Increasing drought and declining precipitation in the Amazon:
a statistical assessment of climate extremes over nearly half a century

Secas em ascensão e precipitação em declínio na Amazônia:
diagnóstico estatístico de extremos climáticos ao longo de quase meio século

Aumento de las sequías y disminución de la precipitación en la Amazonía:
diagnóstico estadístico de los extremos climáticos a lo largo de casi medio siglo

Sécheresses en hausse et précipitations en baisse en Amazonie :
analyse statistique des extrêmes climatiques sur près d'un demi-siècle

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Abstract
The objective of this study is to identify changes in precipitation patterns and the occurrence of extreme events in the Amazon from 1979 to 2024. The analysis was regionalized into five sub-regions: Northwest (NW), Northeast (NE), West (W), East (E), and Southeast (SE). Monthly precipitation data from the National Oceanic and Atmospheric Administration (NOAA), via the Climate Prediction Center (CPC), were used. Extreme dry and wet events were defined based on values below the 15% percentile and above the 85% percentile, respectively. To identify temporal trends, simple linear regression was applied, and statistical significance was assessed using the Student's t-test. Results show a statistically significant reduction in monthly precipitation, particularly in the E and SE sub-regions. There was also an increase in the frequency of extreme dry events across all sub-regions, with SE showing the highest intensity, suggesting growing vulnerability to drought. In contrast, extreme wet events showed a

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decreasing trend, although with less statistical consistency. The findings indicate that the Amazon rainfall regime has become more irregular, with a predominance of dry extremes, posing risks to ecological sustainability, water security, and local population resilience. These results underscore the urgent need for climate adaptation policies and regional climate monitoring systems in the Amazon.

Keywords: climate change; linear regression; ENSO.

Resumo

Este estudo tem como objetivo identificar mudanças nos padrões de precipitação e na ocorrência de eventos extremos na Amazônia, no período de 1979 a 2024. As análises foram regionalizadas em cinco sub-regiões: Noroeste (NW), Nordeste (NE), Oeste (W), Leste (E) e Sudeste (SE). Utilizou-se de dados mensais de precipitação do *National Oceanic and Atmospheric Administration* (NOAA), via *Climate Prediction Center* (CPC). Eventos extremos secos e chuvosos foram definidos com base nos valores abaixo do percentil 15% e acima do percentil 85%, respectivamente. Para identificar tendências temporais, aplicou-se regressão linear simples, com teste t de *Student* para verificar a significância estatística. Os resultados apontam redução significativa na precipitação mensal, especialmente nas sub-regiões E e SE. Verificou-se também aumento na frequência de eventos secos extremos em todas as sub-regiões, com maior intensidade em SE, sugerindo crescente vulnerabilidade à estiagem. Os eventos extremos chuvosos apresentaram tendência de redução, mas com menor consistência estatística. Conclui-se que o regime pluviométrico da Amazônia se tornou mais irregular, com predomínio de extremos secos, o que acarreta riscos à sustentabilidade ecológica, à segurança hídrica e à resiliência das populações. Os resultados reforçam a necessidade de políticas públicas de adaptação climática e de sistemas regionais de monitoramento.

Palavras-chave: mudanças climáticas; regressão linear; ENOS.

Resumen

Este estudio tiene como objetivo identificar cambios en los patrones de precipitación y en la ocurrencia de eventos extremos en la Amazonía entre 1979 y 2024. Los análisis se regionalizaron en cinco subregiones: Noroeste (NW), Noreste (NE), Oeste (W), Este (E) y Sureste (SE). Se utilizaron datos mensuales de precipitación del National Oceanic and Atmospheric Administration (NOAA), a través del Climate Prediction Center (CPC). Los eventos extremos secos y lluviosos se definieron con base en valores por debajo del percentil 15% y por encima del percentil 85%, respectivamente. Para identificar tendencias temporales, se aplicó regresión lineal simple, con la prueba t de *Student* para verificar la significancia estadística. Los resultados señalan una reducción significativa en la precipitación mensual, especialmente en las subregiones E y SE. También se observó un aumento en la frecuencia de eventos secos extremos en todas las subregiones, con mayor intensidad en SE, lo que sugiere una creciente vulnerabilidad a la sequía. Los eventos extremos lluviosos mostraron una tendencia a la disminución, aunque con menor consistencia estadística. Se concluye que el régimen pluviométrico de la Amazonía se ha vuelto más irregular, con predominio de extremos secos, lo que genera riesgos para la sostenibilidad ecológica, la seguridad hídrica y la resiliencia de las poblaciones. Los resultados refuerzan la necesidad de políticas públicas de adaptación climática y de sistemas regionales de monitoreo.

Palabras clave: cambio climático; regresión lineal; ENSO.

Résumé

Cette étude vise à identifier les changements dans les régimes de précipitations et l'occurrence d'événements extrêmes en Amazonie sur la période allant de 1979 à 2024. Les analyses ont été régionalisées en cinq sous-régions : Nord-Ouest (NW), Nord-Est (NE), Ouest (W), Est (E) et Sud-Est (SE). Les données mensuelles de précipitations proviennent de la National Oceanic and Atmospheric Administration (NOAA), via le Climate Prediction Center (CPC). Les événements extrêmes secs et humides ont été définis sur la base de valeurs inférieures au 15% et supérieures au 85%, respectivement. Pour identifier les tendances temporelles, une régression linéaire simple a été appliquée, accompagnée du test t de *Student* pour en vérifier la signification statistique. Les résultats indiquent une diminution significative des précipitations mensuelles, en particulier dans les sous-régions E et SE. Une augmentation de la fréquence des épisodes extrêmes de sécheresse a été observée dans toutes les sous-régions, avec une intensité plus marquée dans la région SE, suggérant une vulnérabilité croissante à l’aridité. Les épisodes extrêmes de précipitations montrent une tendance à la baisse, bien que de manière statistiquement moins consistante. Il en ressort que le régime pluviométrique amazonien est devenu plus irrégulier, avec une prédominance des extrêmes secs, ce qui représente un risque pour la durabilité écologique, la sécurité hydrique et la résilience des populations. Ces résultats soulignent la nécessité de politiques d’adaptation climatique et de systèmes régionaux de surveillance.

Mots-clés : changement climatique ; régression linéaire ; ENSO.

1 INTRODUCTION

The Amazon region is home to the largest tropical rainforest on the planet and one of the world's largest hydrographic networks. Furthermore, studies conducted by Nobre *et al.* (2016) highlight the crucial role this region plays in climate regulation, both regionally and globally. Precipitation is one of the region's main meteorological elements, sustaining diverse ecosystems, the hydrological cycle, and the socioeconomic activities of local populations, including agriculture, fishing, river transport, and water supply (Marengo, 2008). The region is characterized by a predominantly high precipitation regime, with annual averages between 1,500 and 3,000 mm across much of its area, marked by moderate seasonality and a strong influence from large-scale atmospheric systems (Figueroa; Nobre, 1990).

Rainfall distribution in the Amazon is modulated by climate variability phenomena related to Sea Surface Temperature (SST) anomalies in the tropical Pacific and Atlantic oceans. The *El Niño*-Southern Oscillation (ENSO) phenomenon, with its *El Niño* (anomalous warming of SSTs) and *La Niña* (anomalous cooling of SSTs) phases in the Equatorial Pacific, is associated with rainfall deficits and excesses in the region, especially during the austral summer (Aceituno, 1988; Nobre; Shukla, 1996; Marengo *et al.*, 2001; Ronchail *et al.*, 2002). In addition to ENSO, the Atlantic Dipole pattern, characterized by opposing thermal anomalies between the northern and southern basins of the tropical Atlantic, also influences the regional rainfall regime (Souza *et al.*, 2000).

These climate variability phenomena modulate the action and intensity of meteorological systems that cause precipitation in the Amazon, such as the Inter-Tropical Convergence Zone (ITCZ), the Bolivian High, Upper-Level Cyclonic Vortices (ULCVs), the South Atlantic Convergence Zone (SACZ), frontal systems, the South Atlantic Subtropical High (SASH), and mesoscale convective systems (Rao; Hada, 1990, Kodama, 1992, Gan; Kousky, 1986; Kousky; Kagano, 1981; Ferreira *et al.,* 2009; Oliveira, 1986; Satyamurty *et al.,* 2013; Cohen *et al.,* 1995).

Since 2000, there has been growing concern about climate change and its potential adverse consequences. Reports from the Intergovernmental Panel on Climate Change (IPCC) indicate changes in rainfall patterns in various parts of the world, with an increase in the frequency and intensity of extreme events in the Amazon (IPCC, 2021), and several studies have identified signs of these changes in the region. Brito *et al.* (2014) analyzed different types of extreme precipitation events in the region between 1998 and 2013, evaluating their frequency, intensity, and contribution to the climatology of accumulated precipitation, observing an intensification of these events in the last seven years of the period, peaking between 2011 and 2012. Santos *et al.* (2015), in turn, investigated trends in daily precipitation for the Brazilian Amazon and identified a significant increase in the number of days with extreme precipitation in the northwestern portion of the region, while in the south a trend of reduction in these events was observed. These changes, often associated with climate variability phenomena such as *El Niño/La Niña*, result in profound socio-environmental impacts, including increased wildfires, rises or falls in river levels, and damage to transportation and biodiversity (Marengo *et al.*, 2024).

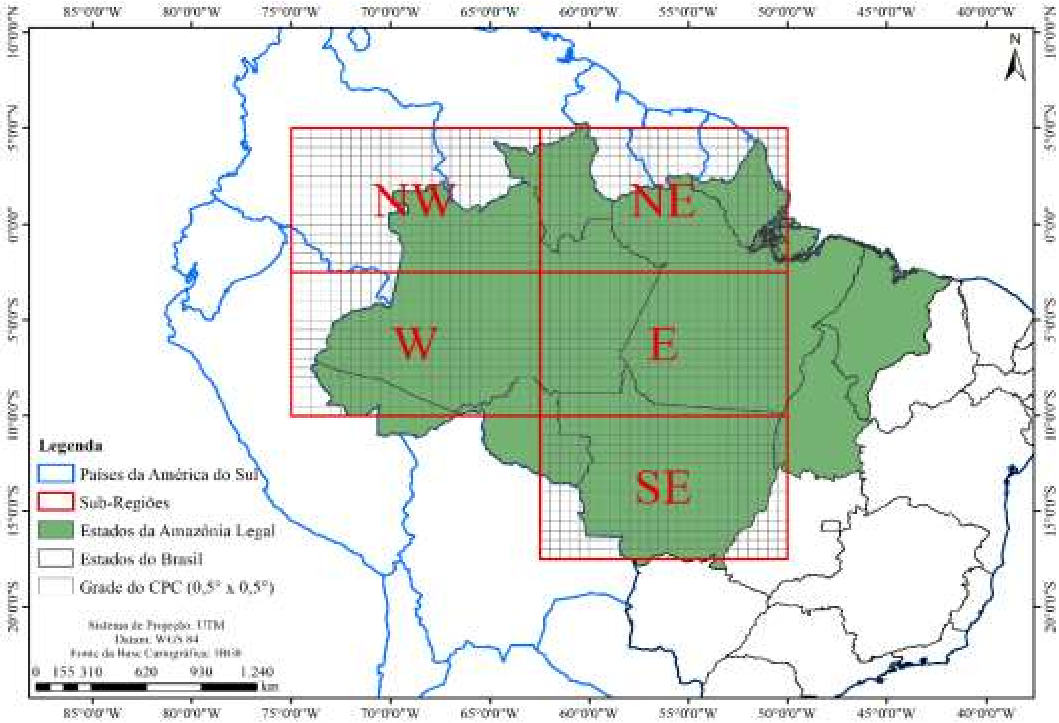
Despite increasing scientific and political attention, gaps persist in understanding the spatial and temporal variability of precipitation and its extremes in the Amazon. In this context, this study aimed to identify changes in precipitation patterns and the occurrence of extreme events in a regionalized manner in the Amazon, throughout the period from 1979 to 2024. Using simple linear regression techniques, it seeks to detect temporal trends and assess their statistical significance, contributing to a more accurate regional climate diagnosis and supporting adaptation strategies and climate risk management in the region.

2 MATERIALS AND METHODS

2.1 STUDY AREA

The study area was divided based on the geographic location of the sectors of the Amazon region, using five sub-regions delimited by latitudinal and longitudinal bands. The methodology follows a criterion similar to that adopted by Alves *et al.* (2013), who employed this approach to classify drought years in the Amazon. The defined sub-regions were: Northwest (NW): 75°W to 62.5°W and 5°N to 2.5°S; Northeast (NE): 62.5°W to 50°W and 5°N to 2.5°S; West (W): 75°W to 62.5°W and 2.5°S to 10°S; East (E): 62.5°W to 50°W and 2.5°S to 10°S; and Southeast (SE): 62.5°W to 50°W and 10°S to 17.5°S (Figure 1). The Northeast sub-region includes the capitals Boa Vista-RR and Macapá-AP; the West sub-region includes the capitals Rio Branco-AC and Porto Velho-RO; and the Southeast sub-region includes the capital Cuiabá-MG. These subdivisions represent areas with distinct climatic characteristics within the Amazon, allowing for a regionalized analysis of precipitation variability and the occurrence of extreme events.

Figure 1 – Study area, highlighting the five sub-regions of the Amazon used in the analysis: Northwest (NW), Northeast (NE), West (W), East (E), and Southeast (SE)



Source: The authors (2025).

2.2 DATA

Monthly accumulated precipitation data from the National Oceanic and Atmospheric Administration (NOAA), provided by the Climate Prediction Center (CPC), were used. This data consists of a dense observational network distributed around the world, interpolated on a grid of 0.5° latitude by 0.5° longitude (Silva *et al.*, 2007), as shown in Figure 1. This dataset was generated based on observations collected by orbital satellite platforms, interpolated with data from surface stations, and adjusted with estimates from the satellites themselves. This type of data was chosen considering the scarcity of conventional measurements with long historical series in the Amazon, making it suitable for climatological studies (at least 30 years). The period analyzed was from January 1979 to December 2024. Monthly spatial averages were calculated for each of the five delimited areas, resulting in time series representative of each region.

For the calculation of climatology and as a basis for identifying extreme events, the period from 1981 to 2010 was adopted, as recommended by the World Meteorological Organization (WMO, 2017).

2.3 METHODOLOGY

To identify the annual and monthly climatology of the sub-regions, the annual and monthly arithmetic mean (Equation 1) of precipitation for the period from 1981 to 2010 was calculated.

$$\overline{Prp} = \frac{1}{n}\sum_{i=1}^{n} Prp_i \qquad \text{(Equation 1)}$$

Where: $\overline{Prp}$ is the average annual or monthly climatological precipitation; Prp is the precipitation value in year or month i of the reference period; n is the number of years in the reference period (n = 30, in the case of 1981 to 2010).

The identification of extreme precipitation events was carried out based on the statistical methodology proposed by Xavier (2002), similar to that applied in Tavares *et al.* (2021), which uses the empirical distribution of data to calculate percentiles. This approach is recommended when one wishes to avoid assumptions about the shape of the distribution (e.g., normality), being particularly useful for rainfall data that frequently exhibit asymmetries. Thus, given a set of n monthly precipitation values $x1$, $x2$, …, xn, ordered in ascending order, the percentile value p (where 0<p<1) is obtained by linear interpolation between the ordered elements, according to Equation 2:

$$P_p = x_i + (n.p - i).(x_{i+1} - x_i) \qquad \text{(Equation 2)}$$

Where: P_p is the value of the percentile p; x_i is the value of the i-th element of the ordered series and i=$\lfloor n{\cdot}p \rfloor$, with $\lfloor\cdot\rfloor$ being the integer part.

The following thresholds were used to define extreme events: dry extreme: monthly precipitation below the 15th percentile ($P0.15$) and wet extreme: monthly precipitation above the 85th percentile ($P0.85$).

The percentile calculation was performed individually for each month of the year and for each sub-region, in order to consider the seasonality of precipitation. Thus, all Januarys were grouped together, as were all Februarys, and so on, forming 12 monthly distributions per sub-region for the climatological reference period (1981 to 2010). This approach allowed the identification, for each month and region, of significant deviations from the normal precipitation behavior, distinguishing it from parametric methods such as the Standardized

Precipitation Index (SPI), which require assumptions about the statistical distribution of the data (McKee *et al.*, 1993).

To analyze temporal trends in the precipitation series and the annual frequency of extreme events (dry and wet), simple linear regression was applied, a statistical method widely used to describe the relationship between a dependent variable and an independent variable (Montgomery; Runger, 2003). Simple linear regression models a variable y (in this study, monthly precipitation or the number of months in the year with extreme events) as a function of time x (represented by the year or the month number throughout the time series). The equation of the fitted line is given by Equation 3.

$$y = a + bx \qquad \text{(Equation 3)}$$

Where: y is the dependent variable (precipitation or number of events per year), x is the independent variable (time), a is the intercept, which represents the expected value of y when x=0, b is the slope (or inclination of the line), which represents the rate of change of y over time.

A positive value of b indicates an increasing trend, while a negative value indicates a decreasing trend. The slope coefficient (b) was estimated using the least squares method, which minimizes the sum of the squares of the residuals between the observed values and the fitted values of the line.

The regression was applied in two ways: to the monthly precipitation time series (1979 to 2024) in each sub-region, to identify seasonal and interannual trends; and to the annual series of the number of months with extreme dry and rainy events, to verify changes in the frequency of these events over time.

In this way, it was possible to objectively assess the presence of trends of intensification or reduction of precipitation and the frequency of extreme events in different sectors of the Amazon. Such trends may be associated with changes in the regional and global climate, possibly linked to climate change processes (IPCC, 2021).

To assess the statistical significance of the trends identified in the time series (1979 to 2024) of monthly precipitation and the number of months in the year with extreme events (dry and rainy), the Student's t-test (t) was applied to the slope of the line obtained by simple linear regression (Equation 4). This test verifies the null hypothesis that the slope b is equal to zero, that is, that there is no significant trend over time (Montgomery; Runger, 2003; Wilks, 2011).

The significance of the test is assessed by the p-value corresponding to the value of t, considering the degrees of freedom $n-2$, where n is the total number of observations. Values of p less than 0.05 indicate that the trend is statistically significant at the 5% level, rejecting the null hypothesis.

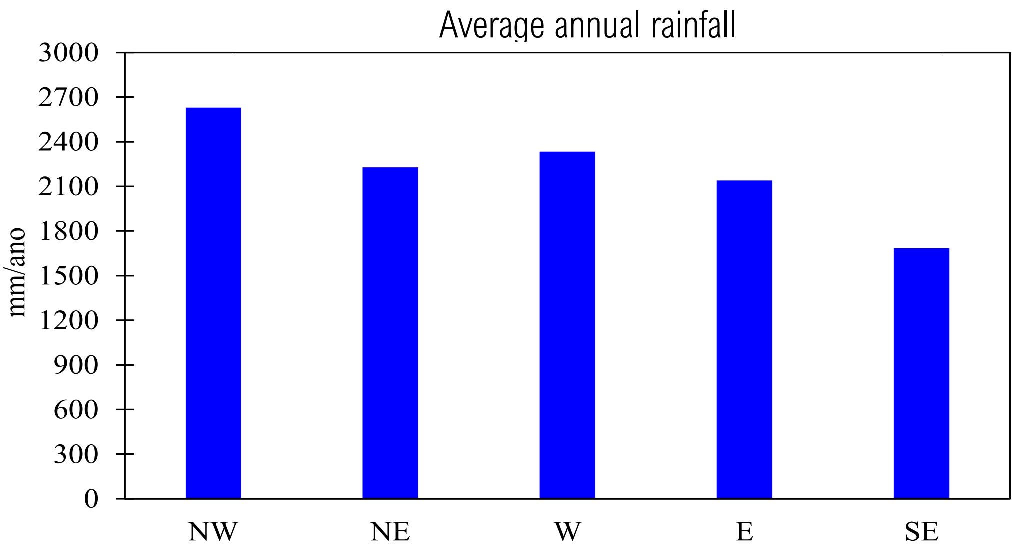
$$t = \frac{b}{SE(b)} \qquad \text{(Equation 4)}$$

Where: b is the slope of the regression line; $SE(b)$ is the standard error associated with the slope.

3 RESULTS AND DISCUSSIONS

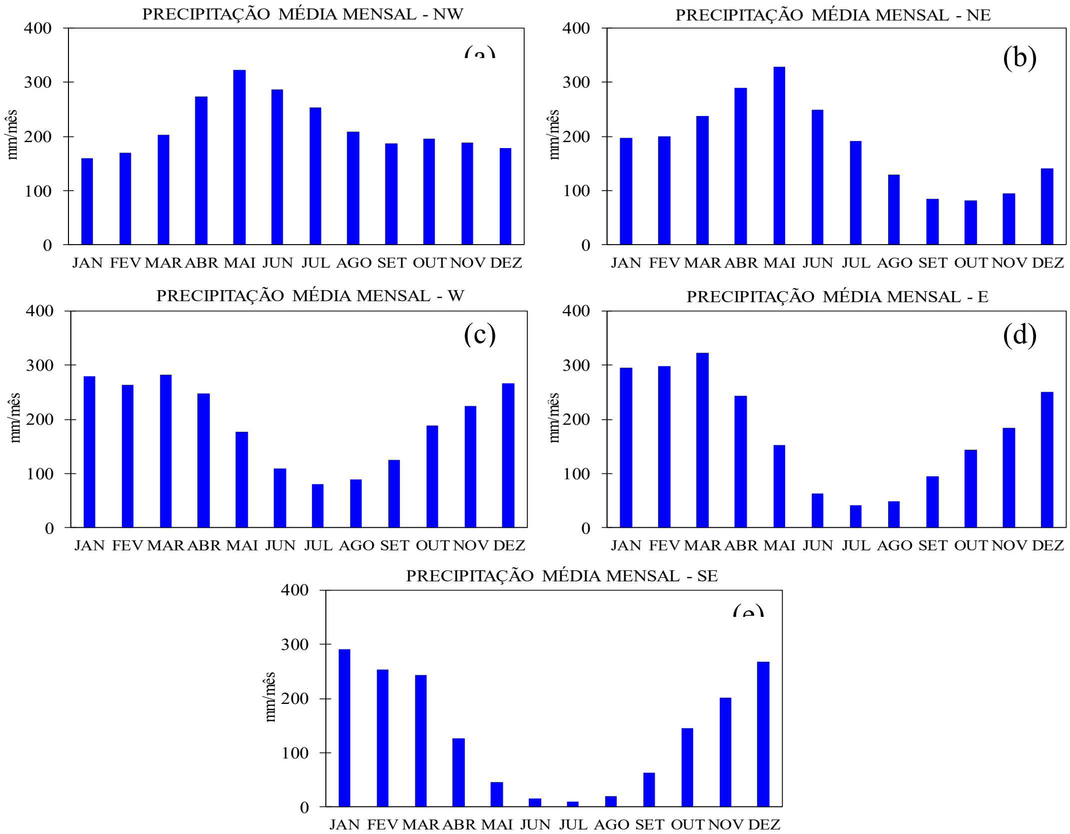
Figure 2 illustrates the precipitation climatology, averaged from 1981 to 2010, in the five sub-regions of the Amazon, highlighting the existence of spatial variations, with the highest accumulation in the NW (2,629 mm) and the lowest in the SE (1,685 mm). Figure 3 (a-e) shows the monthly climatology, highlighting distinct seasonal patterns: the NW and NE sub-regions have high rainfall throughout the year, without a well-defined dry season, despite the relative reduction between August and November. The peaks in May (323 mm in the NW and 328 mm in the NE) reflect the prolonged influence of the ITCZ in the northern Amazon (Rao; Hada, 1990; Ribeiro *et al.,* 2023). The reduction in precipitation in the second half of the year, although less intense than in the southern regions, maintains high volumes, suggesting the persistence of atmospheric humidity and the occurrence of local-scale meteorological systems (Souza *et al.*, 2021).

Figure 2 – Average annual rainfall (1981 to 2010) in the five sub-regions of the Amazon: Northwest (NW), Northeast (NE), West (W), East (E) and Southeast (SE)



Source: The authors (2025).

Figure 3 – Average monthly precipitation (1981 to 2010) in the five sub-regions of the Amazon: (a) Northwest (NW), (b) Northeast (NE), (c) West (W), (d) East (E) and (e) Southeast (SE)



Source: The authors (2025).

Although the climatology of precipitation has well-defined seasonal patterns in the Amazonian sub-regions, it was essential to investigate whether these regimes have been changing over time. The analysis of monthly precipitation trends across the entire time series allowed us to identify signs of changes in the region, in response to recent climatic and environmental factors, such as the influence of the ENSO phenomenon, for example. Figure 4 (a-e) presents the time series of monthly precipitation for the five sub-regions analyzed between 1979 and 2024, accompanied by their respective linear trend lines. The results indicate a statistically significant negative trend in precipitation across all sub-regions, as indicated by the slope coefficients of the simple linear regression equations (values of “b”) and confirmed by Student's t-tests, with a p-value less than 0.05 in all cases (Table 1).

Table 1 – p-values of linear regressions applied to time series of monthly precipitation, rainfall extremes, and drought extremes in the sub-regions of the Amazon (1979 to 2024)

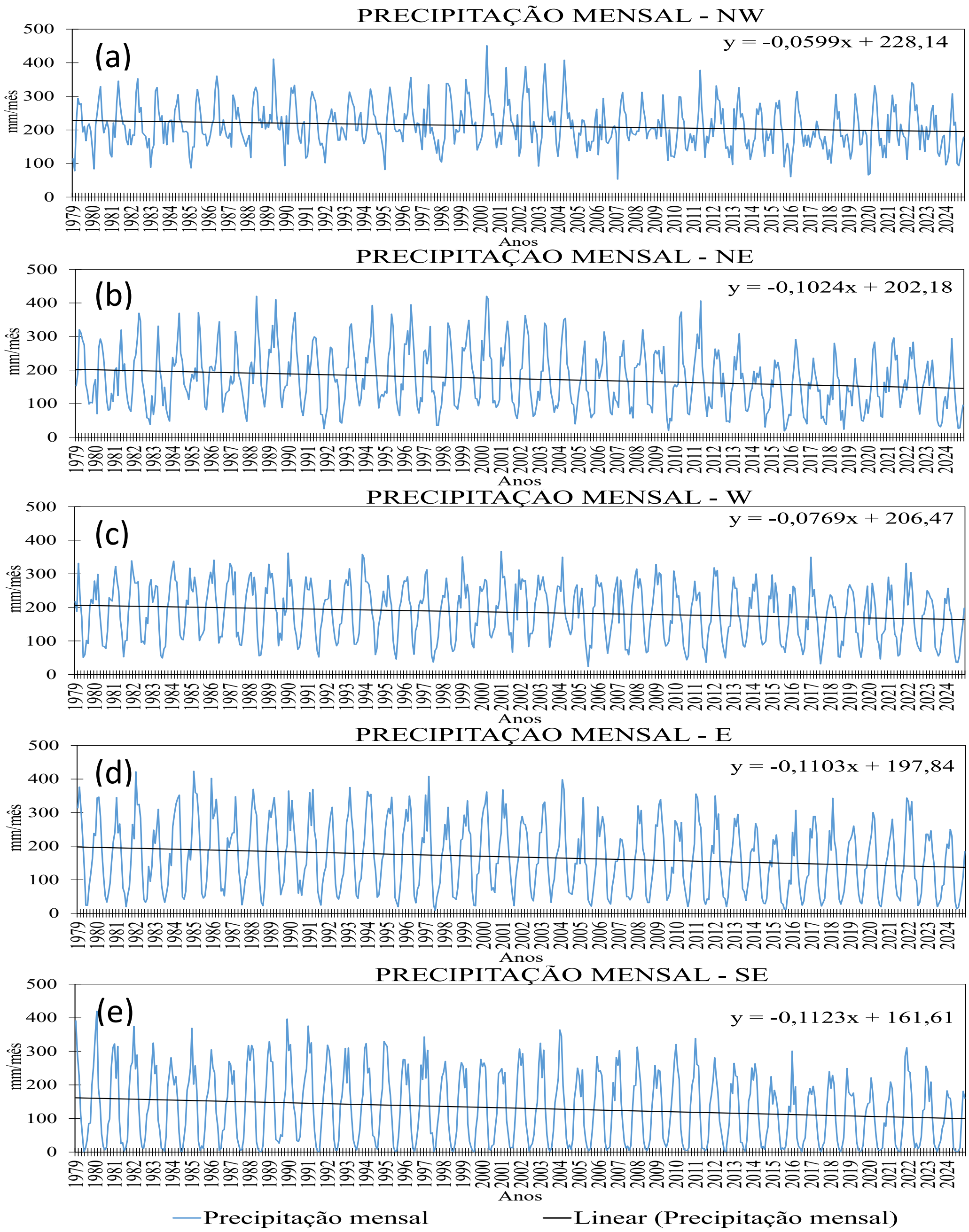
SUB-REGION	PRECIPITATION	EXTREME RAINY	EXTREME DRY
NW	0.012	0.052	5.760E-05
NE	0.000	0.088	8.556E-04
W	0.000	0.003	1.424E-03
E	0.000	0.000	1.716E-05
SE	0.000	0.000	1.186E-07

Source: The authors (2025). The significance level considered was p less than 0.05, indicating that the trend is statistically significant. Values less than 0.05 are shown in gray.

The NW sub-region showed an average decline of approximately -0.60 mm/month (y = -0.599x + 228.14), reflecting a gradual reduction in rainfall over the period, although this region still maintains high average monthly volumes, exceeding 300 mm during the rainy season months. The NE sub-region showed a more pronounced downward trend, with -1.02 mm/month (y = -1.024x + 202.18). Sub-region W recorded the lowest rate of reduction among the areas analyzed (-0.077 mm/month), on the other hand, sub-region E showed a reduction of -0.110 mm/month and the Southeast (SE) showed a decline of -0.112 mm/month (y = -0.1123x + 161.61), which is consistent with other studies that point to an increase in the dry season and intensification of extreme droughts in the southern part of the Amazon, especially in the transition to the Cerrado biome (Souza *et al.*, 2005; Marengo *et al.*, 2018). These results corroborate previous studies that show a trend of reduced rainfall in the Amazon in recent decades, especially in the eastern and southern portions, potentially associated with global climate change, the expansion of deforestation, and the feedback loop between loss of vegetation cover and reduced atmospheric humidity (Marengo *et al.*, 2011; Aragão, 2012).

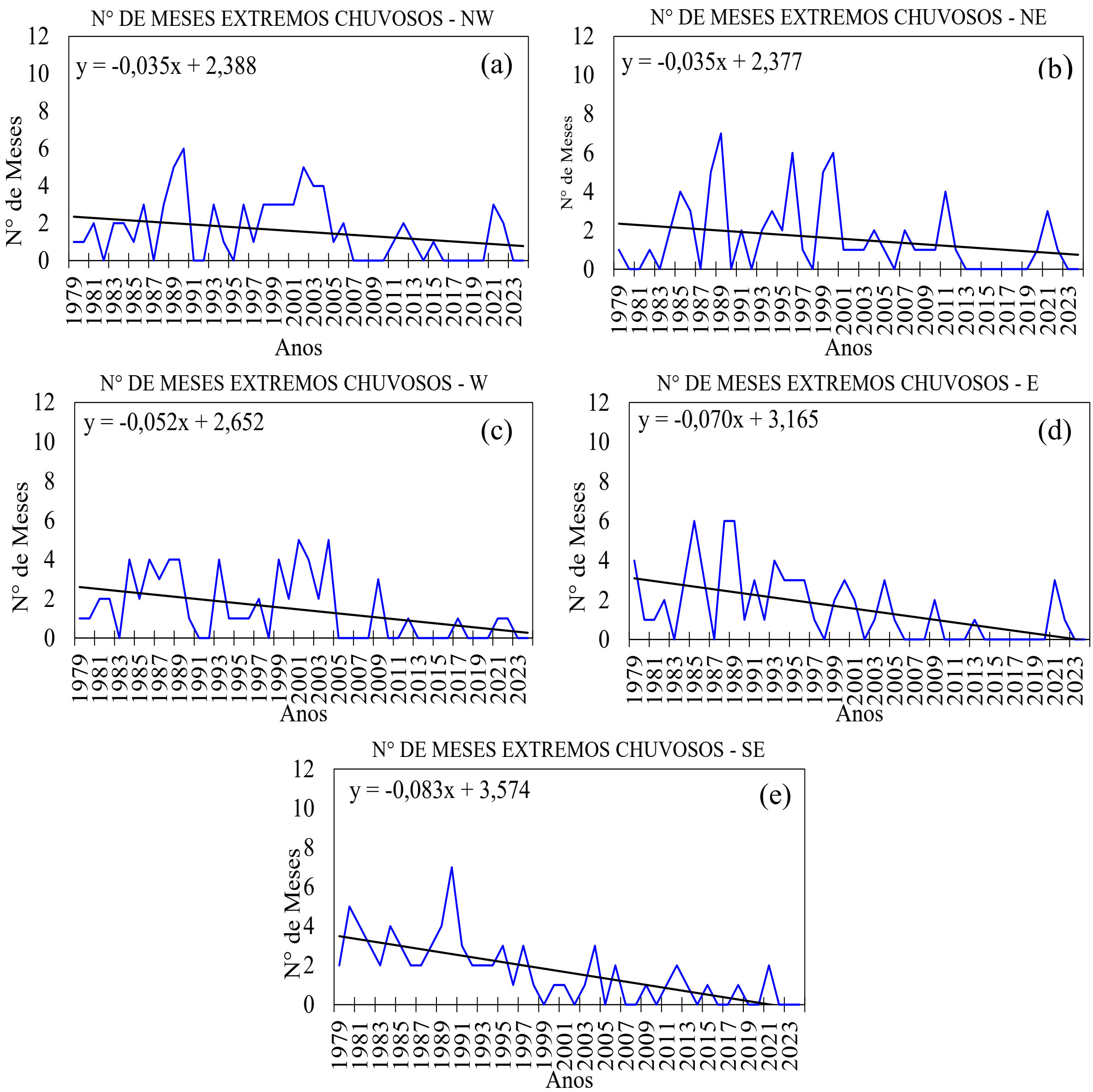
In addition to the trends of decreasing monthly precipitation totals observed in all Amazonian sub-regions, it is equally relevant to assess changes in the frequency of extreme events. These occurrences, often masked by climatological averages, have direct implications for water availability, river navigability, and the socio-environmental resilience of the region. Figure 5 (a-e) shows the trends in the annual number of months classified as extreme rainfall months, for the period from 1979 to 2024, in the five sub-regions of the Amazon. The results showed a predominance of negative trends in all areas, with varying magnitudes among the sub-regions. However, statistical significance tests (t) indicated that only the W, E, and SE regions showed statistically significant trends, while the NW and NE regions did not demonstrate significance, as can be seen in Table 1.

Figure 4 – Trend of monthly precipitation in the sub-regions of the Amazon (1979 to 2024). Monthly precipitation (blue lines) and respective linear trends (black lines) for the sub-regions: (a) Northwest (NW), (b) Northeast (NE), (c) West (W), (d) East (E) and (e) Southeast (SE)



Source: The authors (2025).

Figure 5 – Trend in the annual number of months with extreme rainfall events (above the 85th percentile) in the Amazon sub-regions: (a) Northwest (NW), (b) Northeast (NE), (c) West (W), (d) East (E) and (e) Southeast (SE), from 1979 to 2024. The black line represents the linear trend



Source: The authors (2025).

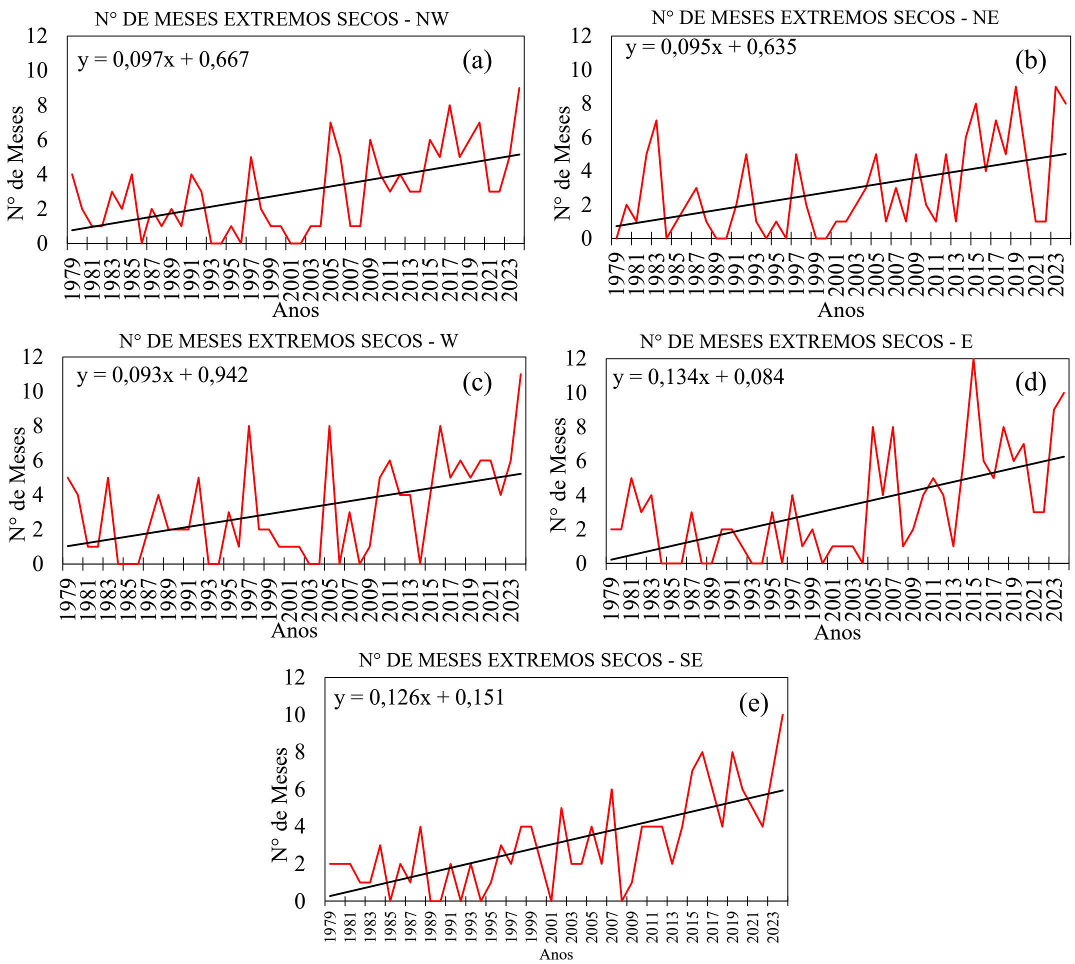
The NW and NE regions showed slopes of -0.035 events/year, with intercepts close to 2.4 annual events. Despite the visible negative trend, the absence of statistical significance suggests that interannual variability still predominates in the behavior of rainfall extremes in these areas. In the W, E, and SE sub-regions, the negative trend was more pronounced and statistically significant, with slopes of -0.052, -0.070, and -0.083 events/year, respectively. This suggests a consistent reduction in the frequency of extreme rainfall events in these areas, possibly linked to the intensification of seasonal drought anomalies, the advancement of the dry season, and large-scale climate variability. The SE, for example, located in the transition between the Amazon and the Cerrado, showed the highest rate of decline, reinforcing evidence that this area is among the most sensitive to climate change (Souza *et al.*, 2005; Coe *et al.*, 2013).

Analysis of extreme rainfall events indicates that the years 1989 and 1990 were the most significant in the NE, NW, E, and SE of the Amazon. In 1989, the frequency of months with extreme rainfall was highest in the NE (up to 7 months), as well as high in the NW and E, reflecting the strong influence of the 1988–1989 *La Niña* event, which intensified the ITCZ and increased moisture transport to the north of the region (Ronchail *et al.*, 2002). In 1990, the SE stood out, with up to 6 months of extreme events (Figure 5e), still under the residual influence of the previous *La Niña*, since, according to Silva and Silva (2015), there is a correlation between precipitation in the northern region of South America and sea surface temperature (SST) in the Equatorial Pacific, with a time lag. This means that atmospheric effects can persist even after the end of the oceanic event, due to the inertia of the large-scale circulation, which takes time to adjust to thermal variations in the ocean. This temporary decoupling between the ocean and the atmosphere contributes to prolonging the climatic impacts on tropical areas, such as the Amazon.

Figure 6 (a-e) illustrates the trends in the annual number of months classified as extremely dry (below the 15th percentile) for the period 1979 to 2024 in the five sub-regions of the Amazon. The results indicate an increasing trend in the number of months with extreme drought events in all sub-regions analyzed. The t-test confirmed that all trends are statistically significant, reflecting a consistent increase in the frequency of these events (Table 1).

The SE sub-region showed the highest annual growth rate ($b = 0.126$), followed by the E, NW, NE, and W regions, with b of 0.134, 0.097, 0.095, and 0.093, respectively, suggesting a systematic increase in the occurrence of severe droughts, which may be associated with changes in tropical atmospheric patterns and the impacts of global climate change (Coe *et al.*, 2013). The intensification of dry events has significant implications for the Amazon rainforest, which depends on a balanced hydrological cycle for its ecological maintenance. The increased frequency of dry months can intensify water stress in vegetation, reduce river flow, and increase susceptibility to forest fires, especially on the edges of the biome and in areas of deforestation and degradation (Aragão *et al.*, 2014; Souza *et al.*, 2003). Furthermore, the higher incidence of droughts can compromise local livelihoods, river transport and the food security of traditional populations (Nobre *et al.*, 2016).

Figure 6 – Trend in the annual number of months with extreme dry events (below the 15th percentile) in the Amazon sub-regions: (a) Northwest (NW), (b) Northeast (NE), (c) West (W), (d) East (E) and (e) Southeast (SE), from 1979 to 2024. The black line represents the linear trend



Source: The authors (2025).

In general, the year 2024 was particularly critical for the NW, NE, E, and SE regions, with a high frequency of months experiencing extreme drought. Although this event is recent, preliminary research has indicated that the 2023-2024 drought in the Amazon was characterized by a combination of climatic factors, including *El Niño* and the anomalous warming of the North Atlantic, Indian, and North Pacific oceans. This combination significantly reduced precipitation and increased temperatures, affecting water availability, prolonging droughts, and causing temperature spikes (Marengo *et al.*, 2024).

Furthermore, the year 2015 stood out in sub-region E, where all 12 months recorded extreme dry values. This period coincided with one of the most intense *El Niño* events of the 21st century, as observed in the data from the Oceanic Niño Index (Alves, 2025). According to Marengo *et al.* (2018), the 2015 *El Niño* caused a significant reduction in rainfall in the Amazon region, with severe droughts between August and October, affecting ecosystems and hydrological regimes. The authors highlight that the combination of *El Niño* with local low humidity conditions resulted in one of the worst droughts observed in recent decades.

These results show that extreme drought events have become more frequent and widespread, especially in years strongly influenced by El Niño, reinforcing the importance of monitoring and adaptive management strategies in the face of increasing climate variability.

4 FINAL CONSIDERATIONS

Linear regression analyses applied to monthly precipitation series and the frequency of months with extreme precipitation (referred to as dry extreme and wet extreme) show statistically significant changes in the rainfall regime of the Legal Amazon in the period from 1979 to 2024. A generalized trend of reduction in total precipitation was observed in all sub-regions analyzed, with greater intensity in the E and SE sub-regions of the Amazon.

Particular attention should be given to the intensification of dry extremes, whose statistical sign

ificance was robustly verified in all sub-regions, with expressively low *p*-values, especially in the SE sub-region. This pattern suggests an increase in the frequency of severe drought periods, which has direct implications for water resource management, food security, and the resilience of Amazonian populations.

Although rainfall extremes show less statistical consistency in trends, some sub-regions, such as W and E, indicated significance in their regressions, pointing to a possible expansion of intra-annual precipitation variability. This behavior, coupled with the intensification of dry extremes, reinforces the scenario of increasing climate instability and a greater risk of natural disasters associated with both water scarcity and excess.

These results corroborate recent evidence in the literature on the impacts of climate change in the Amazon and highlight the urgency of strengthening climate monitoring strategies, territorial planning, and integrated public policies, focusing on risk mitigation and adaptation to the new hydrometeorological conditions of the region. The statistical characterization of extreme rainfall trends is, therefore, an essential tool for the sustainable and sovereign management of the Amazon in the face of the challenges posed by global changes.

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