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More Erratic and More Extreme: Trends in Precipitation in the State of São Paulo, Brazil

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Abstract

The study assessed changes in rainfall variability and the frequency of extreme events (very wet and very dry) in the state of São Paulo, Brazil, for a 40-year period that divided into two sub-groups: 1973-1992 (P1) and 1993-2012 (P2). Data of 79 rain gauge stations were selected to represent the different climatic and geomorphological domains of the state. The annual pattern was evaluated through the scale and the shape parameters of the gamma distribution and the 95th and the 5th percentiles thresholds, the latter also employed to evaluate the seasonal spatial patterns (rainy season, Oct.-Mar. and sub-humid to dry season, Apr.-Sep.). Results showed that the average precipitation was similar in P1 and P2, but São Paulo evolved to a pattern of increased irregularity in the rainfall distribution, with a rise of approximately 10% in the number of extremes between 1973 and 2012, especially in the very dry occurrences, and in the north and west of the state, which are the least rainy regions. Moreover, while 55% of the evaluated rain gauges recorded more extreme wet episodes in P2, 76% registered more dry extreme episodes in the same period. Some very dry or very wet events recorded after the 40-year period evaluated were discussed in terms of the associated weather patterns and their impacts on society and attested to the validity of the results found in the quantitative assessment. The qualitative analysis indicates that if the trends of more irregular distribution of rain and increase in extreme events persist, as pointed out by the gamma and percentile analyses, they would continue to bring serious effects on the natural and social systems in the state, which is the most populous and has the strongest and most diversified economy in Brazil.

Keywords

Rainfall, Extremes, São Paulo, Gamma Distribution, Percentiles, Impacts

1. Introduction

Defining and understanding the dynamics, variation and shifts in precipitation distribution are relevant to all human activities and gains relevance in a time of changes taking place throughout the planet. One of the main effects of these changes is the shift in the extremes, as major effects on natural and human systems would be conveyed not through its effects on mean rainfall, but through changes in the frequency and severity of extreme events (Tebaldi et al., 2006; IPCC, 2012; Pendergrass et al., 2017; Botzen et al., 2019; Madakumbura et al., 2021; Tabari, 2020; Kirchmeier-Young & Zhang, 2020; Fowler et al., 2021).

Extremes are part of the natural variability of the climate system but amounts of rain so far considered exceptional have been recorded more frequently, indicative of changes in the current pattern in the distribution of rain (Fowler et al., 2021). Because extreme occurrences are often associated with immense consequences, there is great concern that the number of precipitation-related disasters will increase, with devastating direct and indirect societal impacts: it could worsen environmental degradation and hamper the resilience of the most vulnerable population (Banholzer et al., 2014; Cramer et al., 2018; Benevolenza & DeRigne, 2019), influence poverty by affecting agricultural productivity, raising prices of staple foods (Ahmed et al., 2009) and contribute to the increase of social inequality, as climate change affects marginalized people disproportionally (IPCC, 2012; Hallegatte et al., 2020; Cappelli et al., 2021). From 1970 to 2019 more than 11,000 events were reported in the entire world, with over 2 million deaths and US$3.64 trillion in losses (WMO, 2021a).

Rapid changes might have an even greater effect by not allowing the prevention or adaptation to these changes (Alley et al., 2003) and would contribute to the increase of recurrent climate-related disasters, which in turn would weaken the ability of a given place to recover and to prepare for future episodes (Cappelli et al., 2021).

According to The Assessment Report 6 of IPCC (IPCC, 2021) heavy precipitation is projected to become more intense and frequent in several regions of the world, including SES (South-Eastern South America, medium confidence, for a 2˚C Global Warming Levels, GWL). Other studies indicate that changes in extreme precipitation are already detectable on a regional basis (Orlowsky & Seneviratne, 2012; Donat et al., 2019; Madakumbura et al., 2021).

Changes in rainfall distribution and patterns of extreme events have the potential to impact much more intensely places with large populations and diverse and dynamic economies: this is the case in São Paulo, one of the 26 Brazilian states and the largest economic and industrial centre in the Southern Hemisphere (InvestSP, 2022). The economic and population importance of the state is deeply associated with its ecological diversity, such as rich soils and humid to sub-humid tropical climate. Due to natural favourable conditions, coffee cultivation was successfully introduced in São Paulo in the mid-19th century and became the mainstay of the economy. From the 1930s onwards industrialization gained importance and gave impulse to the rapid process of urban expansion

(Figuerôa, 1985). However, the economic and demographic pressures promoted accelerated deforestation, loss of diversity and land degradation, which along with the lack of urban planning and the growth of population living in hazard-prone areas contributed to the continuous growth of the society's vulnerability to rainfall events.

The combination of profound environmental disarticulation at a time of rapid climate change might be contributing to the increase in the irregularity of rainfall distribution and, as a consequence, of natural disasters. Every year the state faces significant economic losses, with a high number of people affected, including deaths, especially in the rainy season (summer) when floods and landslides occur (Nobre et al., 2011; Zilli et al., 2016). Severe droughts have also affected the state of São Paulo and has generated situations of water, food and energy insecurity (Marengo et al., 2015; Marengo & Alves, 2015; Nobre et al., 2016; Coelho et al., 2016; Rodrigues et al., 2019; Gozzo et al., 2019; Getirana et al., 2021).

The strong urban and industrial concentration and the important agriculture and agribusiness sectors, highly competitive in the globalized market, especially in sugarcane, soybean, orange and beef (InvestSP, 2022), requires not only high but constant demand for water in São Paulo. Thus, changes in precipitation distribution may have a significant impact at the state and national levels. Among the consequences are water and energy shortages, competition for water sources within and outside the state, increase of crop failures, outbreak of diseases such as dengue fever, as well as impact in infrastructure and transportation. Many of these effects present a strong socioeconomic component, as they impact low-income communities most significantly (Erhart et al., 2009; Castellano & Nunes, 2010; Romero-Lankao, 2011; Cappelli et al., 2021).

Although several studies evaluated the rainfall patterns in the state of São Paulo (Schroeder, 1956; Setzer, 1972; Monteiro, 1973; Salvi, 1984; Sugahara, 1991; Santos, 1996; Nunes, 1997; Sant'Anna Neto, 1997; Nery et al., 1999; Liebmann et al., 2001; Dufek & Ambrizi, 2008), the major ongoing transformations in the area demand constant re-evaluation, especially in terms of its spatio-temporal distribution, providing the basis for future actions to reduce negative impacts which might be aggravated in the context of climate change.

Therefore, the present study aimed to detect and evaluate changes in the rainfall distribution in the state of São Paulo, with emphasis on extreme events. The analyses were undertaken with data from 79 stations spread across the state for a 40-year period (1973-2012, P0). In addition to the analyses of P0, which presented the main features of the spatio-temporal distribution of precipitation in the state, two sub-groups (P1, 1973-1992 and P2, 1993-2012) were evaluated and compared, in view of observing whether the same trends were found in all periods. The shape and scale parameters of the gamma distribution were employed at the annual level to detect regions of the state where the distribution of precipitation is more regular or more heterogeneous; while the 5th and the 95th percentiles were used do define, respectively, the extreme dry and wet events at the monthly and seasonal levels. A qualitative evaluation was performed for a period outside of the quantitative analysis undertaken, confronting some recent extreme episodes (too wet and too dry) that had major socio-environmental impacts in the state with the patterns found by the quantitative evaluations.

The article is organized as follows: Section 2 describes the physical and socioeconomic characteristics of the study area and presents the dataset and the analyses performed for evaluating the spatio-temporal pattern of rainfall. In Section 3 the results of the analyses for a reference period (P0, 1973-2012) and for two sub-groups (P1, 1973-1992 and P2, 1993-2012) are presented in the form of maps, and the spatial and temporal trends revealed are compared and discussed. Some recent occurrences of drought and heavy precipitation recorded after the period evaluated (1973-2012) are also discussed and compared with the verified patterns of the quantitative analysis. Conclusions and further discussion of general implications of the changes found appear in Section 4.

2. Data and Methods

2.1. Study Area

The state of São Paulo (**Figure 1**) is a place of interactions among the terrestrial, maritime and atmospheric environments, with extensive climatic, topographic

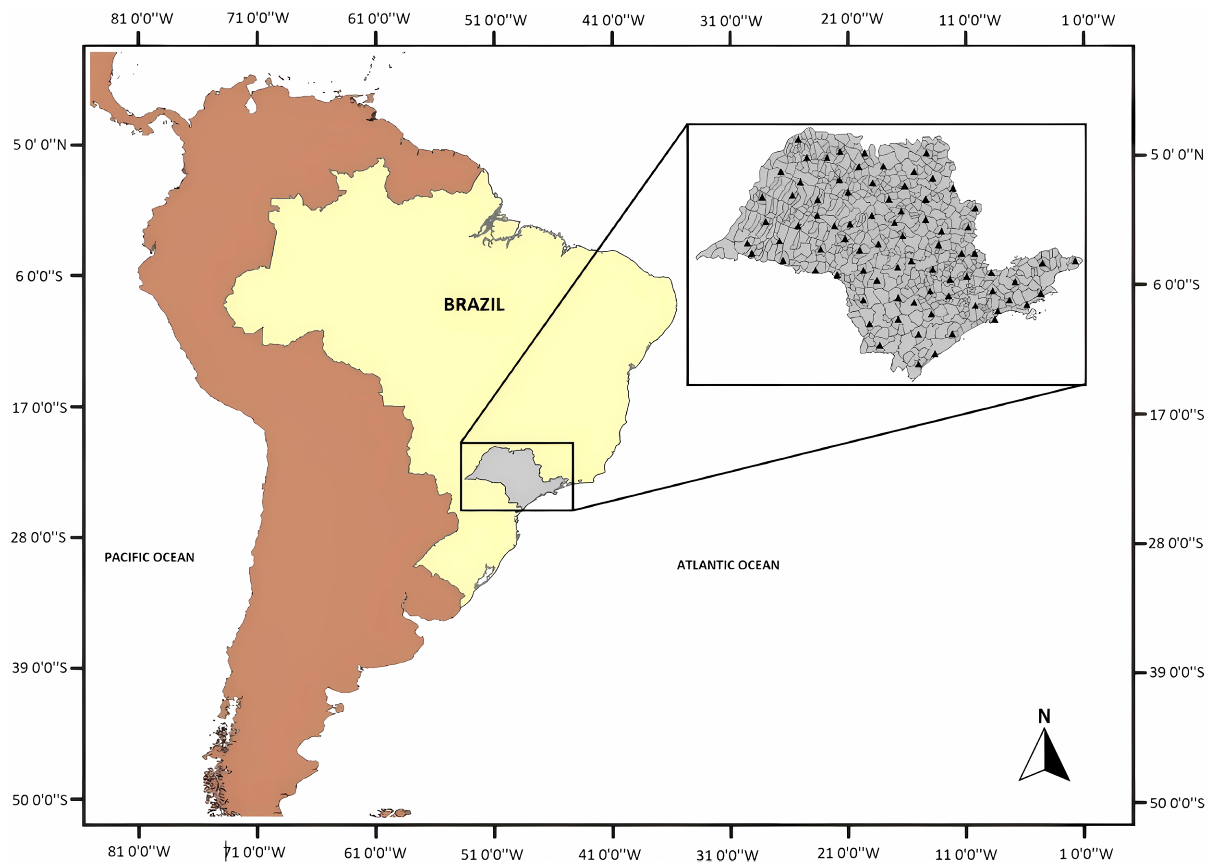


Figure 1. Location of the state of São Paulo in Brazil and South America; triangles in the zoomed view represent the set of rain gauges analysed.

and biological diversity. At zonal level, the state is crossed by the Tropic of Capricorn, ensuring tropical and subtropical characteristics. At regional level, the state is under the influence of various air masses which are associated with different conditions of temperature, stability and moisture content: maritime tropical, continental tropical and polar. At local level, the surface configuration, changes in land use, which includes replacement of vegetation by urban elements, as well as river channelling, are important elements in the range of precipitation.

By **Figure 2**, which presents the altimetry of the state, one can observe that São Paulo presents an undulating terrain, and although the elevation variations are not pronounced (about 85% of the territory is between 300 and 900 m. altitude), they promote important alterations in the volume of precipitation (Conti, 1975; Candido & Nunes, 2008). The prevalent topographic characteristic of the state is a relatively uniform plateau which extends east-west across the state. The coastline of 600 km is bordered by the slopes of the Serra do Mar Escarpment,

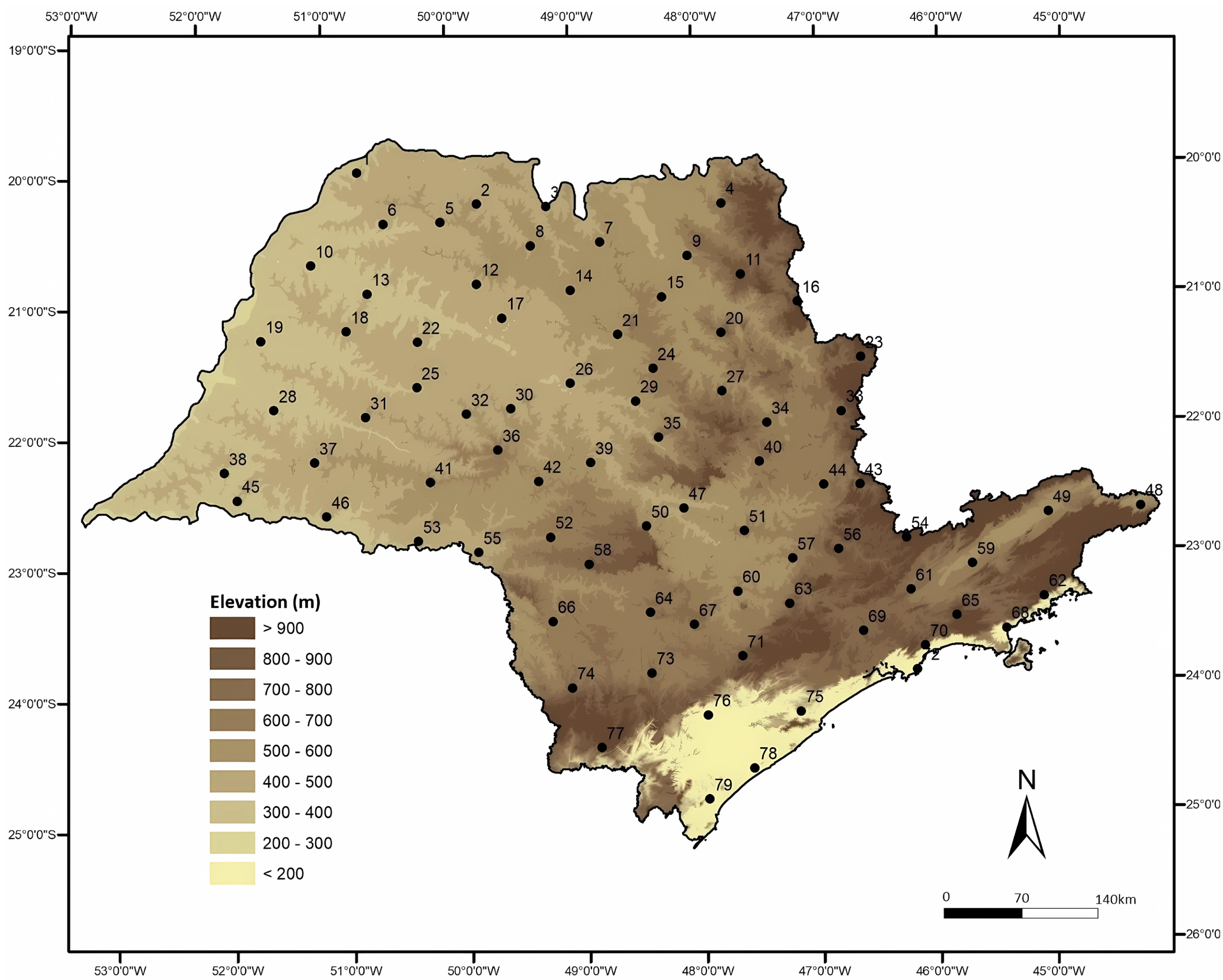


Figure 2. Altimetry and rain gauge stations evaluated in this study. The sequence of numbers (rain gauges) follows an increasing order of latitude.

on the edge of a plateau 460 to 920 m. above sea level. In the eastern, the Mantiqueira Escarpment is the predominant feature. The state is drained by various rivers and tributaries, most of them running through the state from southeast to west (Silva, n.d; Martinelli, 2009).

The state presents significant spatio-temporal rainfall variability (Setzer, 1972; Monteiro, 1973; Nunes, 1997; Sant'anna Neto, 1997) associated with global and regional meteorological phenomena such as the South Atlantic Convergence Zone (SACZ), which is a band of persistent cloudiness associated with convergent flow in the low troposphere from the southern Amazon to the south-central Atlantic, which generates conditions of great instability (Sugahara, 1991; Carvalho et al., 2004; Carvalho & Jones, 2009; Malvestio, 2013; Drummond et al., 2014). El Niño also interferes in the patterns of precipitation distribution in São Paulo, with strong events tending to be wet (Nunes, 1997; Nery et al., 1999).

State-wide averages of annual precipitation ranges from more than 4500 mm in the central coast to less than 1200 mm in the interior. The spatial distribution of precipitation presents a clear gradient, with a decrease in total precipitation in the coast-inland direction. The temporal distribution of rainfall in the state is also uneven: 70% of the total volume is recorded in the spring-summer period (Nunes, 1997).

Home to over 46.6 million people, corresponding to 21.9% of the Brazilian population (IBGE, estimate 2021), the state of São Paulo covers an area of 208,219.5 km^2 or 2.9% of the Brazilian territory, but accounts for 31.0% of the national GDP, a volume greater than entire economies like Chile, Belgium, South Africa and Singapore. The state has the fourth largest consumer market in Latin America, behind Brazil as a whole, Mexico and Colombia. The relative participation of São Paulo in the different economic sectors in Brazil is very significant: 36.0% of the industrial production, 33.5% of revenues generated in the service sector and 12.0% of the agricultural income (InvestSP, 2022).

The state of São Paulo has undergone severe and rapid environmental changes due to urban growth, deforestation, pollution, soil degradation, and exploitation of natural resources. After centuries of significant loss of original vegetation (Victor et al., 2005) in recent years the state has experienced an increase in the area covered by the native vegetation in various stages of recomposition, which went from 17.9% in 2010 to 22.9% in 2020. However, the fragmentation of biomes in São Paulo is one of the main problems to be faced regarding the conservation of the remnants (Instituto Florestal, 2020).

Furthermore, between 1980 and 2021 the population increased from 24,953,238 to 46,649,132 inhabitants. In 2021, the urban population was estimated at 96.6% while in 1980 this rate was 88.6% (IBGE). The large population and economic activities make the state dependent on a regular distribution of precipitation, so that any change in the pattern of rain distribution can cause major disturbances. In the state, excess of rain that causes floods and landslides and droughts are the most frequent and disruptive hazard events, with important impacts for both urban and rural areas.

Nonetheless, the excess or the deficit of rain on local and national economy is but one of multiple stresses facing the state of São Paulo, whose consequences can be exacerbated by the disorderly growth of cities combined with lack of infrastructure, unplanned land occupation, socio-spatial segregation, pollution and absent or inadequate public actions.

2.2. Methodology

Rainfall data of 79 rain gauge stations encompassing a 40-year period were selected to represent the different climatic and geomorphological domains of the state (**Figure 1**, **Figure 2** and **Table 1**). The 40-year period (P0, 1973-2012) was divided into two: P1 (1973-1992) and P2 (1993-2012) and the same analyses were performed for both sub-groups to observe whether the spatio-temporal trends have been maintained or changed and if so, where the greatest variations would be occurring. The evaluation was undertaken at annual, monthly and seasonal levels (wet and sub-humid to dry seasons) by analysing the parameters of the gamma distribution, shape (α) and scale (β), as well as percentiles that defined positive (R95p) and negative (R5p) extreme values of rain, i.e.: too wet and too dry episodes.

The selected stations (**Table 1**) were obtained from the Sistema de Informações para Gerenciamento de Recursos Hídricos do Estado de São Paulo, Banco de Dados Hidrológicos, DAEE, from the Secretaria de Saneamento e Recursos Hídricos do Estado. From **Figure 2** one can verify that the rain gauge network was sufficiently dense to reflect the spatial variations throughout the state as well as to observe the altimetric variations over São Paulo.

Overall, 78 out of 79 stations presented only 5.0% of gaps throughout the period of 40 years (**Table 1**). The only exception (station 13) was maintained because the percentage of gaps (7.5%) was considered acceptable and the station is in a region of regular relief which, therefore, tends to present a more homogeneous distribution of rainfall in space (Jackson, 1969).

The linear regression method was used to fill missing values as proposed by the National Water Agency (Brasil, ANA, 2012), which states that "the spatial condition of precipitation always suggests the need to analyse data from groups of nearby pluviometric measuring stations to fill gaps in records or replace observed and erroneous data". Therefore, for the replacement of the gaps the criteria were geographical proximity, linear correlation between the stations greater than 0.90 and absence of gaps in the month at the station used for substitution.

Table 1. Rain gauge stations and percentage of gaps (monthly data), http://www.hidrologia.daee.sp.gov.br/.

	Rain Gauge	Lat (S)	Lon (W)	% Gaps		Rain Gauge	Lat (S)	Lon (W)	% Gaps
1	B7-013	20˚02'	50˚44'	-	41	D7-046	22˚26	50˚13'	1.88
2	B6-033	20˚18'	49˚46'	0.83	42	D6-021	22˚27'	49˚19'	0.46

Continued

3	B6-001	20˚20'	49˚12'	1.25	43	D3-014	22˚31'	46˚39'	0.21
4	B4-034	20˚20'	47˚46'	-	44	D3-009	22˚31'	46˚57'	0.42
5	B7-011	20˚26'	50˚04'	0.63	45	D8-004	22˚31'	51˚49'	1.04
6	B7-038	20˚26'	50˚32'	0.42	46	D8-013	22˚40'	51˚05'	0.21
7	B5-012	20˚37'	48˚46'	0.63	47	D5-044	22˚41'	48˚07'	0.21
8	B6-003	20˚38'	49˚20'	0.63	48	D1-001	22˚41'	44˚19'	1.04
9	B5-004	20˚44'	48˚03'	-	49	D2-035	22˚44'	45˚05'	0.63
10	B8-001	20˚44'	51˚08'	0.63	50	D5-019	22˚49'	48˚26'	-
12	B6-034	20˚55'	49˚47'	-	52	D6-006	22˚53'	49˚14'	1.67
13	B7-048	20˚58'	50˚41'	7.50	53	D7-031	22˚53'	50˚20'	-
14	B6-009	20˚59'	49˚01'	-	54	D3-054	22˚56'	46˚16'	0.42
15	C5-040	21˚03'	48˚16'	-	55	D6-011	22˚59'	49˚50'	-
16	C4-001	21˚06'	47˚09'	0.21	56	E3-015	23˚01'	46˚50'	-
17	C6-036	21˚11'	49˚35'	-	57	E4-015	23˚05'	47˚13'	-
18	C7-034	21˚15'	50˚52'	-	58	E5-014	23˚06'	48˚55'	0.42
19	C8-008	21˚18'	51˚34'	0.42	59	E2-034	23˚08'	45˚43'	-
20	C5-073	21˚20'	48˚38'	-	60	E4-019	23˚20'	47˚41'	0.21
21	C4-032	21˚20'	47˚47'	-	61	E3-049	23˚20'	46˚14'	0.63
22	C7-024	21˚21'	50˚17'	-	62	E2-009	23˚23'	45˚07'	0.63
23	C3-014	21˚32'	46˚38'	0.21	63	E4-043	23˚26'	47˚15'	2.08
24	C5-074	21˚36'	48˚21'	0.42	64	E5-017	23˚29'	48˚25'	-
25	C7-064	21˚42'	50˚18'	0.21	65	E2-054	23˚32'	45˚51'	-
26	C5-082	21˚42'	49˚02'	3.54	66	E6-013	23˚32'	49˚14'	-
27	C4-019	21˚47'	47˚47'	0.21	67	E5-015	23˚35'	48˚03'	-
28	C8-026	21˚50'	51˚29'	-	68	E2-046	23˚38'	45˚26'	1.04
29	C5-016	21˚51'	48˚30'	0.21	69	E3-035	23˚39'	46˚38'	-
30	C6-051	21˚53'	49˚32'	1.04	70	E3-040	23˚46'	46˚07'	1.46
31	C7-062	21˚55'	50˚44'	0.63	71	E4-028	23˚50'	47˚39'	-
32	C6-071	21˚55'	49˚54'	0.83	72	E3-043	23˚57'	46˚11'	0.21
33	C3-031	21˚57'	46˚48'	-	73	E5-071	23˚57'	48˚25'	0.83
34	C4-033	22˚02'	47˚25'	-	74	F6-003	24˚03'	49˚05'	-
35	D5-023	22˚08'	48˚19'	-	75	F4-006	24˚16'	47˚10'	0.21
36	D6-018	22˚12'	49˚39'	-	76	F4-025	24˚17'	47˚57'	0.21
37	D8-041	22˚15'	51˚10'	-	77	F5-019	24˚31'	48˚51'	-
38	D8-008	22˚18'	51˚55'	1.46	78	F4-028	24˚42'	47˚34'	0.21
39	D5-018	22˚19'	48˚53'	0.21	79	F4-029	24˚56'	47˚57'	1.04
40	D4-016	22˚20'	47˚29'	-					

Outcomes were mapped, enhancing the spatial patterns. Isoline maps were generated through kriging, which is a geostatistical interpolation technique widely used in geosciences that considers both the distance and the degree of variation between known data points when estimating values in unknown areas (Paramasivam & Venkatramanan, 2019).

Additionally, some events registered after 2012 that brought major impacts were surveyed and compared with the results of the gamma and percentile analyses. The distinct period between the quantitative and qualitative assessments allowed to observe, in a more independent way, how much the qualitative evaluation corroborated the previous quantitative analysis.

2.2.1. Gamma Distribution

The gamma distribution is useful for indicating changes in extreme totals and to reveal changes in the variability, and has been extensively used in climatology and hydrology (Thom, 1958; Ison et al., 1971; Wilks, 1995; Ben-Gai et al., 1998; Juras, 1994; May, 2004; Michaelides et al., 2009; Liang et al., 2012; Martinez-Villalobos & Neelin 2019).

Gamma is a two-parameter probability distribution suitable to model continuous variables that contain only positive values, i.e., equal or greater than zero, and have skewed distribution, like rain. As state by Markovic (1965), Juras (1994) and Husak et al. (2007), there is no single distribution for studies addressing precipitation, but the gamma distribution presents a number of advantages: it reduces the essential information of the values observed to a few parameters, is limited to the left by zero, i.e., it does not admit negative values (which is the case of precipitation) and because of its very flexible parameters of shape (α) and scale (β) it can be adjusted to several precipitation regimes (Wilks, 1995; Husak et al., 2007).

The shape parameter (α) expresses the degree of asymmetry of data distribution, while the scale parameter (β) represents the range of values; in other words, α describes the distribution curve: the smaller the value, the more distorted the distribution is and the higher its value, the more the sample approaches the normal curve, that is, the more symmetrical and equally distributed is the rainfall. In turn, the scale parameter represents the probability of having a specific value: the higher the value of β, the greater the probability of extreme events and the greater the variance of the rainfall data, and vice versa (Wilks, 1995).

The gamma distribution function is described by Thom (1958) through the equation:

$$f(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad \beta > 0 \quad \alpha > 0$$

where x represents the study variable (rainfall), β is the scale parameter, α is the shape parameter, e is the mathematical constant Euler's number and Γ is the gamma function.

The two parameters of gamma distribution were calculated using the maximum likelihood estimation method which, according to Thom (1958), is the most efficient and produces the best results. The outcomes allowed to observe the spatio-temporal patterns of irregularity and extremes of precipitation in the state of São Paulo.

2.2.2. Extreme Events

The extreme events of rainfall, i.e., those in the upper and lower limits of the probability distribution, were defined by percentiles at monthly and seasonal levels, which divide the values into classes or categories of certain probabilities/frequencies (Xavier et al., 2007).

The extreme events of rainfall, i.e., those in the upper and lower tails of the probability distribution, were defined by the percentile, used for the same purpose by May (2004), Rodrigo (2010) and Zolina et al. (2014). A k-th percentile of order p (defined for $0 < p < 1$) is a numerical value that sections the distribution into two parts, with probabilities p to the left of this theoretical percentile, and $1 - p$ to the right, where values above and below that set by a given percentile make up 100.0.

Averaged monthly data of all 79 rain gauge stations for the 40-year period defined the 95th and the 5th percentiles i.e., the 5% largest and the 5% smallest rainfall events, respectively. Using the procedure employed by Rodrigo (2010), the same monthly rainfall amount equal to or greater than 319.7 mm defined all monthly wet episodes, while totals equal to or below than 6.1 mm identified the dry extremes in all months, enabling the spatial comparison of wet and dry extremes between P1 and P2 to highlight the spatial differences between the two periods.

In view of the seasonal differences in rainfall distribution in the state of São Paulo, since autumn and winter record, on average, only 30% of annual totals (Nunes, 1997), the pattern of extreme events (95th and 5th) was analysed for the rainy period (October to March) and for the sub-humid to dry period (April to September). The thresholds that defined the positive (95th) and negative (5th) extreme seasonal occurrences were, respectively, 353.1 mm and 59.5 mm for the rainy season and 167.5 mm and 4.5 mm for the sub-humid to dry season.

The results of the gamma distribution and percentile analyses are presented in the form of maps for P1 and P2, which revealed the spatio-temporal patterns of the variables.

3. Results and Discussion

3.1. Rainfall Pattern in the State of São Paulo

From **Figure 3** it can be observed the influence of the topographic and atmospheric conditions described in Section 2.1, with higher rainfall volumes near the coast and mountain ranges and a noticeable decrease towards the northern and western regions. In the coastal zone the annual rainfall can exceed 3000 mm per year, while the rest of the state presents total annual precipitation that can reach 1000 mm per year in some locations. The state average is about 1500 mm per year.

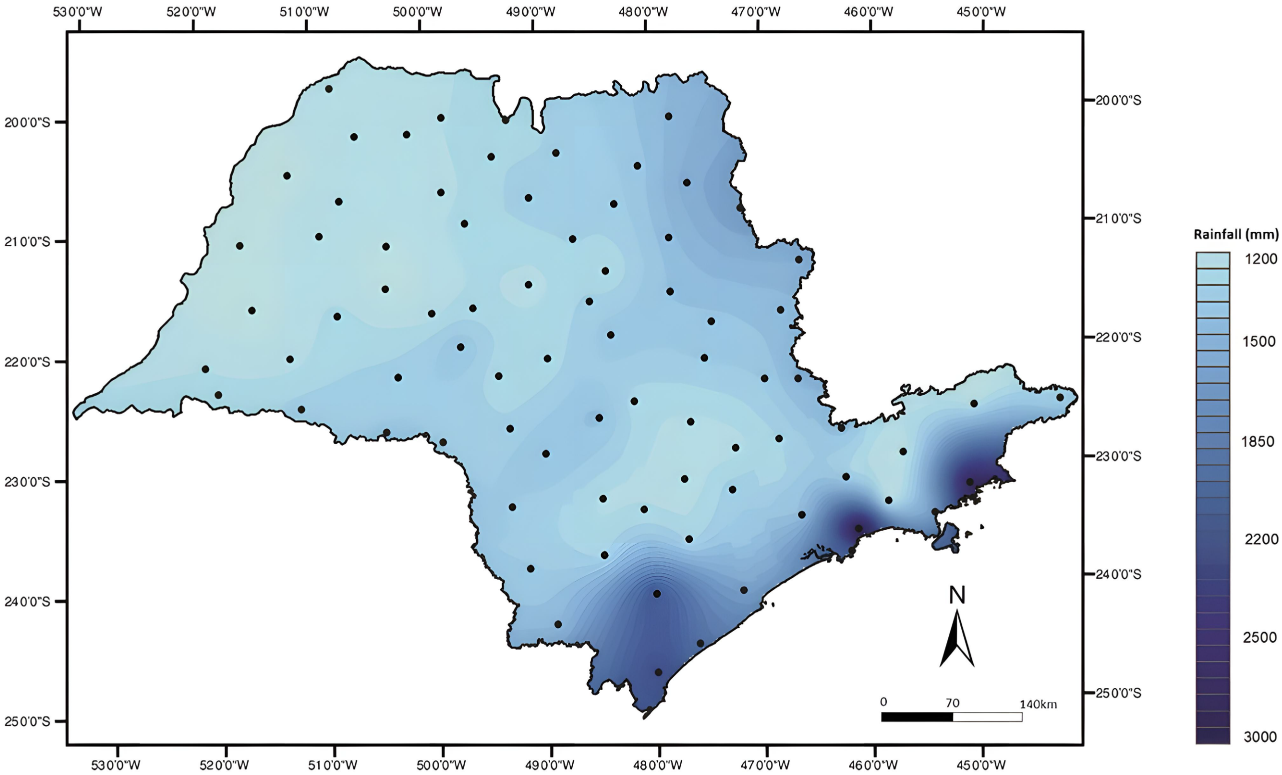


Figure 3. Annual rainfall distribution over the state of São Paulo for the period 1973 to 2012.

Figure 4 shows the distribution of the 5th percentile (dry extremes) and the 95th percentile (rainy extremes) for the period P0. It can be noted a coast-inland gradient, with a gradual reduction of extremes from the innermost areas to the coast, and a remarkable latitudinal pattern in the distribution of dry events, also observed by Setzer (1972), Monteiro (1973) and Nunes (1997) when analysing the precipitation in the state during winter, which is the drier season. This is so because winter rains are strongly related to polar air masses that roughly move from south to north and gives a latitudinal pattern to the distribution of rain in drier periods (Monteiro, 1973), while precipitation in summer and spring is associated with various other phenomena, such as local convection (convective or summer rains) and the SACZ (Carvalho et al., 2004; Carvalho & Jones, 2009; Malvestio, 2013; Rosa et al., 2020).

3.2. Gamma Distribution Parameters

Figure 5 shows the scatter plot of the rain gauge stations in relation to the shape and scale parameters of the gamma distribution for P1 and for P2. Across the state there is a significant difference in the values of the shape parameter, observed in both periods, which indicates greater irregularity in the distribution of precipitation in areas where values are lower (for most rain gauge stations, as can be observed in **Figure 5**) and better distribution where this parameter is higher. The values of the scale parameter also differ across the state, with the highest values associated with places where the probability of extreme events is

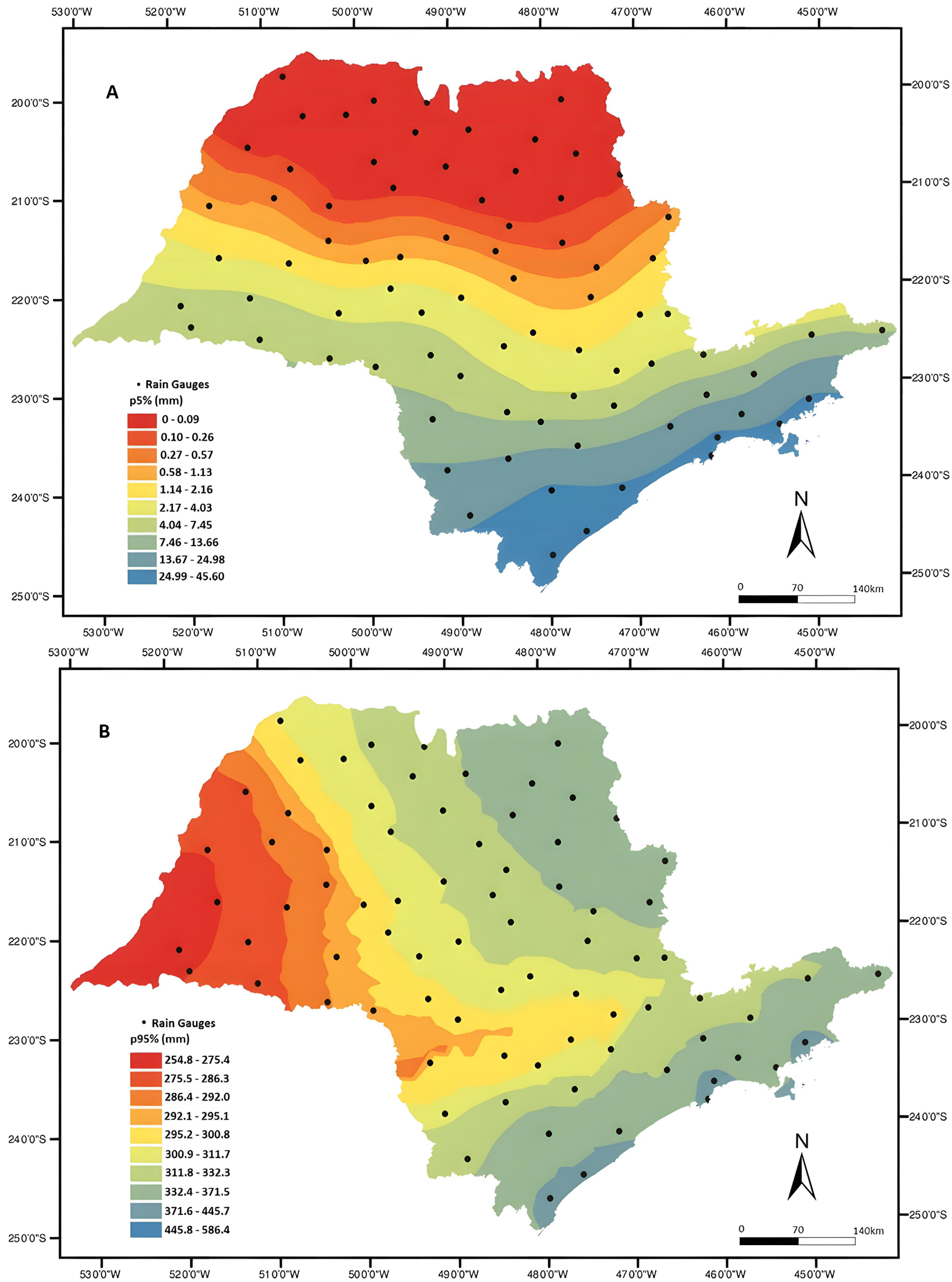


Figure 4. Averaged rainfall values of 5th (A) and 95th (B) percentiles (mm) for the period P0 (1973-2012) for the state of São Paulo.

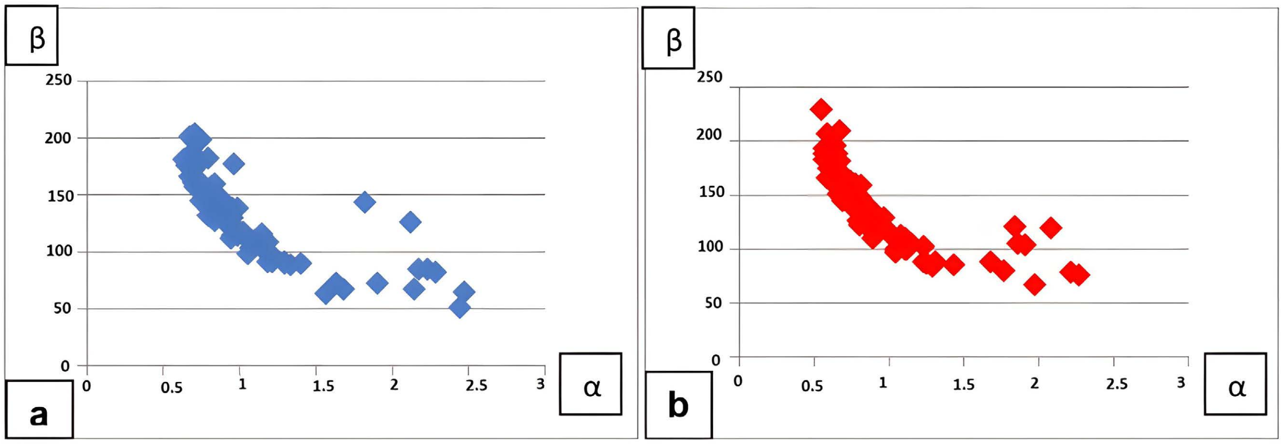


Figure 5. Scatter plot of precipitation values in relation to the parameters of shape (x axis) and scale (y axis), for 1973-1992 (a) and 1993-2012 (b).

higher. The most recent period (b) showed a decrease in the values of the shape parameter concurrent with an increase in the values of the scale parameter, indicating an increase in the area of the state with more irregular rainfall and in the area with incidence of extreme events.

Husak et al. (2007) point out that, as a rule, the gamma distribution shows three characteristics: 1) stations dominated by the scale parameter (high β and low α), where the variability is greater, 2) stations dominated by the shape parameter (high α and low β), where rainfall is constant and 3) areas where rainfall is very low, with low capacity to sustain agriculture (arid climates). In the state of São Paulo the rainfall stations further south and on the coast would be dominated by the shape parameter, with more regular rainfall and fewer extreme events due to the constant contribution of moisture (greater frequency of polar masses that bring moisture and the sea breeze), while the stations in the central and northern areas of the state, less subject to the moderating effect of humidity, would be dominated by the scale parameter, with a more variable rainfall and more extreme occurrences. There are no stations in the third category, since those with very low α values present high β values, ensuring enough rainfall to maintain agricultural and other activities. **Figure 6** shows the rainfall stations dominated by the scale and by the shape parameter.

The spatial variability of the shape parameter (**Figure 7**) shows a clear coast-inland gradient for both P1 and P2. The lower values toward the interior of São Paulo in both periods reveal that most of the state is dominated by a more irregular rainfall regime, with a tendency to become drier, while the distribution of precipitation in the coast is more regular, given that the values of the shape parameter are higher. Although the minimum values of the shape parameter in the north of the state are lower in the first period (which indicates greater heterogeneity in the rainfall distribution), the highest values (on the coast) are also lower in P2, which suggests an increase in rainfall irregularity in the entire state.

The isolines of the scale parameter (**Figure 8**) show a general trend of increasing values from the interior to the coast, which implies a higher probability

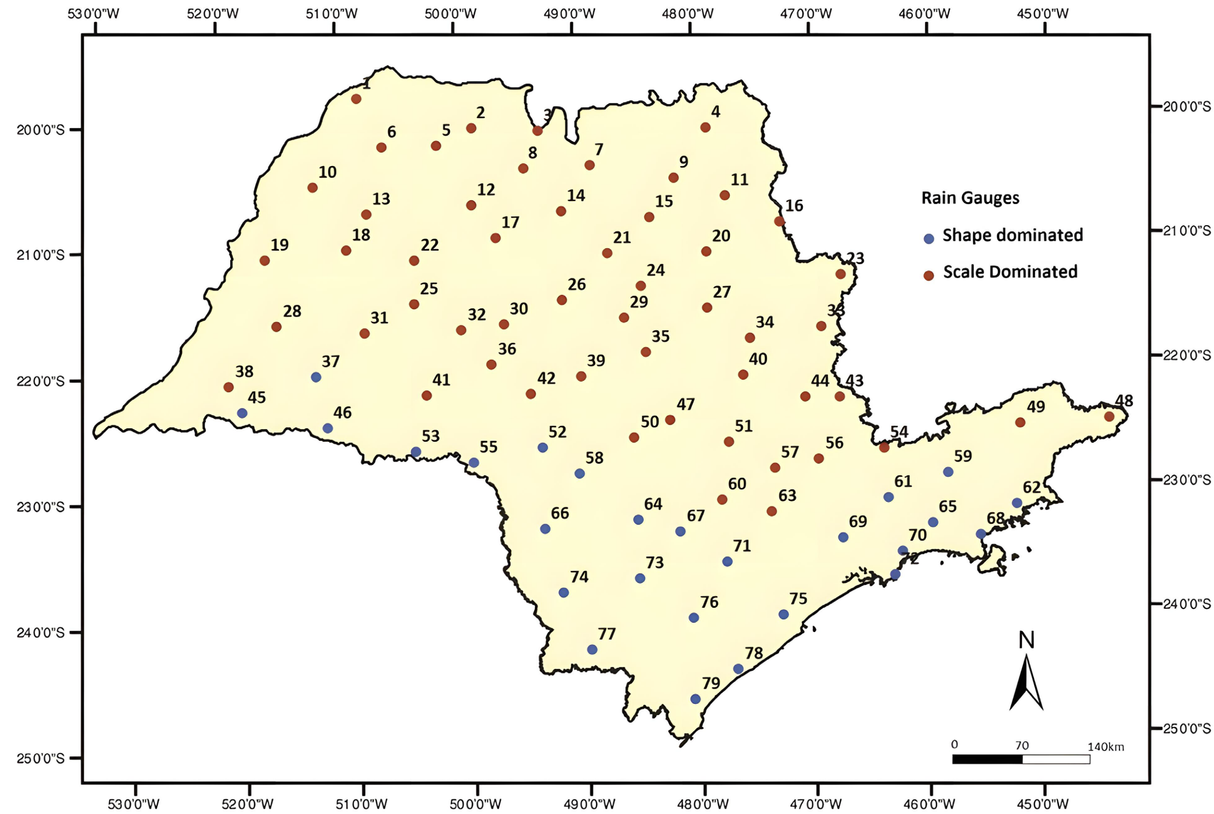
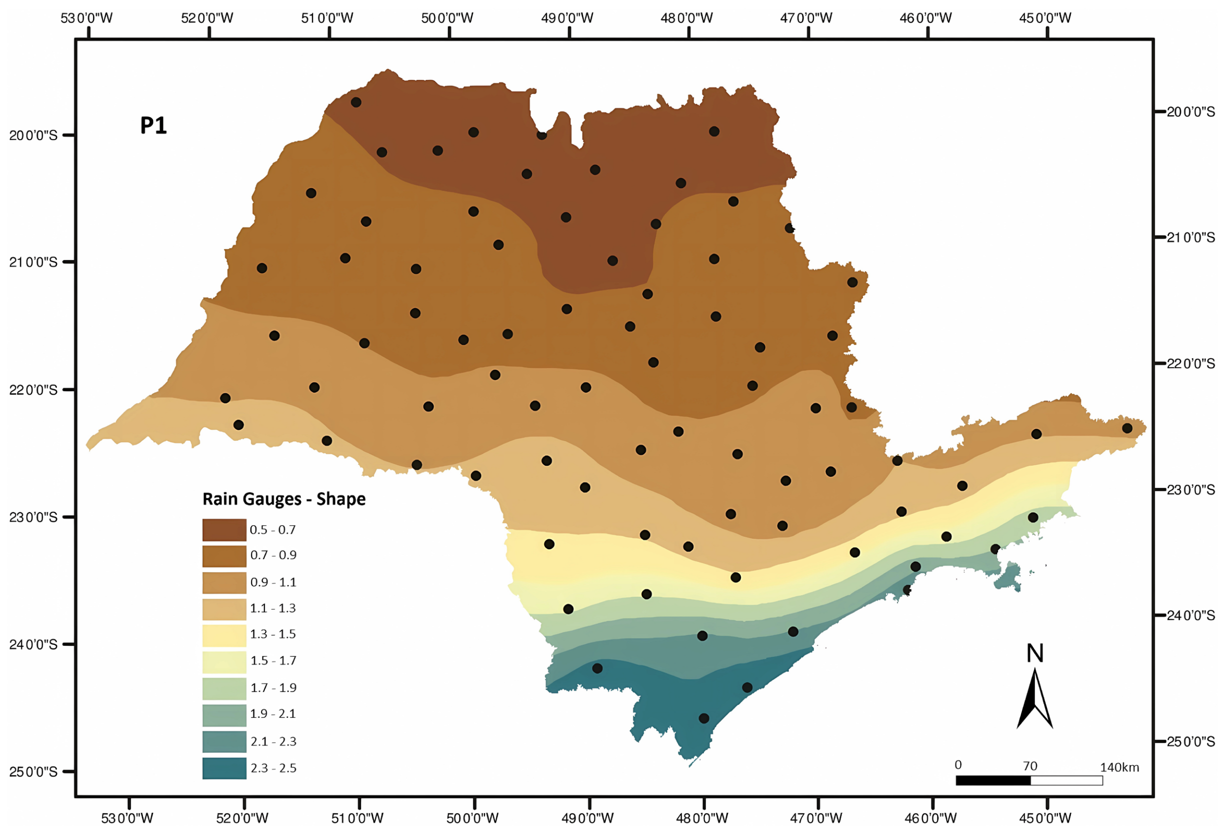


Figure 6. Rain gauge stations dominated by the shape parameter (which indicates more constant distribution of rainfall) and by the scale parameter (which indicates extremes) in the state of São Paulo for the period 1973 to 2012.



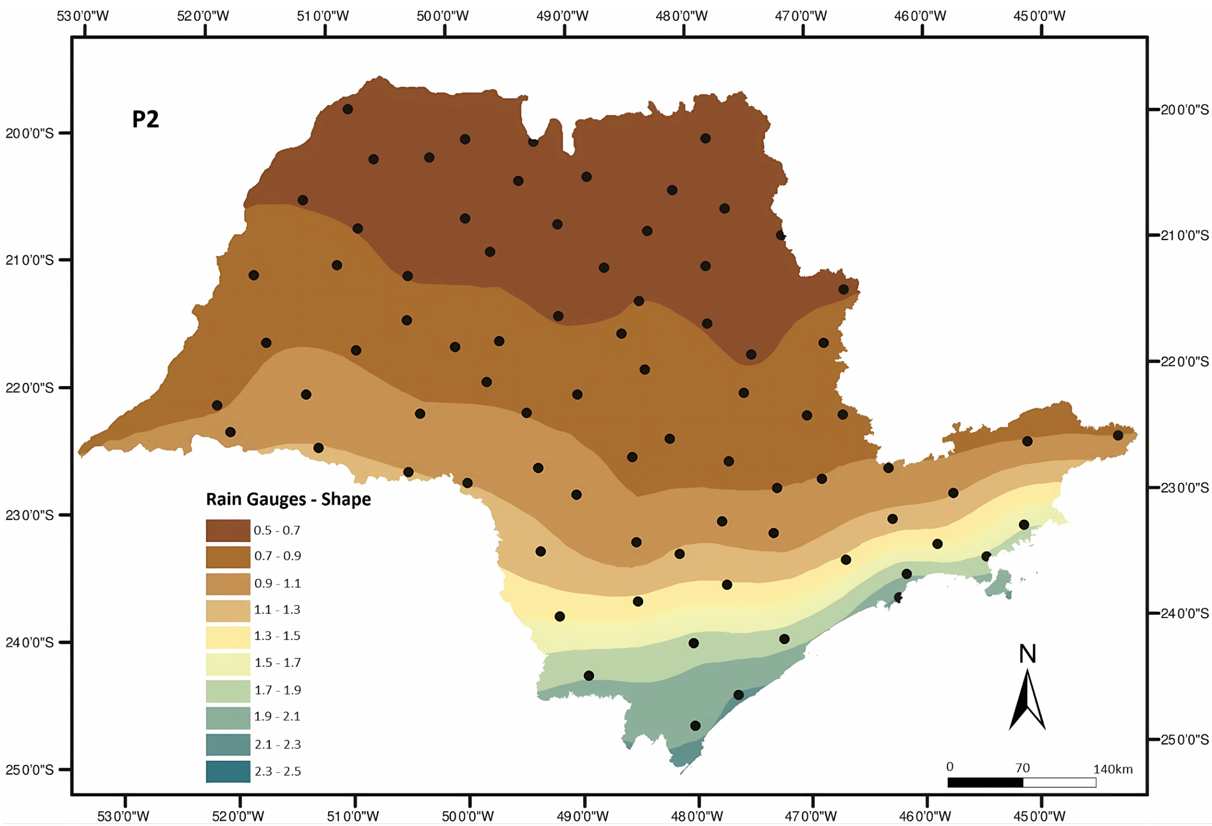
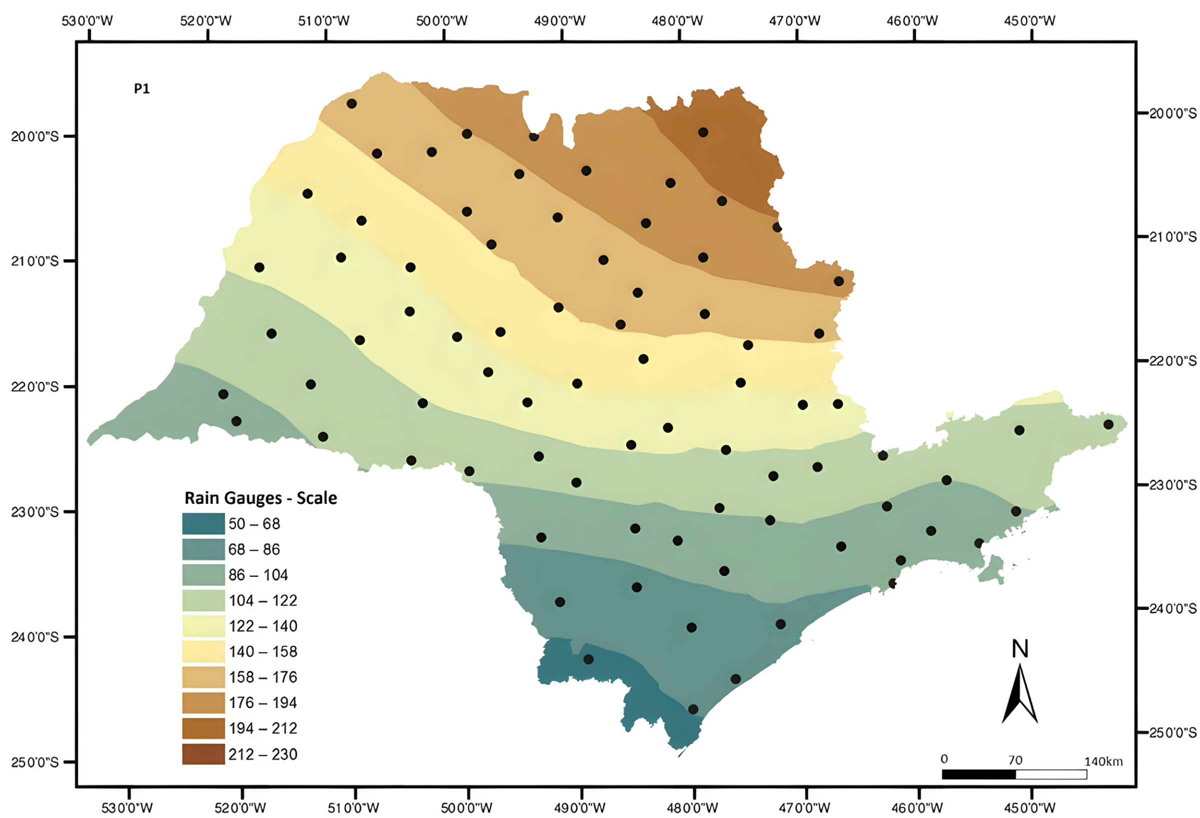


Figure 7. Spatial distribution of shape parameters for annual values of precipitation in the state of São Paulo in two periods: 1973 to 1992 (P1) and 1993 to 2012 (P2).



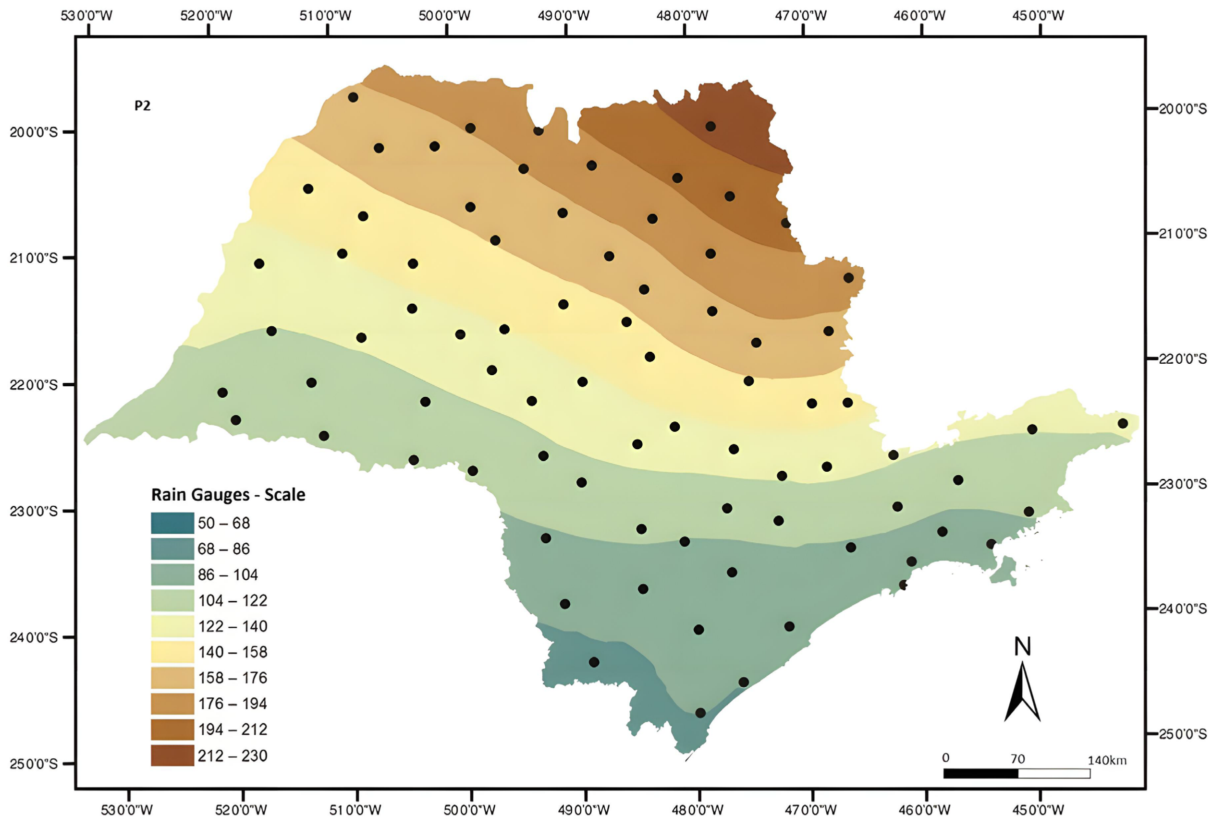


Figure 8. Spatial distribution of scale parameters for annual values of precipitation in the state of São Paulo in two periods: 1973 to 1992 (P1) and 1993 to 2012 (P2).

of extreme events (very dry and very rainy) towards the interior. Even for the coast the scale parameter in P2 present higher values than in P1, which indicates the increasing probability of occurrence of extremes.

It is worth noting that the isolines follow a latitudinal pattern for both the scale and the shape parameter, revealing well-marked contrasts between the coastal area and the inland.

Based on the results of the analysis of shape and scale parameters in two periods, the state of São Paulo evolved to a pattern of increased irregularity in the rainfall distribution, besides an increase in extreme events, since the characteristics observed in P1 were enhanced in P2.

Figure 9 shows no significant change in average rainfall totals between P1 and P2. Over the 40 years the annual rainfall averaged over the state ranged from just over 1000 mm in 2000 to about 2100 mm in 1983 (**Figure 9**). The anomaly of precipitation in the early 2000s would be related to surface temperatures significantly below normal in the Pacific in the whole year and to the unusual presence of upper tropospheric cyclonic vortices which acted more frequently in the continent (Cavalcanti & Kousky, 2001). Drummond & Ambrizzi (2005) associated the anomaly with an anomalous low-level anticyclonic circulation in eastern Brazil, which inhibited the occurrence of the SACZ events. In turn, the high precipitation in 1983 was strongly influenced by a powerful El Niño event: in this

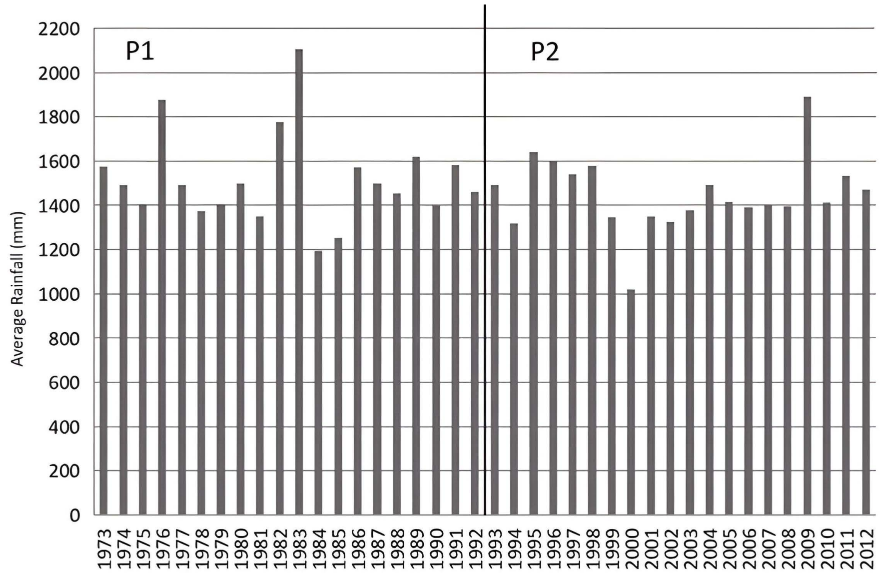


Figure 9. Average annual precipitation (mm) for (P1 and P2 enhanced). Each column expresses the average rainfall of the 79 stations for a given year.

year, the position of the subtropical jet stream over South America and to the west of the South Pacific Ocean favoured the entrance of active frontal systems that brought heavy precipitation in southern Brazil, including São Paulo (Kousky & Cavalcanti, 1984; Kayano & Moura, 1986).

A higher irregularity in P2 can be also identified in **Figure 10**, which presents the average anomalies (how much it rained above or below the state average) and the average rainfall in the state of São Paulo for the period of 1973 to 2012 divided into five-year intervals. The average rainfall anomalies present a negative variation of over 150.0 mm in the five-year period of 1998-2002 compared with the general average of the state, which reflects the remarkable dry period between 2000 and 2001 above mentioned.

3.3. Analysis of Extreme Events

Complementing the results obtained with the application of gamma distribution, the analysis of percentiles evaluated the monthly and seasonal extreme events.

An increase of approximately 10.0% in the number of both extreme wet and dry events is observed in P2 (**Figure 11**), which is consistent with the temporal evolution of the scale parameter of gamma distribution. Should this trend persist in the coming years, it would indicate a rapid and significant change in the rainfall pattern.

While 55.0% of the stations presented an increase in the values of extreme wet events in P2, 76.0% showed a reduction in the 0.05 percentile in the same period, which is in line with the reduction of the shape parameter and the increase of the scale parameter. These facts indicate a strong irregularity in the rainfall regime and a positive distortion in the distribution curve, with a greater number of very dry events compared with the very wet events.

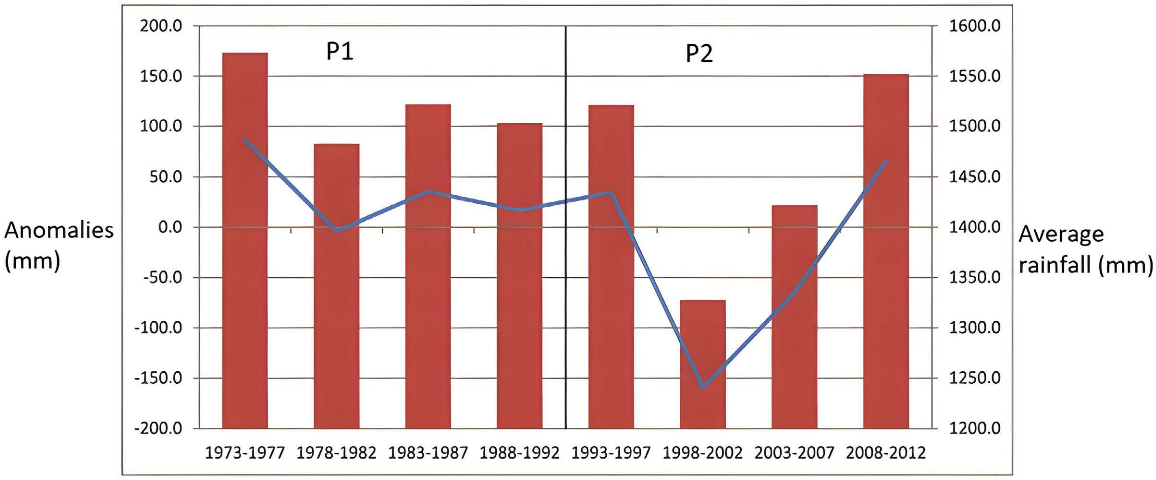


Figure 10. Five-year average rainfall anomalies (line) and average annual rainfall (columns) for the period of 1973 to 2012 (P1 and P2 enhanced).

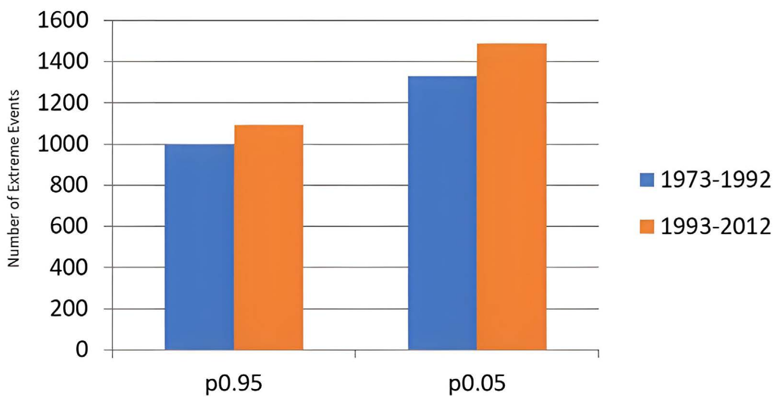


Figure 11. Number of extreme events (wet and dry) for the average of all rain gauge stations in the state of São Paulo for two periods: 1973-1992 (P1) and 1993-2012 (P2).

To observe the temporal evolution of the extreme events, Figure 12 and Figure 13 present, respectively, the spatial distribution of the percentiles of the extremes of the rainy season (October to March) and of the sub-humid to dry season (April to September) for P1 and P2.

Figure 12 presents the 95th percentile in the rainy season and shows that P2 also experienced a significant change in the spatial pattern of rainfall distribution, with the central and western areas of the state in classes of higher precipitation volumes in relation to P1.

Notwithstanding, although in P2 there was an increase in the area with higher rainfall volumes in the rainiest season, Figure 13 shows that P2 also registered a southward increase in the area with lower rainfall volumes in the sub-humid to dry period in most of the state, with exception of the coast, which did not present a notable difference.

The spatial pattern of Figure 11(b) and Figure 12(b), which present, respectively, the distribution of wet and dry extremes in P2, consistently support that the area has been experiencing a more contrasting seasonal distribution.

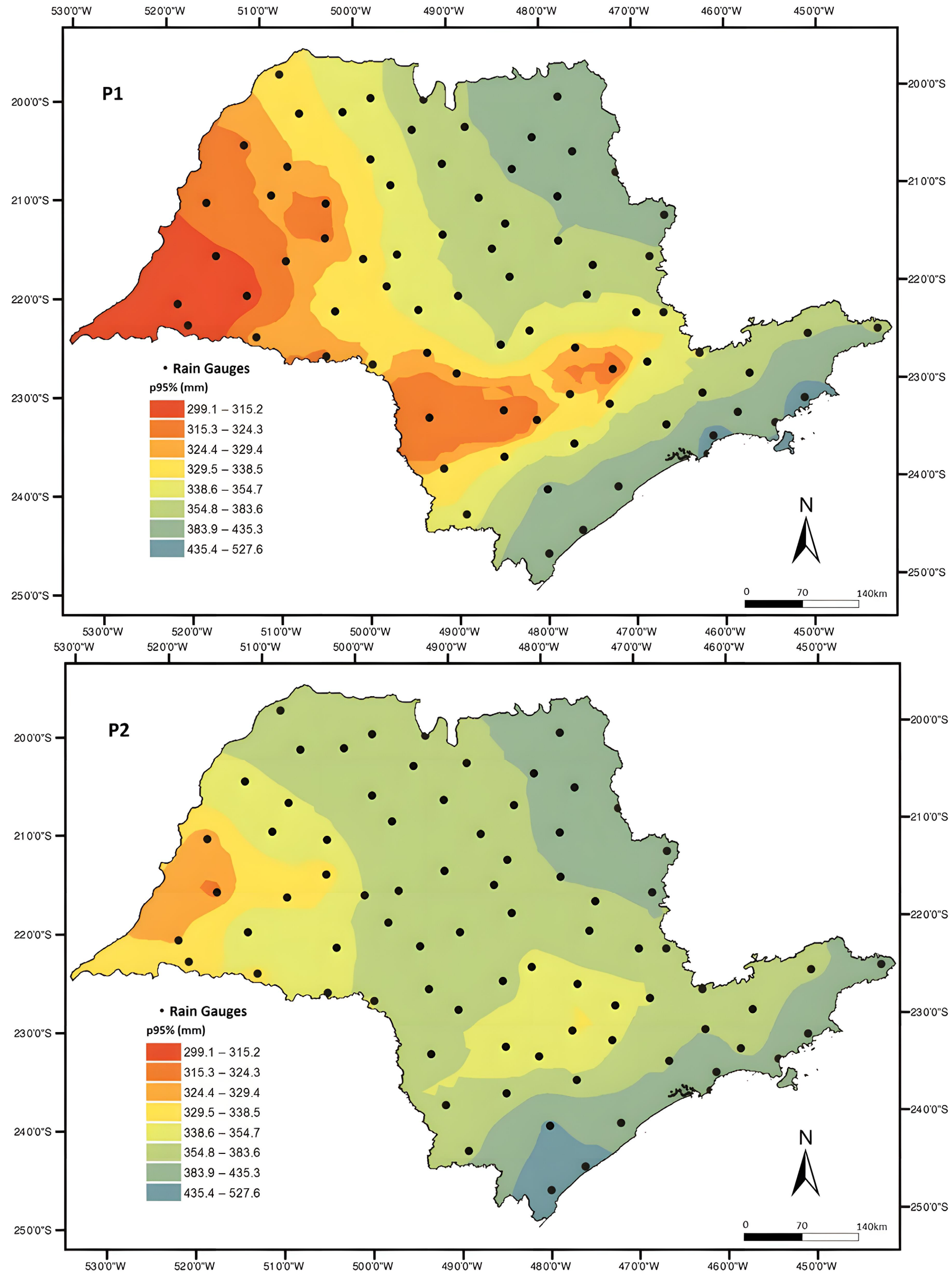


Figure 12. Percentiles of rainy extremes (P95th) in the rainy season in the state of São Paulo for two periods: 1973-1992 (P1) and 1993-2012 (P2).

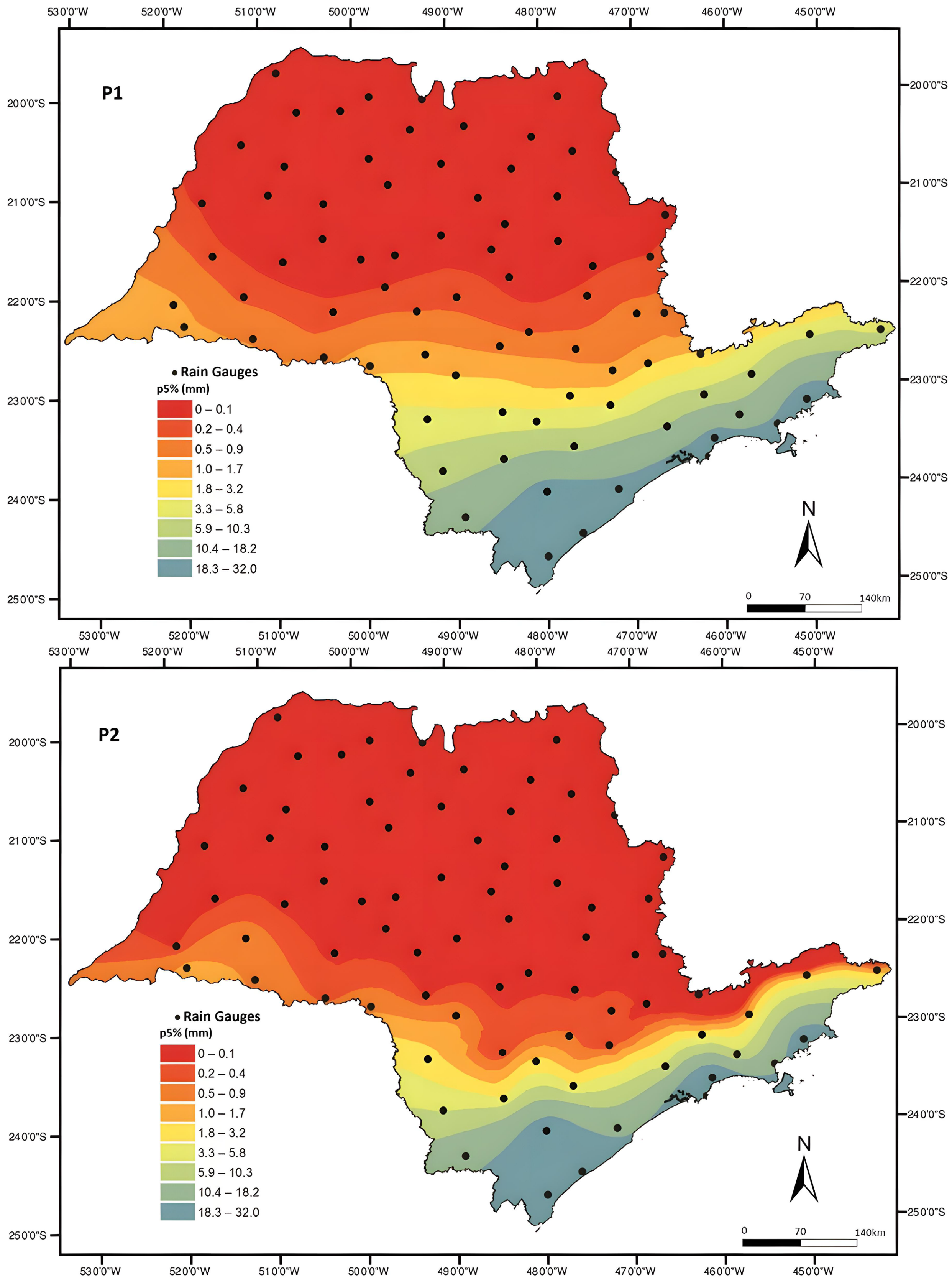


Figure 13. Percentiles of dry extremes (P5%) in the sub-humid to dry season in the state of São Paulo, for two periods: 1973-1992 (P1) and 1993-2012 (P2).

Changes in the spatial distribution of extreme events revealed a comprehensive increase in the rainfall variability within the state of São Paulo, consistent with previous studies. Sant'anna Neto (1997) evaluated rainfall data for the state between 1941 and 1993 and concluded that both positive and negative rainfall extremes showed increasing amplitudes, especially in the west. Rampazo & Nunes (2017) evaluated daily precipitation for the period between 1959 and 2013 and noted that distribution is more heterogeneous in locations of lower rainfall rates (north and west of the state of São Paulo), since the precipitation in these regions tends to be more concentrated, with few days presenting high volume. In a study for a few Brazilian states evaluating two datasets with more than 70 years of data, Zilli et al. (2016) found an increase in the frequency of rainy days and extreme daily precipitation only in the state of São Paulo. Gozzo et al. (2019) evaluated data from 1901 to 2010 and noted an increasing frequency of dry events in the north and northeastern portions of the state during the crop-growing season (spring), a positive trend in the extreme rainy events in the southern region, as well as a decrease of rainfall amounts in the central and western portions during winter, which is the driest season. A study for the Metropolitan Area of São Paulo showed that while between 1941 and 2000 there were 10 occurrences of rainfall above 100.0 mm, between 2001 and 2020 there were 11 episodes. In the case of rainfall above 80.0 mm there were 25 events in the last two decades and 19 in the previous six decades (Marengo et al., 2020). Evaluating the eastern of the state with data from 1940 to 2016, Machado et al. (2021) found that the largest part of the area presented a significant increase in the annual amount of rainfall, in the number of heavy rainfall pentads and in the 95th percentile and observed that mountainous and coastal areas showed opposite extreme rainfall evolution in relation to the other areas. These findings are in agreement with the present study, that also detected different behaviour of rainfall distribution in the coast region and higher variability in the interior.

3.4. Recent Extreme Precipitation Events over the State of São Paulo

In this Section some recent occurrences associated with lack or excess of rain that affected the state are examined in a qualitative way. These events were registered after the period of the quantitative analysis (1973-2012) and the goal was not to provide a comprehensive inventory of the events recorded since 2014 nor to analyse in detail the atmospheric situations associated with the highlighted occurrences, but rather to present very extreme episodes recorded over a few years that validate the results presented. The cases in focus, chosen by the criteria of severity and socioeconomic impacts, reflect the great irregularity that São Paulo has been facing in rainfall distribution, with intensification of heavy precipitation and severe droughts that follow each other in short periods of time, and place significant pressure on vulnerable groups, infrastructure, the economy and the ecosystems of the state.

The state has recorded in the last decades episodes of rainfall scarcity like in

1944, 1953-1954, 1962-1963, 1970-1971 and 2001 associated with different processes, such as the weakening of the SACZ in the rainy season and lower frequency of polar masses in the dry season (Monteiro et al., 1971; Monteiro, 1973; Cavalcanti & Kousky, 2001; Drummond & Ambrizzi, 2005; Cunningham et al., 2017).

In recent years two episodes of severe drought in São Paulo have gained prominence: from the end of 2013 until 2015 precipitation throughout the state registered a substantial decrease, which generated an acute water crisis with a significant impact on the economy. A number of measures was taken by the state government, including energy restrictions, improved pumping capacity and adding new rivers to the water supply in the most populous areas. The volume of water in many reservoirs fell to less than 10% of their total capacity and affected water supply, hydropower generation and agriculture in the state. The severe drought would be associated with disturbances in the atmosphere in the Indian Ocean that spread towards South America and favoured blockages that prevented both the passage of cold fronts over Southeastern Brazil and the formation of SACZ. The consequent absence of clouds would have contributed to the increase in temperatures, both at the surface and in the ocean (Coelho et al., 2016; Cunningham et al., 2017; Rodrigues et al., 2019; Getirana et al., 2021).

In the first half of 2021 the whole state but, in special, the north and western regions, experienced another period of severe drought, classified in the category of exceptional drought, the most severe in the Brazilian Drought Monitor System (Brasil, ANA, 2022a). The system recorded the slowdown of drought in other Brazilian states, but São Paulo continued with 100% of its area with drought until December (Brasil, Ana, 2022b). The drought of 2021 had strong impacts on hydroelectricity generation, since in the Paraná River Basin, which accounts for two-fifths of the energy produced in the country, river discharge fell to its lowest levels in 91 years, causing the country to have to burn more expensive and more polluting fossil fuels (Getirana et al., 2021).

It is interesting to note that only a few years separated these two severe drought events in São Paulo, whose consequences were particularly strong due to the large population of the state and the importance of its economy.

Besides severe droughts, the state has also registered numerous episodes of very intense rains which have brought great damage, displacement and deaths. Some of these events were highlighted in view of the great volume of accumulated rainfall and the balance of destruction and deaths.

In the summer of 2012-2013 about 24% of the cities of the state registered damages due to heavy rains. There was also an increase in fatalities and affected people, mainly in the Metropolitan Region of São Paulo, which encompasses 39 municipalities, as well as in coastal cities (Portal R7 Notícias, 2013). The period recorded 60 days of active SACZ, above the seasonal average for the period 1996-2016 (Rosa et al., 2020).

On 10 February 2019 a rain gauge station in the state capital recorded 184.0

mm, while the monthly average is 249.7 mm (Portal G1, 2019). The amount of February 2020 was the highest accumulated rainfall for the month in 37 years. As a result of such heavy rain dozens of lives were lost and thousands of people lost their homes (WMO, 2021b).

In early March 2020 coastal towns registered abnormal volumes of rain: Guarujá, for instance, recorded 282.0 mm in 12 hours (monthly average: 263.4 mm), and 405.0 mm in 72 hours (Portal G1, 2020a) that caused 38 deaths and displaced hundreds of people (Moreira & Almeida, 2021).

In January 2022 heavy rains left at least 5277 families homeless or displaced and caused 34 deaths across the state due to landslides and floods triggered by intense precipitation (Portal CNN Brasil, 2022). In the beginning of April 2022, Ubatuba, in the north coast, registered very high volumes of accumulated rain: in 72 hours, 585.0 mm, while the monthly average is 232.0 mm (Portal G1, 2022).

In addition, a survey of the Center for Weather Forecasts and Climate Studies of Brazil (CPTEC, INPE and Portal G1, 2020b) revealed that among the Brazilian municipalities with a population above 100,000 people, more than half of rainfall peaks during the last 5 years have occurred in the state of São Paulo.

Although the situations described have been associated with very low or very high volumes of precipitation, it must keep in mind that disasters reflect the conflicting interaction between climatological, socioeconomic and environmental factors (Nunes, 2009) that should be considered together, so that future extreme occurrences have less deleterious effects.

4. Conclusion

The knowledge of possible changes in the spatio-temporal distribution of precipitation is a key element for spatial planning and risk management and becomes more important at a time marked by changes of all kinds. Within this perspective, this work assessed patterns of rainfall distribution as well as the variability of extremes (very wet and very dry) for the state of São Paulo, an area of great concentration of people and economic activities, by examining data of 79 rain gauges for a 40-year period divided into two sub-groups: P1, 1973-1992 and P2, 1993-2012. The patterns were evaluated through the scale and the shape parameters of the gamma distribution and the 95th and the 5th percentiles. In addition, acute recent episodes associated with excess or lack of rain in São Paulo were analysed qualitatively and compared with the patterns found in the analyses undertaken for the period 1973-2012.

The results showed that although there was no significant change in rainfall totals between P1 and P2, in the most recent period there was a remarkable and widespread shift in the precipitation distribution in the state, with increase in both the irregularity and extreme events. There were a greater number of rain gauge stations that registered very dry events compared with the very wet events in P2. The differences were more significant in the north and west of the state, which present more continental conditions. However, even the coast, which has a more uniform distribution of rain, became less homogeneous. These conclusions are in line with others that have evaluated the spatial variability of precipitation in São Paulo using other techniques and temporal scale.

The rapid alternation between major droughts and very intense rainfall episodes verified in recent years is essential information for a complete explanation of the hydrologic cycle's response to climate change and its impacts (Pendergrass et al., 2017). The drier-than-normal periods are affecting the production of important crops such as sugarcane, coffee and oranges while the intense rainfall occurrences have impacted the urban centres dramatically.

The fact that these shifts occur throughout the territory, although in different magnitudes, opens new possibilities for interpreting these changes beyond those related to local and regional conditioning factors, especially in a context of global climate change. The results are in accordance with trends identified in other areas which also indicate increase in rainfall variability (IPCC, 2021) and reflect the extent to which human activities are changing the environment, being a good example to what Crutzen & Stoermer (2000) called the *Anthropocena Era*, when human activities become a significant force in the planetary dynamics. If the rainfall patterns found persist in the coming years, this would be a clear indication that the factors governing the rainfall variations would be associated with external controls being, thus, a consistent signal of climate change. Therefore, the present conclusions should be seen not as clear evidence, but as an indication of likely climate change. Further evaluations and an extended period of data are needed to eventually establish a connection with high level of confidence.

Given the large insertion of São Paulo in the global market, the increasing irregularity in rainfall distribution would pose mounting risks for the society and environment, whose consequences go beyond state, national and even regional borders. For example, the north and the west are the areas where agriculture and livestock production for the external market are the most important in the state. Severe droughts such as those faced in recent years in addition to making production more expensive, can even compromise the expected harvest and make the market less reliable, affecting the state and national economy. The uncertainty related to rainfall distribution might also bring impacts on water resource management, health, transport, industry, tourism and hydroelectric power generation. In addition, the state of São Paulo is very urbanized (it currently has nine cities with a population of over 500,000 inhabitants, IBGE) and most of the population lives in the capital and near the coast, where the accumulated rainfall causing floods and landslides has been breaking successive records. Therefore, local/regional environmental modifications should be considered for the understanding of changes in rainfall distribution patterns, which can have very negative impacts on the safety of the population and on the economy.

The outcomes have potential to be used by scholars and policy makers to prepare a safer future for people and to improve actions aimed at risk management. The state governance system, which involves state and municipal levels, has failed so far to adequately address the challenges posed by a changing environment. Some measures have been taking for preventing the effects of drought and heavy rainfall, such as the construction of long-distance channels to transport water and improvement in local warning systems when heavy rains are forecast, but many other steps must be taken to avert future impact, including community-based initiatives with permanent campaigns for more efficient use of water and energy and preservation of ecosystems. In special, it is necessary to change the timing of the procedures, valuing preventive measures rather than post-disaster emergency management policies.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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