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Assessment of extreme precipitation events in Brazil during 2023: Insights from CHIRPS and rain gauge data

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Abstract

This study conducts a comprehensive analysis of extreme precipitation events that occurred during the year 2023 in Brazil, aiming to provide valuable insights into climate risks and support decision-making related to disaster prevention. Leveraging data from the Climate Hazard Infrared Precipitation with Stations (CHIRPS) and complementing it with observational data from the network gauges of the National Center for Monitoring and Alerts of Natural Disasters (Cemaden), the research focuses on assessing indices derived from rainfall data, notably days with precipitation exceeding 50 mm, and juxtaposes these events against historical averages from 1992 to 2022 to discern anomalies. Data are aggregated at the municipal level, considering the maximum value within each municipal domain. The results highlight the influence of the El Niño phenomenon in the Southern region of Brazil, especially in Rio Grande do Sul, underscoring the importance of considering global and local climatic factors in impact assessment. Additionally, specific analyses are presented for municipalities such as Petrópolis (RJ), Manaus (AM), and São Sebastião (SP), revealing trends and anomalies that warrant attention for adaptation measures and disaster risk reduction. The study concludes that 2023 served as an illustrative year for climate projections, emphasizing the urgency to advance mitigation actions and reduce greenhouse gas emissions to address future climate challenges.

Keywords: Extreme precipitation; CHIRPS; Rain gauge; El Ninõ; Climate change

1. Introduction

In this paper, information on extreme precipitation events in 2023 is presented, complementing the data provided from Camarinha et al. (2024) [1], a research with the objective of providing a database, at the national level, regarding precipitation events with the potential to trigger landslides. The database aim to guide subsequent analyses on existing climate risks in Brazilian territory and to support decision-making, especially concerning disaster prevention actions.

To access rainfall data on a nationwide scale, we utilized the CHIRPS dataset. Developed by the Climate Hazards Group, the InfraRed Precipitation with Station data comprises a quasi-global rainfall dataset spanning over 35 years [2]. This dataset features satellite imagery with a resolution of 0.05° and integrates climatological satellite-based precipitation measurements and estimates derived from Cold Cloud Duration (CDD) infrared observations. Additionally, it incorporates surface precipitation observations obtained from rain gauges through an intelligent interpolation algorithm.

Numerous international studies have harnessed CHIRPS data to investigate extreme climatological phenomena [3, 4]. Likewise, within Brazil, researchers have employed CHIRPS datasets to explore climate variability, leading to a deeper understanding of national precipitation patterns and climate change dynamics. These data serve as invaluable resources

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for decision-makers, empowering them to craft more informed disaster risk reduction policies and climate adaptation strategies.

For instance, Marengo et al. (2017) [5] leveraged CHIRPS data to scrutinize the characteristics of extreme precipitation events in Brazil's southeast region and their relationship with large-scale atmospheric circulation patterns. Similarly, Palharini et al. (2022) [6] utilized various precipitation datasets, including CHIRPS, to pinpoint and analyze extreme rainfall events across different Brazilian regions, such as the South, Southeast, and Northeast, and their association with natural disasters like flash floods and landslides. Their research revealed a notable increase in the frequency of extreme rainfall events in certain regions of Brazil, particularly in the Northeast.

While our focus remains on Brazil's precipitation dynamics, it's imperative to contextualize our analysis within the broader framework of climatic phenomena. El Niño and La Niña, integral components of the El Niño-Southern Oscillation (ENSO), exert profound influences on global weather patterns. El Niño, characterized by anomalous warm sea surface temperatures in the Equatorial Pacific, and its counterpart, La Niña, representing the cold phase, engender atmospheric circulation changes, precipitating climatic irregularities like altered precipitation patterns, droughts, anomalous temperatures, and dry spells.

El Niño and La Niña episodes exert a profound influence on extreme precipitation events in South America, altering both their frequency and intensity throughout the ENSO cycle. These changes are particularly prominent during the rainy season and vary spatially across different regions of the continent. Southeastern South America stands out as experiencing significant alterations in both frequency and intensity, especially during late spring and autumn. Understanding the relationship between ENSO and extreme events is vital due to the substantial societal and economic impacts associated with these phenomena [7].

Historical records attest to Brazil's vulnerability to the oscillations of El Niño and La Niña. During El Niño events, such as those in 1982-1983 and 1991-1993, Brazil witnessed starkly divergent precipitation patterns. While the northeast and parts of the Amazon endured severe droughts, the southern region grappled with heavy rainfall and flooding. These events, along with anomalies like snowfall in the south during the winter of 1993, serve as poignant reminders of Brazil's susceptibility to ENSO-driven climatic perturbations [8, 9].

By seamlessly integrating insights from studies on ENSO dynamics with our examination of extreme precipitation events in 2023, we strive to provide a holistic understanding of Brazil's climatic tapestry. This interdisciplinary approach equips policymakers and stakeholders with nuanced insights, facilitating the formulation of evidence-based strategies to navigate the challenges posed by climate variability and enhance resilience against extreme weather events.

Objective

The objective of this paper is to conduct a quantitative analysis of extreme precipitation events that occurred in Brazil during the year 2023, with a focus on identifying regions prone to rapid landslides and flash floods. By comparing the 2023 data with historical averages from 2013 to 2022, the study aims to assess the impact of climatic phenomena such as El Niño on precipitation patterns. Additionally, specific analyses are conducted for municipalities known for their vulnerability to geo-hydrological events in 2023, providing insights into the frequency, magnitude, and spatial extent of extreme rainfall events. The ultimate goal is to provide valuable information for decision-makers to enhance disaster prevention measures and climate adaptation strategies.

Scope

The analyses, at the national level, for the year 2023, were based on rainfall data from CHIRPS. The results for the year 2023 are compared with those related to the historical average for the period 1992-2022, with the objective of identifying both the regions that experienced higher frequencies and rainfall exceeding 50 mm, as well as those with greater anomalies. The threshold of rainfall exceeding 50 mm in 24 hours was considered significant for events with the potential to cause various geo-hydrological impacts (landslides, flash floods, urban flooding, and riverine flooding) in Brazilian municipalities, depending on their vulnerabilities, population exposure, and coping capacity.

Additionally, results of analyses using only the rainfall stations of the National Center for Monitoring and Alerts of Natural Disasters (Cemaden) are also presented, considering the historical period from 2013 to 2022 and specifically, data from the year 2023. For this analysis, some municipalities were selected that stood out in 2023 for being heavily impacted by geo-hydrological processes triggered by intense and voluminous rainfall, such as Manaus (AM), São

Sebastião (SP), Petrópolis (RJ), São Sebastião do Caí (RS), Lageado (RS), and Estrela (RS). Information about the impacts recorded by Cemaden in the year 2023 can be found in the Information Note:

https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/noticias/2024/01/em-2023-cemaden-registrou-maior-numero-de-ocorrencias-de-desastres-no-brasil

Figure 1 presents the results with the quantity, by municipality, of rainfall amounts exceeding 50 mm in 2023 (background map of Brazil, as per legend), in addition to comparing the results with the historical average found in the period between 1992-2022 and identifying anomalies.

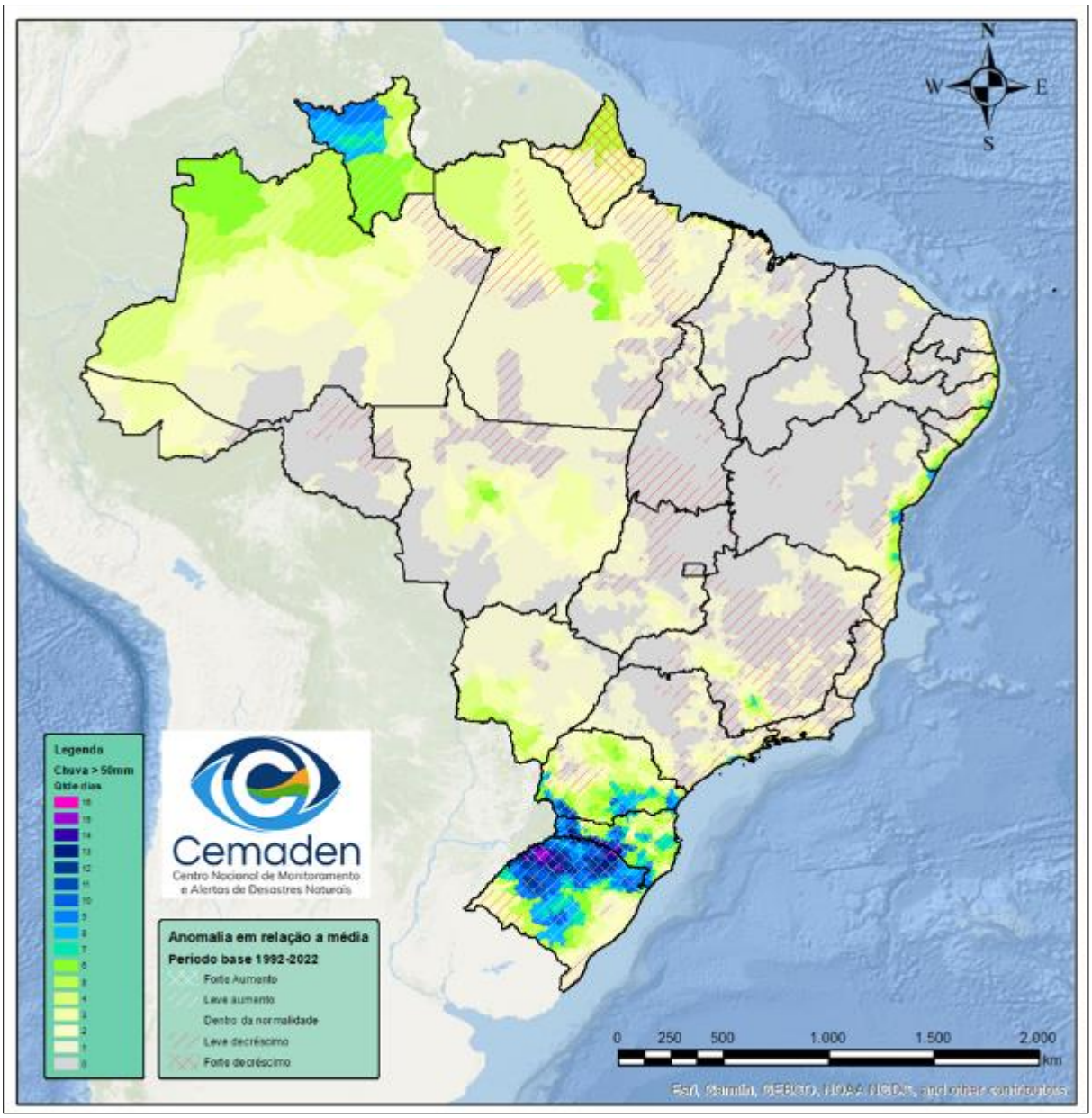

Figure 1 Quantitative analysis of days with precipitation exceeding 50 mm (background) for the year 2023 and anomaly in relation to the period from 1992-2022 (hatching). Data aggregated by municipality, considering the maximum value found within the municipal domain. Database used: CHIRPS

The results demonstrate the strong influence that the El Niño event had on the Southern Region of Brazil, especially in the state of Rio Grande do Sul, where a significant number of municipalities with more than 10 days of rainfall exceeding 50mm/24h (bluer tones) can be observed, which were exceptionally above the average (white crosshatching). These results are in line with information highlighted in the Cemaden Technical (2024) [10] regarding the El Niño forecast.

Overall, it is noted that the Southern Region stood out as the one with the highest frequency of rainfall events exceeding 50 mm in 2023, with significantly elevated positive anomalies, such that many municipalities that historically had an average of 4 to 5 events per year reached values around 15 events in 2023. In addition to Rio Grande do Sul mentioned above, some locations in the states of Santa Catarina and Paraná, on the coast of São Paulo, and in the eastern portion of the Northeast region, are also highlighted as having moderately high frequency of events above 50 mm, although within normality (no shading), overall.

Although CHIRPS data allows comparative analyses between different locations in Brazil, they do not refer to *in situ* information; therefore, they have some associated uncertainties that make more in-depth and representative analyses of extreme events unfeasible, especially for specific cases. Thus, aiming to complement the analyses for some particular municipalities, which stood out due to the impacts of great magnitude recorded during the year 2023, analyses were conducted based on data from the environmental monitoring network of Cemaden/MCTI.

2. Methodology and Data

The complementary analyses conducted based on *in situ* data were based on rainfall data from the observational network of Cemaden/MCTI, available with a temporal frequency of 10 minutes, via the Data Delivery Platform (PED) of the Center. The raw data were handled and organized to compose a climatology based on daily results.

For recent climatology analyses, temporal series of 10 years (2013-2022) were considered, and subsequently compared with the observed data particularly in 2023. The following indicators related to extreme events were considered:

- N50days: number of days per year where precipitation exceeded 50 mm;
- Rx2day: maximum precipitation recorded in 2 consecutive days, considering the annual calendar.

For the historical series (2013-2022), these indicators were calculated year by year and then averaged over the period. This value is used as a comparative reference (baseline) to assess the increase/decrease of the indicators found for the year 2023. This difference between what occurred in 2023 and the reference period (2013-2022) is called "positive anomaly" when referring to the increase of the indicator and "negative anomaly" for the decrease.

Three municipalities were analyzed individually to represent the impacts recorded in 2023, which have at least 10 rain gauges in their territory, such as Petrópolis (RJ), Manaus (AM), and São Sebastião (SP). Additionally, data from Lageado (RS), São Sebastião do Caí (RS), and Encantado (RS) were aggregated to represent the region affected by the floods in the state of Rio Grande do Sul in September 2023, totaling 5 rain gauges, whose data obtained are summarized in Tables 1 and 2, below.

Table 1 Analysis of the Rx2day indicator: maximum rainfall in 2 consecutive days

Municipality	**FU**	**Global Analysis (all rain gauges)**				**Individual rain gauges with particular significance**			
		Qty Rain Gauges analyzed	Rx2day (2013-2022)	Rx2day (2023)	Rx2day Anomaly	Qty Rain Gauges analyzed	Rx2day (2013-2022)	Rx2day (2023)	Rx2day Anomaly
Petrópolis	RJ	21	106.9	91.7	**-14.25%**	Independência 2	188.3	167.5	**-11.05%**
Manaus	AM	13	105.7	111.3	**+5.29%**	Jorge Teixeira	89.1	120.1	**+34.87%**
São Sebastião	SP	15	146.9	291.3	**+98.22 %**	Barra do Una	188.2	648.6	**+244.63 %**
Lageado	RS	5	116,7	182,1	**+56.03 %**	Rio Caí	110,1	235,4	**+113.85 %**
Encantado									
São Sebastião do Caí									

Table 2 Analysis of the N50days indicator: number of days with rainfall exceeding 50mm

Municpality	**FU**	**Global Analysis (all rain gauges)**				**Individual rain gauges with particular significance**			
		Qty Rain Gauges analyzed	N50days (2013-2022)	N50days (2023)	N50days anomalia	Qty Rain Gauges analyzed	N50days (2013-2022)	N50days (2023)	N50days anomalia
Petrópolis	RJ	21	3.3	3.0	-7.46%	Independência 2	7.7	9.0	+16.88%
Manaus	AM	13	4.3	6.4	+49.51 %	Puraquequara	4.6	9.0	+95.65%
São Sebastião	SP	15	5.8	4.4	-24.52%	Barra do Una	7.8	5.0	-35.71%
Lageado	RS	5	4,4	8,2	+85.16 %	Moinhos D'Agua	4,3	10	+135.29 %
Encantado									
São Sebastião do Caí									

3. Results and discussions

The analysis for the municipality of Petrópolis, RJ, for the year 2023 indicates that, overall, extreme precipitation events were within normality, with minor negative anomalies, except for the rain gauge "Independência 2" which indicated an increase in the number of days with rainfall above 50 mm, totaling 9 events (an increase of 16.88%), which can be considered a deviation within normality. The mentioned rain gauge is installed in one of the most critical areas of the municipality of Petrópolis, standing out for monitoring rainfall in a region representative of events impacting the municipality, especially because it is located in an area most affected by orographic rainfall (many other rain gauges are located in rural areas, in more distant regions, which contributes to lower values in the municipal average).

Even considering the occurrence patterns of extreme events in 2023 within climatological normality, Petrópolis was the 3rd municipality with the highest number of rainfall events causing impacts according to the survey conducted by Cemaden. These facts indicate that the high number of geo-hydrological impacts registered in 2023 are not related to climatic anomalies in the same year and, therefore, cannot be attributed to climate change. This suggests that the impacts in Petrópolis during the year 2023 can be better explained by the municipality's high vulnerability to rainfall events that historically occur in its territory in addition to the large population exposed to geo-hydrological risks. Between 1940 and 1990, 1,616 catastrophic events, including landslides, mudslides, rockfalls, and floods, were recorded in the Petrópolis, alarmingly, nearly 90% of these events took place within urbanized areas [11], underscoring the significant population exposed to geo-hydrological risks amidst poorly planned urban growth. On December 24, 2001, Petrópolis experienced an intense rainfall event, with precipitation reaching up to 190 mm within a 12-hour period, resulting in numerous landslides and 50 fatalities. Research conducted by Oliveira et al. (2014) [12] revealed that approximately 60% of these mass movements were attributed to steep terrain conditions, compounded by the presence of unauthorized settlements. Specifically, areas lacking adequate rainwater drainage infrastructure were identified as particularly susceptible. These incidents predominantly transpired in regions devoid of any drainage systems. This calls attention to the potential for even greater and more recurrent impacts in Petrópolis in future periods when extreme events occur more frequently and intensely.

Regarding the municipality of Manaus, AM, where negative deviations of rainfall (how much it fell below the average for the period) in in the 2023 June-July-August quarter were more pronounced. At the INMET weather station in Manaus, it was 130.9 mm, while its average is 202.2 mm [NT]. Despite of that, the Rx2day index indicates that the intensity of extreme events was slightly above average, with notable rainfall recorded by the rain gauge "Jorge Teixeira," with one event reaching 120.1 mm (34.9% above average). On the other hand, the analysis o, the number of days above 50 mm indicates a systematic increase in the frequency of more intense events, as the average went from 4.3 events per

year to 6.4, with the "Puraquequara" rain gauge registering 9 events in 2023, almost double (95.65%) the average between 2013-2022.

It is worth noting that most of these events in Manaus occurred in the first half of the year, considering that the municipality was impacted by severe droughts in the second half. That is, in years of climatological normality (without El Niño and such high global warming favoring droughts and dry spells), these extreme event indicators would likely be even higher. Thus, it is emphasized that the high number of impacts recorded in Manaus during the year 2023 is also due to the increased frequency and magnitude of heavy and intense rains observed this year, especially in the first six months; in addition to the high vulnerability and large population exposed in the municipality, which often arises from anthropogenic occupation in steep areas and unstable terrains, or in proximity to river channels and their floodplains. This is frequently the result of irregular land subdivisions later regularized [13]. Factors that highlight the urgent need for climate adaptation measures and disaster risk reduction.

In São Sebastião, SP, the results obtained point to two indicators that present opposite but relevant results for the evaluation of extreme events. Overall, there was a 25% reduction in the number of days with rainfall above 50 mm in the municipality, as the average found in Cemaden rain gauges was 4.4 days in 2023 compared to 5.8 in the period between 2013-2022. The analysis considers data from the rain gauge installed in Barra do Una, located on the south coast of São Sebastião (one of the rainiest portions of the São Paulo coast), indicating a reduction of up to 35%.

On the other hand, the Rx2day index indicates an increase in the magnitude of extreme events, reaching 291.3 mm in 2023 versus 149.6 mm from the period between 2013-2022, representing an almost 100% positive anomaly. This value is even more extreme when analyzing the station installed in Barra do Una, near Vila do Sahy, which recorded the event in February 2023 that reached 648.6 mm in 2 days, compared to the historical average in this location of 188.2 mm, resulting in an increase of more than 240%. It is important to mention that, although the Rx2day indicator indicates maximum rainfall in two consecutive days, the accumulated 648.6 mm was actually recorded in about 12 hours, between the night of February 18th and the morning of February 19th. Thefore, it was an even more intense and extreme event when analyzed over a shorter time frame, resulting in one of the largest climatic disasters in the history of the state of São Paulo.

Considering both indicators, it is concluded that 2023 was a year in which the frequency of heavier rains (above 50 mm) was lower compared to the average of the reference period (2012-2022), but this reduction in frequency is not related to the occurrence of individual extreme events, such as what happened in February 2023, which led to a significant increase in the Rx2day indicator. Therefore, an analysis solely looking at the N50days indicator would not be able to diagnose, individually, the size of the impact that São Sebastião suffered in 2023. That is, indicators representing the frequency of certain rainfall events (such as those above 50 mm in 24h) are not capable of diagnosing the possibility of the occurrence of more critical and extreme situations, such as the one observed in a single event that resulted in the heaviest rainfall ever recorded in 24 hours in Brazil. This represents another facet of climate change, which manifests in a complex manner and interacts with local climatic characteristics, and may provide ingredients for the occurrence of very rare and extreme individual events, such as the one observed in São Sebastião in February 2023. At the time of the disaster in February 2023, the passage of a strong cold front that became semi-stationary in the Southeast region due to the action of an Upper-Level Cyclonic Vortex (ULCV) slightly further south of the Northeast region, along with the warmer ocean near the São Paulo coast (around 27°C), were the fundamental ingredients to explain the storm between February 18th and 19th, along with local factors such as the interaction of winds coming from the ocean and interacting with the slopes of the Serra do Mar, which led to the formation of intense orographic rainfall for many hours [14].

Considering the municipalities of Lageado, Encantado, and São Sebastião do Caí, all in the state of RS, it is highlighted that this region of Southern Brazil well represents the impacts caused in the second half of 2023, especially due to the action of the El Niño phenomenon, which directly influences regional rainfall. The two analyzed indices indicate a significant increase, both in frequency and magnitude of extreme events, in these locations. On one hand, the number of days with rainfall exceeding 50 mm practically doubled, going from an average of 4.4 events per year between 2013-2022 to 8.2 events in 2023 (an increase of 85.16%), with the "Moinhos d'água" station in Lageado registering 10 events, representing a local anomaly of 135%. On the other hand, the Rx2day index went from an average of 116.7 mm to 182.1 mm (+56%), with the observation in the "Rio Caí" station in São Sebastião do Caí, which recorded an event of 235.4 mm versus the historical average of 110.1 mm, representing an anomaly of 113.8%.

That is, in this region of the Vale do Taquari, extreme rainfall events increased both in frequency and magnitude, emphasizing that a large part of these events occurred only in the second half of 2023, when El Niño was active. Furthermore, considering that this increase is systematic among all the analyzed rain gauges, which are distant from

each other, it is also noted that extreme events reached a very wide spatial extent, which is essential to explain the major floods that impacted the southern region in the second half of 2023. That is, the extreme events that impacted the Southern region in 2023 increased both in frequency and magnitude, as well as in spatial extent, highlighting the regional susceptibility to severe floods in situations of extreme events, as well as many local and regional vulnerabilities regarding the coping with extreme events, especially because locally these events can lead to even more extreme and rare geo-hydrological threats, which consequently cause impacts of large proportions and even unprecedented ones, as observed in 2023.

4. Conclusion

In summary, this study presents a comprehensive analysis of extreme precipitation events in Brazil during the pivotal year of 2023. Leveraging data from the Climate Hazard Infrared Precipitation with Stations (CHIRPS) dataset and in situ measurements from the National Center for Monitoring and Alerts of Natural Disasters (Cemaden), the research elucidates the complex dynamics of rainfall patterns and their implications for disaster risk management.

The findings underscore the significant influence of the El Niño phenomenon on precipitation distribution, particularly evident in the Southern region of Brazil. The year 2023, marked by shifts from intense La Niña to robust El Niño conditions, showcased the heightened vulnerability of certain municipalities to extreme weather events, including rapid landslides and flash floods.

Through comparative analyses with historical averages, the study highlights the escalating frequency and magnitude of extreme rainfall events, especially in regions like Rio Grande do Sul, Manaus, and São Sebastião. These observations emphasize the urgent need for proactive measures to mitigate the impacts of climate change and enhance resilience to natural disasters.

Furthermore, the research underscores the importance of localized analyses, as demonstrated by individual assessments of municipalities such as Petrópolis, Manaus, and São Sebastião. These case studies elucidate the nuanced interactions between climatic factors, geographical characteristics, and socio-economic vulnerabilities, providing valuable insights for targeted intervention strategies.

As climate change continues to exacerbate extreme weather phenomena, the findings of this study serve as a call to action for policymakers, urban planners, and community stakeholders. Effective disaster risk reduction strategies must be informed by robust scientific analyses, tailored to the specific challenges faced by each region.

In conclusion, the year 2023 serves as a poignant reminder of the urgent need for concerted efforts to adapt to changing climatic conditions, strengthen disaster preparedness, and mitigate the impacts of extreme weather events on vulnerable communities across Brazil. By prioritizing proactive measures and fostering collaboration at local, national, and international levels, we can build a more resilient future in the face of climate uncertainty.

Conclusion Remarks

Climate change is complex and can manifest in various ways, often adding to natural factors of climate variability, such as El Niño and La Niña, which can generate even more challenging extreme events. From the results presented, it can be said that 2023 was an "illustrative" year to represent the scenarios that had been projected decades ago and are now materializing, with the tendency to intensify even further in the coming years.

At the beginning of 2023, a long and intense La Niña was still configured, which quickly inverted11 to a strong El Niño in the second half. In addition to this, 2023 was the hottest year recorded in recent history, reaching for the first time an increase of 1.5 °C above the pre-industrial average. This resulted in adverse climatic dynamics, establishing challenging scenarios in some locations, such as those reported in this Technical Note, but practically no Brazilian municipality is prepared to face, highlighting the need for advances in discussions and implementations of adaptation actions, disaster risk reduction (especially preventive measures), as well as reducing greenhouse gas emissions.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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