



Climate extremes related with rainfall in the State of Rio de Janeiro, Brazil: a review of climatological characteristics and recorded trends

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Abstract

This paper presents a synthesis of the main characteristics of precipitation in the State of Rio de Janeiro (Brazil) based on extreme rainfall indicators. Daily precipitation data are derived from 56 rainfall stations during the second half of the twentieth century and the 2000s. Eight indices related to extreme precipitation were analyzed. The Mann–Kendall nonparametric test and the Sen’s Curvature were employed to evaluate the significance and magnitude of trends. The primary climatological aspects and identified trends throughout the last decades are discussed, besides the hydrometeorological impacts associated with them. Lower values of annual total precipitation are recorded in northern Rio de Janeiro (around 800 mm) and higher in the southern State (up to 2,200 mm). The Serra do Mar affects the frequency of heavy precipitation, and the areas near the sea and high relief present the highest values of consecutive days with expressive rainfall (more than 150 mm in 5 days). These areas also showed a high concentration of flood and landslides events. Most of Rio de Janeiro exhibits precipitation intensity of about 13 mm/day. The maximum number of consecutive dry days shows a gradient from the coast (about 30 days) to the State’s interior (around 50 days). Regarding trends, there is a growth of accumulated extreme precipitation in various stations near the ocean. The extreme rainfall in 24 h displays an increase in most Rio de Janeiro (+1 to +5 mm/decade). The consecutive dry and rainy days present similar signs of decreasing trends, suggesting irregularly distributed precipitation in the State. This study is especially relevant for decision-makers who need detailed information in the short and long term to prevent natural hazards like floods and landslides and the related impacts in the environmental and socioeconomic sectors of the Rio de Janeiro.

Keywords Climate change · Climate extremes · Climatology · Natural hazards · Precipitation · Rio de Janeiro

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1 Introduction

The climate change currently detected in different parts of the world is responsible for the increase in the frequency and intensity of extreme climate events, such as heatwaves, heavy precipitation, and prolonged droughts, according to the Intergovernmental Panel on Climate Change (IPCC 2013). Consequently, these alterations have a marked impact on human and natural systems (Thornton et al. 2014). According to the sixth IPCC report (IPCC 2021), the anthropogenic influence on global warming, which has reached + 1.1 °C in the global average temperature since the twentieth century, is undeniable. Global warming is expected to get an expressive elevation in atmospheric water vapor content and alterations in the hydrological cycle, leading to a rise in extreme precipitation events (Westra et al. 2014).

Knowledge about the behavior of these extreme events over the years is crucial for establishing possible adaptation measures and risk management. Specifically in South America, regionally averaged precipitation indices show clear wetting and a signature of intensified heavy precipitation events over the eastern part of the continent during the last few decades (Skansi et al. 2013). However, Gallina et al. (2016) say that multi-risk approaches in the world do not consider the effects of climate change and mostly rely on static vulnerability analysis.

Natural disasters associated with heavy precipitation are widespread in Brazil, mainly due to the complex interaction between atmospheric phenomena and the physiographic aspects of each region, such as relief, vegetation, and proximity to the ocean. Furthermore, the occurrence of these catastrophes is explained too by the profound socio-spatial inequalities, which increase the exposure of populations, especially those living in risk areas (Debortoli et al. 2017; Oscar-Júnior, 2021). So, in these disasters, the damages and impacts affect poorer populations. According to the Brazilian Atlas of Natural Disasters (CEPED/UFSC 2013), landslides and floods are the main disasters causing deaths in Brazil, especially in the face of heavy precipitation in large urban centers and hillsides regions.

The data provided by the EM-DAT (Emergency Events Database. <http://www.em-dat.net/>), between 1900 and 2021, more than 3 billion people were affected by floods, and more than 6 million died around the world. According to this database, in Brazil, about the ten main natural/biological events that caused deaths, excluding COVID-19, six were related to floods, and four occurred in the State of Rio de Janeiro. According to Jha et al. (2012), considering the same data up to 2011, a close look at those affected reveals that the impact of hydrometeorological disasters is disproportionate, much more significant for poor people, particularly women and children. Thus, it is essential to carry out studies at a regional level on the main characteristics of these extreme events, mainly related to precipitation.

Several studies have been concentrating efforts on identifying extreme precipitation patterns in Brazil and their trends over the last decades. For example, more extreme drought conditions were observed in eastern Amazonia during the late 20th and early twenty-first centuries (Silva et al. 2019). In addition, some areas in the Northeastern region of Brazil, such as the east coast and part of the interior, have been exhibiting increasing trends in precipitation during the rainy season and decreasing trends during the dry season (Oliveira et al. 2017). Avila et al. (2016) found positive trends in precipitation extremes in vulnerable areas of Southern Brazil, which are highly susceptible to mass landslides in the face of heavy precipitation. An increase in average and extreme precipitation was also recorded in much of the Paraná River basin (Zandonadi et al. 2016; Luiz-Silva et al. 2019), one of the most important in Brazil in terms of energy generation and agriculture.

The Southeastern region of Brazil is known for its economic strength and its large cities. A predominantly tropical climate mainly characterizes this portion of the country: a rainier season between October and March and a drier period between April and September (Luiz-Silva et al. 2021). Thus, extreme rainfall events, especially in austral spring and summer due to the warm and humid climate, along with the region's physical geography and its complex urbanization process, bring out the need to prepare for disaster situations. Marengo et al. (2020) state that in the metropolitan area of São Paulo, the largest in Brazil, the number of days with precipitation above 50 mm has been increasing considerably since the second half of the twentieth century. Furthermore, rainfall volumes seem to be more concentrated in a smaller number of events in most of the coast of the Southeastern region (Zilli et al. 2016), including the State of Rio de Janeiro.

The State of Rio de Janeiro presents a heterogeneity of physiographic elements that give distinct climatic aspects between its regions. The topography is mainly marked by the Serra do Mar from the south of Rio de Janeiro to its central portion, stimulating orographic precipitation. Adding more complexity to this geographic context, we also highlight the Serra da Mantiqueira, the extensive domain of lowlands and the coastal massives, domains of high susceptibility to hydrometeorological events (Oscar-Júnior 2018). The vegetation is dominated by the Atlantic Forest, a tropical forest biome with rich biodiversity that contributes to the hydrological cycle through evapotranspiration. The Atlantic Ocean bathes the State's entire coast, often influencing it through moisture from the sea toward the continent. Allied to these factors is the development of large urban centers that cause physicochemical and thermodynamic changes, affecting atmospheric parameters through heat islands (Lucena et al. 2013).

Thus, through the interaction between some local mechanisms, extreme precipitation events can be induced (Silva et al. 2019) and cause natural disasters, such as various tragedies that occurred in recent decades and caused severe damage to the population and infrastructure (Nehren et al. 2019). In January 2011, the worst disaster associated with slope slides in Brazil occurred in the mountainous region of Rio de Janeiro due to the high total rainfall concentrated in few hours (Coelho-Netto et al. 2013). On the other hand, prolonged droughts can also become significant climate problems, such as the lack of precipitation in the austral summer of 2014 in the Southeastern region of Brazil (Luiz-Silva et al. 2015), which led to a water crisis in Rio de Janeiro and other States (Nobre et al. 2016).

In this context, this study aims to provide an overview of the main climatological characteristics of precipitation extremes throughout the State of Rio de Janeiro and the trends recorded over the last few decades, and its spatial association with hydrometeorological impacts episodes. This analysis is essential to identify attributes that help minimize vulnerability through prevention and increase resilience concerning natural disasters. In addition, the relevance in the planning and management of water resources in the State of Rio de Janeiro is highlighted (Oscar-Júnior 2021). Section 2 presents the data used and the methods employed in this research; Sect. 3 displays the results and discussions about the impacts of precipitation extremes; Sect. 4 shows the main conclusions and final considerations of this work.

2 Methodology

2.1 Study area

The State of Rio de Janeiro is located in the Southeastern region of Brazil, and the Atlantic Ocean entirely bathes its coast. According to the Brazilian Institute of Geography and

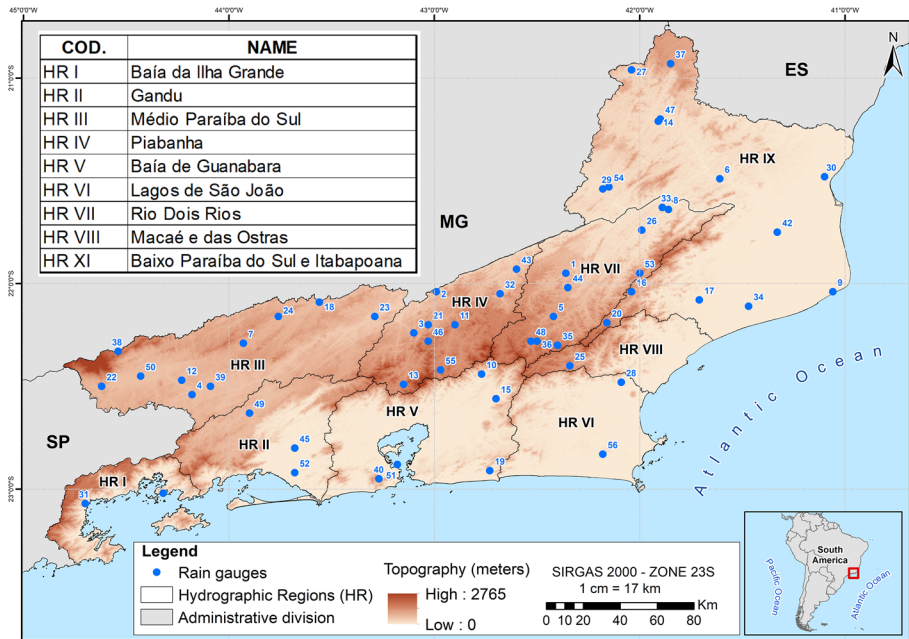


Fig. 1 State of Rio de Janeiro according to the 9 (nine) hydrographic regions and location of rainfall stations used in this study

Statistics (IBGE), Rio de Janeiro occupies about 43,000 km², and despite being the third smallest State in Brazil, it concentrates 8.4% of the country's population (about 16 million inhabitants), thus having the largest demographic density of the territory. The climate of Rio de Janeiro is predominantly tropical (rainy summer and dry winter; Alvares et al. 2013) and is influenced by several physiographic aspects of the State. The relief of Rio de Janeiro can be divided into three units (IBGE 2018): the plateaus (or highlands), primarily represented by the Serra do Mar; the lowlands, located mainly between the plateaus and the sea; and the coastal massifs highlighted by the topography a little more accentuated in the lowland areas close to the ocean. The predominant vegetation in the State is the Atlantic Forest. According to IBGE, Rio de Janeiro can be divided into 9 (nine) hydrographic regions (INEA 2013) according to the State's lakes and rivers (Fig. 1).

2.2 Data and precipitation extremes indices

Daily precipitation data come from 39 pluviometric stations of the National Water and Sanitation Agency (ANA) and 17 meteorological stations of the National Institute of Meteorology (INMET). Most datasets cover the entire second half of the twentieth century and the 2000s: 1940–2014 for ANA data and 1961–2012 for INMET data. As stated by ANA (2012), the “consistency” analysis of precipitation employed in its data aims to identify and correct errors, as well as to fill in faults in the rainfall series, using the regional weighting method, the linear regression method (Tucci 2012), the artificial neural network method (Billib and Freitas 1996), the double mass method (United States Geological Survey 1960), and the regional vector method (Hiez and Rancan 1983).

The Expert Team on Climate Change Detection and Indices (ETCCDI) of the Commission for Climatology (CCI) of the World Meteorological Organization (WMO) created a set of climate extremes indicators based on daily data of maximum temperature, minimum temperature and precipitation (PRCP) to identify trends (Karl et al., 1999; Frich et al., 2002). In this research, 8 indices related to precipitation were selected (Table 1) for the analysis of climatology and trends in the State of Rio de Janeiro. The RCLimDex software (Zhang et al., 2018) was used to calculate these indicators.

2.3 Statistical tests

The Mann–Kendall nonparametric test (Mann 1945; Kendall and Stuart 1963; Sneyers 1990) is used to assess the statistical significance of trends. This test is the most appropriate method to assess the significance of possible changes in climate series (Goossens and Berger 1986). Several researchers have applied this technique in studies on climate trends in several regions of the globe, including Brazil (Sansigolo et al. 2010; Carvalho et al. 2014; Almeida et al. 2016; Oliveira et al. 2017; Luiz-Silva et al. 2019; Regoto et al. 2021; among others).

The null hypothesis considered in the Mann–Kendall test is the non-existence of growing or declining trends in the time series. Besides, this technique assumes that the sequence of values occurs independently and that the probability distribution remains stable, that is, the data do not need to belong to a specific distribution. The confidence level adopted is 95%, which corresponds to a significance level α of 5%.

The Sen’s Curvature test (Sen 1968) is used to analyze the magnitude of the trends. It is also a nonparametric method that assumes a linear trend in the data series. The test is calculated as follows:

$$SEN = \text{median} \left(\frac{x_j - x_i}{j - i} \right), \forall j > i \tag{1}$$

which x_j is the value of the variable in a specific period (for example, a year) and x_i is the value of the variable in the previous period.

Sen’s Curvature test is insensible to outliers and absent information, thus being more realistic and accurate than a simple linear regression. Mann–Kendall and Sen’s Curvature

Table 1 Precipitation extremes indices analyzed in this research

Indices	Definition
PRCPTOT	Annual total precipitation [mm]
R30mm	Annual count of days when PRCP ≥ 30 mm [days]
R95p	Annual total PRCP when daily PRCP > 95th percentile [mm]
RX1day	Annual maximum 1-day precipitation [mm]
RX5day	Annual maximum consecutive 5-day precipitation [mm]
CWD	Consecutive wet days– Maximum number of consecutive days with PRCP ≥ 1 mm [days]
CDD	Consecutive dry days– Maximum number of consecutive days with PRCP < 1 mm [days]
SDII	Simple precipitation intensity index–PRCPTOT / wet days [mm.day ⁻¹]

tests are very efficient for determining trends in climatological series when compared to other parametric methods.

2.4 Data spatialization

Interpolation is used to spatialize data in a given area, thus being a mathematical procedure for fitting a function to unsampled points. This function is based on values obtained from observed points, and then, it is generated a continuous surface with the distribution of the variable (Lam 1983; Landim 2000).

Then, based on the rainfall stations, digital models of the spatial distribution of the indicators were tested applying the main interpolators used in the literature (Borges et al., 2016; Xavier et al., 2016). Following Farias et al. (2017), the Inverse Squared Distance (IDW) showed the best performance for spatial data variation, especially given the topographic contrasts and the distribution of pluviometric stations. Xavier et al. (2016) found that the inverse distance weighting and angular distance weighting methods produced the best results in interpolating climate variables, including precipitation, at daily timescales, and for river basins in Brazil. The IDW interpolator is based on weighted means, proportional to the inverse of the distance between the interpolated and measured points (Isaaks and Srivastava 1989), and is available in the 3D Analyst extension of ArcGIS® software. Climatological data were interpolated with annual averages of each station, and trends were interpolated with decadal magnitudes of each station.

2.5 Hydrometeorological impacts episodes

Data about the occurrence of flood and landslide events from the entire second half of the twentieth century and the 2000s, considering at least one dead, were analyzed to identify areas with more remarkable recurrence of these events. Data about floods, excluding coastal floods, were obtained in the State Environmental Institute (INEA) database in the period 1979–2014 and landslides in the Geological Survey of Brazil (CPRM) database in the period 1986–2014. The Kernel density interpolator was applied, which quantifies the relationships of points within a radius of influence, based on a given statistical function, analyzing the patterns traced by a given time series data, estimating their density in km² in the study area (Landim 2000).

3 Results and discussion

3.1 Climatological characterization of the precipitation extremes

The climatology of the climate extremes indicators related to precipitation in the State of Rio de Janeiro is shown in Fig. 2. Regarding the average annual rainfall (PRCPTOT), it is noted that there is a kind of gradient (Fig. 2a). So, lower values are concentrated in the northern Rio de Janeiro (Paraíba do Sul and Itabapoana basin) and higher in the southern State (especially in the Ilha Grande Bay and Médio Paraíba do Sul basins). Thus, PRCPTOT presents values of about 800 mm in the northern area of Rio de Janeiro, which receives more significant influence from the South Atlantic Subtropical Anticyclone–SASA (Reboita et al. 2019). Consequently, the northern region is configured as the warmest in Rio de Janeiro, with higher minimum and maximum temperatures than the remainder of

the State (Luiz-Silva and Dereczynski 2014). On the other hand, the southern part of the State and areas of mountainous region exhibits values around 2200 mm, mainly due to the higher frequency of passage of cold fronts associated with the region's physiographic aspects (such as relief and vegetation), favoring the occurrence of higher total precipitation.

The distribution of PRCPTOT by hydrographic regions shows that the Ilha Grande Bay basin is the area of the State with the highest observed values (Fig. 3a), with an average of 2000 mm. The other sectors of the State of Rio de Janeiro have PRCPTOT predominantly between 1200 and 1500 mm (Fig. 2a), mainly modulated by transient synoptic atmospheric phenomena, such as frontal systems. Also, according to Fig. 3a, there is a marked spread in the recorded values of PRCPTOT in the Baixo Paraíba do Sul and Itabapoana basin. This region includes some rainfall stations near the mountainous region of Rio de Janeiro, where accumulated precipitation is higher. However, as already mentioned, the average is low concerning other areas of the State (about 1000 mm). It is also essential to highlight the extreme values of accumulated annual rainfall recorded in the Médio Paraíba do Sul basin, indicating a higher frequency of extremely rainy years concerning other areas of the State (Fig. 3a).

When observing the historical averages of the indicator that counts the number of days in the year with precipitation volumes above 30 mm (R30mm) in the State of Rio de Janeiro, the accentuated effect of topography in the record of higher accumulated rainfall can be seen (Fig. 2b). In the extreme south of Rio de Janeiro, there is R30mm around 20 days in areas close to Serra da Mantiqueira (cities such as Itatiaia and Resende in the Médio Paraíba do Sul basin) and Serra do Mar (municipalities of Angra dos Reis and Paraty in the Ilha Grande Bay basin). The climatological values of R30mm also exceed 20 days in some parts of the Guanabara Bay basin, particularly around the Tijuca massif in the city of Rio de Janeiro and in the continuation of the Serra do Mar in the central portion of the State, near to municipalities such as Guapimirim and Teresópolis.

The relief also influences high records of R30mm in part of the Macaé and Ostras basin, especially in the cities of Casimiro de Abreu and Silva Jardim. This fact also explains the large spread of R30mm in the Lagos de São João basin (Fig. 3b). In this region, there is a pluviometric post in the Lagos region and another one closer to the State's mountainous region. It causes values in the range of 10 to 25 days to be recorded frequently. In fact, the expressive topography of the State of Rio de Janeiro, combined with the significant total precipitation in short periods, contributes considerably to landslides (Fernandes et al. 2004). Once again, the northern State presents the lowest values of R30mm (around 7 days), and regions such as the Rio Dois Rios, Piabanha, and Guandu basins show values in the range of 9 to 14 days (Fig. 2b). It is also worth mentioning the considerable frequency of rainfall above 30 mm in the Guanabara Bay basin, which occasionally causes disturbances in the metropolitan region of the State (Fig. 3b).

The R95p index represents the total precipitation associated with the heaviest rainfall in the State of Rio de Janeiro (Fig. 2c). It is noticed that the areas furthest from the ocean have the lowest values, while the regions closer to the sea have the highest values. Once again, the influence of the Serra do Mar in the most intense precipitation in Rio de Janeiro stands out. The portion of the State between this expressive topography and the ocean exhibits average annual values of R95p that exceed 500 mm. It occurs mainly due to the effect of the sea breeze that concentrates much of the moisture in this sector, providing rain showers that occasionally result in significant precipitation volumes, mainly between the austral spring and summer seasons. The passage of vigorous cold fronts during the rainy season, which, in some cases, favor the establishment of the South Atlantic Convergence Zone—SACZ (Carvalho et al. 2004; Marengo et al. 2012) also

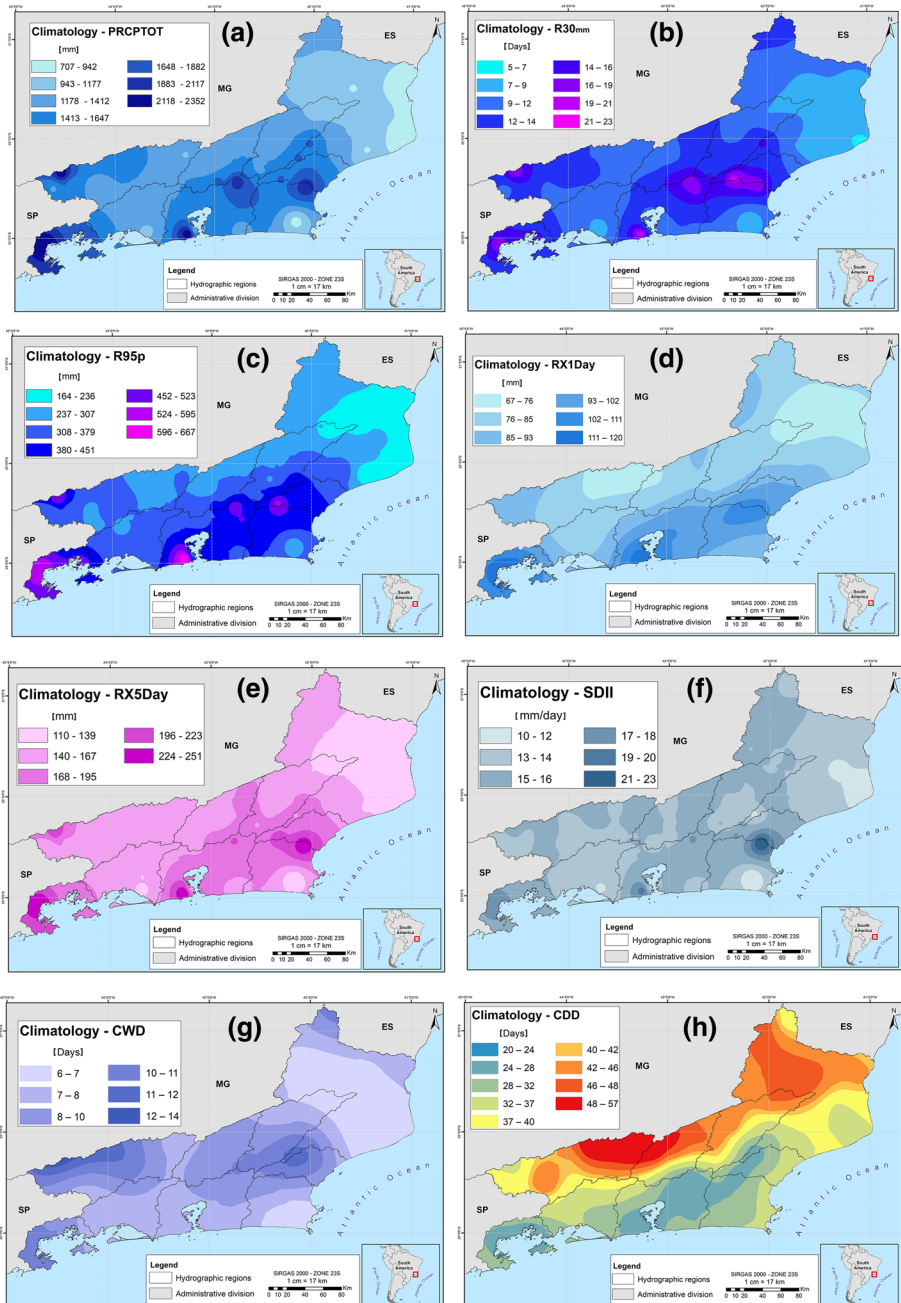


Fig. 2 Climatology of climate extremes indicators associated with precipitation **a** PRCPTOT, **b** R30mm, **c** R95p, **d** RX1day, **e** RX5day, **f** SDII, **g** CWD, and **h** CDD in the State of Rio de Janeiro predominantly during the second half of the twentieth century and the 2000s through data from ANA and INMET

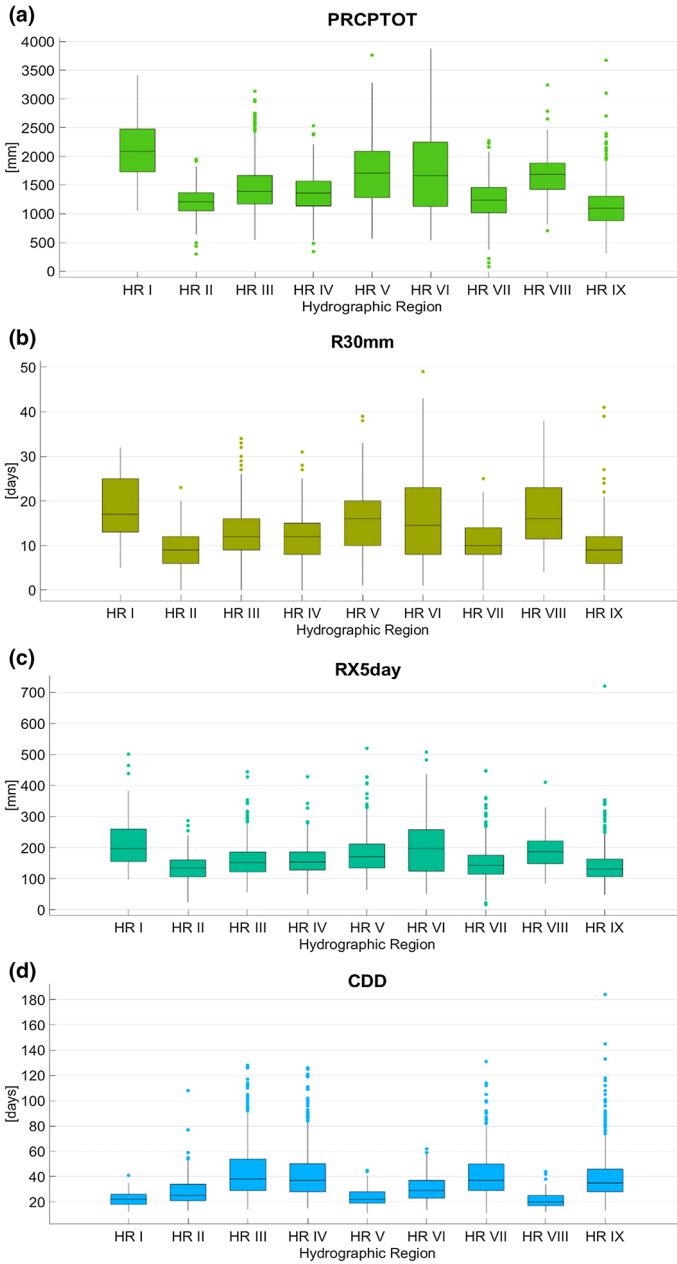


Fig. 3 Distribution of climate extremes indicators of precipitation **a** PRCPTOT, **b** R30mm, **c** RX5day, and **d** CDD in the hydrographic regions of the State of Rio de Janeiro predominantly during the second half of the twentieth century and the 2000s through ANA and INMET data

effectively contribute to these high precipitation accumulations (Oscar-Júnior 2021). In the more interior part of the State, R95p prevails between 200 and 300 mm, values that often also come from frontal systems and SACZ events. According to Machado et al.

(2010) and Lima et al. (2021), the manifestation of orographic precipitation on the area of the Serra do Mar siding the Atlantic Ocean is facilitated by its position, almost parallel to the seaside, so rising the chance of extreme episodes related with the moisture from the ocean.

It is noteworthy that the extreme precipitation indicators RX1day and RX5day, which indicate the highest total rainfall of the year in 1 day and 5 consecutive days (Fig. 2d and e), respectively, follow a distribution pattern similar to R95p in the State of Rio de Janeiro. This fact means that the areas closest to the ocean concentrate the highest values of these indices. However, interior areas are also very susceptible to extremes of precipitation. According to Tavares and Ferreira (2020) and Lima et al. (2021), atmospheric systems carrying moisture from the continent, as instability lines and, in some cases, related to the band of rainfall from SACZ influence the extreme precipitation over the interior of the State. In addition, there is a relevant synergy between physiography and occupation, marked by the abrupt transition from cliffs to coastal lowlands, intensifying the potential impact of precipitation. The high degree of urbanization in these areas also changes the characteristics of infiltration, permanence, and flow of water and selecting those with the right to urban infrastructure and drainage, establishing a pattern for the most exposed people (Jha et al. 2012).

In the Costa Verde region and the Metropolitan region, there are climatological records of around 130 mm in just one day. In parts of Rio de Janeiro, such as the northern State and the border with the State of Minas Gerais, RX1day values are smaller and generally do not go beyond 60–90 mm. It should be noted once again that the physiographic aspects already mentioned, such as relief and vegetation, associated with the passage of cold fronts, are capable of promoting considerable precipitation volumes in 5 subsequent days, mainly during the SACZ action.

RX5day presents values that exceed 200 mm in several portions of the Ilha Grande Bay, Guanabara Bay, and Macaé and Ostras basins. RX5day values around 150 mm are more common in other sectors of the State (Fig. 2e). Heat islands also contribute to the intensification of convective rainfall, as in the Metropolitan Region of Rio de Janeiro (Lucena et al. 2013). Thus, higher values of RX1day and RX5day are also concentrated in these areas.

It is worth mentioning that practically all hydrographic regions of the State have already registered around 400 mm in 5 consecutive days (Fig. 3c), a fact that justifies the need to prepare for such extreme events that could happen again. The most outstanding dispersion of RX5day occurs in the Lagos de São João basin (Fig. 3c). This area of the Coastal Lowlands of the State presents low PRCPTOT, but it can be concentrated in short periods, especially during austral spring and summer. Even in the face of extreme precipitation values in a single day, given by the RX1day indicator, high rainfall often occurs in a few hours, causing inconveniences such as floods and overflowing rivers, especially in large cities such as Rio de Janeiro (Armond and Neto 2019). This fact means that the climatological values of 110 mm for RX1day in the Metropolitan Region of Rio de Janeiro are usually recorded in 2 or 3 h by heavy precipitation (Fig. 2d).

The average annual intensity of precipitation is evaluated using the SDII index (Fig. 2f). Most of the State of Rio de Janeiro exhibits SDII values around 13–14 mm/day. As expected, a portion of the Ilha Grande Bay basin has values of up to 16 mm/day due to heavier rainfall occurring in a short period with greater frequency throughout the year. These same SDII values are also highlighted for some stretches between the Serra do Mar and the Baixadas Litorâneas, involving areas of the Guanabara Bay, Macaé and Ostras, and Lagos de São João basins. The particular case of Lagos de São João highlights that regions with high values of PRCPTOT are not always those with

higher values of SDII (about 20 mm/day in this area). This indicator of rainfall intensity depends mainly on the number of days when precipitation occurs, which can be poorly distributed throughout the year.

The most significant maximum number of consecutive rainy and dry days in the State of Rio de Janeiro is computed by the CWD and CDD indicators (Fig. 2g and h), respectively. It is observed that a large part of the Médio Paraíba do Sul basin, in addition to the southern part of the Rio Dois Rios basin and the central-western portion of the Macaé and Ostras basin—are the areas that show the highest values of CWD. The CWD values are 11 up to 14 days in a row with a rainfall record in these regions. The topography dramatically assists in the upward movements that develop the clouds and cause precipitation in these regions, especially when the thermodynamics of summer are also involved, with sufficient heat and humidity. The other sectors of Rio de Janeiro show CWD values around 7 to 10 days (Fig. 2g).

The influence of physiographic factors driven by continentality and maritimacy is verified in the maximum number of subsequent dry days (Luiz-Silva and Dereczynski 2014). So, there is a CDD gradient from the coast to the interior of the State (Fig. 2h). While the climatological CDD varies from 20 to 32 days on the coast, in the interior, these values reach 42–57 days. The boxplots in Fig. 3d show the lowest CDD values precisely in the hydrographic regions closest to the sea. There are extreme records of more than 100 consecutive dry days in more continental areas. These CDD values are mainly recorded during the austral winter when a drier air mass is acting. According to Fig. 3d, the basins in the north-northwestern portion of the State are those that record high values of CDD with great frequency, which often happens due to the influence of the SASA action. Coastal regions tend to have consecutive dry days interrupted more easily due to the passage of frontal systems and the humidity that comes from the sea toward the continent, causing precipitation, even if of low intensity. According to Sobral et al. (2018), fewer consecutive dry days are recorded over areas in the State close to broad potential evaporation regions, such as the ocean, lakes, or bays. Meanwhile, the prolonged periods of drought in the State's interior can favor forest fires (Andrade et al. 2019).

From the precipitation extremes indicators previously analyzed and strongly conditioned by the landscape physiography of the State of Rio de Janeiro (Fig. 2), the spatial panorama of precipitation extremes is evident and consistent with the spatial concentration of floods and landslides episodes (Fig. 4). Other factors can influence these events, such as topography, overland storage, groundwater, and hydraulic factors. The spatial pattern of these disasters presents a differentiation inherent to the dynamics of the processes, equally conditioned by the physiographic aspects of the State.

Mass movement events assume greater prominence in the Serra do Mar and Mantiqueira escarpments, in the mountainous domain of the State of Rio de Janeiro, and the background in the coastal massifs (Fernandes et al. 2004), according to Fig. 4. Floods show a high recurrence in the domain of coastal lowlands and valley bottoms, which in addition to the natural characteristics of water accumulation suffer from the intense process of waterproofing from the cities expansion (Oscar-Júnior, 2018) with changes in the permeability of ground surfaces. These regions become very susceptible and vulnerable due to the higher rainfall accumulated in the State. As precipitation is an important triggering element of hydrometeorological impact events, evaluating its variability and trends is extremely important for risk management and distribution of adequate infrastructure for mitigation and adaptation.

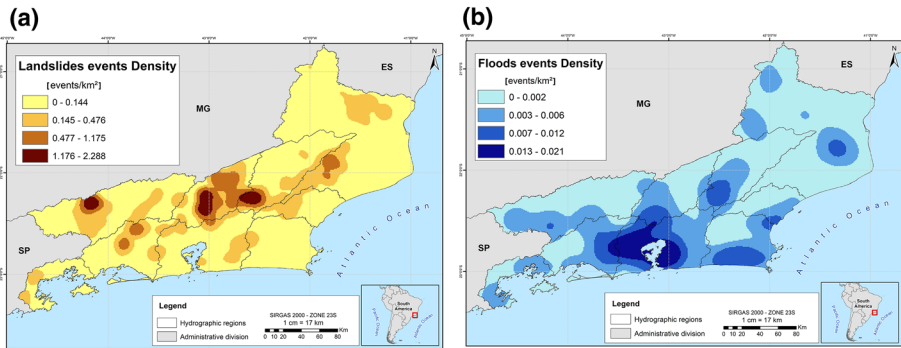


Fig. 4 Spatial density (per km²) of impacts episodes to **a** mass movements, and **b** floods, with at least one death in the State of Rio de Janeiro, during the second half of the twentieth century and the 2000s through data from INEA and CPRM

3.2 Observed trends in the rainfall indices

Figure 5 shows the spatial distribution of detected trends over the last few years in extreme precipitation indices over the State of Rio de Janeiro. The first point to stand out are the markedly heterogeneous trends across Rio de Janeiro, even in rainfall stations close to each other. It is worth remembering that the spatialization was based on the existing stations, but occasional specific differences may exist due to local aspects. The behavior of total rainfall in a given region is considerably influenced by several physiographic aspects that mark its climatology, as seen previously. However, this precipitation pattern changes over time as these factors can also be modified. In addition, the predominant rise that has been detected in air temperature over almost the entire State significantly contributes to changes in the hydrological cycle and, consequently, in precipitation extremes (Luiz-Silva and Dereczynski 2014; Sobral et al. 2019a, b).

There is a predominant trend of increasing PRCPTOT without statistical significance over the central area of Rio de Janeiro (Fig. 5a) in the period 1940–2014. Part of the Médio Paraíba do Sul basin shows decreasing trends in accumulated annual rainfall, however, also without statistical significance. There is also a decrease in PRCPTOT of -10 to -40 mm/decade in large part of the Baixo Paraíba do Sul and Itabapoana basin, especially in pluviometric posts close to the sea. It means that from the 1940s to the 2010s, PRCPTOT decreased by an average of 200 mm in some locations. This fact confirms the need for improvement in water resources management in these areas (Sobral et al. 2020) since the PRCPTOT climatology already has the lowest values in the State's northern region. The stations located in the coastal areas of the Guanabara Bay and Lagos de São João basins show an increase in total annual rainfall around $+10$ to $+70$ mm/decade; that is, PRCPTOT increased by around 300 mm at various points. This same elevation of PRCPTOT was identified in some posts located in the northwestern State. When analyzing PRCPTOT trends in all stations located in the Rio Dois Rios basin, it is noted that annual precipitation volumes are increasing significantly in practically the entire area gradually over the years (Fig. 6a), with an expressive magnitude of $+30, 5$ mm/decade.

The trends associated with the R30mm indicator reveal an increase in these heavy precipitation episodes in much of the State of Rio de Janeiro in the period 1940–2014 (Fig. 5b). Verified magnitudes prevail around $+0.5$ day/decade. The regions that stand out

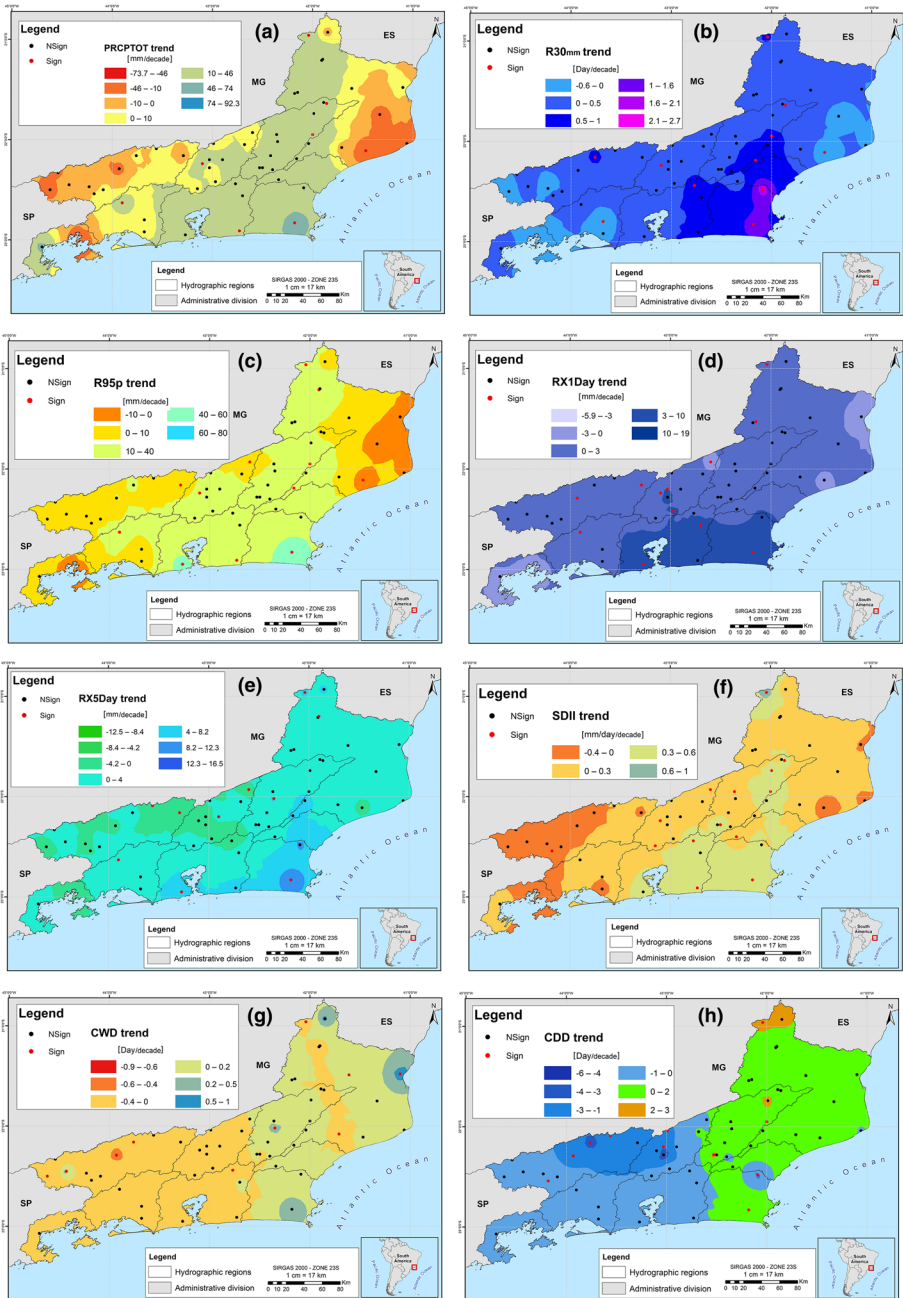


Fig. 5 Observed trends (per decade) in precipitation-related climate extreme indices **a** PRCPTOT, **b** R30 mm, **c** R95p, **d** RX1 day, **e** RX5 day, **f** SDII, **g** CWD, and **h** CDD in the State of Rio de Janeiro predominantly throughout the second half of the twentieth century and the 2000s through the ANA and INMET records

the most are the Rio Dois Rios, Macaé e das Ostras, and Lagos de São João basins, with several stations showing statistically significant growth trends of R30mm in the order of up to +2 days/decade. The intense precipitation represented by the R95p index also exhibits a discrete elevation pattern in the central sector of Rio de Janeiro (Fig. 5c), with values from about +10 to +40 mm/decade, which are significant in a few stations, mainly those closest to the border with the State of Minas Gerais.

It is worth mentioning the increase in R95p in several stations close to the ocean in the States' Metropolitan Region, in addition to the Baixadas Litorâneas, as observed in PRCP-TOT. In these areas, the growth of R95p reaches magnitudes around +10 to +60 mm/decade. Many coastal locations that climatologically observed around 350 mm of R95p in the second half of the twentieth century now register about 500 mm. When evaluating the R95p trends in all stations located in the Baixo Paraíba do Sul and Itabapoana basin, it is observed that the heavy precipitation events have become even stronger gradually over the last few years (Fig. 6b), with a considerable magnitude of +11, 3 mm/decade. These trends observed in precipitation volumes related to heavy precipitation in the State are consistent with the trends observed by Regoto et al. (2021), who identified a significant increase in strong precipitation in several stations on the east coast of the Southern and Southeastern regions of Brazil. This fact alerts to an equally worrisome trend of intensifying the frequency and magnitude of hydrometeorological disasters.

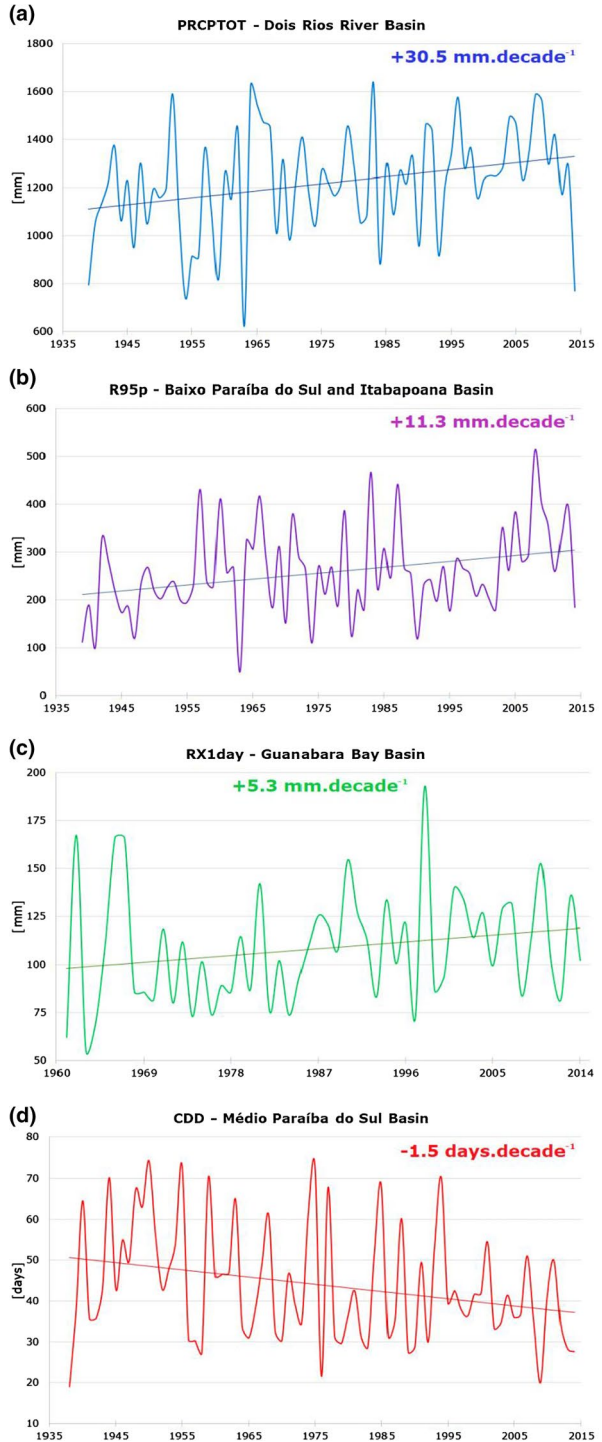
Concerning the extreme rainfall episodes registered in a single day, there is once again the hegemony in the magnitudes that point to an increase in RX1day, this time in practically the entire State of Rio de Janeiro, with only minor exceptions (Fig. 5d). RX1day shows trends with values of up to +3 mm/decade in several stations and, following the pattern of previous indices, reaches an order of magnitude higher in the Guanabara Bay and Lagos de São João basins. In these regions, RX1day is established between 3 and 10 mm/decade; that is, the accumulated precipitation in just 24 h has increased by more than 30 mm in several coast points over the last decades. In fact, RX1day has become increasingly higher over the last few decades in the Guanabara Bay basin (Fig. 6c), where the magnitude is +5.3 mm/decade. It is worth remembering that this region is the most developed in the State, with considerable growth in urban density over the last years that could favor more heavy precipitation than in its surroundings.

The observed changes in extreme precipitation, mainly in the Baixo Paraíba do Sul and Itabapoana (Fig. 6b) and Guanabara Bay (Fig. 6c) basins, may be associated with thermodynamic effects, as already mentioned by Zilli et al. (2016). Thus, growth in convective instability due to increased air temperature over the last few decades in the State of Rio de Janeiro (Luiz-Silva et al. 2014) could favor more intense precipitation concentrated in short periods in specific locations. Other mechanisms such as land use modifications should be further investigated.

When examining the RX5day indicator, it is noticed that this panorama holds (Fig. 5e). In much of Rio de Janeiro, the trends of these high rainfall volumes in 5 consecutive days are between -4 and +4 mm/decade, without statistical significance. However, in the Metropolitan Region and the Coastal Lowlands, the magnitudes of RX5day have values of up to +12 mm/decade, which may also be related to changes in land use in these areas, such as the growth of the urban perimeter (Smyth and Royle 2000; Miguez et al. 2015).

Precipitation intensity has also shown changing trends in most Rio de Janeiro State (Fig. 5f). Except for the southern part of Rio de Janeiro, which shows a downward trend of up to -0.4 mm/day.decade without statistical significance, the remainder of the State shows an upward trend in SDII. In the interior of Rio de Janeiro, trends with magnitudes of up to +0.3 mm/day.decade predominate. However, in sectors closer to the coast, the values

Fig. 6 Observed trends in the climate extremes indices related to precipitation **a** PRCPTOT in the Rio Dois Rios basin, **b** R95p in the Baixo Paraíba do Sul and Itabapoana basin, **c** RX1day in the Guanabara Bay basin, and **d** CDD in the Médio Paraíba do Sul basin, predominantly throughout the second half of the twentieth century and the 2000s, through ANA and INMET records



reach up to +0.6 mm/day.decade. Several stations showed trends that were considered statistically significant at the 95% level, even with an order of magnitude considered small. In fact, they exhibit a significant change in the pattern of rainfall distribution when observing the climatology. However, once again highlighting the coastal areas and the central part of the State, some stations had SDII of 12 mm/day in the last century and currently reach 15 mm/day.

Consecutive rainy days seem to show a different pattern between two areas of the State of Rio de Janeiro. The central-southern part of Rio de Janeiro shows decreasing trends in CWD, while the northern portion of the state shows increasing trends (Fig. 5g). It is noteworthy that few pluviometric posts registered statistically significant trends. On the other hand, the accentuated trends in the Médio Paraíba do Sul basin lead to the prospect of a decrease in the maximum number of consecutive rainy days, with magnitudes of around -0.4 day/decade. CWD growth trends in northern Rio de Janeiro are also largely without statistical significance, with values around $+0.2$ day/decade.

The trends signs for the maximum length of consecutive dry days are similar to those for consecutive rainy days, but with a higher order of magnitude for CDD (Fig. 5h). The central-southern region of Rio de Janeiro shows CDD reduction trends of up to -3 days/decade. However, in part of the Médio Paraíba do Sul and Piabanha basin, the magnitude of these trends reaches up to -6 days/decade. In the northern sector of the State, CDD elevation trends show values around $+1$ to $+3$ days/decade, thus indicating that CDD may be lasting about 10 days longer compared to previous decades. This fact aggravates hot spots in this area, which registers the highest concentration in the State, in addition to a significant upward trend (Caula et al. 2017). Thus, the exposure of the northern region of the State to extremes of precipitation is highlighted, with a reduction in PRCPTOT and an increase in CDD, and the historical averages of maximum number of consecutive dry days already show high values in this area. Upward (downward) trends of both the CWD and CDD indices in the same region may indicate poorly (well) distributed precipitation throughout the year. This pattern happens, for example, in the Médio Paraíba do Sul basin, where CWD and CDD decreased together over the twentieth century. For CDD, this reduction was -1.5 days/decade (Fig. 6d).

4 Conclusions and final remarks

The development of climate studies that characterize the frequency and intensity of extreme precipitation episodes in a given area is highly relevant, especially for decision-makers who need qualified and quantified information. In association with the socio-spatial processes of Rio de Janeiro, the physiographic aspects of the State, notably the relief, vegetation, and proximity to the ocean, impose risk factors concerning heavy precipitation and natural disasters, as presented. In this sense, preparing a compendium with the primary configurations related to accumulated precipitation in the State is essential so that a synthesis of extreme rainfall indicators is satisfactorily understood and serves as a basis for future preparation measures for these events.

Lower records of PRCPTOT are localized in the northern Rio de Janeiro (around 800 mm) and higher in the southern State (up to 2,200 mm). Most portions of Rio de Janeiro have PRCPTOT predominantly driven by transient synoptic meteorological systems, such as cold fronts. The prominent influence of topography in the values of higher total precipitation (frequency and intensity) can be seen, as in R30mm and R95p. The

effect of the Serra do Mar in the most extreme precipitation in the State is highlighted. The regions near the ocean present the highest values of RX1day (more than 100 mm) and RX5day (more than 150 mm). It is outstanding that some atmospheric phenomena, such as SACZ, can develop accentuated accumulated rainfall in some consecutive days, provoking disasters such as floods, landslides, and overflowing rivers. Most of the State of Rio de Janeiro shows SDII records of about 13–14 mm/day. The relief considerably sustains the ascensive shifts that form the clouds and cause precipitation in areas with higher CWD values. There is a CDD gradient from the shore (lower values—20 to 40 days) to the inland (higher values—40 to 60 days) of Rio de Janeiro in the function of the sea proximity. The lengthy periods of drought in the State's interior can prompt forest fires.

There are notably contrasted trends across the State of Rio de Janeiro, considering all the analyzed pluviometric stations. The northern and southern areas of Rio de Janeiro show reducing trends in total annual precipitation, but most of them are without statistical significance (– 10 to – 30 mm/decade). The trends related to the R30mm index show an elevation in the frequency of these heavy precipitation events in much of the State. There is a growth of R95p in various stations near the sea in the Metropolitan Region and Baixadas Litorâneas. Concerning the heavy precipitation episodes observed in just a day, there is once again a heterogeneity in the magnitudes that reveal an increase in RX1day in most of the State of Rio de Janeiro (+ 1 to + 5 mm/decade). A mixed panorama in the RX5day indicator is also verified, with the trends of this high accumulated precipitation in 5 subsequent days between – 4 and + 4 mm/decade. So many stations presented increasing trends in SDII that were evaluated as statistically significant at the 95% level, even with slight order of magnitude, indicating more intense precipitation. The central-southern sector of Rio de Janeiro shows diminishing trends in CWD (about – 0.5 days/decade), while the northern part of the State presents elevating trends (about + 0.5 days/decade). The trends signs for the maximum number of consecutive dry days are like those for consecutive rainy days, but with a superior magnitude for CDD, pointing to irregular rainfall volumes during the year.

Due to the gradual effects of current climate change, climate information has become increasingly relevant to the scientific community, decision-makers, and society. The significant growth of R95p in several populated areas of Rio de Janeiro deserves special attention due to the recurrent disasters associated with heavy precipitation in these portions, such as the mountainous region and the metropolitan region of the State. Proper knowledge of historical averages and verified trends over the last years in the State of Rio de Janeiro is also fundamental for planning actions in various segments, such as agriculture, urban development, energy generation and transmission, water resources management, among other sectors. Therefore, research on future projections of climate change over the next few decades has also been progressively structured to feed the environmental and socio-economic spheres with elucidations that assist in measures to prevent disasters of any magnitude and nature. Besides, attribution studies can help determine whether a human influence on precipitation can be distinguished from natural variability.

Author contributions Wanderson Luiz-Silva elaborated on the organization and presentation of the results, as well as the bibliographic structuring and the data and methodology of the study. Antonio Carlos Oscar-Júnior interpolated the data and built the figures and wrote some of the work's main discussions.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Ethical approval The authors are committed to upholding the integrity of the scientific record.

Consent for publication All individuals listed as authors have agreed to be listed and approved the submitted version of the manuscript.

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