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Frequency Rather Than Intensity Drives Projected Changes of Rainfall Events in Brazil

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Key Points:

- Coupled Model Intercomparison Project 6-based assessment of projected changes in the distribution of rainfall events in Brazil
- Extreme and light/moderate rainfall events are expected to increase and decrease in the country, respectively
- Frequency, rather than intensity, dictates the projected changes in future rainfall events

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Extreme rainfall events are expected to intensify with global warming, posing significant challenges to both human and natural environments. Despite the importance of such assessments, they are unevenly widespread across the globe. Here, using bias corrected climate simulations of the latest phase of the Coupled Model Intercomparison Project (CMIP6), we provide a comprehensive assessment on how different rainfall events are expected to change across Brazil. Specifically, (a) we explored the projected changes in both intensity and frequency of rainfall events belonging to the right-tail of the rainfall distribution using a non-parametric approach, and (b) quantified how rainfall events associate with different return periods are expected to intensify, using a parametric approach. We found that extreme rainfall events will become more frequent and intense by the end of the century, with averaged projected changes for rainfall exceeding the historical rainfall quantile $q_{0.99}$ of nearly 100% and 10% on frequency and intensity, respectively. Non-extreme rainfall events, in contrast, are expected to be less frequent, aligning with the compensation hypothesis. For instance, Brazilian 100-year rainfall are anticipated to intensify, on average, 17% and 31% under the moderate and the highest CMIP6 emission scenarios, respectively. Finally, our findings suggest that frequency, rather than intensity, dictates the projected changes of rainfall. We believe that the evidence gathered here will certainly contribute to not only an improved understanding of Brazilian rainfall events but also to a better comprehension of the different rainfall properties, their interplay and how the different ways of assessing them may affect climate studies.

Plain Language Summary

The dynamics of rainfall events are expected to change in the future due to global warming. Understanding how this is likely to happen is extremely important for society, since this information is usually required for water resources management and for the design of infrastructure systems. To this end, studies commonly rely on climate models simulations, as they can offer a preview of forthcoming scenarios, helping us to understand the potential effects of such changes to society. Here, using the last generation of climate model projections, we propose an alternative way to explore how rainfall events might change in Brazil. Our results show that heavy rainfall events will be much more frequent and stronger in the future. For example, heavy rain that usually happens once in 100 years in Brazil could become nearly 31% stronger by the end of the century. Less intense rainfall events, on the other hand, might happen less often. Our results also indicated that changes in the frequency of rainfall events, rather than in their intensity, rules how they are expected to change. This study helps us understand not only what might happen to rainfall events in Brazil but also to improve future climate change impact studies.

1. Introduction

Extreme precipitation events underlie many of the most significant challenges society faces (Kirchmeier-Young & Zhang, 2020). Their negative impacts on both natural and human environments are responsible for billions of dollars in economic damages and immeasurable human losses (Doocy et al., 2013; McBean & Rodgers, 2010; Nissen & Ulbrich, 2017). Consequently, the understanding of extreme rainfall has gained considerable attention in recent decades, being recognized as one of the scientific Great Challenges by the World Climate Research Programme (Diffenbaugh et al., 2017; Sillmann et al., 2017). Despite significant advancements in characterizing such events, there remain unresolved questions that underscore the need for an enhanced understanding of their characteristics to improve water resources management (Gründemann et al., 2023). Such efforts become even more critical in the context of global warming (Fan et al., 2021), as it is expected to significantly affect the intensity and frequency of extreme events (Chagas et al., 2022; Myhre et al., 2019).

Numerous recent studies have been dedicated to assessing changes in observed extreme rainfall events (Alexander, 2016; Markonis et al., 2019; Myhre et al., 2019; Papalexiou & Montanari, 2019; Robinson et al., 2021). Despite their importance for an improved comprehension of extreme events, there are still some shortcomings that impose a great challenge for hydrological practices in an uncertain future (Diffenbaugh et al., 2017). First, many local observations span only the past few decades, not being able to capture precipitation's long-term variability and changes (Peterson et al., 2013). Consequently, in some cases, observations may not be representative of the underlying events, substantially affecting the characterization of extreme events (Ballarin, Anache, & Wendland, 2022; Marani & Zanetti, 2015). Furthermore, global warming is expected to alter global water cycle dynamics, potentially affecting the likelihood and magnitude of both extreme and non-extreme rainfall events (Min et al., 2011; Sharifinejad et al., 2022). These changes on rainfall dynamics challenge an accurate projection based solely on observational analysis, as their future statistical properties might no longer be the same (Miniussi & Marani, 2020; Swain et al., 2016).

In view of these limitations, several recent studies are relying on climate model projections to identify changes in extreme events (Abdelmoaty & Papalexiou, 2023; Gründemann et al., 2022; John et al., 2022; Lima et al., 2018). Despite the coarse resolution and inherent uncertainties exhibited by them, studies have already confirmed their robust agreement with observed data and theory (Abdelmoaty et al., 2021; Asadieh & Krakauer, 2015; Fischer & Knutti, 2016; Mishra et al., 2020). For instance, multiple studies have been employing CMIP6-based projections to assess projected changes in the statistical properties of rainfall events worldwide, such as in India (Chaubey & Mall, 2023), China (Yu et al., 2023), East Africa (Gebrechorkos et al., 2023), and United Kingdom (Cotterill et al., 2021). This confirms the utility of climate projections for identifying and quantifying future changes in extreme rainfall events (Moustakis et al., 2021; Ragno et al., 2018; Ukkola et al., 2018).

Nevertheless, even with the fundamental importance attached to such an assessment in shaping local-to-global water-related policies, studies on extreme rainfall are not universally prevalent across the globe. For instance, in Brazil—a country that has faced several widespread extreme climate-related hazards in the last decades (Ávila et al., 2016; Cunha et al., 2018; Lucas et al., 2021; Marengo et al., 2023; Regoto et al., 2021; Santos et al., 2016; Zilli et al., 2017)—future extreme events have not been extensively investigated through the use of climate model projections. The existing studies (a) have focused on individual regions of the country (Gesualdo et al., 2021); (b) relied on previous versions of CMIP; and/or (c) focused on evaluating changes only in the intensity of extreme rainfall events, since this information is commonly required for infrastructure design (Myhre et al., 2019; Sarkar & Maity, 2022). In general, previous studies did not assess how the rainfall distribution is expected to change in both intensity and frequency. Such assessment is, however, fundamental to shaping water resources management practices and to improving our understanding of the climate in the context of global warming (Harp & Horton, 2023).

Here we address this gap by assessing how global warming is expected to affect both extreme and non-extreme rainfall events in Brazil using bias-corrected Coupled Model Intercomparison Project (CMIP6) future projections. Instead of evaluating projected changes focusing solely in the intensity of rainfall events, here we assessed the expected changes in both their frequency and intensity (Mukherjee et al., 2018; Myhre et al., 2019). Finally, we examined how extremely rare rainfall events, commonly required for infrastructure design, are anticipated to change. Precisely, we aimed to address the following research questions: Will Brazilian extreme rainfall events be more frequent and/or intense in the future? How will these changes manifest spatially across the country's domain? Will extreme events of varying magnitudes change similarly? We believe our study is significant not only for drawing a picture of future rainfall events in Brazil, but also for enhancing our comprehension of the interplay between rainfall intensity and frequency and their roles in climate change impact studies.

2. Data

We used here the CLIMBra—Climate Change Data set for Brazil (Ballarin et al., 2023a), which provides bias-corrected rainfall time series for both historical (1980–2010) and future (2015–2100) periods under two distinct

CMIP6 Shared Socioeconomic Pathways: SSP2-4.5 and SSP5-8.5. The data set encompasses daily simulations of 19 CMIP6-climate models (Table S1 in Supporting Information S1) at a catchment scale (spatially-averaged, point-based time series) for 735 Brazilian catchments included in the CABRa data set (Almagro et al., 2021). The daily simulations were bias-corrected following the Quantile Delta Method (Cannon et al., 2015). For more details about the framework used to develop CLIMBra and its performance in representing observed climate variables, the readers are referred to Ballarin et al. (2023a).

3. Changes in Extreme Rainfall Events

Changes in rainfall properties can be assessed by evaluating the empirical distribution of the data or fitting a parametric distribution to the observations (Beranová et al., 2018; John et al., 2022; Papalexiou & Koutsoyiannis, 2016). While the latter approach enables the assessment of changes in non-observed events (Moustakis et al., 2021), it requires a priori assumption regarding the statistical model used to describe the observed data (Marani & Ignaccolo, 2015). This fact, combined with the inherent uncertainties of the parameter estimation procedure (Nerantzaki & Papalexiou, 2022), may hinder an accurate assessment of the changes in rainfall properties. The non-parametric approach, on the other hand, allows the computation of changes in pre-established thresholds without requiring specific knowledge about the underlying distribution. Nevertheless, it cannot be used to assess changes in non-observed events present in the extrapolation range (Volpi, 2019). In view of these considerations, we opted here to use both non-parametric and parametric approaches. The former will be employed to assess how different extreme and non-extreme rainfall events are expected to change, while the latter will be used to assess changes in extreme events present in the extrapolation range.

3.1. Non-Parametric Approach—Assessing Changes in the Distribution of Rainfall Events

For the non-parametric assessment, we proposed an alternative framework based on the studies of Markonis et al. (2019) and Myhre et al. (2019). It consists in evaluating changes in the frequency and intensity of rainfall events exceeding varying q_i quantile-thresholds (where, $i = 0.5, 0.7, 0.9, 0.95, 0.99$, and 0.999) of the right-tail of the distribution of wet days (>1 mm). To account for the potential effects of overlapping rainfall events defined by the quantile-thresholds approach, we also repeated the analysis considering the rainfall events that falls within varying $q_{[i,i+1]}$ quantile-intervals (Figure 1). For instance, the first interval of the thresholds approach encompasses all events exceeding the historical rainfall quantile $q_{0.5}$, whereas the first interval of the intervals approach encompasses all rainfall events lying between the historical quantiles $q_{0.5}$ and $q_{0.7}$. The last interval in both the thresholds and intervals approaches is the same and includes all events that exceeds the historical rainfall quantiles $q_{0.999}$. In the thresholds approach, extreme rainfall events, such those exceeding $q_{0.999}$, are included (and consequently influences the relative changes) in all considered intervals. In the intervals approach, in contrast, rainfall events are stratified in different intervals, allowing for a more detailed understanding of how different rainfall events are expected to change.

For both approaches, we assessed future changes in the frequency of rainfall events by computing relative changes (Δ) in the number of events that falls within the historical q-interval, defined either by the quantile-thresholds or quantile-intervals approaches. Here, we considered relative changes as the percentage difference between historical and future periods (Gründemann et al., 2022). To assess future changes in the intensity of rainfall events, we computed the future changes in the averaged rainfall of the events lying within the historical q-interval. Finally, to assess the relative contribution of changes in intensity and frequency to the total changes, we computed the relative changes in the total amount of rainfall events within the historical q-interval. We conducted these analyses considering a long-term temporal perspective. To account for climate models' uncertainties and variability, we performed these analyses for each of the 19 CLIMBra's CMIP6 climate models individually, and subsequently computed multi-model ensemble statistics (mean and median).

3.2. Parametric Approach—Assessing Changes in Extreme Rainfall Events Present in the Extrapolation Range

The non-parametric approach provides a general overview of expected changes in rainfall distribution. Nevertheless, it does not allow us to assess extremely rare rainfall events, such as those occurring once in 100 years, due

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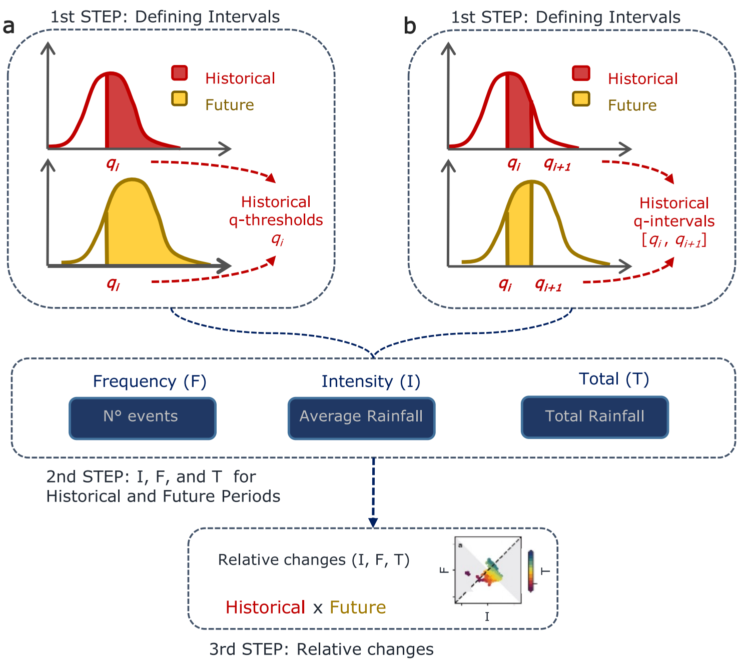

Figure 1. Flowchart depicting the core steps of the non-parametric approach, developed to compute relative changes in the frequency, intensity, and total rainfall between historical and future periods using the (a) quantile-thresholds and (b) quantile-intervals approaches.

to the inability of observed data to support extrapolation estimates (Volpi et al., 2019). Thus, we also employed here a parametric approach, in which we fit a statistical model to rainfall series and compute expected changes on extreme rainfall events belonging to the extrapolation range.

The most popular method for assessing extreme rainfall events relies on the extreme value theory (EVT). This approach posits that extreme events, defined as the maximum event occurring in a predefined temporal block (commonly 1 year), converge asymptotically to one of three different distribution classes (Gumbel, Frechét, and Reversed Weibull) summarized by the Generalized Extreme Value distribution (GEV). This theory assumes that (a) the events occurring in each block are independent and identically distributed and (b) the number of occurrences in each block tends to infinite (e.g., Marra et al., 2019; Zorzetto et al., 2016). Nevertheless, these conditions are rarely met. The parent distribution of daily rainfall events is typically unknown, and the number of events in a block is not nearly sufficient to assure the asymptotic assumption (Papalexiou & Koutsoyiannis, 2013). Additionally, the EVT framework neglects a substantial proportion of observations since it uses only one observation per block (De Michele & Avanzi, 2018; Volpi et al., 2019). The same limitations extend to the peak-over-threshold approach and the Pareto distribution (Zorzetto et al., 2016).

As an alternative to the recently questioned EVT (De Michele, 2019; Veneziano et al., 2009), some studies are turning to non-extreme distributions (Papalexiou, 2018; Zaghloul et al., 2020) or proposing alternative distributions that relaxes the asymptotic assumptions, assuming a known parent distribution $F(x)$ of ordinary rainfall events (Miniussi & Marani, 2020). Here, based on the recent finds of Papalexiou (2022) and Marra et al. (2023) and on physical reasoning (Wilson & Toumi, 2005), we assumed (and further verified) that the tail of the distribution of rainfall events is stretched-exponential or follows a Weibull distribution tail (Equation 1). This assumption enable us to employ the Metastatistical Extreme Value (MEV) distribution (Equation 2) for assessing extreme events within the extrapolation range (see Marani & Ignaccolo, 2015; Zorzetto et al., 2016 for an in-depth description of the MEV formulation).

$$F_{\mathrm{W}}(x) = 1 - \exp\left(-\frac{x}{\beta}\right)^{\gamma} \quad (1)$$

$$F_{\mathrm{MEV}}(x) = \frac{1}{T}\sum_{j=1}^{T}\left[1 - \exp\left(-\frac{x}{\beta_j}\right)^{\gamma_j}\right]^{n_j} \quad (2)$$

where β is a scale parameter, γ a shape parameter, n is the number of wet days within the year j, and T is the number of available years in the time series. Instead of the traditional MEV, we adopted here a simplified version of it (SMEV, Equation 3). In SMEV, we disregard interannual variations and compute β and γ considering all precipitation values above the quantile-based threshold for all years, while considering the average yearly number of rainfall events present in the tail, $\bar{n}$ (Schellander et al., 2019). We estimated Weibull parameters using the probability weighted moment method, as it attributes a greater weight to the tail and is not very sensitive to outliers and low samples (Greenwood et al., 1979).

$$F_{\mathrm{MEV}}(x) = \frac{1}{T}\sum_{j=1}^{T}\left[1 - \exp\left(-\frac{x}{\beta}\right)^{\gamma}\right]^{\bar{n}} \quad (3)$$

To validate the assumption that the parent distribution of daily rainfall can be approximated by the Weibull distribution and to determine the portion of the daily rainfall distribution that defines the tail, we conducted a Monte Carlo tail-test originally developed by Marra et al. (2022). The tail-test proceed as follows: first, we estimate Weibull parameters β and γ corresponding to daily rainfall events exceeding a specific quantile-threshold θ. In this step, we explicitly censored all the annual maxima to ensure an independent assessment of the model's performance in describing observed rainfall extremes. Using the estimated parameters, we generate 1,000 synthetic rainfall daily series with the same number of rainfall events present in the tail of the observed rainfall daily series. Finally, we extracted the corresponding annual maxima series from the synthetic series and tested if the observed annual maxima series are likely sample from them.

If more than $p = 5\%$ of the observed maxima lie outside the $1 - p = 95\%$ confidence interval defined by the synthetic annual maxima series, we rejected the hypothesis that rainfall events exceeding the threshold θ follow a Weibull tail. Otherwise, we assume that the left-censored θ rainfall events can be described by a Weibull distribution. We run this test for varying left-censoring θ ($q_{0.10}$ to $q_{0.95}$, with increments of 0.05) and selected the smallest θ for which the test is not rejected to define the tail of the parent distribution. If the test was rejected for all evaluated θ, it means that the Weibull distribution cannot serve as the parent distribution. We run the tail-test for all 735 catchments' daily historical rainfall series present in the CLIMBra data set, considering the 19 CMIP6 climate models historical simulations. It is important to highlight that in the tail test, we assume wet days to be independent when fitting the Weibull distribution, as daily rainfall typically exhibit low values of lag-1 autocorrelation (Papalexiou, 2022). Nevertheless, following previous studies (Marra et al., 2023; Zorzetto et al., 2016), we conducted Monte Carlo simulations to confirm that this serial correlations do not affect the fitting and our general conclusions.

Once the suitability of the Weibull distribution to represent Brazilian catchments' rainfall events was confirmed (see Figure 5), we fit the SMEV distribution for the future simulations driven by the SSP2-4.5 and SSP5-8.5 scenarios. For catchments where the Weibull distribution were not rejected, we used the portion of rainfall events defined in the tail-test to fit the SMEV. For the others, we adopted $q_{0.95}$ to define the tail, following Marra et al. (2023). We used the fitted SMEV to compute the projected changes in rainfall quantiles associated with varying return periods T (5, 10, 50, 100, 200, and 500 years) between historical and future simulations. Alternatively, we fit the SMEV distribution using all wet rainfall events and obtained similar results in terms of projected relative changes (not showed here).

4. Results

The interplay between the expected changes in intensity and frequency of rainfall events vary significantly across the evaluated quantile-thresholds intervals (Figure 2). Here we focus on the projected changes computed for the SSP5-8.5 future scenario, although similar results were obtained for SSP2-4.5 (see Figure S1 in Supporting Information S1). In general, for all quantile-thresholds intervals, the intensity of rainfall events is projected to increase similarly. This intensification, however, does not always translate into an increase in the total rainfall due to the divergent expected changes in rainfall frequency. For example, approximately 80% (multi-model ensemble

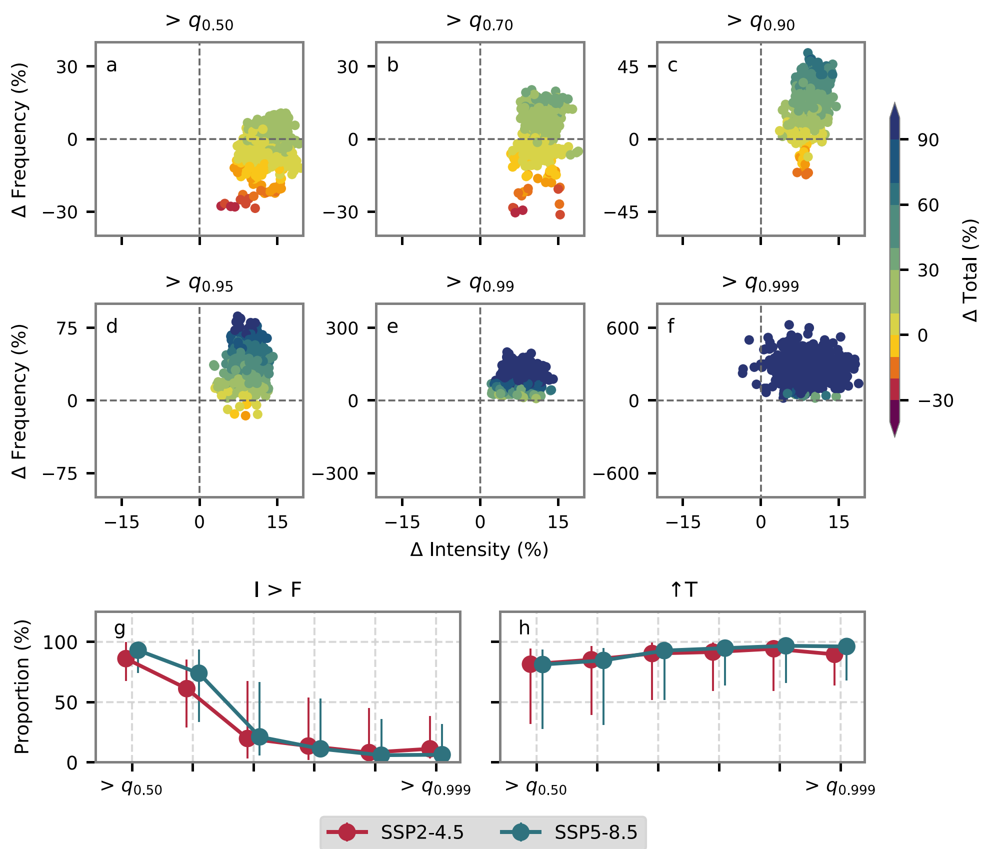

Figure 2. (a–f) Relative changes (Coupled Model Intercomparison Project (CMIP6) multi-model ensemble median) between historical (1980–2010) and distant future (2070–2100; SSP5-8.5) periods in frequency, intensity and total rainfall for different quantile-thresholds obtained for the 735 catchments. Changes in frequency, intensity and total rainfall were computed for CMIP6 GCMs individually and we display the CMIP6 multi-model ensemble median of these changes. (a) $>q_{0.50}$, (b), $>q_{0.70}$, (c) $>q_{0.90}$, (d) $>q_{0.95}$, (e) $>q_{0.99}$, and (f) $>q_{0.999}$. Black, dashed lines divides the quadrants (g) proportion of catchments were the relative change in intensity was larger than the relative changes in frequency for each quantile-thresholds intervals considering both SSP2-4.5 and SSP5-8.5 scenarios. (h) Proportions of catchments with positive relative changes in total rainfall for each quantile-thresholds intervals considering both SSP2-4.5 and SSP5-8.5 scenarios. The central points (bars) indicate the median (95% confidence intervals) proportion obtained using the 19 CMIP6 climate models.

median) of the catchments are projected to exhibit an increase in rainfall for the events exceeding $q_{0.50}$. Yet, nearly 100% of the catchments are expecting heightened rainfall intensity. This somewhat counterintuitive pattern can be explained by the fact that approximately 54% of the catchments are projected to experience a reduction in the frequency of rainfall events at this specific threshold (Figure 2a). That is, even with an enhanced intensity, some catchments may experience a reduction in total rainfall exceeding $q_{0.50}$ due to a reduction in rainfall frequency (Figure 2a). However, as we progress through the evaluated quantile-thresholds, we observe a gradual increase in the expected changes in rainfall frequency. When combined with the intensification of rainfall events, this leads to overall positive projected changes for the total rainfall. For instance, for events exceeding $q_{0.99}$ and $q_{0.999}$, almost all catchments showed an increase in both frequency and intensity (Figures 2e and 2f), culminating in a rise in the total rainfall.

Furthermore, it becomes evident that projected rainfall frequency changes surpass intensity changes as we progress through the evaluated intervals (Figure 2g). For the lower quantile-thresholds intervals (Figures 2a and 2b), the magnitudes of expected changes are quite similar. For $q_{0.50}$, we found mean changes of approximately −3% and 12% for frequency and intensity, respectively. For $q_{0.70}$, the changes in frequency and intensity are approximately 6% and 11%, respectively. In these cases, CMIP6 models generally project slightly larger increases in intensity when compared to frequency for Brazilian catchments (Figure 2g). A contrasting scenario, however, emerges for the larger quantiles, where CMIP6 models project notably greater changes in frequency than in

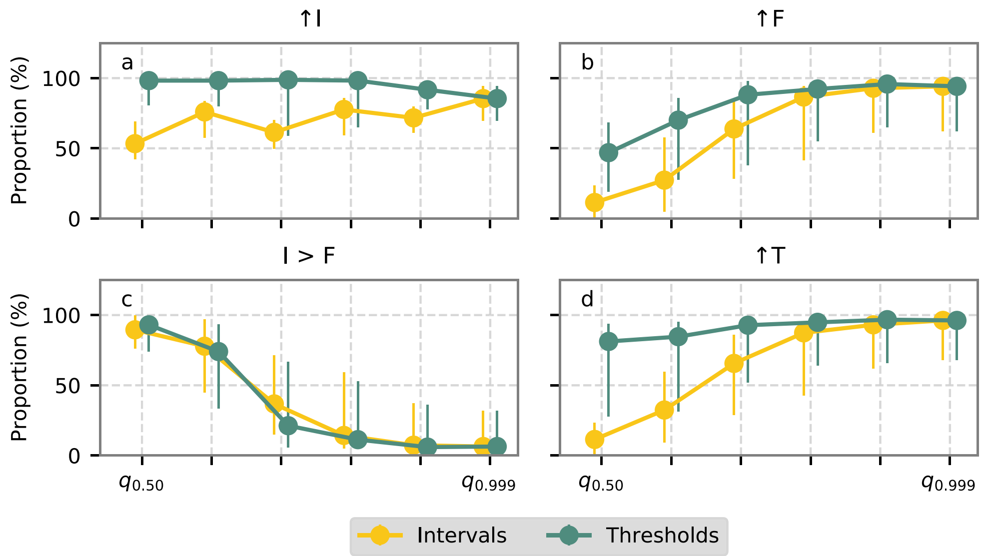

Figure 3. (a–d) Relative changes (Coupled Model Intercomparison Project (CMIP6) multi-model ensemble median) between historical (1980–2010) and distant future (2070–2100; SSP5-8.5) periods in frequency, intensity and total rainfall for both quantile-thresholds and quantile-intervals approaches. Changes in frequency, intensity and total rainfall were computed for CMIP6 GCMs individually and we display the CMIP6 multi-model ensemble median of these changes. (a) Proportions of catchments with positive relative changes in rainfall intensity. (b) Proportions of catchments with positive relative changes in rainfall frequency. (c) Proportion of catchments were the relative change in intensity was larger than the relative changes in frequency. (d) Proportions of catchments with positive relative changes in total rainfall. The central points (bars) indicate the median (95% confidence intervals) proportion obtained using the 19 CMIP6 climate models.

intensity. For instance, for the rainfall events exceeding $q_{0.99}$, the mean absolute expected changes are approximately 10% and 100% for intensity and frequency, respectively (Figure 2e). This implies that the projected increase in the extreme rainfall is mainly driven by an increase in rainfall frequency, rather than intensity, such as observed in previous studies (Myhre et al., 2019; Sarkar & Maity, 2022).

Despite the importance of such assessment, the overlapping rainfall intervals within the quantile-thresholds approach may affect it. That is, extreme high rainfall events, such as those exceeding $q_{0.999}$, influences the relative changes computed for all evaluated quantile-thresholds. To mitigate this undesired effect and gain a better understanding of projected changes, we conducted an alternative analysis using the quantile-intervals framework (Figure S2 in Supporting Information S1). The results of both approaches are summarized in Figure 3. Unlike what we observed in the quantile-thresholds approach, there is no dominant pattern of intensification. For the lower quantile-intervals (such as the interval $q_{0.50}$–$q_{0.70}$), we see a similar count of catchments showing increasing/decreasing intensity (Figure 3a). As we progress across the intervals, this proportion gradually raises, suggesting that most of Brazilian catchments are prone to have more intense extreme rainfall events. These contrasting results between approaches where also found for frequency. For the lower quantile-intervals, we found that most catchments exhibited negative changes, whereas, for the lower quantile-thresholds, only half of the catchments exhibited negative changes (Figure 3b). For the higher quantiles, in contrast, both approaches converge, indicating that Brazil will likely experience extreme rainfall events more frequently. In general, total rainfall of events present in the lower quantile-intervals are projected to decrease (Figure 3d), while the total rainfall of events present in the higher quantile-intervals are projected to increase. The increase in total rainfall was as also indicated by the quantile-thresholds approach, since the overlapping effects fade over across the evaluated quantiles.

We displayed on Figure 4 the spatial distribution of projected changes using the quantile-intervals approach. The corresponding figures with catchments classified according to their increasing/decreasing condition considering both quantile-intervals and quantile-thresholds approach can be found in Figures S3 and S4 in Supporting Information S1. We did not depict projected changes of the higher rainfall quantiles as they exhibited an almost uniform pattern of increasing intensity and frequency for both approaches. In general, the entire country will experience a reduction in moderate rainfall events, primarily driven by a decrease in rainfall frequency, and an

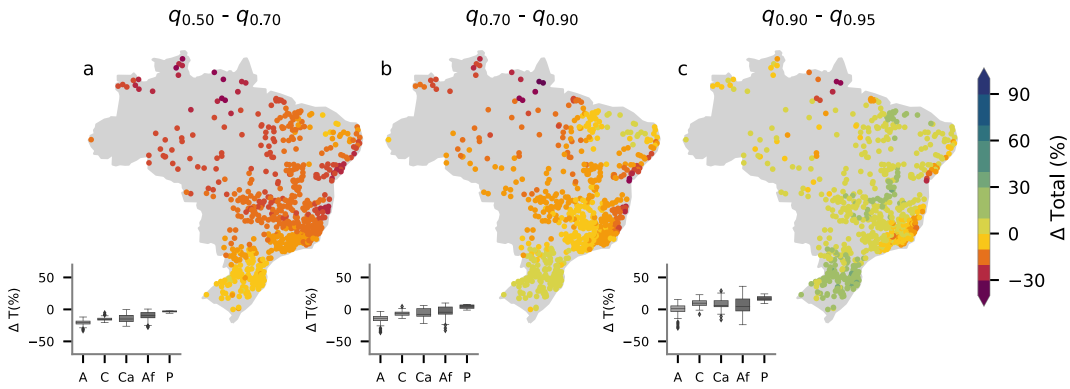

Figure 4. (a–c) Spatial distribution of the relative changes (Coupled Model Intercomparison Project (CMIP6) multi-model ensemble median) between historical (1980–2010) and distant future (2070–2100; SSP5-8.5) periods in total rainfall for different quantile-intervals. (a) $q_{0.50}$–$q_{0.70}$, (b)$q_{0.70}$–$q_{0.90}$, (c) $q_{0.90}$–$q_{0.95}$. Changes in frequency, intensity and total rainfall were computed for CMIP6 GCMs individually, and we display the CMIP6 multi-model ensemble median of these changes. Changes per Brazilian biome are displayed in traditional boxplots (A: Amazon, C: Cerrado, Ca: Caatinga, Af: Atlantic Forest, and P: Pampa).

increase in extreme rainfall events (Figure S3 in Supporting Information S1). The Amazon is the biome that will experience the most substantial reduction in non-extreme rainfall events (−23%, on average), and the Pampa, the lowest one (−3%, Figure 4a). The others evaluated biomes—Caatinga, Cerrado, and Atlantic forest—exhibited a more diverse spatial pattern, but all of them will experience an overall reduction in moderate rainfall events (Figures 4a and 4b) accompanied by an increase in the other evaluated quantiles. It is interesting to note that, with exception of the Amazon and Pampas biomes, which exhibited a more homogenous and evident decreasing/increasing pattern, this features cannot be observed for the quantile-thresholds approach, given the overlapping-effect (Figure S4 in Supporting Information S1). Overall, such combination of decrease (increase) in moderate (extreme) rainfall events are expected to alter the shape of the distribution of rainfall events (Pendergrass & Knutti, 2018). Heavy rainfall will likely exhibit a larger contribution to the accumulated, total rainfall in the future period than the contribution observed in the historical period (Figure S5 in Supporting Information S1). For instance, according to the SSP5-8.5 distant future simulations, the ratio between total rainfall events surpassing the future $q_{0.99}$ quantile and total accumulated 30-year rainfall may increase up to 15% in comparison with the historical period (1980–2010).

To assess how rainfall events within the extrapolation range are expected to alter, we used here the parametric SMEV distribution, assuming that daily rainfall tails of Brazilian catchments follow the Weibull distribution. The outcomes of the tail-test confirmed our hypothesis: the tail of Brazilian catchments' rainfall can indeed be represented by the Weibull distribution (Figure 5a). On average across the 19 CMIP6 historical simulations, the assumption of having historical annual maximum daily rainfall emerging from Weibull tails could not be rejected in nearly 98% of the catchments. The catchments in which the assumption were rejected are mainly situated in the Amazon biome. In these cases, extreme precipitation could have a different type of tail, such as heavier than the stretched-exponential Weibull tail, or the Weibull tail could be consist in smaller fractions of the data (Marra et al., 2022). For almost 60% of the evaluated catchments the left-censoring threshold—defined as the smallest θ in which the null hypothesis of the tail test is not rejected—fell above $q_{0.75}$, which is in line with the proportion found by Marra et al. (2023). For the remaining 40%, only the most extreme rainfall events can be employed to represent the tail.

We also assessed the yearly number of wet-days present in the tail defined by the specific threshold (Figure 5b). On average, nearly 90 daily rainfall data points are available, per year, for the estimation of the Weibull parameters. This large sample ensures a robust fit with reduced uncertainties when compared with the GEV-block maxima approach (Volpi et al., 2019), commonly employed in the country (Ballarin, Calixto, et al., 2022). It is also interesting to note the clear spatial pattern of available data points in the tail: for the Amazon and Pampa biomes more data are available for the Weibull fitting (138 and 102 wet-days per year, on average, respectively). For the Caatinga biome, a lower amount of data is available (nearly 50 wet-days per year). This is consistent with the wet and dry rainfall regimes of these biomes. The Cerrado and Atlantic forest biomes, in contrast, did not

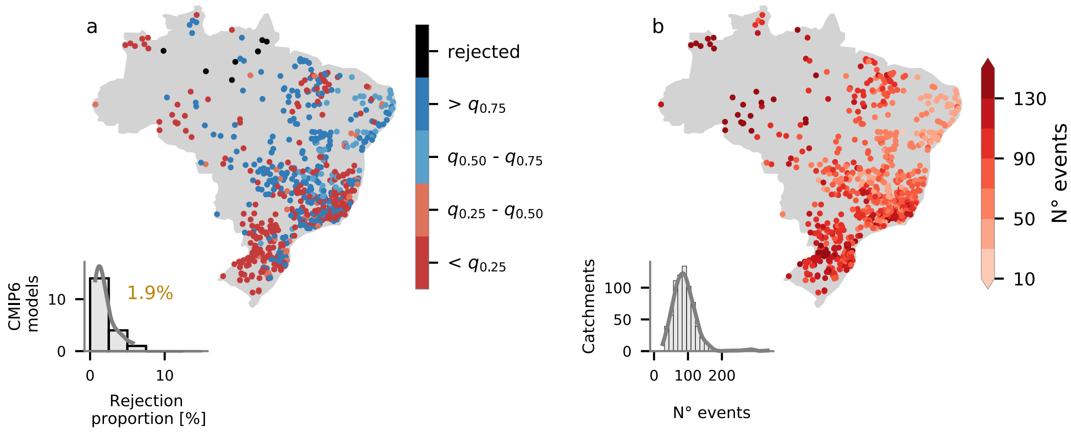

Figure 5. Suitability of the Weibull distribution to represent Brazilian catchments' rainfall in the historical (1980–2010) period. (a) Left censoring threshold θ (quantile-based) used to define the Weibull tails, as the smallest θ in which the null hypothesis of data Catchments were the assumption of the Weibull tail was rejected are colored in black. The histogram exhibits the rejection proportion obtained for the 19-CMIP6 climate models simulations. Average rejection proportion is displayed in yellow. (b) Average yearly number of wet-days in the tail as defined by the left-censoring threshold.

exhibit a clear spatial pattern given their heterogeneous distribution throughout Brazil, encompassing different climate regions with varying rainfall distributions (Ballarin et al., 2023a).

After confirming the suitability of the Weibull distribution, we used the SMEV distribution to assess how extreme events associated with different return periods might change. In general, we found that they are expected to increase throughout the country (Figure 6). The average changes (and also its spatial variability) are expected to be more pronounced for the rarest extreme events (Figures 6d–6f), suggesting a future trend toward heavier-tailed

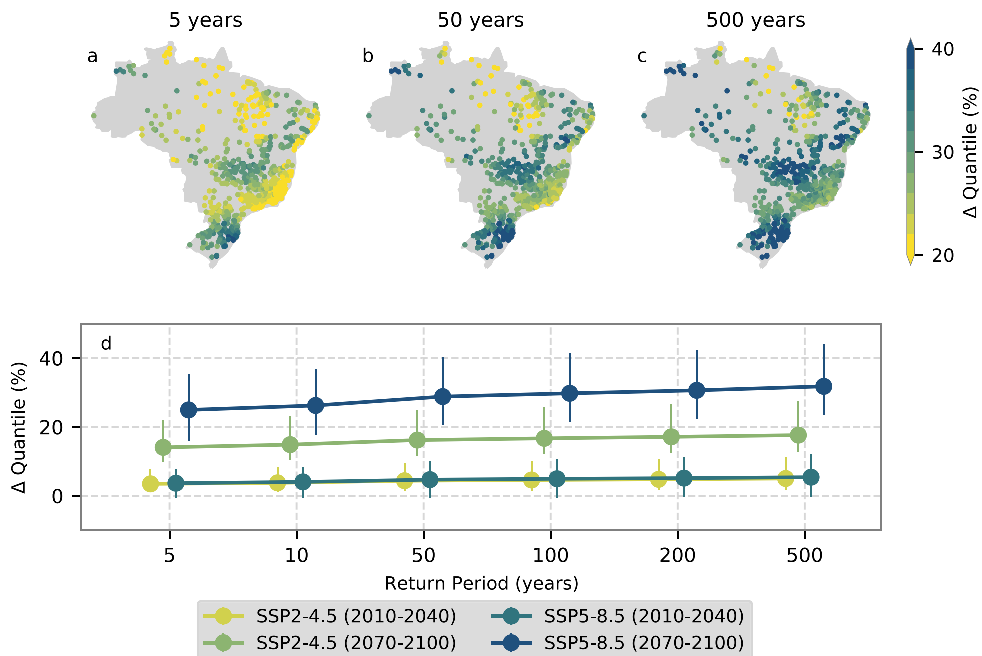

Figure 6. (a–c), Spatial distribution of the relative changes (Coupled Model Intercomparison Project (CMIP6) multi-model ensemble median) between historical (1980–2010) and distant future (2070–2100; SSP5-8.5) periods in the SMEV-rainfall quantiles associated to different return periods: (a) 5 years, (b) 50 years, (c) 500 years. Changes in frequency, intensity and total rainfall were computed for CMIP6 GCMs individually, and we display the CMIP6 multi-model ensemble median of these changes. (d) Summary of projected changes in future extreme rainfall events for the immediate (2010–2040) and distant (2070–2100) future under the SSP2-4.5 and SSP5-8.5 scenarios. The central points (bars) indicate the median (95% confidence intervals) projected changes obtained for the 735 Brazilian catchments considering the multi-model ensemble mean.

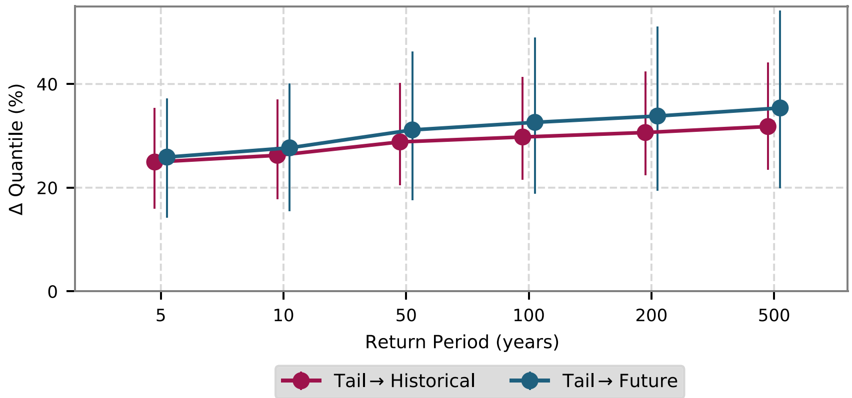

Figure 7. Projected changes in SMEV-rainfall quantiles computed using Weibull tails defined in the historical (1980–2010) and future (2070–2100; SSP5-8.5) periods. Changes in frequency, intensity and total rainfall were computed for Coupled Model Intercomparison Project (CMIP6) GCMs individually, and we display the CMIP6 multi-model ensemble median of these changes. The central points (bars) indicate the median (95% confidence intervals) standard deviation of the projected changes obtained for the 735 Brazilian catchments.

rainfall. The magnitude of the differences between relative changes obtained for different return periods are in agreement with the findings of Gründemann et al. (2022), which also assessed projected changes in rainfall extremes using a MEV-based approach.

As observed in the non-parametric approach, the Pampa and part of the Cerrado biomes will experience the most significant intensification in extreme rainfall, particularly for the rarest events (Figure 6c). The Amazon biome, on the other hand, will exhibit the lowest increase. Actually, for a few Amazon catchments, the projected changes will be quite similar across the evaluated return periods. As expected, relative changes are notably lower in the immediate future (2010–2040) than in the distant future (2070–2100; Figure 6d). Interestingly, we found almost no difference between the changes projected in the immediate future under SSP2-4.5 and SSP5-8.5 scenarios. For the distant future, however, the differences are significantly greater, with the higher emission scenario SSP5-8.5 projecting greater changes. For instance, the 100-year rainfall event is expected to increase 17% and 31%, on average, in the SSP2-4.5 and SSP5-8.5 distant future, respectively. Finally, we found a relatively low variability among CMIP6 projections, indicating a strong model agreement. That is, all evaluated models projected enhanced extreme rainfall, with low between-model standard deviation (Figure S6 in Supporting Information S1).

For simplicity, we adopted here the same Weibull tail defined for the historical period to estimate projected changes in future extreme rainfall events (Figure 6). Nevertheless, future rainfall can be made up by different climate processes, and therefore, might be better represented by alternative left-censoring thresholds θ (or even by other heavier/lighter tail distributions). Hence, we repeated the tail-test for the SSP5-8.5 distant future (2070–2100) simulations (Figure S7 in Supporting Information S1). The results reaffirmed the suitability of the Weibull distribution to represent future Brazilian rainfall events. The mean proportion of rejections slightly increased (from 1.9% to 3.9%) and there was a slight shift in the spatial distribution of the left-censoring threshold. Even so, the Weibull distribution was not rejected in 96% (on average) of the catchments. We employed these updated θ-values to fit the SMEV-distribution and to calculate changes between historical and future extreme rainfall quantiles (such as did in Figure 6). This approach helped us to assess how the use of historical (or future) left censoring thresholds affects our results (Figure 7). For the lower evaluated return periods, both historical and future θ-tails yielded high similar relative changes. As we progress across the return periods, the difference between the relative changes (both in terms of mean and variability) marginally increased, with future θ-tails projecting slightly heavier tails. Even so, the projected changes are of the same order of magnitude.

5. Discussion

Here we first examined how rainfall events are expected to change in Brazil in terms of both frequency and intensity, using two different—and complementary—non-parametric frameworks. From this two-sided perspective, three important aspects emerged. First, changes in frequency, rather than intensity, appears to dictate the projected changes of future rainfall (Myhre et al., 2019; Nissen & Ulbrich, 2017; Sarkar & Maity, 2022). We observed an intensification of future rainfall events even with a reduction in rainfall intensity given an enhanced rainfall frequency. This finding underscores the importance of incorporating frequency on climate assessments (Pendergrass & Hartmann, 2014). Furthermore, it takes on even greater significance in view of the relative frequency changes observed in this study, which greatly surpassed the magnitude of changes reported in previous studies that only assessed rainfall intensity (Westra et al., 2013).

Second, the varying pattern of changes across different rainfall quantiles (Figures 2 and 3) demonstrates the advantages of assessing different parts of the rainfall distribution, rather than exclusively focusing on extreme events. Heavy and light/moderate rainfall events have different driving mechanisms and, consequently, respond differently to climate changes (Allan & Soden, 2008). Nevertheless, the majority of previous studies have primarily focused on extreme rainfall events, given their relevance for water resources planning (Markonis et al., 2019). Our findings indicates that in Brazil, moderate rainfall events ($<q_{0.70}$) are expected to reduce while heavy ones are expected to enhance, with both of them governed by changes in the frequency (Figure 3). These change patterns align with the compensation hypothesis, which states that increases in heavy rainfall events would be compensated by a reduction in light/moderate rainfall (Allen & Ingram, 2002; Fischer & Knutti, 2016; Hennessy et al., 1997; Moustakis et al., 2021). Nevertheless, it is noteworthy that this hypothesis has been formulated in the basis of climate model simulations, which mainly reported enhanced heavy combined with reduced light/moderate rainfall. The underlying mechanisms of how rainfall events are predicted to change, however, remain unclear, and the observed compensation mechanism might be an outcome of the application of climate model simulations. For instance, Markonis et al. (2019), when assessing changes in the rainfall distribution using a global data set reported results that go against the compensation mechanism, underscoring the need of future research focused on this topic.

Third, our findings highlight the importance of considering the complementary quantile-thresholds and intervals approaches to gain a deeper understanding of the expected changes in future rainfall events (Figure 3). While the former provides us with a general overview of the expected changes in precipitation events, the latter allows us to assess how different precipitation events are likely to change (Allan & Soden, 2008). For example, it was only possible to identify the compensation hypothesis after evaluating the quantile-intervals approach. This suggests that the light/moderate rainfall intensification pattern observed for the threshold approach is actually a consequence of the overlapping-effect. This finding is particularly important considering that many climate change impact studies relies on the quantile-thresholds reasoning, which is embedded in the indices developed by the Extreme Team on Climate Change Detection and Indices (ETCCDI; Zhang et al., 2011). Notably, the exclusive use of these indices to assess changes in rainfall characteristics has already faced criticism (Schär et al., 2016). We showed here that indeed the overlapping effect of threshold-based approaches can lead to misleading conclusions, and therefore should be accounted for in future studies.

We further validated the intensification pattern of extreme rainfall events through a parametric approach, using a SMEV-based analysis. There is a clear pattern suggesting that the expected increase of extreme events is proportional to its rareness (Figure 6). Moreover, projected changes are in the same order of magnitude of changes reported in previous studies (Abdelmoaty & Papalexiou, 2023; Crévolin et al., 2023; Gründemann et al., 2022). For instance, for the higher emission scenario, a 100-year rainfall event is expected to increase nearly 31% in Brazil, in comparison with the averaged globally value of 32.5% obtained by Gründermann et al. (2022). Furthermore, the changes are expected to escalate over time and with varying emission scenarios. Across all return periods, changes between historical and future rainfall events will (a) be nearly 50% larger for the SSP5-8.5 scenario than for the SSP2-4.5, in the distant future; and (b) more than 100% larger in the distant future than in the immediate future, for the same scenarios.

Even though both non-parametric and parametric approaches suggested that extreme events are expected to increase, we should emphasize some aspects that may affect our results. As one can note in Figure 7, altering the way in which we fit the parametric distribution affected our findings (albeit to a small extent in our particular case). This indicates that different conclusions can arise by varying, for example, the parameter estimation or the probability distribution. For instance, for a distant future, SSP5.8-5, 100-year return period, the GEV distribution projected averaged changes of 45% (not showed here) in comparison with the 33% obtained using the SMEV approach. As already mentioned, the SMEV uses way larger sample sizes in the fitting procedure, besides relaxing the asymptotic assumption, which may explain these differences. Even so, both GEV and SMEV projected positive changes for all scenarios and futures periods, reinforcing the validity of our findings.

Another factor that influences our results is the uncertainty present in climate models projections, which are known to exhibit a lower accuracy in representing extreme high and low rainfall events (Londoño Arteaga & Lima, 2021; Mishra et al., 2014; Sherwood et al., 2010; Trenberth et al., 2017). To reduce these undesirable effects, we used here a bias-corrected data set that includes a variety of climate models projections to encompass different climate representations (see Li et al., 2017). Nevertheless, even presenting a better performance to represent observed values, the bias-corrected data set may contain inherent uncertainties and physically unrealistic values (Casanueva et al., 2020). Finally, it is important to note that we assessed projected changes from a catchment-perspective. We emphasize that using averaged daily series may hinder extreme events, especially in large basins, since extreme high events of a specific grid may be smoothed by non-extreme events recorded in neighboring grids (Ballarin et al., 2023a).

6. Conclusion

We assessed how future Brazilian rainfall events are projected to change. Rather than focusing solely on extreme events, we propose an alternative framework to assess how rainfall events of varying magnitudes are projected to change in both intensity and frequency. Our findings suggested that changes in Brazilian future rainfall are asymmetric: light/moderate rainfall are expected to reduce, while extreme rainfall are expected to increase. For instance, on average, a 100-year rainfall event is expected to increase nearly 31% across Brazil for the SSP5-8.5 CMIP6 scenario at the end of the century. This uneven change pattern aligns with the compensation hypothesis. Moreover, we showed that changes in frequency, rather than intensity, rules the projected changes of rainfall events. Namely, rainfall events exceeding the historical rainfall quantile $q_{0.99}$ are projected to increase nearly 10% and 100% in intensity and frequency, respectively. Finally, we showed that using a threshold-based approach to assess future rainfall changes can result in misleading conclusions. We believe that the evidences gathered here will certainly contribute to not only a better understanding of future rainfall events in Brazil but also to an enhanced comprehension of the different rainfall properties and their interplay. Future research toward this topic—such as investigating how rainfall properties are expected to change seasonally and how these changes are linked to temperature—should shed more light to the compensation hypothesis and to the controlling mechanisms of the changes in rainfall intensity and frequency.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Bias-corrected, catchment-scale CMIP6-climate projections for the Brazilian territory can be found in the CLIMBra's data set, freely available in Ballarin et al. (2023b).

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