



Changes in rainfall rates and increased number of extreme rainfall events in Rio de Janeiro city

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Abstract

Increased temperature rates have the potential to change the rainfall regime in a given region, as well as to intensify its extreme events, which may lead to significant and negative socioeconomic and environmental impacts on urban populations. However, knowledge about the extent of changes in rainfall rates in Rio de Janeiro City (RJC) remains incipient; thus, it is necessary applying indices climate change to help better understanding this phenomenon. The aim of the current study is to investigate changes in rainfall distribution and increase in the number of extreme rainfall events in RJC. Daily rainfall data deriving from fifteen weather stations distributed in RJC were analyzed in the RclimDex software and Mann–Kendall test. The analysis has shown increased rainfall rates from the beginning of the series to approximately the first ten years of study. Total rainfall rate has decreased after this period. Rainfall intensity in almost all seasons has decreased after 2005; this outcome has indicated reduced annual rainfall rate and number of wet days. However, there was prevalence of positive trends in daily rainfall rates (R_{x1day}) and in total rainfall of five consecutive days (R_{x5day}). The increased number of extreme rainfall events in RJC can cause sudden inundations, floods, runoffs and river overflows with potential to cause landslides and human death due to irregular occupation of hills and slopes.

Keywords Daily rainfall rate · Trend · Extreme rainfall indices · Hillside landslide

1 Introduction

Rainfall is one of the most important meteorological variables used to help in maintaining the balance and conservation of biodiversity, agriculture, urban supply and life on the planet (Wanderley and Bunhak 2016). Pluviometric measurements play an essential role

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in gathering information about rainfall magnitude, frequency and distribution in space and time, since such a knowledge enables identifying regions susceptible to experience natural disasters such as floods, runoffs, mass wasting, among others. Rainfall intensity has been fluctuating in space and time over the years; the spatial scale of these events ranges from few meters to hundreds of kilometers; they are often called extreme climatic events. Changes in extreme weather and climate events comprise temperature and rainfall extremes often correlated to each other. It is of paramount importance to understand atmospheric teleconnection patterns and their underlying mechanisms to enable forecasting overall weather and extreme events, mainly if one takes into consideration that extreme events' features have changed due to anthropogenic climate changes underway (Boers et al. 2019).

Extreme rainfall events stand out among the most disturbing atmospheric phenomena, since they can have negative and significant socioeconomic and environmental impact on different populations (Liebmann et al. 2001). Scientific studies available in the literature highlight the application of climate change indices (Zhang et al. 2011) to identify changes in rainfall rates and extreme events; among them, one finds Halimatou et al. (2017), Shi et al. (2017), Shao et al. (2019), Terassi et al. (2022) and Carvalho and Wanderley (2022). Thus, coherent assessments of changes in rainfall rates should analyze extreme events of consecutive dry and wet days, daily rainfall rate higher than the 95th percentile and total rainfall rates (Casanueva et al. 2014). The number of records of these extreme events has increased worldwide and raised concern in the international community due to the magnitude of impacts caused by them, since they are harmful to the most vulnerable populations (Filho et al. 2016). Information about extreme events, such as changes in rainfall regime due climate change, is essential to enable public managers to take actions to manage water resources and mitigate the impacts of such events on urban and agricultural environments (Trenberth et al. 2015; Salviano et al. 2016).

Large urban centers, such as RJC, present variations in pluviometric distribution at temporal and spatial scale, throughout the year. The analysis of such a behavior makes it possible in assessing changes in rainfall regime and determining regions where this variable changes over time (Salviano et al. 2016). These changes can be associated with anthropic factors such as deforestation, rampant urbanization processes or intensification of natural phenomena (Salviano et al. 2016; Wanderley and Miguel 2019; Pereira et al. 2021). Historical accounts about RJC are often intermingled with the history of inundations and floods in the city since the sixteenth century. According to Maia (2012), heavy rainfall events in the city cause inundations, landslides, house and street flooding, trading losses, transportation issues, diseases, lack of food, among other issues that often lead to death of citizens. Floods and storms represent about of 70% of all-natural disasters caused by extreme weather events in Europe (Lechowska, 2018). In Brazil, intense rainfall events that triggered flash floods and landslides were responsible for 74% of the deaths related to natural disasters in the 1991–2010 period (Debertoli et al. 2017).

The catastrophe that hit the mountainous region of Rio de Janeiro State in January 2011 was classified as the most striking natural disaster in the state; it left thousands of individuals homeless and killed more than 1.000 people (Filho 2012). Although landslides and heavy rainfall events are common phenomena in this region, the catastrophic event was surprising due to its magnitude, range and destruction power. Rio de Janeiro City also experiences extreme events; 82% of heavy rainfall cases were classified as extreme events due to the significant damages they have caused to the population, such as death, injuries, material damage, mudslides, inundations, floods, landslides, among others (Dereczynski et al. 2017). It is essential in identifying locations presenting changes in rainfall distribution in order to estimate their likely harmful effects on socioeconomic activities, as well

as to help decision-makers in analyzing the risks in case action is not taken by management bodies. The hypothesis about the growing interest in investigating climate variability results from likely effects of human activities on the climate; these effects override natural climatic processes, which end up masking or intensifying their impact (Párraga 2003).

Some Brazilian regions recorded statistically significant trend to present changes in rainfall rates (Wanderley et al. 2013; Obregón et al. 2014). Some cases recorded changes in rainfall and temperature rates (Wanderley et al. 2014; Salviano et al. 2016).

In Northeast Brazil, there are changes toward a drier climate, especially in summer and autumn. In the Southern region, the climate is becoming wetter, with a reduction in consecutive dry days, especially in spring. In the Southeast Region extreme precipitation affects 11 million people on city of São Paulo, by without statistical significance of positive and negative precipitation extreme trends mostly in Southeast Region where is it located CRJ (Regoto et al. 2021).

Increased temperature is one of the main indicators used to investigate how anthropic actions can change the climate. Rio de Janeiro City recorded increase by 0.66 °C in minimum air temperature and by 1.21 °C in maximum air temperature in the last decades, as well as daily temperature increase of approximately 7 °C, due to degradation of Tijuca urban forest (Wanderley et al., 2019; Wanderley and Miguel 2019). However, studies and data about rainfall events and their move toward CRJ remain scarce in the literature. Thus, it is essential to conduct specific research focused on identifying any increase in the frequency and magnitude of extreme rainfall events. In light of the foregoing, the aim of the current study was to investigate changes in rainfall distribution and increase in the number of extreme rainfall events in RJC.

2 Materials and methods

2.1 Study area and data sources

The study was carried out in RJC, which has tropical, hot and humid climate with local variations, due to differences in altitude, vegetation and proximity to the Atlantic Ocean (Dereczynski et al. 2009). Its morphology comprises a mountainous geo-ecosystem surrounded by fluvial-marine plains interconnected by networks of channels that drain water into different terminal reservoirs (Coelho Netto 2005).

The rugged and extremely diverse topography of the investigated city stands out among its physical features; it is characterized by the formation of massifs, whose hillsides—originally covered by the Atlantic Forest—present high slope degree (Dereczynski et al. 2009). The main massifs in the city are Gericinó-Mendanha, to the North; Tijuca, to the East; and Pedra Branca, to the West (Coelho Netto 2005). However, plains are the most typical form of terrain in the city; they account for 64% of the local territory and their altitude variation does not exceed 20 m above sea level, on average. Approximately 20% of the total territorial area is located at altitude higher than 100 m. Rio de Janeiro is the second most populous city in Brazil, with approximately 7 million inhabitants (IBGE 2021).

Data analyzed in the current research referred to daily rainfall (0–23 h) series collected from 15 stations that make up the RJC's rainfall monitoring network, which derives from

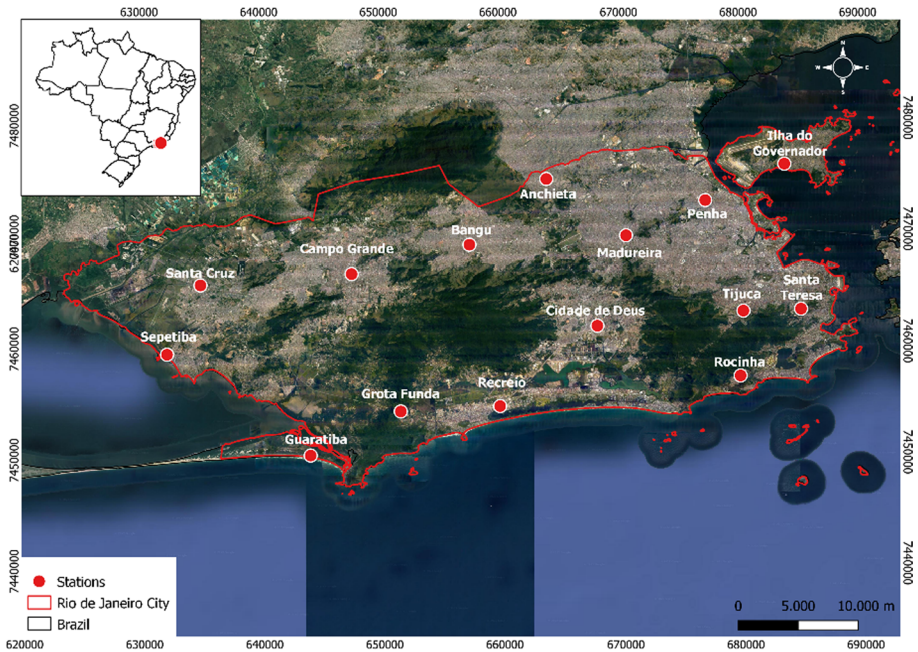


Fig. 1 Location of the pluviometric stations belonging to Sistema Alerta Rio used in the current study

Sistema Alerta Rio¹ (Rio Warning System), as shown in Fig. 1. These data are reliable, since they were subjected to quality control by Sistema Alerta Rio, which periodically calibrates and gives maintenance to its telemetric network. Even so, the pluviometric stations had failures of less than 2% in Anchieta (0,42%), Campo Grande (0,56%), Guaratiba (0,66), Ilha do Governador (1,95%) e Rocinha (0,51%).

Rainfall measurements are taken every 15 min by pluviometric stations belonging to Sistema Alerta Rio, which also analyzes the total daily rainfall rate. Total daily rainfall rates were analyzed to calculate climate change indices, based on ETCCDI (Expert Team on Climate Change Detection and Indices). Stations comprising historical rainfall series that did not present significant database flaws from 1997 to 2017 were taken into consideration to assure greater result reliability (Table 1).

Daily rainfall data were used to calculate climate change detection rates in RJC in the RCLimDex free software (version 1.3), which is available for download at the ETCCDMI² website. This software has a graphical interface capable of calculating 27 climatic indices; it enables disclosing extreme events, as well as monitoring and detecting climatic changes. The current study has used 7 of the 27 indices made available by the software (Zhang and Yang 2004), as shown in Table 2.

These indices were subjected to statistical analysis in the RCLimDex in software R (version 4.1.1; R Core Team 2022) in order to investigate likely trends and to measure changes in daily rainfall records over the years. All missing data were identified through value 99.9

¹ Available at: <http://alertario.rio.rj.gov.br/download/dados-pluviometricos>. Access on: January 22.nd, 2018.

² Available at: <http://etccdi.pacificclimate.org/software.shtml>. Access on: August 15 th, 2018.

Table 1 Geographic information about the stations used for analysis purposes

Stations	Latitude (°)	Longitude (°)	Altitude (m)
Anchieta	−22.82694	−43.40333	50
Bangu	−22.88028	−43.46583	15
Campo Grande	−22.90361	−43.56194	30
Grota Funda	−23.01444	−43.52139	11
Guaratiba	−23.05028	−43.59472	0
Ilha do Governador	−22.81806	−43.21028	0
Cidade de Deus	−22.94556	−43.36278	15
Madureira	−22.87333	−43.33889	45
Penha	−22.84444	−43.27528	111
Recreio	−23.01000	−43.44056	10
Rocinha	−22.98583	−43.24500	160
Santa Cruz	−22.90944	−43.68444	15
Santa Teresa	−22.93167	−43.19639	170
Sepetiba	−22.96889	−43.71167	62
Tijuca	−22.93194	−43.22167	340

Table 2 Index provided by the ETCCDMI platform for rainfall analysis purposes

Indices	Description	Unit
RX1day	Monthly maximum 1-day rainfall	mm
RX5day	Monthly maximum consecutive 5-day rainfall	mm
SDII	Annual total rainfall divided by the number of wet days (defined as PRCP > = 1.0 mm) throughout the year	mmday ^{−1}
CDD	Maximum number of consecutive days with RR < 1 mm	days
CWD	Maximum number of consecutive days with RR > = 1 mm	days
R99p	Total annual PRCP when RR > 99 th percentile	mm
PRCPTOT	Total annual PRCP in wet days (RR > = 1 mm)	mm

at the time the software was running. Data must be arranged in file comprising columns corresponding to year, month, day and rainfall volume (separated by one, or more, spaces), in chronological order. The software has calculated climate change indices and provided statistical information—such as linear trend calculated based on the least squares method, statistical significance level of the trend (*p* value) at 95%, coefficient of determination (*r*²), standard error of the estimate—and annual series graphs, for each calculated index.

The application of statistical tests to check the statistical significance of slope coefficients (slope of the line) is an important stage adopted to check the adequacy of linear regression models. The current study has used the Student’s *t* statistical test (Triola 2005) to assess whether the slope of the line was significantly different from zero. Possible climatic trends were indicated as indices presenting linear trend (positive or negative) higher than the standard error of the estimate and statistical significance at *t*₉₅, which corresponds to 95% statistical significance (*p* < 0.05) in the Student’s *t* test conducted in the RCLimDex software.

The climate change indices were subject the Mann–Kendall (MK) test (Mann 1945; Kendall 1975). The test presents as null hypothesis (*H*₀) the absence of trend in the

Table 3 Minimum and Maximum values

Stations	Minimum	Maximum	Medium	Standard deviation
Anchieta	645.40	1607.80	1117.51	267.61
Bangu	696.20	1369.00	1005.12	209.55
Campo Grande	679.80	1638.00	1052.20	251.34
Cidade de Deus	684.20	1682.40	1048.17	279.80
Grota Funda	902.00	2058.60	1363.72	319.86
Guaratiba	660.40	1914.70	1050.54	281.10
Ilha do Governador	520.00	1796.80	1055.22	307.78
Madureira	695.60	1495.20	1015.05	241.82
Penha	598.50	1363.40	877.70	219.20
Recreio	634.60	1588.80	1087.98	264.54
Rocinha	883.10	2519.20	1667.41	444.71
Santa Cruz	771.50	1740.00	1177.97	229.51
Santa Teresa	722.60	2022.20	1274.31	363.16
Sepetiba	468.20	1641.40	1089.59	327.77
Tijuca (Sumaré)	852.80	2580.90	1455.27	445.05

Mean and standard deviation (mm) recorded for the total annual rainfall rate in Rio de Janeiro City

population. To test the statistical significance of S for the alternative hypothesis (H_1), which express presence of trend, one must use a bilateral test to H_1 , by which the alternative hypothesis may be rejected for large values of Z -test. One may take into account the Z -test analysis to accept or reject the null hypothesis (H_0) of trend absence to confirm the hypothesis of data stability, or to reject in favor of the alternative hypothesis (H_1) to admit presence of trend in the data series. The sign of the Test- Z statistics can indicate if trend is crescent ($Z > 0$) or decrescent ($Z < 0$). In a bilateral test for trend, H_1 must be accepted if $|Z| \geq Z_{\alpha/2}$, where $Z_{\alpha/2}$ is obtained in table of standardized normal distribution. The level of significance is 0.05, which interval of tabled Z is ± 1.96 . The MK test was done in R software, by Trend package (Pohlert 2020).

3 Results and discussion

The local topography influences the spatial–temporal rainfall distribution in RJC; the highest total annual rainfall rate was observed in the highest altitude regions, whereas the lowest one was observed in the coastal and lowland regions (Table 3). Local orography is a key modulator of the spatiotemporal connections and substantially enhances the probability of co-occurrence of extreme precipitation events even for distant locations (Mastrantonas et al. 2021). The same influence was observed in the distribution of total maximum and minimum rainfall rates in the city. The highest minimum values recorded for rainfall distribution ranged from 468.20 mm to 902.00 mm, whereas the maximum values ranged from 1363.40 mm to 2580.90 mm.

Based on the comparison between the current results and those of previous studies carried out by Dereczynski et al. (2009) and Silva and Dereczynski (2014), there was increase in total maximum rainfall rates in RJC. The increase recorded for Tijuca station reached 11.7%; rainfall rates increased from 2.200 mm to 2.580 mm. The Northern region of the

city recorded the lowest total rainfall rates, although it presented the highest increase in total maximum rainfall rates in Penha neighborhood—values increased by 56.71% and reached 1,363.4 mm. Similar increase was also observed in the Western side of the city; Bangu neighborhood presented rainfall increase close to 40%—from 991 mm to 1,369 mm. Rainfall rates ranging from 1,000 mm to 1,200 mm prevailed in the Western side of the city. Avila et al. (2016) show positive annual and seasonal precipitation trends during all seasons except for the winter season in the mountainous regions, specifically the Rio de Janeiro.

Rainfall events in RJC are influenced by the rugged terrain, preserved Atlantic Forest areas and several climatic factors. These features account for the local diversity in the rainfall regime, mainly due to influence of atmospheric and oceanic phenomena that happen at large scale and lead to concentrated rainfall events in specific times of the year (Siciliano et al. 2018). The irregular and mountainous terrain deriving from Serra do Mar influences rainfall distribution in RJC. Mastrantonas et al. (2021) show the influence of orography on precipitation intensity.

The rugged terrain of the city is represented by large geographic massifs inserted in the urban zone, which are fundamental physical elements in rainfall standardization processes taking place in specific regions of it. There is a strong correlation between the slope degree and the landslide occurrence so that the weights are increased with a greater degree of the slope apart from the slope above fifty degrees (Varnes, 1984). Proximity of the coastal region and the presence of the Atlantic Forest help in increasing rainfall levels in the Southern coast of Rio de Janeiro City, whereas distancing from coastal areas toward inland tends to reduce mean rainfall levels (Wanderley and Miguel 2019).

Proximity to the coastal region can be seen in the position of Grota Funda and Rocinha, downwind Pedra Branca and Tijuca massifs, where the humid air coming from the ocean condenses as it rises into the atmosphere and causes the highest total rainfall rates in RJC. The high rainfall volume in RJC results from orographic effect. The rising air cools and condenses, and forms clouds and rain, which produce maximum rainfalls downwind the slopes, as the ones observed in Rocinha and Tijuca neighborhoods.

Rainfall rates in lowland regions of RJC are lower than the total values observed by the massifs, with emphasis on the lowest total rainfall rates observed in the Northern region of the city, where Madureira and Penha neighborhoods are located in. The air after humidity gets reduced; air descends the slopes the massifs, gets compressed and heated, which inhibits the formation of clouds and consequently, reduces the rainfall leeward the massifs. This phenomenon explains the lower mean total rainfall rates observed in Bangu, Madureira and Penha neighborhoods. Despite the increased maximum extreme rainfall events in RJC, adjustments in the PRCPTOT index for the analyzed neighborhoods have shown trend to total annual rainfall reduction in Campo Grande, Cidade de Deus, Grota Funda, Guaratiba, Ilha do Governador, Madureira, Penha, Santa Cruz, Santa Teresa, Sepetiba and Tijuca (Fig. 2A). However, only Sepetiba recorded statistically significant trend and linear trend to PRCPTOT reduction. Linear adjustment was only positive in Anchieta, Bangu, Recreio and Rocinha. The majority of precipitation-related indexes present positive trends, especially in the extreme precipitation indexes. The annual total precipitation in wet days (PRCPTOT) largely increased in the mountainous regions, specifically the Rio de Janeiro, with positive trends in ~60% (Avila et al. 2016).

Analysis has shown changes in the total annual rainfall rate in RJC. All stations have shown increased PRCPTOT from the beginning of the series to approximately the first ten years of study. After this period, there was total rainfall rate reduction. The extreme precipitation and temperature events increased in the second half of the twentieth century

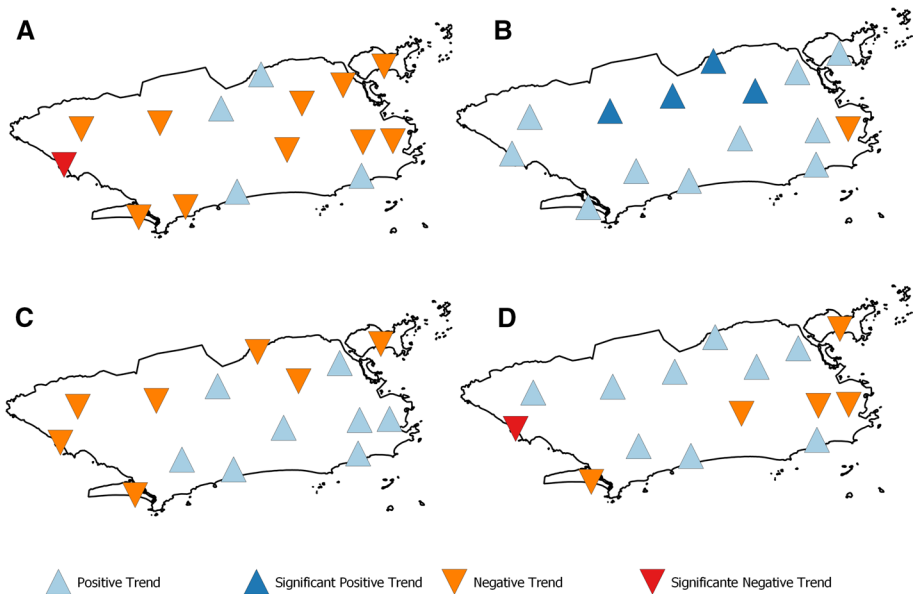


Fig. 2 Climate change indices trend in Rio de Janeiro City: **a** PRCPTOT, **b** CDD, **c** CDW and **d** DSII

whit increasing occurrences of extremely hot and humid weather in Africa, Asia, Australia, South and North America (Donat et al. 2016; Zhou et al. 2016; Raymond et al. 2020). PRCPTOT has shown rainfall change identification pattern. Rocinha and Grota Funda stations recorded changes in rainfall rates in 2006, whereas the other stations recorded changes in 2007. The management of water resources of a region helps in identifying the regions reflecting the similar characteristics which could be useful in designing structures and planning hydrological (Goyal et al. 2019). PRCPTOT has shown increased rainfall rates from 1997 to 2006 or 2007. After 2007, total annual rainfall rates have decreased in all stations until 2017. This decrease may have resulted from the positive surface-pressure trend in the South Atlantic Ocean, which is influenced by equatorial Pacific cooling conditions likely linked to changes in Pacific Decadal Oscillation (Wanderley and Bunhak 2016). The intensified pressure system over the South Atlantic Ocean hinders the migration of the subtropical low-pressure system and reduces rainfall rates in Southeastern Brazil (Clem and Fogt 2015). Another factor that may have contributed to reduce total rainfall rates in RJC lies on changes in Northeast Trade winds, which often decrease rainfall rates in South America when they are weak (Marengo and Espinoza 2016). Light winds reduce the amount of water vapor directed to the Brazilian Southern region. Moisture advection, cold front intensification near Rio de Janeiro State and South Atlantic Convergence Zone formation are limited (Raia and Cavalcanti 2008).

The total number of consecutive days without (CDD—Fig. 2B) and with rain (CWD—Fig. 2C) was analyzed to help better understand how rainfall rates have changed in RJC. Positive trends and linear trend toward CDD were observed in almost all stations, in almost all analyzed neighborhoods; Santa Teresa was the only exception. Statistically significant trends were observed in Anchieta, Bangu, Campo Grande and Madureira neighborhoods. CDD ranged from 15 to 60 consecutive days without rain throughout the analyzed period. Neighborhoods close to the coast recorded shorter CDD (from 25 to 35 days) than that

observed in the most distant neighborhoods (from 35 to 60 days). According to Luiz-Silva and Oscar-Júnior (2022), the maximum number of consecutive dry days shows a gradient from the coast (about 30 days) to the State's interior (around 50 days). Coastal neighborhoods present sea breezes. Southern winds carry moisture from the ocean toward the continent and increase convergence on the coast; this phenomenon generates upward movement of water vapor and enables moisture to rise into the lower atmosphere. Carvalho and Wanderley (2022) showed that for the last decades, the total annual precipitation and consecutive wet days have decreased, which is mainly due to increase on consecutive dry days.

RJC's orography guides moisture-flow rise, as well as the condensation and formation of clouds that continuously precipitate over the coastline (Silva and Dereczynski 2014). The most distant regions of the coast are not directly influenced by this phenomenon since the local topography works as barrier for the penetration of humid winds coming from the Atlantic Ocean. Therefore, lower CDD values are observed on the coastline, whereas the inshore region experiences rainfall events more often, even if at low intensity. Increased number of CDDs in recent years has confirmed results recorded for PRCPTOT, which showed reduced rainfall rates in almost all analyzed neighborhoods. However, CDD has shown oscillations; it recorded maximum values before 2005, which decreased by 2010 and then increased again until 2017. Increased CDD directly affects several economy sectors such as agriculture, power generation, urban supply, among others.

Results recorded for CWD confirmed the ones recorded based on PRCPTOT and CDD indices. CWD presented the same oscillation observed for PRCPTOT. All analyzed stations recorded increased CWD until 2008. Then, values kept on dropping until 2017. This phenomenon had direct impact on total monthly and annual rainfall rates in RJC. CWD presented the same influence observed for places close to the Atlantic Ocean and Guanabara bay, which was also seen in CDD. CWD reduction observed from 2008 in stations located in these regions was milder than that observed in neighborhoods farther from the coastal region. This outcome has evidenced the influence of local systems on rainfall distribution in Rio de Janeiro City.

Changes in CDD and CWD were ratified by SDII, since this index is used to check daily rainfall intensity based on the number of wet days (Fig. 2D). SDII has shown negative trend in Cidade de Deus, Guaratiba, Ilha do Governador, Santa Teresa, Tijuca and Sepetiba. Sepetiba presented statistically significant SDII. The Western zone of RJC presented the greatest change in rainfall distribution; this zone has the second largest population and the three most populous neighborhoods of RJC, namely Campo Grande, Bangu and Santa Cruz. Madureira, Santa Cruz and Grota Funda have shown trend increase in SDII; however, SDII has decreased after 2005 in almost all neighborhoods, as previously observed for PRCPTOT and CWD; this outcome has indicated reduced annual rainfall rate and number of wet days. Similar results were found by Carvalho and Wanderley (2022) which SDII also showed reduction trend and the decrease in annual precipitation is causing the SDII to decrease, as the number of consecutive wet days is also decreasing. The reduction in rainfall in the CRJ exacerbates the problem experienced in recent years of urban supply, which was aggravated by the 2014 water crisis in Southeast Brazil. PRCPTOT and CWD index results have justified results presented by SDII. Decreased rainfall rates also led to reduced number of wet days—this association reflects on SDII.

Rx1day (Fig. 3A) and Rx5day (Fig. 3B) indices of extreme rainfall events were also analyzed given the identification of changes in rainfall distribution in RJC; these indices express the maximum rainfall amount recorded in 1 and 5 consecutive days. Although the total annual rainfall rate has decreased in RJC. Dereczynski et al. (2017) have indicated that the number of extreme rainfall events in the city has increased. Similar results are

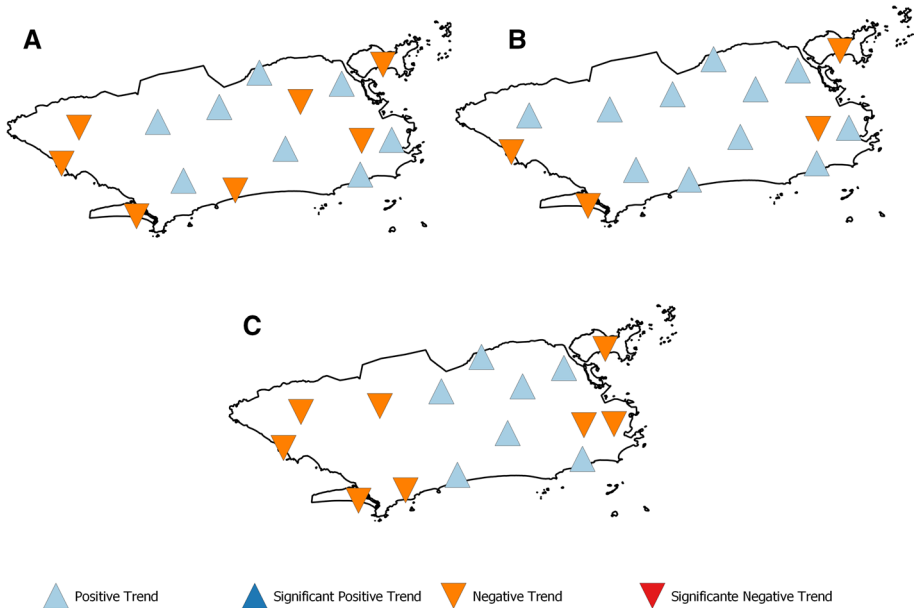


Fig. 3 Climate change indices trend in Rio de Janeiro City: **a** Rx1day, **b** Rx5day, **c** R99p

found for daily thresholds of Rx1day and Rx5day, with positive trends in the majority of stations by Avila et al. (2016). The Rx1day index reflects the highest daily rainfall magnitude recorded throughout the year and indicates the rainfall intensity capable of causing sudden inundations, floods, runoffs and mudflows. Whereas the Rx5day index shows the potential incidence of landslides caused by waterlogged soil resulting from infiltration caused by the rain. Maximum daily precipitation data are important to assessments of flood risk (Westra et al. 2013). The occurrence of mass movements observed in the RJC is also a consequence of the natural instability of the environment together with the occupation model, which involves deforestation and drastic modifications of the hillside profile. In general, the hazardous areas encompass low-income populations that occupy parts of the hillsides with pronounced slopes and without appropriate care (Lorentz et al. 2016).

The analysis of extreme rainfall indices has shown linear trend of Rx1day decrease in 6 of the 15 analyzed stations, namely Guaratiba, Ilha do Governador, Recreio, Santa Cruz, Sepetiba and Tijuca; as well as of Rx1day increase in the remaining stations, namely Anchieta, Bangu, Campo Grande, Cidade de Deus, Grota Funda, Madureira, Penha, Rocinha and Santa Teresa. None of the analyzed stations recorded statistically significant Rx1day index. Increased Rx1day was observed in neighborhoods subjected to rainfall-associated disasters, such as Rocinha. The physical and geographic position of Rocinha neighborhood often leads to mass movements and human death, since Rocinha accounts for the highest total rainfall rate in RJC. Landslides are the most common environmental accidents and have caused the most deaths; one example is the incident that occurred in the mountainous region of the state of Rio de Janeiro (Brazil) in January 2011 (Lorentz et al. 2016).

Part of the rainfall-related disasters observed in RJC is associated with irregular occupation of city slopes and hills in Tijuca massif region. According to D'Orsi et al. (2016), approximately 90% of the 50 largest geological-geotechnical accidents recorded in RJC,

from 1966 to 2016, took place in Tijuca massif region. According to Pereira et al. (2021), the orography of the Tijuca massif is a determining factor for natural disaster related to precipitation in RJC. The collapse of two buildings in Muzema community was the last major disaster seen in Tijuca massif; it resulted from high rainfall rates recorded in the region in April 2019, which killed 24 citizens. April 2019 has also recorded the highest rainfall rate of the last 22 years; 212 mm rain was recorded within four hours on the same day, when 7 and 3 citizens died in Southern and Western RJC, respectively (Araújo 2019). According to Marengo et al. (2021), regions already considered to be of high vulnerability will become even more vulnerable, such as the mountainous region of Rio de Janeiro. The results of Debortoli (2017) indicate a large increase in Brazil's vulnerability to landslides and flash floods in the context of climate change.

The highest daily rainfall rate (Rx1day) recorded in the analyzed period was recorded for Tijuca neighborhood, in 1998 (250 mm/day). Climate projections for the rest of the century show continued intensification of daily precipitation extremes. Increases in total and extreme precipitation in dry regions are linearly related to the model-specific global temperature change, so that the spread in projected global warming partly explains the spread in precipitation intensification in these regions by the late twenty-first century. The temperature increase has implications for the risk of flooding, particularly for the world's dry regions (Donat et al. 2016). Zhang e Villarini (2017). Thus, the temperature increase of 2 °C intensification the annual frequency of heavy precipitation across the globe.

The total daily rainfall rate recorded for RJC in 2010 was the highest in 44 years. Rainfall events in RJC have caused the death of 96 citizens and landslides in several neighborhoods of the city. These rainfall events resulted from the combination of a cold front to high temperatures observed in the city; it was similar to the one observed in 2013. The combination of heat, cold front and local geomorphological features has led to rainfall rates higher than 120 mm. Heavy precipitation exerts strong societal and economic impacts, including flooding, and these precipitation events are projected to increase under anthropogenic warming (Zhang et al. 2017).

Total rainfall for five consecutive days (Rx5day) measured in Rocinha neighborhood recorded values above 400 mm. Rx5day index presented features similar to those of the Rx1day index, as well as the prevalence of positive trends for indexes (Fig. 3B). Only three neighborhoods have shown negative trends, namely Madureira, Recreio dos Bandeirantes and Santa Cruz. Rx5day is the indicator used to investigate the likelihood of landslide event occurrence; rainfall accumulation in five days can have significant impact on society, even at low rainfall intensity level, because soaked soil tends to break and lead to mass movements. This phenomenon can be worsened due to irregular occupation of hills and slopes. The vulnerability and residual risk are an important factors in determining overall vulnerability to flood hazards (Scolobig et al. 2012; Oulahen et al. 2015)

Rainfall events higher than the 99th percentile were used to help better understand the increased frequency of extremely rare events in RJC. R99p has shown alternation of positive and negative trend (Fig. 3C). Extreme event as a rare and infrequent occurrence at a specific time and site. It is a low-probability event corresponding to a certain climate variable from either of the tails of that variable's probability density function (Seneviratne et al. 2012). Specifically, we usually define extreme events as those that occur in the highest or lowest 5% or 10% (Seneviratne et al., 2012; Vincent et al., 2018).

There was upward trend in 6 stations (Bangu, Cidade de Deus, Grota Funda, Penha, Sepetiba and Tijuca). Whereas the remaining ones presented negative trend—none of them has shown statistically significant values. Anchieta, Guaratiba, Madureira and Santa Teresa stations recorded increased number of extremely humid days in 2008–2017, whereas the

other stations recorded decrease in this parameter. Just as observed for the other analyzed indices, R99p has shown similar trend results for stations geographically close to each other. These results highlight the relevance of local factors—such as altitude of the analyzed stations, and their proximity to Tijuca forest and to the oceanic region—for rainfall distribution in RJC.

Madureira station has shown increased R99p, and this finding was ratified by increased Rx1day. Although Rx5day has decreased, changes in rainfall intensity and magnitude in this RJC region happen on a daily basis. Rainfall intensity and magnitude increase in stations close to the coastal region happen at scale greater than one day due to location influence. Thus, changes in rainfall rates in RJC do not only result from synoptic systems, but also from the geo-ecological and socioeconomic features of RJC. The public risk perception must be in the center of attention to assure an improvement in the effectiveness of flood risk management, because the authorities' lack of understanding the society is the reason for failure in the politics of flood risk management (Kellens et al. 2011; Bradford et al. 2012).

4 Conclusion

The current study has analyzed changes in rainfall distribution and identified extreme rainfall events based on the application of climate change indices in RJC. Results have shown changes in annual rainfall distribution (PRCPTOT), which increased from 1997 to 2006–2007 and decreased after this period until 2017, and most of the RJC shows a trend to reduce precipitation. CWD has shown the same oscillation as PRCPTOT. Decreased rainfall rates have led to increased CDD, mainly in the last herein analyzed decade with almost all stations showing a negative trend and statistical significance. There was SDII decrease after 2005, and it indicated decreased PRCPTOT and CWD. Rx1day and Rx5day have shown prevalence of positive trends. This increase may be indicative of the increase in precipitation-related disasters in the RJC. The increase in the number of extreme rainfall events in RJC is observed in only part of the city (R99p). The region of the city that shows this increase is the one that has the highest number of extreme rainfall events.

Some locations in RJC showed a pattern for the reduction of PRCPTOT, CWD and SDII and increase in CDD showing the pattern of rain distribution in the city in meso- and macro-scale. It was also observed that the rainfall distribution in RJC is influenced by local factors such as altitude of the analyzed stations, and their proximity to Tijuca forest and to the oceanic region. Stations close to the coastal region presented increased rainfall intensity and magnitude. Disasters associated with rainfall events in RJC resulted from the irregular occupation of hills and slopes in the city.

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Declarations

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