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ARTIGO

CLIMATOLOGICAL CHARACTERIZATION OF EXTREME PRECIPITATION INDICES IN THE CITY OF RIO DE JANEIRO, BRAZIL

CARACTERIZAÇÃO CLIMATOLÓGICA DOS ÍNDICES EXTREMOS DE PRECIPITAÇÃO NA CIDADE DO RIO DE JANEIRO, BRASIL

CARACTERIZACIÓN CLIMATOLÓGICA DE LOS ÍNDICES DE PRECIPITACIÓN EXTREMA EN LA CIUDAD DE RIO DE JANEIRO, BRASIL

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ABSTRACT

Knowing the climatological factors related to extreme rainfall events on a regional scale is essential for risk management and decision-making. In this sense, this study evaluates the temporal behavior and spatial distribution of extreme rainfall in the city of Rio de Janeiro between October and April (the so-called rainy season). Six extreme precipitation indices were also used to evaluate possible changes in precipitation behavior in the region using 28 rain gauges from the Alerta Rio System between 1997 and 2021, a period with dates available in the System. Average rainfall totals between October and April on the windward side of the massifs reach 1000-1100 mm, compared to 800-900 mm inland. The proximity to the ocean also showed an importance in the rainfall variability, considering the frequency of days with precipitation above 30 mm, which was higher on the coast. On the other side, verifying the importance of controlling the behavior of rainfall records in 1 day and 5 consecutive days was possible. The overall aspects showed that each neighborhood in the municipality is impacted differently by severe precipitation, corroborating the importance of local knowledge for preventive measures and risk reduction.

Keywords: climatology; precipitation; climate extremes; extreme precipitation indices; Rio de Janeiro.

RESUMO

É essencial conhecer as principais características climatológicas associadas à precipitação extrema em uma região para a gestão de riscos e tomada de decisões. Assim, o objetivo deste estudo é avaliar o comportamento temporal e a distribuição espacial dos extremos de chuva na cidade do Rio de Janeiro entre outubro e abril (período chuvoso) nos últimos anos (1997 a 2021). Dados diários de precipitação de 28 estações pluviométricas do Sistema Alerta Rio são utilizados para calcular 6 (seis) indicadores de extremos climáticos relacionados à frequência e intensidade da precipitação. Quanto às principais características associadas aos acumulados pluviométricos, observa-se que os maiores valores estão no entorno dos maciços e em pontos do litoral. Os totais médios de precipitação entre outubro e abril a barlavento dos maciços atingem 1000-1100 mm, em comparação com 800-900 mm no interior. A proximidade do oceano faz com que a frequência de dias com precipitação superior a 30 mm seja maior no litoral. A topografia local influencia nos maiores volumes de chuva em 1 dia e em 5 dias consecutivos. Cada localidade municipal é impactada diferentemente por precipitações severas, logo tais limites devem ser estudados.

Palavras-chave: climatologia; precipitação; extremos climáticos; índices extremos de precipitação; Rio de Janeiro.

RESUMEN

Es fundamental conocer las principales características climatológicas asociadas a la precipitación extrema en una región para la gestión de riesgos y la toma de decisiones. Por lo tanto, el objetivo de este estudio es evaluar el comportamiento temporal y la distribución espacial de los extremos de lluvia en la ciudad de Río de Janeiro entre octubre y abril (temporada de lluvias) en los últimos años (1997 a

2021). Se utilizan datos diarios de precipitación de 28 estaciones pluviométricas del Sistema Alerta Rio para calcular 6 indicadores de extremos climáticos relacionados con la frecuencia e intensidad de la precipitación.Los totales promedio de precipitación entre octubre y abril en el lado del viento de los macizos alcanzan los 1000-1100 mm, en comparación con 800-900 mm en el interior. La cercanía del océano hace que la frecuencia de días con precipitación superior a 30 mm sea significativamente mayor en la costa. La topografía local influye significativamente en los mayores volúmenes de lluvia en 1 día y en 5 días consecutivos. Cada localidad del municipio se ve afectada de manera diferente por las precipitaciones severas, por lo tanto, estos límites deben ser estudiados.

Palabras Clave: climatología; precipitación; extremos climáticos; índices de precipitación extrema; Rio de Janeiro.

INTRODUCTION

The increase in the frequency and intensity of climate extremes events associated with temperature and precipitation is one of the most significant impacts of global warming on society (MULLER *et al*., 2011). The study of how precipitation panorama in a region is being modified in the present climate is relevant for the perception of the average atmospheric characteristics and for understanding its variations and future behavior (LUIZ-SILVA AND DERECZYNSKI, 2014). Scientific analyses published in the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change, IPCC (2021), which gathered the main conclusions of the contribution of Working Group 1 (WG1), indicate growing evidence from detection and attribution studies, which support that undeniably human influence has been generating direct impacts related to climate change in the world. The rise in the mean global temperature affects the energy budget, modifying the frequency of heat waves, heavy precipitation, and droughts (ALLAN *et al*., 2021). Thus, regional, and social inequalities increase the population's vulnerability to climate change as the threats become more severe.

Climate change detection and attribution studies have increasingly focused on alterations in extreme events. Modifications in the hydrological cycle impact the precipitation extremes, such as an increase in the frequency of heavy rainfall or severe droughts and precipitation volumes. These extreme episodes have a much more significant impact on society, ecosystems, and the economy than just the average (KARL *et al*., 1997; MEEHL *et al*., 2000; FRICH *et al*., 2002; ALEXANDER *et al*., 2006). Thus, to monitor the behavior and trends of such extreme events, sets of climate extreme indices have been used, developed, and maintained by many meteorological centers and researchers worldwide (EASTERLING *et al*., 2000; MARENGO *et al*., 2009).

Brazil has been showing observed trends and future projections of changes in some climate extremes related to precipitation (REGOTO *et al*., 2021). The Southeastern region has climate projections generated by global and regional models that indicate alterations in the frequency and intensity of precipitation extremes (MARENGO *et al*., 2009; LUIZ-SILVA AND DERECZYNSKI, 2014; CHOU *et al*., 2014; LUIZ-SILVA *et al*., 2014; GIORGI *et al*., 2014; LYRA *et al*., 2018; AVILA-DIAZ *et al*., 2020). Future scenarios of precipitation climate extremes indices in the Southeastern Brazil indicate trends toward an increase in consecutive dry days and an increase in the frequency and intensity of highly wet days (ARMOND AND NETO, 2017; DERECZYNSKI *et al*., 2018).

Different precipitation regimes are found in the State of Rio de Janeiro due to the heterogeneity and physiographic elements. According to Luiz-Silva and Dereczynski (2014) and Luiz-Silva and Oscar-Júnior

(2022), there is an increase in total extreme rainfall in several areas near the ocean, and the extreme precipitation in just one day exhibits a growth in most Rio de Janeiro. The city of Rio de Janeiro is the second largest in Brazil and presents a significant interaction between atmospheric systems and some aspects, such as ocean, relief, and vegetation. Specifically in the Metropolitan Region of Rio de Janeiro (MRRJ), Dereczynski *et al*. (2013) and Luiz-Silva *et al*. (2023) found a significant increase in the rainfall volume associated with severe precipitation in the Alto da Boa Vista, a neighborhood in the north part of the municipality inside the Atlantic Forest and Tijuca Massif.

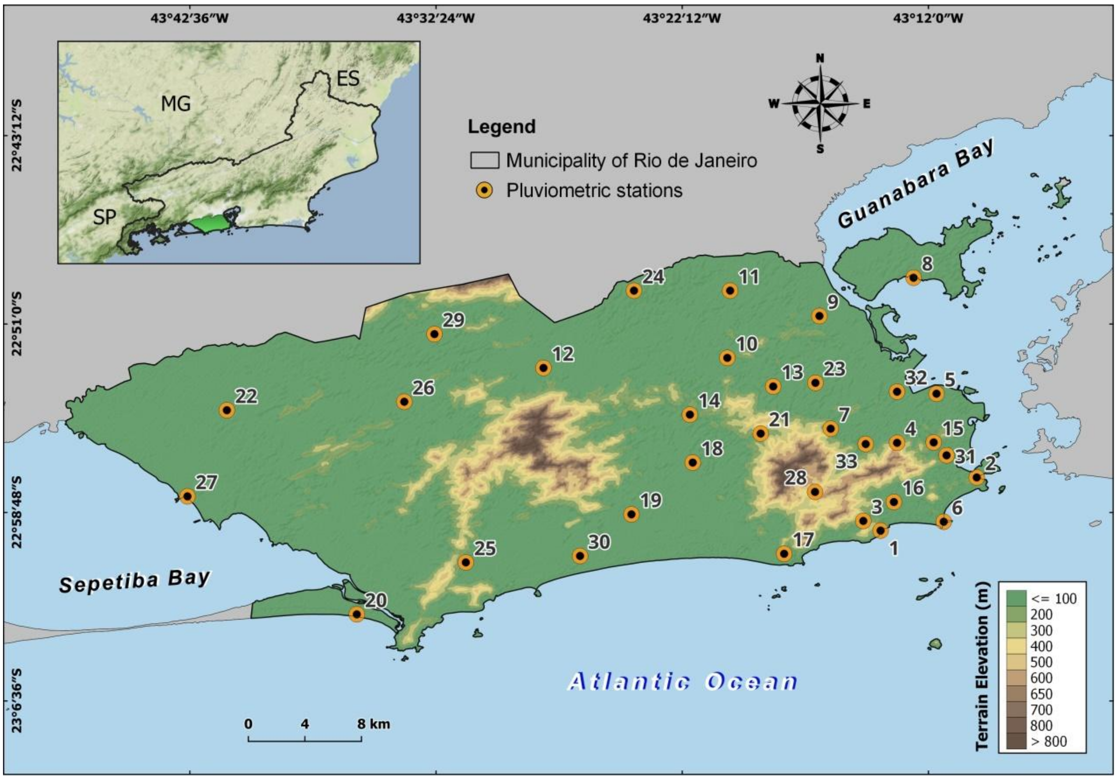
The city of Rio de Janeiro, capital of the State of Rio de Janeiro, is the second most important metropolis in the Southeast Region of Brazil. This region (Fig. 1), located in the Southeast Region of Brazil, has a high population density, with 6,221,423 inhabitants (2022 Census) residing in an urbanized area of 600 km2, with the city's total territorial area being 1204 km2 (DATA.RIO, 2024). In the city's topography, the Tijuca Massif divides it into the South and North Zones, with the Gericinó Massif to the north and the Pedra Branca Massif to the west. Additionally, the city is influenced by the Atlantic Ocean to the south, the Sepetiba bays to the west, and the Guanabara Bay to the east.

The interaction of sea conditions and orography, with climatic elements, mainly precipitation, causes the climate of the city of Rio de Janeiro to vary according to zones or neighborhoods (ARMOND AND NETO, 2017), generating microclimates.

Given the tropical climate in which the city of Rio de Janeiro is located (ALVARES *et al*., 2013), most precipitation totals occur in the warmest months of the year (austral spring and summer). Intense rainfall events have always occurred especially during the summer and autumn months, causing significant disruptions for the local population (DERECZYNSKI *et al*., 2017). The occurrence of the strongest rains in the city of Rio de Janeiro at certain times the population can leave vulnerable, to a lesser or greater degree and quality, to the impacts that may be triggered by the rains. These impacts necessarily depend on the differences in the historic urbanization process, which has materialized differently throughout the city (ARMOND, 2019).

Suburban areas are more susceptible to climate events and have high levels of socio-environmental vulnerability. Levels of vulnerability are much more related to issues related to the loss of material goods than to situations of displacement or loss of life (ARMOND, 2019; ARMOND AND NETO, 2017). An example of extreme rainfall event, that affected the city and state of Rio de Janeiro, occurred during the 5th and 6th of April 2010, causing floods and landslides mainly in the municipalities of Rio de Janeiro and Niterói, where more than 200 people died (LIRA AND CATALDI, 2016).

Figure 1. The topography (m) of the city of Rio de Janeiro and the location of the Alerta Rio System rainfall stations are listed in Table 1.



Source: Prepared by the authors

Dereczynski *et al*. (2017) and Abelheira *et al*. (2016), have shed light on the significant impacts of extreme rainfall events on various facets of communities, ranging from infrastructure damage to public health concerns. These events not only lead to immediate disruptions such as power and water outages, displacement, and loss of life, but they also have enduring consequences, including heightened vulnerability to disease outbreaks and persistent challenges like sewer blockages and flooding. Recognizing these impacts is pivotal for crafting effective mitigation and adaptation strategies to mitigate the mounting risks associated with extreme weather events. Hence, gaining insight into how rainfall extremes manifest in the current climate is crucial for comprehending their alterations more comprehensively.

In this context, the present study aims to analyze the climatology of seasonal and annual precipitation and evaluate the extreme climate indices in the municipality of Rio de Janeiro from 1997 to 2021.

MATERIALS AND METHODS

Data

For the analysis of seasonal and annual rainfall and the composition of the climatology of the extreme precipitation indicators, daily observational data on precipitation from the 28 rain gauges (Figure 1) were obtained by the Alerta Rio System - Rainfall Alert System of the City of Rio de Janeiro (http://alertario.rio.rj.gov.br/), managed by the Geotechnical Institute Foundation - GEO-RIO.

For the seasonal analysis, this study includes rainfall data from the rainy season in the Brazilian Tropical climate (LUIZ-SILVA *et al*., 2021), from October to April, collected between 1997 and 2021 (25 years). This period, selected and named as the rainy season in this work, also includes the month of April, a month belonging to the autumn season, due to some extreme precipitation events that have already occurred this month in the city of Rio de Janeiro.

Armond and Neto (2017) and Siciliano *et al*. (2018), highlighted the importance of April in observing extreme rainfall (average rainfall more significant than 100 mm) in terms of rainfall episodes, especially in transition months between the summer and winter seasons. The atmosphere still has some summer heat and humidity, while more significant frontal systems can influence it. Lima and Armond (2022) characterized the pluviometric dynamics of the MRRJ, highlighting the analysis of the spatial and temporal variability of rainfall and extreme events in the region, where it was observed that concerning seasonal variability, approximately 90% of the extremes occurred between November and April. According to the authors, April presents the highest number of pluviometric stations with the most intense events, thus demonstrating the revelation of rainfall in this month.

The daily rainfall totals of this work are accumulated between 00:00 local time and 23:59 local time on the day in question, and the Brazilian Summertime is considered. The period of data from Alto da Boa Vista, Av. Brazil/Mendanha, Estr. Grajaú/Jacarepaguá and Tijuca/Muda are different, as they were installed between 2010 and 2011.

Flaws in the time series of rainfall pose the primary hindrance to a more thorough explanatory analysis of extreme indices. Its constrain our ability to comprehend the nature and extent of climate extremes' evolution due to climate change (VINCENT *et al*., 2005).

Oliveira *et al*., (2017) underscore the significance of utilizing datasets with minimal gaps, highlighting their importance in addressing this challenge. As a first step, the precipitation time series was analyzed to identify missing data, to generate the climatologies of the precipitation extremes indicators, and for seasonal analysis of rainfall. The total period of data available from each pluviometric station used is shown in Table 1, as well as the information referring to each pluviometer, including latitude, longitude, altitude, total period of the daily precipitation, and number of years missing.

To maintain uniformity among the results in the present study, a limit of failures for the analysis in annual (monthly) data series needs to be defined. In the literature, it is observed that in the calculation of regional series and trends, according to Data (2009), the exclusion of years from the series of regional mean indices occurs for those in which less than 75% of the stations have valid values. In Dos Santos et al. (2011), the time series of temperature and precipitation that had more than 20% of missing values in the analysis period from 1971 to 2010 were excluded. In the study by Keggenhoff et al. (2014), the time series of temperature and precipitation with more than 20% of missing values in the analysis period from 1971 to 2010 were also deleted. In Regoto *et al*. (2021), the years with more than 25% of failures in the series of daily rainfall totals from each of the 80 stations were excluded.

In this study, it was established that years (months) with more than 10% of failures in the series were excluded from the analysis. This threshold was chosen for both annual and monthly analyses, given the focus on the rainy season. The absence of data would compromise the accuracy of the statistical analysis of the results. A percentage greater than 10%, such as in the rainy period (October to April), which comprises 210 days, would exceed 21 days in the series, nearly equivalent to 1 month of missing data. Thus, this article adopts a more conservative approach in establishing this threshold. The number of absent years and percentage by the number of daily records is also shown in Table 1.

Table 1. Geographic position and temporal data availability of the pluviometric network of Alerta Rio system

ID	Station	Lat. (°)	Lon. (°)	Altitude (m)	Period	Years Absent (10%)	Days Absent (%)
1	Vidigal	-22,99	-43,23	85	1997 - 2021	0	0.2
2	Urca	-22,96	-43,17	90	1997 - 2021	0	0.2
3	Rocinha	-22,99	-43,25	160	1997 - 2021	0	0.2
4	Tijuca	-22,93	-43,22	340	1997 - 2021	0	0.2
5	Santa Teresa	-22,90	-43,19	170	1997 - 2021	0	0.2
6	Copacabana	-22,99	-43,19	90	1997 - 2021	0	0.2
7	Grajaú	-22,92	-43,27	80	1997 - 2021	0	0.2
8	Ilha do Governador	-22,82	-43,21	0	1997 - 2021	2	1.9
9	Penha	-22,84	-43,28	111	1997 - 2021	0	0.2
10	Madureira	-22,87	-43,34	45	1997 - 2021	0	0.2
11	Irajá	-22,83	-43,34	20	1997 - 2021	0	0.3

12	Bangu	-22,88	-43,47	15	1997 - 2021	0	0.2
13	Piedade	-22,89	-43,31	50	1997 - 2021	0	0.2
14	Jacarepaguá/Tanque	-22,91	-43,36	73	1997 - 2021	0	0.2
15	Saúde	-22,93	-43,20	15	1997 - 2021	0	0.2
16	Jardim Botânico	-22,97	-43,22	0	1997 - 2021	0	0.2
17	Barra/Barrinha	-23,01	-43,30	7	2013 - 2021	0	0.0
18	Jacarepaguá/Cidade de Deus	-22,95	-43,36	15	1997 - 2021	0	0.2
19	Barra/Riocentro	-22,98	-43,41	0	1997 - 2021	1	0.7
20	Guaratiba	-23,05	-43,59	0	1997 - 2021	2	2.7
21	Est. Grajaú/Jacarepaguá	-22,93	-43,32	105	2010 - 2021	0	0.2
22	Santa Cruz	-22,91	-43,68	15	1997 - 2021	1	0.6
23	Grande Méier	-22,89	-43,28	25	1997 - 2021	0	0.2
24	Anchieta	-22,83	-43,40	50	1997 - 2021	0	0.2
25	Grota Funda	-23,01	-43,52	11	1997 - 2021	1	0.4
26	Campo Grande	-22,90	-43,56	30	1997 - 2021	0	0.2
27	Sepetiba	-22,97	-43,71	62	1997 - 2021	0	0.2
28	Alto da Boa Vista	-22,97	-43,28	355	2010 - 2021	0	0.1
29	Av. Brasil/Mendanha	-22,86	-43,54	30	2010 - 2021	0	0.1
30	Recreio dos Bandeirantes	-23,01	-43,44	10	1997 - 2021	1	0.3
31	Laranjeiras	-22,94	-43,19	60	2000 - 2021	0	0.2
32	São Cristóvão	-22,90	-43,22	25	2000 - 2021	3	2.7
33	Tijuca/Muda	-22,93	-43,24	31	2011 - 2021	0	0.1

Source: Prepared by the authors

Methods

The Expert Team on Detection and Indexes of Climate Change (ETCCDI) of the Commission on Climatology (CCl) of the World Meteorological Organization (WMO) generated a set of indicators of climate extremes based on daily data of maximum temperature, minimum temperature, and precipitation to identify trends and climate extreme indices (FRICH *et al.*, 2002; LUIZ-SILVA AND OSCAR-JÚNIOR, 2022).

The primary ensemble of 27 extreme indices formulated by the ETCCDI serves as a widely utilized instrument for evaluating and overseeing alterations in extreme conditions (COSTA *et al.*, 2020; PETERSON, 2001). The indices designate events that occur several times per season or year. This imparts upon them stronger statistical properties compared to extreme measures, which are far enough into the tails of the distribution so as not to be observed during some years (ALEXANDER *et al.*, 2006).

These extreme indices also have enabled researchers to understand and advance their knowledge of global changes in patterns of climate extremes. Moreover, they have spurred efforts in the recovery, homogenization, quality control, and gap-filling procedures of these meteorological variables' time series, facilitating studies across various parts of the world (COSTA *et al.*, 2020).

The extreme precipitation indicators used in this work are listed in Table 2.

Table 2. Precipitation extreme indicators used in this study, where RR is the daily precipitation.

Indicator	Definition	Unity
PRCPTOT	Total accumulated rainfall	mm
R95p	Annual total precipitation on the days when RR > 95th percentile of the wet days	mm
R99p	Annual total precipitation on the days when RR > 99th percentile of the wet days	mm
Rx1day	Annual max 1-day precipitation	mm
Rx5day	Annual max consecutive 5-day precipitation	mm
R10mm	Annual count of days when RR ≥ 10 mm	days
R30mm	Annual count of days when RR ≥ 30 mm	days

Source: Prepared by the authors

Data processing and manipulation, as well as the generation of additional graphs, were performed using Python 3.11 software. The QGIS Desktop 3.26.3 software was used for the composition of climatological maps.

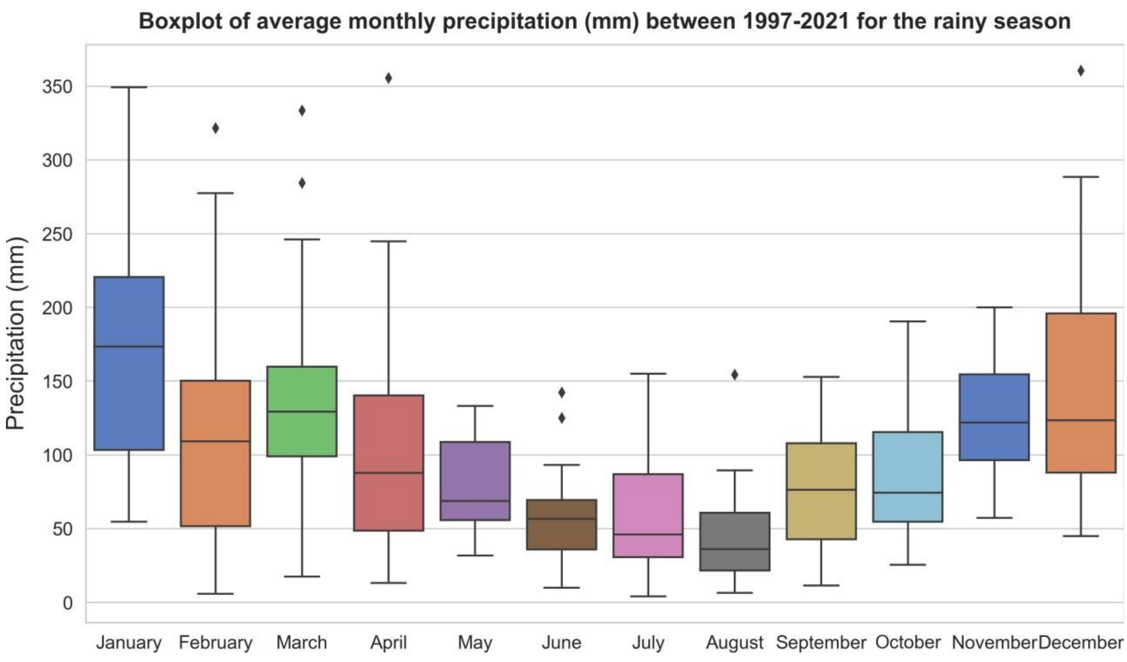
RESULTS

Seasonal Characterization of Precipitation in the Municipality of Rio de Janeiro for the period 1997 to 2021

In this section, a climatological analysis is carried out for the period analyzed here (1997 to 2021) of daily precipitation based on data from the 33 active rainfall stations of the Alerta Rio System, listed in Table 1. The spatial distribution of rainfall stations is shown in Figure 1. It noted that such distribution is not homogeneous, with most stations concentrated in the North Zone, close to the Tijuca Massif, and few stations in the city's West Zone. It occurs because GEO-RIO's objective is to alert the population during extreme rainfall events that may trigger landslides in areas with higher population density. Based on the analysis of meteorological conditions from these stations, the system issues alerts in case of possible landslides.

The annual distribution of precipitation between 1997 and 2021 in the city of Rio de Janeiro can be seen in Figure 2. It is observed that the tropical climate in which the city of Rio de Janeiro is located is seen in the seasonal variability of precipitation, with higher rainfall in austral summer (~150 mm) and lower rainfall in austral winter (~50 mm). These high precipitation values are associated with episodes of the South Atlantic Convergence Zone (SACZ) in Brazil, in addition to combining the passages of cold fronts with the heat and humidity available at this time of year. As described in Siciliano *et al*. (2018) and Lima and Armond (2022) and analyzed in Figure 2, the lowest monthly values occur in February, along with the other rainy season months. Regarding the dry period, August is the month whose mean has the lowest value (less than 50 mm). However, in both June and August, outlier values are observed, thus indicating more voluminous and rarer rainy events. The frequent occurrence of extreme precipitation events in April justifies that we consider this month in the rainiest period in the municipality.

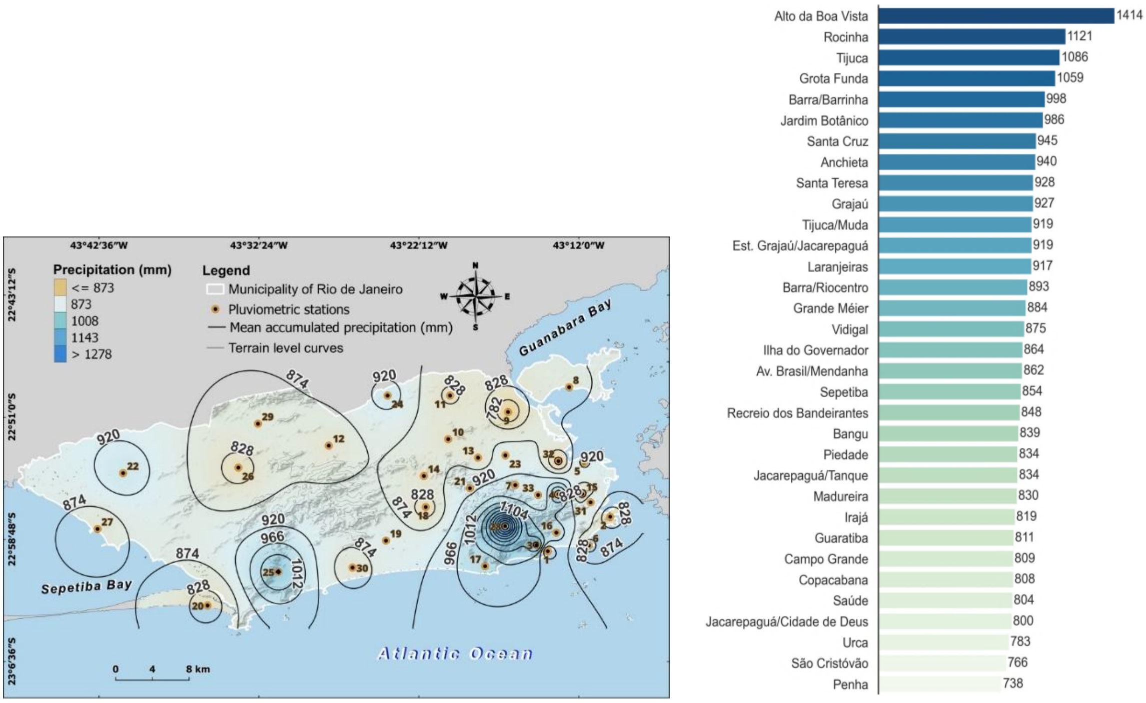
Figure 2. Boxplot of average monthly rainfall (mm) from 1997-2021.



Source: Prepared by the authors

The spatial distribution of average precipitation in the rainy season (1997 -2021) over the city of Rio de Janeiro can be seen in Figure 3a. The most significant rainfall accumulations are concentrated close to the massifs due to the air that is forced to rise in these areas, thus causing more precipitation. The maximum precipitation is near the Tijuca Massif, where the Alto da Boa Vista rainfall station is located, with an average of 1414 mm in the rainy season, as shown in Figure 3b. This rainfall total is double that recorded in stations such as São Cristóvão and Penha, neighborhoods further away from the massifs and the ocean. Other secondary maximums can also be observed near the Gericinó Massif, recorded at the Anchieta station, and other sites near the Pedra Branca Massif (Figure 3b).

Figure 3. (a) Average accumulated precipitation isohyets (mm) from October to April in the city of Rio de Janeiro (1997-2021); **(b)** Average accumulated precipitation (mm) from October to April (1997-2021) in the stations of the city of Rio de Janeiro.



(a) **(b)**

Source: Prepared by the authors

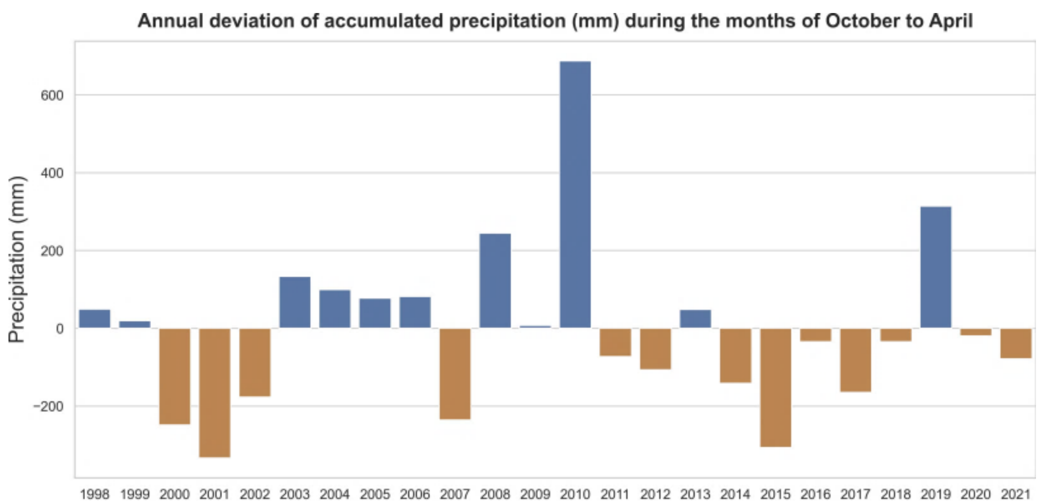
Figure 4 shows the annual deviation of the accumulated precipitation for the rainy season, emphasizing a marked positive anomaly for 2010 and 2019, indicating a very likely occurrence of extreme events in these years. In contrast, several years with negative precipitation anomalies were recorded in the 2010s, especially in 2014 and 2015.

In 2010, the high accumulated annual precipitation in Figure 4 was favored by an extreme precipitation event in April, associated with the passage of a frontal system that led to one of the highest accumulated precipitation totals in 24 hours of the entire historical series. It caused one of the most floods recorded in the city of Rio de Janeiro in the last 100 years (REBELLO *et al.*, 2012; LIRA AND CATALDI, 2016). In this event, a combination of accumulated rainfall with the high tide level was observed, making it difficult for water to flow in most coastal locations and worsening the floods

(COELHO *et al.*, 2010). These high rainfall volumes also motivated the structuring of control and monitoring centers for alerts in the city of Rio de Janeiro and Brazil.

After establishing several measures to prevent disasters in conditions of heavy precipitation in the city of Rio de Janeiro, the chaotic situations resulting from these events began to be monitored and predicted more effectively and with a faster response to the population. The high annual precipitation accumulated in Figure 4 in 2019 was favored by a frontal system over the Southeast region of Brazil, establishing a moisture convergence zone in the State of Rio de Janeiro in April. This pattern created an atmospheric environment favorable to deep convection, where the accumulated rainfall in 24 hours showed values above 100% of the accumulated climatological precipitation for the month, with a maximum of 394% in the Copacabana pluviometer (SILVA *et al.*, 2022) in the South Zone of the city. Episodes of severe rainfall in a short period that exceed the municipality's ability to react quickly within its vulnerabilities are still frequent threats and, therefore, maintain the degree of risk inherent to this scenario.

Figure 4. Annual deviation of accumulated rainfall between the months October and April (1997-2021).



Source: Prepared by the authors

Precipitation Extreme Indicators

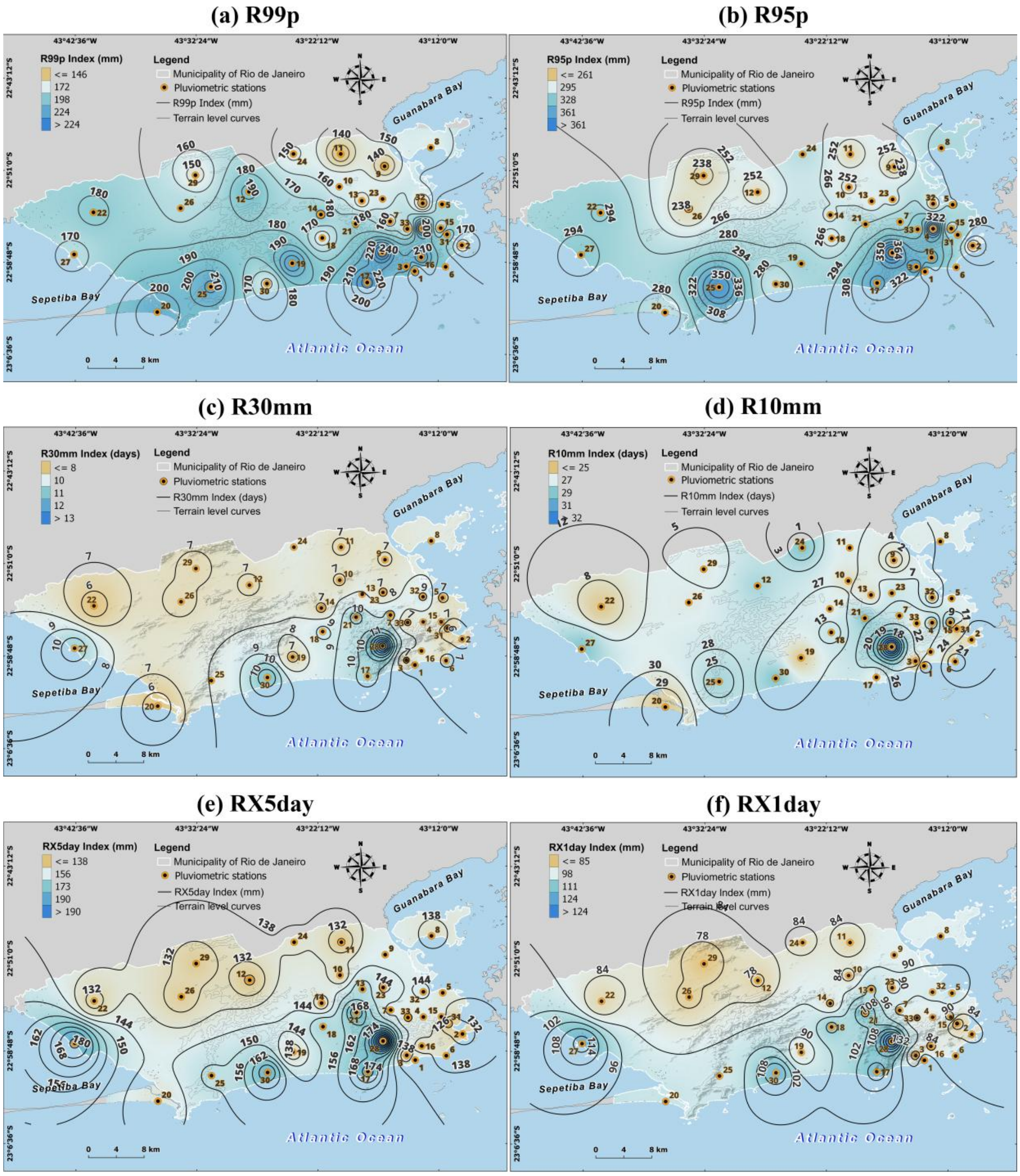
Figure 5 presents the average annual fields of the extreme precipitation indicators (R99p, R95p, R30mm, R10mm, RX5day and RX1day) in the city of Rio de Janeiro. Initially analyzing the indicators of extreme annual precipitation (R99p) and annual heavy rainfall (R95p) for rainy season, it is observed that both present higher values close to the Tijuca Massif, with high R99p values of 240 mm and in the West Zone (Fig. 5a), relative to the region of Grota Funda, reaching values of 210mm. During the summer, the continent-ocean temperature gradient is strengthened, thus intensifying the sea breeze, which brings moisture from the ocean towards the continent, which can contribute to accentuated rainfall accumulations that are reflected in the sum of these percentiles. These same areas also presented high values of heavy rainfall (R95p) (Fig. 5b) and total annual precipitation (Fig. 3a). In the West Zone, the lowest rainfall percentiles observed for R95p and R99p were found, with values below 100 and 250 mm in much of the region, respectively.

Absolute extreme values, such as R95p and R99p, are not ideal for direct impact comparisons but can still offer useful information for impact and adaptation studies. These values typically reflect higher amounts of rainfall in humid climates than in dry climates, which can lead to different impacts respectively. However, both nature and society have closely adjusted to the local pattern of climate variability, and in some cases, local infrastructure has been designed to handle region-specific extremes (DATA, 2009).

Regarding the average field of R30mm (Fig. 5c) and R10mm (Fig. 5d), it is noted that the highest number of days in the year with daily precipitation above 30 and 10 mm maintains the same configuration: higher values in mountainous regions and close to the coast of the city of Rio de Janeiro. On average, there are between 8 and 12 days with rainfall above 30 mm (R30mm) in the town in the year and between 25 and 31 days with precipitation above 10 mm (R10mm). The furthest portion of the West Zone of the city of Rio de Janeiro records a high frequency of R10mm, probably due to the proximity to Costa Verde and Sepetiba Bay, which provide humidity, especially during the passage of cold fronts coming from the southwest that hit primarily this part of the municipality.

Maximum rainfall for five consecutive days (RX5day) and maximum rainfall for one day (RX1day) again follow expectations, with high values in the Tijuca Massif's region. It is observed that the city is divided by these indicators, and unlike the others, the entire northern area of the municipality is characterized by the lowest values (region bordering the Baixada Fluminense, north of the West Zone, and a large part of the North Zone). Baixada Fluminense has many areas covered by asphalt and concrete and portions of municipalities with low vegetation index values (DE MEIRELES *et al.*, 2014). However, it is observed that the West and South Zones coasts present influence of the Atlantic Ocean, maintaining high maximum rainfall in five consecutive days (Fig. 5e) and just one day (Fig. 5f). RX5day presents values around 150 mm in these areas, and RX1day shows values around 100 mm. In addition to the significant rainfall volumes due to cold fronts and SACZ, the coastal portion of the city of Rio de Janeiro is influenced by post-frontal maritime circulation, which is intensified by the local topography. Therefore, precipitation of even moderate intensity can be recorded more frequently. It is noteworthy that, according to Data (2009), values of absolute extremes, such as the highest amount of precipitation in five days within a year (RX5day), often may be related to extreme events affecting human society and the natural environment.

Figure 5. Average fields for the period 1997-2021 of the precipitation extremes indicators: (a) R99p and (b) R95p (mm) in the first line; (c) R30mm and (d) R10mm (days) in the second line; (e) RX5day and (f) RX1day (mm) in the third line.



Source: Prepared by the authors

Thus, in the Municipality of Rio de Janeiro, areas are formed with significant variations of maximum and minimum values of the precipitation extreme indices analyzed. The maximum values of these indices are generally influenced by the humidity resulting from the concentration of vegetation and by the influence of water bodies, especially the Atlantic Ocean. Areas favoring moisture from both sources tend to have maximum precipitation, with values above 100 mm in 1 day in the West Zone and close to the Tijuca Massif. The passage of Frontal Systems (FSs), establishment of the SACZ, occurrence of Mesoscale Convective Systems (MCSs), and maritime circulation interact with the orography of the entire State of Rio de Janeiro, producing spatial irregularities in the precipitation field (LUIZ-SILVA *et al*., 2014). Furthermore, the heat islands in the city generate relatively lower pressures that facilitate the convergence of humidity over the city, favoring more intense rainfall.

Consequently, the climatological pattern seen in precipitation extremes within Rio de Janeiro is predominantly shaped by the interplay of local topography, surrounding vegetation, the dynamics of passing weather systems, and the impact of the Atlantic Ocean and Guanabara Bay. This expansion has resulted in a dense concentration of population and infrastructure in areas prone to floods and landslides, such as those situated between hills and coastal areas, as well as near lagoons and bays (ABELHEIRA *et al*., 2016).

Consequently, the Tijuca Massif, which records the maximum values for most of the indices in this study, exhibits significant vulnerability. A study conducted by Silva *et al*. (2020), highlighted that urbanization in the vicinity of the Tijuca Massif is associated with significant environmental impacts, including deforestation, biodiversity loss, and increased vulnerability to natural disasters. Therefore, it is crucial to implement public policies that promote sustainable urban development and conservation of natural resources.

According to Peterson (2001), time series of the indicators can be used between and used by both modelling groups and climate monitoring centers. Global datasets of unambiguously defined indicators could also provide the baseline data for evaluating climate change scenarios in the future.

Thus, studies using climatic indicators, particularly precipitation in Rio de Janeiro, provide a fundamental basis for the development of research aimed at understanding the climatic behavior in the city and assisting in the determination of strategies in various human activities

CONCLUSIONS

In this article, observed daily precipitation data from the Alerta Rio System are used to detect and analyze the precipitation behavior, thus contributing to studies of vulnerability and adaptation actions. The climatological data, annual precipitation, and rainy season distribution are analyzed.

Maximum central accumulated values of precipitation are always located close to the Tijuca Massif, recorded at the Alto da Boa Vista station and nearby (Rocinha station), and other secondary maximums, close to the Gericinó Massif, recorded at the Anchieta station. The climatologies of the precipitation extremes indicators (R95p, R99p, RX5day, RX1day, R10mm, and R30mm) in 1997-2021 are carried out.

For indicators of extreme annual rainfall (R99p) and annual heavy rainfall (R95p), it is observed that both have higher values close to the Tijuca Massif, with higher values of R99p (240 mm) and in the West Zone, close to the Grota Funda region, with values of 210 mm. Compared to these high values from these two rainfall stations, with the average accumulated precipitation shown in Figure 3ab, it is observed that the daily values follow the trend of high values in their monthly accumulated precipitation in the Tijuca Massif region and the West Zone, near the Sepetiba/Grota Funda region. In this way, it is noted that more intense events have exceeded the climatological average of events, with considerable rainfall volumes in short periods.

Regarding the mean field of R30mm and R10mm, it is noted that it maintains the same spatial configuration as the previous indices. The most significant spatial amplitudes of the indices occur for R95p and R99p, with maximums (minimums) over the Tijuca region, points in the West Zone, and on the coast of Sepetiba Bay (points close to the border with Baixada Fluminense).

As for the maximum annual precipitation in five consecutive days and the maximum annual precipitation in just one day (RX5day, RX1day), these are influenced by the humidity from the concentration of vegetation and forests and the influence of water bodies. Thus, areas favoring moisture from both sources tend to have higher maximum annual precipitation and extreme precipitation indicators. When these extreme indicators are compared with the climatology, it is noted that precipitations in one day and five consecutive days are higher than the average monthly, enhancing the scenario for extreme events.

Therefore, it is observed that there is an increase in frequency and intensity in most of the precipitation-related indices on this work. This reinforces that in large cities, there is a need to address the challenges brought by extreme events, as they significantly impact infrastructure, public services, and the population, especially those residing around massifs.

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