TEMPORAL DYNAMICS OF THE DRY SEASON IN AMAZÔNIA

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ABSTRACT

Climate change is predicted to intensify extreme weather events, leading to prolonged dry seasons and reduced rainfall in Amazônia. This, coupled with human-induced ignition, can increase wildfires' frequency across the region. We investigated the spatial and temporal changes in the dry season extent and intensity across Amazonia from 2000 to 2023. Using precipitation and multiple evapotranspiration datasets, Maximum Cumulative Water Deficit (MCWD) and dry season length were calculated. Highlights include increasing frequency, severity and spatial extent of droughts since 2010, with 2023 marking the largest affected area (68%), and 2016 with largest water deficit. Overall, the increasing frequency of extreme droughts in Amazônia raises concerns about the rainforest's long-term resilience and heightened fire risk.

Key words **—** Climate change, water deficit, MCWD, precipitation, remote sensing.

1. INTRODUCTION

Tropical forests, particularly Amazônia forest, play a vital role in regulating global climate, acting as significant carbon sinks that mitigate increasing atmospheric CO_2, and maintaining precipitation patterns [1]. However, climate change is expected to intensify climate extremes, leading to prolonged dry seasons and reduced rainfall in the region [2]. Future climate predictions for Amazônia suggest an increase in the number of hot and dry days across the region [3, 4]. As a result, the forest's resilience is being compromised, making it more susceptible to fires, which are becoming more frequent and severe in recent years [5, 6].

In Amazônia, the dry season's onset and the end dictate the fire season in the region, therefore the climate acts primarily as a temporal determinant of fire, affecting its ignitability and spread [6, 7]. Extended dry periods, combined with human-induced ignition, has already led to an increase in fire frequency across Amazônia [6]. For example, during the 2005 drought, fires ravaged over 300,000 hectares of forest in the southern Amazônia, with economic losses exceeding US$50 million [8]. A similar pattern of fires occurred during the 2015-2016 drought, when fire activity increased by 36% due to prolonged dry conditions [9]. As the dry season lengthens, the Amazônia's susceptibility to fire continues to grow, pushing the ecosystem closer to a critical threshold, possibly leading to widespread vegetation dieback [3, 9].

In addition to climatic factors, forest degradation such as deforestation plays a significant role in exacerbating fire risk by reducing rainfall during the dry season, which diminishes the forest's ability to recover from droughts [2, 10]. As climate change continues to intensify droughts and increase fire occurrence, threatens the effectiveness of forest conservation and restoration programs outlined in international agreements and policy initiatives, such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation), Brazil's Nationally Determined Contribution (NDC) under the Paris Agreement, and the Sendai Framework for Disaster Risk Reduction 2015-2030. [11, 12]

Understanding the effects of climate change and land use on the dynamics of fires is crucial for developing strategies to mitigate the impacts of fires in the landscape. Here, we investigated the spatial and temporal changes in the dry season across the Amazon from 2000 to 2023, evaluating the extent and intensity of droughts during this period.

2. MATERIAL AND METHODS

2.1. Study Area

The study area encompasses the Amazon region, spanning nine South American countries and covering approximately 8.5 million km² (Fig. 1A). Brazil accounts for 62% of this area, with the rest distributed across Peru, Bolivia, Colombia, Venezuela, Guyana, Suriname, Ecuador, and French Guiana.

As one of the world's most biodiverse ecosystems, Amazônia has an average annual rainfall of 2,200 mm, exceeding 5,000 mm in some regions, although extreme droughts linked to El Niño events occur periodically [13]. Studies indicate a decline in rainfall in the southern Amazon alongside a rise in mean temperature in the last 40 years [14].

2.1. Data preparation

We used precipitation and evapotranspiration as a measure of water stress in forests for the entire Amazonia (Table 1).

Description	Spatial resolution	Product
Monthly evapotranspiration	0.004º	MOD16A2GF
	0.25º	GLDAS
	0.1º	FLDAS
	0.25º	GLEAM
Monthly precipitation	0.05º	CHIRPS

Table 1. Input data.

The monthly total precipitation data are provided by the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) platform (https://www.chc.ucsb.edu/data/chirps). This dataset is derived from satellite observations and local weather stations, producing a spatial and temporal grid suitable for trend analysis [15]. Similarly, evapotranspiration data are derived from several products. MOD16A2GF, obtained from the MODIS sensor on the Terra satellite, offers global evapotranspiration estimates at an 8-day interval [16]. GLDAS and FLDAS, developed by NASA, integrate satellite observations with ground-based data to provide comprehensive information on land surface states and water fluxes [17, 18]. The GLEAM product utilizes satellite observations to estimate land evaporation and soil moisture [19]. To enhance the robustness of our analysis, we computed a multi-ensemble model average from these datasets. Using multiple products is crucial in the Amazon due to challenges in acquiring accurate in situ data and the region's extensive size. This approach mitigates the limitations of individual datasets and enhances the overall reliability of water balance calculations. The period used in this study is from January 2000 until December 2023 when all data sets evapotranspiration and precipitation overlap.

All data were regridded to a 0.25º x 0.25º common spatial resolution. For each grid cell, the monthly variation in the dry season from 2000 to 2023 was calculated following the method proposed by Carvalho et al. [7], which relates the amount of evapotranspiration and total precipitation to generate an indicator of water deficit period.

The dry season was defined as the persistence of evapotranspiration exceeding total precipitation. The spatial pattern of the dry season across Amazonia was estimated by grouping pixels that occurred in the same month at the onset and end of the dry season on the month when it started and ended. The length of the dry season was calculated as the number of consecutive months during which precipitation was lower than evapotranspiration. The mean climatological water deficit was then calculated for each month to establish an average length of the dry season. Finally, we classified each year's dry season as shorter, longer, or unchanged with reference to the average length of the dry season. Additionally, we evaluated the intensity of dryness for each year using the maximum cumulative water deficit (MCWD) which was calculated following the method adopted in reference [9].

3. RESULTS

On average, the dry season in Amazônia predominantly varied between three (11%), four (26%), and five (26%) months (Figure 1A), with these durations occurring mainly in the eastern part of the region. The shortest dry season, lasting one or two months, covered 11% of the basin and was primarily located in central-western Amazônia. No dry season was observed in approximately 12% of the region, with the largest area concentrated near the equator in the northwestern Amazônia. Areas with a dry season exceeding five months were found in 13% of the region, primarily in the northern and northeastern areas of Venezuela and Brazil, and southern Bolivia.

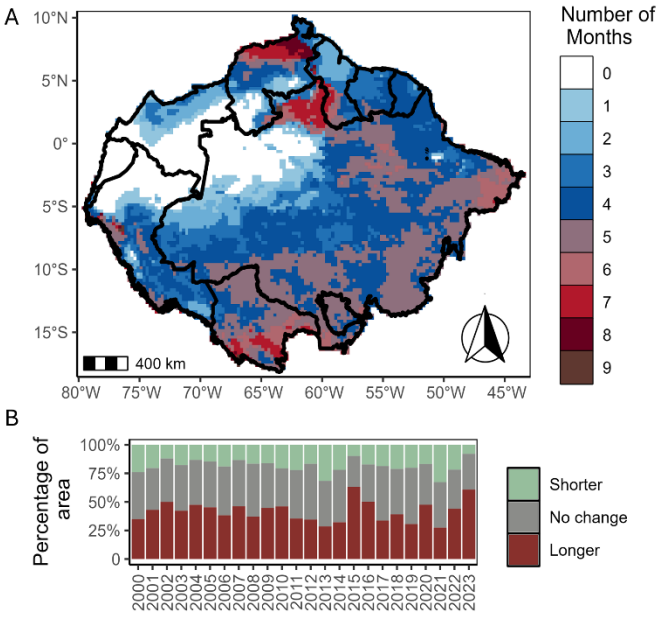


Figure 1. A: Mean dry season length from 2000 to 2023 across Amazonia. B: Variation in dry season length from 2000 to 2023 relative to the mean dry season length over the same period.

Variation in spatial extent of dry season length across Amazônia from 2000 to 2023 with respect to the average dry season duration expressed in percentage f is shown in figure 1B. Overall, the proportion of the area with no change in the dry season duration has remained relatively stable over time, with only minor annual fluctuations. Areas experiencing a prolonged dry season compared to the average have exhibited a progressive increase, from 2010 onwards. Notable peaks occurred in 2015, 2016, 2020, and 2023, with these extended dry seasons affecting more than half of the studied region in 2015 (63%), 2016 (51%), and 2023 (61%). This suggests an intensification of the dry season duration in certain areas of Amazônia. Additionally, the areas experiencing the longest

dry seasons are primarily regions of Cerrado (e.g., Roraima and Venezuela) and transition zones between Cerrado and Amazônia, particularly along the deforestation arc.

Time series of the spatial distribution of Maximum Cumulative Water Deficit (MCWD) across Amazônia categorized into five intensity classes (in mm) is shown in Figure 2. Throughout the study period, regions experiencing high water deficits of less than 200 mm have been predominant, particularly in the northern and southeastern parts of Amazônia, accounting for more than half of the total area in 18 out of the 24 years analyzed. Despite variations in spatial distribution, extensive drought conditions were observed in 2005, 2010, 2015, 2016, and 2023, with deficits exceeding 60% of the region during these years. In 2023, the extent of the drought was particularly pronounced, surpassing that of both 2015 and 2016, and affecting approximately 68% of Amazônia and representing the largest affected area recorded in the entire time series. Nevertheless, the 2016 drought remains the most severe in terms of intensity, due to its extensive area with deficits surpassing 400 mm. Overall, the data indicates that since 2010, Amazônia has experienced an increased frequency and severity of extreme droughts, with 2023 marking a significant escalation in the spatial extent of droughts.

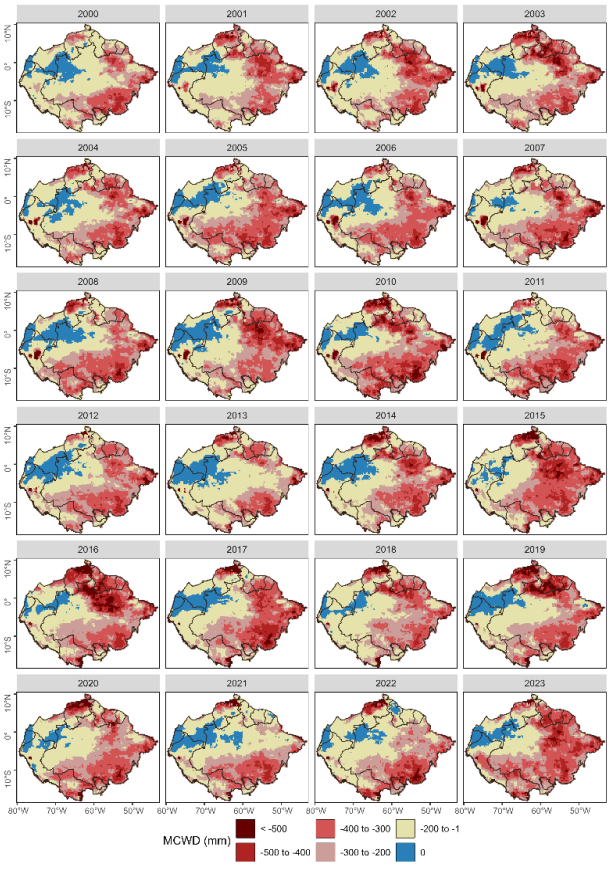


Figure 3. Spatial distribution of Maximum Cumulative Water Deficit (MCWD) across Amazônia from 2000 to 2023.

4. DISCUSSION

In this study we investigated changes in the dry season extent and duration in Amazônia from 2000 to 2023. Our results suggest water deficit intensity varies temporally and spatially in the region. Especially in 2023, results indicate increased spatial extent of water deficits, affecting 68% of the region. These prolonged dry periods, particularly in northern and southeastern Amazônia, heighten fire susceptibility, as drought-stressed vegetation becomes more flammable.

Regions experiencing the longest dry seasons, such as areas of Cerrado areas (e.g., Roraima and Venezuela) and transitional zones between Cerrado and Amazônia, particularly along the deforestation arc, are disproportionately affected. These areas, having undergone significant land-use changes over the past decades, are more vulnerable to prolonged dry periods [2]. Converting natural ecosystems into agricultural or pasturelands reduces evapotranspiration and alters local and regional hydrological cycles, intensifying water deficits [10].

The combination of high temperatures, reduced precipitation, deforestation, and the increased woody material creates favorable conditions for fire spread, increasing forest flammability [20]. The lengthening of the dry season in parts of Amazônia has coincided with a rising fire activity [7]. Most fires occur after the dry season, when vegetation is highly vulnerable [6, 7]. Reduced rainfall between August and October, coupled with rising temperatures, exposes larger forest areas to elevated fire risk, as observed in recent years. Repeated droughts, such as 2015, 2016, and 2023, demonstrate climatic conditions drive intensified fire risks across the Amazon basin [21].

Recurring extreme droughts directly impacts tree mortality, exacerbating the forest fire cycle. Prolonged drought reduce trees' photosynthetic capacity, increasing mortality and declining growth rates [2]. Dead biomass accumulation, combined with dry and hot conditions, makes the forest even more fire-prone, creating a feedback loop of degradation. Therefore, intensified extreme events in Amazônia could significantly compromise the forest resilience, increasing the risk of large-scale vegetation loss.

5. CONCLUSIONS

In conclusion, this study highlights the increased frequency and severity of extreme drought across Amazônia, particularly since 2010, driven by climate change, increasing the region's vulnerability to fire. The intensification of water deficits in 2023 underscores the heightened the fire risk in areas with prolonged dry seasons and vegetation stress. These findings raise serious concerns about the forest's recover capacity, with long-term implications for its resilience.

As the frequency and intensity of droughts continue to rise, the susceptibility of the forest to fire is likely to increase, posing a threat to the stability of this important ecosystem. Addressing these challenges requires coordinated efforts to

strengthen climate adaptation strategies and improve fire management, aiming to protect Amazônia's biodiversity and mitigate the risks of large-scale forest degradation and long-term climate change.

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