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Drought intensification in Brazilian catchments: implications for water and land management

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Abstract

Droughts exert widespread impacts on both natural and social systems, and there is accumulating evidence that this situation may worsen in the context of global warming. Despite the importance of assessing changes in droughts to understand their potential future impacts on society, studies are unevenly distributed worldwide. In this study, utilizing bias-corrected CMIP6 simulations and a standard precipitation-evaporation index based approach, we quantified expected changes in future drought properties across 735 Brazilian catchments under SSP2-4.5 and SSP5-8.5 scenarios. Beyond evaluating the statistical properties of future droughts, we assessed their occurrence under both land use and water demand perspectives and propose a new framework to better understand their link with changes in long- and short-term conditions of precipitation (P) and potential evapotranspiration (PET). Our results indicate that drought events are projected to become more frequent and severe in the future, with high CMIP6 model agreement. According to the SSP5-8.5 scenario, at least half of Brazilian cropland and pasture areas will experience an increase of over 30% in drought properties by the end of the century. Furthermore, among the 85% of catchments expected to experience more severe droughts, nearly 90% are also projected to exhibit increased water demand, which will likely exacerbate future water scarcity. The investigation of the relationship between droughts changes and climate variables suggests that catchments with augmented droughts in the future will likely exhibit increased long-term average PET and P-variability, but not necessarily long-term average P. For instance, over 50% of evaluated Brazilian catchments are expected to experience an intensification of drought properties even with increases in P_{mean}. We believe this study may contribute (a) to improve Brazilian water resiliency by helping achieve the objectives of the National Water Security Plan and (b) to deepen our understanding of droughts in an uncertain future.

1. Introduction

Among climate-related hazards, droughts emerge as the most challenging for natural and social systems (De Luca and Donat 2023), as they might disrupt a myriad of facets, including food production, power generation, and water resources (Vicente-Serrano *et al* 2022, Cardenas Belleza *et al* 2023). Hence, understanding and predicting drought properties are essential to address their potential impacts on society and develop mitigation strategies, especially in the context of global warming, which is expected to alter the frequency and magnitude of drought events worldwide (Cook *et al* 2020, Araujo *et al* 2022, Adeyeri *et al* 2023).

Despite the importance of such assessments, studies of droughts are unevenly distributed globally, hindering a detailed characterization of droughts for informing local-to-regional policy decisions. This gap is particularly pronounced in Brazil, a country with paramount importance in global food security and climate regulation (Nepstad *et al* 2008, Pereira *et al* 2012). While Brazil faces rising concerns about drought events (Getirana *et al* 2021), there is a lack of studies assessing projected changes of drought from a countrywide perspective (Ferreira *et al* 2023). The country is already suffering from several water deficits (Marengo *et al* 2008, 2022, Otto *et al* 2015, Nobre *et al* 2016, Lucas *et al* 2021), and this condition might worsen (Ballarin *et al* 2021, Wang *et al* 2021, Sone *et al* 2022). For instance, global warming is expected to exacerbate drought events in the Amazon region, likely increasing fire activity, tree mortality, and carbon emissions (Duffy *et al* 2015). This situation might not only affect Brazil, but the world, given the role of the Amazon forest in regulating Earth's climate and biodiversity (Feng *et al* 2021, O'Connor *et al* 2021). Therefore, understanding the impact of global warming on future droughts in Brazil is crucial for climate stakeholders.

Here, we attempt to bridge this gap by assessing how Brazil's meteorological drought events are expected to change. Beyond evaluating future drought properties and signal of changes—which is commonly done in the vast majority of drought-based studies (Araujo *et al* 2022, Zhao and Dai 2022)—we investigate the link between drought properties and meteorological conditions, discussing the potential consequences of droughts intensification across Brazilian catchments using both a land cover and water use viewpoints. To this end, we evaluate the link between changes in *P* and PET properties and drought changes, employing two different temporal perspectives: long-term (i.e. identification of change signals with climate change) and short-term (i.e. event-based impacts of drought events). This dual approach is fundamental for gaining insights into the differences between long-term and intra-annual climatological characteristics, shedding light on climate variability and its connection with drought events. Our study aims to answer the following questions: How are drought events projected to change across Brazilian catchments and what are their potential implications? How are the expected changes of drought events linked with changes in meteorological conditions and its temporal variability? This work not only provides a general overview of expected changes in drought events in Brazil, which may help to achieve the main goals of the National Water Security Plan (PNSH; ANA 2019b) but also contributes to an enhanced understanding of drought and their spatiotemporal characteristics.

2. Data

Daily climatological time series were retrieved from the CLIMBra dataset (Ballarin *et al* 2023b). It provides raw and bias-corrected historical and future simulations of six meteorological variables for 10 climate models forced by two CMIP6 scenarios: SSP2-4.5 and SSP5-8.5. The dataset employed the delta quantile method (Cannon *et al* 2015) and a widely used station-based gridded Brazilian dataset (Xavier *et al* 2016) to bias correct CMIP6-simulated daily series, which were further spatially averaged to a catchment-scale to encompass the 735 catchments present in the CABra dataset (Almagro *et al* 2021). PET values were computed using the formulation proposed by Yang *et al* (2019), which modifies the Penman–Monteith equation to account for the effects of increased CO_2 concentrations on plants' water use. This effect reduces vegetation water losses and diminishes dry biases in future PET estimations (Milly and Dunne 2016, Greve *et al* 2019, Yang *et al* 2020, Ballarin *et al* 2023a). Land use data were retrieved from the Land Use Harmonization (LUH v2) project (Hurtt *et al* 2020). LUH v2 provides annual data on land use states and transitions for historical (1850–2014) and future (2015–2100). The dataset were used as input for multiple CMIP6 experiments, including the ScenarioMIP (O'Neill *et al* 2016), to generate future CMIP6 scenarios. The dataset comprises different land use states with a 0.25° spatial resolution, which we grouped into two different classes (crops/pasture and forest) to assess their susceptibility to future droughts in Brazilian's catchments. To further assess drought events from a water demand perspective, we extracted water consumption data from the ANA database (ANA 2019a). The dataset provides historical and future projections (until the middle of the century) of water consumption for different water uses in a micro-catchment scale for Brazil. Water consumption information was further aggregated to a catchment-scale to correspond to the CABra's dataset used in the present study (see Ballarin *et al* 2023a for a detailed description).

3. Methods

3.1. Drought's identification and characterization

We employed a non-parametric framework proposed by Ukkola *et al* (2020) to identify and quantify meteorological droughts. The framework relies on the reasoning of popular standard indices—such as the standard precipitation and evaporation index (SPEI)—but does not involve assumptions about data distribution. It proceeded as follows: first, precipitation minus potential evapotranspiration (*P*–PET) series were transformed into a 6-month accumulation running series. Although other temporal scales can be used, we focused on 6-month accumulations since they are more suitable for characterizing meteorological drought events (Papalexiou *et al* 2021). Then, for each month of the historical period (1980–2010), we computed the 15-percentile threshold of 6-month accumulations. Finally, we used these thresholds to identify drought events, defined by periods when monthly 6-month accumulations fell below these thresholds. The 15-percentile corresponds approximately to the SPEI of −1, which is usually adopted in drought studies (McKee *et al* 1993, Ukkola *et al* 2020). We also identified drought events through the traditional SPEI framework (Vicente-Serrano *et al* 2010) and obtained close drought events to reinforce the findings. Noteworthy, since this study aims to assess projected changes in drought events, the 15-percentile thresholds computed for the historical period were used to identify drought properties for both historical and future periods.

Using the definitions proposed by Ukkola *et al* (2020), we computed (a) drought duration as the period between the start and end of a drought event; (b) drought intensity as the mean difference between the 15-percentile and the 6-month accumulations during a drought event, expressed by a monthly deficit, (c) drought severity as the cumulative difference between the 15-percentile and the 6-month accumulations during a drought event, and (d) drought frequency as the number of drought events during the evaluated period. Here, we consider a 31-year, long-term perspective. Hence, drought's properties are reported on a 31-year average. To assess how drought events are expected to change, we computed the relative changes in long-term drought properties between distant future (2070–2100) and historical (1980–2010) periods. The results for the intermediate (2040–2070) and near (2040–2070) futures can be found in the supporting information.

3.2. Exploring changes in drought events and their link with long- and short-term changes of *P* and PET

To further explore future drought properties and their relationship with changes in meteorological conditions, we assessed how projected changes in *P* and PET are connected to changes in drought's properties. Namely, we examined the relationship between projected changes in drought properties and the following meteorological properties: number of wet days ($N_w; P > 1$ mm), (b) average precipitation of wet days (P_{mean}), (c) average potential evapotranspiration (PET_{mean}), and (d) the number of days when *P* surpasses PET (N_{wb}). We employed these four properties to account for both the intensity and frequency of *P* and PET. We used two different temporal perspectives: long- and short-term (event-based). For the former, meteorological properties were reported as 31-year average values. For the latter, only drought event periods were considered to compute the meteorological averaged properties (see supporting information for a detailed description). Such assessment is fundamental for better comprehending meteorological conditions in drought-triggering periods and how they differ from long-term climate characteristics (Vicente-Serrano *et al* 2022). We emphasize here that we are not assessing the drivers of future droughts changes, but rather focusing on better understanding their link with changes in meteorological conditions. While assessing droughts' drivers would require a meticulous exploration of the underlying dynamic processes, here we are interested in assessing the proportion of catchments experiencing positive or negative changes in *P* and PET and in droughts properties and how these changes are linked.

4. Results

4.1. Future intensification of meteorological drought properties

Drought events are generally expected to be more common, severe, and longer in Brazil (figure 1). As anticipated, changes in the CMIP6 pessimistic scenario, SSP5-8.5, are larger and exhibit greater variability across Brazilian catchments than those observed for the moderate scenario, SSP2-4.5. On average, for the long-term period, all catchments are expected to experience an intensification of drought intensity. The largest increases are projected in the North and on the coastal side of Brazil, where the Amazon and Atlantic Forest biomes are located. This pattern, however, does not hold for drought duration and frequency. Some catchments, mainly located in the southern and northeastern parts of Brazil, are projected to experience less frequent and shorter drought events, which can be explained by the coupled effect of lower atmospheric demand and higher precipitation projected in the future for these regions (Almazroui *et al* 2021, Reboita *et al* 2022, Ballarin *et al* 2023a, 2024). It is important to note that the projected changes in drought properties exhibit a high model agreement. In approximately 80% of the catchments, at least seven CMIP6 models (out of ten) agreed on the change signal.

Besides the increase in long-term, averaged droughts' properties, CMIP6 future simulations also indicate that drought properties (duration and intensity) are expected to show increased variability and reduced skewness, expressed in terms of the *L*-variation and *L*-skewness (figure S2; see Abdelmoaty *et al* 2021 for a detailed description). We opted for the use of *L*-moments as they represent an advancement over traditional moments in characterizing the statistical properties of samples,

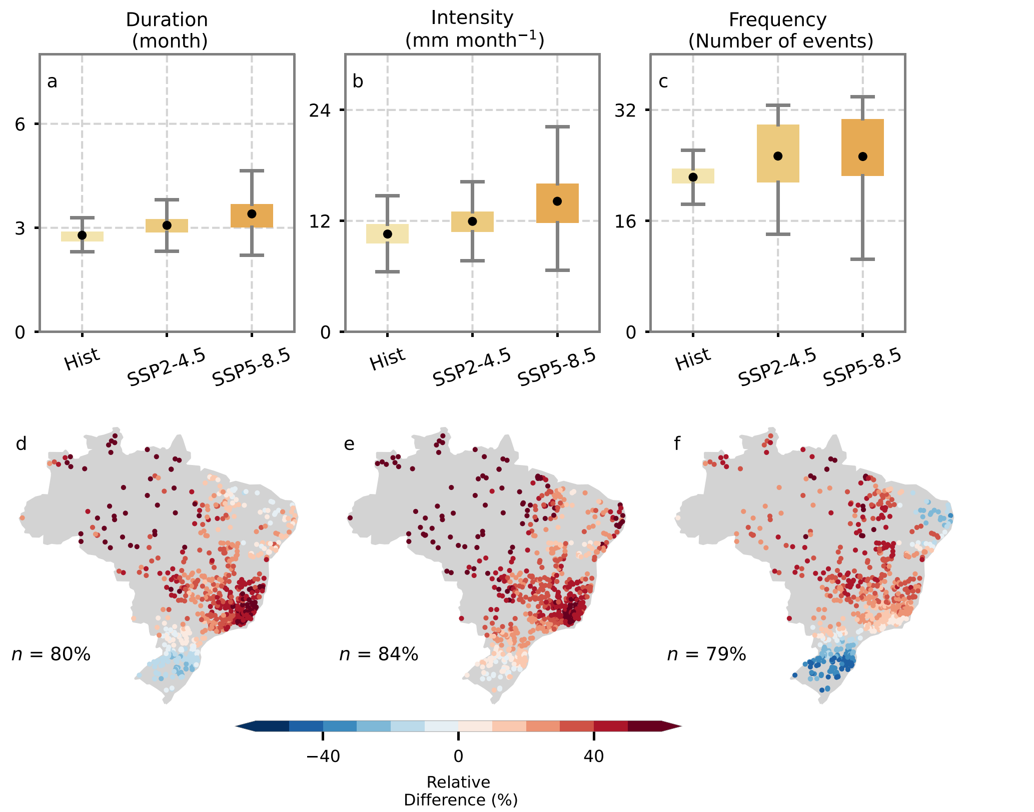

Figure 1. Projected changes in the 31-years, long-term averaged drought's (a), (d) duration, (b), (e) intensity and (c), (f) frequency between historical (Hist; 1980–2010) and distant future (SSP2-4.5 and SSP5-8.5; 2070–2100) periods in Brazil. Boxplots represent the CMIP6 multi-model ensemble median observed for the 735 Brazilian catchments. The spatial distribution of changes (d)–(f) was computed considering the historical and SSP5-8.5 distant future. *n* in the bottom-left corner of each map indicates the percentage of catchments with at least 70% of CMIP6 model agreement (signal of change). Projected changes in drought properties for Brazil are statistically significant according to the Mann–Whitney U test and Monte Carlo resampling techniques (p-value < 0.05).

such as variation, skewness and kurtosis, showing reduced sensitivity to variations in sample size and outliers (Hosking 1990, Sankarasubramanian and Srinivasan 1999). This increase in variability, combined with changes in the other evaluated statistical moments, affects the projected changes in rarer drought events. For instance, if we focus only on the five events with the largest values for each drought property occurring in the 31-year period (historical and future), we observe projected changes greater than those obtained considering all drought events (figure S3). Such aspects, often overlooked on drought assessments, can profoundly impact water resources management practices in the country (Reyniers *et al* 2023).

To further explore future droughts and their potential implications for Brazilian catchments, we assessed their projected changes from both land cover and water demand perspectives (figure 2). In terms of land cover, by the end of the century for SSP5-8.5, most Brazilian forests, pastures, and croplands will experience enhanced drought properties (figures 2(a)–(f)). At least half of the Brazilian cropland/pasture areas will experience an average increase of 30%, 37% and 29% in droughts' duration, intensity, and frequency, respectively. For forests, the changes are even greater, with changes in droughts intensity and duration projected to exceed more than 50% in half of forest areas. Similarly to what we observed for drought changes, CMIP6-models exhibited a relatively high model agreement towards drought intensification in most parts of Brazilian forests and crops.

Moving to a water-demand perspective (figures 2(g) and (h)), one can note that, according to SSP5-8.5, most catchments with anticipated increases in drought severity are also projected to exhibit augmented water consumption (figure 2(g)). By the middle of the century, from the almost 87% of the catchments with expected increase in drought severity, nearly 85% are also expected to present augmented water consumption in the future, mainly dictated by irrigation (Ballarin *et al* 2023a). The South region of the country is expected to exhibit the best water security condition, with some catchments presenting reduced drought severity and water demand. The Central region of the country, known for intense agriculture activity, in contrast, is projected to experience the greater coupled water demand-drought impacts, which will likely affect Brazilian agricultural production, such as coffee, soybean, and sugarcane (Koh *et al* 2020). As highlighted

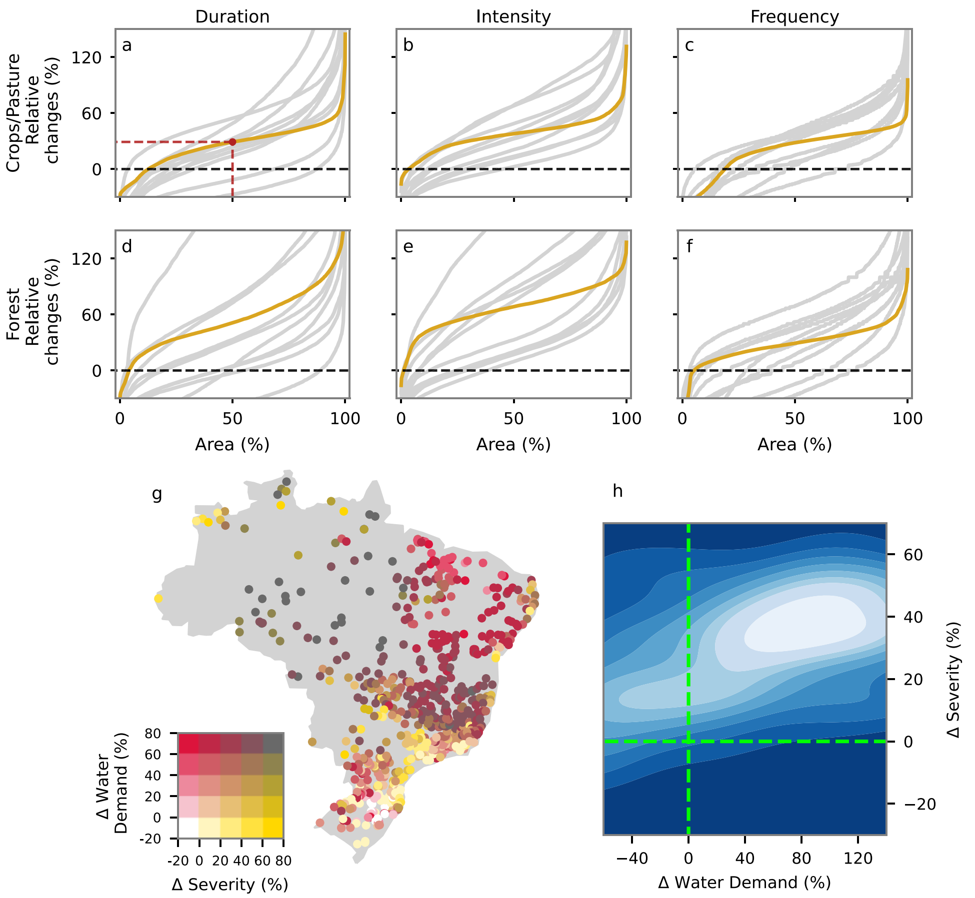

Figure 2. Projected changes (%) in the 31-years, long-term averaged drought's (a), (d) duration, (b), (e) intensity and (c), (f) frequency between historical (Hist; 1980–2010) and distant future (SSP5-8.5; 2070–2100) periods as a function of the relative area (%) of two different land uses classes: Forest and Pasture and Crops. CMIP6 multi-model ensemble median is displayed in yellow. Individual models' projections are displayed in light gray. Panels (a)–(c) can be interpreted as the proportion of crops/pasture (x-axis) projected to experience a particular relative change in drought's properties (y-axis). As an example, in panel (a), red, dashed lines indicate that 50% of the crops/pasture areas are projected to experience 30% of increase in drought's duration. The same holds for panels d–f for forest cover. The results for the gridded dataset were used for panels (a)–(f). (g) Spatial distribution of relative changes in long-term, averaged drought's severity (SSP5-8.5) and total water demand for the intermediate future (2040–2070). (h) Bivariate histogram of projected relative changes in drought's severity (SSP5-8.5) and irrigation-water demand for crop catchments (crop cover > 50%) in the intermediate future (2040–2070). Green, dashed lines divide the panel into regions of negative/positive changes.

by Multsch *et al* (2020), part of this region is already experiencing concerning conditions in terms of water scarcity given the higher water use for irrigation, that may even aggravate due to agricultural expansion plans. These circumstances, however, are not restricted to this Central region: approximately 70% of crops catchments (crop cover > 50%) are expected to show increased irrigation-based water demand and more severe droughts in the middle of the century (figure 2(h)).

4.2. Future changes in droughts and their link with *P* and PET in Brazilian catchments

To gain a better understanding of future drought events in the country, we explored their relationship with the projected changes in climate properties in both long-term and drought-triggering periods (figure 3). Precisely, we quantified the proportion of catchments projected to experience positive or negative changes in drought's properties and in *P* and PET metrics, and how these changes are linked. We focused on droughts' severity, which encompasses both droughts' duration and intensity, but similar conclusions can be inferred for the other properties (figures S4 and S5). As expected, for both long- and short-term perspectives, changes in the frequency and intensity of climatological properties are correlated to changes in drought properties, since enhanced PET and *P*-deficits can trigger and/or aggravate drought events (Mukherjee *et al* 2018). Furthermore, both *P* and PET are directly used in the SPEI-based methodology for drought identification, and so, such correlation does not necessarily implicate causation. Based on the scatterplots and regression lines obtained for both temporal perspectives, in general, catchments with larger positive changes in PET_{mean} are projected to exhibit drought events with larger duration, intensity and frequency. For the other climate properties,

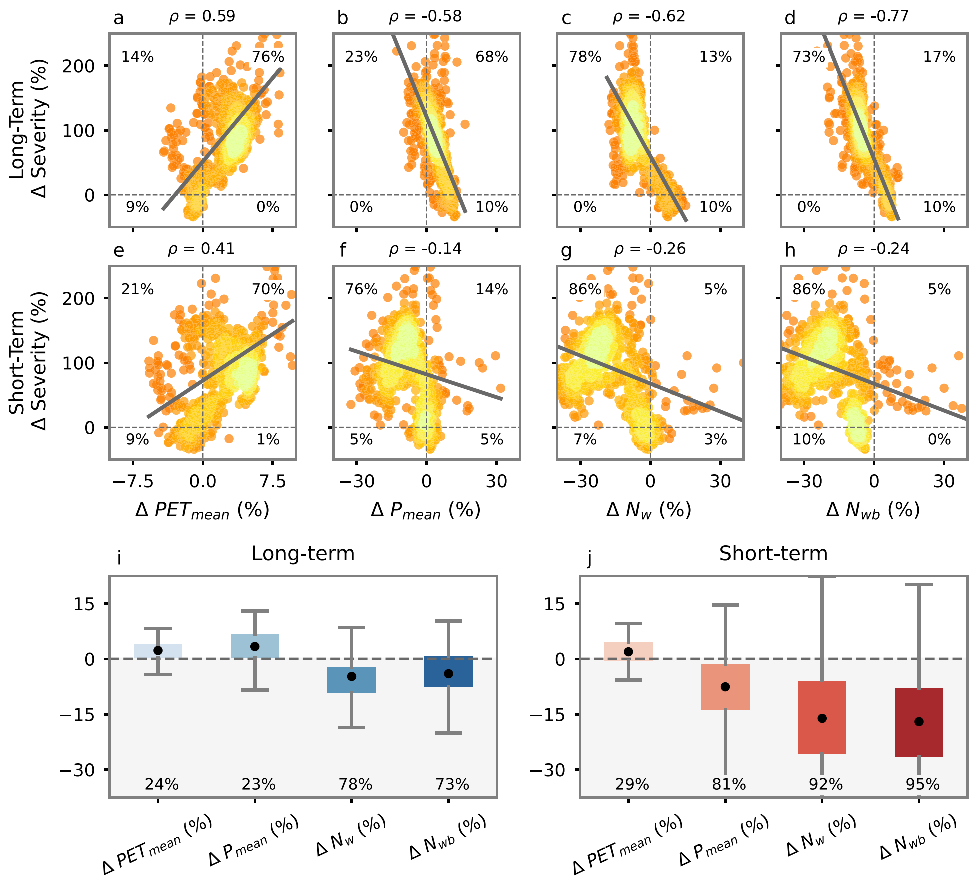

Figure 3. Relationship between projected changes (SSP5-8.5; distant future) in drought's severity and long- (first row, (a)–(d) and short-term (second row, (e)–(g) meteorological properties (PET_{mean}, P_{mean}, N_w, and N_{wb}; from left to right) for the Brazilian catchments. Pearson's correlation between projected changes is displayed on each subplot's top. Only significant correlations (p-value < 0.05) were considered. Black, dashed lines divide the quadrants. The regression line is displayed in dark grey. The percentage of catchments (points) in each quadrant is indicated on the corners. For all plots, light color regions indicate high density. Boxplots in the bottom of the figure summarize the projected relative changes in meteorological properties (PET_{mean}, P_{mean}, N_w, and N_{wb}) for the long- and short-term ((i) and (j), respectively) across the Brazilian catchments. The percentage below each boxplot indicate the proportion of catchments with projected negative changes. A black, dashed line represents the region with no changes.

the opposite is valid: catchments with reduced P_{mean}, N_w, and N_{wb} will experience intensified droughts.

According to the long-term perspective, more than 70% of the catchments are projected to show enhanced PET_{mean}, whereas only 23% show a decreased P_{mean} (figure 3(i)). More pronounced increases in PET_{mean} are expected to occur in the Northwestern and Central parts of Brazil, where Amazon and Cerrado are located. For P_{mean}, larger increases are projected for the southern region (see figure S6 for the spatial distribution of changes). At first glance, this might indicate that droughts intensification is highly linked with enhanced PET_{mean}, but not necessarily with decreased P_{mean}, as more than 50% of the catchments are projected to undergo an increase in drought properties even with an increase in P_{mean}. For instance, one can note that the very similar spatial patterns of future increased PET_{mean} and drought properties do not match the spatial distribution of future P_{mean} decreases (figures 1 and S6). However, looking at changes in frequency aspects (N_w and N_{wb}), it becomes apparent that they also have an important link with drought' changes. More than 70% of the catchments that are expected to experience more severe droughts will also undergo a reduction in N_w and N_{wb}. Moreover, all catchments with projected decrease in drought's severity (10% of the catchments) are expected to present larger N_w and N_{wb} (figures 3(c) and (d)), which suggests a strong link between changes in P and PET frequency and changes in drought's properties.

In the short-term perspective, we observed a similar pattern for PET_{mean}, N_w, and N_{wb}: catchments with projected increases in drought severity are projected to exhibit, in general, increases in PET and decreases in N_w and N_{wb} (see figure S7 for spatial distribution). For instance, out of the 90% of the catchments with expected enhanced drought severity, nearly 80% and 95% of them are expected to show enhanced PET and decreased N_w and N_{wb}, respectively, confirming the role of evapotranspiration and climate frequency in shaping the changes in drought properties in a warmer world (Vicente-Serrano *et al* 2014, Otkin *et al* 2018, Wang and Sun 2023b). Interestingly, a different situation was found for P_{mean}. According to this event-based perspective, P_{mean} is expected to decrease in more than 80% of the catchments during drought-triggering periods (figure 3(j)), which contrasts with the results found for the long-term perspective. That is, even showing enhanced P in the future, some catchments in Brazil are projected to show more severe droughts due to changes in intra-annual variability of P towards less frequent, and more extreme and concentrated events (Ballarin *et al* 2024).

5. Discussion and final remarks

While there is an extensive literature about projected changes in future drought's properties according to CMIP6 models outputs (Ukkola *et al* 2020, Wang *et al* 2021, Xu *et al* 2023, Wang and Sun 2023a, 2023b), little is known about how droughts are expected to change and impact Brazilian catchments and what is the link between changes in droughts and meteorological conditions. This aspect is crucial for assisting decision-makers in developing mitigation strategies and improving water resources management practices. This study addresses this gap by assessing projected changes in Brazilian droughts and meteorological conditions and their potential impacts on Brazilian catchments from both land use and water demand viewpoints.

CMIP6 models suggest robust and generally more severe conditions of long-term mean drought properties in Brazil. Such patterns were also observed by Ferreira *et al* (2023) when assessing rainfall patterns in the country. Although certain catchments may experience decreased droughts' duration and frequency, which aligns with the future wetter conditions reported for some Brazilian regions by previous studies (Medeiros *et al* 2022, Reboita *et al* 2022), the overall trend for the country indicates a general increase in all droughts properties. Beyond the long-term mean, changes in the variability and extremes of droughts are also projected (figures S2 and S3), which will likely pose even greater consequences to the country in the future (Gutiérrez *et al* 2014, Getirana *et al* 2021, Satoh *et al* 2022). This challenging scenario may not affect only Brazil but global proportions as well, given the country's role in global food security and agricultural production (Pereira *et al* 2012, Strassburg *et al* 2014, Maluf *et al* 2022). Most of Brazilian's forests, pasture, and cropland areas are projected to experience worse drought events. This, combined with the expected increases in water consumption throughout Brazil, will certainly affect water security and food production in the country. For instance, the greater water demand-drought impact is expected to occur in the Central region of the country (figure 2(g)), known for its high agricultural activity. As highlighted by Koh *et al* (2020) and Silva *et al* (2023), climate impacts are already reducing coffee and soybean yields in the region, and are expected to be aggravated by water use increases due to agriculture expansion. Such findings are pivotal to inform Brazilian water resources and food agriculture practices, mainly for the Cerrado ecoregion, which is expected to experience a larger intensification of water scarcity due to both climate and water use changes (Multsch *et al* 2020).

The assessment of the relationship between changes in drought properties and meteorological conditions highlighted two aspects. From the long-term perspective approach, we observed that droughts' intensification is mainly linked to an increase in $\mathrm{PET}_{\mathrm{mean}}$ and a reduction of N_{w} and N_{wb}, confirming that changes in the atmospheric demand and rainfall frequency affect drought characteristics (Trenberth *et al* 2014, Greve *et al* 2019, Araujo *et al* 2022). For example, more than 50% of the catchments are expected to experience an increase in drought properties even with enhanced P_{mean}. Nevertheless, when we turn our attention to the event-based approach, we note that even these catchments with an expected greater long-term P_{mean} are projected to show reduced P_{mean} before and during drought events, reinforcing the role of rainfall variability and timing in controlling drought events (Ukkola *et al* 2020). Indeed, as underscored by Ballarin *et al* (2024), the country is expected to experience fewer but more concentrated and extreme rainfall events. For instance, the Southern/Southeastern of Brazil presents an interesting case for such findings. From a long-term perspective, both P_{mean} and N_{w} are expected to increase, while $\mathrm{PET}_{\mathrm{mean}}$ shows small changes, which would suggest a wetter condition in the region (see figures S6 and S7). Nevertheless, according to the short-term perspective, the region will experience a slight reduction in N_{w} and P_{mean}, which likely explains the expected increase in drought severity even with enhanced P_{mean}. Hence, according to this dual approach, catchments with enhanced droughts in Brazil are, in general, expected to exhibit an enhanced PET and P-variability, which might trigger or aggravate drought events even in places with a projected averaged wetter condition. That is, changes in future droughts in the country are not linked only with the amount of water, but also with its timing, and, therefore, having more P may not be enough to diminish drought events. Such information can be beneficial for water resources planning in the country seeking to improve water security and achieve the objectives of the National Water Security Plan (ANA 2019b). Still, we underscore that our proposed approach aimed to understand the projected changes in the meteorological conditions of catchments expected to exhibit enhanced future droughts, rather than assessing drought drivers, which would require additional analysis that goes beyond the scope the manuscript.

Despite the high model agreement towards drought intensification, it should be stressed that some aspects might introduce uncertainties and affect our findings. It is known that 'offline' PET formulations may not faithfully represent physical or biological processes and consequently affect drought characterization (Milly and Dunne 2016, Swann *et al* 2016, Yang *et al* 2019, Wang and Sun 2023b). To avoid possible misrepresentations, we used the formulation proposed by Yang *et al* (2019) which considers CO_2 effects on plants and reduces potential drying biases. Nevertheless, we also computed projected drought changes across Brazil using the reference crop Peanman–Monteith formulation and obtained a slightly higher (although similar) intensification of drought properties (figure S8).

Another factor influencing our findings is the inherent uncertainties associated with climate model outputs and pre-and post-processing tasks related to bias adjustment and spatial downscaling. For instance, reggriding climate simulations may affect the statistical properties of time series, especially those related to extreme events (Rajulapati *et al* 2021). Furthermore, although usually required for improving the applicability of climate simulations (Johnson and Sharma 2015, Ansari *et al* 2023), bias correction outputs may show physically unrealistic values and hide climate model deficiencies (Casanueva *et al* 2020). In this context, we repeated our analysis using the raw simulations present in the CLIMBra dataset (Ballarin *et al* 2023b). The results suggest a worse scenario in terms of changes in droughts' duration and intensity and a similar condition in terms of droughts' frequency (figure S9). In comparison to the bias-corrected outputs, raw simulations project, in general, (1) lower P_{mean}, (2) higher PET_{mean}, and (3) higher N_w, which is probably causing the differences in projected droughts' properties (figure S10). Nevertheless, despite the divergences in the magnitude of changes, both outputs agree with the overall intensification of drought properties in the future. We also repeated the analysis considering different wet thresholds (0.1 and 1 mm) and obtained quite similar findings (figures S11 and S12).

Finally, we highlight that the results reported here are related to the pessimistic CMIP6 scenario (SSP5-8.5) for the distant future (2070–2100). Alternative pathways with lower projected changes for drought properties were found when considering the immediate (2010–2040) and intermediate (2040–2070) future (figures S13 and S14). As expected, almost no changes are projected for the former, whereas changes with lower magnitude are projected for the latter, which highlights the role of climate policies in reducing potential impacts on water resources. We found a lower model agreement for both future periods compared to the distant future. Nevertheless, on average, both point towards intensifying drought properties, except for drought frequency in the immediate future.

Further studies on this topic are needed to improve water resources management in Brazil. For instance, understanding how rainfall events of different magnitudes contribute to drought conditions and how these projected changes in droughts might impact food production certainly contributes to an enhanced comprehension of drought impacts in an uncertain future. Furthermore, it is noteworthy to mention that while we focused here on changes in future drought conditions and their connection with local climate dynamics, Brazil is not an isolated system, and, as such, complementary research exploring future drought changes in terms of climate indices (e.g. ENSO) can certainly contribute to an improved understanding of droughts dynamics and drivers (Kay *et al* 2022). Even so, we believe that the evidence gathered here is insightful for water-related practices in the country and that the proposed approach to assess drought relationship to climate change under different temporal perspective can serve as a valuable method for understanding drought characteristics and patterns in Brazil.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.57760/sciencedb.02316.

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Open research

Bias-corrected, catchment-scale CMIP6-climate projections for the Brazilian territory can be found in the CLIMBra's dataset (see, Ballarin *et al* 2023a, 2023b).

Conflict of interest

The authors declare no competing interests.

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