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Papers

Rainfall in Metropolitan Region of Rio de Janeiro: characterization, extreme events, and trends

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Abstract

Physical-natural, economic, social, and spatial factors constitute processes that, when associated, form and give meaning to the spatial complexity of the Metropolitan Region of Rio de Janeiro, configuring it as a susceptible and vulnerable space to the occurrence of climate exceptionalities. Thus, this paper aims to analyze the spatial and temporal variability of extreme precipitation events in the Metropolitan Region of Rio de Janeiro. Daily data regarding 48 rainfall stations were used: 40 stations in a series from 2008 to 2019 and 8 stations concerning the period between 1970 and 2019. The percentile technique was used to establish standard years (1, 10, 90, and 99 percentile) and to define the extremes (99th percentile). The R software was used to perform autocorrelation tests, to extract the RX1Day and RX5Day indices, and to perform the Mann-Kendall, Pettitt, and Sen's Slope tests. The influence of altitude, slope orientation, and sea level was verified on the spatial distribution of precipitation and extreme events. The years with the highest occurrence of extremes, as well as concentrated and persistent events of greater magnitude, are identified as rainy and extremely rainy, namely 1988 e 2009. 90% of extremes occur in the rainy season, especially during December, January, and March. However, April manifests extremes of a greater magnitude. Four stations with negative and two with positive trends were identified.

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INTRODUCTION

Environmental issues triggered by weather phenomena are frequent in the Metropolitan Region of Rio de Janeiro (MRRJ), Rio de Janeiro, southeastern Brazil, especially those related to precipitation events (ARMOND; SANT'ANNA NETO, 2019; BRANDÃO, 1987, 2003; GONÇALVES, 2003; GOUDARD, 2019; MENDONÇA, 2003; NEIVA et al., 2017; SANT'ANNA NETO, 2011). Considering a climate change scenario, two aspects are particularly critical in MRRJ: sea level rise and an increase in the occurrence of extreme events such as intense winds, storm waves, torrential rains and longer droughts (INPE, 2011). With the imminent intensification of these effects, a worldwide scientific effort took place in order to understand the variability and trends of these phenomena as impacts affect unequal spaces and, therefore, are experienced in different ways (CONTI, 1975; GOUDARD, 2019; MONTEIRO, 1971, 1999; STEPHENSON, 2008 apud ARMOND, 2018).

The Intergovernmental Panel on Climate Change (IPCC) defines extreme events as "an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations" (IPCC, 2021). In addition to percentiles, 1-day and 5-day maximum rainfall indices from the Expert Team on Climate Change Detection and Indices (ETCCDI) are widely used in climate extremes studies (ARMOND, 2018; BENAVIDES et al., 2007; DOS SANTOS et al., 2006; REBELLO et al., 2008; GOUDARD, 2019; SILVA; DERECZYNSKI, 2014; ZHANG et al, 2004). Furthermore, the applicability of ETCCDI is also found in trend studies as it enables the measurement and characterization of climate variability in order to detect changes in climate.

Considering Rio de Janeiro, extreme precipitation events studies are recurrent in the literature, with a preponderance of researches regarding Rio de Janeiro state (ARMOND, 2018; DERECZYNSKI et al., 2013; SILVA; DERECZYNSKI, 2014) and its capital (ARANHA; BRANDÃO, 2007; ARMOND, 2014; ARMOND; SANT'ANNA NETO, 2017, 2019; DERECZYNSKI et al., 2009), while specific papers concerning the Metropolitan Region remain with little expression in the bibliography (MOURA et al., 2013).

Thus, the objective of this manuscript is to analyze the spatial and temporal variability of extreme precipitation events in the Metropolitan Region of Rio de Janeiro. To do that, a climate dynamics characterization was produced considering the spatial and temporal variability of precipitation in the MRRJ, as well as an extreme rainfall events characterization with the intent to identify magnitude, frequency and trends related to the occurrence of these events.

An intense vulnerability to the occurrence of exceptionalities (ABREU, 1987; CONTI, 1975; CRUZ, 1975) is shaped on the MRRJ through the orographic and hydrological complexity in association with the regional atmospheric circulation, that is, the transition between atmospheric systems (SANTANNA NETO, 2005). It is noted that this scenario singularizes the spatial aspect of precipitation dynamics in the region. Therefore, it is necessary to observe the variability and trends in magnitude, frequency and extent of precipitation events, considering the multiplicity of the spatial dynamics aforementioned, in order to understand the possible climate change impacts on different scales.

THEORETICAL FRAMEWORK

Geographical Climatology (MONTEIRO, 1971; 1999), as well as Climate Geography (SANT'ANNA NETO, 2001, 2008), are configured as landmarks in geographic science as they incorporate space as a central category. These theoretical matrices support the idea of space beyond a receptacle of meteorological and climatic phenomena, but as a form of "establishing interrelationships between phenomena, dynamics and processes with a space that, in this approach, has a relative existence as its reason for being" (ARMOND, 2018, p. 96). Thus, relative space is an approach for understanding climate phenomena – in the present study, extreme rainfall events – considering that the existence of both space and climate extremes are related to each other (HARVEY, 2015).

Furthermore, Geographical Climatology offers central concepts that lead this investigation. One of those is rhythm, understood as the usual succession of types of weather (MONTEIRO, 1971) that expresses the reality of regional atmospheric systems and, within relative space, builds a totalizing perspective on phenomena based on the relationship between atmospheric circulation dynamics and space, especially regarding geographic factors (NIMER, 1979).

Associated with that, the concept of variability allows the observation of variations of magnitude, frequency and extent of climatic events (NASCIMENTO JUNIOR, 2013). When associated with climatic rhythm, it is possible to identify and comprehend the fluctuation of climatic exceptionalities, as the usual establishes what exceptionalities are (MONTEIRO, 1971).

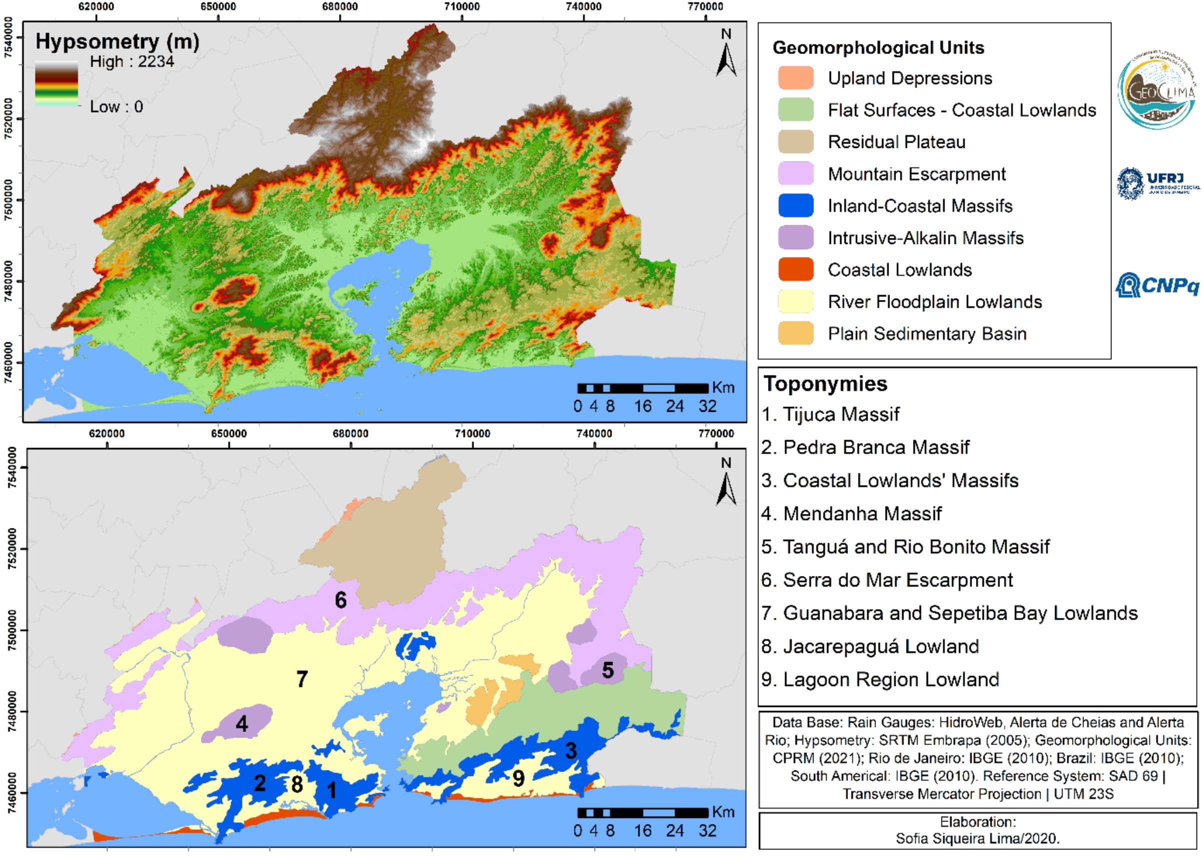
Regarding extreme events, the main focus of this research, these are approached by considering the accumulated precipitation value above a certain threshold or distant from the usual pattern (ARMOND; SANT'ANNA NETO, 2017; MENDONÇA; ROSEGHINI, 2012 apud GOUDARD, 2019; MONTEIRO, 1991; NASCIMENTO JUNIOR, 2013).

STUDY AREA

The Metropolitan Region of Rio de Janeiro was institutionalized in 1974, but it was in 2018 that its current legal composition was formed with 22 municipalities. The different cycles of occupation, which began in the metropolitan capital, marked the urban expansion of the MRRJ in the gradual growth to neighboring municipalities, consolidating the metropolization of the region (ABREU, 1987).

In order to understand precipitation variability and, consequently, the extreme events in the MRRJ, it is worth emphasizing the physical-natural aspects that dictate the spatialization of this phenomenon. The key to this apprehension is the interaction of geographic factors – maritime and landform, considering the altitude and slope orientation – among themselves and in conjunction with dynamic factors – the regional atmospheric dynamics.

Figure 1 – Hypsometry map (upper) and geomorphological units map (lower) of the Metropolitan Region of Rio de Janeiro.



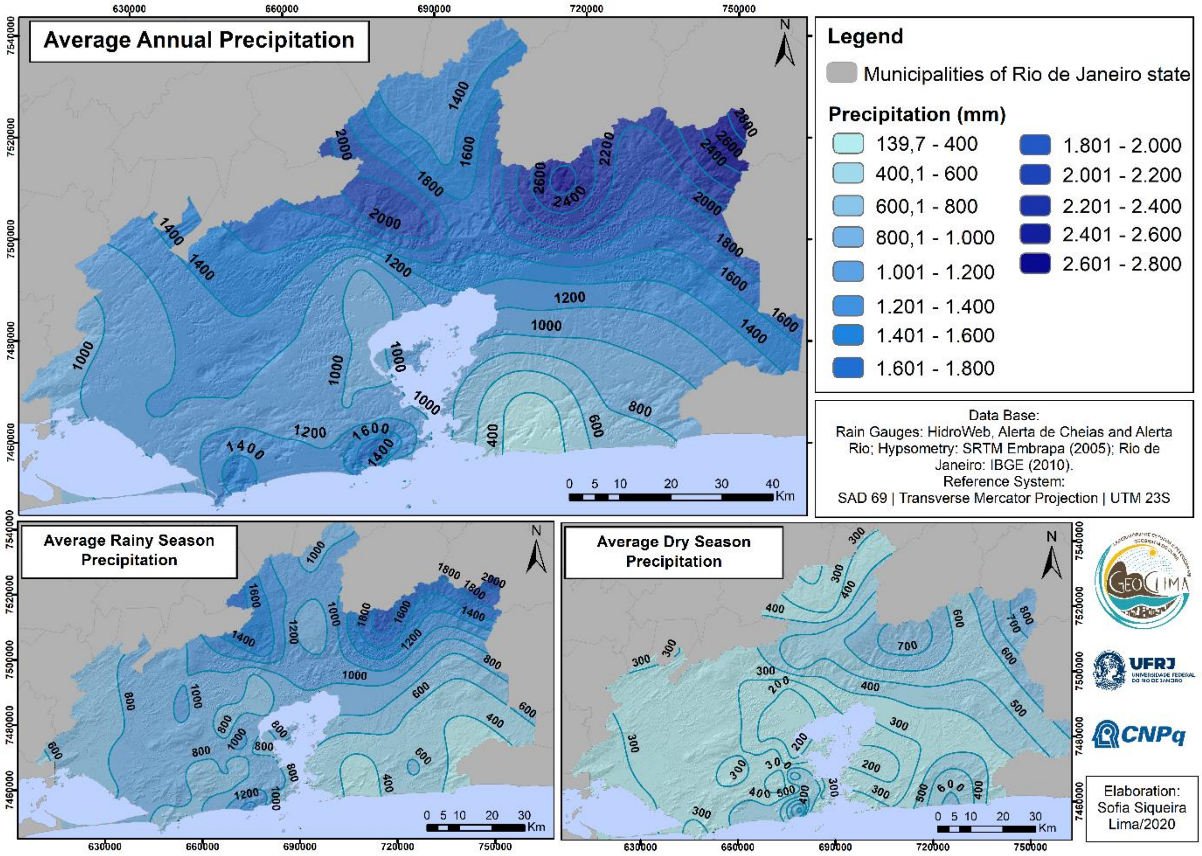
Source: The authors (2021).

The presence of lowlands, massifs and mountains, the Guanabara and Sepetiba bays and the extensive longitudinal coastline compose the orographic and hydrological complexity of the region, reflected in the regional hypsometry that reaches more than 2,000 meters in altitude. The longitudinal arrangement of the MRRJ provides an incursion of humidity from the ocean to the continent — generally from the southern quadrant originating in frontal systems (ARMOND, 2014; NIMER, 1979) and the local breeze system (DERECZYNSKI et al., 2009). The abrupt ruptures of altimetric quotas and gradient of slopes favor the orographic ascent of air that causes its adiabatic cooling and, considering the high relative humidity and speed of the ascension, can create convective conditions for rain.

In this context, the windward side of Escarpa Serrana (6) and the Massifs (1, 2 and 4), are identified as the highest average values of precipitation, favored by the south quadrant winds, usual in the MRRJ due to its longitudinal coastal extension that provides an incursion of humidity due to the dominance of the breeze and frontal systems (DERECZYNSKI et al., 2009). This dynamic occurs in the Metropolitan East, with average annual rainfall between 1,250 and 2,600 mm, and in Rio de Janeiro, to the windward side of the Pedra Branca and the Tijuca Massifs, with averages between 1,200 and 1,800 mm (Figure 2) .

In lowland areas (Figure 1), to the leeward of high topographies, there is a gradual decrease in rainfall due to the rain shadow effect. The Guanabara and Sepetiba lowlands stand out, with annual rainfall between 9,00 and 1,200 mm, with averages below 1000 mm at the Penha (28) and Piedade (29) stations in Rio de Janeiro city (Figure 2).

Figure 2 – Spatial distribution of average rainfall in the Metropolitan Region of Rio de Janeiro (1970 – 2020).



Source: The authors (2021).

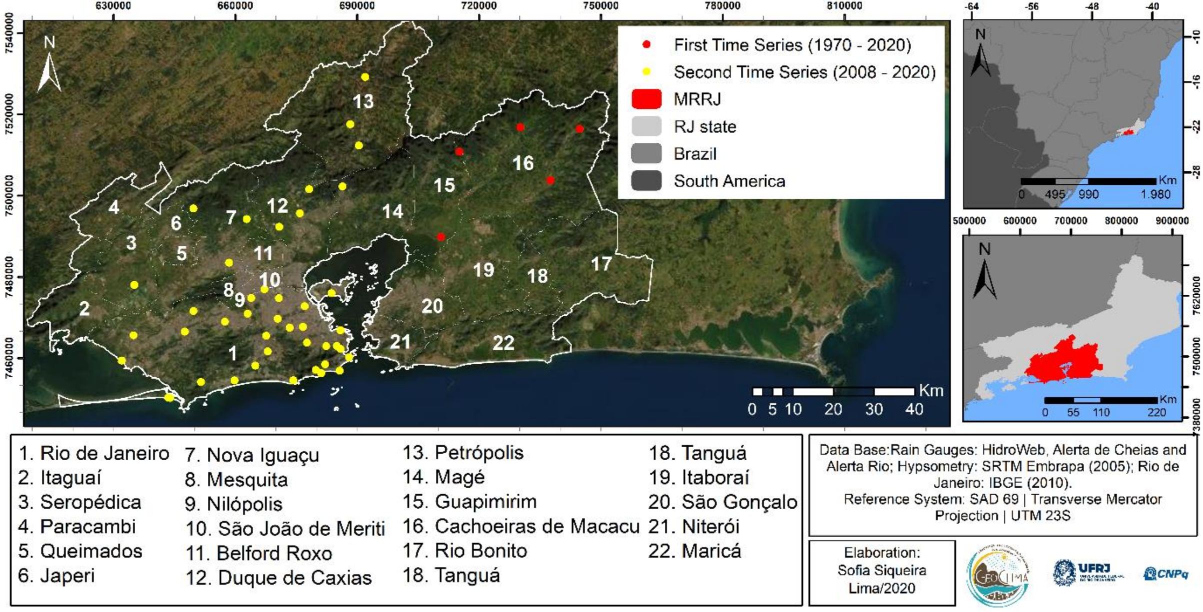
In the synoptic aspect, the influence of low troposphere systems, such as air masses and frontal systems — mainly Cold Fronts —, alongside singular atmospheric systems, such as the South Atlantic Convergence Zone (SACZ) associated with the Continental Equatorial Mass, the tropical instability lines, which accompany the Cold Fronts, and the South Atlantic Semifixed Anticyclone (ASAS) express the complex climatic dynamics produced in the region (NIMER, 1979; SANT'ANNA NETO, 2005). These atmospheric systems dictate the regional climatic seasonality that, when in contact with local geographic factors, provides the spatio-temporal variability of precipitation in the MRRJ.

METHODOLOGICAL PROCEDURES

Quantitative data relating to daily precipitation were used, obtained from a) the HidroWeb portal – Hydrological Information Systems of the Agência Nacional de Águas (ANA, in Portuguese), the federal agency responsible for the implementation of Brazilian water resources management; b) Sistema Alerta de Cheias' telemetric stations of the Instituto Estadual do Ambiente (INEA, in Portuguese), the state institute for the environment, c) Sistema Alerta Rio made available by the Municipality of Rio de Janeiro, and d) the Instituto Nacional de Meteorologia (National Institute of Meteorology). In total, 48 rainfall stations were chosen, located in the municipalities of Rio de Janeiro, Duque de Caxias, São João de Meriti, Nova Iguaçu, Seropédica, Cachoeiras de Macacu, Magé, Guapimirim and Petrópolis, following the criteria defined by Goudard (2019).

Data consistency is an issue in Climatology studies due to the need for reliable historical series. Therefore, two historical series were established: one of greater temporality, from 1970 to 2019, with 8 rainfall stations; and a shorter one, but with 40 posts, between 2008 and 2019.

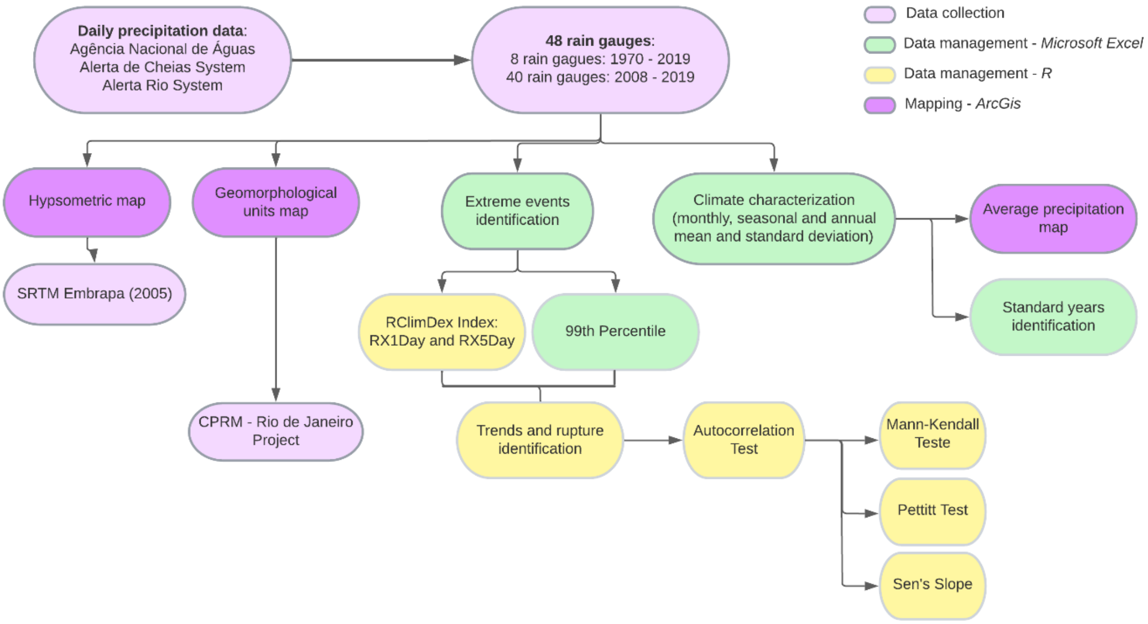
Figure 3 - Location Map



Source: The authors (2021).

The percentile technique, applied to all rainfall stations, was used to establish standard years with the delimitation of the 1, 10, 90 and 99 percentiles, as well as to define extreme daily events, with the 99th percentile threshold. To define extremes, ETCCDI indexes were generated using daily data: maximum precipitation in 24 hours (RX1day) and maximum precipitation in five days (RX5day), performed through the RClimDex package in the R software.

Figure 4 - Flowchart of methodological procedures



Source: The authors (2021).

In data processing, the autocorrelation test was previously applied to the Mann-Kendall tests, using the ACFM period package in the R environment. In the case of autocorrelation, the modified Mann-Kendall test was used, using the MODIFIEDMK package, which does not consider the internal-natural trend of the time series in the Mann-Kendall trend.

For trends, also in the R software, the non-parametric tests of Mann-Kendall and of the slope value of Sem were applied, by the trend package, to verify the existence of a statistically significant trend of extreme events and to evaluate the magnitude of trends, respectively. Pettitt's test was also applied to determine the significance of a rupture in extreme data in the historical series. A 95% confidence interval was used in all tests.

Graphs were generated in Microsoft Excel 2019® software and Surfer 16 software. Maps were made in ArcGis 10.5 software. The spatial representation of precipitation data was performed using the Spline Tension interpolation method, in ArcGis software (SOARES; FRANCISCO, 2014).

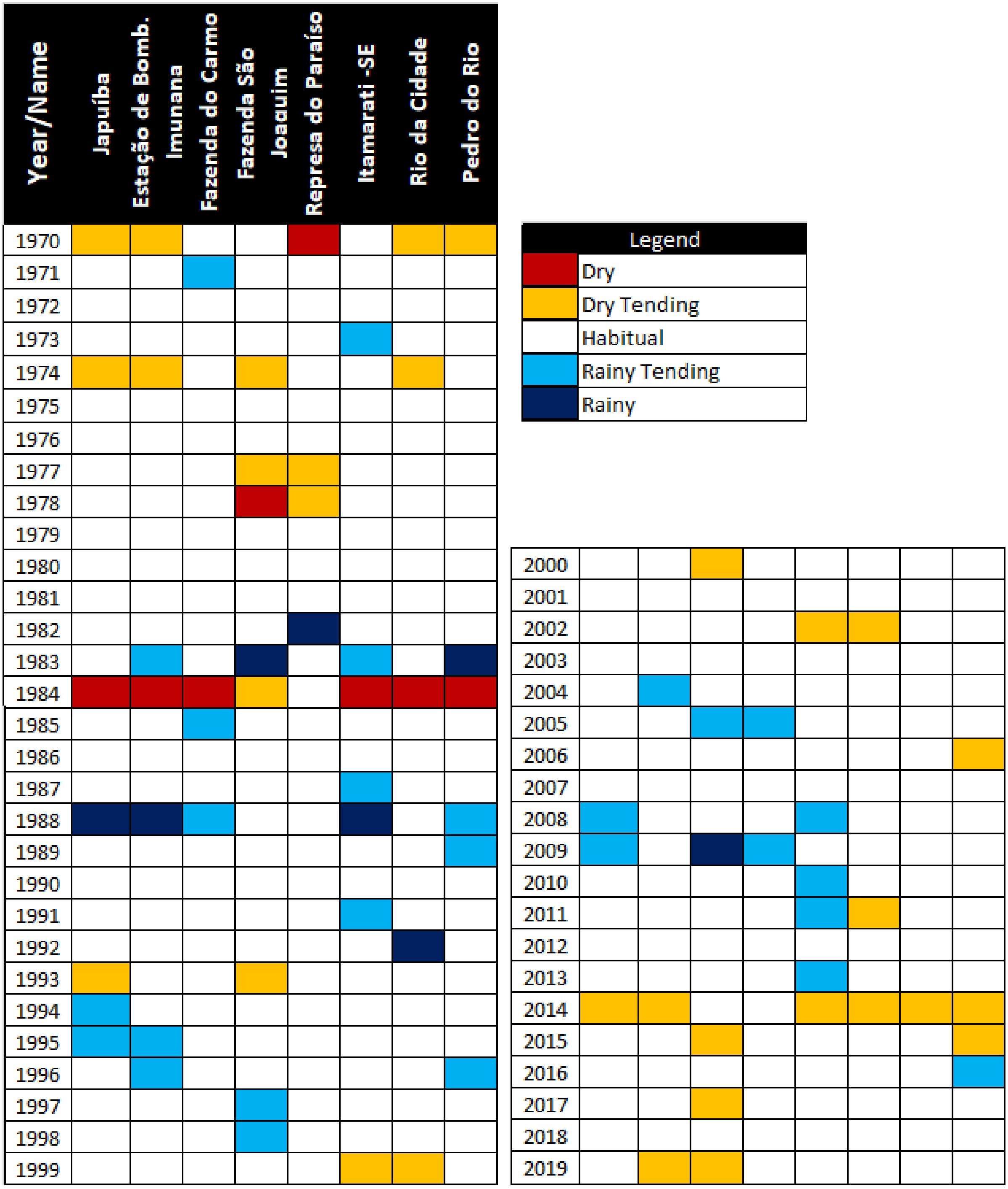
RESULTS AND DISCUSSION

Characterization and temporal variability of precipitation

The temporal characterization of precipitation is segmented into two analytical sections, given the different dynamics of variability and teleconnections that imply its internal phenomena: an interannual section, based on the analysis of standard years; and a seasonal cut out, based on descriptive statistics. Both observations were split into the two-time series used.

In the interannual cutout, the standard years highlight 1970 (with the exception of Fazenda do Carmo, Fazenda São Joaquim and Itamarati), 1974 (except for Fazenda do Carmo, Represa do Paraíso and Itamarati), 1984 (except for Represa do Paraíso), 1984 (except for Represa do Paraíso) and 2014 (except for Fazenda do Carmo and Fazenda São Joaquim) as dry years. For the rainy season, the evidence for 1982 (rainy for Represa do Paraíso), 1983 (for Imunana Pumping Station, Fazenda São Joaquim, Itamarati and Pedro do Rio), 1988 (Japuíba, Imunana Pumping Station, Fazenda do Rio Carmo, Itamarati and Pedro do Rio), 1992 (Rio da Cidade) and 2009 (Japuíba, Fazenda do Carmo and Fazenda São Joaquim) shows at least one of the rain stations used as rainy or prone to rainy (Figure 5). The decade between 1982 and 1992 is also noteworthy, as it was significantly rainy based on standard years. The other years presented a usual pattern of precipitation in most stations.

Figure 5 - Standard years in the first time series (1970-2019)



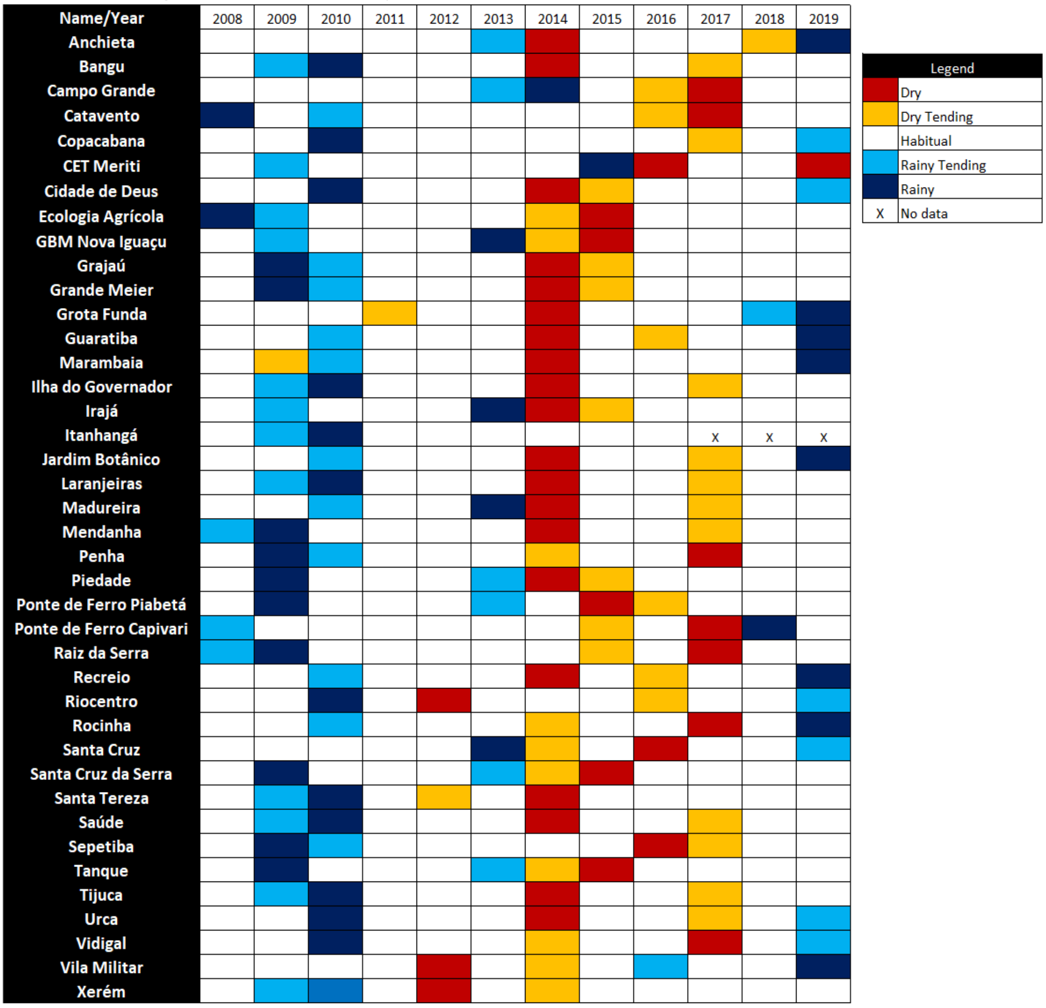
Legend	
🟥	Dry
🟨	Dry Tending
□	Habitual
🟦	Rainy Tending
⬛	Rainy

Year/Name	Japuíba	Estação de Bomb. Imunana	Fazenda do Carmo	Fazenda São Joaquim	Represa do Paraíso	Itamarati -SE	Rio da Cidade	Pedro do Rio
1970	🟨	🟨			🟥		🟨	🟨
1971			🟦					
1972								
1973						🟦		
1974	🟨	🟨		🟨			🟨	
1975								
1976								
1977				🟨	🟨			
1978				🟥	🟨			
1979								
1980								
1981								
1982					⬛			
1983		🟦		⬛		🟦		⬛
1984	🟥	🟥	🟥	🟨		🟥	🟥	🟥
1985			🟦					
1986								
1987						🟦		
1988	⬛	⬛	🟦			⬛		🟦
1989								🟦
1990								
1991						🟦		
1992							⬛	
1993	🟨			🟨				
1994	🟦							
1995	🟦	🟦						
1996		🟦						🟦
1997				🟦				
1998				🟦				
1999						🟨	🟨	
2000			🟨					
2001								
2002					🟨	🟨		
2003								
2004		🟦						
2005			🟦	🟦				
2006								🟨
2007								
2008	🟦				🟦			
2009	🟦		⬛	🟦				
2010					🟦			
2011					🟦	🟨		
2012								
2013					🟦			
2014	🟨	🟨			🟨	🟨	🟨	🟨
2015			🟨					🟨
2016								🟦
2017			🟨					
2018								
2019		🟨	🟨					

Source: The authors (2021).

For the second series (2008 to 2019), 2014 stands out as a dry year as 30 out of 40 rain stations tend to be dry or are dry, with the exception of Campo Grande, which is rainy (Figure 6). 2015, 2016 and 2017 also registered a significant number of posts with a tendency to dry and/or dry, but with less spatial expression. For the rainy season, 2009 and 2010 stand out, with a tendency to be rainy and/or rainy in 22 and 24 pluviometric stations, respectively.

Figure 6 - Standard years in the second time series (2008-2019)



Name/Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Anchieta						🟦	🟥				🟨	⬛
Bangu		🟦	⬛				🟥			🟨		
Campo Grande						🟦	⬛		🟨	🟥		
Catavento	⬛		🟦						🟨	🟥		
Copacabana			⬛							🟨		🟦
CET Meriti		🟦						⬛	🟥			🟥
Cidade de Deus			⬛				🟥	🟨				🟦
Ecologia Agrícola	⬛	🟦					🟨	🟥				
GBM Nova Iguaçu		🟦				⬛	🟨	🟥				
Grajaú		⬛	🟦				🟥	🟨				
Grande Meier		⬛	🟦				🟥	🟨				
Grota Funda				🟨			🟥				🟦	⬛
Guaratiba			🟦				🟥		🟨			⬛
Marambaia		🟨	🟦				🟥					⬛
Ilha do Governador		🟦	⬛				🟥			🟨		
Irajá		🟦				⬛	🟥	🟨				
Itanhangá		🟦	⬛							X	X	X
Jardim Botânico			🟦				🟥			🟨		⬛
Laranjeiras		🟦	⬛				🟥			🟨		
Madureira			🟦			⬛	🟥			🟨		
Mendanha	🟦	⬛					🟥			🟨		
Penha		⬛	🟦				🟨			🟥		
Piedade		⬛				🟦	🟥	🟨				
Ponte de Ferro Piabetá		⬛				🟦		🟥	🟨			
Ponte de Ferro Capivari	🟦							🟨		🟥	⬛	
Raiz da Serra	🟦	⬛						🟨		🟥		
Recreio			🟦				🟥		🟨			⬛
Riocentro			⬛		🟥				🟨			🟦
Rocinha			🟦				🟨			🟥		⬛
Santa Cruz						⬛	🟨		🟥			🟦
Santa Cruz da Serra		⬛				🟦	🟨	🟥				
Santa Tereza		🟦	⬛		🟨		🟥					
Saúde		🟦	⬛				🟥			🟨		
Sepetiba		⬛	🟦						🟥	🟨		
Tanque		⬛				🟦	🟨	🟥				
Tijuca		🟦	⬛				🟥			🟨		
Urca			⬛				🟥			🟨		🟦
Vidigal			⬛				🟨			🟥		🟦
Vila Militar					🟥		🟨		🟦			⬛
Xerém		🟦	🟦		🟥		🟨					

Legend	
🟥	Dry
🟨	Dry Tending
	Habitual
🟦	Rainy Tending
⬛	Rainy
X	No data

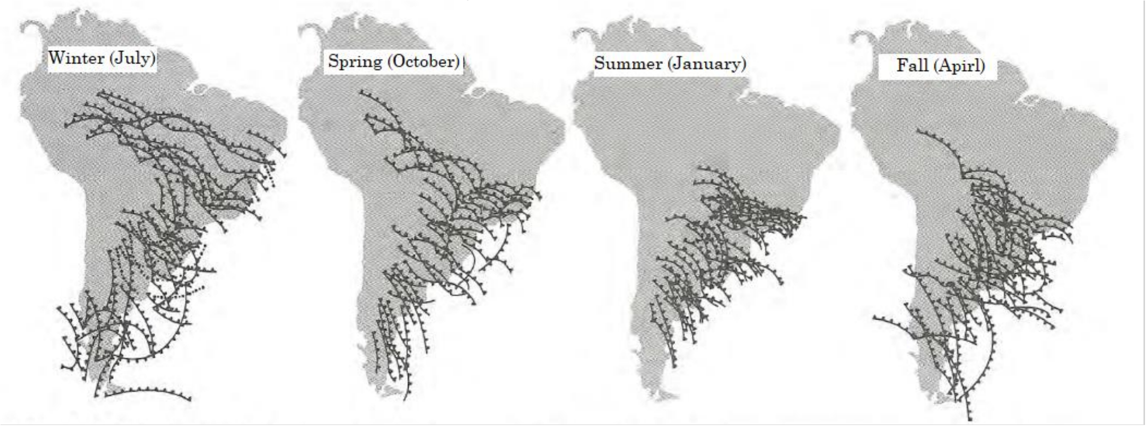
Source: The authors (2021).

It is known that variability and teleconnections are aspects that explain the interannual variability of the aforementioned precipitation, such as the El Niño Southern Oscillation (ENSO). It is noted that the years with strong El Niño episodes (INPE, 2020) had at least one pluviometric station as tending to be rainy and/or rainy. This is the case of 1972/73 (Itamarati), 1982/83 (Represa do Paraíso, Estação de Bombeamento de Imunana, Fazenda São Joaquim, Pedro do Rio), 1987/88 (Itamarati, Japuíba, Estação de Bombeamento de Imunana, Fazenda do Carmo, Itamarati e Pedro do Rio) and 1997/98 (Fazenda São Joaquim).

In the seasonal cutout, the rainfall dynamics of the MRRJ are defined by two seasons: the rainy season, from November to April (which corresponds to 71% of the total rainfall), and the less rainy season, from May to October (29%). Time periods were established through the used stations, corroborating with Nimer (1979) and Sant'Anna Neto (2005).

This precipitation concentration occurs due to the strengthening of the South Atlantic Semifixed Anticyclone (ASAS) and the weakening of the Polar Anticyclone during austral summer, which restricts the advance of the Atlantic Polar Mass to higher latitudes and allows the formation of several frontal systems over Rio de Janeiro (ARMOND; SANT'ANNA NETO, 2017). Frontal systems, in addition to convective conditions, local geomorphological characteristics and potential episodes of the South Atlantic Convergence Zone (SACZ) (AGUIAR, 2018; DE QUADRO et al., 2016; SANT'ANNA NETO, 2005) cause intense rains during the spring/summer period. Thus, January is the month with the highest concentration of precipitation throughout the year, with 14.2% of the total volume of annual precipitation, followed by March and December, corresponding to 13.2% and 12.7%, respectively.

Figure 7 - Spatial variation of the occurrence of cold fronts and warm fronts throughout four seasons of the year, in South America.



Source: Monteiro (1969) *apud* Mendonça e Danni-Oliveira (2017).

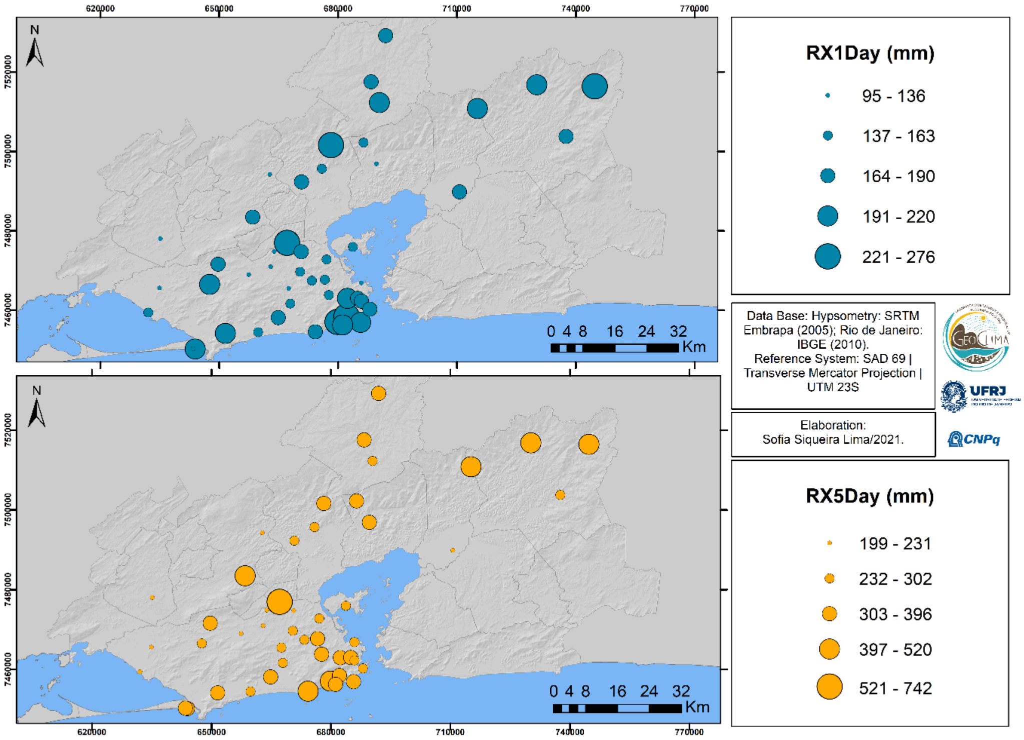
From April onwards, a transition period between active atmospheric systems, the fragility of the Polar Anticyclone blockade leads to a decrease in the accumulated precipitation over the MRRJ, which marks the beginning of the less rainy season. Therefore, rainfall events in August and July are equivalent to 3.2% and 3.8% of the total volume in the historical series.

Extreme events

RClimDex

The use of parameters generated by the RclimDex allows the identification of concentrated events, that is, the maximum monthly rainfall accumulated in a day (RX1Day) and persistent events, the maximum monthly rainfall accumulated in 5 days (RX5Day) (GOUDARD, 2019). A spatial and temporal – interannual and seasonal – analysis of concentrated and persistent events will be explored.

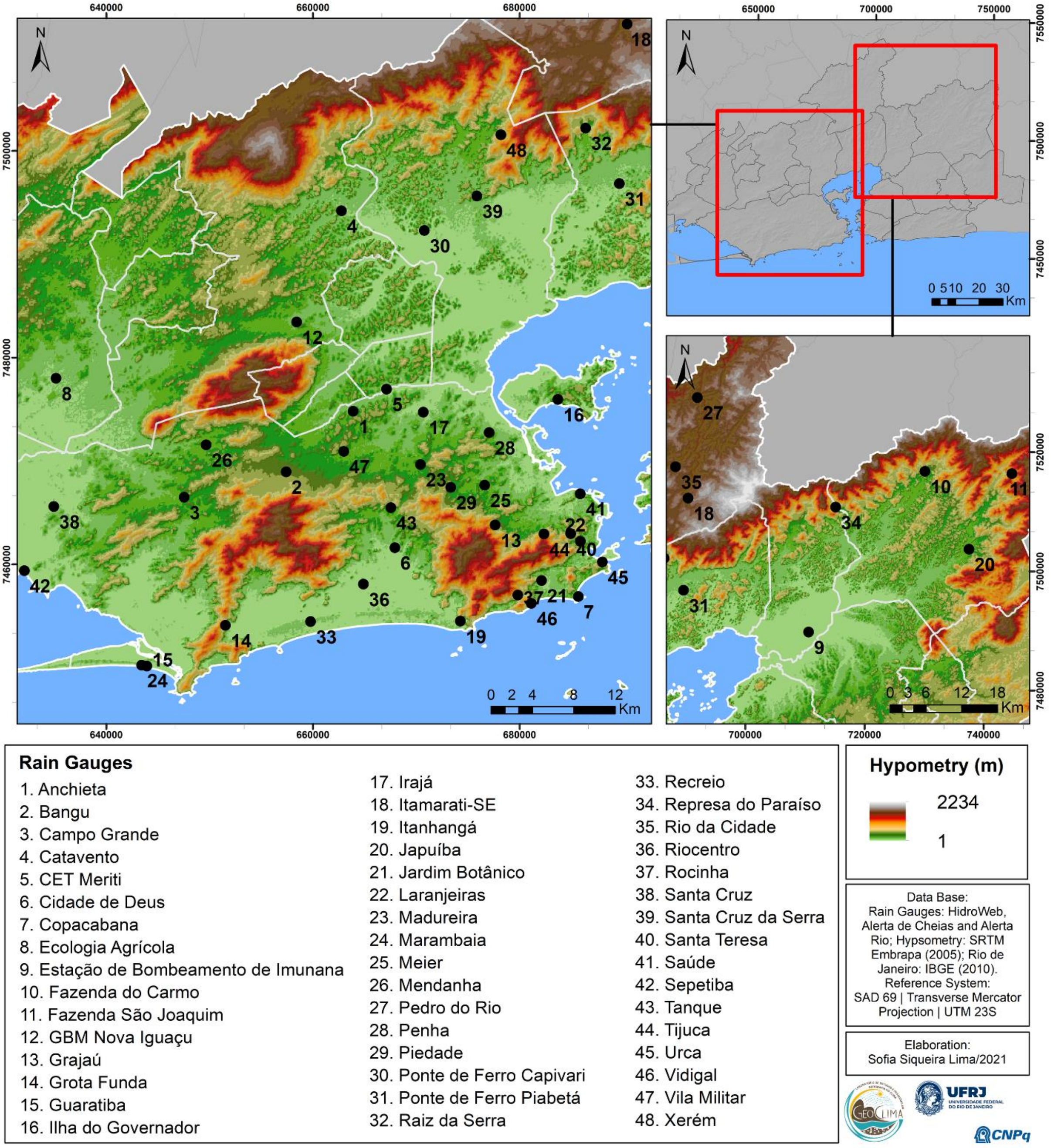
Figure 8 - Parameters RX1Day (upper) and RX5Day (lower) by rainfall station.



Source: The authors (2021).

The stations with the highest values of concentrated events are located on the windward side of the mountain escarpment, with event records of 204.2 mm (1976), 224 mm (2009), 216 mm (2009) and 275.8 mm (2016) (Figure 8) in 24 hours. The stations located on the windward side of the coastal massifs show significant values of RX1Day, with emphasis on Rocinha, Jardim Botânico and Copacabana with a 241.2 mm total of accumulated rainfall (2010), 239 mm (2010) and 218 mm (2019). The lowest values of concentrated events were recorded at stations in the Guanabara and Sepetiba lowlands with values below 130 mm, such as Santa Cruz, Bangu, Vila Militar, Anchieta and Irajá stations.

Figure 9 - MRRJ Hypsometry Map

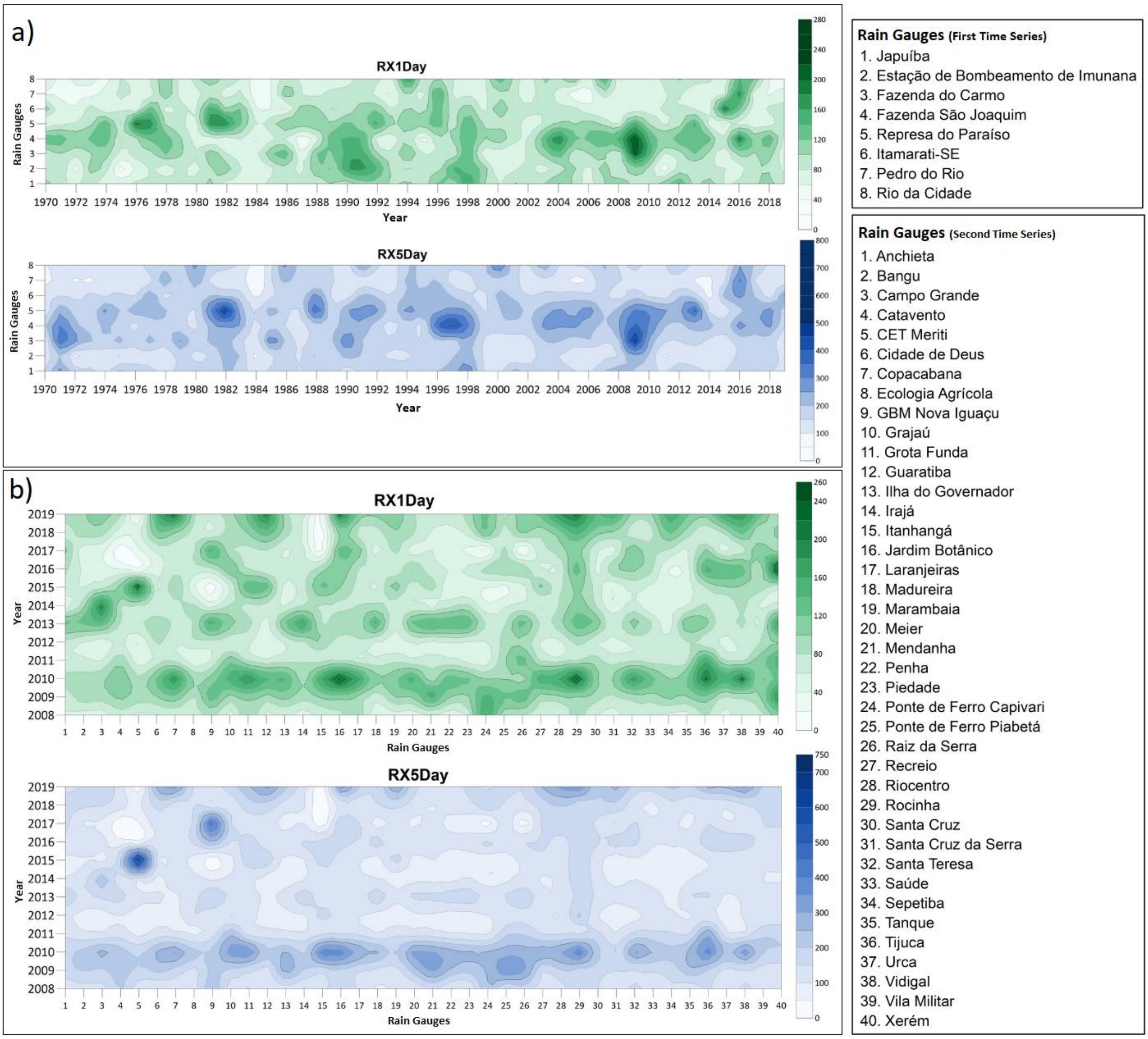


Source: The authors (2021).

Regarding persistent events, the largest accumulated in 5 days is also registered in the Metropolitan East, to the windward side of the mountain escarpment, with more than 500 mm. Despite the stations on the windward side of the Tijuca Massif presenting high values for concentrated events, the persistent events are not as expressive when compared to the stations in the Metropolitan East. In this area, the Rocinha and Jardim Botânico stations showed the most significant persistent events, recording 415.2 mm and 395.8 mm in 2010.

Considering temporal variability, it is possible to perceive a correspondence in the occurrence of concentrated and persistent events of greater magnitudes in years that are rainy or tend to be rainy in the analysis of the standard years. 1982, 1983, 1988, 1992, 2009 and 2010, classified as rainy for at least one pluviometric station of the first time series, manifested concentrated and persistent events of historical intensity (Figure 10).

Figure 10 - Space-time panel of the annual parameters of the RClimDex: a) First historical series (1970-2019); b) Second historical series (2008-2019)

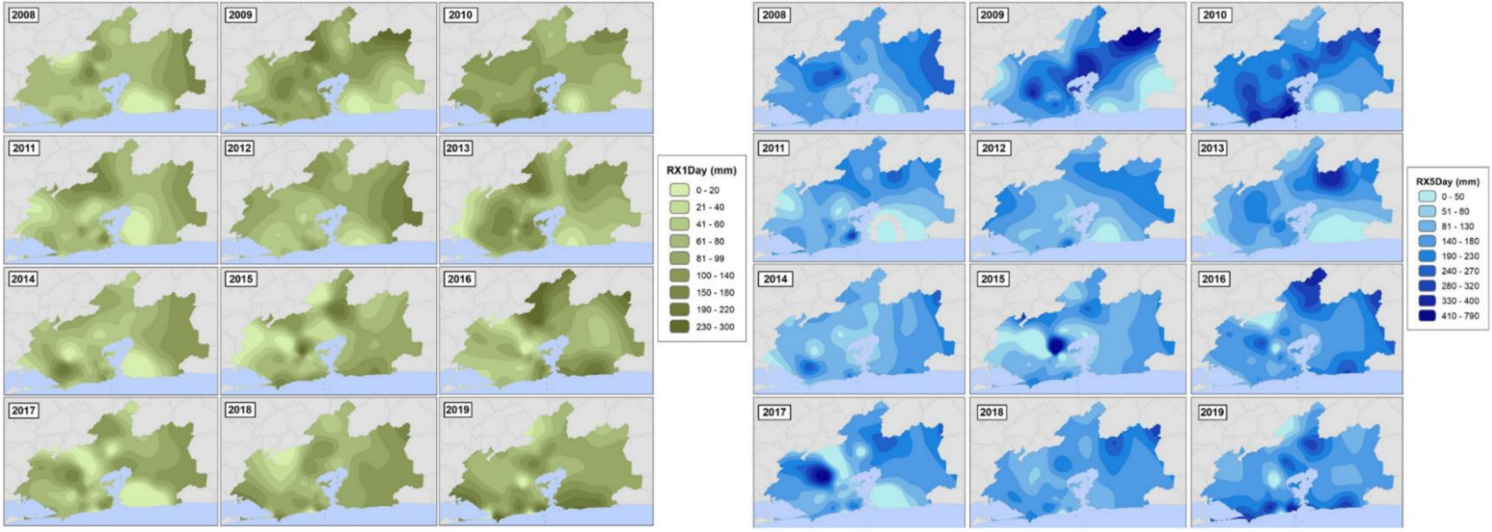


Source: The authors (2021).

However, an extreme concentration in 24 hours does not always result in a persistent event of the same magnitude and vice versa. Between 1988 and 1992, for example, more than half of the pluviometric stations of the first time series manifested concentrated events of high magnitude, while no equally significant persistent extremes were observed.

Regarding the spatial distribution of the interannual variability of the concentrated and persistent extremes (Figure 11), the same pattern is observed: the windward zones of the mountain escarpment and the Tijuca and Pedra Branca massifs are areas of high magnitude rainfall extremes. Thus, the influence of orography on the distribution of precipitation is clear, also impacting the spatialization of the extremes.

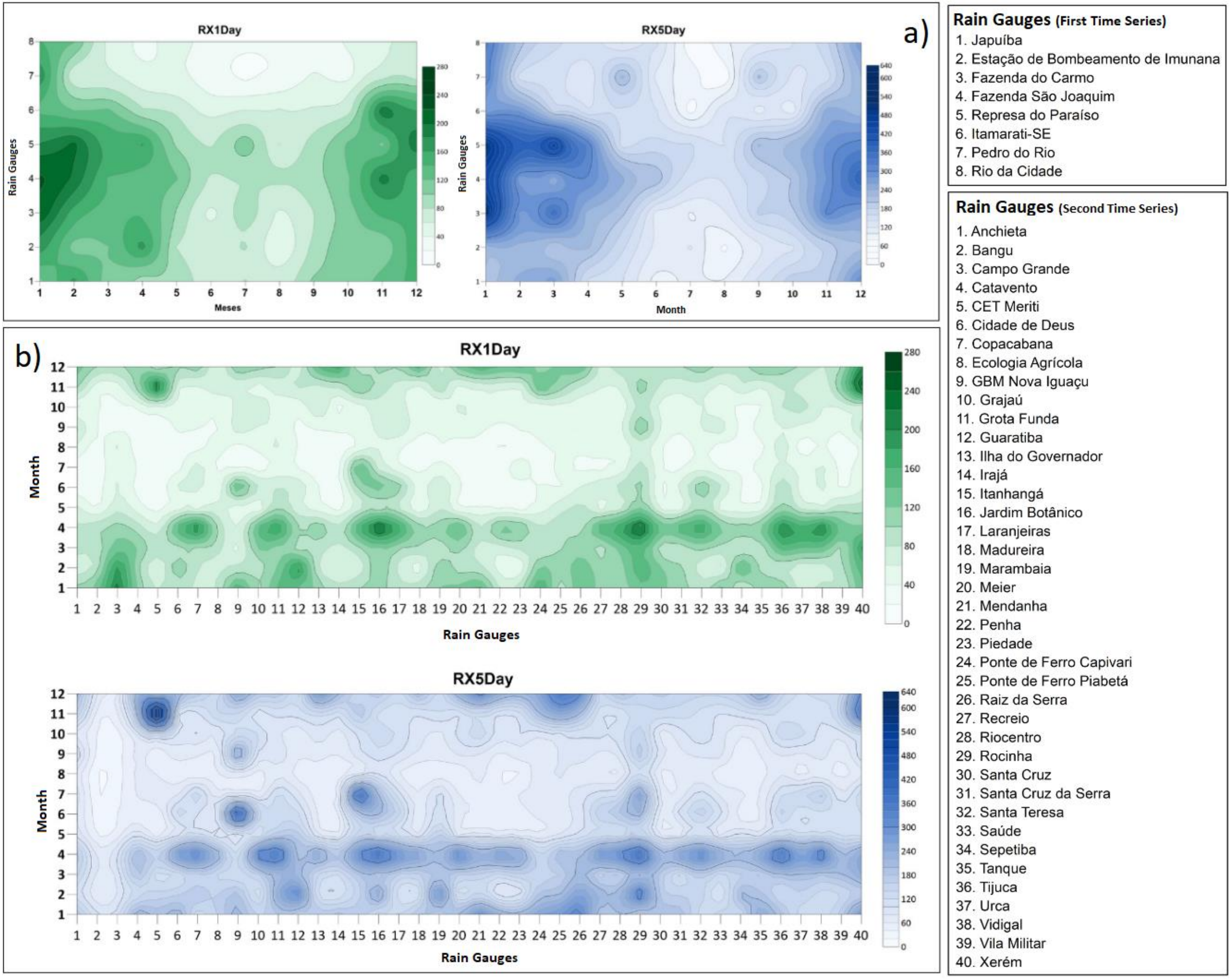
Figure 11 - Temporal distribution (2008 – 2019) of the maximum annual magnitude of concentrated events (left) and persistent events (right).



Source: The authors (2021).

In terms of seasonal variability, rainy season months show concentrated and persistent extremes of greater magnitude in most rainfall stations, especially in December, January and April (Figure 12). Studies on atmospheric circulation in Rio de Janeiro associated with the occurrence of extreme rainfall indicate that frontal systems are essential in their genesis (DERECZYNSKI, 2009; MOURA et al., 2013; NIMER, 1979; ARMOND; SANT'ANNA NETO, 2017; SILVA; DERECZYNSKI, 2014), which may explain the high occurrence of extreme events in this period of the year.

Figure 12 - Space-time panel of the monthly parameters of the RClimDex: a) First historical series (1970-2019); b) Second historical series (2008-2019)



Source: The authors (2021).

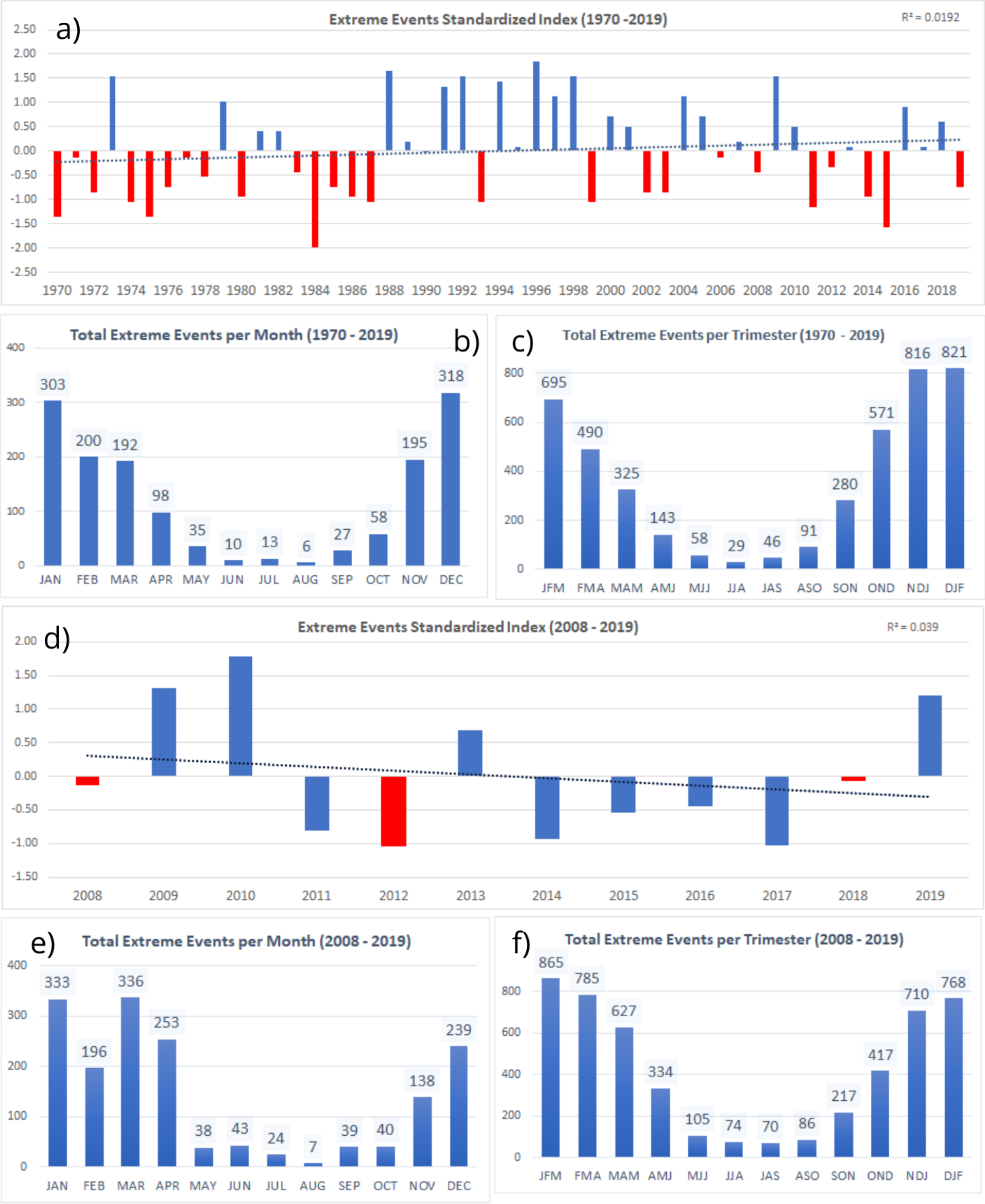
It is worth noting that April, a transitional month in the regional synoptic dynamics that leads to a decrease in precipitation, demonstrates concentrated and persistent events of greater magnitudes in the posts of the 1970-2019 time series. In this sense, it can be inferred that the distribution of precipitation in April is concentrated due to the lower average accumulation of rainfall, compared to other months of the rainy season, accompanied by extremes of higher magnitudes.

Percentiles

In this section, the temporal variability of the frequency of extremes will be analyzed following, again, the interannual and seasonal cutouts. The 99th percentile analysis, applied to each of the 48 rainfall stations used, provides insights into the frequency of precipitation extremes.

In the interannual variability, three cycles of trends can be identified for the series from 1970 to 2019 (Figure 13a). The first cycle begins in the 1970s and goes on until 1987, when a lower frequency of extremes in relation to the average of occurrence is identified. We highlight 1984, the year with the lowest occurrence of extremes, with ten events. The second cycle from 1988 to 2001 shows occurrences above the temporal average, registering years with more than 40 extreme events, confirming results on the annual variability of extremes (ARANHA; BRANDÃO, 2007; BRANDÃO, 1997; DERECZYNSKI et al., 2013) that highlight 1996 and 1998 as years with storms of great intensity and that "remain in the memory of the contemporary Carioca (people from Rio de Janeiro) as true calamities" (BRANDÃO, 1997). The third cycle, from 2002 to 2019, does not show a homogeneous pattern in the frequency of extremes, with years of intense (2009) and low (2015) occurrence of extremes, identified as tending to be rainy and dry, respectively. Data from the second historical series (2008 to 2019) (Figure 13d) corroborate the third cycle identified above, with emphasis on the years 2009 and 2010 with positive occurrences in relation to the average.

Figure 13 - Temporal distribution of extreme events (P99) for the first historical series (1970-2019): a) Annual Standardized Index; b) Monthly Accumulated; c) Quarterly Accumulated; and for the second historical series (2008-2019): d) Annual Standardized Index; e) Monthly accrued; f) Accumulated Quarterly.



Source: The authors (2021).

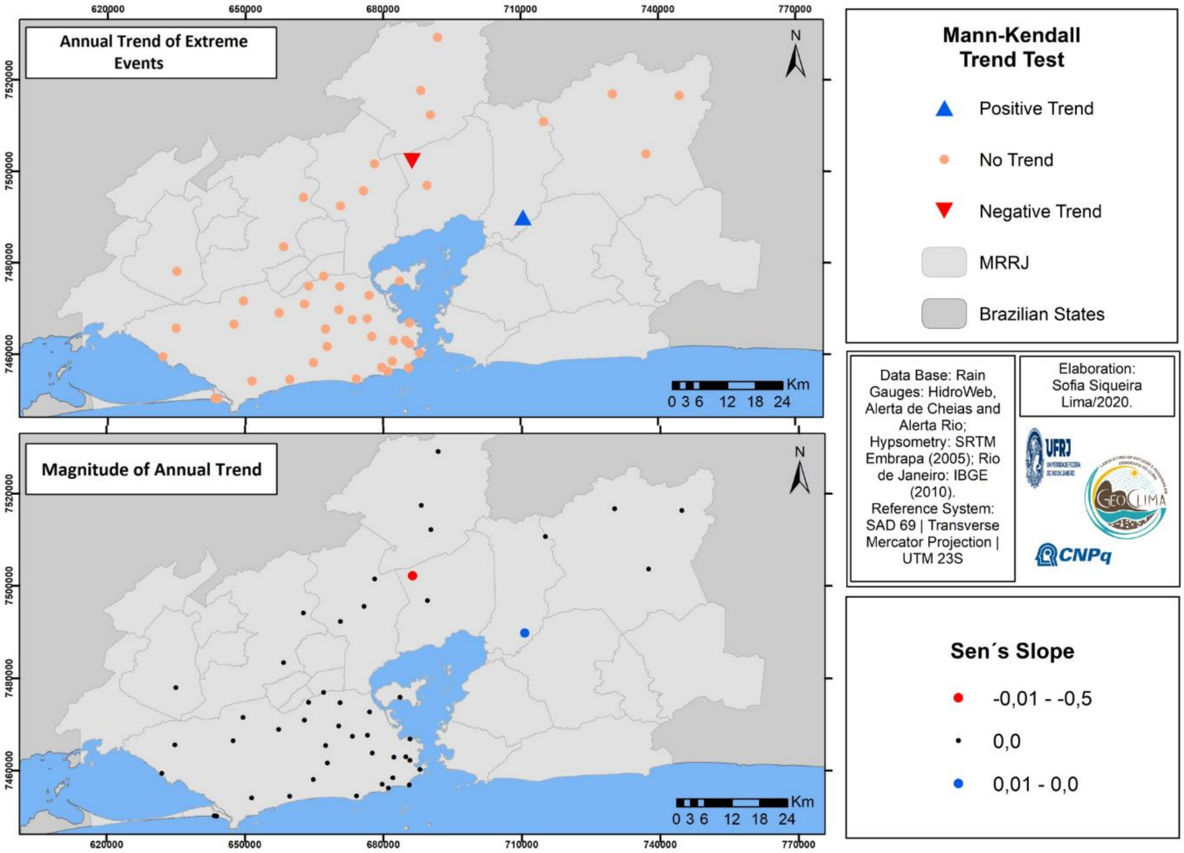
Thus, there is an immediate relationship between the frequency of extremes and the classification of standard years, as observed in 1988 and 2009, standard rainy years for at least one rainfall station, and with a high occurrence of extreme rainfall events. Regarding the relationship between frequency (percentile) and magnitude (RClimDex), years with a high frequency of extremes, such as 1973, 1988, 1996, 1998, 2009 and 2010, manifested concentrated and persistent events of high magnitude.

Concerning seasonal distribution, the rainy season registers a higher frequency of extreme events, as well as a higher concentration of concentrated and persistent events of greater magnitude. In the first time series (1970-2019), the months with the highest frequency of extremes (Figure 13b) correspond to the months of the highest magnitude events (in the case of December and January), with a record of accumulated totals of 223.90 mm (Fazenda São Joaquim) in 24 hours, and a total accumulated in 5 days of 519.80 mm (Fazenda do Carmo) in January. The same relationship cannot be established for the second time series as, despite January and March registering more occurrences of extremes (Figure 13e), April manifested concentrated and persistent events of greater magnitude.

Trends

Concerning the total number of extreme events per year, there was a trend towards an increase in the frequency of extremes in the eastern portion of Guanabara Bay, and a negative trend in the north of this geomorphological unit, in the surroundings of the mountain escarpment (Figure 14).

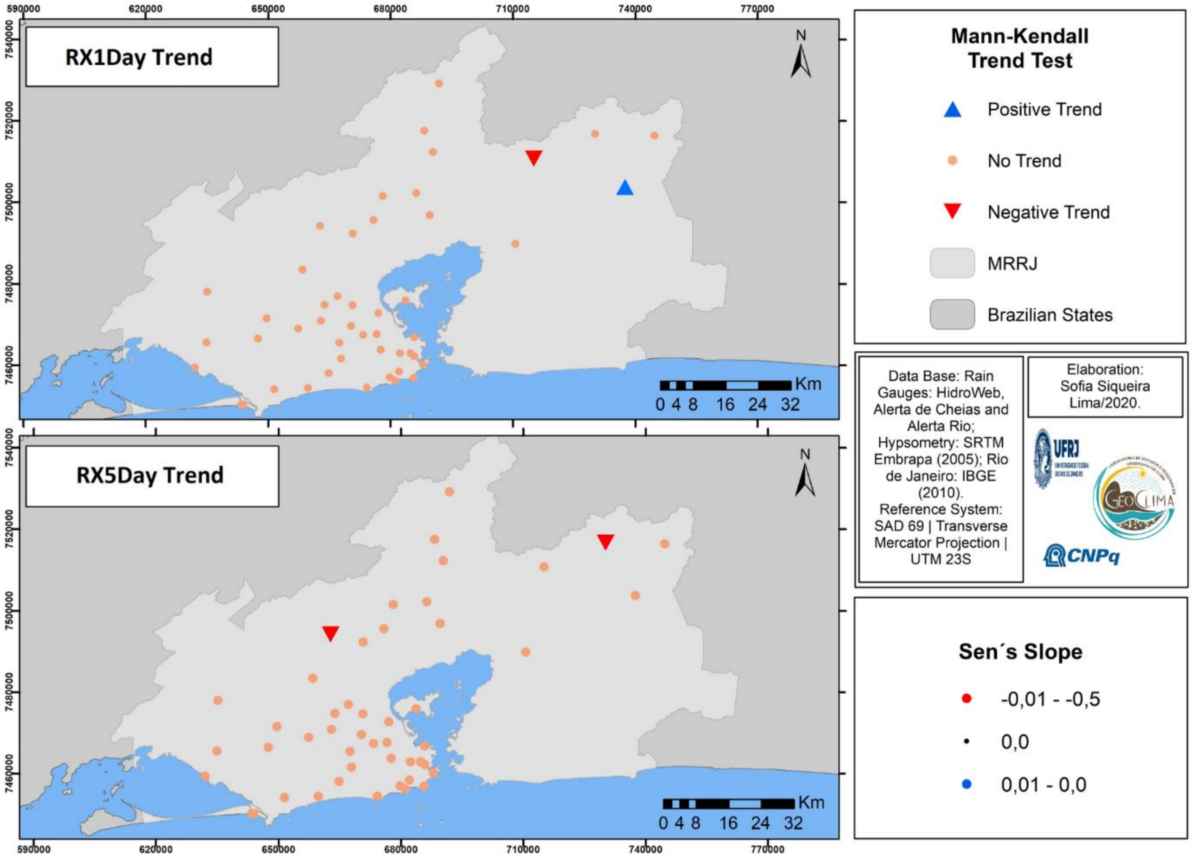
Figure 14 -Trend (upper) and magnitude (lower) for the annual total of extreme events



Source: The authors (2021).

Considering concentrated events, the Metropolitan East shows a positive trend near the Guanabara lowland and a negative trend in the mountainous escarpment. For persistent events, two trends of decreasing intensity of these events were identified to the northeast and northwest of the MRRJ.

Figure 15 - Trend test for RX1Day (upper) and RX5Day (lower)



Source: The authors (2021).

The pluviometric stations and historical series used, as well as the applied methodology, are factors that can explain the results. Furthermore, the literature demonstrates that rainfall trends are less significant and have a less defined spatial pattern when compared to temperature trends, given the greater spatial and temporal variability of precipitation data (BEZERRA et al, 2019).

FINAL CONSIDERATIONS

Based on a dynamic approach to climate through the theoretical-methodological matrix of Monteiro's Geographical Climatology, space, understood as a relative space, was a structuring concept in the development of this paper due to its possibility of incorporating spatial elements in the interpretation of extreme precipitation events. Understanding the phenomenon in a relational way, associating it with the elements that compose the MRRJ, allows the geographical approach of extreme events.

For spatial variability, it is evident that altitude, slope orientation and sea level are essential spatial elements in regional rainfall distribution. The windward areas of high altitudes – mountain escarpments and inland and coastal massifs – register the highest volumes of rainfall, as well as the extremes of greater magnitude, while the areas to the leeward of these geomorphological units and on the lowlands have significantly lower precipitation volumes.

In terms of temporal variability, the interannual cutout showed that 1988 and 2009, standard rainy years for at least one pluviometric station, were years with a high frequency of extremes, and concentrated and persistent events of intense magnitude. In opposition, 1984 was a dry standard year (in 6 out of the 8 rainfall stations in the first series) and presented events of lower intensity, concentrated and persistent, as well as having a lower frequency of events, considering the 99th percentile.

In seasonal variability, approximately 90% of the extremes occurred in the rainy season months (November to April), especially December, January and March. Regarding the magnitude, December and January show concentrated and persistent events of high magnitudes, but April has the highest number of pluviometric stations with the most intense events, which demonstrates the time concentration of rain.

Regarding trends, 6 trends were identified – 4 negative and 2 positive – accounting for the three variables applied. The trends were manifested in the northeast, north and northwest portions of the MRRJ.

The present article, therefore, sought to characterize rainfall dynamics of the Metropolitan Region of Rio de Janeiro, with emphasis on the analysis of the spatial and temporal variability of rainfall and extreme events in the region. Thus, the complexity given to the phenomenon of extreme precipitation events is not only in its strictly physical-atmospheric character, but also in the space – full of complexities – in which it impacts. In this sense, when analyzing the range of indices used in this article, it is important to consider the geographic factors that affect and shape rainfall in the MRRJ.

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REFERENCES

ABREU, M. de A. **Evolução urbana no Rio de Janeiro**. Rio de Janeiro: IPLANRIO/Zahar, 1987.

AGÊNCIA NACIONAL DE ÁGUAS. Rede Hidrometeorológica Nacional. Sistema HidroWeb. Available: https://www.snirh.gov.br/hidroweb/serieshistoricas. Access on: jul. 04, 2020

AGUIAR, L. de F. **Vulnerabilidade socioambiental na região sudeste do Brasil associada à configuração da ZCAS**. 2018. 80 f. Trabalho de Conclusão de Curso (Bacharelado em Engenharia de Recursos Hídricos e do Meio Ambiente) - Escola de Engenharia, Universidade Federal Fluminense, 2018.

ARANHA, R.l de C.; BRANDÃO, A. M. de P. M. **Os extremos pluviométricos cariocas**. XVII Simpósio Brasileiro de Recursos Hídricos, São Paulo, 2007.

ARMOND, N. B.; SANT'ANNA NETO, J. L. **Entre eventos e episódios**: ritmo climático e excepcionalidades para uma abordagem geográfica do clima no município do Rio de Janeiro. Revista Brasileira de Climatologia, v. 20, 2017. https://doi.org/10.5380/abclima.v20i0.49792

ARMOND, N. B.; SANT'ANNA NETO, J. L.. The Urban Climate System and the Impacts of Flooding on Rio de Janeiro, Brazil. In: **Urban Climates in Latin America**. Springer, Cham, 2019. p. 259-280. https://doi.org/10.1007/978-3-319-97013-4_10

ARMOND, N. B. **Entre eventos e episódios: as excepcionalidades das chuvas e os alagamentos no espaço urbano** do Rio de Janeiro. 2014. xx, 239 f. Dissertação (mestrado) - Universidade Estadual Paulista, Faculdade de Ciências e Tecnologia, Presidente Prudente, 2014. Available: http://hdl.handle.net/11449/124041. Access on: feb. 01, 2021

ARMOND, N. B. **Dinâmica climática, excepcionalidades e vulnerabilidade: contribuições para uma classificação geográfica do clima do estado do Rio de Janeiro**. Tese (Doutorado em Geografia) - Universidade Estadual Paulista, Faculdade de Ciências e Tecnologia, Presidente Prudente, 2018. Available: http://hdl.handle.net/11449/154354. Access on: aug. 27, 2021

BEZERRA, B. G. et al. Changes of precipitation extremes indices in São Francisco River Basin, Brazil from 1947 to 2012. **Theoretical and Applied Climatology**, v. 135, n. 1, p. 565-576, 2019. https://doi.org/10.1007/s00704-018-2396-6

BRANDÃO, A. M. de P. M. **Tendências e oscilações climáticas na área metropolitana do Rio de Janeiro**. 1987. Dissertação (Mestrado em Geografia) – Universidade de São Paulo, São Paulo, 1987.

BRANDÃO, A. M. de P. M. As chuvas e a ação humana: uma infeliz coincidência. In: Tormentas Cariocas. In: **Seminário prevenção e controle dos efeitos dos temporais no Rio de Janeiro**. Universidade Federal do Rio de Janeiro Rio de Janeiro, 1997, p.21-42.

BRANDÃO, A. M. de P. M. O clima urbano na cidade do Rio de Janeiro. In: MONTEIRO, C. A. F.; MENDONÇA, F. (orgs). **Clima urbano**, São Paulo: Contexto, v.2, 2003.

BENAVIDES, H.; MAYORGA, R.; HURTADO, G. Análisis de índices de extremos climáticos para Colombia usando el RCLIMDEX. **Instituto de Hidrología, Meteorología y Estudios Ambientales**, 2007.

CONTI, J. B. **Circulação secundária e efeito orográfico na gênese das chuvas na região**

lesnordeste paulista. Instituto de Geografia, Universidade de São Paulo, São Paulo, 1975.

CRUZ, O. **A Serra do Mar e o litoral na área de Caraguatatuba: contribuição à geomorfologia tropical litorânea**. Tese (Doutorado em Geografia) – Universidade de São Paulo, Instituto de Geografia. 1974.

DE QUADRO, M. F. L.; PEZZI, L. P.; ROSA, E. B.. **O Climanálise e o monitoramento da ZCAS nos últimos 30 anos**. 2016.

DERECZYNSKI, C.P.; OLIVEIRA, J. S. de; MACHADO, C. O. Climatologia da precipitação no município do Rio de Janeiro. **Revista Brasileira de Meteorologia**, v. 24, n. 1, p. 24-38, 2009. https://doi.org/10.1590/S0102-77862009000100003

DERECZYNSKI, C.; SILVA, W. L.; MARENGO, J. **Detection and projections of climate change in Rio de Janeiro, Brazil**. 2013. https://doi.org/10.4236/ajcc.2013.21003

DOS SANTOS, L. A.R. et al. **Caracterização de extremos climáticos utilizando o Software RClimDex**. Estudo de caso: Sudeste de Goiás. 2006.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA. Shuttle Radar Topography Mission (SRTM), 2020. Available: https://www.embrapa.br/satelites-de-monitoramento/missoes/srtm. Access on: aug. 10, 2020

GONÇALVES, N. M. S. Impactos pluviais e desorganização do espaço urbano em Salvador. In: MONTEIRO, C. A. F.; MENDONÇA, F. (orgs). **Clima urbano**, 2003.

GOUDARD, G. **Eventos pluviais extremos e riscos hidrometeorológicos híbridos na Bacia do Alto Iguaçu (Paraná).** Dissertação (Mestrado em Geografia) – Universidade Federal do Paraná, Curitiba, 2019.

HARVEY, D. O espaço como palavra-chave. **Revista em Pauta**, n. 35, v. 13, p. 126-152, 2015. https://doi.org/10.12957/rep.2015.18625

INPE - Instituto Nacional de Pesquisas Espaciais. **Megacidades, vulnerabilidade e mudanças climáticas: Região Metropolitana do Rio de Janeiro**. Centro de Ciência do Sistema Terrestre do Instituto Nacional de Pesquisas Espaciais CST/INPE. Núcleo de Estudos de População da Universidade de Campinas. NEPO/UNICAMP. 2011. Relatório.

INPE – Instituto Nacional de Pesquisas Espaciais. **Centro de Previsão de Tempo e Estudos Climáticos**. Available: http://enos.cptec.inpe.br/. Access on: Oct. 20, 2020.

IPCC. **Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change** [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press. 2021

INSTITUTO ESTADUAL DO AMBIENTE. Sistema de Alerta de Cheias. Available: http://alertadecheias.inea.rj.gov.br/mapa.php. Access on: jul. 15, 2020

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. Base de faces de logradouros do Brasil, 2010. Available: https://www.ibge.gov.br/geociencias/organizacao-do-territorio/malhas-territoriais/28971-base-de-faces-de-logradouros-do-brasil.html?=&t=downloads. Access on: aug. 10, 2020

MENDONÇA, F. A. Clima e planejamento urbano em Londrina. In: MONTEIRO, C. A. F.; MENDONÇA, F. (orgs). **Clima urbano**, 2003.

MENDONÇA, F.; DANNI-OLIVEIRA, I M. Climatologia: noções básicas e climas do Brasil. Oficina de textos, 2017.

MONTEIRO, C A de F. A frente polar atlântica e as chuvas de inverno na fachada sul-oriental do Brasil: contribuição metodológica à análise rítmica dos tipos de tempo no Brasil. . São Paulo: Instituto de Geografia/Universidade de São Paulo, 1969

MONTEIRO, C. A. de F. **Análise rítmica em climatologia: problemas da atualidade climática em São Paulo e achegas para um programa de trabalho**. Climatologia, n. 1, p. 1-21, 1971.

MONTEIRO, C. A. de F. **Clima e excepcionalismo: conjecturas sobre o desempenho da atmosfera como fenômeno geográfico**. Florianópolis: EdUFSC, 1991.

MONTEIRO, C. A. de F. O estudo geográfico do clima. **Cadernos Geográficos**, Florianópolis, v. 1, n. 1, p. 7-72, 1999.

MONTEIRO, C. A. de F. Teoria e clima urbano: um projeto e seus caminhos. In: MONTEIRO, C. A. F.; MENDONÇA, F. (orgs). **Clima urbano**, 2003.

MONTEIRO, A. As cidades e a precipitação: uma relação demasiado briguenta. **Revista Brasileira de Climatologia**, v. 5, n. 1, 2009. https://doi.org/10.5380/abclima.v5i0.49390

MONTEIRO, J. B. **Chover mas chover de mansinho: desastres naturais e chuvas extremas no Estado do Ceará**. Dissertação (Mestrado em Geografia) - Universidade Estadual do Ceará. 2011.

MOURA, C.R.; ESCOBAR, G. C. J.; ANDRADE, K. M. Padrões de circulação em superfície e altitude associados a eventos de chuva intensa na Região Metropolitana do Rio de Janeiro. **Revista Brasileira de Meteorologia**, v. 28, n. 3, p. 267-280, 2013. https://doi.org/10.1590/S0102-77862013000300004

NASCIMENTO JÚNIOR, L. **As chuvas no Paraná: variabilidade, teleconexões e impactos de eventos extremos**. Dissertação (Mestrado em Geografia) - Universidade Estadual Paulista, Presidente Prudente, 2013.

NEIVA, H.; SILVA, M.; CARDOSO, C. Analysis of climate behavior and land use in the city of Rio de Janeiro, RJ, **Brazil. Climate**, v. 5, n. 3, p. 52, 2017. https://doi.org/10.3390/cli5030052

NIMER, E. Clima da região Sudeste. In: Geografia do Brasil. Rio de Janeiro/IBE, 1971,**Climatologia no Brasil**. Rio de Janeiro: IBGE, 1979.

PREFEITURA DO RIO DE JANEIRO. Fundação GEO-RIO. Sistema Alerta Rio da Prefeitura do Rio de Janeiro, 2020. Available: http://alertario.rio.rj.gov.br/download/dados-pluviometricos/. Access on: jul. 15, 2020

REBELLO, E. R. G. et al. Observação de mudanças de extremos climáticos (precipitação e temperatura) utilizando o software RClimDex. Estudo de caso: Distrito Federal. **Congresso Brasileiro de Meteorologia** (CBMET), v.1, 2008.

SANT'ANNA NETO, J. L. Por uma Geografia do Clima – antecedentes históricos,
paradigmas contemporâneos e uma nova razão para um novo conhecimento. **Terra Livre**, v. 17, p. 49-62, 2001.

SANT'ANNA NETO, J. L. Decálogo da climatologia do sudeste brasileiro. **Revista Brasileira de Climatologia**, v. 1, n. 1, 2005. https://doi.org/10.5380/abclima.v1i1.25232

SANT'ANNA NETO, J. L. Da climatologia geográfica à geografia do clima Gênese, paradigmas e aplicações do clima como fenômeno geográfico. **Revista da ANPEGE**, v. 4, n. 04, p. 51-72, 2008. https://doi.org/10.5418/RA2008.0404.0004

SANT'ANNA NETO, J. L. O clima urbano como construção social: da vulnerabilidade polissêmica das cidades enfermas ao sofismo utópico das cidades saudáveis. **Revista Brasileira de Climatologia**, v. 8, 2011. https://doi.org/10.5380/abclima.v8i0.25794

SERRA, A.; RATISBONNA, L. As Massas de Ar da América do Sul:(PRIMEIRA PARTE). **Revista Geográfica**, p. 67-129, 1959.

SERVIÇO GEOLÓGICO DO BRASIL. Geomorfologia do estado do Rio de Janeiro. CPRM. **Geologia do Estado do Rio de Janeiro: texto explicativo do mapa geológico do Estado do Rio de Janeiro. Brasília,** 2001. Available: https://rigeo.cprm.gov.br/jspui/bitstream/doc/17229/14/rel_proj_rj_geoambiental.pdf. Access on: Nov. 12, 2020.

SILVA, W. L.; DERECZYNSKI, C. P. Caracterização climatológica e tendências observadas em extremos climáticos no estado do Rio de Janeiro. **Anuário do Instituto de Geociências**, v. 37, n. 2, p. 123-138, 2014. https://doi.org/10.11137/2014_2_123_138

SOBRAL, B.S.; OLIVEIRA-JÚNIOR, J. F.; GOIS, G.; TERASSI, P. M. B.; MUNIZ-JÚNIOR, J. G. R. Variabilidade espaço-temporal e interanual da chuva no estado do Rio de Janeiro. **Revista Brasileira de Climatologia**, ano 14, v. 22, p. 281-308, 2018. https://doi.org/10.5380/abclima.v22i0.55592

SOARES, F. S.; FRANCISCO, C. N.; SENNA, M. C. A. Distribuição espaço-temporal da precipitação na Região Hidrográfica da Baía da Ilha Grande-RJ. **Revista Brasileira de Meteorologia**, v. 29, n. 1, p. 125-138, 2014. https://doi.org/10.1590/S0102-77862014000100012

STEPHENSON, D. Definition, diagnosis, and origin of extreme weather and climate events. In: DIAZ, Henry; MURNANE, Richard (eds.). **Climate extremes and society**. Cambridge University Press, 2008. https://doi.org/10.1017/CBO9780511535840.004

ZHANG, X. et al. RClimDex (1.0) user manual. Climate Research Branch Environment Canada, v. 22, 2004

AUTHORS CONTRIBUTION

Sofia Siqueira Lima conceived or studied, collected, treated, analyzed the data and wrote the text. Núbia Beray Armond guided the treatment and processing of data, as well as guided the analyzes performed.