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Scientific Paper

Spatiotemporal variability analysis of extreme rainfall events in the city of Petrópolis, Rio de Janeiro, Brazil

Análise da variabilidade espaço-temporal de eventos de chuvas extremas na cidade de Petrópolis, Rio de Janeiro, Brasil

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ABSTRACT

The city of Petrópolis is frequently affected by heavy rainfall events that favor the occurrence of natural disasters, such as landslides and flash floods, causing material and life loss. In this context, knowing spatial and temporal precipitation behavior during extreme events can be a valuable tool for preventing natural hazards. This work seeks to characterize the spatiotemporal distribution of extreme rainfall events in Petrópolis, utilizing rainfall data between 2011 and 2021. It proposes identifying extreme rainfall events using the daily and hourly accumulations to verify spatial and temporal statistical patterns between them. The spatial behavior of the accumulated daily precipitation showed that the central-south region of Petrópolis presented the highest percentiles, which decreased toward the north of the city. From the 99% daily and hourly percentiles, extreme precipitation events might tend to occur in the center-south region of the city with lower intensity but long-lasting precipitation rain cores. In the northern part, however, the hourly rainfall rate tends to occur due to intense and short-lived precipitation. The hourly rainfall records also show that the highest precipitation rates (51 mm/h) preferably happened at the end of the afternoon. Lastly, considering the meteorological systems that lead to extreme rainfall events, it was observed that the South Atlantic Convergence Zone was related to 40% of them. Considering the presented approach, this work aims to reinforce scientific research on the challenges faced by monitoring centers and contribute to the prevention of socio-environmental disasters associated with extreme precipitation events in Petrópolis.

Keywords: rainfall; extreme events; warnings; natural disasters; decision makers.

INTRODUCTION

Intensification of extreme precipitation episodes is expected due to increased humidity offers and changes in the hydrological cycle from global warming (O'GORMAN; SCHNEIDER, 2009; WESTRA *et al*., 2014). Such environmental occurrences are relevant since the frequency and intensity of extreme rainfall events have been elevated in many regions of the globe over the last few years, according to the Intergovernmental Panel on Climate Change (IPCC, 2021). Especially over mountain regions, daily rainfall accumulations and high hourly rates can lead to natural hazards, such as floods and landslides, resulting in numerous financial impacts and loss of lives. Considering that extreme precipitation forecasts are a crucial demand for human safety and a daily challenge for operational weather centers, enhancing the knowledge of the rainfall variability during extreme event occurrence can provide new ways of recognizing the areas more prone to heavy rainfall records and anticipating possible actions by the decision makers (LIU *et al*., 2020; SPIRIDONOV *et al*., 2020). So, enhancing academic and operational researchers to understand extreme weather better is a continuous crucial demand for human safety.

According to the World Meteorological Organization (WMO, 1997) Expert Meeting on Automation of Visual and Subjective Observations (Trappes/Paris, France, May 14–16, 1997), extreme precipitation can be characterized if the hourly rates are above 50 mm. However, the criteria for defining such events do not follow a single selection pattern. Still, they depend on the local precipitation characteristics, the prevailing meteorological systems, and the research objectives. In other words, extreme rainfall events can be recognized as occurring very infrequently. There is no rigid definition in the literature on whether a given amount of rainfall in a specific period is considered to vary from weak to

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intense and/or extreme (DERECZYNSKI; CALADO; BARROS, 2017). So, the identification of extreme rainfall events can start by establishing a statistical threshold in which the rainfall values can be considered unusual for a determined area and year. Such values vary considerably for large countries; daily rainfall data are used to quantify them (GITAU, 2018).

In Brazil, large-scale weather phenomena such as the configuration of the South Atlantic Convergence Zone (SACZ) generate an expressive role in the precipitation with intermittent rainfall over the country's southeastern region. The SACZ is also responsible for transporting moisture and heat from the Amazon into the Southeast Region, which can create an atmospheric environment for locally heavy rainfall occurrence (VELASCO; FRITSCH, 1987; SATYAMURTI; RAO, 1988; QUADRO, 1994; LENTERS; COOK, 1995; NOGUÉS-PAEGLE; MO, 1997; LIEBMANN *et al*., 1999; SILVA DIAS, 1999; FERREIRA; CORREIA; RAMIREZ, 2004). The frontal systems (FS) connected to extratropical cyclones are another atmospheric phenomenon that can develop high hourly rainfall rates if a thermodynamic environment is favorable to deep convective cloud development. In the Southeastern Region of Brazil, extreme rainfall events generally happen during the austral summer (between December and March), given the coexistence of enhanced moisture offer, conditional atmospheric instability, and dynamic triggers generated by the SACZ and FS weather phenomena (CARVALHO; JONES; LIEBMANN, 2002; SILVA *et al*., 2019; SILVA *et al*., 2022).

In the Rio de Janeiro State, during the wet and warm seasons, the proximity of the Atlantic Ocean, the different soil types, and the Mata Atlântica biome create atmospheric instability in the lower atmospheric levels due to the effects of solar heating and evapotranspiration (LUIZ-SILVA; DERECZYNSKI, 2014). In addition, the mountainous area of Rio de Janeiro is located on the continent-facing side of Serra do Mar. Thus, this region suffers the effect of topography-induced rainfall on that side of the ridge, with deep convection and more significant rainfall accumulations concerning the other areas of Rio de Janeiro state (BRITTO *et al*., 2016; SILVA *et al*., 2022). Located in the mountainous region of Rio de Janeiro, the Petrópolis city in the summer of January 2011 suffered one of the most severe natural disasters in Brazilian history. On January 11, 2011, high-accumulation rainfall caused landslides and floods, leaving 187 people homeless, 6956 displaced, and claiming 71 fatal and 267 partial victims (ARAUJO *et al*., 2013). Almost 10 years later, Petrópolis again suffered from another extreme rainfall event. On February 15, 2022, the city received an unusually high volume of rain (258 mm) within 3 h. It resulted in flash floods and subsequent landslides that caused the deadliest disaster recorded in Petrópolis, with 231 fatalities (ALCÂNTARA et al., 2022).

An important guideline for environmental forecasting is the knowledge of rainfall and atmospheric patterns for determining the potential of their development and the corresponding possible damage to society (BROOKS *et al*., 2007). In light of the above scenario, this work first proposes to characterize spatially and temporally the extreme rainfall events that occurred in Petrópolis between 2011 and 2022. Second, we sought to analyze the behavior (frequency and intensity) of hourly rainfall rates, total daily precipitation, and meteorological systems associated with extreme rainfall. Lastly, this study also aims to reinforce the importance of local research for operational forecasters, civil defenses, and decision makers. It is organized as follows: Section 2 presents the main characteristics of the study region and the identification and categorization of extreme rainfall events. The results are discussed in Section 3, and in Section 4, the final considerations and conclusions are made.

METHOD

Study region and database

Located in Southeast Brazil (Figure 1a) and in the metropolitan region of Rio de Janeiro state (Figure 1b), Brazil, Petrópolis city occupies an area of 795.798 km^2 (Figure 1c) at an average of 838 m above sea level and has a population of approximately 278,000 inhabitants according to IBGE (2024). According to Luiz-Silva and Dereczynski (2014), in Rio de Janeiro state, the highest average annual rainfall levels and lower temperatures are found in the mountainous region, where Petrópolis is located, showing the influence of the topography over these atmospheric variables. Considering the periodic occurrences of floodings and landslides over the region, the Environmental State Institute (INEA), through the Flood Alert System, implemented in 2011 a network of pluviometers and fluviometers in strategic areas of Petrópolis (Figure 1c), aiming to monitor adverse weather conditions and those favorable to natural disasters. In the INEA flood alert system, meteorologists and hydrologists perform hydrometeorological monitoring 24 h a day and send watches and warning notices for civil defenses and populations when an environmental risk is identified (BAHIENSE *et al*., 2015).

Having established as the objective of our work, the characterization of spatiotemporal variability of extreme rainfall events that occurred over Petrópolis city, the rainfall database collected by INEA from 13 telemetric gauges is used (Table 1). The only exception is the Pico do Couto rain gauge, which belongs to the National Meteorological Institute (INMET) (Instituto Nacional de Meteorologia). Considering this, this study was conducted with data from November 5, 2011, to September 15, 2021, and considered only the days where the missing measurements account for less than 6 h. The telemetric rain gauges collect the data in 15-min intervals, except the Pico do Couto gauge which collects data hourly. From these time series, we calculated the daily accumulations (mm/day) and the hourly rates (mm/hour) for all pluviometers.

These gauges were chosen to minimize the amount of days lost due to errors in the register of rainfall data while maximizing spatial coverage. However, as shown in Figure 1, there is a concentration of gauges in the center-south region of the city; the lack of gauges in the western and northern areas may compromise the representativeness of the spatial distribution of extreme rainfall events in these regions.

As shown in Table 2, the decision to only utilize days with less than 6 h of measurement significantly affects the years 2015, 2016, and 2017. The lost days in 2019 and 2020 are concentrated in September, October, and November, which could indicate repairs and routine checks being made in preparation for the rainy season. The lack of suitable temporal coverage may impact the results, making them biased toward the extreme events that occurred at the start of the decade or susceptible to the influence of low-frequency phenomena that may occur during the duration of the study. However, this choice is made to guarantee that the detected extreme events are well characterized spatially.

Identification and categorization of extreme rainfall events

As recommended by the World Meteorological Organization (WMO, 1997) Expert Meeting on Automation of Visual and Subjective Observations (Trappes/Paris, France, May 14–16, 1997), extreme precipitation can be characterized

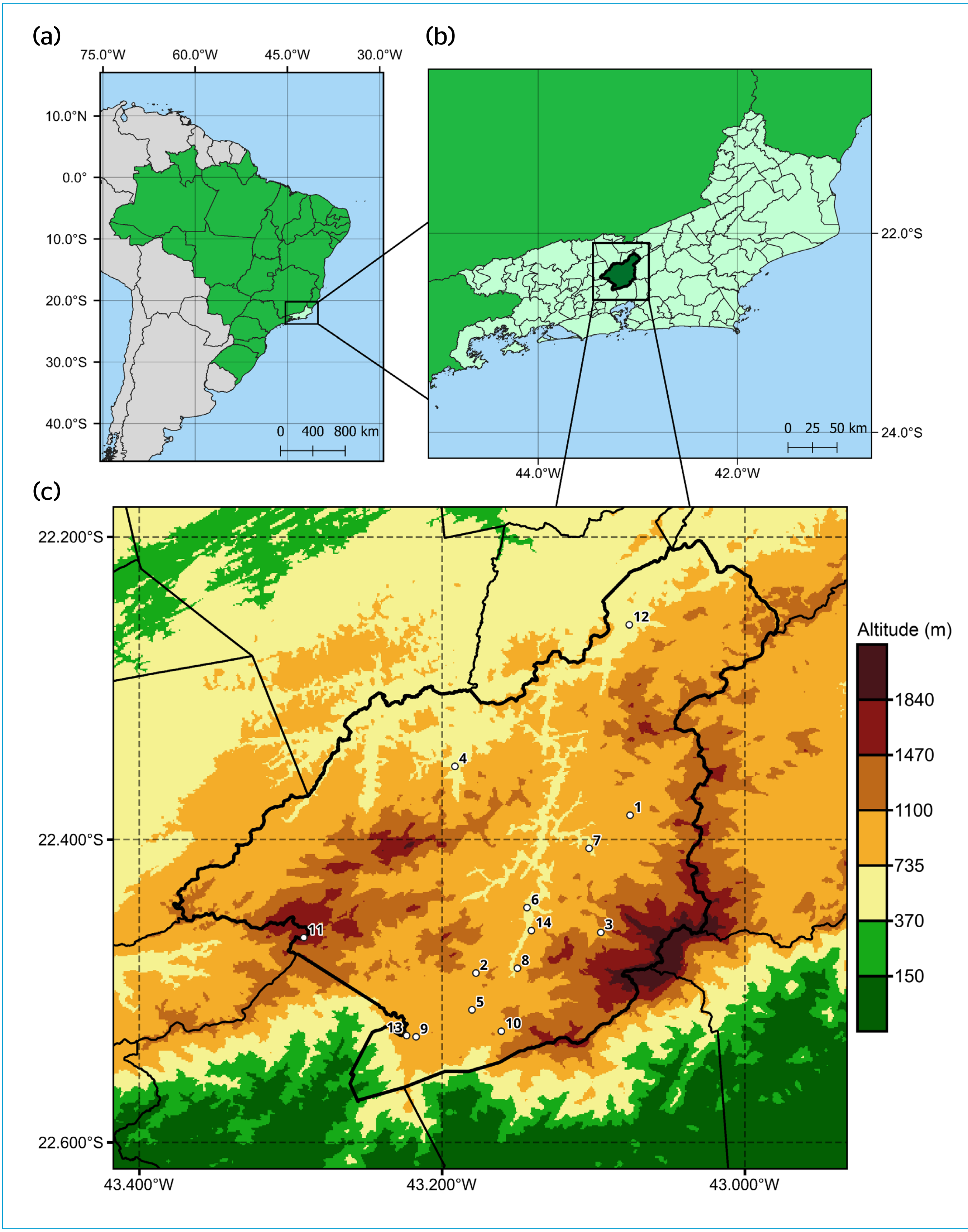

Figure 1 – (a) South America with the Brazilian territory and the state of Rio de Janeiro highlighted in green and light green, respectively; (b) Southeastern Brazil with a focus on Rio de Janeiro and its municipalities, with the city of Petrópolis highlighted in dark green; (c) Height map of Petrópolis and the surrounding areas with the data points utilized in this study.

Table 1 – Telemetric rain gauges over the Petrópolis city.

ID	Location	S	W	Start (dd/mm/yyyy)
1	Araras	-22.383889	-43.075833	01/10/2011
2	Barão do Rio Branco	-22.488167	-43.177667	17/10/2011
3	Bonfim	-22.461333	-43.095167	01/10/2011
4	Capim Roxo	-22.351611	-43.191556	01/10/2011
5	Centro	-22.512472	-43.180278	01/10/2011
6	Corrêas	-22.444917	-43.143917	20/10/2011
7	Itaipava	-22.405806	-43.102944	04/11/2011
8	Itamarati	-22.484972	-43.150250	13/10/2011
9	LNCC	-22.530278	-43.217222	10/06/2011
10	Morin	-22.526611	-43.160889	14/10/2011
11	Pico do Couto	-22.464722	-43.291389	01/01/2011
12	Posse	-22.258111	-43.076361	01/09/2011
13	Quitandinha	-22.529444	-43.223500	26/10/2011
14	Samambaia	-22.460111	-43.141028	01/09/2011

Table 2 – Relation of days utilized per year.

Year	Available days	Days lost	% of loss
2011	57	0	0
2012	366	2	0.5
2013	365	0	0
2014	365	9	2.5
2015	365	365	100
2016	366	347	95
2017	365	288	79
2018	365	128	35
2019	365	193	53
2020	366	189	52
2021	257	24	9
TOTAL	3,602	1,545	42.9

if the hourly rates are above 50 mm. However, there is no rigid definition in the literature to determine whether a given amount of rain accumulated in a specific period is categorized as weak, moderate, strong, intense, or extreme (DERECZYNSKI; CALADO; BARROS, 2017). So, the characterization of extreme rainfall events can start by considering the establishment of a threshold beyond which a rainfall event occurs very infrequently over a determined region (GITAU, 2018). That work considered the daily (P99d) and the hourly (P99h) 99th percentiles, which were used to identify the extreme rainfall events in Petrópolis. The calculus of this percentile was considered when the daily accumulated rainfall was above 1 mm and the hourly rainfall rates were above zero, as recommended by the World Meteorological Organization (WMO, 1989; RAJCZAK; PALL; SCHÄR, 2013; DINIZ; RAMOS; REBELLO, 2018; SAEDI *et al.*, 2020). These percentiles were calculated for each gauge. We generated interpolated fields utilizing the inverse distance weighted method with the QGIS application to visualize the spatial distribution of the results obtained. Lastly, we aimed to categorize the meteorological systems related to the identified daily extreme rainfall events using the synoptic charts provided by the Climanálise Bulletin made by the Brazilian Institute for Space Research (http://www.inpe.br/) and Brazilian Marine Meteorological Center (https://www.marinha.mil.br/dhn/).

RESULTS AND DISCUSSION

Annual and rainy season precipitation spatial characteristics

The distribution of the annual accumulated precipitation (Figure 2a) and the proportion between the annual accumulated precipitation and the accumulated precipitation between October and March, the so-called rainy season (Figure 2b), are initially presented to characterize the rainfall behavior over Petrópolis. From Figure 2a, it is possible to observe the spatial variability of precipitation over the city of Petrópolis, with the highest accumulations (shades of blue) occurring in the center-south region of the city, reaching up to 2,720 mm/year, while lower values (shades of dark orange) are observed toward the northern region of Petrópolis, not exceeding 1,100 mm/year. Based on the spatial variability of the proportion between precipitation accumulated during the rainy season and that observed throughout the year (Figure 2b), it can be seen that in the central-south region, precipitation tends to be equally distributed between the rainy and dry seasons, with values of approximately 50% (shades of gray), while in the central-north region, precipitation tends to occur mainly during the rainy season, with values above 75% (shades of black). Such characteristics reinforce the heterogeneity of precipitation occurrence in the Petrópolis region and emphasize the need to implement varied operational strategies to prevent natural disasters according to the risk of each location.

Rainfall daily accumulations and hourly rates over Petrópolis City

The statistical distribution of daily accumulations and hourly precipitation rates over the city of Petrópolis and the values of the P99d and P99h are shown in Figure 3. For this initial study, rainfall data were collected at all regional rainfall stations (Table 1 and Figure 1c) to determine the values at which daily and hourly rain events can be extreme on a municipal scale. This approach aims to map the rainfall values that can trigger natural disasters in Petrópolis. From Figure 3, it is possible to verify that both histograms present a positive asymmetric pattern or the right-skewed distribution characterizing a non-Gaussian distribution for the daily and hourly rainfall records. In other words, these patterns show a higher probability of lower rainfall values than greater values, as expected of the nature of rainfall. The vertical lines in red explain the positioning of the values of P99d (Figure 3a) and P99h (Figure 3b), that is, an extreme daily (hourly) precipitation event in the city of Petrópolis can be like this, considering when the accumulated amounts (rates) are more significant than 86.3 (20.5) mm. In the work of Silva *et al.* (2022), P99d values were found to be around 54 mm for the city of Rio de Janeiro. The higher values of P99d in the Petrópolis highlight the influence of orographic effects on the formation and development of more significant rainfall accumulations, as highlighted in the works of Britto *et al.* (2016) and Luiz-Silva and Oscar-Júnior (2022).

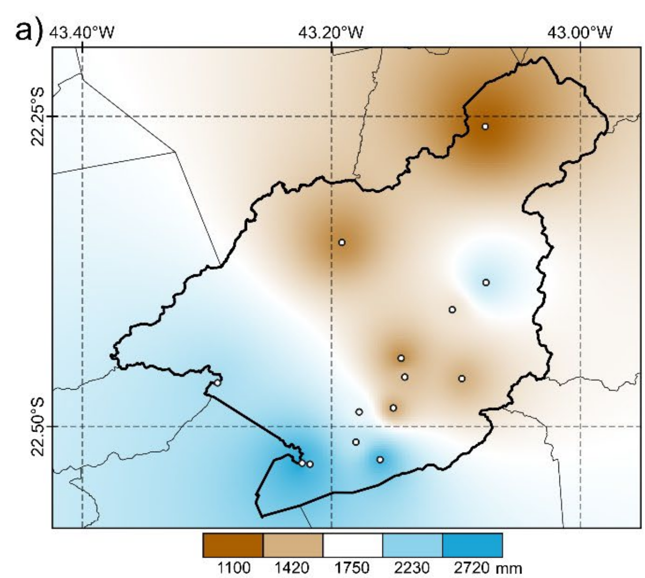

Figure 2 – Interpolated map of (a) average annual precipitation and (b) the proportion of annual precipitation in the rainy season from 2012 to 2014.

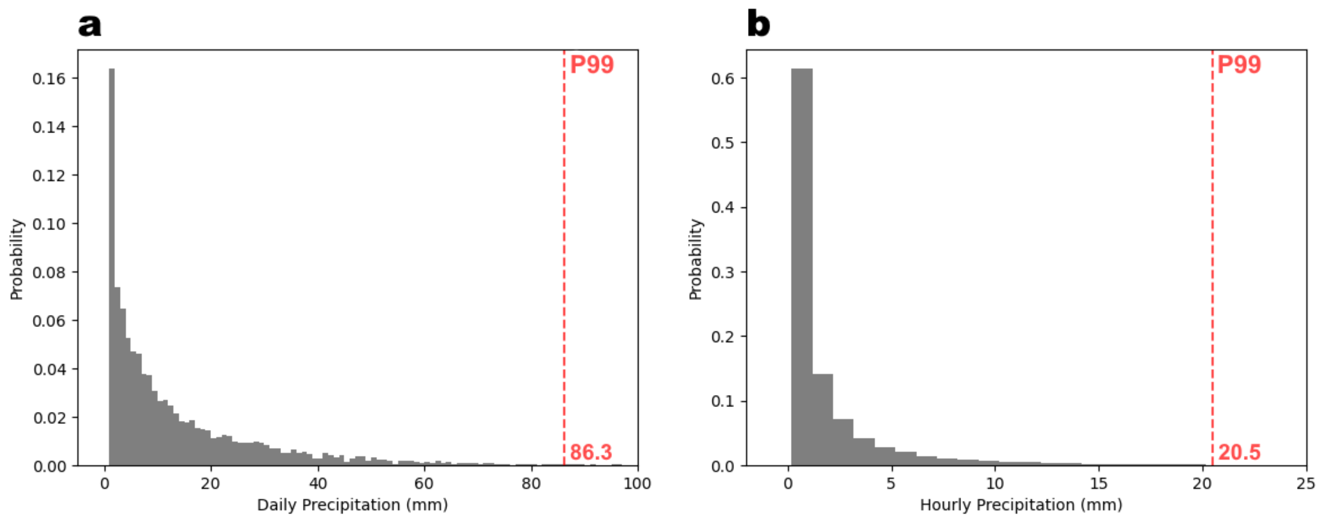

Figure 3 – Probability distribution graph of (a) daily and hourly precipitation (b). The dashed red vertical line highlights the thresholds obtained using P99.

Spatiotemporal distribution of extreme rainfall events

In addition to calculating the percentiles considering all rain gauges in Petrópolis, we also sought to carry out the same approach for each one individually to evaluate the variability of P99d and P99h over the region. This analysis initially included the quantification of P99d and P99h for the entire historical series (Figures 4a, 4c, 5a and 5c) and subsequently considered only the extreme events that occurred during the rainy season (Figures 4b, 4d, 5b and 5d) between October and March to observe possible seasonal differences in the distribution of extreme events. After quantifying P99d and P99h, we sought to verify how many times the daily [quantification of the days with rainfall above P99d (QTDd)] and hourly [quantification of the hours with rainfall above P99h (QTDh)] percentiles were exceeded and to determine the synoptic systems associated with extreme daily rainfall, aiming at a better understanding of the mechanisms responsible for their occurrence.

Figures 4a and 4b shows the spatial distribution of P99d for all months and only for the rainy season, respectively. In both figures, P99d presents higher values in the southern region of Petrópolis, around 120 mm (dark blue tones), decreasing progressively to the north of the city, around 75 mm (salmon tones). This characteristic indicates that the most intense extreme events tend to occur in the southern region. Itaipava station stands out with the maximum P99d concerning the northern part throughout the year (Figure 4a) or only during the rainy season (Figure 4b). Through the spatial distribution of quantification of the

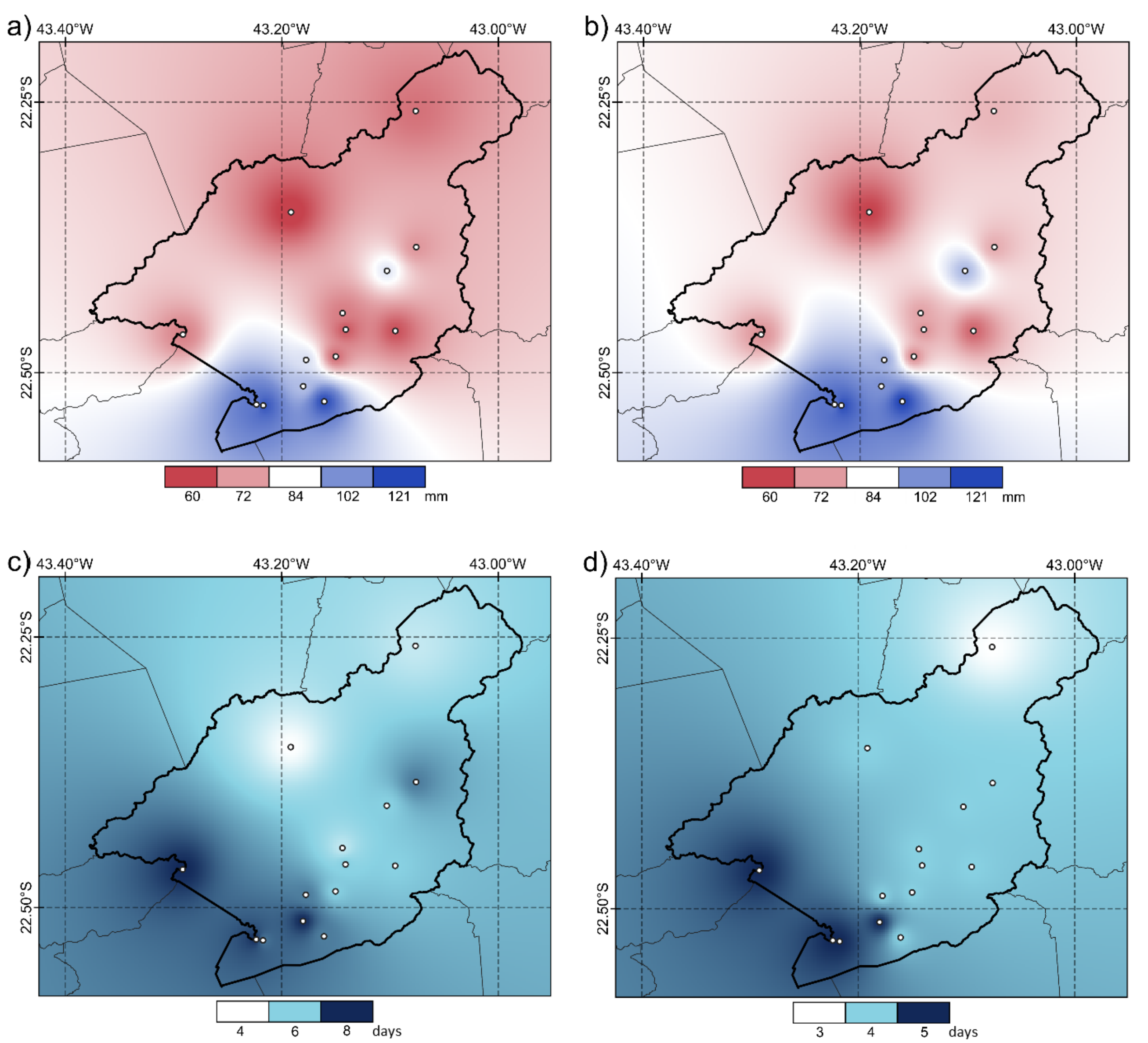

Figure 4 – Interpolated map of (a) P99d percentile, (b) 99d percentile considering only the rainy season, (c) number of days that exceeded P99d, and (d) number of days that exceeded P99d during the rainy season, over the city of Petrópolis between 2012 and 2021.

days with rainfall above P99d for the entire series (Figure 4c) and only for the rainy season (Figure 4d), it is possible to observe that again, the central-southern region (dark blue tones) presented higher occurrences of extreme events concerning the northern portion (light blue tones) of the city. The joint analysis of P99d and QTDd shows that in the central-southern region, extreme precipitation events tend to be simultaneously more intense and more frequent. Thus, with these results, it can be inferred that due to the greater intensity and occurrence of extreme events in the central-southern region, it is necessary to have planning aimed at mitigation actions and differentiated alert protocols for this region.

Figures 5a and 5b shows the spatial distribution of P99h for all months and only for the rainy season, respectively. In both figures, P99h shows more homogeneous values of hourly precipitation percentiles over Petrópolis, with values around 20 mm (light blue tones) except for the northern and western regions of the city, with values around 25 mm (dark blue tones) and 15 mm (salmon tones), respectively. Through the spatial distribution of QTDh for the entire series (Figure 5c) and only for the rainy season (Figure 5d), it is possible to observe that, again, the central-southern region (dark green tones) presented higher occurrences of hourly extreme rates concerning the northern portion (light green tones) of the city, similar to the spatial behavior of QTDd (Figures 4c and 4d). However, the joint analysis of P99h and QTDh shows that the southern (northern) part presents more (less) extreme hourly events (Figure 5d) with lower (higher) thresholds (Figure 5c). Such a characteristic suggests that the north region tends to develop more intense hourly rainfall rates at a lower frequency (around 30 occurrences) and could be related to showers driven

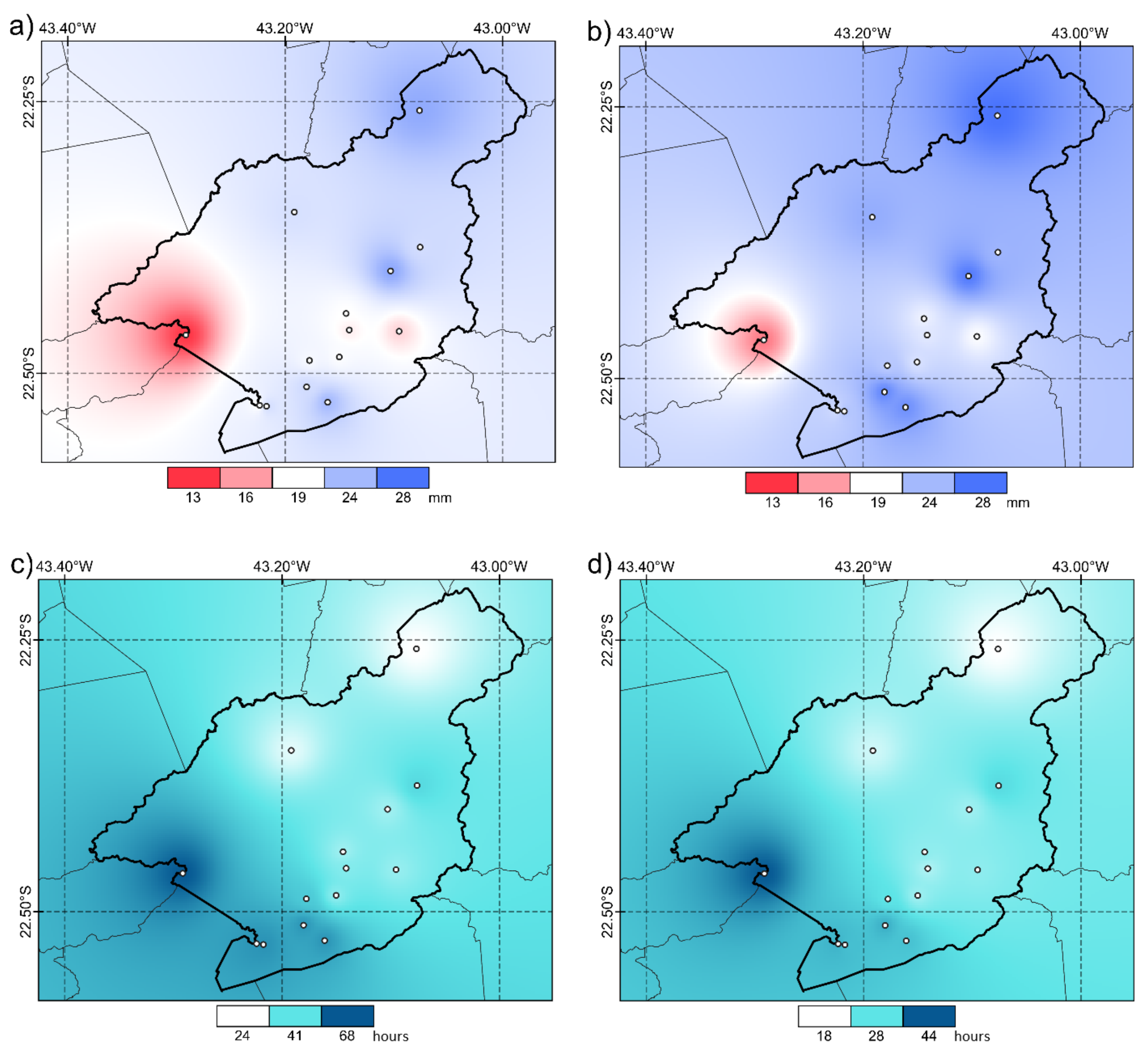

Figure 5 – Interpolated map of (a) P99h percentile, (b) 99h percentile considering only the rainy season, (c) number of days that exceeded P99h, and (d) number of days that exceeded P99h during the rainy season, over the city of Petrópolis between 2012 and 2021.

by isolated Cumulonimbus. Meanwhile, in the south of Petrópolis, instead of lower P99h, it presents a higher frequency (around 70 occurrences), suggesting precipitation with a longer duration related to large-scale weather systems.

The occurrence of daily events over the region was verified by identifying the extreme rainfall events, that is, days with daily accumulated rainfall above the P99d in at least one gauge. With this, the identification of the meteorological systems associated with daily events was made using the information provided by the *Climanálise Journal*, edited by the Brazilian Institute for Space Research (http://www.inpe.br/), alongside information supplied by the Brazilian Marine Meteorological Center (https://www.marinha.mil.br/dhn/). Of the cases detected, 40% were related to the SACZ, 35% to FS passage, and 25% to the diurnal convection (DC) occurrence (Figure 6). In this work, "diurnal

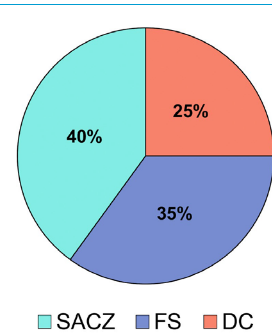

Figure 6 – Proportion of synoptic systems associated with daily extreme precipitation (P99d).

convection" was categorized to classify the days with rainfall occurrence without FS and SACZ. The rainfall on DC days was characterized by local conditions related to buoyancy, topography, low-level wind convergence, local low pressure related to daily warming, and breeze effects.

Especially regarding the efforts of mitigation action during extreme rainfall event occurrence, knowing patterns related to past events can be useful as a tool for decision makers. Considering this, this work also sought to verify the distribution of hourly rainfall rates during the extreme rainfall events identified. The main idea is to ascertain the possibility of preferential hours of rainfall occurrence and its intensity in response to the physical process of related meteorological systems. Figure 7 shows the rainfall occurrence hourly frequency and the average precipitation in each hour in Petrópolis. The analysis of the hourly behavior of precipitation during daily extreme events demonstrates that it is at the time starting from the end of the afternoon that there is a greater probability of precipitation (Figure 7a). Considering the average precipitation intensities, it is possible to see that 17 Coordinated Universal Time (UTC) presents the highest average rate with values around 51 mm/h; during dawn, intensity rains are also recorded (around 45 mm/h) but less frequently (three occurrences). These results show that during extreme precipitation events over Petrópolis, the hours between 06 UTC and 16 UTC could be strategically used for possible preventive actions, given the less frequent hourly rainfall events and lower intensity.

The data about the occurrence of natural disasters associated with rain over Petrópolis were granted by the UFRJ Cartography Laboratory (GEOCART). This is a compilation of the data from the Instituto de Pesquisas Tecnológicas de São Paulo (IPT) that surveyed and registered the disasters between 1933 and 1989 and the surveys conducted by GEOCART from 1990 to 2015. Such data were collected through information from newspapers, available means of communication, and available pluviometers (NEVES, 2017). Figure 8 shows the overlay of the spatial distribution of daily extreme precipitation events with the data supplied by GEOCART and the distribution of the population in the city of Petrópolis and the surrounding areas. Figure 8 shows the positioning of disaster occurrences in the areas with the highest occurrence of extreme daily and hourly rainfall events and with the highest population density, that is, in the central-south region of Petrópolis. Possible explanations suggest the consequences of improper construction of houses on slopes and the accentuated silting of rivers, as highlighted in the works of Alcântara *et al.* (2022). These results corroborate the importance of scientific studies aimed at generating environmental information that quantitatively and qualitatively highlights regions vulnerable to extreme rain events with a view to their use in warning centers and public policy planning.

The assumption that the lack of data may affect the yearly distribution of detected extreme events is proven correct as shown in Table 3. However, this fact does not affect the validity of the results obtained when considering the spatial distribution of the extreme rainfall events.

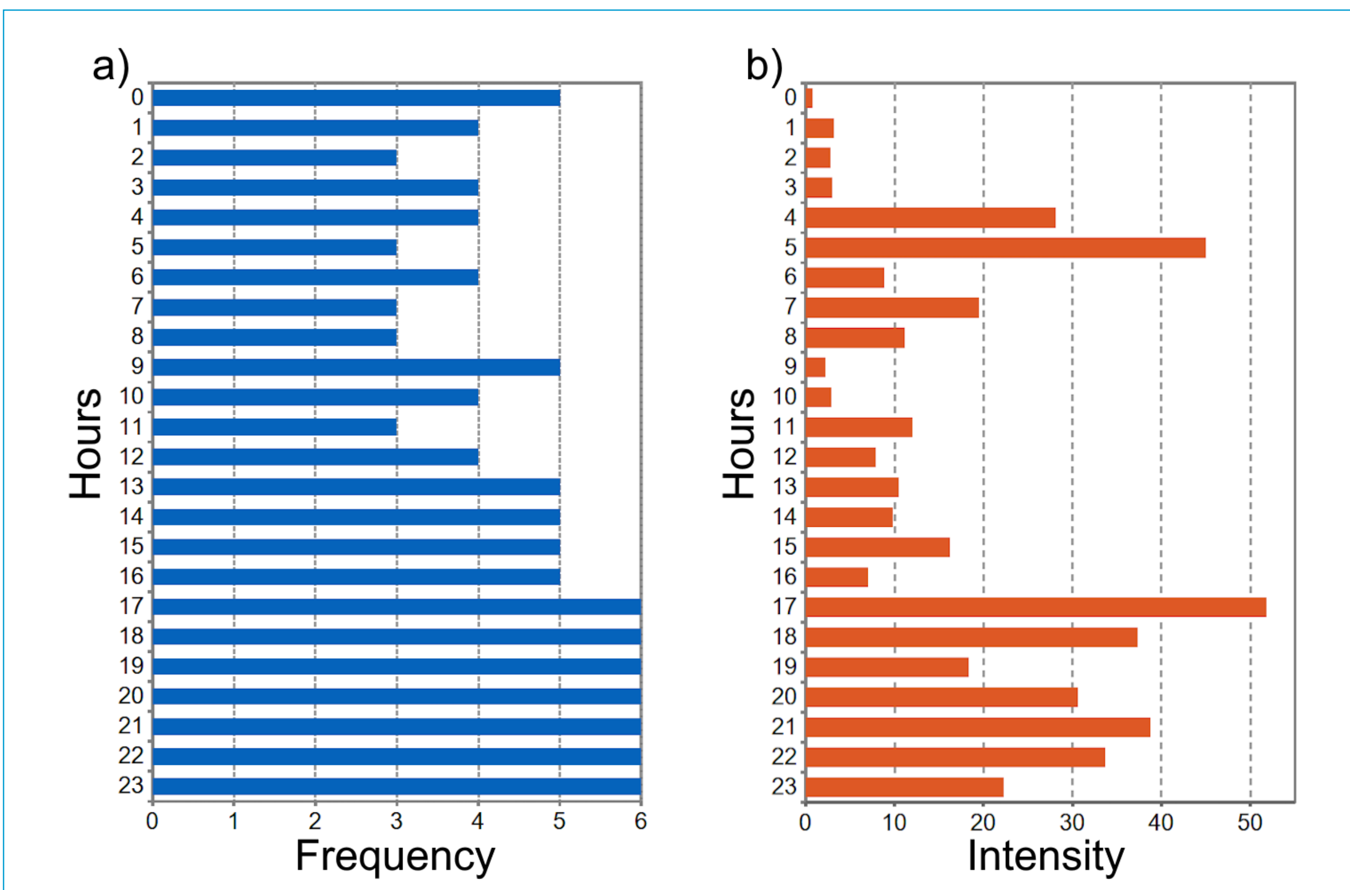

Figure 7 – Frequency of precipitation occurrence (a) per hour in extreme events and (b) precipitation intensity per hour in extreme events.

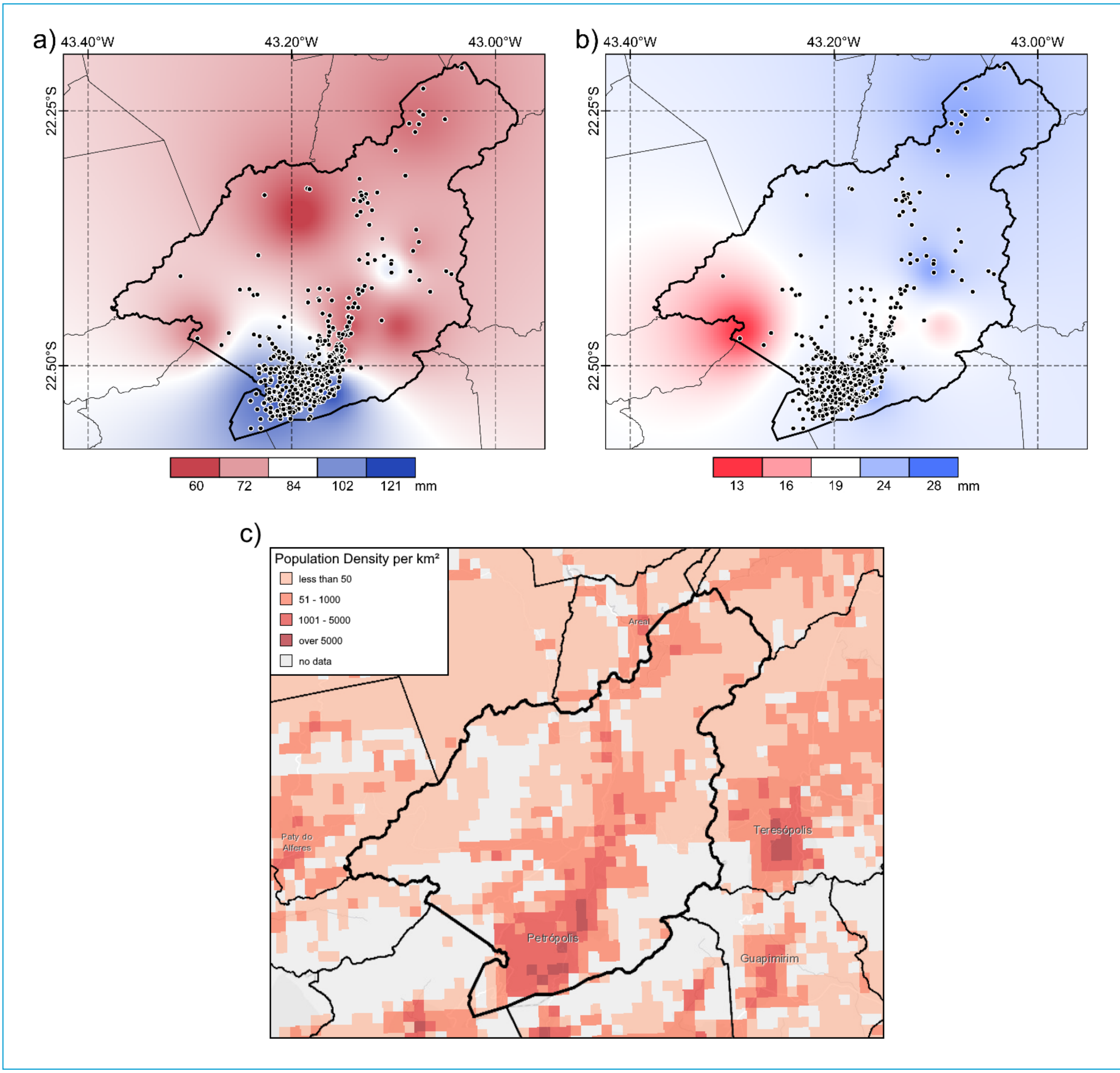

Figure 8 – Overlay of the locations where natural disasters associated with rain were recorded and (a) P99d and (b) P99h over Petrópolis city and population distribution in the city (c).

Table 3 – Identified daily rainfall extreme events.

Year	Daily extreme events	%
2011	1	3
2012	9	24
2013	10	27
2014	5	14
2015	0	0
2016	0	0
2017	0	0
2018	2	5
2019	2	5
2020	1	3
2021	7	19

CONCLUSIONS

This study examined the spatiotemporal variability of extreme rainfall events in Petrópolis city between 2011 and 2021 using the INEA and INMET rainfall databases. We chose to only consider the days where all of the gauges presented mostly at 6 h with no collected data so as to preserve the integrity of the daily and hourly results. However, in doing so, the results we obtained may be less representative of the overall reality of extreme rainfall events. Furthermore, the lack of rain gauges in the northern and western regions of the city may compromise the accuracy of the spatial distribution of extreme rainfall events in those regions.

Two approaches were used to evaluate the extreme events. The 99th percentile methodology was used to identify the extreme events. The first considers the total daily accumulations (P99d) and the second one the hourly rainfall rates

(P9h). From the rainfall data, this study sought to provide information about the spatial variability of annual precipitation and the daily and hourly extreme events, considering the total time series and only considering the rainy season. The *Climanálise Journal*, edited by the Brazilian Institute for Space Research (http://www.inpe.br/) and the Brazilian Marine Meteorological Center (https://www.marinha.mil.br/dhn/), was used to categorize the weather systems related to the extreme rainfall events. After that, the temporal variability of hourly rainfall events during extreme events was also evaluated.

First, from the rainfall annual distribution of Petrópolis city, it was possible to verify higher values (2,720 mm/year) over the southern part and lower values over the northern region of Petrópolis, not exceeding 1,100 mm/year. Based on the spatial variability of the proportion between precipitation accumulated during the rainy season and that observed throughout the year, it was verified that in the central-south region, precipitation tends to be equally distributed between the rainy and dry seasons, with values of approximately 50%. In the central-north region, precipitation tends to occur mainly during the rainy season, with values above 75%. From the 99th percentile results for extreme rainfall events, higher values were found in the southern region of Petrópolis, around 120 mm, decreasing progressively to the north of the city, around 75 mm. The hourly extreme events presented more homogeneous values of hourly precipitation percentiles over Petrópolis, with values around 20 mm except for the northern and western regions of the city, with values around 25 mm and 15 mm, respectively. Also, it was verified that the north region tends to develop more intense hourly rainfall rates at a lower frequency (around 30 occurrences) and could be related to showers driven by isolated Cumulonimbus. Meanwhile, in the south of Petrópolis, instead of lower hourly percentiles, it presents a higher frequency (around 70 occurrences), suggesting precipitation with a longer duration related to large-scale weather systems.

From the categorization using the synoptic charts, 39% were related to the SACZ, 37% to FS passage, and 24% to the DC occurrence. The analysis of the hourly behavior of precipitation during daily extreme events demonstrates that it is at the time starting from the end of the afternoon that there is a greater probability of precipitation, with records at 17 UTC and rainfall rate of around 51 mm/h. Using the information provided by the GEOCART database, it was possible to verify the positioning of disaster occurrences in the areas with the highest occurrence of extreme events, that is, in the central-south region of Petrópolis. Possible explanations suggest the consequences of improper construction of houses on slopes and the accentuated silting of rivers.

Lastly, this study sought to motivate and support research to show the importance of local knowledge related to the spatial rainfall variability during extreme rainfall events over mountainous regions. In future works, we tend to simulate the identified extreme rainfall events using numerical models. We aim to discuss the physical parameters, interactions between the synoptic scale and the mesoscale, and analysis of the vertical atmospheric profile in which heavy rainfall events can develop. The results presented in this initial study corroborate the importance of scientific research in generating environmental information that quantitatively and qualitatively highlights regions vulnerable to extreme rain events with a view to their use in warning centers and public policy planning.

AUTHORS' CONTRIBUTIONS

Cardoso, M.A.: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration. Silva, F.P.: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration.

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