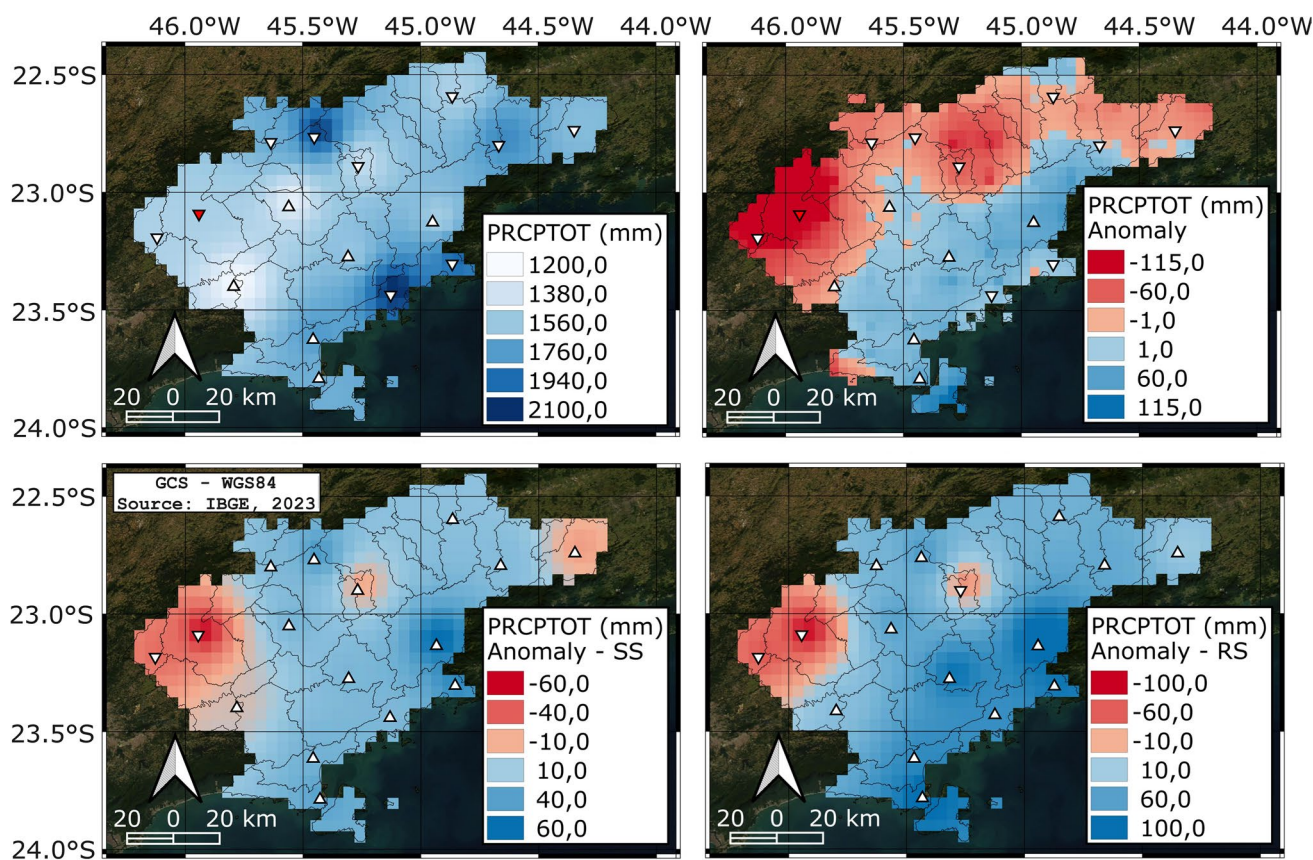
Fig. 4 Annual and seasonal distribution of rainfall in the RMV-PLN. SS represents the summer season and RS the rainy season. The upward triangles represent positive rainfall trends and when blue with statistical significance. Downward triangles represent negative trends and when red with statistical significance. The statistical significance is at a level of 95%

The maximum 1-day rainfall (Rx1day) ranges between 48.0 and 106.6 mm/year, while the 3-day (Rx3day) ranges between 81.8 and 155.2 mm/year, with more intensity in the North Coast and mountainous regions. The daily rainfall intensity (SDII) was more homogeneous according to the topography in the RMVPLN and became more intense in mountainous topography regions in the Serra do Mar, Bocaina, and Mantiqueira, ranging between 13.8 and 25.9 mm/day.

According to threshold defined by Santoro et al. (2010), Mendes et al. (2015), and São Paulo (2022), the Rx1day rainfall indicates the possibility of triggering landslides between September and April on the North Coast and in the Serra do Mar, Bocaina, and Mantiqueira during the rainy season. The Rx3day rainfall, which occurs between December and March, has the potential to cause landslides in the North Coast, Serra da Mantiqueira, and Boicaina regions. This period is longer in Serra da Mantiqueira, spanning from November to March, and shorter in Paraiba Valley, occurring only in January. These findings are consistent with

the records of landslides that impacted the local population between September and May in the period 1991/2022. Coelho-Netto et al. (2009) also report that this period of the year had the highest concentration of large landslides in Brazil throughout the twentieth century.

3.2.3 Climatological tendency: 2002/2022 minus 1981/2001

The precipitation patterns in the region reveal a distinct trend. The Atlantic Ocean vicinity, spanning across the entire North Coast, Serra do Mar, and Bocaina, witnessed a noteworthy increase in rainfall (PRCPTOT), whereas the Paraiba Valley and Serra da Mantiqueira region witnessed a decline in rainfall during the analyzed period.

The North Coast and the municipalities of São Luiz do Paraitinga and Cunha experienced a rise in rainfall up to 112.4 mm/year (4.9%) and 68.9 mm/year (4.6%), respectively, particularly in the hydrographic basin of the Paraitinga and Paraibuna Rivers (blue areas in Fig. 4). Our findings

confirm and replicate the studies conducted by Senna et al. (2023), which demonstrated an increase in PRCPTOT, particularly in the municipality of Cunha. These areas are vulnerable to weather-related disasters such as floods and landslides (Santos 2016), emphasizing the necessity of an early warning system in these areas (Marchezini et al. 2018). Additionally, the region experiences substantial variability in rainfall and flow of the Paraitinga River (Vilanova 2014), particularly after 2010 as showed by PRCPTOT analysis.

On the other hand, the Paraiba Valley and Serra da Mantiqueira experienced a decline in rainfall up to − 174.6 mm/ year (already confirmed by the climatological normal of Campos do Jordão, comparing the periods 1961/1990 to 1981/2010) (INMET 2023), highlighted in red areas in Fig. 4. Studies with climate simulation models in the same area show a decline in total annual precipitation (Chou et al. 2014; Lyra et al. 2018). Throughout the analyzed period, there was a noteworthy reduction in precipitation within the municipality of São José dos Campos, amounting to a decrease of 10.8%. While a downward trend in precipitation was also discernible in Igaratá and Aparecida, with respective decreases of 8.7% and 6.5%, the statistical significance of these decreases was not established. In other regions, a decrease in precipitation of less than 1.7% was observed.

According to several studies, PRCPTOT tends to increase during the rainy and summer seasons (by Folhes and Fisch 2006; Santos and Fisch 2016; Silva and Fisch 2019). The North Coast experiences the most significant increase in PRCPTOT during the rainy season, with a range of 77.2 to 112.4 mm, representing an increase of up to 9.3%. Similarly, in the mountain regions of Serra do Mar and Bocaina, there

is also an increase in PRCPTOT during the rainy season, ranging between 58.4 and 135.8 mm in the municipality of Cunha, representing an increase of up to 10.8%. However, the western part of RMVPLN shows a decrease in PRCPTOT during the rainy season, ranging between − 67.1 and − 94.1 mm (up to − 7.8%).

Likewise, during the summer season, we observe an increase in PRCPTOT, mainly in the North Coast (range between 23.2 and 49.6 mm, representing an increase up to 6.5%) and in the Serra do Mar and Bocaina (range between 19.6 and 24.4 mm, representing an increase up to 10.2%). The projected increase in PRCPTOT during the summer season was also estimated using the Global Climate Model and Eta Regional Model for the scenarios RCP's 4.5 and 8.5, up to 45 mm (Reboita et al. 2022).

Thus, the increase in PRCPTOT during the rainy and summer seasons may also increase the risk of disasters triggered by extreme rainfall, such as floods and landslides. These disasters can cause significant economic and social impacts (Corsi et al. 2012; Haddad and Teixeira 2015; Batista et al. 2019). The annual and seasonal trends and distribution of PRCPTOT can be viewed in Table 4.

3.2.4 Extreme rainfall tendency (ETCCDI): 2002–2022 minus 1981–2001

Our research reveals that there have been changes in extreme rainfall patterns across different regions of RMVPLN. The western region of Paraiba Valley has experienced a decline in the frequency and intensity of extreme rainfall, particularly in the municipalities of Igarata and São Jose dos

Table 4 Annual and seasonal precipitation (PRCPTOT) in the RMVPLN

	São Sebastiao				Caraguatatuba				Ubatuba				Ubatuba II			
	PRCPTOT (mm)	Δ (mm)	Trend	p.value	PRCPTOT (mm)	Δ (mm)	Trend	p.value	PRCPTOT (mm)	Δ (mm)	Trend	p.value	PRCPTOT (mm)	Δ (mm)	Trend	p.value
TR	1675.3	80.7	↑ NS	0.242	1769.5	33.5	↑ NS	0.778	2132.5	9.2	↓ NS	0.931	1941.6	15.4	↓ NS	0.785
SS	714.3 42.6%	35.1	↑ NS	0.294	712.3 40.2%	23.2	↑ NS	0.220	854.5 40.0%	23.5	↑ NS	0.412	817.6 42.1%	51.6	↑ NS	0.156
RS	1263.3 75.4%	112.4	↑ NS	0.063	1258.9 71.1%	77.2	↑ NS	0.147	1557.1 73.0%	79.2	↑ NS	0.181	1557.1 75.2%	108.2	↑ NS	0.256
	São Luiz do Paraitinga				Cunha				São Jose do Barreiro				Bananal			
	PRCPTOT	Δ (mm)	Trend	p.value	PRCPTOT	Δ (mm)	Trend	p.value	PRCPTOT	Δ (mm)	Trend	p.value	PRCPTOT	Δ (mm)	Trend	p.value
TR	1572.2	55.1	↑ NS	0.603	1533.1	68.9	↑ NS	0.488	1827.1	-1.7	↓NS	0.888	1616.2	-27.8	↓ NS	0.862
SS	708.2 45.0%	24.4	↑ NS	0.399	707.3 46.1%	68.9	↑ NS	0.077	945.6 51.7%	19.6	↑ NS	0.374	787.7 48.7%	-13.0	↑ NS	0.919
RS	1215.7 77.3%	102.4	↑ NS	0.057	1213.4 79.1%	135.8	↑ S	0.081	1592.5 87.1%	58.4	↑ NS	0.374	1328.7 82.2%	23.7	↑ NS	0.991
	Igarata				São Jose dos Campos				Campos do Jordão				Pindamonhangaba			
	PRCPTOT	Δ (mm)	Trend	p.value	PRCPTOT	Δ (mm)	Trend	p.value	PRCPTOT	Δ (mm)	Trend	p.value	PRCPTOT	Δ (mm)	Trend	p.value
TR	1496.7	-139.0	↓ NS	0.095	1516.2	-174.6	↓ S	0.008	1693.7	-25.7	↓ NS	0.363	2071.0	-12.3	↓ NS	0.603
SS	700.5 46.8%	-42.6	↓ NS	0.463	684.5 45.1%	-57.7	↓ NS	0.212	712.3 42.0%	11.2	↑ NS	0.596	1051.4 50.7%	38.6	↑ NS	0.181
RS	1170.5 78.2%	-67.1	↓ NS	0.444	1164.6 76.8%	-94.1	↓ NS	0.212	1258.9 74.3%	30.1	↑ NS	0.362	1704.9 82.0%	62.1	↑ NS	0.118
	Santa Branca				Taubate				Aparecida				Queluz			
	PRCPTOT	Δ (mm)	Trend	p.value	PRCPTOT	Δ (mm)	Trend	p.value	PRCPTOT	Δ (mm)	Trend	p.value	PRCPTOT	Δ (mm)	Trend	p.value
TR	1206.3	-18.3	↑ NS	0.762	1286.1	24.2	↑ NS	0.573	1416.8	-95.1	↓ NS	0.138	1497.9	-17.7	↓ NS	0.410
SS	569.3 47.1%	-12.8	↑ NS	0.702	598.1 46.5%	27.6	↑ NS	0.261	659.3 46.5%	-12.1	↑ NS	1	686.7 45.8%	18.4	↑ NS	0.339
RS	926.5 76.8%	17.8	↑ NS	0.339	1023.2 79.5%	62.1	↑ NS	0.118	1131.3 79.8%	-22.1	↓ NS	0.727	1193.9 79.7%	41.5	↑ NS	0.238

TR total rainfall, *SS* summer season, and *RS* rainy season. Δ represents the anomalies (2002/2022 minus 1981/2001). *S* means trend which is statistically significant, and *NS* is not statistically significant. The statistical significance is at a level of 95%
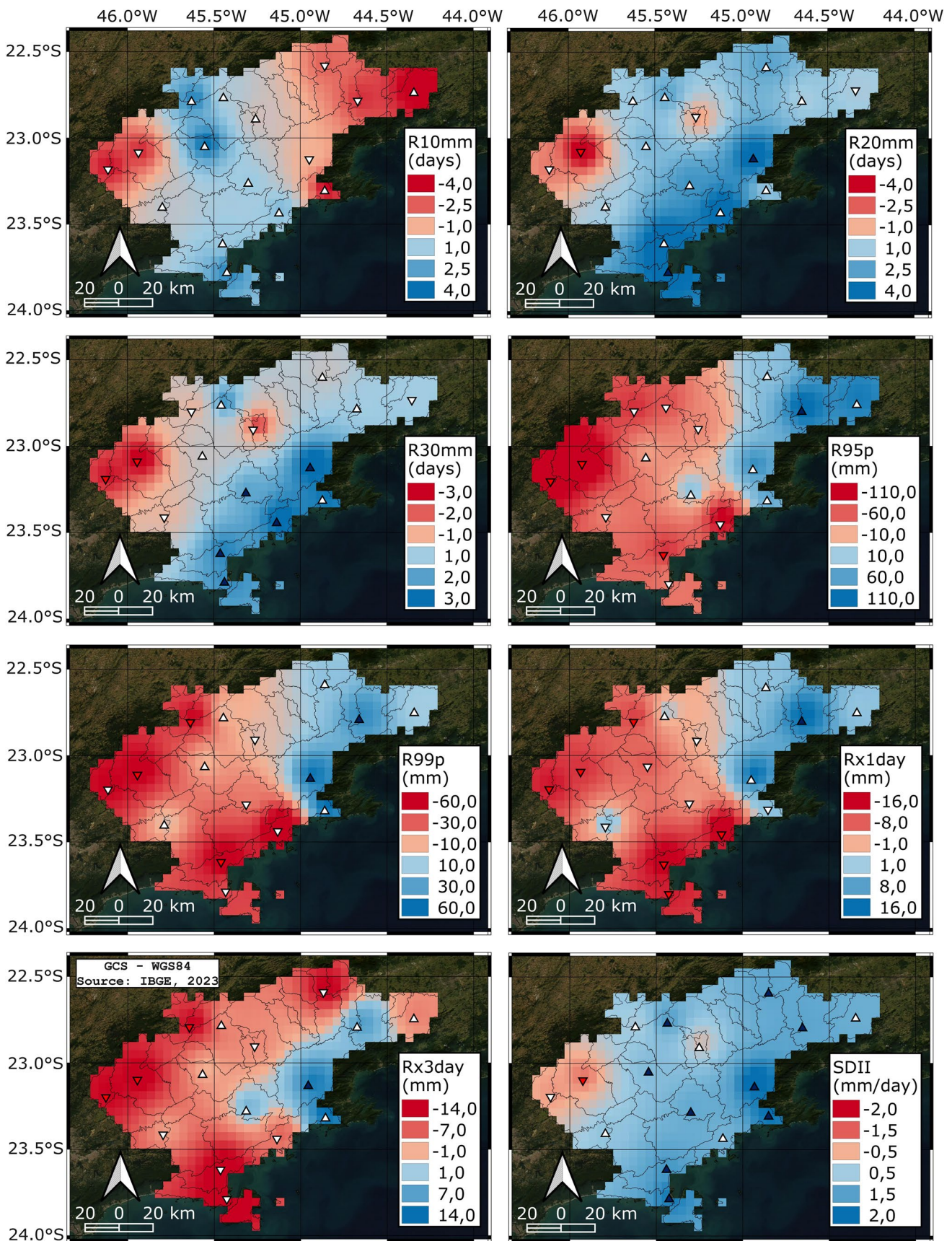
Campos. In these areas, the frequency of R20mm rainfall has decreased by up to 4.8 days, while the intensity of R95p has decreased by up to 164.3 mm/year. Additionally, Rx3day rainfall has decreased up to 15.7 mm/year. Figure 4 highlights these areas in red.

Conversely, the region from Serra da Mantiqueira to the North Coast has witnessed an increase in the frequency of extreme rainfall. Specifically, R20mm has increased by up to 5.1 days, while R30mm has increased by up to 3.3 days. Moreover, the daily rainfall intensity (SDII) has increased by up to 2.0 mm/day in this region (blue areas in Fig. 5). The previous study conducted by Cerón et al. (2021) found that extreme rainfall indicators such as R20mm and R30mm, as well as the daily intensity of precipitation (SDII), have increased in the La Plata basin, which is a neighboring area of RMVPLN.

In Serra do Mar, Bocaina, and eastern RMVPLN, the frequency and intensity of extreme rainfall indicators have increased. In the basin of the Paraitinga and Paraibuna rivers, there has been an increase in R20mm rainfall by up to 4.9 days, whereas R30mm has increased by up to 3.5 days. Moreover, the increase in Rx1day rainfall intensity has been up to 17.0 mm/year, and the daily rainfall intensity (SDII) by up to 2.3 mm/day. Similar findings of an increase in daily rainfall intensity have been reported in earlier studies by Teixeira and Satyamurty (2011), Zandonadi et al. (2016), Silva et al. (2020), and Abou Rafee et al. (2020) in regions adjacent to the RMVPLN but using different indices.

When we observe the changes in extreme rainfall with a focus on the possibility of triggering landslides on the North Coast, Serra do Mar, and Bocaina (Santoro et al. 2010; Mendes et al. 2015; São Paulo 2022), the scenarios tend to be more favorable, since the number of R20mm, R30mm, R95p, R99p, and Rx1day rainfall is increasing. Observed changes in land use and land cover indicate a large increase in the disordered urban area in land with high slopes close to the BR-101 highway (North Coast). These factors increase the vulnerability and risk of the local population (Haque et al. 2019). The same characteristics can be observed in the Paraitinga and Paraibuna River basin, as they combine many elements that trigger landslides, such as steep terrain, deforested areas, and extreme rainfall. Rainfall anomalies and their trends can be seen in Table 5.

Within the context of climate change, our research indicates that there is a notable uptick in the frequency and intensity of extreme rainfall events. These findings align with previous studies that have noted increased rainfall in

South America's coastal regions (Dore 2005) and in its southeastern area (Re and Barros 2009). In the state of São Paulo, indicators of extreme rainfall have revealed significant events of lower return periods (Ballarin et al. 2022). The heightened precipitation is creating more propitious conditions for soil erosion processes (Burt et al. 2016) and landslides (Marengo et al. 2023), which could lead to increased risk and vulnerability for local communities.

By using the disasters that occurred on 02/19/2023 in the municipality of São Sebastião as a reference, we realize that extreme rainfall is just one of the elements that trigger landslides, but there is a combination of several factors that make the local population vulnerable to these disasters. It is evident that social vulnerability and respective inequality forced the population to occupy risk areas and steep slopes in São Sebastião, exposing them to the risk and increasing their vulnerability to disasters triggered by extreme rainfall. Data from the Mapbiomas project points to an increase of 346.6% in urban infrastructure in São Sebastião between 1985 and 2021, in contrast to the population increase of 254.6% in the same period (SEADE 2023).

These data also show a great transformation of native vegetation into urbanized infrastructure along the BR-101 highway, pointing out that the highway played a fundamental role in local urbanization, occupying risk areas and combining elements that help in triggering landslides such as the occupation of high-slope topography, deforestation, and constructions with low-quality standards and in a disorderly way (Mantovani et al. 2023; Marengo et al. 2023). The transformation of an area with native vegetation into urban infrastructure with a slope greater than 20° increased by 4,050% in the period 1985/2021, a fact that reinforces the relationship between social inequality, vulnerability, and exposure (Moraes 2023) to disasters in the RMVPLN, given that these areas are the less valued and for this reason occupied by the low-income population. Figure 6 illustrates the distribution of extreme rainfall increase/decrease in the RMVPLN.

3.3 Regional atmospheric circulation

Looking to improve the atmospheric conditions explanation related to landslide events the regional atmospheric circulation analysis was made. The moisture transport from Amazon Forest to the Brazilian southeast (Ruv Lemes et al. 2023) might indicate a main propulsor effect to increase precipitation. The vertically integrated moisture flow may indicate an increased moisture transport that enhances rainy seasons and corroborates with extreme rainfall. This was the case in 2009/2010 for the wet season (DJF), when the inflow of moisture was positive from the north (tropical region) 13.9 kg m^{-1} and 7.0 kg m^{-1} from the east (oceanic), transported related to SASA activity (Fig. 7).

Table 5 Trends and variation of extreme rainfalls in the RMVPLN

	São Sebastiao				Caraguatatuba				Ubatuba				Ubatuba II			
	1981-2022	Δ	Trend	p.value	1981-2022	Δ	Trend	p.value	1981-2022	Δ	Trend	p.value	1981-2022	Δ	Trend	p.value
R10mm	57.9	3.3	↑ NS	0.059	62.8	1.1	↑ NS	0.46	67.3	1.6	↑ NS	0.778	65.0	-3.9	↓ NS	0.241
R20mm	31.6	4.5	↑ S	0.003	34.8	5.1	↑ S	0.002	42.6	4.9	↑ S	0.014	37.9	1.3	↑ NS	0.664
R30mm	17.9	2.4	↑ S	0.007	17.7	2.7	↑ S	0.011	25.0	3.3	↑ S	0.023	21.2	3.0	↑ NS	0.078
R95p	281.5	-42.2	↓ NS	0.129	279.6	-81.5	↓ S	0.004	357.4	-120.0	↓ NS	0.083	322.0	54.2	↑ NS	0.455
R99p	78.0	-35.9	↓ NS	0.040	78.2	-74.1	↓ S	0	102.2	-96.5	↓ NS	0.051	90.8	61.1	↑ NS	0.713
Rx1day	89.0	-13.5	↓ S	0.019	85.0	-19.4	↓ S	0	106.6	-20.2	↓ S	0.032	95.6	3.3	↓ NS	0.495
Rx3day	127.3	-19.2	↓ NS	0.368	126.0	-17.0	↓ NS	0.190	155.2	-6.5	↓ NS	0.435	142.7	14.8	↑ NS	0.837
SDII	22.0	1.9	↑ S	0.001	21.5	1.6	↑ S	0.005	25.9	1.1	↑ NS	0.079	23.3	2.0	↑ S	0.023

	São Luiz do Paraitinga				Cunha				São Jose do Barreiro				Bananal			
	1981-2022	Δ	Trend	p.value	1981-2022	Δ	Trend	p.value	1981-2022	Δ	Trend	p.value	1981-2022	Δ	Trend	p.value
R10mm	59.9	1.1	↑ NS	0.323	59.4	-1.0	↓ NS	0.385	64.4	-3.3	↓ NS	0.211	60.6	-4.6	↓ NS	0.125
R20mm	29.5	2.9	↑ NS	0.125	28.2	4.9	↑ S	0.014	34.6	0.9	↑ NS	0.557	29.7	0.9	↑ NS	0.594
R30mm	13.5	2.0	↑ S	0.018	12.9	3.5	↑ S	0.004	17.9	1.0	↑ NS	0.486	14.0	1.0	↑ NS	0.127
R95p	238.6	20.0	↑ NS	0.398	244.8	79.2	↑ NS	0.076	314.4	118.6	↑ S	0.013	265.5	99.6	↑ NS	0.153
R99p	65.0	-23.1	↓ NS	0.341	68.0	57.4	↑ S	0.024	91.7	42.6	↑ S	0.013	76.1	9.7	↑ NS	0.531
Rx1day	68.5	-3.2	↓ NS	0.229	73.3	16.0	↑ NS	0.091	88.3	17.0	↑ S	0.020	76.6	2.4	↑ NS	0.795
Rx3day	108.2	4.1	↑ NS	0.516	111.1	12.4	↑ S	0.298	137.0	7.2	↑ NS	0.116	119.8	-4.5	↑ NS	0.392
SDII	18.6	1.3	↑ S	0.004	18.3	2.3	↑ S	0	20.8	1.5	↑ S	0.049	18.7	1.3	↑ NS	0.056

	Igarata				São Jose dos Campos				Campos do Jordao				Pindamonhangaba			
	1981-2022	Δ	Trend	p.value	1981-2022	Δ	Trend	p.value	1981-2022	Δ	Trend	p.value	1981-2022	Δ	Trend	p.value
R10mm	59.9	-3.8	↓ NS	0.288	59.8	-3.3	↓ NS	0.282	66.0	3.1	↑ NS	0.595	73.0	0.7	↑ NS	0.905
R20mm	24.1	-2.1	↓ NS	0.258	25.6	-4.8	↓ S	0.019	30.5	1.1	↑ NS	0.640	42.1	2.5	↑ NS	0.158
R30mm	9.9	-2.9	↓ S	0.003	10.0	-3.4	↓ S	0.004	13.7	-0.6	↓ NS	0.353	22.1	2.3	↑ NS	0.145
R95p	236.4	-140.6	↓ S	0.003	231.7	-164.3	↓ S	0	267.6	-84.4	↓ NS	0.074	327.0	-67.4	↓ NS	0.386
R99p	64.0	-62.0	↓ NS	0.059	62.5	-66.4	↓ S	0.001	73.7	-58.9	↓ S	0.007	92.1	-6.8	↑ NS	0.739
Rx1day	59.3	-14.3	↓ S	0.037	61.7	-11.6	↓ S	0.002	70.8	-10.3	↓ S	0.019	88.0	0.8	↑ NS	0.530
Rx3day	98.7	-14.1	↓ S	0.050	95.5	-15.7	↓ S	0.007	109.1	-14.0	↓ S	0.036	147.7	-3.6	↑ NS	0.905
SDII	16.1	-0.8	↓ NS	0.351	16.1	-1.3	↓ S	0.042	17.9	0.4	↑ NS	0.633	22.5	1.6	↑ S	0.023

	Santa Branca				Taubate				Aparecida				Queluz			
	1981-2022	Δ	Trend	p.value	1981-2022	Δ	Trend	p.value	1981-2022	Δ	Trend	p.value	1981-2022	Δ	Trend	p.value
R10mm	48.3	0.5	↑ NS	0.632	52.5	4.1	↑ NS	0.298	57.3	-0.1	↑ NS	0.728	57.8	-2.4	↓ NS	0.103
R20mm	17.5	0.9	↑ NS	0.203	19.1	1.8	↑ NS	0.075	23.2	-1.5	↓ NS	0.983	26.1	2.4	↑ NS	0.102
R30mm	6.0	-0.7	↓ NS	0.947	6.7	0.2	↑ NS	0.417	8.3	-2.3	↓ NS	0.234	11.2	0.2	↑ NS	0.383
R95p	185.4	-38.9	↓ NS	0.116	201.8	-21.3	↑ NS	0.879	223.2	-35.3	↓ NS	0.461	244.6	23.1	↑ NS	0.795
R99p	51.3	-4.8	↑ NS	0.936	56.1	-9.5	↑ NS	0.535	61.6	-3.9	↓ NS	0.809	68.5	15.2	↑ NS	0.328
Rx1day	52.8	2.4	↓ NS	0.974	48.0	-8.3	↓ NS	0.618	61.2	-0.7	↓ NS	0.802	66.4	2.7	↑ NS	0.544
Rx3day	81.8	-2.5	↓ NS	0.922	85.6	-1.0	↑ NS	0.618	95.7	-3.9	↓ NS	0.854	105.5	-15.0	↓ NS	0.269
SDII	13.8	0.7	↑ NS	0.474	14.2	1.0	↑ S	0.013	15.7	-0.2	↑ NS	0.649	16.8	1.4	↑ S	0.032

S means trend which is statistically significant, and *NS* is not statistically significant. The statistical significance is at a level of 95%

In years with below-average rainfall in the RMV-PLN, moisture inflow to São Paulo was -5.3 kg m s^{-1} from the north and -16.1 kg m s^{-1} from the west in the year 2011/2012, and -9.6 kg m s^{-1} from the north and -1.3 kg m s^{-1} from the east in the year 2013/2014. In these years, there were also negative wind anomalies from the Atlantic Ocean, both directly contributing to the decrease in rainfall. The years that negative moisture anomalies incoming in Sao Paulo and less moisture input from the South Atlantic Ocean have great strength to induce severe droughts, such that occurred in 2014 and 2015 in the Brazilian southeastern (Nobre et al. 2016).

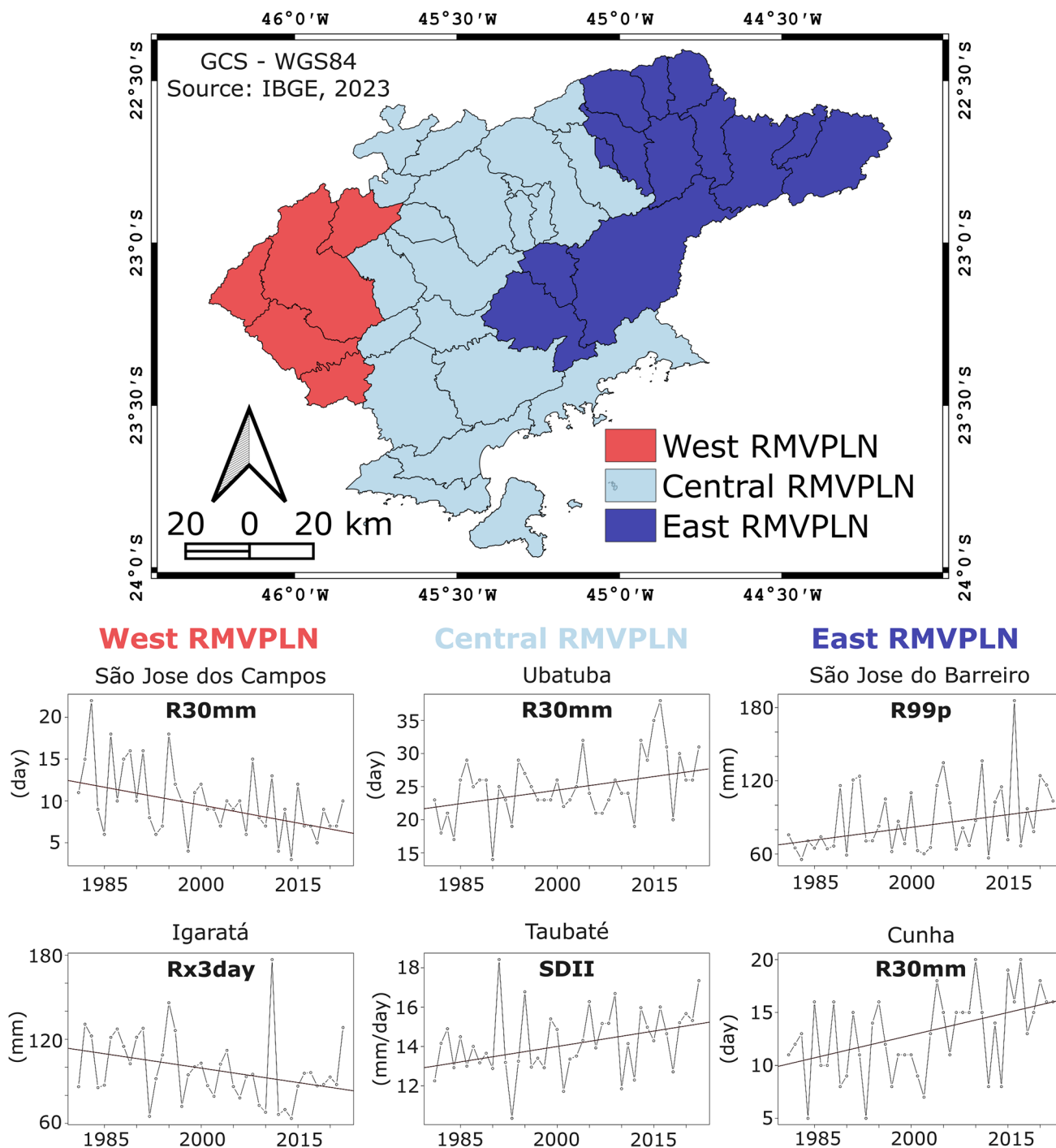In the normal years (2010/2011) and with above-average rainfall (2022/2023), we can see a more intense SASA

Fig. 6 Regionalization of extreme rainfall based on the predominance of trends for selected ETCCDI indices. The West RMVPLN has a predominance in decreased frequency and intensity, while the Central RMVPLN has a predominance of an increase in frequency, and the East RMVPLN has a predominance in an increase in frequency and intensity

activity, where in 2010/2011 the anomaly of moisture inflow in São Paulo was -13.9 kg m s^{-1} from the north (continental), however with 1.0 kg m s^{-1} from the east (oceanic). In 2022/2023, there were negative anomalies of moisture inflow from the west (-3.4 kg m s^{-1}), but positive from the north and east (4.5 kg m s^{-1}), associated with positive anomalies of winds from the Atlantic Ocean of 2 m s^{-1}, indicating that the SASA position has contributed for higher precipitation in wettest years (extreme rainfalls in the RMVPLN).
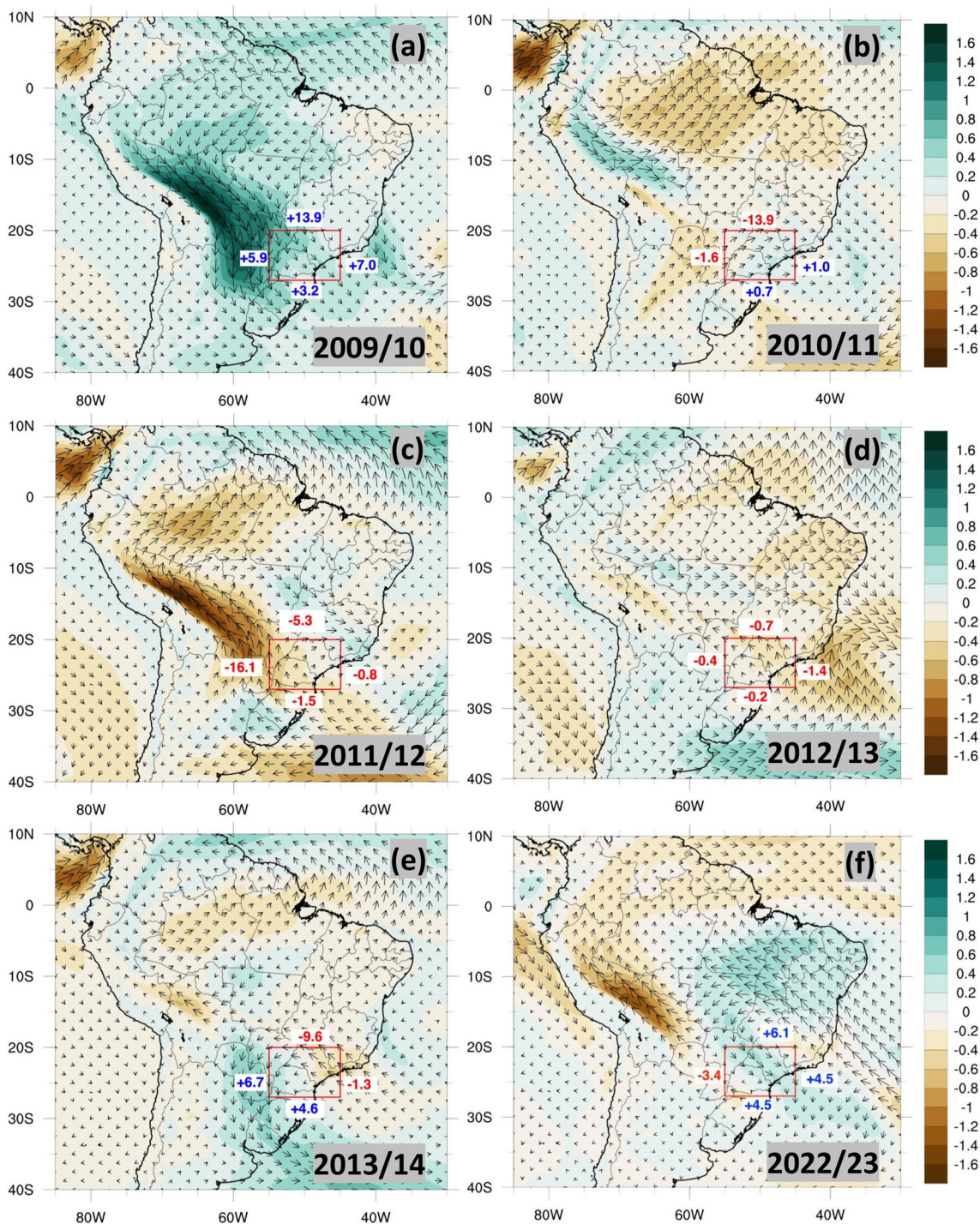
Fig. 7 Anomaly of vertically integrated moisture flux inflow to the RMVPLN for 2009/2010 (**a**), 2010/2011 (**b**), 2011/2012 (**c**), 2012/2014 (**d**), 2013/2014 (**e**), and 2022/2023 (**f**)

Finally, the results corroborate with Marengo et al. (2020b), which indicated a relationship between extreme precipitation events increase in the Metropolitan Region of São Paulo in recent decades and the intensification and small movement to the southwest of the SASA (Reboita

et al. 2019). Thus, the positive precipitation trends observed before were supported by either high moisture transport from Amazon Forest or SASA contribution. Especially, in the 2022/2023 case, the Atlantic Ocean had

a substantial role to increase the vertical moisture profile in the Southeast coast.

The wind anomalies in the rainy years (2009/2010) showed positive anomalies up to $+4$ m s^{-1} (Fig. 8) from the north and west in the São Paulo state, demonstrating the increase of moisture transport coming from the tropical Atlantic and crossing the Amazon region, which is indicated in Fig. 7 as well. The DJF 2012/2013 and 2022/2023 showed wind anomalies from the north and positive from the west around $+2$ m s^{-1}, but further away from the study area, while there were positive anomalies of winds incoming from the Atlantic Ocean around $+1$ m s^{-1}. In such summers, the higher intensity SASA activity and positive easterly wind anomalies played an active role in the precipitation rates in the RMVPLN.

It is important to highlight that in 2010/2011 the rainfall was close to the average in the period 1981/2022, where the north and west winds were also neutral, however with positive anomalies of east winds (1 m s^{-1}). In all years that were wet or normal, positive continental wind anomalies can reach up to 4 m s^{-1}, while oceanic ones remain at 1 m s^{-1}, pointing to an apparently well-defined pattern of wind anomalies coming from the Atlantic Ocean South.
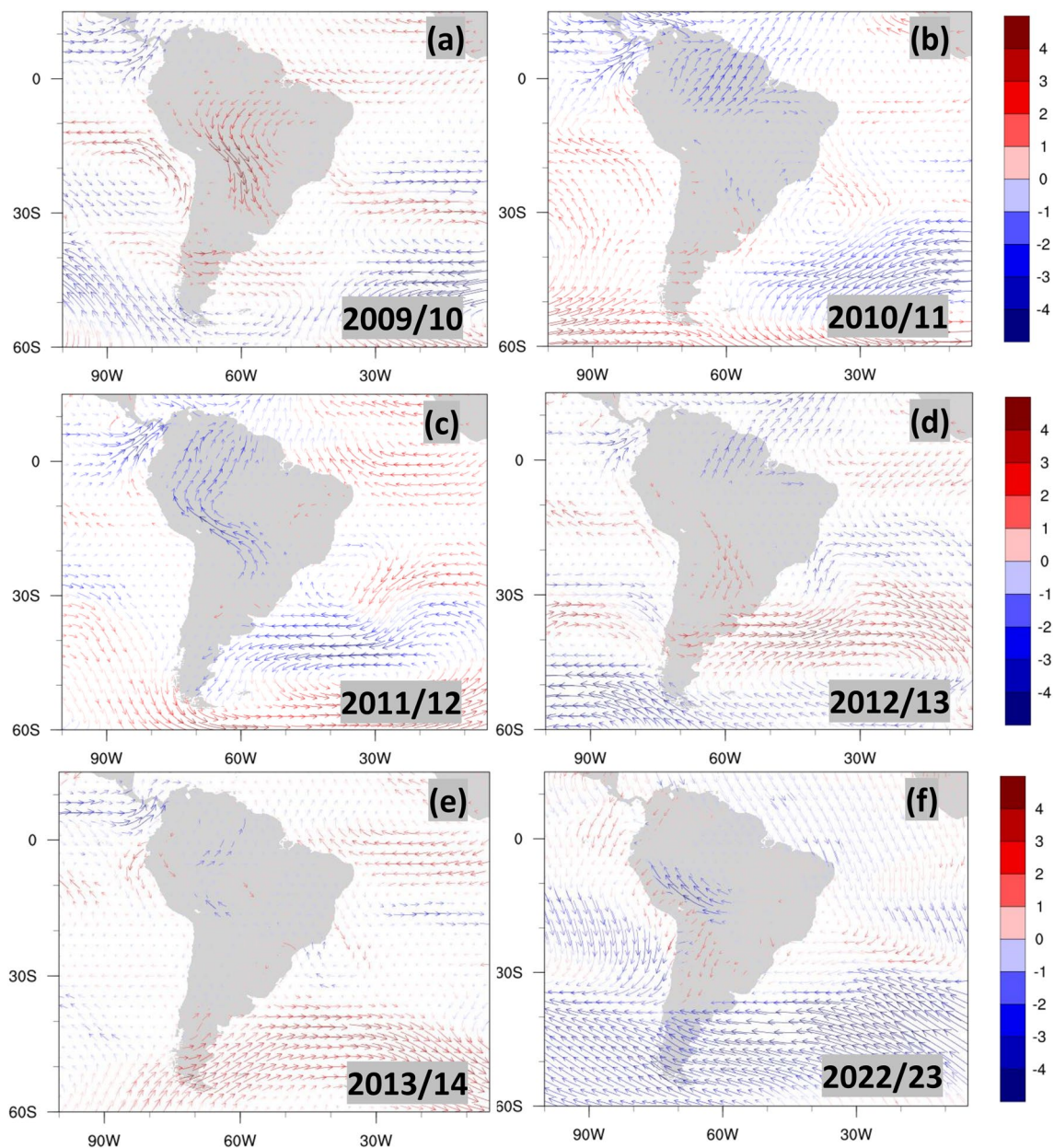
Fig. 8 Wind speed anomaly in 850 hPa for 2009/2010 (**a**), 2010/2011 (**b**), 2011/2012 (**c**), 2012/2013 (**d**), 2013/2014 (**e**), and 2022/2023 (**f**)

In the dry years, in 2011/2012, we noticed negative anomalies of winds coming from tropical South America from the north and west of up to -3 m s^{-1}, while from the east (oceanic) of -2 m s^{-1}. In 2013/2014, the winds were neutral from the north and west; however, there were negative anomalies from the east (-3 m s^{-1}). The data show that years where there are negative anomalies of tropical or continental or oceanic winds tend to be drier years, while positive anomalies, especially when coming from the east (oceanic), tend to be rainy and with more extreme rainfall. Wind anomalies (DJF) at 850 hPa can be seen in Fig. 8.

4 Conclusion

The RMVPLN region is particularly susceptible to landslides, which can have a devastating effect on both the transportation infrastructure and local population. Numerous factors contribute to this vulnerability, including steep terrain, limited vegetation coverage, and extreme rainfall in the mountainous regions of Serra do Mar, Mantiqueira, Bocaina, and the North Coast.

Recent observations indicate that the rainfall patterns in the RMVPLN region have shifted, with a marked increase during the rainy and summer seasons. Given that landslides tend to occur during these periods, this rise in precipitation may exacerbate the risk of disasters stemming from extreme rainfall. Taking this into consideration, the global warming process enhances the probability of this disaster occurrence through increase in the frequency and intensity of extreme weather events (storms).

When analyzing the changes in extreme rainfall in the RMVPLN, we have noticed an increase in the frequency of R20mm and R30mm rainfall and the intensity of daily rainfall (SDII) and Rx1day, mainly in the North Coast, Serra do Mar, and Bocaina regions, which are highly susceptible to landslides. Wet years and those with extreme rainfall are directly influenced by the positive anomaly of continental (up to 13.9 kg m s^{-1}) and oceanic (up to 7.8 kg m s^{-1}) atmospheric moisture transport, and by the positive anomalies of winds at 850 hPa from the north and west up to 4 m s^{-1}, and from the east of 1 m s^{-1}, influenced by the intensification of SASA.

When observing the locations where landslides have occurred, we have noticed that each region of the RMVPLN has its population vulnerable to disasters due to the combination of several elements. This exposure differs according to geographic location. In the Paraitinga and Paraibuna River basins, an increase in extreme rainfall can trigger disasters such as landslides, floods, and flash floods. The risk is high due to the combination of elements such as deforested areas, high slope topography, and the increase in extreme rainfall in these areas. On the North Coast, the vulnerability of the local population is associated with the increase in extreme rainfall, disorderly urban areas in high slope topography, and the very high increase in urbanization in these areas, mainly close to the BR-101 highway. This increases exposure, vulnerability, and risk to the local population.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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