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LUIZ OCTAVIO FABRICIO DOS SANTOS

**CLIMATE EXTREMES IN SOUTH AMERICA AND THE PANTANAL: PATTERNS,
TRENDS, OCEANIC FORCINGS AND IMPACTS**

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RESUMO

Dos SANTOS, L. O. F. **EXTREMOS CLIMÁTICOS NA AMÉRICA DO SUL E PANTANAL: PADRÕES, TENDÊNCIAS, FORÇANTES OCEÂNICAS E IMPACTOS.**

Cuiabá, 2024, 107f, Tese (Doutorado em Física Ambiental) – Instituto de Física, Universidade Federal de Mato Grosso.

A intensificação dos eventos climáticos extremos nas últimas décadas tem alterado significativamente os padrões hidrológicos e térmicos na América do Sul, com impactos particularmente severos em ecossistemas sensíveis como o Pantanal. Esta tese, com base na análise de séries temporais de precipitação e temperatura, índices climáticos extremos e anomalias de temperatura da superfície do mar (TSM), identifica tendências robustas de aquecimento e alterações importantes na distribuição e intensidade das chuvas, tanto em escala regional quanto continental. Em nível continental, observou-se um aumento generalizado na frequência de dias e noites quentes, redução consistente de eventos frios e padrões contrastantes nos extremos de precipitação. Algumas regiões experimentaram maior intensidade e frequência de chuvas extremas, enquanto outras enfrentaram secas prolongadas e declínio no volume total precipitado. Tais mudanças estão fortemente associadas às anomalias de TSM no Pacífico equatorial (região Niño 3.4) e no Atlântico Tropical Norte (TNA), com o El Niño frequentemente associado a déficits hídricos e a La Niña à intensificação de chuvas, especialmente no norte e leste do continente. No Pantanal, a situação é mais crítica. A região vem registrando aumento na frequência, severidade e duração das secas, intensificadas por mudanças no uso e cobertura do solo, como desmatamento e expansão agropecuária. A análise do índice SPEI-12 entre 1980 e 2022 confirma essa tendência, com destaque para o agravamento entre 2019 e 2022. Os índices TX90p (dias quentes) e CDD (dias secos consecutivos) foram os principais condicionantes do estresse hídrico observado. Projeções climáticas com modelos CMIP6 (cenário SSP585) apontam para um futuro com mais ondas de calor, redução da precipitação total e riscos elevados de incêndios e colapsos hidrológicos. Nesse cenário, os resultados reforçam a urgência de políticas públicas integradas de adaptação climática, gestão hídrica e ordenamento territorial sustentável para mitigar os impactos ambientais e socioeconômicos das mudanças climáticas.

Palavras-chave: Anomalias oceânicas; Eventos extremos; Mudanças climáticas; Pantanal; Uso do solo.

ABSTRACT

SANTOS, L. O. F. **CLIMATE EXTREMES IN SOUTH AMERICA AND THE PANTANAL: PATTERNS, TRENDS, OCEANIC FORCINGS, AND IMPACTS.** Cuiabá, 2024, 107p, Thesis (Ph.D. in Environmental Physics) – Institute of Physics, Federal University of Mato Grosso.

The intensification of extreme climate events in recent decades has significantly altered hydrological and thermal patterns in South America, with particularly severe impacts on sensitive ecosystems such as the Pantanal. Based on the analysis of precipitation and temperature time series, extreme climate indices, and sea surface temperature (SST) anomalies, this thesis identifies robust warming trends and significant changes in rainfall distribution and intensity, both at regional and continental scales. At the continental level, there has been a widespread increase in the frequency of hot days and nights, a consistent reduction in cold events, and contrasting patterns in precipitation extremes. Some regions experienced higher intensity and frequency of extreme rainfall, while others faced prolonged droughts and a decline in total precipitation. These changes are strongly associated with SST anomalies in the equatorial Pacific (Niño 3.4 region) and the Tropical North Atlantic (TNA), with El Niño often linked to water deficits and La Niña to increased rainfall, particularly in the northern and eastern parts of the continent. In the Pantanal, the situation is more critical. The region has seen an increase in the frequency, severity, and duration of droughts, exacerbated by land-use and land-cover changes such as deforestation and agricultural expansion. Analysis of the SPEI-12 index between 1980 and 2022 confirms this trend, with a notable worsening between 2019 and 2022. The TX90p (hot days) and CDD (consecutive dry days) indices were the main drivers of observed water stress. Climate projections from CMIP6 models (SSP585 scenario) indicate a future with more heatwaves, reduced total precipitation, and heightened risks of wildfires and hydrological collapse. These findings underscore the urgent need for integrated public policies on climate adaptation, water management, and sustainable land-use planning to mitigate the environmental and socioeconomic impacts of climate change.

Keywords: Oceanic anomalies; Extreme events; Climate change; Pantanal; Land use.

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1 GENERAL INTRODUCTION

In recent decades, the intensification of extreme climate events has emerged as one of the most evident manifestations of climate change and variability on a global scale (AVILA-DIAZ *et al.*, 2023a). Phenomena such as heavy rainfall, prolonged droughts, heat waves, and floods have become more frequent and severe, causing significant impacts on natural ecosystems, infrastructure, agricultural production, public health, and water security. In tropical regions such as South America, these impacts tend to be even more pronounced due to the combination of high climate sensitivity and socio-environmental vulnerability (LAGOS-ZÚÑIGA *et al.*, 2024).

South America presents a complex interplay between local atmospheric processes and large-scale oceanic forcings, such as sea surface temperature (SST) anomalies in the Pacific, Atlantic, and Indian Oceans (CAI *et al.*, 2020a). Modes of variability such as the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Tropical Atlantic Dipole strongly influence precipitation and temperature patterns, modulating the occurrence and intensity of climate extremes across the continent. Identifying these influences is essential to better understand the mechanisms underlying the interannual and decadal variability of extremes (REHBEIN; AMBRIZZI, 2023).

Advances in observational databases, climate reanalyses, and global modeling products, such as those from the Coupled Model Intercomparison Project Phase 6 (CMIP6), have enabled more robust and spatially detailed analyses of climate extreme trends (JOHN *et al.*, 2022; SENEVIRATNE; HAUSER, 2020). The application of standardized indices of extremes, including R10mm, R20mm, PRCPTOT, TXx, TNn, RX1day, and WSDI, provides consistent and comparable assessments of long-term changes in temperature and precipitation regimes (JEFERSON DE MEDEIROS; PRESTRELO DE OLIVEIRA; AVILA-DIAZ, 2022a).

Among the regions most sensitive to alterations in extremes across South America, the Pantanal biome stands out as the world’s largest tropical wetland (LIBONATI *et al.*, 2022). Its hydrological dynamics, highly dependent on seasonal rainfall, make it particularly vulnerable to climate variability and ocean-forced teleconnections. Recent events, such as the severe droughts of 2019–2021, underscore the role of oceanic anomalies—especially those linked to ENSO—in intensifying periods of critical water scarcity and ecological disruption (MARENGO *et al.*, 2021b). Analyzing the Pantanal as a case study provides valuable insights into the regional responses of terrestrial ecosystems to large-scale ocean–atmosphere interactions.

Within this context, the present research starts from the hypothesis that climate extremes in South America—particularly in the Pantanal—have intensified significantly in recent decades, driven by the synergistic interaction between tropical ocean forcings (notably ENSO and the Atlantic Dipole) and local anthropogenic pressures such as land-use and land-cover change. This combination tends to amplify the increase in hot days, the occurrence of prolonged droughts, and greater rainfall variability, with projections indicating a worsening of these trends under future scenarios. Accordingly, this study aims to provide a substantial contribution to the understanding of recent climate extreme patterns in South America and the mechanisms modulating them, offering insights to support climate monitoring, risk management, and adaptation strategies, with particular focus on environmentally vulnerable regions such as the Pantanal.

1.1 General Objective

To investigate the trends and the spatial and temporal patterns of precipitation and temperature extremes in South America, with emphasis on the Pantanal biome, and to analyze their relationships with the main sea surface temperature anomalies in the Pacific and Atlantic Oceans, in order to understand the mechanisms of climate variability that modulate these extremes.

1.1.1 Specific Objectives

- i. To detect trends and spatial patterns of precipitation and temperature extremes in South America between 1979 and 2020, using internationally recognized standardized climate indices;
- ii. To assess the influence of the main modes of oceanic variability—such as the El Niño–Southern Oscillation (ENSO), the Atlantic Dipole, and Tropical Atlantic variability—on the occurrence and intensity of extreme climate events in South America;
- iii. To investigate the climate response of the Pantanal biome to precipitation and temperature extremes, considering its hydrological dynamics, sensitivity to ocean-driven climate oscillations, and land-use changes, integrating historical analyses and climate projections to identify future implications for biodiversity and water resources;

iv. To provide technical and scientific support for climate monitoring, risk management, and adaptation strategies, with special focus on environmentally vulnerable areas such as the Pantanal and other sensitive regions of South America.

2 THEORETICAL BACKGROUND

2.1 Fundamental Concepts of Climate Extremes

Climate extremes refer to meteorological or climatic events of unusually high or low intensity, typically occurring at the upper or lower bounds of the observed variability of a given parameter. These events include torrential rainfall, severe droughts, extreme heat waves or cold spells, among others (DOS SANTOS *et al.*, 2023a). For instance, an extreme rainfall event is generally defined by accumulated precipitation far above typical values, such as daily totals exceeding a high threshold, e.g., above the 95th or 99th percentile of the historical distribution (YU *et al.*, 2020).

Similarly, a temperature extreme may be characterized by exceptionally high or low daily maxima or minima relative to local climatology. A heat wave is defined as a prolonged period of abnormally high temperatures, often operationalized as several consecutive days with maximum temperatures far above the climatological mean of the region (MARX; HAUNSCHILD; BORNMANN, 2021). Specific criteria vary: some definitions adopt absolute thresholds (e.g., days above 35 °C), whereas others use relative thresholds (e.g., temperatures above the 90th percentile for at least 3 to 5 days) to classify both heat and cold waves. Regardless of the metric, heat and cold waves (i.e., prolonged periods of anomalous heat or cold) can exert significant impacts on human health, agriculture, and ecosystems (HIRSCH *et al.*, 2021).

Within the context of dry climate extremes, the most representative events are those associated with prolonged water scarcity, resulting from an imbalance between water supply and demand. These events range from periods of persistently below-average precipitation to conditions exacerbated by high temperatures and increased evapotranspiration, which intensify water deficits (ZHANG *et al.*, 2019).

Droughts can be classified according to their predominant effects: meteorological drought is defined by negative precipitation anomalies; agricultural drought manifests as soil moisture deficits insufficient to sustain crops; and hydrological drought refers to reductions in streamflow, lake levels, reservoirs, and aquifers. These categories are not mutually exclusive and frequently occur sequentially or simultaneously, amplifying the scope of impacts (GIMENO *et al.*, 2022; SUN *et al.*, 2021a).

Extreme dry events typically evolve more slowly but persist for longer durations, producing cumulative effects on ecosystems, agricultural production, urban water supply, and energy generation (CREMADES *et al.*, 2021). Moreover, global warming has contributed to

intensifying such events by increasing atmospheric water demand, thereby further reducing water availability. Understanding these dry extremes, as well as quantifying them through appropriate indices, is essential for assessing vulnerabilities, planning adaptation strategies, and ensuring water security in critical regions (GUMUS, 2023).

In contrast, extreme precipitation events tend to be shorter in duration (minutes to days), manifesting as intense rainfall or severe storms capable of triggering flash floods and landslides. Metrics for these pluvial extremes may include, for example, 24-hour (or 5-day) accumulated rainfall above a high threshold, or the frequency of rainy days exceeding specific values (e.g., days with rainfall ≥ 20 mm) (DOS SANTOS *et al.*, 2024). Such extreme rainfall events are frequently associated with intense meteorological systems (cold fronts, squall lines, cyclones, etc.) and can cause severe impacts on infrastructure, agriculture, and local populations due to floods and flash floods.

2.2 ETCCDI Climate Extremes Indices: Definitions and Applications

To objectively quantify climate extremes, the scientific community adopts a standardized set of indicators. The most widely used are the indices defined by the *Expert Team on Climate Change Detection and Indices* (ETCCDI), an international group linked to the World Meteorological Organization (WMO), which established consistent methodologies for monitoring changes in temperature and precipitation extremes. ETCCDI indices are calculated from daily maximum and minimum temperature and precipitation data, enabling the assessment of both absolute extremes (e.g., annual maximum temperature) and the frequency of moderately extreme events (e.g., very hot days, very wet days) on annual or seasonal scales (CHAPARINIA *et al.*, 2025).

The ETCCDI originally defined 27 core indices covering a broad range of thermal and precipitation extremes. However, in region-specific analyses—such as in tropical South America—not all 27 indices are relevant (e.g., frost days or ice days are of limited use in much of the tropics). Therefore, studies commonly employ a reduced set of approximately 22 ETCCDI indices, focusing on those related to temperature (heat and cold) and precipitation (heavy rainfall and dry spells) that are more applicable to South American conditions (DOS SANTOS *et al.*, 2023a).

A variety of climate indices have been widely used to characterize temperature and precipitation extremes, particularly in the context of climate change. For temperature extremes, the TXx index represents the highest daily maximum temperature of the year, serving as a direct indicator of heat extremes, with increasing trends observed across much of South America

(REBOITA *et al.*, 2022b). Similarly, TN_x, which measures the highest annual minimum temperature, reflects the occurrence of exceptionally warm nights, highlighting reduced nocturnal cooling as reported in the tropical Andes. Conversely, TX_n and TN_n—representing the lowest annual maximum and minimum, respectively—help quantify the decline of extreme cold events, with upward trends especially in southern Brazil and Argentina, suggesting milder winters and fewer frost occurrences (COLLAZO; BARRUCAND; RUSTICUCCI, 2022a; LAGOS-ZÚÑIGA *et al.*, 2024).

The relative frequency of extreme days or nights is also assessed using percentile-based indices. TX90p and TN90p correspond to the proportion of days and nights, respectively, in which temperature exceeds the 90th percentile of the reference climatology. Both have shown significant increases, indicating a greater incidence of heat waves, including nocturnal ones (TAN *et al.*, 2021). In contrast, TX10p and TN10p capture the frequency of cold days and nights (below the 10th percentile), which has declined markedly, especially across central and southern South America. Complementary duration indices, WSDI and CSDI, quantify prolonged warm and cold spells, respectively. While WSDI has increased consistently in areas such as central-southern Brazil and northeastern Argentina, CSDI has decreased, although it remains relevant at higher latitudes such as Patagonia (DOSIO *et al.*, 2018; MARENGO *et al.*, 2025).

The DTR index, representing the diurnal temperature range (difference between daily maximum and minimum), reveals contrasting patterns: reductions in the Amazon indicate stronger nocturnal warming, whereas increases in arid regions reflect enhanced daytime heating (LUCAS *et al.*, 2021).

Regarding precipitation extremes, the Rx1day and Rx5day indices evaluate the highest accumulated rainfall over one and five consecutive days, respectively, and are particularly useful to detect short- and medium-duration extremes. Rx1day increases have been observed in southeastern South America, while Rx5day has shown growth under CMIP6 projected warming scenarios. The mean precipitation intensity is expressed by the SDII index, whose increase indicates more concentrated and intense rainfall, even without a rise in the number of rainy days—a phenomenon especially evident in central Brazil (MASSON-DELMOTTE *et al.*, 2021).

The frequency of heavy rainfall days is captured by the R10mm, R20mm, and R30mm indices, which count days with precipitation exceeding 10, 20, and 30 mm, respectively. While increases in R20mm and R30mm have been reported in southern Brazil and the Pantanal (during wet years), decreases have occurred under severe drought conditions, such as in northeastern

Brazil (COSTA *et al.*, 2020a). The R95p and R99p indices, which measure the total rainfall from events above the 95th and 99th percentiles, indicate that an increasing fraction of annual precipitation is being delivered by rare and extreme events (DA SILVA *et al.*, 2019). This trend is particularly evident in southeastern Brazil and the La Plata Basin, heightening hydrological risks.

In addition, persistence indices assess dry or wet spells, including CWD (maximum number of consecutive wet days) and CDD (maximum number of consecutive dry days). Declines in CWD have been recorded in parts of the Amazon and Northeast Brazil, suggesting increased rainfall irregularity, while increases in CDD in regions such as the Pantanal have intensified the risk of prolonged droughts and wildfires, as observed in 2020. Finally, PRCPTOT represents the annual total precipitation on wet days (≥ 1 mm), providing a useful metric for evaluating the “effective” rainfall volume throughout the year. Decreasing trends in PRCPTOT have been reported in central and northern South America, reflecting shifts in rainfall distribution patterns.

Collectively, these findings underscore the utility of ETCCDI indices for characterizing climate change. Moreover, the indices are widely used in climate model performance evaluations—for instance, to verify whether General Circulation Models (GCMs) adequately reproduce observed statistics of extremes. CMIP6 validation studies show that many models successfully simulate the historical increase in TX90p and the decrease in TX10p across South America, though regional biases persist (COLLAZO; BARRUCAND; RUSTICUCCI, 2022a; REBOITA *et al.*, 2022b). For example, Reboita *et al.* (2022b) employed 19 extreme indices in global and regional model projections and identified robust signals of increased precipitation extremes in South America under future scenarios, particularly SSP5-8.5, while cold extremes virtually disappear by the end of the century.

2.3 Types of Drought and Monitoring Indices: Foundations and Applications in the Context of Climate Change

Drought is a complex and multifaceted climatic phenomenon, whose understanding requires integrated approaches across different disciplines. Traditionally, droughts are classified as meteorological, agricultural, hydrological, or socioeconomic, according to the sector affected or the stage of the hydrological cycle impacted (VICENTE-SERRANO; BEGUERÍA; LÓPEZ-MORENO, 2010). Meteorological drought begins with an abnormal reduction in precipitation relative to the climatological norm of a region. Agricultural drought emerges subsequently, when rainfall scarcity leads to insufficient soil moisture to sustain

vegetation and agriculture. Hydrological drought, in turn, manifests through persistent reductions in river flows, reservoir levels, and aquifers, and often continues even after rainfall returns (VAN LOON, 2015). Finally, socioeconomic drought represents the most critical phase, when water scarcity directly impacts water supply, agricultural production, the energy sector, and regional economies, highlighting the interconnection between the climate system and social structures.

To diagnose and monitor these different drought manifestations, several climatological indices have been employed, each with specific emphases and applications. The Standardized Precipitation Index (SPI), developed by McKee et al. (1993), is based solely on precipitation and is useful for characterizing meteorological droughts at multiple time scales. Its simplicity makes it ideal for operational monitoring in diverse regional contexts. However, its inability to incorporate variables such as temperature makes it less effective under global warming conditions (LAIMIGHOFER; LAAHA, 2022).

The Standardized Precipitation–Evapotranspiration Index (SPEI) represents an evolution of the SPI, as it incorporates potential evapotranspiration (PET), thereby capturing the effect of rising temperatures on the water balance. Recent studies—including the present analysis in the Pantanal biome—show that the SPEI is particularly sensitive to drought intensification under global warming, better reflecting the impacts of prolonged thermal stress, as observed during the drought events of 2019–2022. The application of SPEI-12 (12-month scale) has proven effective for assessing long-term hydrological impacts and their relationship with temperature extremes, such as the sharp increase in the TX90p index (hot days), which has emerged as a key indicator of hydrological stress in the Pantanal.

Another widely used index is the **Palmer Drought Severity Index (PDSI)**, which is based on a soil water balance model and is sensitive to long-term anomalies. Despite its extensive historical use, the PDSI has limitations in tropical regions due to its fixed calibration (MIKA *et al.*, 2005). Improved versions, such as the self-calibrated scPDSI, attempt to mitigate these limitations by adapting to local climatology (LIU *et al.*, 2024). The choice of index depends on the study objective. For example, the SPI is well suited for short-term detection of meteorological droughts, whereas the SPEI has become an indispensable tool for drought analyses in the context of climate change, as it captures the crucial role of temperature. The PDSI, with its focus on soil moisture, is more useful for agricultural and hydrological impact assessments at broader scales.

The scientific literature and the results of this study highlight the importance of integrating different types of drought and indices into a systemic approach. In the Pantanal

biome—where climate and land-use interactions are intense—such integration is critical. The intensification of droughts in the region is linked both to ocean temperature patterns (such as North Atlantic warming) and to land-use changes (agricultural expansion and deforestation), which amplify water deficits and the frequency of extreme events (MARENGO; OLIVEIRA; ALVES, 2016).

2.4 Tendências Recentes de Extremos na América do Sul e Uso dos Índices na Literatura

Observational studies over the past decades have documented significant changes in climate extremes across South America, many of which are consistent with the global trends reported by the IPCC (PÖRTNER *et al.*, 2022). In general, there is clear evidence of pronounced warming: heat extremes have become more frequent and intense, while cold extremes have become less common. At the same time, patterns of precipitation extremes display strong spatial heterogeneity, with some regions experiencing increases in heavy rainfall events, while others face more severe and prolonged droughts (DOS SANTOS *et al.*, 2024; REBOITA *et al.*, 2022b).

With respect to temperature extremes, robust evidence indicates widespread warming. Analyses of long-term meteorological station records reveal that since the mid-20th century much of South America has experienced an increase in the frequency of hot days and heat waves (FERON *et al.*, 2019). For instance, studies show that across nearly the entire continent the percentage of hot days and nights (above the 90th percentile) rose significantly between 1960 and 2010, while the percentage of cold days and nights (below the 10th percentile) declined (SKANSI *et al.*, 2013).

Warming has been particularly pronounced in northern South America, northeastern Brazil, and the tropical Andes, with minimum temperatures rising faster than maximum temperatures. Regions of central-eastern South America (southeastern Brazil, Uruguay, eastern Argentina) showed, during some decades of the 20th century, slight reductions in warm extremes—attributed to increased cloudiness and circulation changes associated with the South Atlantic Convergence Zone (SACZ). However, these signals had low confidence and reversed in the 21st century (MASSON-DELMOTTE *et al.*, 2021). Precipitation patterns are more heterogeneous: the IPCC AR6 highlights the absence of a robust continental-scale trend, with regional variations strongly influenced by El Niño/La Niña. The Southern Cone experienced increased rainfall and extreme precipitation between 1970 and 2000, followed by a multi-year

drought (2019–2022), suggesting a possible reversal of that wetting trend (PÖRTNER *et al.*, 2022).

Notable drought events in South America include the recurrent droughts of northeastern Brazil (1998–1999, 2012–2016—the latter considered the most severe in a century in the semiarid region); Amazon droughts (2005, 2010, 2015), which led to record low water levels in the Negro River and widespread forest fires; and the recent drought that severely affected the Pantanal, central Brazil, and the La Plata basin between 2019 and 2021 (MARENGO *et al.*, 2021b). In the case of the 2005 and 2010 Amazon droughts, studies have linked them to anomalous warming of the Tropical North Atlantic and to El Niño events, respectively, both of which suppressed convection over western and southern Amazonia, with severe impacts on forest ecosystems.

The 2019–2020 drought in the Pantanal was driven in part by anomalous atmospheric circulation that inhibited moisture transport from the Amazon into the continental interior, combined with dry air advection from subtropical latitudes (MARENGO *et al.*, 2021b). This atmospheric blocking virtually caused the monsoonal rains to fail in parts of the Pantanal, making 2020 the driest year in several decades—hydrologically, the Paraguay River reached its lowest levels in 50 years. The consequences included not only ecological stress but also economic losses: the fluvial transport route became nearly impassable, isolating riverside communities, while forest fires devastated around 30% of the Pantanal’s area in 2020.

In addition to the gradual increase in frequency, several absolute record-breaking **heat waves** stand out: the 2010 Amazon heat wave associated with El Niño, which combined with drought to produce extensive fires; the October–November 2020 heat waves in central-southern Brazil and Argentina, which set historical records above 40 °C in multiple locations; and more recently, the severe spring 2022 heat wave that extended across much of the continent, from the Amazon basin to Argentina, exacerbating ongoing droughts and producing unprecedented seasonal temperatures (e.g., 42 °C in the Pantanal in September) (LIBONATI *et al.*, 2022; MARENGO *et al.*, 2025).

There is growing evidence that the annual frequency of heat waves (≥ 3 –5 consecutive very hot days) has increased in many South American subregions since the second half of the 20th century. Barros *et al.* (2015) and other regional studies confirm the rise in heat waves, especially in subtropical areas. For example, in northern Argentina and Paraguay the number of extreme hot days and associated wildfires has tripled since the 1970s. These observed increases are consistent with global warming and are modulated by internal decadal variability (e.g., Pacific oscillations).

In terms of precipitation extremes, noteworthy events include: the Amazon floods of 2009 and 2012 (with record river levels in Manaus and surrounding areas); the catastrophic extreme rainfall and landslides in Rio de Janeiro's mountain region in 2011; the historic floods in Bolivia and Peru in 2014; and recurrent flooding across Andean countries and the La Plata basin during La Niña events. Many of South America's national 24-hour rainfall records are associated with organized convective systems over the Chaco or with orographic storms in the tropical Andes. It is worth noting that while continental-scale trends in extreme rainfall remain unclear, interannual variability is very high: El Niño years typically bring droughts to some regions and floods to others, leading to alternating wet and dry extremes. This pronounced variability has been a defining feature of recent South American climate, with major implications for the resilience of societies and ecosystems.

2.5 Climate Variability Mechanisms and Modulation of Extremes in South America

The climate of South America is strongly modulated by global- and regional-scale modes of variability, such as the El Niño–Southern Oscillation (ENSO), the Atlantic Multidecadal Oscillation (AMO), the South Atlantic Convergence Zone (SACZ), and the Tropical North Atlantic (TNA) index. These phenomena, associated with fluctuations in sea surface temperature (SST) and atmospheric circulation patterns, play a decisive role in shaping the occurrence of precipitation and temperature extremes across the region (CAI *et al.*, 2020a).

Walker Circulation and the Influence of ENSO

The Walker circulation is a tropical zonal overturning cell sustained by the east–west SST gradient in the Pacific, characterized by ascending motion over warmer waters, upper-level outflow to the east, subsidence over the eastern Pacific, and low-level return flow via the trade winds. Variations in its intensity and position modulate tropical convection and global teleconnections, with direct impacts on South America (FALSTER *et al.*, 2023).

Recent studies indicate that while global climate models project a weakening of the Walker circulation under global warming, observations suggest that between 1992 and 2011 it anomalously strengthened, possibly linked to internal variability and aerosol forcing (FALSTER *et al.*, 2023). During El Niño events, the Walker circulation weakens, shifting convection toward the central–eastern Pacific and favoring droughts in the Amazon and Northeast Brazil, while enhancing rainfall in southeastern South America. Conversely, La Niña events reinforce the Walker circulation, intensifying moisture transport into the Amazon and central Brazil (FERON *et al.*, 2024).

Hadley Circulation and Meridional Expansion

The Hadley circulation is a large-scale meridional overturning pattern, with rising motion near the Intertropical Convergence Zone (ITCZ), poleward upper-level outflow, subsidence of dry air over the subtropics, and a return of low-level trade winds. The intensity and width of this cell control the mean position of the ITCZ and the distribution of tropical and subtropical precipitation (STATEN *et al.*, 2020).

Both CMIP5 and CMIP6 models indicate a consistent expansion of the Hadley cell's subtropical edge, with rates of 0.1° to 0.5° latitude per decade in the Southern Hemisphere (GRISE; DAVIS, 2020). This expansion has important implications for South America, as it displaces subsidence zones toward higher latitudes, intensifying aridity in central-southern regions and altering the frequency of hydrological extremes (KIM *et al.*, 2023).

Interactions between Large-Scale Cells and Regional Systems in South America

The interaction between the Walker and Hadley cells and regional circulation systems—such as the South Atlantic Convergence Zone (SACZ), the South American Low-Level Jet (SALLJ), the South Atlantic Subtropical High (SASH), and the Bolivian High—is fundamental to understanding the seasonality and interannual variability of precipitation and temperature in South America (FERON *et al.*, 2024).

During austral summer, under neutral conditions or when the Walker circulation is slightly strengthened, enhanced convection develops over the Amazon, the SACZ becomes organized, and efficient moisture transport occurs toward southeastern South America. During El Niño, convection shifts to the central–eastern Pacific, weakening the Bolivian High and inhibiting the SACZ, while subtropical jet anomalies favor precipitation in the La Plata Basin. Under La Niña, the opposite pattern emerges, with intensification of the SACZ and increased rainfall over central Brazil.

The meridional SST gradient in the Tropical Atlantic also influences ITCZ position: relative warming in the northern sector displaces the ITCZ northward, intensifying droughts in Northeast Brazil and eastern Amazonia, whereas relative cooling in the north favors its southward displacement, enhancing rainfall (LIU *et al.*, 2022).

Long-Term Impacts and Hydroclimatic Extremes

Background climate change is expected to reshape both circulation cells. The Hadley cell expansion increases the frequency of dry conditions in subtropical margins and alters the

path and intensity of jets and frontal systems, influencing SACZ persistence and the occurrence of atmospheric blocking events in central-southern South America (GRISE; DAVIS, 2020; KIM *et al.*, 2023)

On a zonal scale, projections indicate a weakening Walker circulation under global warming, although modulated by decadal variability. A weakened Walker reduces moisture transport into the western tropical Pacific and favors convection over the central–eastern Pacific, increasing the risk of drought in northern and central Brazil during El Niño years; a strengthened Walker, in contrast, tends to reproduce typical La Niña patterns (FALSTER *et al.*, 2023).

These changes are associated with: (i) longer dry spells, as indicated by increases in Consecutive Dry Days (CDD) in subtropical areas; (ii) more concentrated rainfall occurring in fewer but more intense events, captured by indices such as SDII and Rx5day; and (iii) greater incidence of heat waves and elevated evapotranspiration in tropical–subtropical transition zones (FERON *et al.*, 2024). For the Pantanal, such alterations may amplify agricultural and hydrological droughts or intensify peak rainfall events when convection becomes organized.

El Niño–Southern Oscillation (ENSO)

ENSO is the primary mode of interannual variability in the global climate system. Its El Niño phase is characterized by anomalous warming of central–eastern equatorial Pacific waters, whereas La Niña is associated with anomalous cooling. The impacts of ENSO in South America are striking and well documented in the literature (CAI *et al.*, 2014, 2020a)

During El Niño, rainfall generally decreases over the Amazon and northeastern Brazil, as enhanced atmospheric subsidence inhibits cloud formation and precipitation in these regions (ESPINOZA *et al.*, 2024; MARENGO; ESPINOZA, 2016). At the same time, heavy rainfall and floods occur along the coasts of Ecuador and northern Peru (*El Niño Costero*), while southeastern South America (southern Brazil, Uruguay, Argentina) experiences increased extreme precipitation events due to shifts in jet streams and frontal systems (FERNANDES; GRIMM, 2023).

In contrast, La Niña events tend to produce the opposite signals: above-average rainfall in the Amazon and Northeast Brazil, combined with drier-than-normal conditions in southern Brazil and Argentina. Several studies have demonstrated significant correlations between the Niño 3.4 index and ETCCDI precipitation extremes such as R10mm and PRCPTOT. In particular, there is a negative correlation between Niño 3.4 and heavy rainfall in the Amazon,

and a positive one in southern South America—highlighting ENSO’s role as a regional driver of hydroclimatic extremes (DOS SANTOS *et al.*, 2024).

Beyond precipitation, ENSO also influences temperature extremes. During El Niño, reduced cloud cover over parts of the continent favors surface warming, contributing to the occurrence of heat waves, particularly in northern South America (FERON *et al.*, 2019; SENEVIRATNE; HAUSER, 2020). The recent 2023–2024 Amazon heat wave occurred in the context of El Niño and concurrent Atlantic warming anomalies, reinforcing the compound nature of such events.

It is important to note that ENSO impacts vary depending on the event type. For example, *El Niño Modoki* tends to shift its strongest impacts westward over South America, producing distinct precipitation patterns (CAI *et al.*, 2020a). Moreover, interactions between ENSO and other forcings, such as the AMO and TNA, may intensify or attenuate its regional effects, increasing the complexity of South American climate responses.

Atlantic Multidecadal Oscillation (AMO) and the Tropical Atlantic Dipole (TAD)

The Atlantic Multidecadal Oscillation (AMO) represents one of the main low-frequency variability modes of the Northern Hemisphere climate system, associated with multidecadal fluctuations in North Atlantic sea surface temperature (SST). Alternating between positive (warm) and negative (cool) phases in cycles of ~60–80 years, the AMO significantly modulates tropical atmospheric circulation, influencing South American climate through shifts in the Intertropical Convergence Zone (ITCZ) and changes in trade winds (FIALHO *et al.*, 2023; TRENBERTH; SHEA, 2006).

During the positive AMO phase, the North Atlantic becomes anomalously warm, displacing the ITCZ northward. This results in reduced rainfall across northern South America, particularly in northeastern Brazil and the Guianas, contributing to severe droughts such as those observed in the 1930s and 1990s (MARENGO *et al.*, 2018; YOON; ZENG, 2010). Conversely, during the negative AMO phase, a cooler North Atlantic shifts the ITCZ southward, enhancing moisture convergence and favoring above-average rainfall in those regions.

Closely linked to the AMO is the Tropical Atlantic Dipole (TAD), which describes the meridional SST gradient between the Tropical North Atlantic (TNA) and the Tropical South Atlantic (TSA). In its positive phase—when the TNA is warmer than the TSA—the dipole reinforces positive AMO effects, intensifying northward ITCZ displacement and exacerbating droughts in northeastern Brazil and eastern Amazonia (MARTINS *et al.*, 2015a). Conversely,

the negative dipole phase, with a relatively cooler TNA, tends to displace the ITCZ southward, enhancing rainfall in the equatorial belt and in the Brazilian semiarid region (DE MEDEIROS; DE OLIVEIRA; TORRES, 2020).

The combined influence of AMO and the Atlantic dipole often drives compound hydrological extremes, especially when positive AMO phases coincide with strong positive dipole events. For example, the severe 2012–2017 drought in northeastern Brazil was partly attributed to the persistence of a positive AMO phase combined with anomalously warm TNA waters, which persistently displaced the ITCZ northward (MARENGO *et al.*, 2018).

In addition to precipitation impacts, both the AMO and the tropical dipole influence temperature extremes. Reduced cloud cover during warm phases (AMO+ and TAD+) increases solar radiation over northeastern South America, raising surface temperatures and favoring extreme heat events and regional heat wave amplification (GRIMM, 2019; REBOITA *et al.*, 2021a; YOON; ZENG, 2010). In contrast, cool phases are associated with greater cloud cover, lower maximum temperatures, and reduced thermal stress.

The AMO also affects large-scale circulation in subtropical South America, modulating the intensity of the South American Low-Level Jet (SALLJ)—a crucial moisture transport pathway from the Amazon to southern South America. Studies indicate that during negative AMO phases, the SALLJ tends to intensify, favoring extreme rainfall in southern Brazil, Paraguay, and northern Argentina, while reducing precipitation in northern Amazonia due to atmospheric moisture redistribution (MONTINI; JONES; CARVALHO, 2019a).

In summary, both the AMO and the Tropical Atlantic Dipole act as key forcings that modulate hydroclimatic extremes across South America. Their combined action can either amplify or attenuate the impacts of global warming and must be considered in climate risk assessments and adaptation policy planning. Recent literature emphasizes that the accurate representation of these variabilities in climate models is essential for realistic projections of future extremes in South America (CAI *et al.*, 2020a; LIU *et al.*, 2022) .

2.6 South Atlantic Convergence Zone (SACZ)

The South Atlantic Convergence Zone (SACZ) is one of the most important meteorological systems for the climatology of tropical and subtropical South America, particularly with respect to summer rainfall distribution. It consists of a persistent northwest–southeast oriented band of cloudiness and precipitation extending from the Amazon region toward the southwestern Atlantic, crossing central Brazil (MA *et al.*, 2011). The SACZ is considered the main continental manifestation of the South American monsoon, predominantly

occurring between November and March, and is associated with intense moisture fluxes from both the Amazon basin and the tropical Atlantic (ESCOBAR *et al.*, 2022).

Variability in the position, intensity, and duration of the SACZ is strongly linked to the occurrence of rainfall extremes in central and southeastern Brazil. Strong and stationary SACZ episodes can produce intense and persistent rainfall for several consecutive days, resulting in severe flooding, landslides, and socio-environmental disasters (CARVALHO *et al.*, 2011; ZHOU; LAU, 2001). Conversely, when the SACZ shifts northward or weakens, *veranicos*—abnormally hot and dry spells during summer—can affect southeastern and west-central Brazil, with direct implications for water supply, agriculture, and hydropower generation (Nobre *et al.*, 2012; Silva *et al.*, 2021).

In addition to interannual variability, the SACZ also responds to intraseasonal modulation induced by phenomena such as the Madden–Julian Oscillation (MJO). Studies show that convective phases of the MJO propagating over South America tend to intensify and prolong SACZ episodes, whereas subsident phases promote its weakening (FERNANDES; GRIMM, 2023)

The SACZ is also directly related to climate extreme indices such as CDD (Consecutive Dry Days), CWD (Consecutive Wet Days), and Rx5day (maximum 5-day precipitation). Prolonged SACZ activity increases CWD and Rx5day values, reflecting continuous and intense rainfall accumulation over a short period. In contrast, its absence may lead to higher CDD and maximum temperatures, often associated with heat waves, due to reduced cloud cover and weaker radiative cooling (LAUREANTI *et al.*, 2024; WONG *et al.*, 2021).

Under climate change scenarios, recent studies suggest that the SACZ may undergo alterations in its frequency, intensity, and zonal positioning. Climate model projections point to a possible trend of shorter but more intense episodes, especially under strong warming scenarios, although projected signals still carry substantial uncertainty (PÖRTNER *et al.*, 2022; REBOITA *et al.*, 2022a). Furthermore, meridional shifts in the mean SACZ position may have important implications for summer rainfall redistribution in central-southern Brazil and the La Plata Basin, potentially increasing water vulnerability and hydrological disaster risk in the region.

2.7 Influence of Tropical North Atlantic SST and Other Teleconnections on South American Climate

Sea surface temperature (SST) anomalies in the Tropical North Atlantic (TNA) play a crucial role in modulating climate extremes over South America, particularly across northern

and central regions of the continent. Several studies show that positive TNA anomalies—that is, when this oceanic region is warmer than average—are associated with a series of climatic impacts over South America (ESCOBAR *et al.*, 2022; WONG *et al.*, 2021).

A warmer TNA tends to induce relative high-pressure anomalies over tropical South America, which suppress atmospheric convection, reduce cloudiness, and favor increased direct solar radiation. This pattern enhances heat waves and raises extreme maximum temperatures (TXx) in regions such as central Brazil, eastern Amazonia, and parts of the Cerrado. Physically, lower relative humidity and reduced cloud cover during warm TNA phases amplify surface warming, creating favorable conditions for extreme heat and meteorological droughts (LIU *et al.*, 2022).

The influence of the TNA is also evident in droughts and severe wildfires. The combination of North Atlantic warming and reduced atmospheric humidity generates particularly critical conditions in regions such as the Pantanal and southern Amazon. Literature shows that in years of exceptionally warm TNA, daily temperature extremes intensify, favoring fire outbreaks and forest degradation (BARICHIVICH *et al.*, 2018; ZEMP *et al.*, 2017).

Beyond TNA, the interaction between different climate variability modes can amplify extremes in South America. For example, when a warm Atlantic phase (positive AMO or TNA+) coincides with La Niña events, the probability of severe droughts in northeastern Brazil and the Amazon increases substantially. Conversely, when the South Atlantic is anomalously warm, the impact of an El Niño event on central Brazil may be partially offset by enhanced tropical convection induced by greater low-tropospheric moisture availability (WAINER *et al.*, 2021a).

Other modes of variability also influence South American extremes. The Antarctic Oscillation (AAO), particularly in its negative phase, favors the incursion of polar air masses toward mid-latitudes of South America, increasing the likelihood of extreme cold events in southern Brazil, Uruguay, and northern Argentina, as observed during the winter of 2021, when frost and snow affected large areas of southern Brazil (REBOITA *et al.*, 2021a; YUAN *et al.*, 2022). The Madden–Julian Oscillation (MJO), an intraseasonal oscillation originating in the tropical Pacific, modulates tropical convection and can directly affect the occurrence, intensification, or suppression of the SACZ, thereby influencing patterns of extreme rainfall during austral summer (ALVAREZ; VERA; KILADIS, 2017).

It is important to note that these modes of variability do not operate in isolation. In many cases, their influences overlap and interact in complex ways, rendering patterns of climate extremes highly nonlinear and challenging for seasonal prediction. For instance, years with

concurrent La Niña and positive AMO phases often produce severe droughts in northern and northeastern Brazil, whereas combinations such as El Niño with a warm South Atlantic may yield weaker-than-expected responses depending on the synergy between teleconnections (CAI *et al.*, 2020a; GRIMM, 2019; REBOITA *et al.*, 2021a)

In conclusion, global and regional modes of climate variability—including ENSO, AMO, TNA, SACZ, AAO, and MJO—act as natural forcings that shape hydroclimatic and thermal extremes across South America. Under continued global warming, the interaction of these modes with anthropogenic climate change is expected to further intensify the frequency and severity of extreme events, such as multi-year droughts, persistent heat waves, and concentrated rainfall episodes. Understanding these dynamics is essential for projecting future scenarios and for developing science-based climate adaptation strategies.

2.8 Future Climate Projections in South America Based on CMIP6

State-of-the-art climate models, such as those from the Coupled Model Intercomparison Project Phase 6 (CMIP6), indicate with high confidence that South America will experience significant changes in the frequency and intensity of extreme events throughout the 21st century, particularly under high greenhouse gas emission scenarios (MASSON-DELMOTTE *et al.*, 2021). These projections point to the continuation and amplification of already observed trends: pronounced warming, more frequent heat waves, a reduction in cold extremes, and changes in the spatial and temporal distribution of precipitation (SENEVIRATNE; HAUSER, 2020).

Increase in Temperature Extremes

Under all emission scenarios assessed by the IPCC—from the most optimistic (SSP1-2.6) to the most pessimistic (SSP5-8.5)—South America is projected to warm more rapidly than the global average. Even under SSP1-2.6 (with global warming limited to ~ 1.8 °C by 2100), heat events currently considered rare (with 50-year return periods) may occur every five years or less (SENEVIRATNE; HAUSER, 2020).

In the high-emission scenario (SSP5-8.5), with mean global warming approaching +4 °C by the end of the century, cold days as defined by current standards would virtually disappear across most of tropical and subtropical South America. Projections also suggest that severe heat waves would occur annually over large areas of the continent, especially in tropical regions such as the Amazon and the Pantanal. The number of days with daily maximum temperatures above 35 °C ($TX > 35$ °C) may increase by several dozen per year, with impacts on ecosystems,

human health, and agricultural productivity (COLLAZO; BARRUCAND; RUSTICUCCI, 2022a).

Heavy Rainfall and Hydrological Extremes

Precipitation projections display greater spatial heterogeneity but also point to significant changes. In general, annual precipitation and extreme rainfall events are projected to increase over northwestern South America (Colombia, Ecuador, upper Amazon) and southeastern South America (southern Brazil, Uruguay, Argentina), while decreases are expected in northeastern Brazil, eastern Amazonia, central Chile, and southern Peru (PÖRTNER *et al.*, 2022)

With global warming, the atmosphere's capacity to hold water vapor increases by about 7% per °C according to the Clausius–Clapeyron relationship, favoring more intense and frequent heavy rainfall events. CMIP6 models project robust increases in the RX5day index (maximum precipitation in five consecutive days) across much of tropical South America under SSP5-8.5 scenarios (REBOITA *et al.*, 2022a, 2022b). This implies that precipitation extremes currently considered rare may become common, with their frequency doubling or even tripling by 2100.

Droughts and Prolonged Dry Spells

Conversely, several South American regions are expected to experience reduced precipitation and more intense droughts. Northeastern Brazil, eastern Amazonia, and central Brazil are particularly vulnerable, with decreases in mean dry-season rainfall and higher evapotranspiration due to elevated temperatures (LIBONATI *et al.*, 2022). These changes increase the likelihood of agricultural and ecological droughts and could push ecosystems such as eastern Amazonia toward a transitional savanna-like state if critical thresholds are surpassed (BOERS *et al.*, 2017).

In the Pantanal, even if annual rainfall totals do not decline significantly, intraseasonal rainfall distribution is projected to become more irregular, with precipitation concentrated in intense events followed by extended dry spells. This pattern points to increases in the CDD index (consecutive dry days), heightening risks of wildfires and ecological collapse, as observed in 2020 (LIBONATI *et al.*, 2022).

Subtropical Regions and Compound Events

For southern Brazil, Uruguay, and Argentina, models project increases in the frequency and intensity of extreme rainfall events, particularly in summer and autumn. This could trigger large-scale flood events and river overflows in major basins such as the Paraná and Uruguay (REBOITA *et al.*, 2022a; SUN *et al.*, 2021c). The associated mechanisms include intensification of the South American Low-Level Jet (SALLJ) and stronger SACZ episodes.

Compound events—such as extreme heat combined with drought—represent a growing threat. Literature suggests that the frequency of such simultaneous events will rise sharply under SSP5-8.5, increasing the risk of agricultural collapse, wildfires, and biodiversity loss (ZEMP *et al.*, 2017).

Although CMIP6 represents an advance over previous generations, important limitations remain, such as the representation of tropical convective processes, forest–rainfall feedbacks, and land-use change. The latter is particularly critical in the Amazon and Cerrado, where land-use scenarios are not fully incorporated into global climate models. Regional studies indicate that deforestation can reduce precipitation and intensify heat extremes, exacerbating projections based solely on global climate change (JOHN *et al.*, 2022; LUO *et al.*, 2024).

3 CHAPTER 1: TRENDS OF CLIMATE EXTREMES AND THEIR RELATIONSHIPS WITH TROPICAL OCEAN TEMPERATURES IN SOUTH AMERICA

ABSTRACT

South America has experienced significant changes in climate patterns over recent decades, particularly in terms of precipitation and temperature extremes. This study analyzes trends in climate extremes from 1979 to 2020 across South America, focusing on their relationships with sea surface temperature (SST) anomalies in the Pacific and Atlantic Oceans. The analysis uses precipitation and temperature indices, such as the number of heavy rainfall days (R10mm, R20mm, R30mm), total annual precipitation (PRCPTOT), hottest day (TXx), and heatwave duration (WSDI), to assess changes over time. The results show a widespread decline in total annual precipitation across the continent, although some regions, particularly in the northeast and southeast, experienced an increase in the intensity and frequency of extreme precipitation events. Extreme temperatures have also risen consistently across South America, with an increase in both the frequency and duration of heat extremes, indicating an ongoing warming trend. The study also highlights the significant role of SST anomalies in both the Pacific and Atlantic Oceans in driving these climate extremes. Strong correlations were found between Pacific SST anomalies (Niño 3.4 region) and extreme precipitation events in the northern and southern regions of South America. Similarly, Atlantic SST anomalies, especially in the Northern Atlantic (TNA), exhibited notable impacts on temperature extremes, particularly heatwaves. These findings underscore the complex interactions between SST anomalies and climate variability in South America, providing crucial insights into the dynamics of climate extremes in the region. Understanding these relationships is essential for developing effective adaptation and mitigation strategies in response to the increasing frequency and intensity of climate extremes.

Keywords: climate extreme; atmospheric field analysis; climate change; trend analysis

INTRODUCTION

Earth's climate is undergoing significant changes, posing a major threat to populations worldwide. South America, with its vast geographic diversity and climate variability, is especially vulnerable to these changes (KHAN *et al.*, 2015). The region contains a wide range of ecosystems, including tropical forests, savannas, deserts, and mountain ranges, all of which face distinct climate-related challenges (REBOITA *et al.*, 2022c). As the frequency and intensity of extreme weather events increase, the societal, economic, and ecological impacts across South America are becoming more severe. Extreme events such as droughts, floods, storms, tropical cyclones, and heat waves are already causing significant damage to infrastructure, water resources, agriculture, and public health (COSTA *et al.*, 2020b).

South America is one of the world's leading food-producing regions and is highly susceptible to climate extremes. These events directly threaten agricultural production, food security, and water resources, with cascading effects on energy, public supply, and economic activity (RAY *et al.*, 2019, p. 20). Prolonged droughts exacerbate water scarcity, impacting agriculture and energy generation, while floods can contaminate drinking water and damage critical infrastructure (DAHER *et al.*, 2021). Additionally, intense storms and tropical cyclones, with their destructive winds and heavy rainfall, lead to flash floods, posing significant risks to human life and property (AFJAL HOSSAIN *et al.*, 2012). Heat waves further stress health systems, increase the risk of wildfires, and contribute to the spread of vector-borne diseases like dengue and malaria (KHAN *et al.*, 2015). Understanding the connections between climate variability and extreme weather events is crucial for improving public health measures, managing water and energy resources, and enhancing community resilience. Therefore, studying extreme climate events in South America is essential for developing effective policies and actions to mitigate their impacts (DOS SANTOS *et al.*, 2022).

Addressing the complexity of climate change requires comprehensive and interdisciplinary mitigation and adaptation strategies. Collaboration among experts from various fields is critical, and decisions must be based on the best available scientific evidence (GLEIXNER; DEMISSIE; DIRO, 2020). However, the lack of tools to analyze long-term climate variables has limited our understanding of the global processes driving climate variability in South America (MORALES *et al.*, 2020). Access to accurate climate data is essential for building a robust framework for climate resilience, which should include targeted adaptation strategies to reduce the region's vulnerability to diverse climate hazards.

Although several studies have examined climate extremes in different parts of South America (ANJOS; TOLEDO, 2018; DE SOUZA *et al.*, 2021; DUNN *et al.*, 2020; RUIZ-VÁSQUEZ *et al.*, 2020), few have explored the potential effects of sea surface temperature (SST) anomalies or used unified datasets combining meteorological station data with interpolation techniques. Integrating observed data with climate models generates consistent time series for various climate variables, making these datasets, such as those from the Climate Prediction Center (CPC), valuable for long-term climate trend studies (COLLAZO; BARRUCAND; RUSTICUCCI, 2022b). The CPC data, produced by one of the leading climate research centers in the United States, are widely used in forecasting and monitoring climate conditions globally. These data help inform decision-making in sectors such as agriculture, energy, and public safety (GHAEDAMINI *et al.*, 2021).

Sea surface temperature (SST) oscillations, particularly in the Pacific and Atlantic Oceans, are key factors influencing extreme climate trends in South America (CAI *et al.*, 2020b). The ocean plays a critical role in the global climate system, affecting atmospheric conditions and influencing temperature and precipitation patterns on continents. El Niño and La Niña events, driven by Pacific SST variations, cause significant shifts in atmospheric pressure and circulation, intensifying droughts and floods (TRENBERTH, 2020). O Oceano Atlântico exibe um padrão recorrente de anomalias da temperatura da superfície do mar (TSM), conhecidas como Dipolo Atlântico. The Atlantic Ocean exhibits a recurring pattern of sea surface temperature (SST) anomalies, known as the Atlantic Dipole. In the Atlantic Ocean, the Atlantic Dipole, which alternates between positive and negative phases, impacts climate patterns by generating SST anomalies in the northern and southern hemispheres (LEYBA *et al.*, 2023)

In this context, this study fills this gap by utilizing advanced climate data products, including those from the Climate Prediction Center (CPC), to analyze trends in precipitation and temperature extremes and their links to SST anomalies in both the Pacific and Atlantic Oceans.

MATERIAL AND METHODS

Study Area: Climatological Features of IPCC Regions South America

This study utilizes the climate reference regions defined by the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) for South America (SA) (ITURBIDE *et al.*, 2020). These regions represent distinct climate regimes and physiographic settings and are designed to maximize coverage by climate model grid boxes (Figure 1).

Climate homogeneity is assessed based on temperature and precipitation gradients according to the Köppen–Geiger climate classification, as well as precipitation seasonality (Table 1).

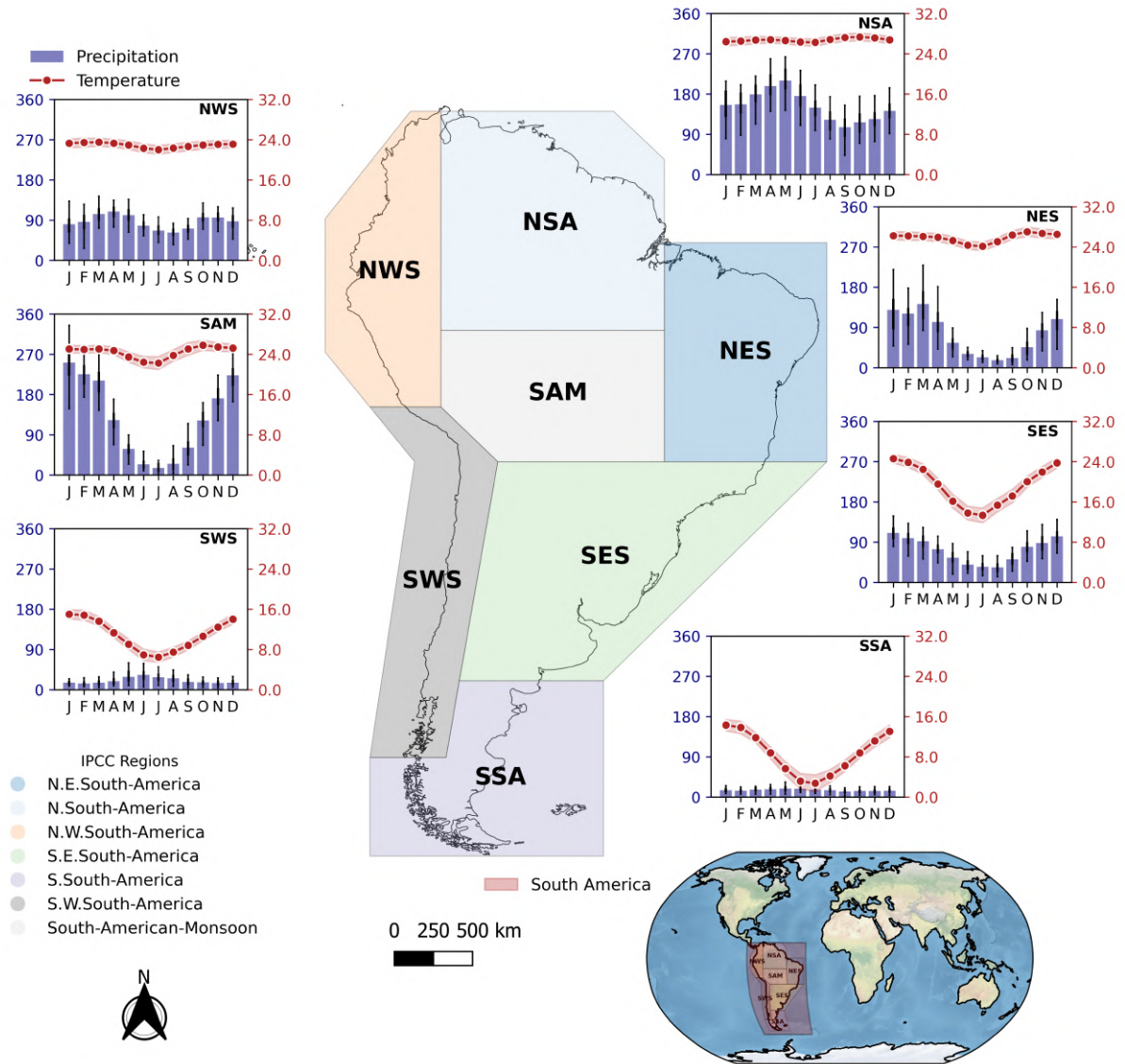


Figure 1: Climate normal for precipitation and air temperature and location of the climate reference regions from the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6) for South America from 1979 to 2020.

Table 1: Climatic Characteristics of South American Regions, based on the classification utilized by the Intergovernmental Panel on Climate Change (IPCC).

Region	Coverage Area	Precipitation Seasonality	Atmospheric Systems
NES	Northeast South America Northeast Brazil	Highs in summer/autumn and lows in winter	Oceanic and atmospheric conditions—ENSO episodes in the Pacific Ocean and/or at an intense meridional sea surface temperature gradient over the tropical Atlantic—High-Level Cyclonic Vortex Episodes
NSA	Northern South America Northern Brazilian Amazon, Eastern Colombia and Venezuela, Guyana,	Rainfall well distributed throughout the year (no drought). However, some	Seasonal meridional movement of the Pacific-Atlantic Intertropical

		Suriname and French Guiana	locations do not have a clear rainy and dry season.	Convergence Zone—Bolivian Upper
NWS	Northwest South America	Peru, Ecuador and Colombia		
SES	Southeast South America	South, Southeast and part of the Brazilian Midwest, Paraguay, Uruguay and a large part of Argentina	Highs in summer and lows in winter	Transport of moisture from the Amazon by the action of the South American Low-Level Jet—Mesoscale convective systems—Surface cyclonic systems—Frontal systems—Instability lines—South Atlantic Convergence Zone
SSA	Southern South America	Extreme South of Argentina and Chile	Highs in winter and lows in summer	It depends on the position of the South Pacific Subtropical Anticyclone—an orographic barrier caused by the Andes.
SWS	Southwest South America	Southern Peru and almost all of Chile		
SAM	South American Monsoon	Southern Brazilian Amazon and part of the Midwest and Bolivia	A rainy season from October to March	Seasonal meridional movement of the Pacific and Atlantic Intertropical Convergence Zone—Bolivian Upper—South American Monsoon—South Atlantic Convergence Zone

Data

Daily precipitation, maximum and minimum air temperature, and monthly sea surface temperature (SST) data were obtained from January 1979 to December 2020. These datasets were sourced from the National Oceanic and Atmospheric Administration (NOAA) and made available by the Climate Prediction Center (CPC; <https://psl.noaa.gov/data/gridded/>, 10 accessed February 2021) (Table 2). The SST regions analyzed include Niño 1+2, Niño 3, Niño 3.4, Niño 4, Oceanic Niño Index (ONI), Tropical Northern Atlantic (TNA) and Tropical Southern Atlantic (TSA) (Figure 2).

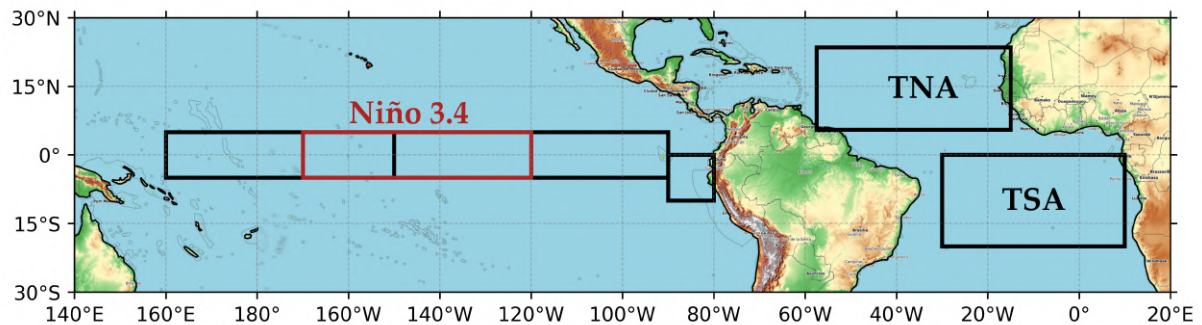


Figure 2: Location of the ENSO (Niño 1 + 2, Niño 3, Niño 3.4, and Niño 4) and Atlantic Dipole (TNA and TSA) regions in the equatorial Pacific and tropical Atlantic, respectively.

The CPC data products, particularly the Global Precipitation and Global Temperature datasets, provide consistent, high-quality data. These datasets are derived from ground-based stations, satellite observations, and advanced interpolation techniques (NASHWAN; SHAHID; CHUNG, 2019; SUN *et al.*, 2018). The NOAA Extended Reconstruction Sea Surface

Temperature (ERSST) version 5 dataset was used for SST data, which employs enhanced spatial and temporal reconstruction methods to ensure accuracy, especially in regions with sparse observations (HUANG *et al.*, 2017; WONG *et al.*, 2020).

Table 2: Description of the precipitation, maximum and minimum temperature, and sea surface temperature datasets used for the study, from January 1979 to December 2020.

Variable	Dataset	Spatial Resolution	Period	Temporal Scale	Source/Reference
Precipitation	CPC—Global Precipitation	0.5×0.5	1 January 1979 to 31 December 2020	Daily	NOAA/Chen et al., 2008
Max-Min Temperature	CPC—Global Temperature	0.5×0.5	1 January 1979 to 31 December 2020	Daily	NOAA/CPC
Sea Surface Temperature	NOAA ERSST V5	2.5×2.5	1 January 1979 to 1 December 2020	Monthly	NOAA/Huang et al., 2017

Climate Extreme Indices

This study evaluates the interannual variability and long-term trends of extreme climate events using indices for precipitation and temperature extremes. The analysis focuses on the magnitude, severity, duration, and frequency of events such as heat waves, cold spells, and extreme rainfall. Precipitation extremes were assessed using indices such as the annual count of days with precipitation ≥ 10 mm, ≥ 20 mm, and ≥ 30 mm, along with the maximum one-day and five-day precipitation totals. Similarly, temperature extremes were analyzed based on maximum and minimum daily temperatures, as well as the duration and intensity of warm and cold periods (DOS SANTOS *et al.*, 2022).

We used the ClimPACT software to calculate the 27 extreme climate indices proposed by the Expert Team on Climate Change Detection Monitoring and Indices (ETCCDMI). ClimPACT software, developed by the Pacific Climate Impacts Consortium, to calculate 23 extreme climate indices, 11 derived from precipitation and 12 from temperature (Table 3). These indices are based on recommendations from the Expert Team on Climate Change Detection and Indices (ETCCDI) and are widely used for global climate assessments, allowing for international comparison (AVILA-DIAZ *et al.*, 2020a).

Table 3: Description of extreme climate indices for precipitation and air temperature for the IPCC AR6 climate reference regions in South America. Tmax: maximum temperature; Tmin: minimum temperature; RR: daily precipitation; PRCP: total precipitation.

Variable	Index	ID	Definition	Units
Precipitation	Number of heavy precipitation days	R10mm	Annual count of days when PRCP $\geq$ 10 mm	days
	Number of very heavy precipitation days	R20mm	Annual count of days when PRCP $\geq$ 20 mm	days
	Number of days above nn mm	R30mm	Annual count of days when PRCP $\geq$ 30 mm	days
	Max 1-day precipitation amount	Rx1day	Annual max 1 day precipitation	mm
	Max 5-day precipitation amount	Rx5day	Annual max 5-day precipitation	mm
	Annual total wet day precipitation	PRCPTOT	Annual total PRCP in wet days—RR $\geq$ 1 mm	mm
	Simple daily intensity index	SDII	Annual total precipitation divided by the number of wet days—PRCP $\geq$ 1 mm	mm/day
	Precipitation on very wet days	R95p	Annual total precipitation (PRCP) when RR. 95th percentile	mm
	Precipitation on extremely wet days	R99p	Annual total PRCP when RR. 99th percentile	mm
	Consecutive wet days	CWD	Max number of consecutive days when RR $\geq$ 1 mm	days
Air temperature	Consecutive dry days	CDD	Max number of consecutive days when RR < 1 mm	days
	Warmest Day	TXx	Annual Maximum value of daily max temperature	°C
	Warmest Night	TNx	Annual Maximum value of daily min temperature	°C
	Coldest Day	TXn	Annual Minimum value of daily max temperature	°C
	Coldest Night	TNn	Annual Minimum value of daily min temperature	°C
	Diurnal Temperature Range	DTR	Daily Tmax—Daily Tmin	°C
	Warm spell duration	WSDI	Annual count of days with a least 6 consecutive days when Tmax > 90th percentile	days
	Cold spell duration	CSDI	Annual count of days with a least 6 consecutive days when Tmin < 10th percentile	days
	Warm Days	TX90p	% of days when Tmax is >90th percentile	%
	Warm Nights	TN90p	% of days when Tmin is >90th percentile	%
	Cool Days	TX10p	% of days when Tmax is <90th percentile	%
	Cool Nights	TN10p	% of days when Tmin is <90th percentile	%
	Frost Days	FD	Annual count of days when TN < 0 °C	days

Data Analysis

Trends in climate extremes were analyzed using the non-parametric Theil–Sen estimator (MENGISTU *et al.*, 2020a), which is robust against non-normal data distributions (SUN *et al.*,

2021b). The significance of these trends was tested using the modified Mann-Kendall (MMK) test, which accounts for autocorrelation in time series data, thus providing more reliable trend detection (BARI *et al.*, 2016). Correlations between SST anomalies and extreme climate indices were calculated using Pearson's correlation coefficient (SANTOS; MELO; BRITO, 2016). The significance of these correlations was adjusted for autocorrelation effects by estimating the effective degrees of freedom (BRETHERTON *et al.*, 1999).

In addition, the probability density function (PDF) of the extreme climate indices was analyzed to assess shifts in the distributions of precipitation and temperature extremes over four decades: 1979–1988, 1989–1998, 1999–2008, and 2009–2020. The PDF method provides a non-parametric way to visualize changes in the frequency and intensity of extreme events across time, capturing shifts in both mean and variance (PAVLIDES; AGOU; HRISTOPULOS, 2022).

RESULTS

Tendências dos Índices de Extremos Climáticos

The IPCC-defined regions of South America (NSW, NSA, NES, SAM, SES, SWS, SSA) exhibit distinct patterns in precipitation and temperature extremes between 1979 and 2020 (Figure 3 and Figure 4). In the northwest of South America (NSW), there has been a significant decrease in extreme precipitation events. The number of days with heavy precipitation (R10mm) declined by 2.80 days/year, and very heavy precipitation (R20mm) fell by 1.62 days/year. Precipitation on very wet (R95p) and extremely wet (R99p) days also decreased by 37.51 mm/year and 11.91 mm/year, respectively (Figure 3). At the same time, the maximum temperature on the hottest day (TXx) showed a decreasing trend, while the coldest night (TNn) exhibited an increase, indicating a reduction in the diurnal temperature range (DTR) (Figure 4).

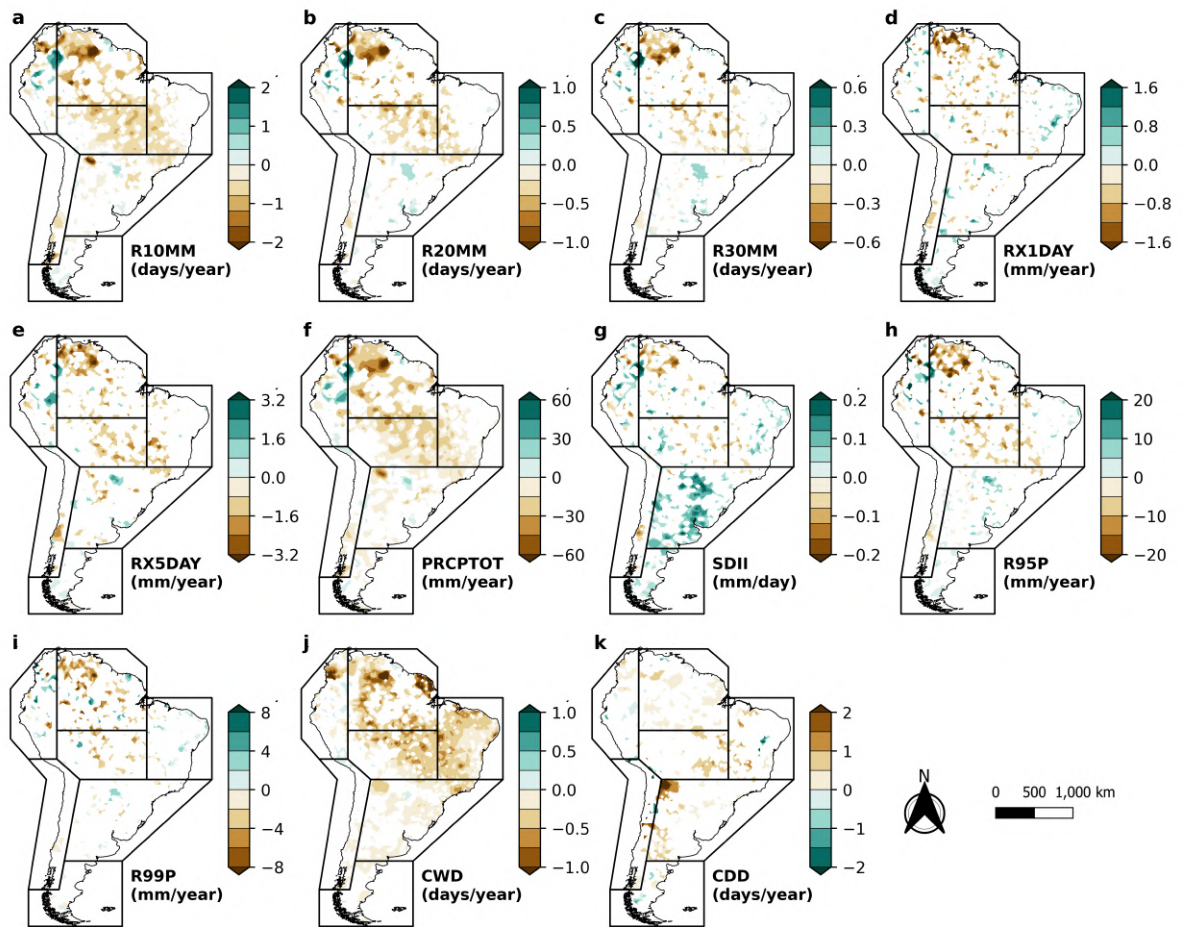


Figure 3: Spatial distribution of trends from 1979 to 2020: number of heavy precipitation days (R10mm) (a); number of very heavy precipitation days (R20mm) (b); number of days above 30 mm (R30mm) (c); max 1-day precipitation amount (Rx1day) (d); max 5-day precipitation amount (Rx5day) (e); annual total wet day precipitation (PRCPTOT) (f); simple daily intensity index (SDII) (g); precipitation on very wet days (R95p) (h); precipitation on extremely wet days (R99p) (i); consecutive wet days (CWD) (j); and consecutive dry days (CDD) (k) over the climate reference regions of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC—AR6) on South America. Only values with statistical significance at the 5% level are presented in the maps.

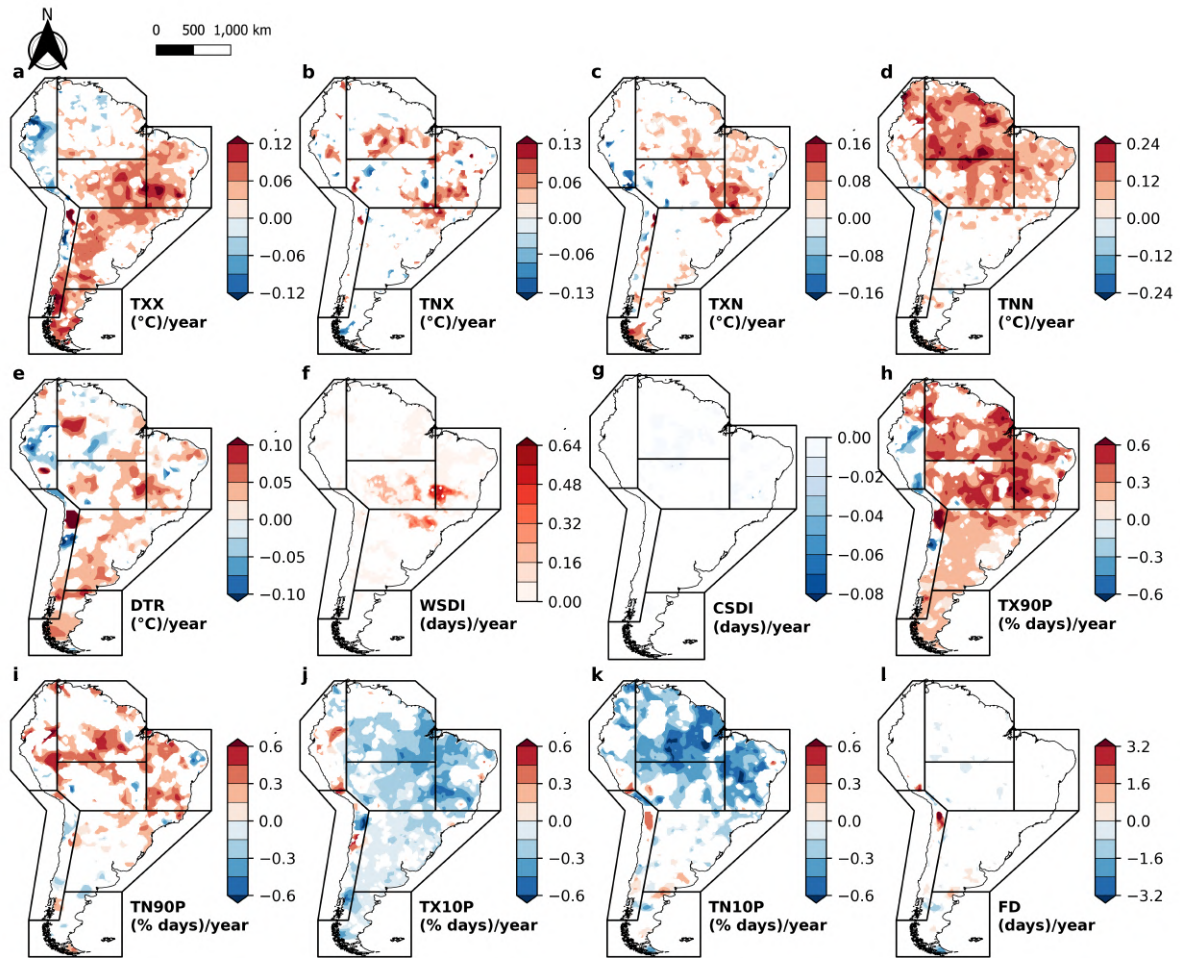


Figure 4: Spatial distribution of trends from 1979 to 2020: warmest day (TXx) (a); warmest night (TNx) (b); coldest day (TXn) (c); coldest night (TNn) (d); diurnal temperature Range (DTR) (e); warm spell duration (WSDI) (f); cold spell duration (CSDI) (g); warm days (TX90p) (h); warm nights (TN90p) (i); cool days (TX10p) (j); cool nights (TN10p) (k); and frost days (FD) (l) over the climate reference regions of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC—AR6) on South America. Only values with statistical significance at the 5% level are presented in the maps.

In northern South America (NSA), extreme precipitation indices also showed a marked decrease. The frequency of intense precipitation (R10mm and R20mm) dropped by 3.03 and 2.00 days/year, respectively, along with a significant reduction of 89 mm/year in total annual precipitation (PRCPTOT). However, the intensity of daily rainfall, as measured by the simple daily intensity index (SDII), showed a slight increase (Figure 3). In terms of temperatures, this region experienced an increase in both warm days (TX90p) and warm nights (TN90p), with corresponding decreases in cold days (TX10p) and cold nights (TN10p), indicating a general warming trend (Figure 4).

In northeast South America (NES), while some extreme precipitation indices showed negative trends, such as a reduction of 1.29 days/year for R10mm, the maximum one-day precipitation (RX1day) increased by 1.51 mm/year. The region also experienced a significant

reduction in consecutive wet days (CWD), contributing to longer dry spells (Figure 3). Regarding temperature, NES showed a marked increase in both warm days and warm nights, leading to more frequent and intense heat waves (WSDI). Cold events (TX10p, TN10p) became less frequent, suggesting that lower temperatures are becoming increasingly rare in this region (Figure 4).

The South American monsoon (SAM) region presented mixed results for precipitation extremes, with both positive and negative trends in daily rainfall intensity (SDII). However, there were clear reductions in total annual precipitation (PRCPTOT) and consecutive wet days (CWD), indicating an overall increase in dry extremes (Figure 3). Temperature extremes in SAM, on the other hand, showed consistent warming trends, with increased maximum and minimum temperatures, more frequent warm days and nights (TX90p, TN90p), and extended heat waves (WSDI) (Figure 4).

In southeastern South America (SES), the trends in extreme precipitation were characterized by high spatial variability. While some areas saw an increase in daily rainfall intensity (SDII), others experienced more frequent extreme precipitation events (R10mm, R20mm, R30mm) (Figure 3). Temperature trends pointed to a general increase in the frequency of heat waves and warm days, with TX90p and WSDI showing consistent upward trends. At the same time, the number of cold days (TX10p) showed a marked decrease (Figure 4).

In southwestern South America (SWS), the trends in precipitation extremes were relatively stable, with only slight increases in intense precipitation (R20mm) and daily rainfall intensity (SDII). However, the region saw the largest increase in consecutive dry days (CDD) across South America, averaging an additional 9.19 days/year (Figure 3). Temperature extremes showed a notable increase in both warm and cold extremes, with TX90p and frost days (FD) increasing significantly, indicating that SWS is sensitive to both hot and cold temperature extremes (Figure 4).

In southern South America (SSA), most precipitation indices exhibited negative trends, except for SDII, which showed a modest increase in daily rainfall intensity (Figure 3). This region experienced warming trends in maximum and minimum temperatures, with TXx and TX90p increasing. Frost days (FD) also showed a decreasing trend, suggesting that SSA is becoming more prone to heat extremes while experiencing fewer cold events (Figure 4).

Probability Density of Extreme Indices

The probability density function (PDF) analysis revealed significant changes in the distribution of extreme precipitation events over time. The number of heavy precipitation days

(R10mm, R20mm, R30mm) showed a leftward shift, indicating fewer days with intense rainfall in recent decades. For instance, R10mm averaged 40 days/year in the most recent decade (2009–2020), compared to previous decades (Figure 5). Similar trends were observed for maximum one-day (Rx1day) and five-day precipitation totals (Rx5day), which also showed a consistent reduction across time (Figure 5).

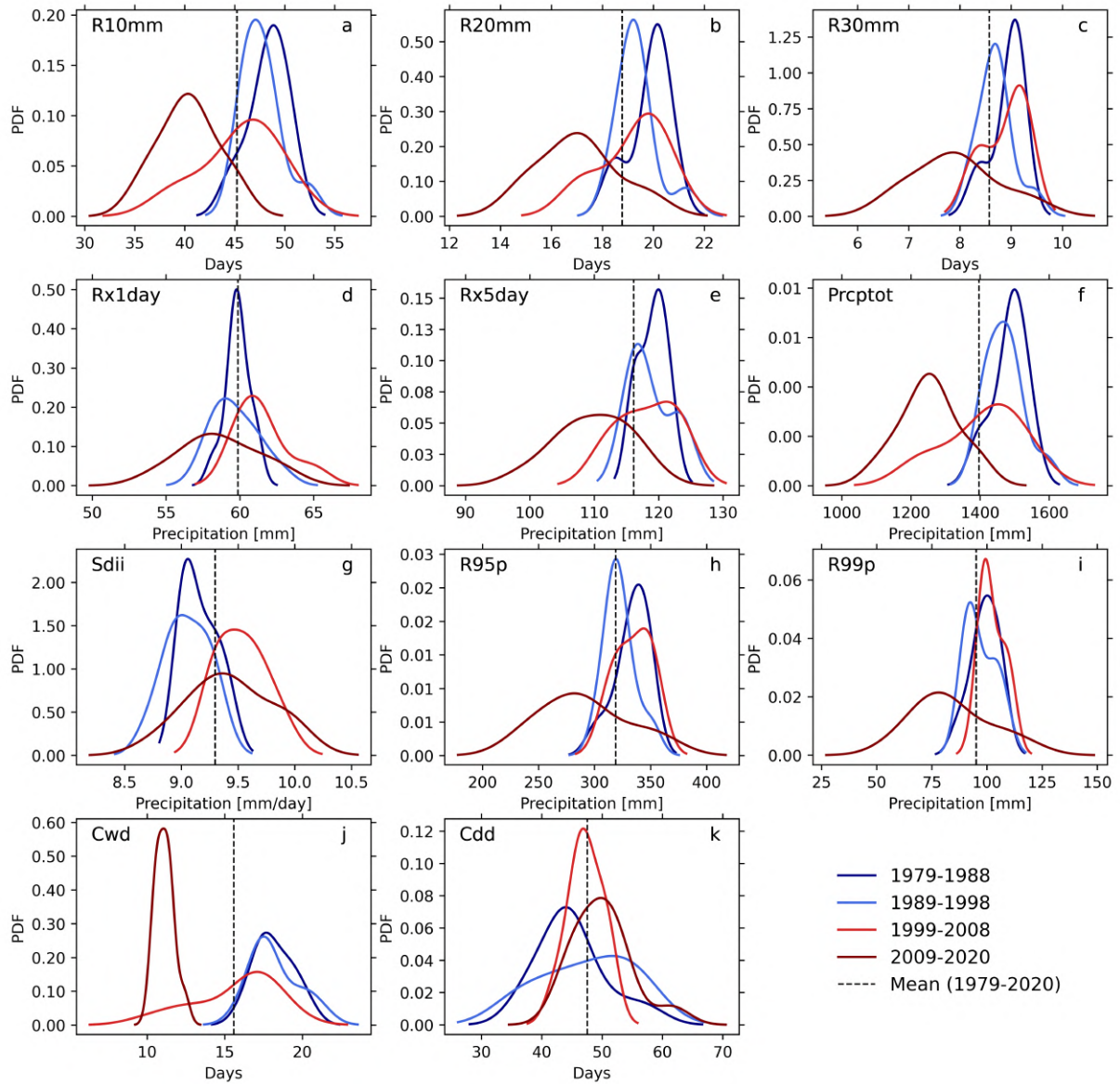


Figure 5: Probability density function (PDF) of the annual frequency of the following extreme precipitation indices over South America from 1979 to 2020: number of heavy precipitation days (R10mm) (a); number of very heavy precipitation days (R20mm) (b); number of days with precipitation above 50 mm (R50mm) (c); maximum 1-day precipitation amount (Rx1day) (d); maximum 5-day precipitation amount (Rx5day) (e); annual total wet-day precipitation (PRCPTOT) (f); simple daily intensity index (SDII) (g); precipitation on very wet days (R95p) (h); precipitation on extremely wet days (R99p) (i); consecutive wet days (CWD) (j); consecutive dry days (CDD) (k).

For temperature extremes, the PDFs of warmest day (TXx), coldest day (TXn), and coldest night (TNn) shifted rightward, indicating an overall increase in temperature extremes. The diurnal temperature range (DTR) also increased each decade, with a mean rise of 0.41 °C

between 1979 and 2020 (Figure 6). The warm spell duration index (WSDI) exhibited high variability, particularly in the SAM and NES regions, suggesting an increase in the duration of heat waves in these areas (Figure 6).

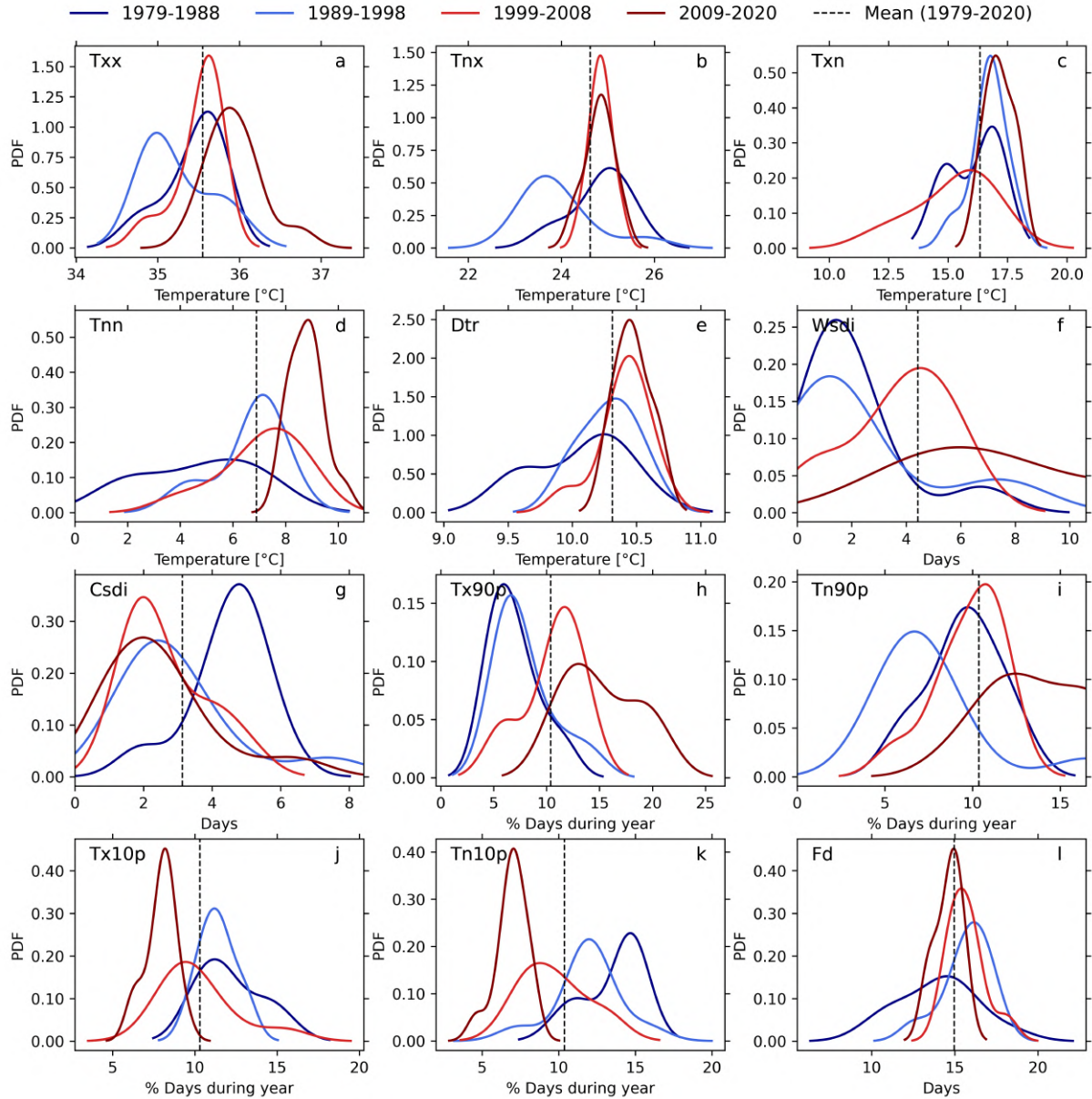


Figure 6: Probability density function (PDF) of the annual frequency of the following extreme temperature indices over South America from 1979 to 2020: warmest day (TXx) (a); warmest night (TNx) (b); coldest day (TXn) (c); coldest night (TNn) (d); diurnal temperature range (DTR) (e); warm spell duration (WSDI) (f); cold spell duration (CSDI) (g); warm days (TX90p) (h); warm nights (TN90p) (i); cool days (TX10p) (j); cool nights (TN10p) (k) and frost days (FD) (l).

Extremes Indices and Sea Surface Temperature (SST)

Extreme precipitation events across South America (SA) showed significant correlations with sea surface temperature (SST) anomalies, with correlation coefficients ranging from weak (0.3 to 0.49), to moderate (0.5 to 0.69), to strong (0.7 to 0.89). The spatial pattern of these correlations with the Niño 3.4 region was clearly defined (Figure 7), particularly

in the northern (NSA), northeastern (NES), and southeastern (SES) regions of the continent, where strong correlations were observed between Pacific SST anomalies and extreme precipitation events.

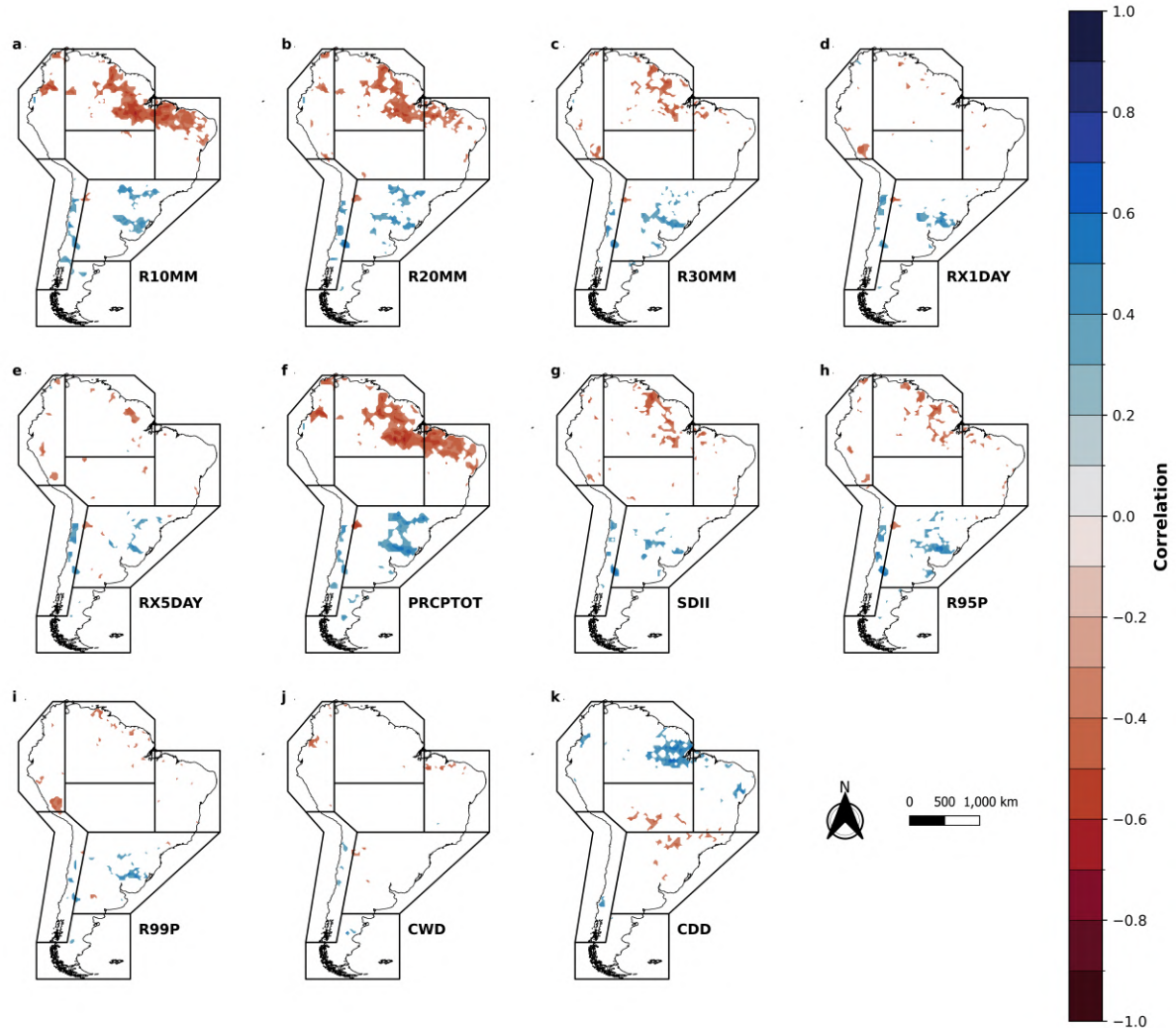


Figure 7: Pearson correlations between Pacific SST anomalies in the Niño 3.4 region and extreme precipitation indices: number of heavy precipitation days (R10mm) (a); number of very heavy precipitation days (R20mm) (b); number of days above 30 mm (R30mm) (c); max 1-day precipitation amount (Rx1day) (d); max 5-day precipitation amount (Rx5day) (e); annual total wet day precipitation (PRCPTOT) (f); simple daily intensity index (SDII) (g); precipitation on very wet days (R95p) (h); precipitation on extremely wet days (R99p) (i); consecutive wet days (CWD) (j); and consecutive dry days (CDD) (k) over the climate reference regions of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC—AR6) on South America from 1979 to 2020. Only values with statistical significance at the 5% level are presented in the maps.

Extreme precipitation events, such as intense rainfall days (R10mm, R20mm, R30mm) and total annual precipitation on wet days (PRCPTOT), showed strong correlations with Pacific SST anomalies. Notably, precipitation extremes were more pronounced during La Niña events, especially when combined with the negative phase of the Atlantic Dipole (Figure 7 and Figure 9). There were also some relationships with neutral climate phases, though these were less consistent. In the Atlantic Ocean, correlations between SST anomalies and precipitation

extremes exhibited notable spatial variability. Indices such as intense rainfall (R10mm), daily precipitation intensity (SDII), total annual precipitation (PRCPTOT), and consecutive dry (CDD) and wet (CWD) days varied in intensity across regions. The SDII index showed an inverse pattern, with moderate positive correlations across much of South America, reflecting the complex dynamics between rainfall extremes and SST fluctuations in the Atlantic Ocean (Figure 8).

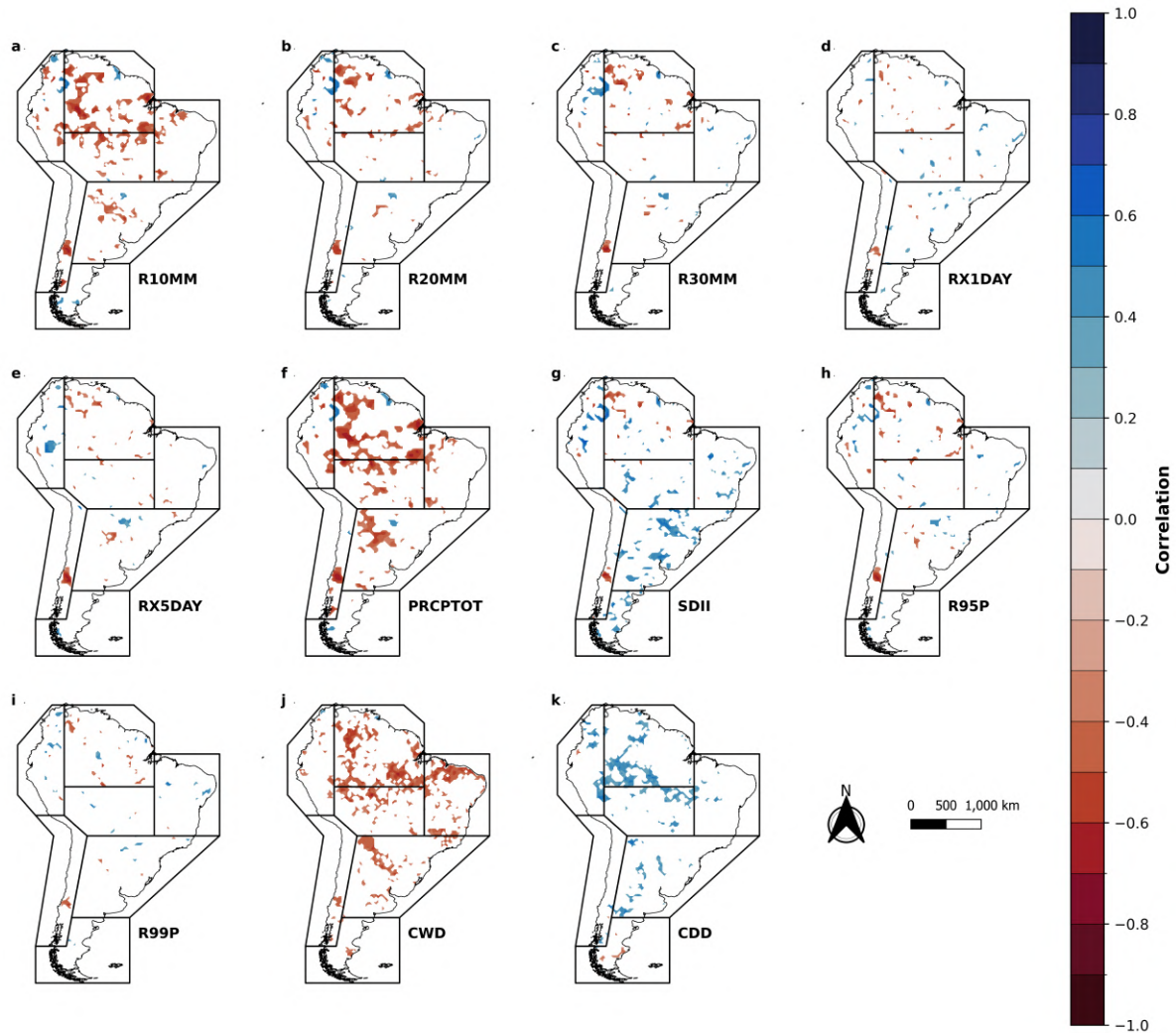


Figure 8: Pearson correlations between Atlantic SST anomalies in the Northern Atlantic Ocean (TNA) sector and extreme precipitation indices: number of heavy precipitation days (R10mm) (a); number of very heavy precipitation days (R20mm) (b); number of days above 30 mm (R30mm) (c); max 1-day precipitation amount (Rx1day) (d); max 5-day precipitation amount (Rx5day) (e); annual total wet day precipitation (PRCPTOT) (f); simple daily intensity index (SDII) (g); precipitation on very wet days (R95p) (h); precipitation on extremely wet days (R99p) (i); consecutive wet days (CWD) (j); and consecutive dry days (CDD) (k) over the climate reference regions of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC—AR6) on South America from 1979 to 2020. Only values with statistical significance at the 5% level are presented in the maps.

In general, extreme precipitation indices reached their highest and lowest values during simultaneous ENSO and Atlantic Dipole events, although some also occurred during neutral SST phases. Specifically, indices such as R10mm, R20mm, R30mm, RX5day, R95p, CWD,

and PRCPTOT exhibited their maximum values during La Niña events combined with the negative phase of the Atlantic Dipole. On the other hand, SDII increased during La Niña events associated with the positive phase of the Atlantic Dipole (Figure 9).

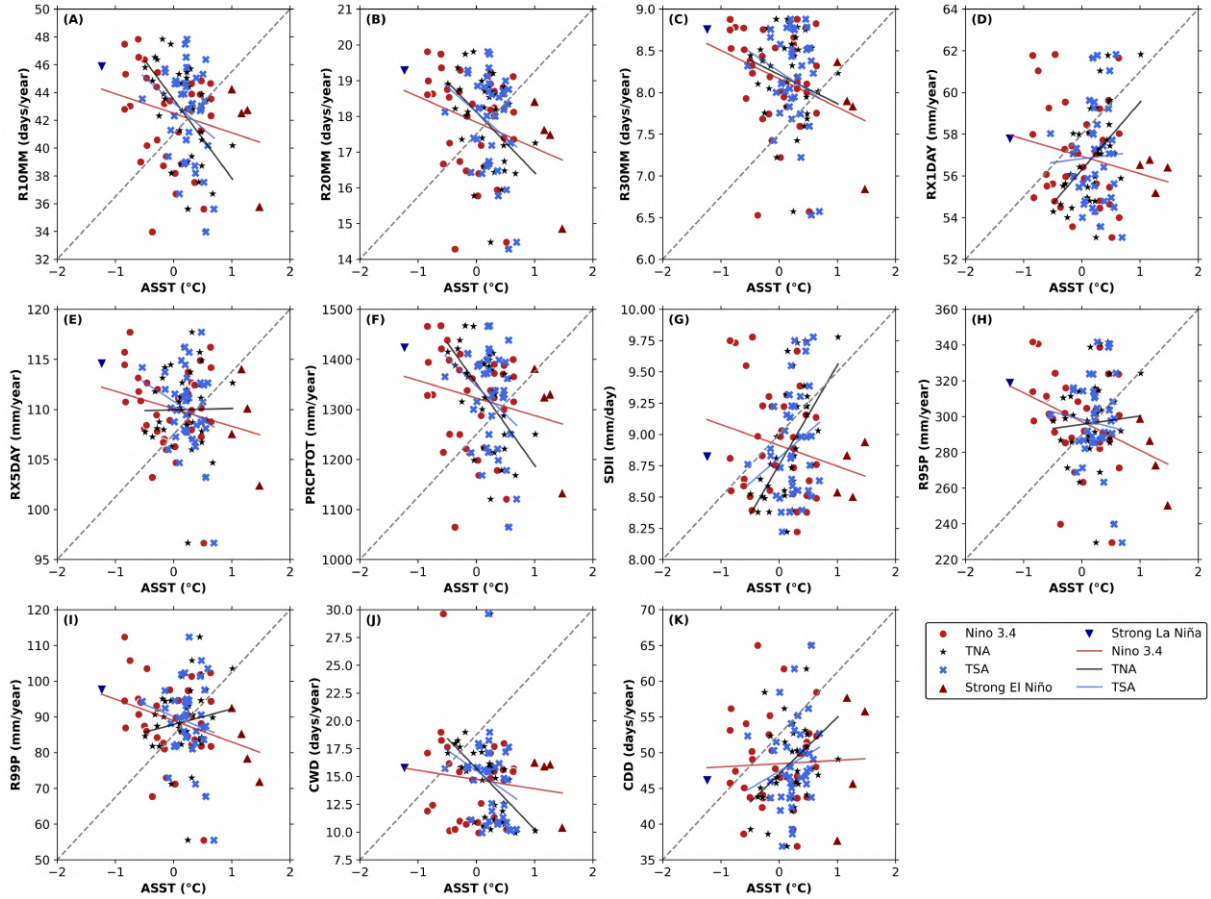


Figure 9: Relationship between sea surface temperature (SST) anomalies in the Pacific Ocean (Niño 3.4), Northern and Southern Atlantic Ocean sectors (TNA) (TSA), and extreme climate precipitation indices: number of heavy precipitation days (R10mm) (A); number of very heavy precipitation days (R20mm) (B); number of days above 30 mm (R30mm) (C); max 1-day precipitation amount (Rx1day) (D); max 5-day precipitation amount (Rx5day) (E); annual total wet day precipitation (PRCPTOT) (F); simple daily intensity index (SDII) (G); precipitation on very wet days (R95p) (H); precipitation on extremely wet days (R99p) (I); consecutive wet days (CWD) (J); and consecutive dry days (CDD) (K) over South America from 1979 to 2020.

In contrast, extreme precipitation indices tended to decrease during neutral SST periods and El Niño events, regardless of the Atlantic Dipole phase. This suggests a potential inhibition of extreme precipitation under these conditions. Minimum values for R10mm, R20mm, R30mm, and PRCPTOT were observed during years of Pacific SST neutrality combined with the negative phase of the Atlantic Dipole. Additionally, SDII decreased during periods of Pacific SST neutrality and a positive Atlantic Dipole. Frequency and intensity indices, such as R95p and R99p, also recorded reduced values during El Niño events associated with a positive Atlantic Dipole phase (Figure 9).

It is important to note that regional responses to El Niño, La Niña, and Atlantic Dipole events vary, with different degrees of association. Generally, extreme precipitation indices

reached their highest values during La Niña events coinciding with a negative Dipole phase. However, several indices also reached their maximum values during Pacific SST neutrality years. In contrast, minimum values were more frequent during climate neutrality periods, covering a large part of the regions. The pattern of maximum and minimum values of extreme indices generally followed the trend of correlations with SST anomalies.

The correlations between temperature extremes and SST anomalies in the Pacific and Atlantic Oceans were also significant, with correlation strengths ranging from weak (± 0.20 to ± 0.39) to moderate (± 0.40 to ± 0.69) and strong (± 0.70 to ± 0.89). In the Pacific (Niño 3.4 region), no clear spatial pattern emerged for temperature extremes (Figure 10). The hottest day (TXx) exhibited strong positive correlations in the northeast (NES), while a negative trend was observed in the southeast (SES) (Figure 10a). The coldest day (TXn) and coldest night (TNn) also showed spatial patterns similar to those of SST anomalies in the Niño 3.4 region, with higher positive correlations in SES and SAM, and considerable spatial variability in these regions (Figure 10c and Figure 11d).

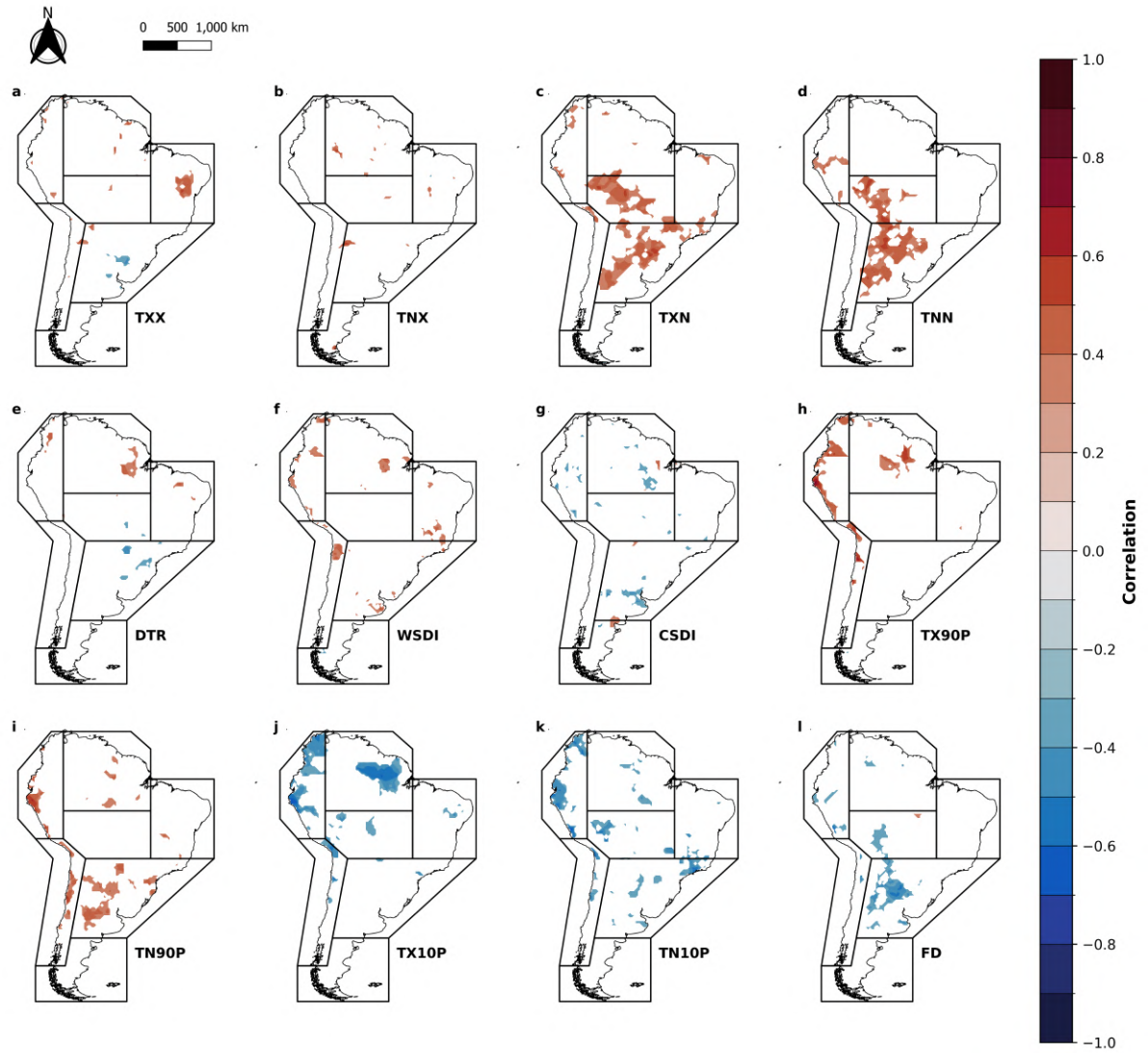


Figure 10: Pearson correlation between sea surface temperature (SST) anomalies in the Pacific Ocean over the Niño 3.4 region and extreme climatic temperature indices: warmest day (TXx) (a); warmest night (TNx) (b); coldest day (TXn) (c); coldest night (TNn) (d); diurnal temperature Range (DTR) (e); warm spell duration (WSDI) (f); cold spell duration (CSDI) (g); warm days (TX90p) (h); warm nights (TN90p) (i); cool days (TX10p) (j); cool nights (TN10p) (k); and frost days (FD) (l) over the climate reference regions of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC—AR6) on South America from 1979 to 2020. Only values with statistical significance at the 5% level are presented in the maps.

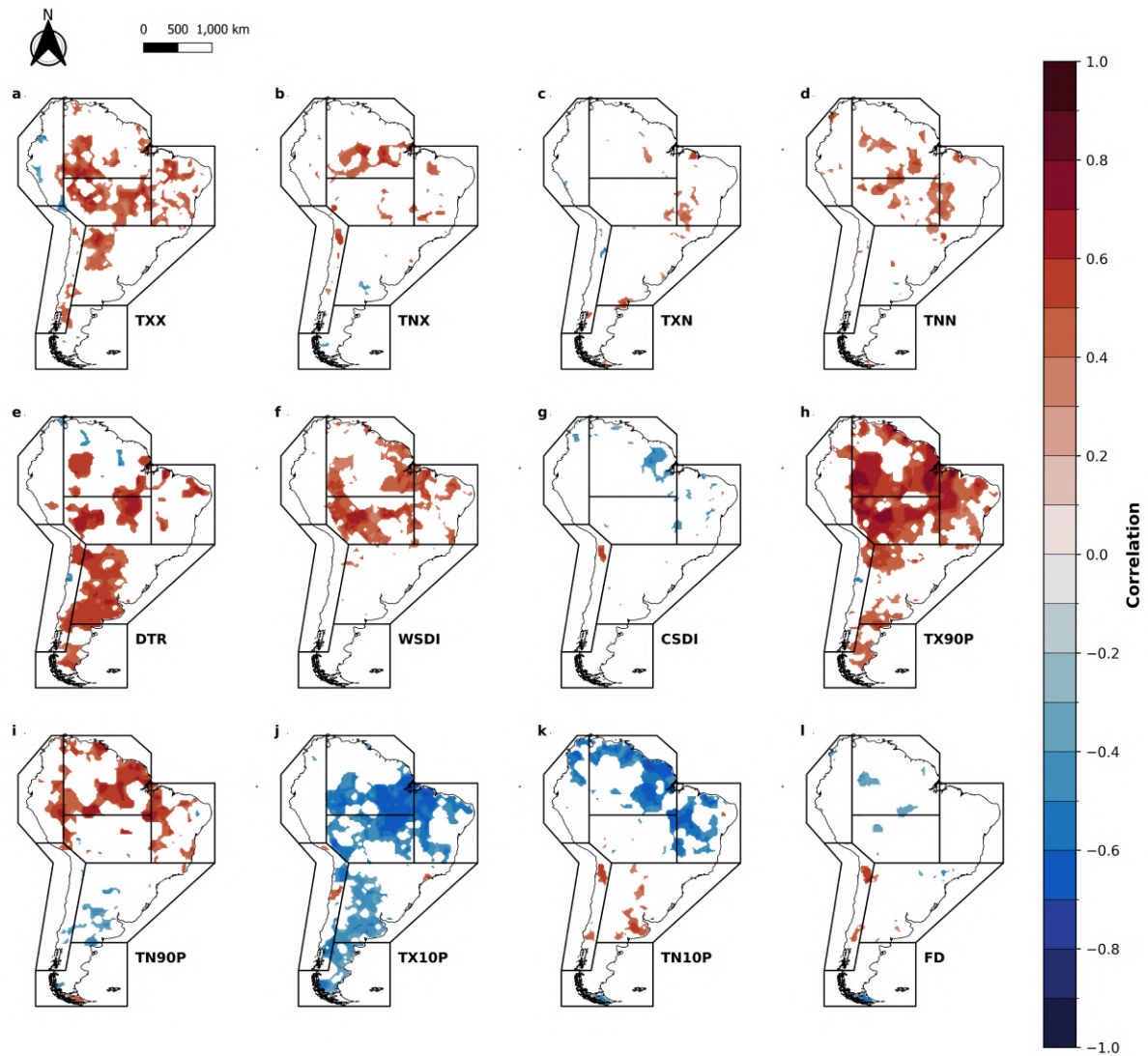


Figure 11: Pearson correlation coefficients between sea surface temperature (SST) anomalies in the Northern Atlantic Ocean (TNA) sector and extreme climatic temperature indices: warmest day (TXx) (a); warmest night (TNx) (b); coldest day (TXn) (c); coldest night (TNn) (d); diurnal temperature Range (DTR) (e); warm spell duration (WSDI) (f); cold spell duration (CSDI) (g); warm days (TX90p) (h); warm nights (TN90p) (i); cool days (TX10p) (j); cool nights (TN10p) (k); and frost days (FD) (l) over the climate reference regions of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC—AR6) on South America from 1979 to 2020. Only values with statistical significance at the 5% level are presented in the maps.

In the Northern Atlantic (TNA), the correlations between temperature extremes and SST anomalies displayed significant spatial variability, extending from the north to the south of SA (Figure 11). The hottest day (TXx) showed moderate positive correlations across much of the NSA, SAM, and NES sectors (Figure 11a). Similarly, the diurnal temperature range (DTR) displayed strong positive correlations in NES and SAM, with moderate correlations in other parts of SA (Figure 11e). Heatwave duration (WSDI) was strongly positively correlated with TNA, particularly over the monsoon region (SAM), with more moderate correlations observed in the NES and NSA regions (Figure 11f).

Extreme hot and cold days (TX90p and TX10p) followed similar spatial patterns, though with inverse magnitudes. Hot days (TX90p) were strongly positively correlated with SST anomalies in the Northern Atlantic (TNA) across NES, SAM, and NSA, while cold days (TX10p) showed negative correlations in these regions (Figure 11h,j). Warm and cold nights (TN90p and TN10p) also correlated with TNA, showing similar spatial distributions but with opposite signs. Warm nights (TN90p) were positively correlated in SAM, NSA, and NWS, while cold nights (TN10p) showed strong negative correlations in NES and NSA (Figure 11i,k).

In summary, hot extremes, such as TX90p and TN90p, reached their highest values in the northern regions of South America (NSW, NSA, NES) during strong El Niño events, regardless of the Atlantic Dipole phase (Figure 12). Cold extremes were more pronounced during La Niña events combined with the negative phase of the Dipole, particularly in NSA and NWS. However, many hot and cold extremes also reached their maximum values during neutral climate periods, spanning both the north and south of South America.

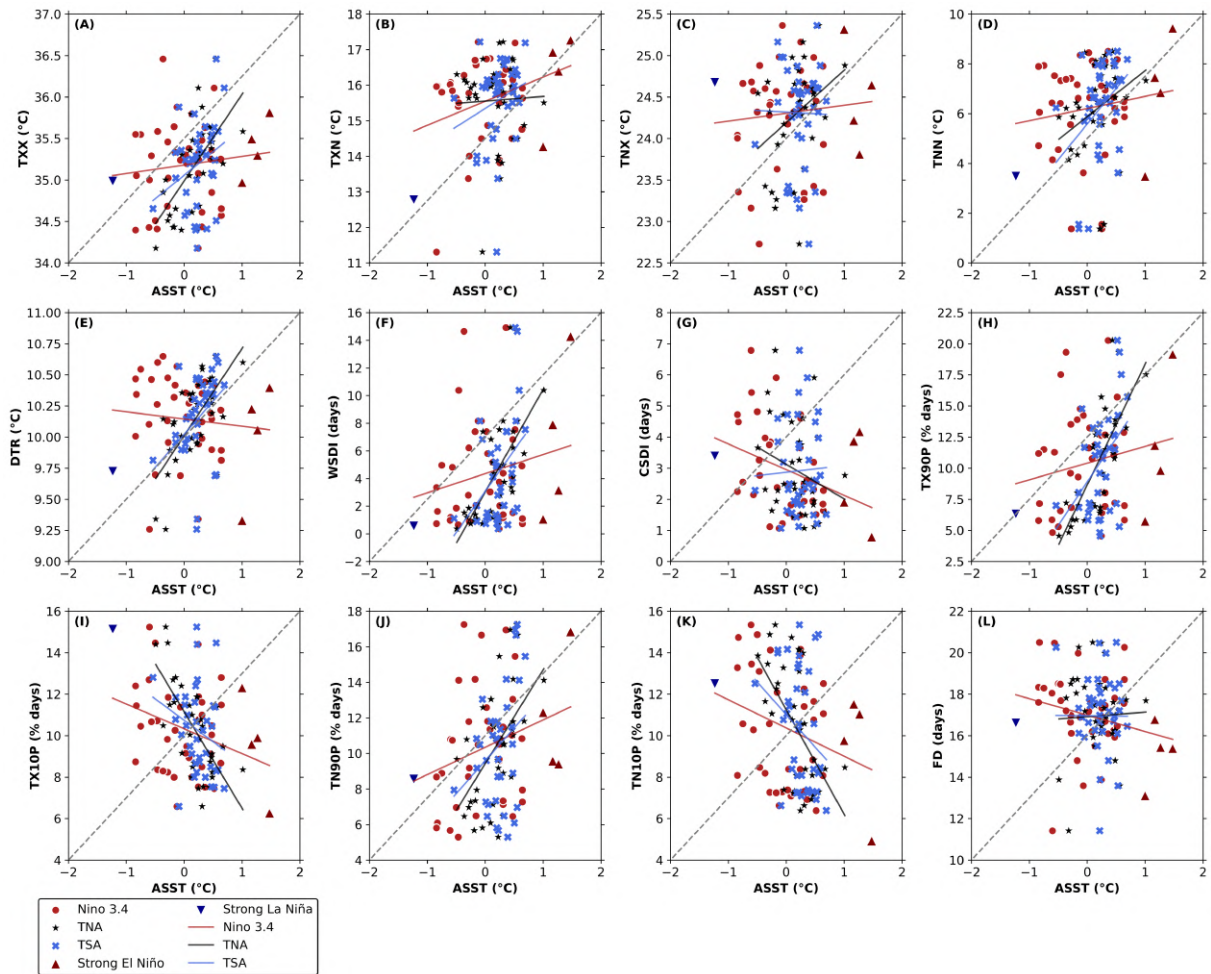


Figure 12: Relationship between sea surface temperature (SST) anomalies in the Pacific Ocean (Niño 3.4), Northern and Southern Atlantic Ocean sectors (TNA) (TSA), and extreme climate temperature indices: warmest day (TXx) (A); warmest night (TNx) (B); coldest day (TXn) (C); coldest night (TNn) (D); diurnal temperature Range (DTR) (E); warm spell duration (WSDI) (F); cold spell duration (CSDI) (G); warm days (TX90p) (H);

warm nights (TN90p) (**I**); cool days (TX10p) (**J**); cool nights (TN10p) (**K**); and frost days (FD) (**L**) over South America from 1979 to 2020.

DISCUSSIONS

Precipitation and Temperature Extremes Trends

South America has experienced significant shifts in its precipitation patterns, with some regions facing prolonged droughts while others endure more intense rainfall and floods (MORALES *et al.*, 2020). These changes are influenced by both natural climate variability and human activities. Overall, there has been a decline in total annual precipitation (PRCPTOT) and a reduction in the number of days with heavy rainfall (R10mm, R20mm, and R30mm) across many areas of the continent. However, some regions, particularly in southeastern South America (SES) and parts of the Amazon (NSA and NWS), have seen an increase in extreme precipitation events. Additionally, there is a widespread increase in daily precipitation intensity (SDII), suggesting a shift towards fewer but more intense rainfall events (Figure 3). This variability in precipitation extremes is consistent with the findings from the IPCC AR6 (CASTELLANOS; LEMOS, 2022).

The observed increase in daily precipitation intensity in regions such as the northwest (NWS), northeast (NES), and southeast (SES) of South America indicates a growing risk of extreme rainfall events, including those with rainfall amounts exceeding the 95th and 99th percentiles (R95p, R99p). These changes, coupled with the sharp decline in consecutive wet days (CWD) and the rise in consecutive dry days (CDD), signal a regional trend toward more pronounced dry spells and shorter, but more intense, periods of rainfall. This pattern heightens the risk of floods and landslides in some areas while increasing drought-related challenges in others.

Regarding temperature extremes, data reveal a clear and widespread warming trend across South America. There has been a consistent increase in the frequency and duration of heat extremes, such as warm days (TX90p) and warm nights (TN90p), alongside a significant reduction in cold events (TX10p, TN10p). The rise in both maximum and minimum temperatures has expanded the diurnal temperature range (DTR), particularly in the southern regions (SES, SSA) and parts of the northeast (NES), where the trend in maximum temperatures is more pronounced. Conversely, in the northern and central regions, the increase in minimum temperatures has been greater, highlighting regional differences in warming patterns ([Figure 4](#)). The rise in heat waves, as indicated by the warm spell duration index (WSDI), is particularly notable in the monsoon region (SAM), northeast (NES), and southeast (SES), where heat waves

are becoming more frequent and prolonged. Cold spell duration (CSDI), on the other hand, showed little spatial variability, indicating that cold extremes are becoming increasingly rare across the continent.

Land use changes, particularly deforestation in the Amazon and other biomes, may be contributing to these shifts in precipitation and temperature extremes. These changes alter regional climate patterns by affecting the water and energy balance, influencing rainfall distribution, and intensifying temperature extremes (JIN *et al.*, 2021). The loss of forest cover reduces moisture recycling and modifies atmospheric circulation patterns, which can exacerbate drought conditions in the Amazon and increase the frequency of extreme heat events (SALAZAR *et al.*, 2015). This highlights the need for integrated land management strategies to mitigate the compounding effects of land use change and climate variability on extreme weather events (BIUDES *et al.*, 2022a; DOS SANTOS *et al.*, 2022).

Changes in extreme precipitation patterns are closely linked to variations in global mean surface temperature. The concentration of atmospheric water vapor, which supplies the water for precipitation, increases in proportion to the saturation concentrations at a rate of about 6–7% per degree rise in temperature according to the thermodynamic Clausius–Clapeyron relationship (WESTRA; ALEXANDER; ZWIERS, 2013; TABARI, 2020). However, these changes in precipitation extremes are also influenced by regional factors such as land use changes, vegetation cover, aerosol emissions, and greenhouse gases. These factors can produce non-local or regionally variable effects, contributing to uncertainties when comparing changes driven by regional processes versus those driven by global thermodynamic forces (PAIK *et al.*, 2020).

Deforestation in the Amazon Basin over recent decades has had significant implications for regional atmospheric circulation and moisture transport (RUIZ-VÁSQUEZ *et al.*, 2020). During the boreal summer, a weakening of the northward moisture flux has been observed, while in the austral summer, this flux strengthens toward the south. These changes affect water vapor advection, reducing humidity and moisture recycling in regions such as the western Amazon and the Amazon-Andean transition area (Peru, Bolivia, and Ecuador) (SIERRA *et al.*, 2022). The reduction in moisture recycling, combined with the intensification of upward air motion caused by deforestation, can redistribute and decrease total rainfall in the region. This contributes to more frequent and severe droughts in the south-central Amazon (MU; BIGGS; JONES, 2023).

Shifts in precipitation and temperature extremes have significant impacts on ecological and human systems. If unaddressed, heavy rainfall can lead to floods and landslides, which are

already occurring in some regions of South America. Longer droughts can lead to aridification, causing hydrological, agricultural, and ecological droughts, and increasing the risk of wildfires. Extreme heat also poses health risks, such as increased mortality, disease outbreaks, and higher energy demand, all of which have implications for urban planning and public health systems (DOS SANTOS *et al.*, 2022).

Precipitation and Temperature Extremes and SST Anomalies

Accurate predictions of climate impacts—such as heat waves, frosts, floods, and droughts—are critical for assessing risks to human society and ecosystems. These predictions help improve our understanding of climate impacts and are influenced by several factors, including teleconnections, which refer to relationships between sea surface temperature (SST) anomalies in different regions of the world.

SST anomalies in the Pacific and Atlantic Oceans have both positively and negatively influenced precipitation extremes (R10mm, R20mm, PRCPTOT, SDII, CWD, and CDD) and temperature extremes (TXx, TNn, TX90p, TX10p, TN90p, TN10p, WSDI, and DTR) across large parts of South America. The most pronounced effects of SST anomalies on precipitation extremes were observed in the northern and southern regions of South America, while the central region showed no significant relationship. This lack of correlation in the central region may result from an indirect influence, as ENSO events alter atmospheric systems that affect precipitation patterns.

El Niño events significantly impact atmospheric circulation at multiple levels, leading to either the weakening or strengthening of weather systems, which in turn affects regional and local climate conditions (TEDESCHI; CAVALCANTI; GRIMM, 2013). In the upper atmosphere (200 hPa), El Niño weakens the Bolivian High (BH), a key weather system in the region, during the December-January-February (DJF) period (Figure 14a,b). The BH forms due to intense surface heating over the Bolivian Altiplano, resulting in the formation of convective clouds that generate heavy rainfall (MESEGUER-RUIZ *et al.*, 2020). However, during El Niño, this system weakens, which reduces rainfall over the Amazon Basin (JUNQUAS *et al.*, 2018). When the BH is properly configured, it plays a crucial role in transporting moisture and sustaining precipitation in the Amazon (SEGURA *et al.*, 2019).

Additionally, during intense El Niño events, the jet stream over southern South America intensifies at upper levels (200 hPa), which can block the passage of weather systems like cold fronts over Central Brazil and the southern Amazon. This often leads to drought conditions and more frequent extreme heat events in these regions (MONTINI; JONES; CARVALHO, 2019b).

Furthermore, the trough along the northeastern coast of South America shifts deeper over the South Atlantic during El Niño (Figure 13a,b). This shift is associated with high-pressure systems at lower levels that inhibit convective cloud formation, contributing to droughts in northeast South America (NES) (DE MORAIS; GAN; YOSHIDA, 2021).

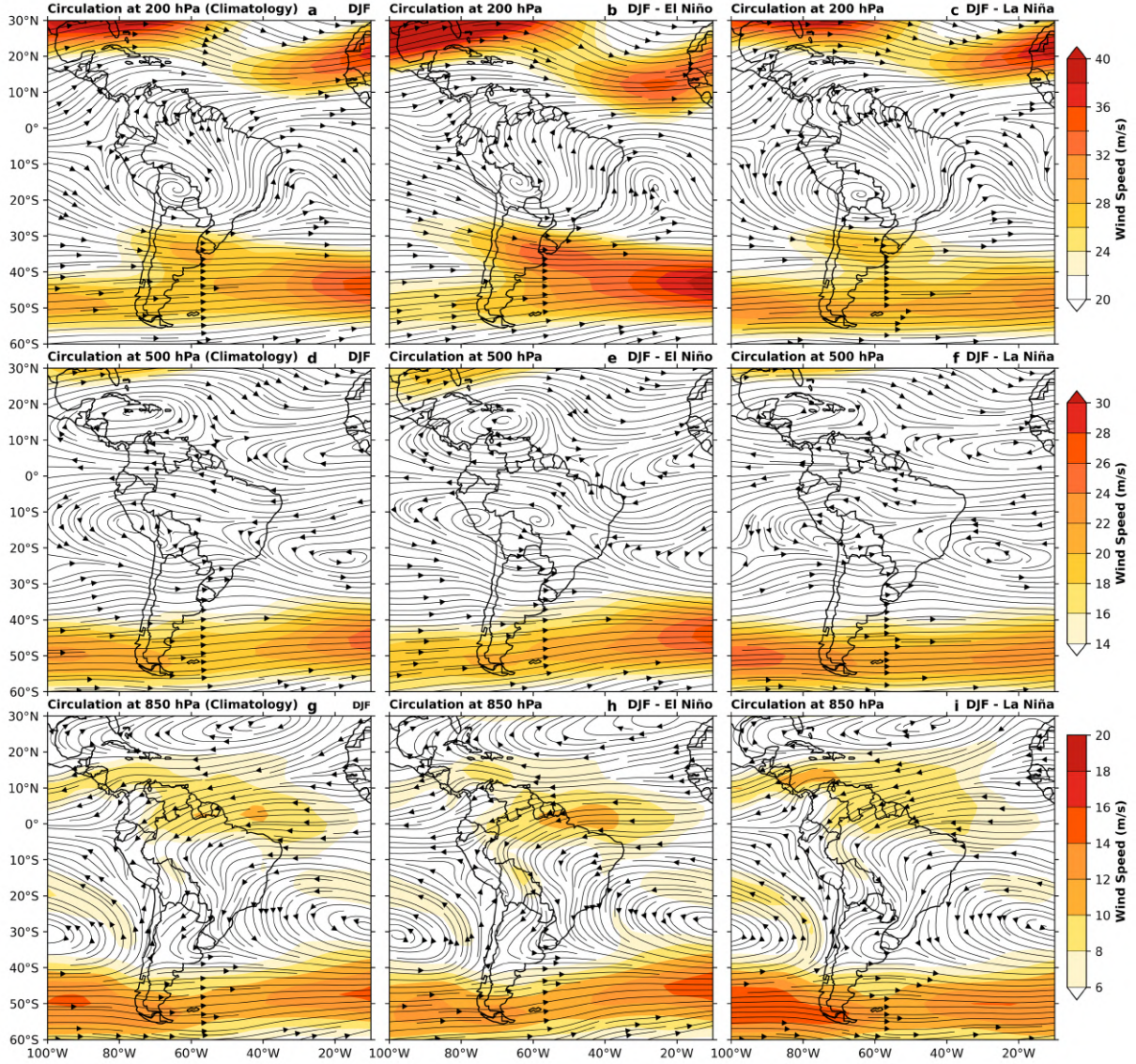


Figure 13: Atmospheric circulation climatology (**a,d,g**) and observed atmospheric circulation under El Niño (**b,e,h**) and La Niña (**c,f,i**) conditions at pressure levels of 200 hPa, 500 hPa, and 850 hPa, respectively, over South America. The shaded region represents wind speed in m s^{-1} . The climatology period is from 1981 to 2010, while the observed data refers to the mean composites of the intense El Niño events in 1982–1983, 1997–1998, and 2015–2016, and La Niña in 1988–1989, 1999–2000, and 2010–2011 in the December–January–February (DJF) quarter.

At mid-level (500 hPa), the semi-permanent South Atlantic High (SASH) usually remains well-defined (Figure 13c). However, during El Niño and when SSTs are warmer in the South Atlantic, this system weakens, allowing subtropical jets near southern Brazil to intensify (Figure 13d). This atmospheric change favors extreme rainfall in southern Brazil, where SASH

typically acts as a barrier to precipitation (WAINER *et al.*, 2021b). At surface levels (850 hPa), SASH maintains its climatological position between 20 °S and 40 °S but shows a slight increase in activity during El Niño, which can enhance moisture transport and increase rainfall in southern Brazil (Figure 13f).

In contrast, La Niña episodes exhibit opposite climate patterns (MCPHADEN; SANTOSO; CAI, 2020). During La Niña, the Bolivian High intensifies and shifts westward toward the Pacific coast (Figure 13c), encouraging the formation of convective clouds and promoting heavy precipitation (GARREAUD, 2009). At upper levels, subtropical jets over southern Brazil weaken, allowing cold fronts to move into the region more easily, leading to temperature extremes (MARENGO *et al.*, 2012). At mid-levels, the semi-permanent South Atlantic High (SASH) moves inland, increasing the likelihood of drought in southeastern South America (Figure 13f). Additionally, La Niña tends to reduce wind intensity along the northern coast of eastern Amazonia, potentially limiting the inflow of moisture from the Atlantic Ocean into the interior, although this does not necessarily imply drier conditions (Figure 13i).

During La Niña in the June-July-August (JJA) period, an anomalous wind divergence pattern appears at upper levels (200 hPa) over the northern Amazon and northeastern South America (Figure 14a,c). This pattern strengthens surface wind convergence, promoting the formation of convective clouds and increasing rainfall (MARENGO *et al.*, 2012). At mid-levels (500 hPa), the semi-permanent South Atlantic High (SASH) is positioned over the continent during both El Niño and La Niña events (Figure 15e,f). During JJA, SASH prevents polar cold air masses from reaching northern South America, maintaining drier and sunnier conditions in the subtropical region (LEE *et al.*, 2013). At surface levels (850 hPa), during La Niña, the SASH center moves closer to the coast, with intensified circulation extending from the southeast to the southern Amazon (Figure 14i). A strong trough over central-southern Brazil also reinforces subsidence, leading to negative precipitation anomalies and higher temperatures in the region.

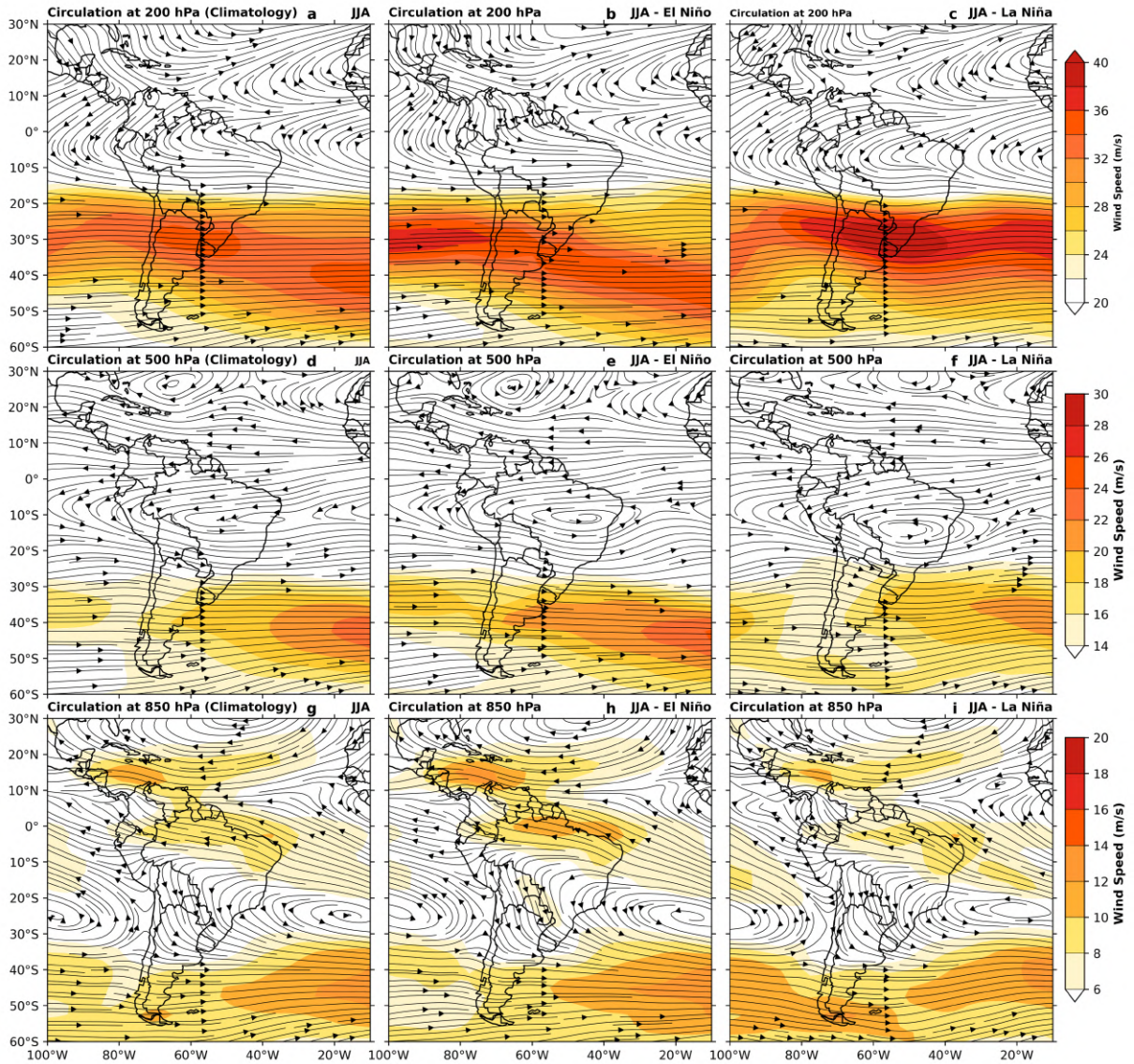


Figure 14: Atmospheric circulation climatology (**a,d,g**) and observed atmospheric circulation under El Niño (**b,e,h**) and La Niña (**c,f,i**) conditions at pressure levels of 200 hPa, 500 hPa, and 850 hPa, respectively, over South America. The shaded region represents wind speed in m s^{-1} . The climatology period is from 1981 to 2010, while the observed data refers to the mean composites of the intense El Niño events in 1982–1983, 1997–1998, and

2015–2016 and La Niña in 1988–1989, 1999–2000, and 2010–2011 in the June–July–August (JJA) quarter.

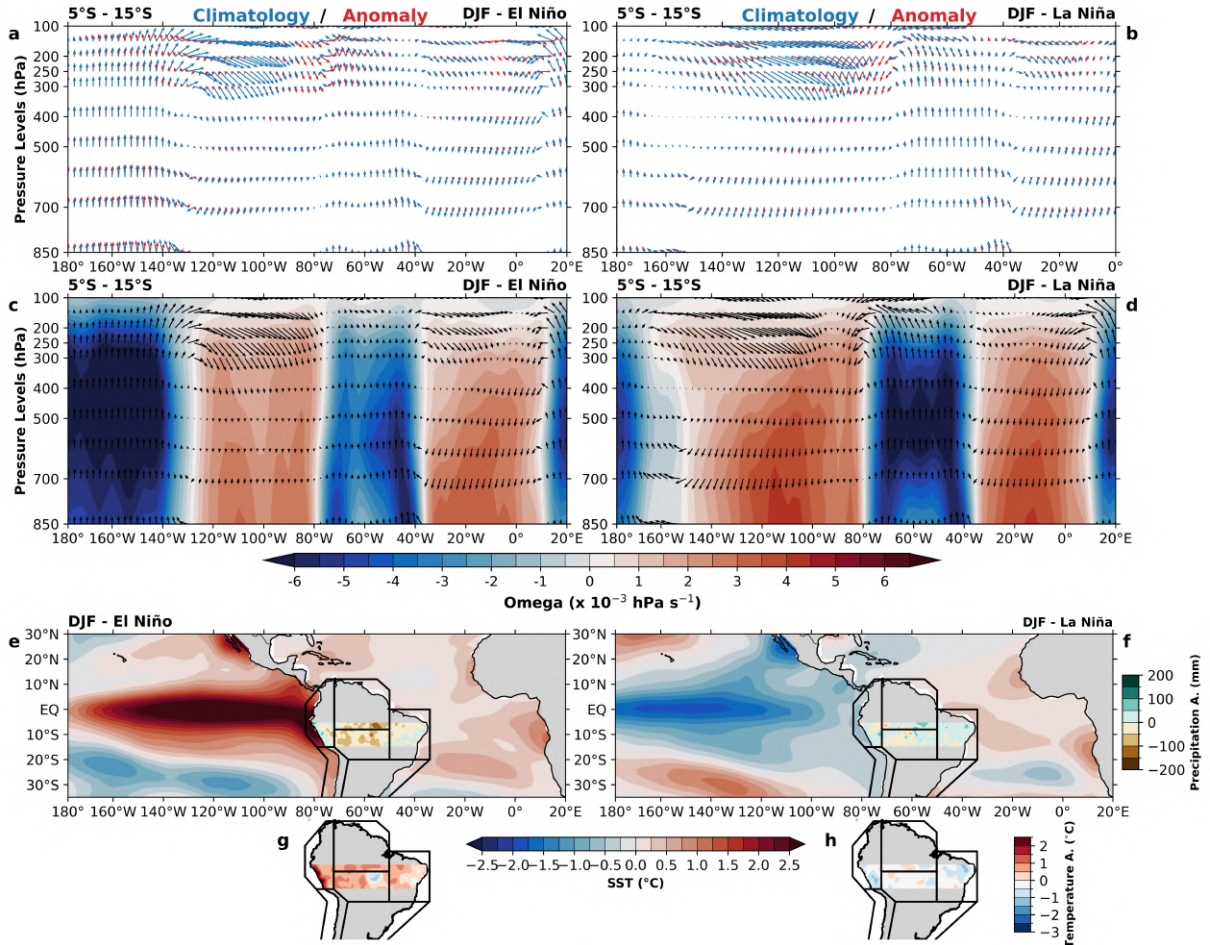


Figure 15: Climatology (blue vectors) and anomaly (red vectors) of vertical wind velocity between 5°S and 15°S during El Niño (a) and La Niña (b) events in the December-January-February (DJF) quarter. (c,d) Vertical wind speed (filled contours) and wind direction (arrows) between 5°S and 15°S during El Niño (c) and La Niña (d) events in the DJF quarter. (e,f) Sea surface temperature (SST) anomalies and precipitation anomalies over the continent between 5°S and 15°S during El Niño (e) and La Niña (f) events in the DJF quarter. (g,h) Air temperature anomalies over the continent between 5°S and 15°S during El Niño (g) and La Niña (h) events in the DJF quarter. Data correspond to the composite averages of El Niño (1982–1983, 1997–1998, and 2015–2016) and La Niña (1988–1989, 1999–2000, and 2010–2011) events in the DJF quarter.

El Niño weakens upward vertical motion in the region between 5°S and 15°S, enhancing subsidence and causing negative precipitation anomalies and higher temperatures (Figure 15a,c,e,g). During La Niña, vertical motion intensifies, favoring deep convection and leading to above-average rainfall (Figure 15b,d,f,h). However, La Niña may also result in negative precipitation anomalies in central and western regions, linked to stronger subsidence at higher levels, which limits deep convection and reduces rainfall.

A clear relationship emerges between vertical motion patterns (omega) and precipitation and temperature anomalies during ENSO phases in northern and southern South America. El Niño is generally associated with negative precipitation anomalies in the north and positive anomalies in the south, while La Niña exhibits the opposite pattern (REHBEIN; AMBRIZZI, 2023). ENSO profoundly influences South America's climate by modulating a complex array

of meteorological processes, including coastal convection, Walker circulation variations, and atmospheric circulation anomalies associated with the Rossby wave train (CAI *et al.*, 2020b).

During the JJA season, the Walker cell showed a pattern of descending vertical motion in the region between 5 °S and 15 °S, even during El Niño events (Figure 16a,c). This downward motion likely suppressed deep convection and cloud formation, leading to negative precipitation anomalies, although these anomalies were relatively small in magnitude (Figure 16e). In contrast, positive air temperature anomalies were observed (Figure 16g). During La Niña, a similar descending vertical motion pattern was observed in the same region (Figure 16b,d), influencing both precipitation and air temperature anomalies. However, it is important to note that the magnitudes of these anomalies during La Niña were closer to normal (Figure 16f,h).

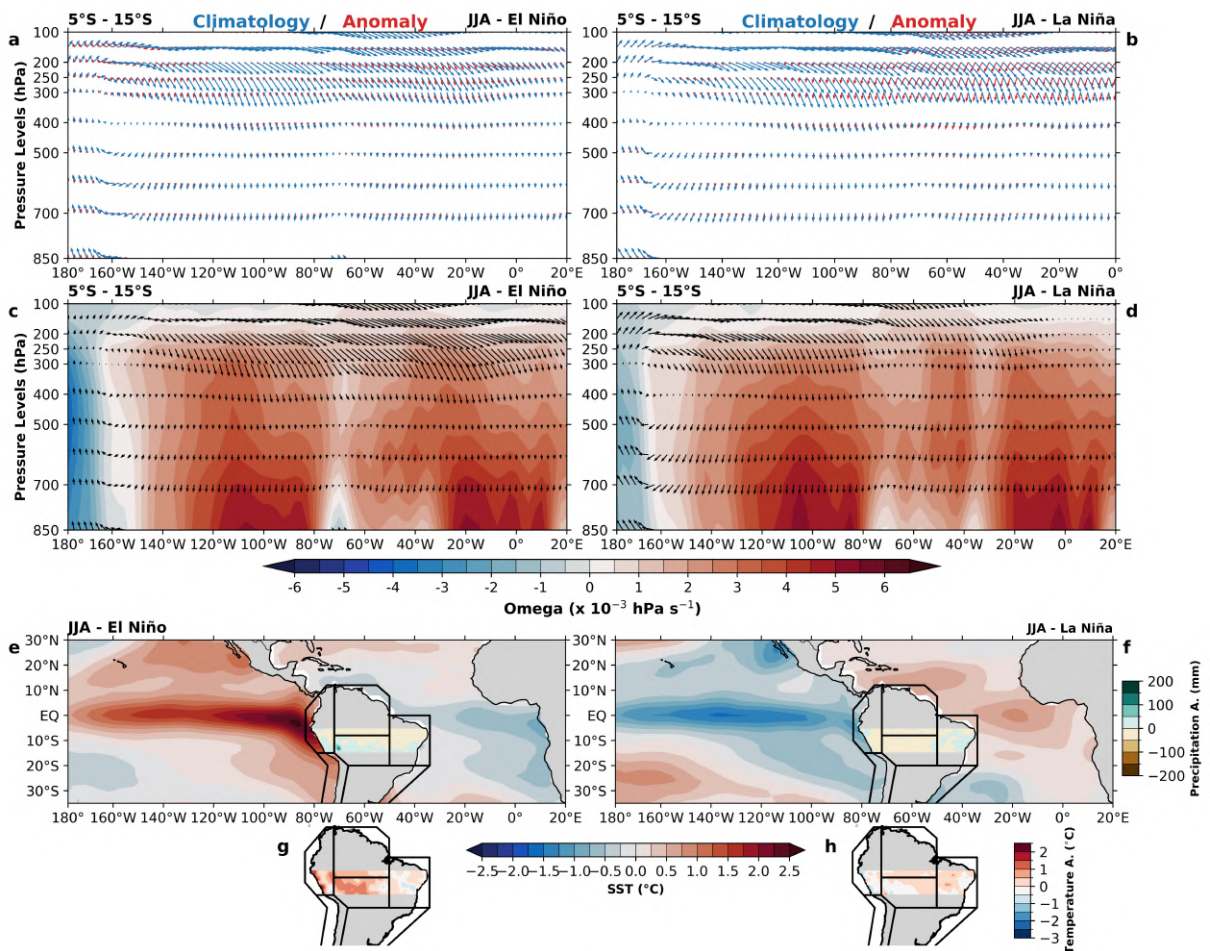


Figure 16: Climatology (blue vectors) and anomaly (red vectors) of vertical wind velocity between 5 °S and 15 °S during El Niño (a) and La Niña (b) events in the June-July-August (JJA) quarter. (c,d) Vertical wind speed (filled contours) and wind direction (vectors) between 5 °S and 15 °S during El Niño (c) and La Niña (d) events in the JJA quarter. (e,f) Sea surface temperature (SST) anomalies and precipitation anomalies over the continent between 5 °S and 15 °S during El Niño (e) and La Niña (f) events in the JJA quarter. (g,h) Air temperature anomalies over the continent between 5 °S and 15 °S during El Niño (g) and La Niña (h) events in the JJA quarter. Data correspond to the composite averages of El Niño (1982–1983, 1997–1998, and 2015–2016) and La Niña (1988–1989, 1999–2000, and 2010–2011) events in the JJA quarter.

The Tropical Atlantic Dipole Pattern and Its Climate Implications for South America

The Tropical Atlantic Dipole (TAD), characterized by a meridional gradient in sea surface temperature (SST) between the Northern and Southern Atlantic, has significant climate implications for South America (LONDOÑO ARTEAGA; LIMA, 2021). During the positive phase of the TAD (TNA(+) and TSA(-)), atmospheric circulation over the North Atlantic shows a thermally direct pattern, with rising air over regions of warmer SST in the north and descending air in the south. This circulation contributes to drought intensification in the northern part of Northeast Brazil and the Amazon by reducing evaporation and moisture convergence. In the negative phase of the TAD (TNA(-) and TSA(+)), the circulation reverses, affecting the Intertropical Convergence Zone (ITCZ) and altering the spatial and temporal distribution of precipitation in areas such as the eastern Amazon and Northeast Brazil. The anomalous surface wind and pressure patterns also influence the north-south migration of the ITCZ (MARTINS *et al.*, 2015b).

The South Atlantic Subtropical Dipole (SAD) is the dominant ocean-atmosphere variability pattern in the South Atlantic (MANTA *et al.*, 2024). This dipole, oriented northeast-southwest, has centers of action over the tropical and extratropical South Atlantic (SSTA and SESA, respectively) (WAINER *et al.*, 2021b). The SAD is closely linked to the variability of the South Atlantic Subtropical High (SASH), which modulates atmospheric circulation and the oceanic mixed layer (ZILLI; CARVALHO; LINTNER, 2019). This variability has significant impacts on regional climate, especially during negative phases, when changes in precipitation and temperature patterns are more pronounced over South America (REBOITA *et al.*, 2019).

During positive SAD events, cold SST anomalies occur south of 35°S during the austral summer, while the rest of the basin experiences warming. SST and wind anomalies shift northward in the following season, with cyclonic wind stress in the northern part of the SAD leading to increased warming (WAINER *et al.*, 2021b, p. 2). Negative (positive) SAD events are characterized by positive (negative) sea level pressure (SLP) anomalies across the South Atlantic and negative (positive) SST anomalies over the TSA and along the African coast (FLANTUA *et al.*, 2016).

El Niño impacts the tropical Atlantic by warming the tropical North Atlantic, typically from late boreal winter to early spring (TASCHETTO *et al.*, 2016). This warming is driven by the tropospheric temperature mechanism and teleconnections via the Pacific/North American (PNA) pattern (TASCHETTO *et al.*, 2020). During El Niño, the Atlantic Walker circulation strengthens in response to equatorial Pacific warming generating strong easterly winds over the equatorial Atlantic, which result in cold SST anomalies in the tropical South Atlantic.

Concurrently, the PNA pattern induces lower-than-average atmospheric pressures over the southeastern U.S., extending into the North Atlantic, weakening the North Atlantic Subtropical High and reducing trade winds, which lowers evaporative cooling and warms the tropical North Atlantic through wind-evaporation-SST feedback (SASAKI *et al.*, 2015). This generates strong low-level easterly winds over the equatorial Atlantic, resulting in cold SST anomalies in the equatorial and part of the tropical South Atlantic. At the same time, a PNA pattern is induced, with below-average atmospheric pressures over the southeastern United States extending towards the North Atlantic. This warming creates an inter-hemispheric SST gradient known as the Atlantic Meridional Mode (AMM), which shifts the ITCZ north or south, affecting precipitation patterns in northeastern Brazil and West Africa (VALLÈS-CASANOVA *et al.*, 2020). However, not all ENSO events result in AMM anomalies due to the intrinsic variability of the Atlantic, and ENSO diversity also leads to varied impacts on the tropical Atlantic (REBOITA *et al.*, 2021b).

The interaction between El Niño and Atlantic Dipole events, whether positive or negative, can create rainfall deficits in Northeast Brazil and the Amazon, although positive precipitation anomalies may occur in parts of the Northeast (REBOITA; SANTOS, 2015, p. 201). Conversely, the South and Southeast regions of South America may experience increased rainfall. During La Niña, when combined with a positive dipole (TNA(+) and TSA(-)), wetter conditions can prevail in central-southern Brazil, while the Northeast and Amazon may become drier (DRUMOND *et al.*, 2014). However, if La Niña coincides with a negative dipole (TNA < TSA), the Northeast and Amazon may see more rainfall, while the southeast experiences drought.

During La Niña, South American precipitation is strongly linked to variability in the South Tropical Atlantic (TSA), while El Niño events amplify the effects of positive TSA. This relationship stems from shifts in the ITCZ, which affects both the Hadley and Walker cells, intensifying rainfall anomalies in Northeast Brazil and the Amazon. Studies also show that ENSO and TSA jointly influence water dynamics in the Amazon Basin, particularly during the peak rainfall period (February to May). The TSA has a greater influence on moisture contributions from the Atlantic to the Amazon, while ENSO variability affects moisture transport from the basin to the subtropics (DRUMOND *et al.*, 2014). During El Niño and positive Dipole years, moisture largely comes from the TSA, while during La Niña and negative Dipole years, the North Atlantic becomes the main moisture source (REBOITA *et al.*, 2021b).

CONCLUSIONS

South America is undergoing substantial changes in climate extremes, with notable shifts in both precipitation and temperature patterns. A general decline in annual precipitation has been observed across much of the continent; however, certain regions—particularly in the northeast and southeast—are experiencing more frequent and intense precipitation events. This shift indicates a redistribution of rainfall patterns, with a tendency toward fewer but more intense precipitation events in specific areas.

Temperature extremes reveal a clear warming trend across South America, marked by an increase in both the frequency and duration of heat events, such as heatwaves and warm nights. This intensification of temperature extremes reflects ongoing global warming, with varying impacts across regions. The increased frequency of warm days and nights, coupled with the decline in cold events, highlights the complexity of climate responses across the continent.

The analysis shows that sea surface temperature (SST) anomalies in the Pacific and Atlantic Oceans play a significant role in driving these climate extremes. Precipitation indices, such as intense rainfall days (R10mm) and total wet-day precipitation (PRCPTOT), respond distinctly to the phases of El Niño and La Niña. La Niña events are associated with higher rainfall frequency and intensity in the northern and northeastern regions, while El Niño and SST-neutral phases tend to correlate with extended dry periods.

Temperature extremes, including indices like TX90p (warm days), TN90p (warm nights), and RX5day (maximum 5-day rainfall), are also influenced by ocean temperature variations. Heatwave duration, measured by the warm spell duration index (WSDI), tends to increase in response to positive phases of the Atlantic Dipole and El Niño events, particularly in the northeast, southeast, and South American monsoon regions. These areas are experiencing more frequent and prolonged heatwaves, while cold nights (TN10p) are becoming increasingly rare.

These findings underscore the importance of understanding SST anomalies as mechanisms driving climate variability in South America. This understanding is essential for informing effective adaptation and mitigation strategies to address the impacts of climate change. Enhanced insight into these interactions will allow for more accurate predictions of climate extremes, aiding policymakers and resource managers in their efforts to protect both human and environmental systems across South America.

4 CHAPTER 2: HYDROCLIMATIC EXTREMES AND DROUGHT DYNAMICS IN THE PANTANAL WETLAND UNDER CLIMATE CHANGE.

ABSTRACT

The Pantanal, the world's largest tropical wetland, is facing intensifying hydroclimatic pressures, with droughts and heat extremes increasingly destabilizing its ecosystems and water resources. This study investigates the combined influence of land-use change, climate variability, and projected warming on the region's hydrological balance. Reanalysis datasets (ERA5 Land and FLDAS) for precipitation, temperature, evapotranspiration, and soil moisture (1980–2022) were analyzed alongside the drought index SPEI 12, drought event metrics derived from Run Theory, and climate extremes including Warm Days (TX90p) and persistence indicators. Spatial and temporal trends were assessed using non-parametric methods, while Random Forest models and CMIP6 projections were applied to evaluate the drivers and future trajectories of drought variability. Results reveal a progressive intensification of droughts, particularly in the Central and Southern Pantanal, where reduced rainfall, rising temperatures, hydrological deficits, wetland loss, and agricultural expansion converge. Run Theory indicates increasing drought duration, severity, and intensity, with Warm Days (TX90p) emerging as the dominant driver of SPEI 12 variability, both historically and in CMIP6 projections, while precipitation extremes contributed less directly. These findings highlight the urgent need for wetland conservation, adaptive water management, and fire mitigation strategies to enhance the resilience of the Pantanal's ecosystems and communities in the face of ongoing and projected climate change.

Keywords: hot extremes; drought severity; hydrological deficit; land-use transformation; wetland loss.

INTRODUCTION

Located in the center of South America, the Pantanal is recognized as one of the largest and most ecologically significant wetlands worldwide. It has been designated as a UNESCO World Natural Heritage site and as a Wetland of International Importance under the Ramsar Convention (THIELEN *et al.*, 2021). The region comprises an extensive and dynamic floodplain system that supports rich biodiversity, vast seasonally flooded grasslands, numerous lakes and ponds, and a network of perennial and intermittent rivers. As the largest continuous floodplain on Earth, the Pantanal is subject to highly variable precipitation regimes that strongly influence its hydrological functioning (THIELEN *et al.*, 2020). Approximately 70% of its area is covered by savanna like vegetation, classifying the biome as a hyperseasonal savanna. These ecosystems are exposed to two recurring hydrological stresses, intense droughts and prolonged floods, which emphasize their ecological complexity and vulnerability (GUERRA *et al.*, 2020).

Drought, defined as a prolonged period of precipitation deficits, is among the most significant natural hazards due to its severe environmental, economic, and social impacts

(ORIMOLOYE *et al.*, 2021). In the Pantanal, whose ecological equilibrium depends on the interaction between aquatic and terrestrial systems, extreme climate events such as severe droughts and heatwaves have become increasingly frequent and intense in recent years (LIBONATI *et al.*, 2022; MARENGO *et al.*, 2021a). Between 2019 and 2022, one of the most severe droughts in recent decades was recorded, accompanied by wildfires that burned approximately one-third of the biome, including Indigenous lands and protected areas (LIBONATI *et al.*, 2022). These impacts are attributed to a combination of climatic drivers, such as extreme heatwaves, and anthropogenic pressures, including land-use and land-cover changes and declining water levels in the Paraguay River. These factors have contributed to a marked reduction in surface water extent, altering flood regimes, shortening the rainy season, and increasing the frequency and magnitude of extreme events (CUNHA; BUERMANN; MARENGO, 2024).

Extreme climate events in the Pantanal have been shown to be influenced by anomalous sea surface temperature patterns in the Atlantic and Pacific Oceans, in addition to changes in land use and land cover (ALMAZROUI *et al.*, 2021; LIU *et al.*, 2022). These drivers alter water availability and ecological cycles, with cascading impacts on biodiversity, trophic interactions, and overall ecosystem functioning. A comprehensive understanding of these dynamics is essential to support water resource management and to inform the development of effective mitigation and adaptation strategies under global change scenarios (AVILA-DIAZ *et al.*, 2023b; MARENGO; ALVES; TORRES, 2016).

To monitor and characterize drought conditions, a variety of indices have been employed, including the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI) (BEVACQUA *et al.*, 2021; VICENTE-SERRANO; BEGUERÍA; LÓPEZ-MORENO, 2010). More recently, the Standardized Precipitation Evapotranspiration Index (SPEI) has been preferred because it incorporates temperature effects into the water balance, allowing for a more accurate assessment of drought severity under warming conditions (ANDERSON *et al.*, 2018; CARVALHO *et al.*, 2020). In addition to capturing temporal variability, the SPEI allows for investigation of linkages between drought and other extreme climate events, such as heatwaves, which have become increasingly relevant in the Pantanal.

Based on this context, it is hypothesized that the severity and frequency of extreme climate events in the Pantanal, particularly prolonged droughts and heatwaves, are being amplified by land-use and land-cover changes as well as by regional climate variability (CUNHA; BUERMANN; MARENGO, 2024). This study, therefore, aims to assess how these events, together with changes in precipitation and temperature patterns, have altered the

hydrological and ecological dynamics of the biome over recent decades. Historical analyses are integrated with future climate projections to identify potential implications for biodiversity and water resources, thereby providing information that may support public policy, guide adaptation strategies, and mitigate socio-environmental impacts. Through this approach, the study seeks to contribute to the conservation of the Pantanal and to the sustainability of socio-economic activities that depend on its ecosystem services (ARAÚJO *et al.*, 2018; GOUVEIA *et al.*, 2022).

MATERIAL AND METHODS

Study Area

The Pantanal biome, situated in the central region of South America, encompasses an area exceeding 140,000 km² across Brazil, Bolivia, and Paraguay, with approximately 80% of its extent located in Brazilian territory, predominantly within the states of Mato Grosso and Mato Grosso do Sul (MARENGO *et al.*, 2021a). This extensive floodplain operates as a natural hydrological reservoir, receiving surface runoff from surrounding plateaus during the rainy season and gradually releasing it into the Paraguay River and its tributaries (ASSINE *et al.*, 2016; THIELEN *et al.*, 2020).

The seasonal flood pulse, regulated by regional precipitation and topographic gradients, propagates as a north-to-south inundation wave that modulates ecological processes, shapes biogeochemical cycles, and sustains biodiversity patterns across the biome. This dynamic is particularly critical in a region characterized by pronounced hydrological contrasts, where periods of severe drought alternate with prolonged flooding. Beyond its ecological relevance, the Pantanal provides essential ecosystem services, including water storage, carbon

sequestration, habitat provision, and regulation of regional climate (MARENGO *et al.*, 2021b).

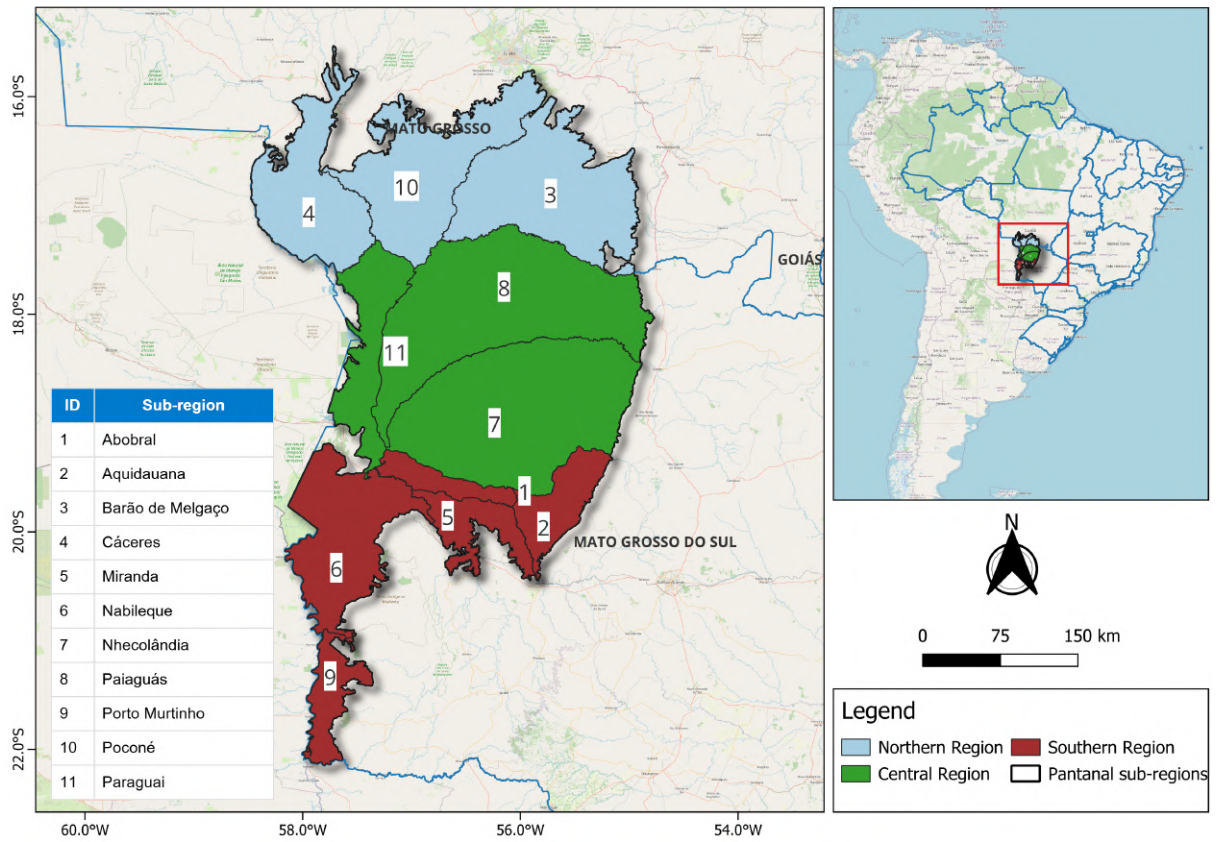


Figure 17: Location of the study area and sub-regions of the Pantanal, Brazil.

Climatic and Hydrological Datasets

Monthly precipitation, evapotranspiration, and near-surface air temperature data for the Pantanal were obtained from the ERA5-Land global reanalysis, provided by the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu>). ERA5-Land offers a spatial resolution of 0.1° (~ 9 km) and represents a refined iteration of the ERA5 reanalysis framework, delivering a consistent and enhanced depiction of the evolution of terrestrial climate parameters (XU *et al.*, 2022). These datasets were used without spatial or temporal interpolation, bias correction, or local calibration, as they present complete coverage with no missing or spurious values.

Monthly soil moisture estimates for the 0–10 cm and 10–40 cm soil layers were obtained from the Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS) L4 product, available through the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) (<https://disc.gsfc.nasa.gov/>). The FLDAS product, with a spatial resolution of 0.1° , was developed to improve agricultural drought monitoring in regions characterized by sparse meteorological observations, including Africa, Central America, and Central Asia (MCNALLY *et al.*, 2017). It integrates land surface parameters

simulated by the NOAH 3.6 model, driven by meteorological forcings from the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), and precipitation data from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) dataset (GRILLAKIS *et al.*, 2021).

All datasets were analyzed for the period between January 1980 and December 2022, preserving their original spatial and temporal resolutions to ensure consistency across all climatic and hydrological variables examined in this study.

Drought Monitoring Indices

Drought conditions were quantified using the Standardized Precipitation Evapotranspiration Index (SPEI) calculated at a 12-month accumulation scale (SPEI-12). The SPEI integrates monthly precipitation (P) and potential evapotranspiration (PET) to represent the climatic water balance, thereby accounting for the influence of atmospheric demand in conjunction with precipitation anomalies (VICENTE-SERRANO; BEGUERÍA; LÓPEZ-MORENO, 2010). Potential evapotranspiration was estimated using Thornthwaite's method, based on monthly mean air temperature and day length, following its widespread application in large-scale drought assessments (ANDERSON *et al.*, 2018; CARVALHO *et al.*, 2020). Monthly water balance anomalies ($P - PET$) were fitted to a Gamma distribution and transformed into standardized units to derive the SPEI time series for each grid cell across the study domain.

Table 4: Classification of drought conditions based on SPEI (VICENTE-SERRANO; BEGUERÍA; LÓPEZ-MORENO, 2010).

SPEI	Drought Classification
≥ 2.00	Extremely wet
1.00 a 1.99	Severely wet
0.50 a 0.99	Moderately wet
0.49 a – 0.49	Near normal
-0.50 a – 0.99	Moderately dry
-1.00 a -1.99	Severely dry
≤ -2.00	Extremely dry

Drought events were identified and characterized following the probabilistic Run Theory, as described by Amin Zargar (ZARGAR *et al.*, 2011) and adopted by Fernandes *et al.* (FERNANDES *et al.*, 2024). An event was defined as any continuous period during which the

SPEI-12 value remained below -1 , corresponding to at least moderate drought conditions (Table 1). The onset and termination of each event were determined by the first and last months in which the SPEI-12 was below this threshold, respectively. For each identified drought event, its characteristics were quantified through three complementary metrics (MA *et al.*, 2023). The duration was defined as the total number of consecutive months during which SPEI-12 remained below -1 . The severity corresponded to the cumulative sum of the absolute SPEI-12 values recorded during this period, representing the integrated magnitude of the water deficit. Finally, the intensity was expressed as the mean monthly deficit, calculated as the ratio between severity and duration ($I = S/D$), which reflects the average strength of the drought conditions throughout the event.

These metrics were derived for each Pantanal subregion (Northern, Central, and Southern) to assess spatial contrasts in drought behavior. This methodology allows for standardized comparisons of drought characteristics across space and time, capturing both the magnitude and persistence of water deficits, while ensuring consistency with previous studies in the region (FERNANDES *et al.*, 2024).

Climate Extremes Indices

Temporal patterns of climate extremes were assessed using eight indices derived from daily ERA5-Land data, encompassing both precipitation- and temperature-based metrics. These indices were calculated following the methodology recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) (AVILA-DIAZ *et al.*, 2020b), ensuring consistency with international standards. The selected metrics included four indices related to precipitation—Consecutive Dry Days (CDD), Consecutive Wet Days (CWD), Precipitation on Very Wet Days (R95p), and the Simple Daily Intensity Index (SDII)—and four indices related to air temperature—Warm Days (TX90p), Warm Nights (TN90p), Cold Days (TX10p), and Cold Nights (TN10p). The definitions, calculation procedures, and reference thresholds for each of these indices are presented in Table 5.

Table 5: Description of selected precipitation and air temperature climate extremes indices used in this study.

Variable	Index	ID	Definition	Units
Precipitation	Simple Daily Intensity Index	SDII	Annual total precipitation divided by the number of wet days - $PRCP \geq 1$ mm	mm/day
	Precipitation on very wet days	R95p	Annual total precipitation (PRCP) when RR. 95th percentile	mm
	Consecutive wet days	CWD	Max number of consecutive days when	days

		RR ≥ 1 mm		
		Consecutive dry days	CDD	Max number of consecutive days when RR ≤ 1 mm
Air Temperature	Warm Days	TX90p	% of days when Tmax is > 90 th percentile	%
	Warm Nights	TN90p	% of days when Tmin is > 90 th percentile	%
	Cool Days	TX10p	% of days when Tmax is < 90 th percentile	%
	Cool Nights	TN10p	% of days when Tmin is < 90 th percentile	%

All indices were computed relative to the 1981–2010 climatological baseline to standardize anomalies and highlight deviations from historical conditions. This approach enables the evaluation of long-term changes in the frequency and intensity of extreme climate events across the Pantanal, as well as their potential associations with drought dynamics as quantified by the SPEI-12.

Trend Analysis

Long-term temporal trends in climatic and hydrological variables were quantified to assess potential directional changes across the study period. For each grid cell, trends in precipitation, evapotranspiration, near-surface air temperature, soil moisture, hydrological deficit ($E - P$), and SPEI-12 were estimated using the Theil–Sen slope estimator, which provides a robust measure of trend magnitude and is less sensitive to outliers (MENGISTU *et al.*, 2020b). The statistical significance of the identified trends was evaluated using the Modified Mann–Kendall test (YUE; WANG, 2004), which corrects for the influence of serial correlation in time series. Only grid cells with statistically significant trends at the 5% level ($p < 0.05$) were considered for spatial mapping and subsequent analyses.

Machine Learning Analysis

The relationships between the 12-month Standardized Precipitation Evapotranspiration Index (SPEI-12) and the eight climate extremes indices presented in Table 2 were examined through a combination of Random Forest modeling and simple linear regression (BELGIU; DRĂGUȚ, 2016; KUMAR *et al.*, 2022). Random Forest was employed as a non-parametric ensemble learning method (BREIMAN, 2001) to quantify the relative importance of each index in explaining SPEI-12 variability across the Northern, Central, and Southern regions of the Pantanal. The algorithm was configured with 500 decision trees, default bootstrapping, and unrestricted tree depth. All variables were analyzed in their original units, without

normalization or standardization, to preserve their intrinsic variability and facilitate physical interpretation.

Model robustness was ensured using 10-fold cross-validation (MUSHAGALUSA; FANDOHAN; GLÈLÈ KAKAI, 2024), in which the dataset was randomly partitioned into training and testing subsets to minimize overfitting and provide reliable performance estimates. Variable importance was derived from the mean decrease in accuracy produced by random permutation of each predictor, allowing for the ranking of indices according to their contribution to the explained variance of SPEI-12.

Complementary simple linear regressions were conducted between each climate extremes index and SPEI-12 for the three subregions. The strength and direction of the relationships were assessed using the coefficient of determination (R^2) and the regression slope, with statistical significance evaluated at the 5% level ($p < 0.05$). The combined use of Random Forest and regression analyses provided a comprehensive assessment of both the individual and combined influence of climate extremes on drought variability in the Pantanal.

Supplementary Datasets for Contextual Analyses

Two additional datasets were incorporated to contextualize the interpretation of hydrological and climatic patterns, although they were not directly used in the statistical analyses. Surface water dynamics were characterized using the Global Surface Water dataset developed by the Joint Research Centre (JRC), available through the Global Surface Water Explorer (PEKEL *et al.*, 2016). This dataset, covering the period from 1984 to 2022, provides spatially explicit information on the extent, recurrence, and persistence of surface water bodies, allowing for the assessment of long-term changes in wetland coverage and hydrological regimes in the Pantanal.

Future climate projections were obtained from 20 Global Climate Models (GCMs) participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6) (EYRING *et al.*, 2016), under three Shared Socioeconomic Pathway (SSP) scenarios: SSP126, SSP245, and SSP585. Ensemble means of the frequency of Warm Days (TX90p) were computed for the Pantanal for the period 2041–2060. These projections were aggregated regionally without bias correction or statistical downscaling, as their use was restricted to qualitative contextualization of potential future trajectories in the discussion.

RESULTS

Spatial and Temporal Patterns of Climate Variables

Annual precipitation exhibited pronounced spatial and temporal variability across the Pantanal during the period 1980–2022. Spatially, the highest annual totals, exceeding $1,500 \text{ mm year}^{-1}$, were concentrated in the Northern and Southern regions, while the Central sector displayed intermediate values between $1,200$ and $1,400 \text{ mm year}^{-1}$ (Figure 18a). Zonal and temporal analyses revealed a progressive decline in precipitation, particularly after the 1990s, with mean annual totals decreasing from values near $1,900 \text{ mm year}^{-1}$ in the early 1980s and 1990s to as low as approximately $1,200 \text{ mm year}^{-1}$ in recent years (Figures 18e, 18i). These reductions were consistent across most latitudes, with marked interannual fluctuations evidenced by the confidence intervals.

Near-surface air temperature displayed a contrasting behavior, characterized by a consistent upward trend throughout the study period. Spatially, the Northern and Central regions recorded the highest mean annual values, with long-term averages near 26.5°C , while the Southern Pantanal remained comparatively cooler, with averages near 25°C (Figure 18b). Temporal trends indicated a steady warming, with annual regional averages rising from approximately 24°C in the early 1980s to peaks approaching 29°C in recent years (Figures 18f, 18j). These increases were most pronounced after the mid-2000s, accompanied by relatively narrow confidence intervals that highlight the persistence of this warming signal.

Soil moisture exhibited a more complex pattern, with spatial averages generally above $0.31 \text{ m}^3 \text{ m}^{-3}$ across much of the biome, but with localized values declining below $0.20 \text{ m}^3 \text{ m}^{-3}$, particularly in portions of the Central region (Figure 18c). Temporal analyses revealed alternating periods of wetness and dryness, especially in the Northern and Central subregions, while the Southern Pantanal displayed comparatively stable conditions (Figures 18g, 18k). Despite these oscillations, a gradual declining trend was observed, though accompanied by wide confidence intervals, which indicate substantial interannual variability.

Evapotranspiration also demonstrated notable spatio-temporal changes. Spatially, annual totals exceeded $1,400 \text{ mm year}^{-1}$ in the western portions of the Northern and Central regions, whereas the lowest values were concentrated in the Central Pantanal (Figure 18d). Temporally, evapotranspiration exhibited a general declining trend, particularly after 2005, when annual regional averages dropped from values near $1,400 \text{ mm year}^{-1}$ to below $1,000 \text{ mm year}^{-1}$, with extreme minima approaching 850 mm year^{-1} (Figures 18h, 18l). These

reductions coincided with periods of declining precipitation and soil moisture, highlighting a coherent pattern of diminishing water availability across the biome.

Overall, the combined spatial and temporal patterns of precipitation, air temperature, soil moisture, and evapotranspiration reveal a progressive reduction in atmospheric and terrestrial water availability over large portions of the Pantanal, alongside sustained warming. These trends create environmental conditions favorable to the intensification of drought processes, as further analyzed through drought indices in the next section.

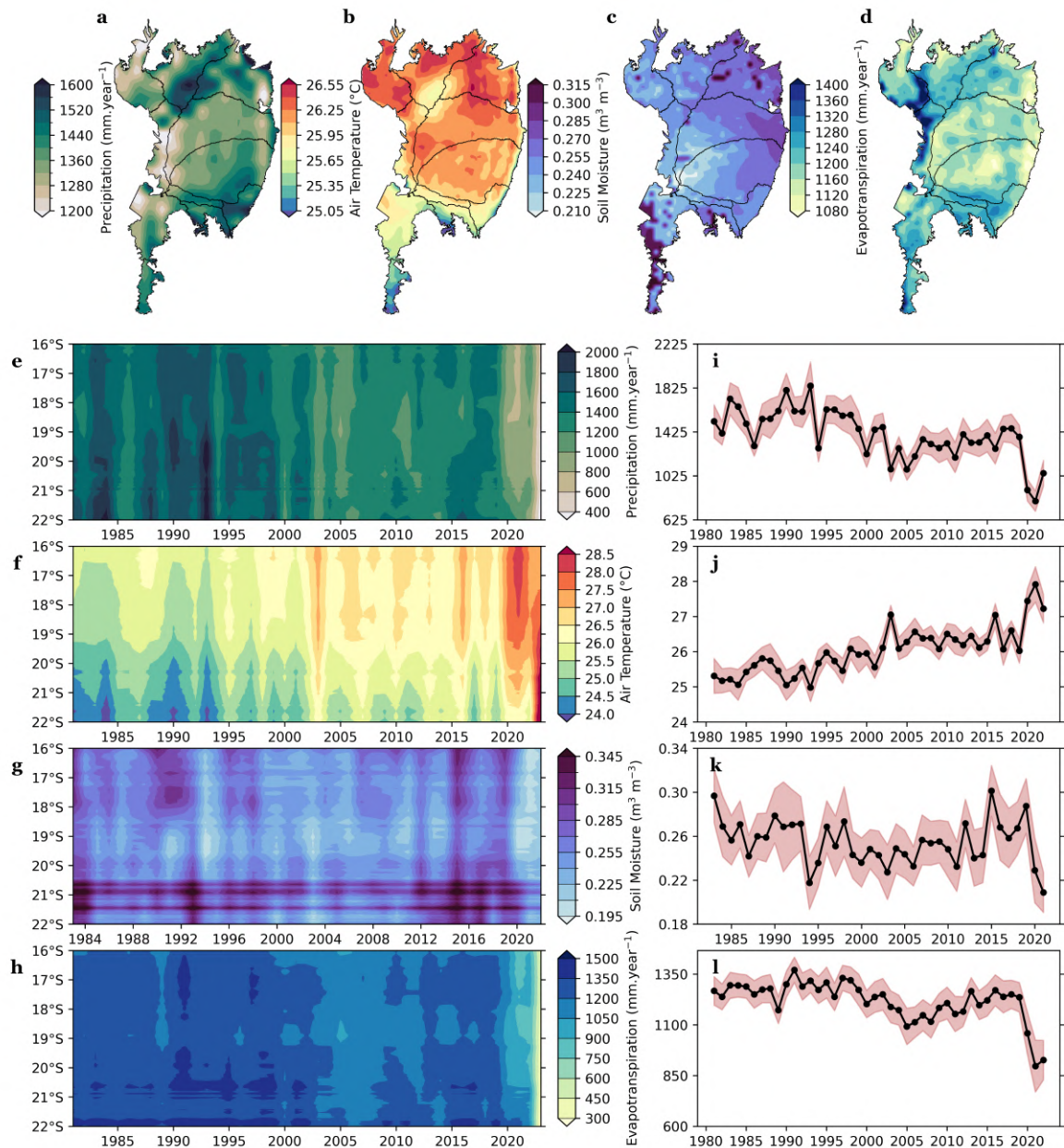


Figure 18: Detailed summary of climate variables in the Pantanal biome from 1980 to 2022, comprising four groups. Spatial distribution of mean annual precipitation (a), mean annual air temperature (b), mean annual soil moisture (c), and mean annual evapotranspiration (d). Zonal and temporal variability of precipitation (e), air temperature (f), soil moisture (g), and evapotranspiration (h). Regional mean annual precipitation (i), air temperature (j), soil moisture (k), and evapotranspiration (l).

Trends and Patterns of the Drought Index

The analysis of the 12-month Standardized Precipitation Evapotranspiration Index (SPEI-12) revealed pronounced spatiotemporal variability in drought dynamics across the Pantanal, with distinct behaviors in the Northern, Central, and Southern subregions (Figure 19). All regions exhibited a significant downward trend in SPEI-12, reflecting the progressive intensification of drought conditions since 1980. The Central and Southern regions recorded the steepest declines, with slopes of -0.04 SPEI decade⁻¹ (Figures 19b, 19c), while the Northern region showed a slightly weaker but still significant trend of -0.03 SPEI decade⁻¹ (Figure 19a). Historically, the Southern Pantanal maintained relatively higher mean SPEI-12 values, indicating wetter baseline conditions compared to the other regions. However, since 2010, this relative buffer has eroded, with all subregions experiencing similar drought intensification, particularly during 2019–2022 when SPEI-12 values reached extreme deficits (SPEI < -2), indicating widespread extreme drought conditions.

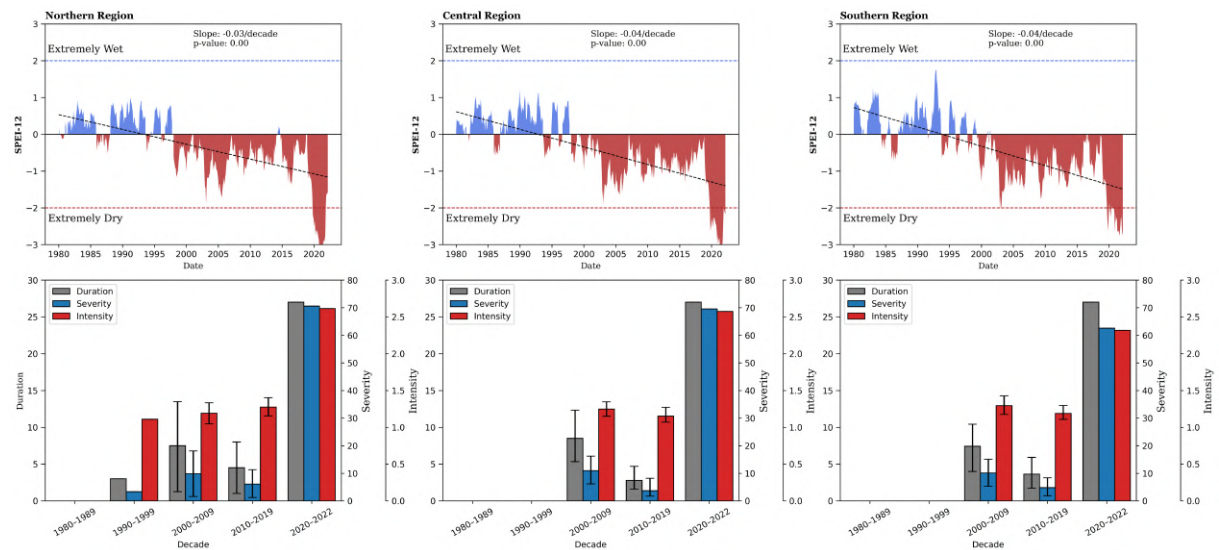


Figure 19: Temporal evolution of the 12-month Standardized Precipitation Evapotranspiration Index (SPEI-12) and drought event characteristics in the Pantanal's Northern (a, d), Central (b, e), and Southern (c, f) regions from January 1980 to March 2022. Panels (a–c) show regional SPEI-12 time series with trend lines (Theil-Sen) and confidence intervals. Panels (d–f) summarize drought event properties derived from Run Theory, including severity, duration, intensity.

Drought event characteristics derived from Run Theory (Figures 19d–19f) demonstrated consistent upward trends in duration, severity, and intensity throughout the study period. During the 1980s and early 1990s, droughts were comparatively short-lived, with mean durations often below 10 consecutive months and severities rarely exceeding cumulative SPEI deficits of 20. However, a marked escalation was observed beginning in the 2000s, intensifying further after 2010. By the period 2020–2022, drought events across all subregions reached mean durations approaching or exceeding 25–30 months, while severities surged to cumulative deficits

surpassing 60–70, nearly tripling the magnitude typical of events in earlier decades. Intensity, expressed as the mean monthly deficit (S/D), also exhibited a clear upward trajectory, rising from values generally near or below 1.0 in the 1980s to above 2.5 during the most recent events, underscoring that individual months within these prolonged droughts were markedly more extreme compared to past events.

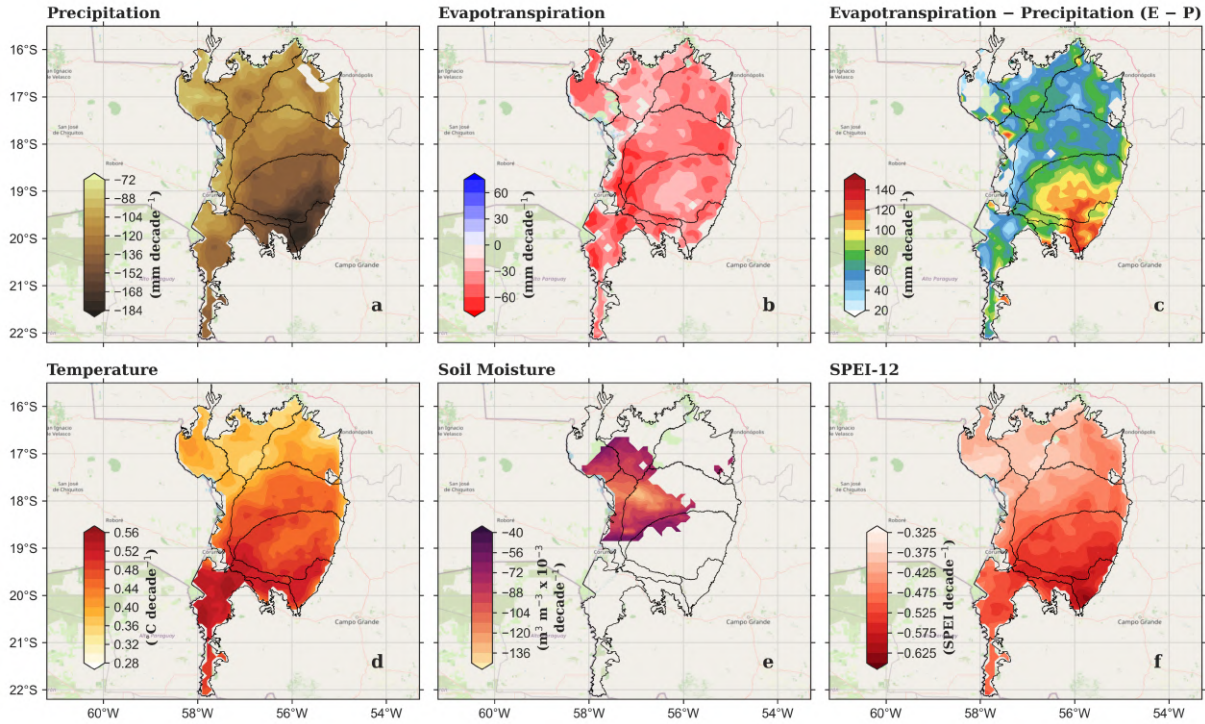


Figure 20: Decadal spatial trends (1980–2022) for (a) precipitation, (b) evapotranspiration, (c) hydrological deficit (evapotranspiration minus precipitation, $E - P$), (d) air temperature, (e) soil moisture, and (f) the 12-month Standardized Precipitation Evapotranspiration Index (SPEI-12) across the Pantanal biome. Trends were calculated using Theil–Sen slope estimators and tested for statistical significance with the Modified Mann–Kendall method, with only values significant at the 5% level displayed.

Although the Northern Pantanal exhibited the greatest variability in interarrival times between droughts, including an exceptional 83-month gap without significant events, the Central and Southern regions emerged as the primary hotspots for severe drought impacts over the last two decades. These regions not only concentrated the longest and most severe droughts but also showed a sustained increase in event intensity, reflecting a compounded effect of climate variability and anthropogenic pressures on hydrological vulnerability.

The decadal spatial trends of precipitation, evapotranspiration, hydrological deficit ($E - P$), air temperature, and soil moisture (Figures 20a–20e) illustrate the underlying drivers of these drought dynamics. Precipitation decreased across most of the biome (Figure 20a), with the most substantial reductions in the Central-Southern sector, particularly around Aquidauana and Nabileque (declines up to $-182 \text{ mm decade}^{-1}$), while northern areas near Cáceres exhibited smaller decreases ($\sim -72 \text{ mm decade}^{-1}$). Evapotranspiration also trended downward in most

regions (Figure 20b), with losses exceeding $60 \text{ mm decade}^{-1}$ in the Central Pantanal, notably around Paiguás, reflecting reduced rainfall and land-use changes that diminished wetland extent and vegetation cover. Localized increases near Cáceres ($+38 \text{ mm decade}^{-1}$) were limited in spatial extent and magnitude, likely influenced by persistent surface water and irrigation. Hydrological deficit ($E - P$) rose substantially across much of the biome (Figure 20c), with the most pronounced increases in the Southern Pantanal, near Aquidauana ($\sim 140 \text{ mm decade}^{-1}$) and Nabileque ($\sim 120 \text{ mm decade}^{-1}$). Air temperature increased consistently throughout the biome (Figure 4d), with the strongest warming concentrated in the south, particularly near Nabileque ($+0.56 \text{ }^{\circ}\text{C decade}^{-1}$), while the northern sector warmed more moderately ($+0.28 \text{ }^{\circ}\text{C decade}^{-1}$). Soil moisture exhibited the sharpest negative trends in the Central Pantanal (Figure 20e), especially in the Paraguai and Nhecolândia subregions, with losses approaching $-144 \times 10^{-3} \text{ m}^3 \text{ m}^{-3} \text{ decade}^{-1}$, while peripheral areas showed weaker or negligible changes.

The spatial pattern of SPEI-12 trends (Figure 20f) reflects the combined influence of these climatic and hydrological drivers, revealing a biome-wide intensification of drought conditions. The most severe negative trends are concentrated in the Southeastern Pantanal, overlapping with the areas that experienced the steepest precipitation losses, greatest hydrological deficits, and highest warming, particularly near Aquidauana, Nabileque, and parts of the Paraguai subregion. Conversely, the Northern Pantanal, notably around Cáceres, shows comparatively weaker declines ($\sim -0.325 \text{ SPEI decade}^{-1}$), suggesting a lower, though still significant, degree of drought intensification. This spatial correspondence underscores the integrated role of precipitation, air temperature, hydrological deficit, and soil moisture in shaping the severity and distribution of drought dynamics across the biome.

Climate Extremes Patterns and Their Relationship with Droughts

The zonal variability of anomalies in precipitation-derived climate extremes indices revealed alternating phases of positive and negative anomalies over time, but with a noticeable shift toward drier conditions after the mid-2000s (Figure 21a–d). From this period onward, negative anomalies became prevalent in most precipitation-related indices, particularly in the Central and Southern Pantanal, suggesting a reduction in consecutive wet periods and a decrease in the frequency and magnitude of intense rainfall events. In contrast, the Northern region maintained intermittent positive anomalies, reflecting a more irregular and spatially heterogeneous pattern of precipitation extremes compared to the southern sectors of the biome.

Anomalies in air temperature extremes displayed a more consistent and spatially homogeneous signal across the Pantanal, with a marked progression toward warmer conditions

throughout the study period (Figure 21e–h). Since the early 2000s, hot extremes (TX90p and TN90p) have become increasingly dominant, exhibiting persistent and intensifying positive anomalies, while cold extremes (TX10p and TN10p) have concurrently declined. This shift was gradual but sustained, with the warming signal apparent across both daytime and nighttime indices and across all subregions.

Indicators of drought persistence and wetness further underscore this transition toward drier conditions. The Consecutive Dry Days (CDD) index (Figure 21a) displayed positive anomalies most prominently after 2010 and during 2020–2022, particularly in the Central and Southern Pantanal, indicating longer dry spells coinciding with the most severe drought episodes. Conversely, the Consecutive Wet Days (CWD) index (Figure 21b) showed more frequent positive anomalies before 2000, especially in the Northern region, with predominantly negative anomalies during the past two decades, highlighting the contraction of extended wet periods in recent years.

Indices representing intense rainfall, including Precipitation on Very Wet Days (R95p, Figure 21c) and the Simple Daily Intensity Index (SDII, Figure 21d), did not exhibit a consistent long-term linear trend, but both demonstrated a pronounced shift after 2005. Negative anomalies became widespread, particularly in the Central and Southern Pantanal, suggesting that extreme precipitation events have become not only less frequent but also less intense in recent decades, despite considerable interannual variability across the biome.

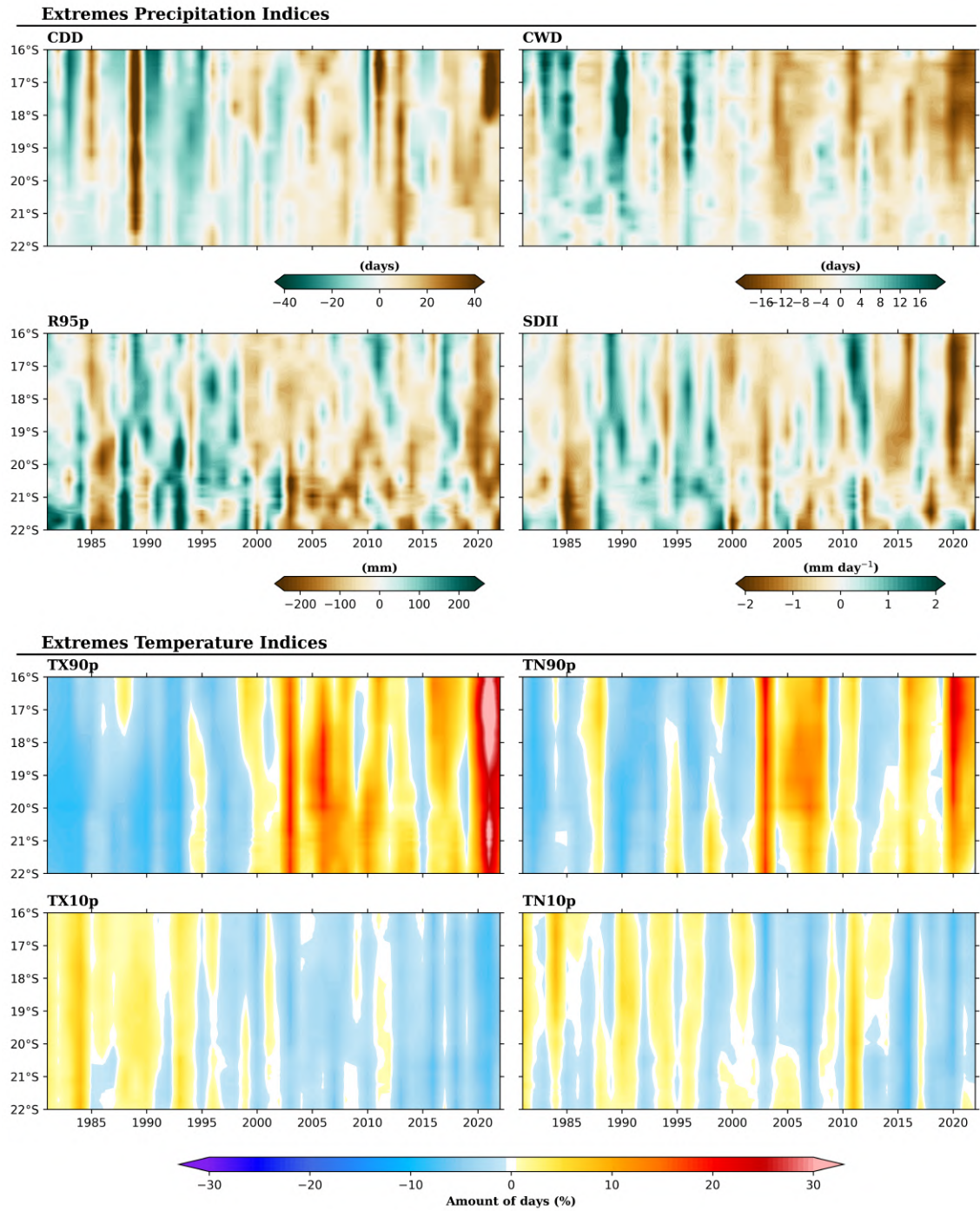


Figure 21: Zonal variability of anomalies in precipitation climate extremes indices: Consecutive Dry Days (CDD), Consecutive Wet Days (CWD), Precipitation on Very Wet Days (R95p), Simple Daily Intensity Index (SDII); and air temperature extremes indices: Warm Days (TX90p), Warm Nights (TN90p), Cold Days (TX10p), and Cold Nights (TN10p) in the Pantanal from 1980 to 2022.

The relationship between climate extremes and drought severity, as measured by SPEI-12, demonstrated that only a subset of indices exhibited statistically significant correlations (Figure 22). Among precipitation-based indices, none displayed consistent or robust relationships across the three subregions. The Consecutive Dry Days (CDD, Figure 22a), Precipitation on Very Wet Days (R95p, Figure 22c), and Simple Daily Intensity Index (SDII,

Figure 22d) indices showed no significant correlations in any region, while the Consecutive Wet Days (CWD, Figure 22b) index exhibited a moderate positive relationship only in the Northern Pantanal ($R^2 = 0.43^*$, $p < 0.05$).

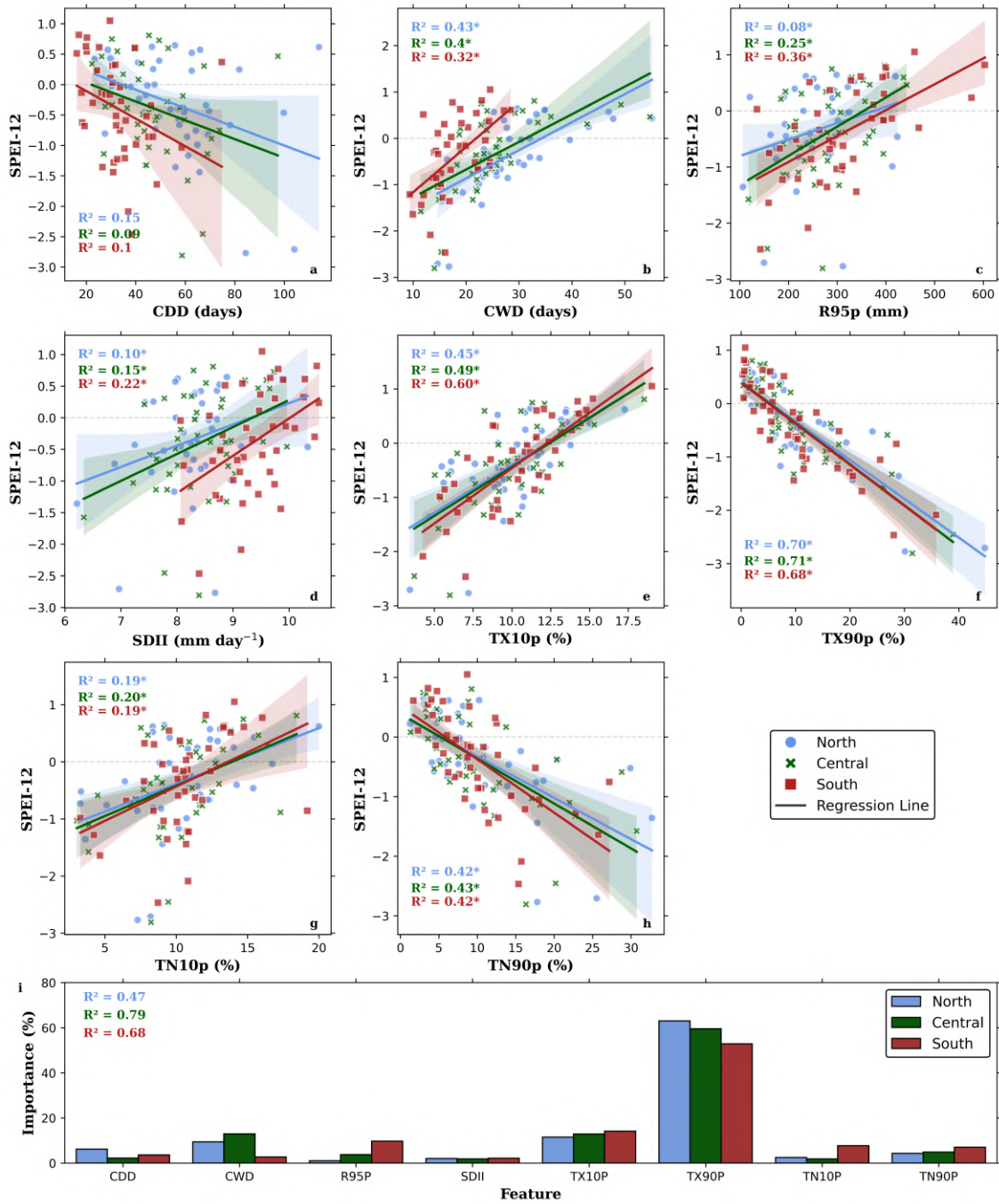


Figure 22: Relationships between the 12-month Standardized Precipitation Evapotranspiration Index (SPEI-12) and precipitation extremes indices — (a) Consecutive Dry Days (CDD), (b) Consecutive Wet Days (CWD), (c) Precipitation on Very Wet Days (R95p), (d) Simple Daily Intensity Index (SDII) — and air temperature extremes indices — (e) Cool Days (TX10p), (f) Warm Days (TX90p), (g) Cool Nights (TN10p), and (h) Warm Nights (TN90p) — in the Northern (blue), Central (green), and Southern (red) regions of the Pantanal. Regression lines include 95% confidence intervals, and asterisks indicate statistically significant relationships ($p < 0.05$). Panel (i) shows the relative importance of each index in the Random Forest model.

In contrast, air temperature extremes demonstrated the strongest and most consistent associations with SPEI-12 across the biome. The Warm Days (TX90p) index (Figure 22f) emerged as the most dominant predictor, showing significant negative correlations in all regions, with $R^2 = 0.70^*$ in the Northern, 0.71^* in the Central, and 0.68^* in the Southern Pantanal ($p < 0.05$). Cool extremes also contributed meaningfully, as the Cool Days (TX10p) index (Figure 22e) correlated positively with SPEI-12 in the Central ($R^2 = 0.49^*$, $p < 0.05$) and Southern ($R^2 = 0.60^*$, $p < 0.05$) regions. Warm Nights (TN90p, Figure 22h) showed significant negative correlations across all subregions ($R^2 = 0.42^*$, $p < 0.05$), while the Cool Nights (TN10p) index (Figure 22g) did not display significant relationships.

The Random Forest model reinforced these findings (Figure 6i), yielding R^2 values of 0.47, 0.79, and 0.68 for the Northern, Central, and Southern regions, respectively. Variable importance rankings highlighted TX90p as the overwhelmingly dominant predictor of SPEI-12 variability, followed by TX10p and TN90p, while all precipitation-related indices (CDD, CWD, R95p, SDII) contributed minimally. These results indicate that extreme heat events, particularly the frequency of hot days, exert the strongest influence on drought dynamics in the Pantanal, surpassing the role of precipitation extremes in shaping SPEI-12 variability.

DISCUSSIONS

Land-Use Change and Climate Variability: Implications for Hydrological Dynamics

The Pantanal biome has been subjected to increasingly frequent and severe drought events, marked by multi-year precipitation deficits and prolonged water scarcity, producing extensive impacts on aquatic and terrestrial ecosystems (THIELEN *et al.*, 2020). These impacts arise from the interplay between natural climate variability and anthropogenic pressures, particularly extensive land-use and land-cover transformations (DOS SANTOS *et al.*, 2023b). Such transformations have driven profound changes in regional biodiversity, ecosystem dynamics, and resilience, undermining the capacity of the biome to recover from extreme hydrometeorological disturbances.

Between 1985 and 2021, agricultural and livestock areas expanded by 373% (Figure 23a), while surface water bodies declined by approximately 80%, from 26,909.58 km² in 1985 to 5,397.92 km² in 2021 (Figures 23b–23c). These shifts represent not only the conversion of native vegetation into agro-pastoral lands but also the systematic degradation of wetland habitats (SOMOROWSKA, 2022). The replacement of natural vegetation, which supports dominant latent heat fluxes, with managed landscapes favoring sensible heat fluxes,

has altered the soil–plant–atmosphere energy balance (BIUDES *et al.*, 2015, 2022b). Such alterations destabilize local and regional climate regimes, diminish evapotranspiration, and exacerbate hydrological stress, compounding the biome’s vulnerability to warming and drought. The fragmentation of aquatic and wetland habitats further reduces ecological connectivity and restricts the mobility of species dependent on floodplain and lacustrine environments, amplifying the ecological consequences of these shifts.

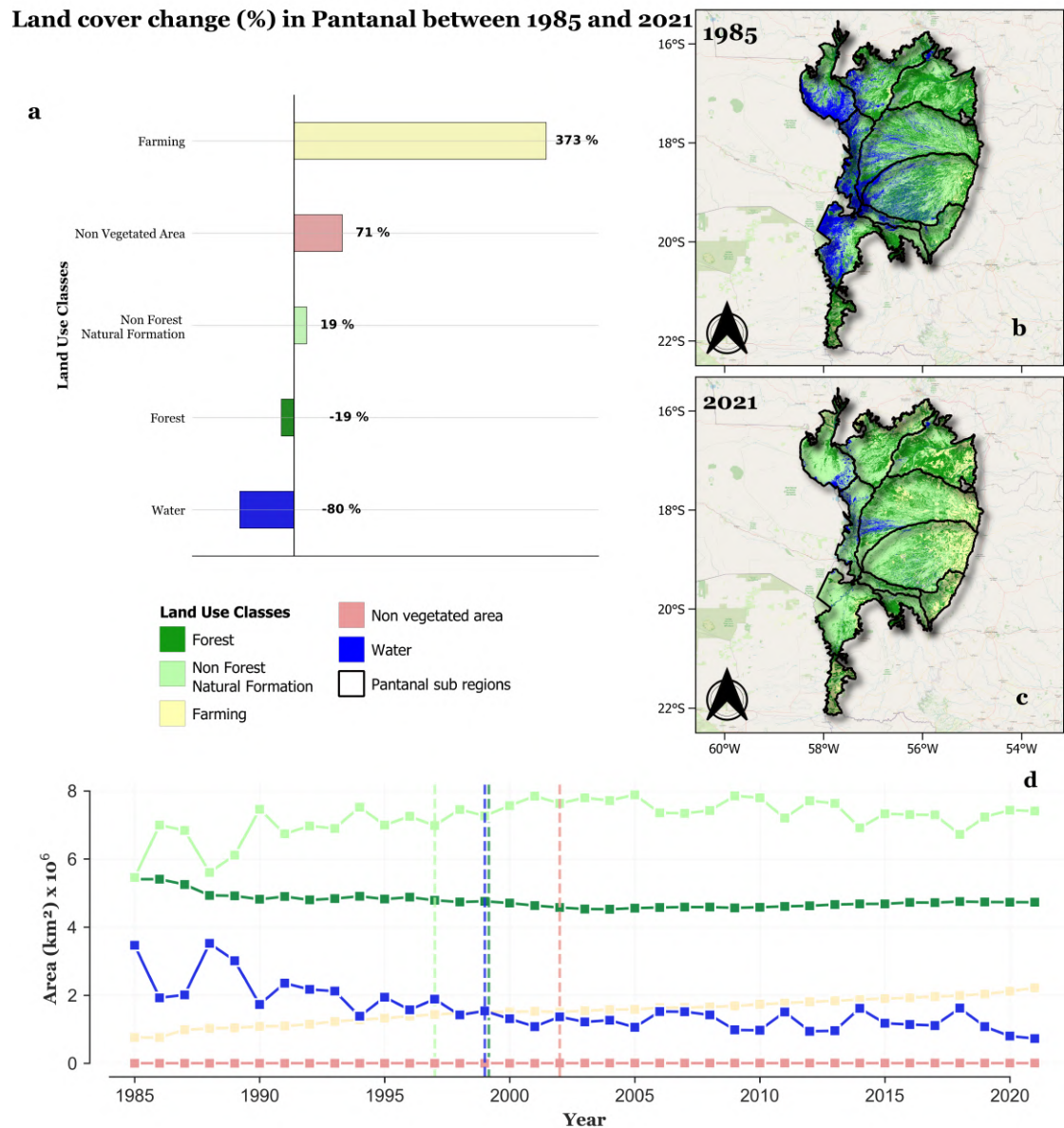


Figure 23: Percent changes (a) in land use and cover. Maps illustrate changes in land use and cover between 1985 (b) and 2021 (c). Time series (d) representing variations in land use from 1985 to 2021 in the Pantanal biome, Brazil. Vertical lines in (d) indicate change points in the time series for each land-use and cover class as identified by Pettitt’s homogeneity test.

The temporal evolution of land-use change further underscores this linkage. Pettitt’s homogeneity test (Figure 23d) identifies a clear inflection between 1996 and 2002, marking the onset of accelerated conversion of wetlands to agricultural and non-vegetated areas, coinciding

with the escalation of extreme droughts and heat episodes in the early 2000s. This synchrony indicates that anthropogenic land-use transformations have likely intensified the sensitivity of the Pantanal to hydroclimatic extremes, both by directly reducing wetland storage and by altering surface energy and moisture fluxes, thereby amplifying hydrological deficit and ecosystem vulnerability (D'ACUNHA *et al.*, 2024; TE WIERIK *et al.*, 2021).

Spatially explicit assessments of hydrological dynamics corroborate these changes (Figure 24). Normalized and absolute change metrics (Figures 24d–24e) show extensive losses in surface water across central and southern sectors of the biome, while occurrence and recurrence maps (Figures 24b–24c) indicate that persistent inundation is now largely restricted to river corridors and peripheral lagoons. The transition classification (Figure 24a) highlights critical zones where permanent or seasonal water bodies have shifted toward ephemeral or highly dynamic states, illustrating the instability of hydrological regimes. Seasonality data (Figure 24f) further reveal that most inundated areas now experience flooding for only one to four months annually, underscoring the disruption of flood pulse regularity. These patterns collectively demonstrate the erosion of wetland persistence and the transition toward shorter-lived, more fragmented aquatic systems.

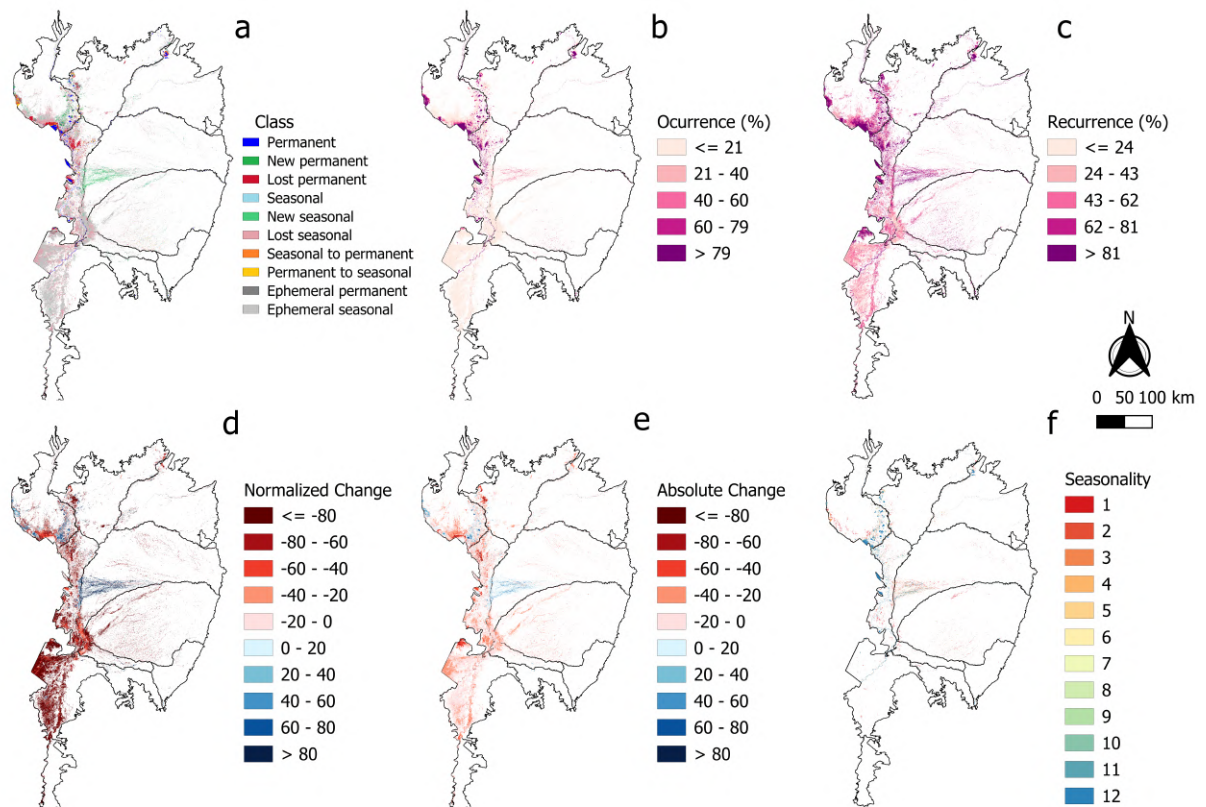


Figure 24. Spatial metrics of hydrological variability in the Pantanal biome derived from the JRC Global Surface Water dataset. Panels show: (a) transition type classification indicating changes in water regime (e.g., loss or gain of permanent/seasonal water, emergence of ephemeral conditions); (b) occurrence (% of years with surface water);

(c) recurrence (% of months flooded annually); (d) normalized change in water presence between 1984–1999 and 2000–2021; (e) absolute change in occurrence; and (f) average flood seasonality (months per year with surface water).

These hydrological and land-use transformations coincide with the intensification of drought metrics observed in this study (Figure 19). Run Theory analyses indicate marked upward trends in drought duration, severity, and intensity since the 2000s, culminating in unprecedented extremes during 2020–2022, when drought events persisted for 25–30 months, cumulative SPEI deficits exceeded 60–70, and average intensities surpassed 2.5. These severe events are geographically concentrated in the Central and Southern Pantanal, overlapping with the sectors that experienced the steepest precipitation declines (VICENTE-SERRANO *et al.*, 2020), the most pronounced increases in hydrological deficit ($E - P$), and the highest warming rates (Figure 20a–d). In particular, the Aquidauana, Nabileque, and Paraguai subregions emerge as drought hotspots, where land-use pressures and hydroclimatic shifts converge to produce the most extreme SPEI-12 declines (Figure 20f). In contrast, the Northern Pantanal, notably around Cáceres, although affected, exhibits comparatively weaker drought trends (~ -0.325 SPEI decade⁻¹), reflecting a relatively higher hydrological resilience where surface water and wetland coverage persist.

Although Bergier *et al.* (BERGIER *et al.*, 2018) reported relatively stable mean annual precipitation between 1926 and 2016, they also identified a significant increase in the frequency of climate extremes during that period. These findings are consistent with the results of this study, which indicate a similar intensification of climate extremes, especially droughts and heatwaves, since the early 2000s, coinciding with more intense land-use changes in the Pantanal. Additional studies highlight marked reductions in flooded areas in the Northern Pantanal, with losses of up to 16% in just one decade, and prolonged periods of hydrological deficit, such as those recorded between 2019 and 2020, when precipitation was 64% below the historical average (FERREIRA BARBOSA *et al.*, 2022; LÁZARO *et al.*, 2020). These data point to a worrying increase in climate variability and its direct impact on regional water security, negatively affecting biodiversity and the ecosystem services essential for the survival and quality of life of local communities.

Additionally, the increase in mean temperatures observed between 2001 and 2019, compared to the previous period (1981–2000), significantly contributed to intensifying extreme climate events in the Pantanal (CURADO *et al.*, 2023; MARQUES *et al.*, 2021). This warming enhances regional evaporation, directly increasing the hydrological deficit and amplifying both the frequency and duration of droughts. Furthermore, higher temperatures favor the occurrence

of wildfires, creating feedback cycles between adverse climate conditions and the degradation of local ecosystems. These conditions also affect the water retention capacity of water bodies, leading to hydromorphological changes that compromise the maintenance of the floodplain and its associated ecosystem services (MARENGO *et al.*, 2021b).

Although drought variability can be modulated by regional factors such as land-use and land-cover change, it is essential to consider the warming and/or cooling patterns of the Tropical Pacific and Atlantic Oceans. The interaction between local climate patterns and tropical oceanic conditions can play a significant role in shaping Pantanal's climate (THIELEN *et al.*, 2020). Studies have demonstrated correlations between oceanic climate indices, such as the Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), Oscillation Niño Index (ONI), and Tropical Northern Atlantic (TNA), with rainfall anomalies and river levels in the Pantanal. However, these relationships generally show low consistency and lack a clear signal. Overall, there is no consistent correspondence between drought years in the Pantanal and the occurrence of El Niño events (MARENGO *et al.*, 2021b). Previous research has also examined large-scale phenomena like ENSO without identifying a clear association with rainfall regimes and river levels in the region.

On the other hand, the TNA index has proven particularly relevant, showing a consistent warming pattern since the mid-1990s and a clearer correspondence with drought periodicity (CABOS; DE LA VARA; KOSEKI, 2019; JIMÉNEZ-MUÑOZ *et al.*, 2016). Thus, drought variability in the Pantanal seems to respond more directly to warming dynamics in the northern Atlantic Ocean, as indicated by the TNA and AMO indices (FERREIRA BARBOSA *et al.*, 2021; MARENGO *et al.*, 2021b). This warming induces a northward shift of the Intertropical Convergence Zone (ITCZ), resulting in reduced rainfall over southern Amazonia and the Pantanal during summer (CABALLERO *et al.*, 2025; LIU *et al.*, 2022). This warming pattern contributes to the formation of low-pressure regions. In this context, a pressure gradient is established between these low-pressure areas and adjacent high-pressure regions, generating variations in wind patterns. These variations, in turn, alter the variability and position of atmospheric systems, potentially inducing negative precipitation anomalies (THIELEN *et al.*, 2020).

Our analysis indicates an increase in the Pantanal's vulnerability to extreme climate events, affecting both precipitation and air temperature. These changes impact seasonal fluctuations as well as the intensity and duration of droughts in the region. Our results highlight the importance of the variability of the Warm Days index (TX90p) in shaping drought patterns in the Pantanal. The increasing occurrence of hot days is elevating surface temperatures,

directly impacting the energy balance. This temperature rise intensifies the evaporation rate, indicating greater energy use (latent heat) to transform water into vapor, leaving a significant share of sensible heat in the system. This process, in turn, increases the regional water demand, as more water is needed to meet the intensified evaporation. In terms of water management, higher temperatures and evaporation rates imply a greater demand for water to maintain ecosystem balance, posing additional challenges for water resource management. This rising demand can significantly contribute to the intensification of drought extremes, given that water supply may not be sufficient to meet growing needs.

Climate Challenges: Historical and Future Projections of Heat and Precipitation Extremes

The recurrence and intensification of extreme climate events in the Pantanal, including persistent droughts and intense rainfall, are strongly tied to the progressive rise in atmospheric greenhouse gas (GHG) concentrations (MARENGO *et al.*, 2021b). The continued increase in carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emissions constitutes a major forcing mechanism driving regional hydroclimatic variability (DALMAGRO *et al.*, 2019; LIAO *et al.*, 2024; NEUBAUER; MEGONIGAL, 2021), with projections suggesting significant amplification of both drought frequency and intensity, as well as more severe flood episodes in the coming decades (Figure 9). The interaction between anthropogenic GHG emissions and regional climate dynamics is expected to further disrupt established patterns, reinforcing trends already observed over recent decades.

Simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP-6) project substantial increases in heat-related extremes, particularly Warm Days (TX90p), across the Pantanal, contributing to a marked rise in the occurrence of heatwaves (DOS SANTOS *et al.*, 2023b; LIBONATI *et al.*, 2022). The spatial anomalies of TX90p (Figure 9a–d) indicate widespread warming relative to the historical baseline (1981–2010), with intensities increasing progressively from the low-emission SSP126 scenario to the high-emission SSP585 pathway. Temporal projections (Figure 9e) further demonstrate steep upward trajectories in TX90p across all scenarios, with the steepest increases under SSP585 extending toward the end of the century. These shifts are of particular concern because heatwaves have been shown to correlate strongly with fire incidence; linear regression models indicate that up to 82% of the interannual variation in burned area in the Pantanal is explained by heatwave variability (SILVA *et al.*, 2022). Most of these fires are triggered during the dry season, when elevated temperatures exacerbate soil desiccation, vegetation flammability, and evaporation rates, while

anthropogenic ignition sources frequently initiate large-scale burn events (BARROS-ROSA *et al.*, 2022; GEIRINHAS *et al.*, 2018).

Warm Days in Pantanal (TX90p) under Historical and Future Projections (CMIP6)

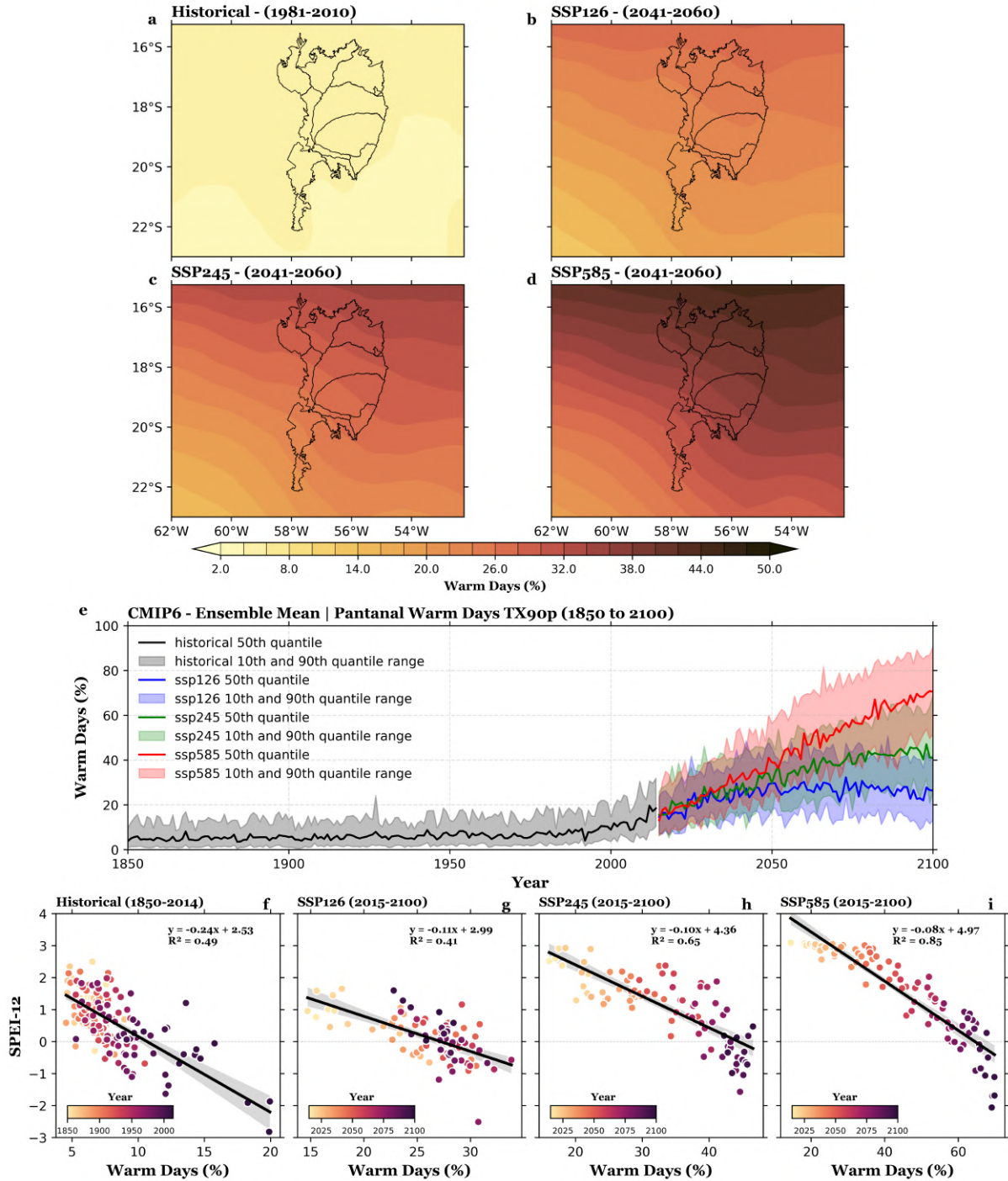


Figure 25: Ensemble mean of the Warm Days index and SPEI-12 derived from 20 Global Circulation Models (GCMs) from CMIP-6. Variability of the Warm Days index (TX90p) in the Pantanal, considering different climate scenarios defined by the Intergovernmental Panel on Climate Change (IPCC). Panels a, b, c, and d illustrate the spatial variation of TX90p anomalies. Panel a highlight historical TX90p anomalies (1981–2010) from CMIP6 simulations. Panels b, c, and d show anomalies relative to the historical period considering different SSP scenarios (SSP-126, SSP-245, SSP-585) during 2041–2060. Panel e offers a temporal view of the Warm Days index (TX90p) across all CMIP6 scenarios. Panels f, g, h, and i depict linear regressions between the Warm Days index (TX90p) and the drought index SPEI, considering all CMIP6 scenarios for the Pantanal biome.

The statistical relationships between TX90p and SPEI-12 across CMIP-6 scenarios (Figure 25f–i) further highlight the persistent role of extreme heat in shaping water balance dynamics in the Pantanal. Historically, TX90p displayed very strong, statistically significant negative correlations with SPEI-12, with R^2 exceeding 0.9 in several model realizations, confirming that increased hot-day frequency is tightly linked to intensified drought conditions. This association remains robust in future projections, with R^2 values above 0.8 even under SSP585, with only minor variations in regression slopes across scenarios that do not diminish the strength of these relationships. The low dispersion around the regression lines in all cases indicates that these projected relationships are consistent across models and pathways. Importantly, these findings are congruent with our observational analyses (Figures 21–22), where TX90p emerged as the dominant driver of drought variability, surpassing all precipitation-derived extremes in explanatory power. This convergence between historical and projected evidence suggests that the intensification of hot days will continue to act as the primary amplifier of drought stress in the Pantanal under advancing climate change.

While TX90p dominates both historical and future drought dynamics, the role of precipitation-based extremes remains secondary in explaining drought variability in the Pantanal. Historical analyses show declining trends in rainfall intensity indices such as R95p and SDII since the mid-2000s (Figure 21c–d), as well as minimal correlation between these indices and SPEI-12 (Figure 22). Although other studies project potential increases in precipitation extremes across parts of Brazil (JEFFERSON DE MEDEIROS; PRESTRELO DE OLIVEIRA; AVILA-DIAZ, 2022b), our analysis focuses exclusively on temperature-driven extremes, as no forecasts of precipitation indices were performed using CMIP-6 data. Consequently, Warm Days (TX90p) remains the most robust indicator of drought amplification both in past observations and future projections, while precipitation extremes, despite their potential regional impacts, contribute far less directly to drought severity and water balance dynamics in the Pantanal.

The projected intensification of TX90p is further influenced by broader atmospheric circulation changes, notably the increasing frequency of extreme oscillations in the Atlantic Intertropical Convergence Zone (ITCZ). CMIP-6 models indicate that the frequency of such oscillations north of the ITCZ will approximately double, rising from one event every 20.4 years in the 20th century to one every 9.3 years in the 21st century (LIU *et al.*, 2022). These oscillations are driven by a projected enhancement of the meridional temperature gradient in the tropical Atlantic, with accelerated warming in the northern hemisphere relative to the

southern hemisphere. This imbalance induces transequatorial wind anomalies and northward ITCZ shifts, processes that can suppress summer rainfall over southern Amazonia and the Pantanal (CABALLERO *et al.*, 2025; LIU *et al.*, 2022). These mechanisms, coupled with internal tropical Atlantic dynamics that operate independently of El Niño (MAKSIC *et al.*, 2022), are likely to exacerbate moisture deficits in the Pantanal (FERNANDES *et al.*, 2024) while simultaneously enhancing flood risks elsewhere in South America (BERGIER *et al.*, 2018; ZANIN; SATYAMURTY, 2020). The duality of these impacts underscores the complex teleconnections that will shape regional hydroclimatic regimes in coming decades.

Taken together, CMIP-6 projections indicate that the Pantanal will face compounding challenges as climate change progresses. Rising TX90p frequencies—historically the strongest predictor of drought severity (Figures 21–22) and projected to remain so (Figure 25)—are expected to elevate evaporative demand, reduce water availability, and heighten wildfire risk. Concurrently, projected changes in precipitation extremes, although less directly tied to SPEI-12 dynamics, will likely concentrate total rainfall into fewer but more intense events, complicating water resource management and flood mitigation (DA SILVA *et al.*, 2023). These findings highlight the urgency of developing integrated adaptation and risk management strategies that account for the synergistic effects of heat extremes, shifting precipitation regimes, and large-scale circulation changes on the Pantanal’s ecosystems and socio-economic systems.

CONCLUSIONS

The Pantanal is experiencing a clear intensification of droughts, with SPEI-12 revealing persistent declines and Run Theory indicating that drought duration, severity, and intensity have all increased in recent decades, culminating in unprecedented multi-year events during 2020–2022, especially in its Central and Southern regions. These changes are driven by the convergence of declining precipitation, rising temperatures, and extensive land-use transformation, including a 373% expansion of agricultural areas and an 80% reduction in surface water bodies since 1985. Warm Days (TX90p) emerges as the dominant driver of drought severity, historically and in CMIP-6 projections, while extreme rainfall indices contribute less directly to drought dynamics despite projected increases.

These findings emphasize the urgency of integrated adaptation and mitigation strategies to protect Pantanal’s ecological and socio-economic systems. Priority actions include conserving and restoring wetlands, implementing water management plans that address rising

evaporative demand and increasingly concentrated rainfall, and strengthening fire mitigation measures tailored to intensifying heat extremes. By connecting observed trends with future projections, this study provides critical guidance for anticipating climate-related risks and informing policies that enhance the resilience of the world's largest tropical wetland.

5 GENERAL CONCLUSION

Os resultados desta tese demonstram a intensificação dos extremos climáticos na América do Sul, com destaque para o Pantanal, caracterizada pelo aumento de dias quentes, maior frequência e duração de secas (SPEI-12) e maior variabilidade da precipitação, incluindo chuvas intensas intercaladas por períodos secos.

As análises revelaram que anomalias de temperatura da superfície do mar no Pacífico (ENSO) e no Atlântico (TNA/TSA) modulam diretamente esses padrões, interagindo com mudanças no uso e cobertura do solo, especialmente a expansão agropecuária e a redução das áreas úmidas, ampliando o déficit hídrico.

As projeções climáticas (CMIP6) indicam o agravamento desses extremos sobre o Pantanal em todos os cenários futuros, reforçando a necessidade de estratégias de gestão hídrica, conservação ambiental e planejamento territorial.

Assim, este estudo fornece subsídios técnicos e científicos relevantes para políticas de adaptação e mitigação, visando reduzir a vulnerabilidade socioambiental e proteger ecossistemas estratégicos como o Pantanal.

6 REFERENCES

- AFJAL HOSSAIN, Md.; IMRAN REZA, Md.; RAHMAN, S.; KAYES, I. Climate Change and its Impacts on the Livelihoods of the Vulnerable People in the Southwestern Coastal Zone in Bangladesh. *Em: LEAL FILHO, W. Climate Change and the Sustainable Use of Water Resources*. Climate Change Management. Berlin, Heidelberg: Springer, 2012. p. 237–259.
- ALMAZROUI, M.; SAEED, F.; SAEED, S.; ISMAIL, M.; EHSAN, M. A.; ISLAM, M. N.; ABID, M. A.; O'BRIEN, E.; KAMIL, S.; RASHID, I. U.; NADEEM, I. Projected Changes in Climate Extremes Using CMIP6 Simulations Over SREX Regions. **Earth Systems and Environment**, v. 5, n. 3, p. 481–497, 1 set. 2021.
- ALVAREZ, M. S.; VERA, C. S.; KILADIS, G. N. MJO Modulating the Activity of the Leading Mode of Intraseasonal Variability in South America. **Atmosphere**, v. 8, n. 12, p. 232, dez. 2017.
- ANDERSON, L. O.; RIBEIRO NETO, G.; CUNHA, A. P.; FONSECA, M. G.; MENDES DE MOURA, Y.; DALAGNOL, R.; WAGNER, F. H.; DE ARAGÃO, L. E. O. e C. Vulnerability of Amazonian forests to repeated droughts. **Philosophical Transactions of the Royal Society B: Biological Sciences**, v. 373, n. 1760, p. 20170411, 8 out. 2018.
- ANJOS, L. J. S.; TOLEDO, P. M. de. Measuring Resilience and Assessing Vulnerability of Terrestrial Ecosystems to Climate Change in South America. **PLOS ONE**, v. 13, n. 3, p. e0194654, 19 mar. 2018.
- ARAUJO, A. G. de J.; OBREGÓN, G. O.; SAMPAIO, G.; MONTEIRO, A. M. V.; DA SILVA, L. T.; SORIANO, B.; PADOVANI, C.; RODRIGUEZ, D. A.; MAKSIĆ, J.; FARIAS, J. F. S. Relationships between Variability in Precipitation, River Levels, and Beef Cattle Production in the Brazilian Pantanal. **Wetlands Ecology and Management**, v. 26, n. 5, p. 829–848, 1 out. 2018.
- ASSINE, M. L.; MACEDO, H. A.; STEVAUX, J. C.; BERGIER, I.; PADOVANI, C. R.; SILVA, A. Avulsive Rivers in the Hydrology of the Pantanal Wetland. *Em: BERGIER, I.; ASSINE, M. L. Dynamics of the Pantanal Wetland in South America*. Cham: Springer International Publishing, 2016. p. 83–110.
- AVILA-DIAZ, A.; ABRAHÃO, G.; JUSTINO, F.; TORRES, R.; WILSON, A. Extreme Climate Indices in Brazil: Evaluation of Downscaled Earth System Models at High Horizontal Resolution. **Climate Dynamics**, v. 54, n. 11, p. 5065–5088, 1 jun. 2020a.
- AVILA-DIAZ, A.; BENEZOLI, V.; JUSTINO, F.; TORRES, R.; WILSON, A. Assessing Current and Future Trends of Climate Extremes across Brazil Based on Reanalyses and Earth System Model Projections. **Climate Dynamics**, v. 55, n. 5, p. 1403–1426, 2020b.
- AVILA-DIAZ, A.; TORRES, R. R.; ZULUAGA, C. F.; CERÓN, W. L.; OLIVEIRA, L.; BENEZOLI, V.; RIVERA, I. A.; MARENGO, J. A.; WILSON, A. B.; MEDEIROS, F. Current and Future Climate Extremes Over Latin America and Caribbean: Assessing Earth System Models from High Resolution Model Intercomparison Project (HighResMIP). **Earth Systems and Environment**, v. 7, n. 1, p. 99–130, 1 jan. 2023a.

- AVILA-DIAZ, A.; TORRES, R. R.; ZULUAGA, C. F.; CERÓN, W. L.; OLIVEIRA, L.; BENEZOLI, V.; RIVERA, I. A.; MARENGO, J. A.; WILSON, A. B.; MEDEIROS, F. Current and Future Climate Extremes Over Latin America and Caribbean: Assessing Earth System Models from High Resolution Model Intercomparison Project (HighResMIP). **Earth Systems and Environment**, v. 7, n. 1, p. 99–130, 1 jan. 2023b.
- BARI, S. H.; RAHMAN, M. T. U.; HOQUE, M. A.; HUSSAIN, Md. M. Analysis of Seasonal and Annual Rainfall Trends in the Northern Region of Bangladesh. **Atmospheric Research**, v. 176–177, p. 148–158, jul. 2016.
- BARICHIVICH, J.; GLOOR, E.; PEYLIN, P.; BRIENEN, R. J. W.; SCHÖNGART, J.; ESPINOZA, J. C.; PATTNAYAK, K. C. Recent intensification of Amazon flooding extremes driven by strengthened Walker circulation. **Science Advances**, v. 4, n. 9, p. eaat8785, 19 set. 2018.
- BARROS-ROSA, L.; DE ARRUDA, P. H. Z.; MACHADO, N. G.; PIRES-OLIVEIRA, J. C.; EISENLOHR, P. V. Fire probability mapping and prediction from environmental data: What a comprehensive savanna-forest transition can tell us. **Forest Ecology and Management**, v. 520, p. 120354, 15 set. 2022.
- BELGIU, M.; DRĂGUȚ, L. Random Forest in Remote Sensing: A Review of Applications and Future Directions. **ISPRS Journal of Photogrammetry and Remote Sensing**, v. 114, p. 24–31, 1 abr. 2016.
- BERGIER, I.; ASSINE, M. L.; MCGLUE, M. M.; ALHO, C. J. R.; SILVA, A.; GUERREIRO, R. L.; CARVALHO, J. C. Amazon rainforest modulation of water security in the Pantanal wetland. **Science of The Total Environment**, v. 619–620, p. 1116–1125, 1 abr. 2018.
- BEVACQUA, E.; DE MICHELE, C.; MANNING, C.; COUASNON, A.; RIBEIRO, A. F. S.; RAMOS, A. M.; VIGNOTTO, E.; BASTOS, A.; BLESIC, S.; DURANTE, F.; HILLIER, J.; OLIVEIRA, S. C.; PINTO, J. G.; RAGNO, E.; RIVOIRE, P.; SAUNDERS, K.; VAN DER WIEL, K.; WU, W.; ZHANG, T.; ZSCHEISCHLER, J. Guidelines for Studying Diverse Types of Compound Weather and Climate Events. **Earth's Future**, v. 9, n. 11, p. e2021EF002340, 2021.
- BIUDES, M. S.; GELI, H. M. E.; VOURLITIS, G. L.; MACHADO, N. G.; PAVÃO, V. M.; DOS SANTOS, L. O. F.; QUERINO, C. A. S. Evapotranspiration Seasonality over Tropical Ecosystems in Mato Grosso, Brazil. **Remote Sensing**, v. 14, n. 10, p. 2482, jan. 2022a.
- BIUDES, M. S.; GELI, H. M. E.; VOURLITIS, G. L.; MACHADO, N. G.; PAVÃO, V. M.; DOS SANTOS, L. O. F.; QUERINO, C. A. S. Evapotranspiration Seasonality over Tropical Ecosystems in Mato Grosso, Brazil. **Remote Sensing**, v. 14, n. 10, p. 2482, jan. 2022b.
- BIUDES, M. S.; VOURLITIS, G. L.; MACHADO, N. G.; DE ARRUDA, P. H. Z.; NEVES, G. A. R.; DE ALMEIDA LOBO, F.; NEALE, C. M. U.; DE SOUZA NOGUEIRA, J. Patterns of Energy Exchange for Tropical Ecosystems across a Climate Gradient in Mato Grosso, Brazil. **Agricultural and Forest Meteorology**, v. 202, p. 112–124, 15 mar. 2015.
- BOERS, N.; MARWAN, N.; BARBOSA, H. M. J.; KURTHS, J. A Deforestation-Induced Tipping Point for the South American Monsoon System. **Scientific Reports**, v. 7, n. 1, p. 41489, 25 jan. 2017.

BREIMAN, L. Random Forests. **Machine Learning**, v. 45, n. 1, p. 5–32, 1 out. 2001.

BRETHERTON, C. S.; WIDMANN, M.; DYMNIKOV, V. P.; WALLACE, J. M.; BLADÉ, I. The Effective Number of Spatial Degrees of Freedom of a Time-Varying Field. **Journal of Climate**, v. 12, n. 7, p. 1990–2009, 1 jul. 1999.

CABALLERO, C. B.; BIGGS, T. W.; VERGOPOLAN, N.; CAMELO, L. G. G.; DE ANDRADE, B. C.; LAIPELT, L.; L. RUHOFF, A. Decadal Hydroclimatic Changes in the Pantanal, the World's Largest Tropical Wetland. **Scientific Reports**, v. 15, n. 1, p. 17675, 21 maio 2025.

CABOS, W.; DE LA VARA, A.; KOSEKI, S. Tropical Atlantic Variability: Observations and Modeling. **Atmosphere**, v. 10, n. 9, p. 502, set. 2019.

CAI, W.; BORLACE, S.; LENGAGNE, M.; VAN RENSCH, P.; COLLINS, M.; VECCHI, G.; TIMMERMAN, A.; SANTOSO, A.; MCPHADEN, M. J.; WU, L.; ENGLAND, M. H.; WANG, G.; GUILYARDI, E.; JIN, F.-F. Increasing Frequency of Extreme El Niño Events Due to Greenhouse Warming. **Nature Climate Change**, v. 4, n. 2, p. 111–116, fev. 2014.

CAI, W.; MCPHADEN, M. J.; GRIMM, A. M.; RODRIGUES, R. R.; TASCHETTO, A. S.; GARREAUD, R. D.; DEWITTE, B.; POVEDA, G.; HAM, Y.-G.; SANTOSO, A.; NG, B.; ANDERSON, W.; WANG, G.; GENG, T.; JO, H.-S.; MARENGO, J. A.; ALVES, L. M.; OSMAN, M.; LI, S.; WU, L.; KARAMPERIDOU, C.; TAKAHASHI, K.; VERA, C. Climate Impacts of the El Niño–Southern Oscillation on South America. **Nature Reviews Earth & Environment**, v. 1, n. 4, p. 215–231, abr. 2020a.

CAI, W.; MCPHADEN, M. J.; GRIMM, A. M.; RODRIGUES, R. R.; TASCHETTO, A. S.; GARREAUD, R. D.; DEWITTE, B.; POVEDA, G.; HAM, Y.-G.; SANTOSO, A.; NG, B.; ANDERSON, W.; WANG, G.; GENG, T.; JO, H.-S.; MARENGO, J. A.; ALVES, L. M.; OSMAN, M.; LI, S.; WU, L.; KARAMPERIDOU, C.; TAKAHASHI, K.; VERA, C. Climate Impacts of the El Niño–Southern Oscillation on South America. **Nature Reviews Earth & Environment**, v. 1, n. 4, p. 215–231, abr. 2020b.

CARVALHO, M. Â. C. C. de; ULIANA, E. M.; SILVA, D. D. da; AIRES, U. R. V.; MARTINS, C. A. da S.; SOUSA JUNIOR, M. F. de; CRUZ, I. F. da; MENDES, M. A. dos S. A. Drought Monitoring Based on Remote Sensing in a Grain-Producing Region in the Cerrado–Amazon Transition, Brazil. **Water**, v. 12, n. 12, p. 3366, dez. 2020.

CASTELLANOS, E. J.; LEMOS, M. F. IPCC Sixth Assessment Report (AR6): Climate Change 2022 - Impacts, Adaptation and Vulnerability: Regional Factsheet Central and South America. 28 fev. 2022. Disponível em: <https://policycommons.net/artifacts/2264324/ipcc_ar6_wgii_factsheet_centralouthamerica-1/3023378/>. Acesso em: 20 fev. 2024.

CHAPARINIA, F.; HADEI, M.; YAGHMAEIAN, K.; HADI, M.; NADDAFI, K. Evaluation of Climate Indices Related to Water Resources in Iran over the Past 3 Decades. **Scientific Reports**, v. 15, n. 1, p. 11846, 7 abr. 2025.

COLLAZO, S.; BARRUCAND, M.; RUSTICUCCI, M. Evaluation of CMIP6 Models in the Representation of Observed Extreme Temperature Indices Trends in South America. **Climatic Change**, v. 172, n. 1, p. 21, 30 maio 2022a.

COLLAZO, S.; BARRUCAND, M.; RUSTICUCCI, M. Evaluation of CMIP6 Models in the Representation of Observed Extreme Temperature Indices Trends in South America. **Climatic Change**, v. 172, n. 1, p. 21, 30 maio 2022b.

COSTA, R. L.; MACEDO DE MELLO BAPTISTA, G.; GOMES, H. B.; DANIEL DOS SANTOS SILVA, F.; LINS DA ROCHA JÚNIOR, R.; DE ARAÚJO SALVADOR, M.; HERDIES, D. L. Analysis of Climate Extremes Indices over Northeast Brazil from 1961 to 2014. **Weather and Climate Extremes**, v. 28, p. 100254, 1 jun. 2020a.

COSTA, R. L.; MACEDO DE MELLO BAPTISTA, G.; GOMES, H. B.; DANIEL DOS SANTOS SILVA, F.; LINS DA ROCHA JÚNIOR, R.; DE ARAÚJO SALVADOR, M.; HERDIES, D. L. Analysis of Climate Extremes Indices over Northeast Brazil from 1961 to 2014. **Weather and Climate Extremes**, v. 28, p. 100254, 1 jun. 2020b.

CREMADES, R.; SANCHEZ-PLAZA, A.; HEWITT, R. J.; MITTER, H.; BAGGIO, J. A.; OLAZABAL, M.; BROEKMAN, A.; KROPF, B.; TUDOSE, N. C. Guiding cities under increased droughts: The limits to sustainable urban futures. **Ecological Economics**, v. 189, p. 107140, 1 nov. 2021.

CUNHA, A. P. M. A.; BUERMANN, W.; MARENGO, J. A. Changes in Compound Drought-Heat Events over Brazil's Pantanal Wetland: An Assessment Using Remote Sensing Data and Multiple Drought Indicators. **Climate Dynamics**, v. 62, n. 1, p. 739–757, 1 jan. 2024.

CURADO, L. F. A.; DE PAULO, S. R.; DE PAULO, I. J. C.; DE OLIVEIRA MAIONCHI, D.; DA SILVA, H. J. A.; DE OLIVEIRA COSTA, R.; DA SILVA, I. M. C. B.; MARQUES, J. B.; DE SOUZA LIMA, A. M.; RODRIGUES, T. R. Trends and Patterns of Daily Maximum, Minimum and Mean Temperature in Brazil from 2000 to 2020. **Climate**, v. 11, n. 8, p. 168, ago. 2023.

DA SILVA, M. L.; DE OLIVEIRA, C. P.; E SILVA, C. M. S.; DE ARAÚJO, J. M. Analysis of Climate Extremes Indices in Tropical South America through the RegCM4.7. **International Journal of Climatology**, v. 43, n. 10, p. 4506–4531, 2023.

DA SILVA, P. E.; SANTOS E SILVA, C. M.; SPYRIDES, M. H. C.; ANDRADE, L. D. M. B. Precipitation and Air Temperature Extremes in the Amazon and Northeast Brazil. **International Journal of Climatology**, v. 39, n. 2, p. 579–595, fev. 2019.

D'ACUNHA, B.; DALMAGRO, H. J.; ZANELLA DE ARRUDA, P. H.; BIUDES, M. S.; LATHUILLIÈRE, M. J.; URIBE, M.; COUTO, E. G.; BRANDO, P. M.; VOURLITIS, G.; JOHNSON, M. S. Changes in evapotranspiration, transpiration and evaporation across natural and managed landscapes in the Amazon, Cerrado and Pantanal biomes. **Agricultural and Forest Meteorology**, v. 346, p. 109875, 1 mar. 2024.

DAHER, B.; HAMIE, S.; PAPPAS, K.; NAHIDUL KARIM, M.; THOMAS, T. Toward Resilient Water-Energy-Food Systems under Shocks: Understanding the Impact of Migration, Pandemics, and Natural Disasters. **Sustainability**, v. 13, n. 16, p. 9402, jan. 2021.

DALMAGRO, H. J.; ZANELLA DE ARRUDA, P. H.; VOURLITIS, G. L.; LATHUILLIÈRE, M. J.; DE S. NOGUEIRA, J.; COUTO, E. G.; JOHNSON, M. S. Radiative Forcing of Methane Fluxes Offsets Net Carbon Dioxide Uptake for a Tropical Flooded Forest. **Global Change Biology**, v. 25, n. 6, p. 1967–1981, 2019.

- DE MEDEIROS, F. J.; DE OLIVEIRA, C. P.; TORRES, R. R. Climatic Aspects and Vertical Structure Circulation Associated with the Severe Drought in Northeast Brazil (2012–2016). **Climate Dynamics**, v. 55, n. 9, p. 2327–2341, 1 nov. 2020.
- DE MORAIS, M. D. C.; GAN, M. A.; YOSHIDA, M. C. Features of the Upper Tropospheric Cyclonic Vortices of Northeast Brazil in Life Cycle Stages. **International Journal of Climatology**, v. 41, n. S1, p. E39–E58, 2021.
- DE SOUZA, I. P.; ANDREOLI, R. V.; KAYANO, M. T.; VARGAS, F. F.; CERÓN, W. L.; MARTINS, J. A.; FREITAS, E.; DE SOUZA, R. A. F. Seasonal Precipitation Variability Modes over South America Associated to El Niño-Southern Oscillation (ENSO) and Non-ENSO Components during the 1951–2016 Period. **International Journal of Climatology**, v. 41, n. 8, p. 4321–4338, 2021.
- DOS SANTOS, C. A. C.; NEALE, C. M. U.; MEKONNEN, M. M.; GONÇALVES, I. Z.; DE OLIVEIRA, G.; RUIZ-ALVAREZ, O.; SAFA, B.; ROWE, C. M. Trends of Extreme Air Temperature and Precipitation and Their Impact on Corn and Soybean Yields in Nebraska, USA. **Theoretical and Applied Climatology**, v. 147, n. 3, p. 1379–1399, 1 fev. 2022.
- DOS SANTOS, L. O. F.; MACHADO, N. G.; BIUDES, M. S.; GELI, H. M. E.; QUERINO, C. A. S.; RUHOFF, A. L.; IVO, I. O.; LOTUFO NETO, N. Trends in Precipitation and Air Temperature Extremes and Their Relationship with Sea Surface Temperature in the Brazilian Midwest. **Atmosphere**, v. 14, n. 3, p. 426, mar. 2023a.
- DOS SANTOS, L. O. F.; MACHADO, N. G.; BIUDES, M. S.; GELI, H. M. E.; QUERINO, C. A. S.; RUHOFF, A. L.; IVO, I. O.; LOTUFO NETO, N. Trends in Precipitation and Air Temperature Extremes and Their Relationship with Sea Surface Temperature in the Brazilian Midwest. **Atmosphere**, v. 14, n. 3, p. 426, mar. 2023b.
- DOS SANTOS, L. O. F.; MACHADO, N. G.; QUERINO, C. A. S.; BIUDES, M. S. Trends of Climate Extremes and Their Relationships with Tropical Ocean Temperatures in South America. **Earth**, v. 5, n. 4, p. 844–872, dez. 2024.
- DOSIO, A.; MENTASCHI, L.; FISCHER, E. M.; WYSER, K. Extreme Heat Waves under 1.5 °C and 2 °C Global Warming. **Environmental Research Letters**, v. 13, n. 5, p. 054006, abr. 2018.
- DRUMOND, A.; MARENGO, J.; AMBRIZZI, T.; NIETO, R.; MOREIRA, L.; GIMENO, L. The Role of the Amazon Basin Moisture in the Atmospheric Branch of the Hydrological Cycle: A Lagrangian Analysis. **Hydrology and Earth System Sciences**, v. 18, n. 7, p. 2577–2598, 11 jul. 2014.
- DUNN, R. J. H.; ALEXANDER, L. V.; DONAT, M. G.; ZHANG, X.; BADOR, M.; HEROLD, N.; LIPPMANN, T.; ALLAN, R.; AGUILAR, E.; BARRY, A. A.; BRUNET, M.; CAESAR, J.; CHAGNAUD, G.; CHENG, V.; CINCO, T.; DURRE, I.; DE GUZMAN, R.; HTAY, T. M.; WAN IBADULLAH, W. M.; BIN IBRAHIM, M. K. I.; KHOSHKAM, M.; KRUGER, A.; KUBOTA, H.; LENG, T. W.; LIM, G.; LI-SHA, L.; MARENGO, J.; MBATHA, S.; MCGREE, S.; MENNE, M.; DE LOS MILAGROS SKANSI, M.; NGWENYA, S.; NKRUMAH, F.; OONARIYA, C.; PABON-CAICEDO, J. D.; PANTHOU, G.; PHAM, C.; RAHIMZADEH, F.; RAMOS, A.; SALGADO, E.; SALINGER, J.; SANÉ, Y.; SOPAHELUWAKAN, A.; SRIVASTAVA, A.; SUN, Y.; TIMBAL, B.; TRACHOW, N.;

- TREWIN, B.; VAN DER SCHRIER, G.; VAZQUEZ-AGUIRRE, J.; VASQUEZ, R.; VILLARROEL, C.; VINCENT, L.; VISCHER, T.; VOSE, R.; BIN HJ YUSSOF, M. N. Development of an Updated Global Land In Situ-Based Data Set of Temperature and Precipitation Extremes: HadEX3. **Journal of Geophysical Research: Atmospheres**, v. 125, n. 16, p. e2019JD032263, 2020.
- ESCOBAR, G. C. J.; MARQUES, A. C. de A.; DERECHYNSKI, C. P.; ESCOBAR, G. C. J.; MARQUES, A. C. de A.; DERECHYNSKI, C. P. Synoptic Patterns of South Atlantic Convergence Zone Episodes Associated with Heavy Rainfall Events in the City of Rio de Janeiro, Brazil. **Atmosfera**, v. 35, n. 2, p. 287–305, 2022.
- ESPINOZA, J.-C.; JIMENEZ, J. C.; MARENGO, J. A.; SCHONGART, J.; RONCHAIL, J.; LAVADO-CASIMIRO, W.; RIBEIRO, J. V. M. The New Record of Drought and Warmth in the Amazon in 2023 Related to Regional and Global Climatic Features. **Scientific Reports**, v. 14, n. 1, p. 8107, 6 abr. 2024.
- EYRING, V.; BONY, S.; MEEHL, G. A.; SENIOR, C. A.; STEVENS, B.; STOUFFER, R. J.; TAYLOR, K. E. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) Experimental Design and Organization. **Geoscientific Model Development**, v. 9, n. 5, p. 1937–1958, 26 maio 2016.
- FALSTER, G.; KONECKY, B.; COATS, S.; STEVENSON, S. Forced Changes in the Pacific Walker Circulation over the Past Millennium. **Nature**, v. 622, n. 7981, p. 93–100, out. 2023.
- FERNANDES, F. A. C.; SANTOS, L. O. F. dos; NUNES, N. da C.; MACHADO, N. G.; BIUDES, M. S. Quantifying Droughts in Mato Grosso with SPI and SPEI: Exploring Connections to Tropical Sea Surface Temperatures. **Theoretical and Applied Climatology**, v. 155, n. 11, p. 9751–9766, 1 nov. 2024.
- FERNANDES, L. G.; GRIMM, A. M. ENSO Modulation of Global MJO and Its Impacts on South America. 13 out. 2023. Disponível em: <<https://journals.ametsoc.org/view/journals/clim/36/22/JCLI-D-22-0781.1.xml>>. Acesso em: 3 jul. 2025.
- FERON, S.; CORDERO, R. R.; DAMIANI, A.; LLANILLO, P. J.; JORQUERA, J.; SEPULVEDA, E.; ASECIO, V.; LAROZE, D.; LABBE, F.; CARRASCO, J.; TORRES, G. Observations and Projections of Heat Waves in South America. **Scientific Reports**, v. 9, n. 1, p. 8173, 3 jun. 2019.
- FERON, S.; CORDERO, R. R.; DAMIANI, A.; MACDONELL, S.; PIZARRO, J.; GOUBANOVA, K.; VALENZUELA, R.; WANG, C.; RENTER, L.; BEAULIEU, A. South America Is Becoming Warmer, Drier, and More Flammable. **Communications Earth & Environment**, v. 5, n. 1, p. 501, 26 set. 2024.
- FERREIRA BARBOSA, M. L.; DELGADO, R. C.; FORSAD DE ANDRADE, C.; TEODORO, P. E.; SILVA JUNIOR, C. A.; WANDERLEY, H. S.; CAPRISTO-SILVA, G. F. Recent trends in the fire dynamics in Brazilian Legal Amazon: Interaction between the ENSO phenomenon, climate and land use. **Environmental Development**, v. 39, p. 100648, 1 set. 2021.
- FERREIRA BARBOSA, M. L.; HADDAD, I.; DA SILVA NASCIMENTO, A. L.; MÁXIMO DA SILVA, G.; MOURA DA VEIGA, R.; HOFFMANN, T. B.; ROSANE DE

SOUZA, A.; DALAGNOL, R.; SUSIN STREHER, A.; SOUZA PEREIRA, F. R.; OLIVEIRA E CRUZ DE ARAGÃO, L. E.; OIGHENSTEIN ANDERSON, L. Compound Impact of Land Use and Extreme Climate on the 2020 Fire Record of the Brazilian Pantanal. **Global Ecology and Biogeography**, v. 31, n. 10, p. 1960–1975, 2022.

FIALHO, W. M. B.; CARVALHO, L. M. V.; GAN, M. A.; VEIGA, S. F. Mechanisms Controlling Persistent South Atlantic Convergence Zone Events on Intraseasonal Timescales. **Theoretical and Applied Climatology**, v. 152, n. 1, p. 75–96, 1 abr. 2023.

FLANTUA, S. G. A.; HOOGHIESTR, H.; VUILLE, M.; BEHLING, H.; CARSON, J. F.; GOSLING, W. D.; HOYOS, I.; LEDRU, M. P.; MONTOYA, E.; MAYLE, F.; MALDONADO, A.; RULL, V.; TONELLO, M. S.; WHITNEY, B. S.; GONZÁLEZ-ARANGO, C. Climate Variability and Human Impact in South America during the Last 2000 Years: Synthesis and Perspectives from Pollen Records. **Climate of the Past**, v. 12, n. 2, p. 483–523, 29 fev. 2016.

GARREAUD, R. D. The Andes Climate and Weather. **Advances in Geosciences**, v. 22, p. 3–11, 13 out. 2009.

GEIRINHAS, J. L.; TRIGO, R. M.; LIBONATI, R.; COELHO, C. A. S.; PALMEIRA, A. C. Climatic and Synoptic Characterization of Heat Waves in Brazil. **International Journal of Climatology**, v. 38, n. 4, p. 1760–1776, 2018.

GHAEDAMINI, H. A.; MORID, S.; NAZEMOSADAT, M. J.; SHAMSODDINI, A.; MOGHADAM, H. S. Validation of the CHIRPS and CPC-Unified Products for Estimating Extreme Daily Precipitation over Southwestern Iran. **Theoretical and Applied Climatology**, v. 146, n. 3, p. 1207–1225, 1 nov. 2021.

GIMENO, L.; SORÍ, R.; VÁZQUEZ, M.; STOJANOVIC, M.; ALGARRA, I.; EIRAS-BARCA, J.; GIMENO-SOTELO, L.; NIETO, R. Extreme Precipitation Events. **WIREs Water**, v. 9, n. 6, p. e1611, 2022.

GLEIXNER, S.; DEMISSIE, T.; DIRO, G. T. Did ERA5 Improve Temperature and Precipitation Reanalysis over East Africa? **Atmosphere**, v. 11, n. 9, p. 996, set. 2020.

GOUVEIA, C. D.; RODRIGUES TORRES, R.; MARENGO, J. A.; AVILA-DIAZ, A. Uncertainties in Projections of Climate Extremes Indices in South America via Bayesian Inference. **International Journal of Climatology**, v. 42, n. 14, p. 7362–7382, 2022.

GRILLAKIS, M. G.; KOUTROULIS, A. G.; ALEXAKIS, D. D.; POLYKRETIS, C.; DALIAKOPOULOS, I. N. Regionalizing Root-Zone Soil Moisture Estimates From ESA CCI Soil Water Index Using Machine Learning and Information on Soil, Vegetation, and Climate. **Water Resources Research**, v. 57, n. 5, p. e2020WR029249, 2021.

GRIMM, A. M. Madden–Julian Oscillation Impacts on South American Summer Monsoon Season: Precipitation Anomalies, Extreme Events, Teleconnections, and Role in the MJO Cycle. **Climate Dynamics**, v. 53, n. 1, p. 907–932, 1 jul. 2019.

GRISE, K. M.; DAVIS, S. M. Hadley Cell Expansion in CMIP6 Models. **Atmospheric Chemistry and Physics**, v. 20, n. 9, p. 5249–5268, 6 maio 2020.

GUERRA, A.; ROQUE, F. de O.; GARCIA, L. C.; OCHOA-QUINTERO, J. M.; OLIVEIRA, P. T. S. de; GUARIENTO, R. D.; ROSA, I. M. D. Drivers and projections of vegetation loss in the Pantanal and surrounding ecosystems. **Land Use Policy**, v. 91, p. 104388, 1 fev. 2020.

GUMUS, V. Evaluating the effect of the SPI and SPEI methods on drought monitoring over Turkey. **Journal of Hydrology**, v. 626, p. 130386, 1 nov. 2023.

HIRSCH, A. L.; RIDDER, N. N.; PERKINS-KIRKPATRICK, S. E.; UKKOLA, A. CMIP6 MultiModel Evaluation of Present-Day Heatwave Attributes. **Geophysical Research Letters**, v. 48, n. 22, p. e2021GL095161, 2021.

HUANG, B.; THORNE, P. W.; BANZON, V. F.; BOYER, T.; CHEPURIN, G.; LAWRIMORE, J. H.; MENNE, M. J.; SMITH, T. M.; VOSE, R. S.; ZHANG, H.-M. Extended Reconstructed Sea Surface Temperature, Version 5 (ERSSTv5): Upgrades, Validations, and Intercomparisons. **Journal of Climate**, v. 30, n. 20, p. 8179–8205, 15 out. 2017.

ITURBIDE, M.; GUTIÉRREZ, J. M.; ALVES, L. M.; BEDIA, J.; CEREZO-MOTA, R.; CIMADEVILLA, E.; COFIÑO, A. S.; DI LUCA, A.; FARIA, S. H.; GORODETSKAYA, I. V.; HAUSER, M.; HERRERA, S.; HENNESSY, K.; HEWITT, H. T.; JONES, R. G.; KRAKOVSKA, S.; MANZANAS, R.; MARTÍNEZ-CASTRO, D.; NARISMA, G. T.; NURHATI, I. S.; PINTO, I.; SENEVIRATNE, S. I.; VAN DEN HURK, B.; VERA, C. S. An Update of IPCC Climate Reference Regions for Subcontinental Analysis of Climate Model Data: Definition and Aggregated Datasets. **Earth System Science Data**, v. 12, n. 4, p. 2959–2970, 18 nov. 2020.

JEFERSON DE MEDEIROS, F.; PRESTRELO DE OLIVEIRA, C.; AVILA-DIAZ, A. Evaluation of extreme precipitation climate indices and their projected changes for Brazil: From CMIP3 to CMIP6. **Weather and Climate Extremes**, v. 38, p. 100511, 1 dez. 2022a.

JEFERSON DE MEDEIROS, F.; PRESTRELO DE OLIVEIRA, C.; AVILA-DIAZ, A. Evaluation of extreme precipitation climate indices and their projected changes for Brazil: From CMIP3 to CMIP6. **Weather and Climate Extremes**, v. 38, p. 100511, 1 dez. 2022b.

JIMÉNEZ-MUÑOZ, J. C.; MATTAR, C.; SOBRINO, J. A.; MALHI, Y. Digital thermal monitoring of the Amazon forest: an intercomparison of satellite and reanalysis products. **International Journal of Digital Earth**, v. 9, n. 5, p. 477–498, 3 maio 2016.

JIN, X.; JIANG, P.; DU, H.; CHEN, D.; LI, M. Response of Local Temperature Variation to Land Cover and Land Use Intensity Changes in China over the Last 30 Years. **Climatic Change**, v. 164, n. 3, p. 34, 8 fev. 2021.

JOHN, A.; DOUVILLE, H.; RIBES, A.; YIOU, P. Quantifying CMIP6 model uncertainties in extreme precipitation projections. **Weather and Climate Extremes**, v. 36, p. 100435, 1 jun. 2022.

JUNQUAS, C.; TAKAHASHI, K.; CONDOM, T.; ESPINOZA, J.-C.; CHAVEZ, S.; SICART, J.-E.; LEBEL, T. Understanding the Influence of Orography on the Precipitation Diurnal Cycle and the Associated Atmospheric Processes in the Central Andes. **Climate Dynamics**, v. 50, n. 11, p. 3995–4017, 1 jun. 2018.

KHAN, M. M. H.; BRYCESON, I.; KOLIVRAS, K. N.; FARUQUE, F.; RAHMAN, M. M.; HAQUE, U. Natural Disasters and Land-Use/Land-Cover Change in the Southwest Coastal Areas of Bangladesh. **Regional Environmental Change**, v. 15, n. 2, p. 241–250, 1 fev. 2015.

KIM, S.-Y.; CHOI, Y.-J.; SON, S.-W.; GRISE, K. M.; STATEN, P. W.; AN, S.-I.; YEH, S.-W.; KUG, J.-S.; MIN, S.-K.; SHIN, J. Hemispherically asymmetric Hadley cell response to CO₂ removal. **Science Advances**, v. 9, n. 30, p. eadg1801, 26 jul. 2023.

KUMAR, S.; GETIRANA, A.; LIBONATI, R.; HAIN, C.; MAHANAMA, S.; ANDELA, N. Changes in Land Use Enhance the Sensitivity of Tropical Ecosystems to Fire-Climate Extremes. **Scientific Reports**, v. 12, n. 1, p. 964, 19 jan. 2022.

LAGOS-ZÚÑIGA, M.; BALMACEDA-HUARTE, R.; REGOTO, P.; TORREZ, L.; OLMO, M.; LYRA, A.; PAREJA-QUISPE, D.; BETTOLLI, M. L. Extreme Indices of Temperature and Precipitation in South America: Trends and Intercomparison of Regional Climate Models. **Climate Dynamics**, v. 62, n. 6, p. 4541–4562, 1 jun. 2024.

LAIMIGHOFER, J.; LAAHA, G. How standard are standardized drought indices? Uncertainty components for the SPI & SPEI case. **Journal of Hydrology**, v. 613, p. 128385, 1 out. 2022.

LAUREANTI, N. C.; CHOU, S. C.; NOBRE, P.; CURCHITSER, E. On the relationship between the South Atlantic Convergence Zone and sea surface temperature during Central-East Brazil extreme precipitation events. **Dynamics of Atmospheres and Oceans**, v. 105, p. 101422, 1 mar. 2024.

LÁZARO, W. L.; OLIVEIRA-JÚNIOR, E. S.; SILVA, C. J. da; CASTRILLON, S. K. I.; MUNIZ, C. C. Climate Change Reflected in One of the Largest Wetlands in the World: An Overview of the Northern Pantanal Water Regime. **Acta Limnologica Brasiliensia**, v. 32, p. e104, 18 set. 2020.

LEE, S.-K.; MECHOSO, C. R.; WANG, C.; NEELIN, J. D. Interhemispheric Influence of the Northern Summer Monsoons on Southern Subtropical Anticyclones. **Journal of Climate**, v. 26, n. 24, p. 10193–10204, 15 dez. 2013.

LEYBA, I. M.; SOLMAN, S. A.; SARACENO, M.; MARTINEZ, J. A.; DOMINGUEZ, F. The South Atlantic Ocean as a Moisture Source Region and Its Relation with Precipitation in South America. **Climate Dynamics**, v. 61, n. 3, p. 1741–1756, 1 ago. 2023.

LIAO, J.; ZHENG, W.; LIAO, Q.; LU, S. Global Latitudinal Patterns in Forest Ecosystem Nitrous Oxide Emissions Are Related to Hydroclimate. **npj Climate and Atmospheric Science**, v. 7, n. 1, p. 187, 15 ago. 2024.

LIBONATI, R.; GEIRINHAS, J. L.; SILVA, P. S.; RUSSO, A.; RODRIGUES, J. A.; BELÉM, L. B. C.; NOGUEIRA, J.; ROQUE, F. O.; DACAMARA, C. C.; NUNES, A. M. B.; MARENGO, J. A.; TRIGO, R. M. Assessing the Role of Compound Drought and Heatwave Events on Unprecedented 2020 Wildfires in the Pantanal. **Environmental Research Letters**, v. 17, n. 1, p. 015005, jan. 2022.

LIU, Q.; YANG, S.; LI, S.; ZHANG, H.; ZHANG, J.; FAN, H. The optimal applications of scPDSI and SPEI in characterizing meteorological drought, agricultural drought and terrestrial

water availability on a global scale. **Science of The Total Environment**, v. 952, p. 175933, 20 nov. 2024.

LIU, Y.; CAI, W.; LIN, X.; LI, Z. Increased Extreme Swings of Atlantic Intertropical Convergence Zone in a Warming Climate. **Nature Climate Change**, v. 12, n. 9, p. 828–833, set. 2022.

LONDOÑO ARTEAGA, V.; LIMA, C. H. R. Analysis of CMIP 5 Simulations of Key Climate Indices Associated with the South America Monsoon System. **International Journal of Climatology**, v. 41, n. 1, p. 404–422, 2021.

LUCAS, E. W. M.; SOUSA, F. de A. S. de; SILVA, F. D. dos S.; ROCHA JÚNIOR, R. L. da; PINTO, D. D. C.; SILVA, V. de P. R. da. Trends in climate extreme indices assessed in the Xingu river basin - Brazilian Amazon. **Weather and Climate Extremes**, v. 31, p. 100306, 1 mar. 2021.

LUO, X.; GE, J.; CAO, Y.; LIU, Y.; YANG, L.; WANG, S.; GUO, W. Local and Nonlocal Biophysical Effects of Historical Land Use and Land Cover Changes in CMIP6 Models and the Intermodel Uncertainty. **Earth's Future**, v. 12, n. 6, p. e2023EF004220, 2024.

MA, H.-Y.; JI, X.; NEELIN, J. D.; MECHOSO, C. R. Mechanisms for Precipitation Variability of the Eastern Brazil/SACZ Convective Margin. 1 jul. 2011. Disponível em: <<https://journals.ametsoc.org/view/journals/clim/24/13/2011jcli4070.1.xml>>. Acesso em: 3 jul. 2025.

MA, Q.; LI, Y.; LIU, F.; FENG, H.; BISWAS, A.; ZHANG, Q. SPEI and multi-threshold run theory based drought analysis using multi-source products in China. **Journal of Hydrology**, v. 616, p. 128737, 1 jan. 2023.

MAKSIC, J.; SHIMIZU, M. H.; KAYANO, M. T.; CHIESSI, C. M.; PRANGE, M.; SAMPAIO, G. Influence of the Atlantic Multidecadal Oscillation on South American Atmosphere Dynamics and Precipitation. **Atmosphere**, v. 13, n. 11, p. 1778, nov. 2022.

MANTA, G.; BACH, E.; TALENTO, S.; BARREIRO, M.; SPEICH, S.; GHIL, M. The South Atlantic Dipole via Multichannel Singular Spectrum Analysis. **Scientific Reports**, v. 14, n. 1, p. 15534, 5 jul. 2024.

MARENGO, J. A.; ALVES, L. M.; TORRES, R. R. Regional Climate Change Scenarios in the Brazilian Pantanal Watershed. **Climate Research**, v. 68, p. 201–213, 4 maio 2016.

MARENGO, J. A.; CAMARINHA, P. I.; ALVES, L. M.; DINIZ, F.; BETTS, R. A. Extreme Rainfall and Hydro-Geo-Meteorological Disaster Risk in 1.5, 2.0, and 4.0°C Global Warming Scenarios: An Analysis for Brazil. **Frontiers in Climate**, v. 3, 3 mar. 2021a. Disponível em: <<https://www.frontiersin.org/journals/climate/articles/10.3389/fclim.2021.610433/full>>. Acesso em: 6 jul. 2025.

MARENGO, J. A.; COSTA, M. C.; CUNHA, A. P.; ESPINOZA, J.-C.; JIMENEZ, J. C.; LIBONATI, R.; MIRANDA, V.; TRIGO, I. F.; SIERRA, J. P.; GEIRINHAS, J. L.; RAMOS, A. M.; SKANSI, M.; MOLINA-CARPIO, J.; SALINAS, R. Climatological Patterns of Heatwaves during Winter and Spring 2023 and Trends for the Period 1979–2023 in Central South America. **Frontiers in Climate**, v. 7, 13 fev. 2025. Disponível em:

<<https://www.frontiersin.org/journals/climate/articles/10.3389/fclim.2025.1529082/full>>. Acesso em: 3 jul. 2025.

MARENGO, J. A.; CUNHA, A. P.; CUARTAS, L. A.; DEUSDARÁ LEAL, K. R.; BROEDEL, E.; SELUCHI, M. E.; MICHELIN, C. M.; DE PRAGA BAIÃO, C. F.; CHUCHÓN ANGULO, E.; ALMEIDA, E. K.; KAZMIERCZAK, M. L.; MATEUS, N. P. A.; SILVA, R. C.; BENDER, F. Extreme Drought in the Brazilian Pantanal in 2019–2020: Characterization, Causes, and Impacts. **Frontiers in Water**, v. 3, 2021b. Disponível em: <<https://www.frontiersin.org/articles/10.3389/frwa.2021.639204>>. Acesso em: 18 ago. 2022.

MARENGO, J. A.; ESPINOZA, J. C. Extreme Seasonal Droughts and Floods in Amazonia: Causes, Trends and Impacts. **International Journal of Climatology**, v. 36, n. 3, p. 1033–1050, 2016.

MARENGO, J. A.; LIEBMANN, B.; GRIMM, A. M.; MISRA, V.; SILVA DIAS, P. L.; CAVALCANTI, I. F. A.; CARVALHO, L. M. V.; BERBERY, E. H.; AMBRIZZI, T.; VERA, C. S.; SAULO, A. C.; NOGUES-PAEGLE, J.; ZIPSER, E.; SETH, A.; ALVES, L. M. Recent Developments on the South American Monsoon System. **International Journal of Climatology**, v. 32, n. 1, p. 1–21, 2012.

MARENGO, J. A.; OLIVEIRA, G. S.; ALVES, L. M. Climate Change Scenarios in the Pantanal. Em: BERGIER, I.; ASSINE, M. L. **Dynamics of the Pantanal Wetland in South America**. Cham: Springer International Publishing, 2016. p. 227–238.

MARENGO, J. A.; SOUZA, C. M. J.; THONICKE, K.; BURTON, C.; HALLADAY, K.; BETTS, R. A.; ALVES, L. M.; SOARES, W. R. Changes in Climate and Land Use Over the Amazon Region: Current and Future Variability and Trends. **Frontiers in Earth Science**, v. 6, 21 dez. 2018. Disponível em: <<https://www.frontiersin.org/articles/10.3389/feart.2018.00228>>. Acesso em: 16 mar. 2024.

MARQUES, J. F.; ALVES, M. B.; SILVEIRA, C. F.; AMARAL E SILVA, A.; SILVA, T. A.; DOS SANTOS, V. J.; CALIJURI, M. L. Fires dynamics in the Pantanal: Impacts of anthropogenic activities and climate change. **Journal of Environmental Management**, v. 299, p. 113586, 1 dez. 2021.

MARTINS, G.; VON RANDOW, C.; SAMPAIO, G.; DOLMAN, A. J. Precipitation in the Amazon and Its Relationship with Moisture Transport and Tropical Pacific and Atlantic SST from the CMIP5 Simulation. **Hydrology and Earth System Sciences Discussions**, v. 12, n. 1, p. 671–704, 15 jan. 2015a.

MARTINS, G.; VON RANDOW, C.; SAMPAIO, G.; DOLMAN, A. J. Precipitation in the Amazon and Its Relationship with Moisture Transport and Tropical Pacific and Atlantic SST from the CMIP5 Simulation. **Hydrology and Earth System Sciences Discussions**, v. 12, n. 1, p. 671–704, 15 jan. 2015b.

MARX, W.; HAUNSCHILD, R.; BORNMANN, L. Heat Waves: A Hot Topic in Climate Change Research. **Theoretical and Applied Climatology**, v. 146, n. 1, p. 781–800, 1 out. 2021.

MASSON-DELMOTTE, V.; ZHAI, P.; PIRANI, A.; CONNORS, S. L.; PÉAN, C.; BERGER, S.; CAUD, N.; CHEN, Y.; GOLDFARB, L.; GOMIS, M. I.; HUANG, M.; LEITZELL, K.; LONNOY, E.; MATTHEWS, J. B. R.; MAYCOCK, T. K.; WATERFIELD,

T.; YELEKÇİ, Ö.; YU, R.; ZHOU, B. (ed.). **Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change**. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2021.

MCNALLY, A.; ARSENAULT, K.; KUMAR, S.; SHUKLA, S.; PETERSON, P.; WANG, S.; FUNK, C.; PETERS-LIDARD, C. D.; VERDIN, J. P. A Land Data Assimilation System for Sub-Saharan Africa Food and Water Security Applications. **Scientific Data**, v. 4, n. 1, p. 170012, 14 fev. 2017.

MCPHADEN, M. J.; SANTOSO, A.; CAI, W. Introduction to El Niño Southern Oscillation in a Changing Climate. *Em: El Niño Southern Oscillation in a Changing Climate*. [s.l.] American Geophysical Union (AGU), 2020. p. 1–19.

MENGISTU, A. G.; TESFUHUNEY, W. A.; WOYESSA, Y. E.; VAN RENSBURG, L. D. Analysis of the Spatio-Temporal Variability of Precipitation and Drought Intensity in an Arid Catchment in South Africa. **Climate**, v. 8, n. 6, p. 70, jun. 2020a.

MENGISTU, A. G.; TESFUHUNEY, W. A.; WOYESSA, Y. E.; VAN RENSBURG, L. D. Analysis of the Spatio-Temporal Variability of Precipitation and Drought Intensity in an Arid Catchment in South Africa. **Climate**, v. 8, n. 6, p. 70, jun. 2020b.

MESEGUER-RUIZ, O.; PONCE-PHILIMON, P. I.; BALTAZAR, A.; GUIJARRO, J. A.; SERRANO-NOTIVOLI, R.; OLCINA CANTOS, J.; MARTIN-VIDE, J.; SARRICOLEA, P. Synoptic Attributions of Extreme Precipitation in the Atacama Desert (Chile). **Climate Dynamics**, v. 55, n. 11, p. 3431–3444, 1 dez. 2020.

MIKA, J.; HORVÁTH, Sz.; MAKRA, L.; DUNKEL, Z. The Palmer Drought Severity Index (PDSI) as an indicator of soil moisture. **Physics and Chemistry of the Earth, Parts A/B/C, Agrometeorology** 2003. v. 30, n. 1, p. 223–230, 1 jan. 2005.

MONTINI, T. L.; JONES, C.; CARVALHO, L. M. V. The South American Low-Level Jet: A New Climatology, Variability, and Changes. **Journal of Geophysical Research: Atmospheres**, v. 124, n. 3, p. 1200–1218, 2019a.

MONTINI, T. L.; JONES, C.; CARVALHO, L. M. V. The South American Low-Level Jet: A New Climatology, Variability, and Changes. **Journal of Geophysical Research: Atmospheres**, v. 124, n. 3, p. 1200–1218, 2019b.

MORALES, M. S.; COOK, E. R.; BARICHIVICH, J.; CHRISTIE, D. A.; VILLALBA, R.; LEQUESNE, C.; SRUR, A. M.; FERRERO, M. E.; GONZÁLEZ-REYES, Á.; COUVREUX, F.; MATSKOVSKY, V.; ARAVENA, J. C.; LARA, A.; MUNDO, I. A.; ROJAS, F.; PRIETO, M. R.; SMERDON, J. E.; BIANCHI, L. O.; MASIOKAS, M. H.; URRUTIA-JALABERT, R.; RODRIGUEZ-CATÓN, M.; MUÑOZ, A. A.; ROJAS-BADILLA, M.; ALVAREZ, C.; LOPEZ, L.; LUCKMAN, B. H.; LISTER, D.; HARRIS, I.; JONES, P. D.; WILLIAMS, A. P.; VELAZQUEZ, G.; ALISTE, D.; AGUILERA-BETTI, I.; MARCOTTI, E.; FLORES, F.; MUÑOZ, T.; CUQ, E.; BONINSEGNA, J. A. Six Hundred Years of South American Tree Rings Reveal an Increase in Severe Hydroclimatic Events since Mid-20th Century. **Proceedings of the National Academy of Sciences of the United States of America**, v. 117, n. 29, p. 16816–16823, 21 jul. 2020.

- MU, Y.; BIGGS, T. W.; JONES, C. Importance in Shifting Circulation Patterns for Dry Season Moisture Sources in the Brazilian Amazon. **Geophysical Research Letters**, v. 50, n. 9, p. e2023GL103167, 2023.
- MUSHAGALUSA, C. A.; FANDOHAN, A. B.; GLÈLÈ KAKAÏ, R. Random Forest and Spatial Cross-Validation Performance in Predicting Species Abundance Distributions. **Environmental Systems Research**, v. 13, n. 1, p. 23, 28 jun. 2024.
- NASHWAN, M. S.; SHAHID, S.; CHUNG, E.-S. Development of High-Resolution Daily Gridded Temperature Datasets for the Central North Region of Egypt. **Scientific Data**, v. 6, n. 1, p. 138, 31 jul. 2019.
- NEUBAUER, S. C.; MEGONIGAL, J. P. Biogeochemistry of Wetland Carbon Preservation and Flux. *Em: Wetland Carbon and Environmental Management*. [s.l.] American Geophysical Union (AGU), 2021. p. 33–71.
- ORIMOLOYE, I. R.; BELLE, J. A.; OLUSOLA, A. O.; BUSAYO, E. T.; OLOLADE, O. O. Spatial Assessment of Drought Disasters, Vulnerability, Severity and Water Shortages: A Potential Drought Disaster Mitigation Strategy. **Natural Hazards**, v. 105, n. 3, p. 2735–2754, 1 fev. 2021.
- PAIK, S.; MIN, S.-K.; ZHANG, X.; DONAT, M. G.; KING, A. D.; SUN, Q. Determining the Anthropogenic Greenhouse Gas Contribution to the Observed Intensification of Extreme Precipitation. **Geophysical Research Letters**, v. 47, n. 12, p. e2019GL086875, 2020.
- PAVLIDES, A.; AGOU, V. D.; HRISTOPULOS, D. T. Non-parametric kernel-based estimation and simulation of precipitation amount. **Journal of Hydrology**, v. 612, p. 127988, 1 set. 2022.
- PEKEL, J.-F.; COTTAM, A.; GORELICK, N.; BELWARD, A. S. High-Resolution Mapping of Global Surface Water and Its Long-Term Changes. **Nature**, v. 540, n. 7633, p. 418–422, dez. 2016.
- PÖRTNER, H.-O.; ROBERTS, D. C.; TIGNOR, M. M. B.; POLOCZANSKA, E. S.; MINTENBECK, K.; ALEGRÍA, A.; CRAIG, M.; LANGSDORF, S.; LÖSCHKE, S.; MÖLLER, V.; OKEM, A.; RAMA, B. (ed.). **Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change**. [s.l.: s.n.]
- RAY, D. K.; WEST, P. C.; CLARK, M.; GERBER, J. S.; PRISHCHEPOV, A. V.; CHATTERJEE, S. Climate Change Has Likely Already Affected Global Food Production. **PLOS ONE**, v. 14, n. 5, p. e0217148, 31 maio 2019.
- REBOITA, M. S.; AMBRIZZI, T.; CRESPO, N. M.; DUTRA, L. M. M.; FERREIRA, G. W. de S.; REHBEIN, A.; DRUMOND, A.; DA ROCHA, R. P.; SOUZA, C. A. de. Impacts of Teleconnection Patterns on South America Climate. **Annals of the New York Academy of Sciences**, v. 1504, n. 1, p. 116–153, 2021a.
- REBOITA, M. S.; AMBRIZZI, T.; CRESPO, N. M.; DUTRA, L. M. M.; FERREIRA, G. W. de S.; REHBEIN, A.; DRUMOND, A.; DA ROCHA, R. P.; SOUZA, C. A. de. Impacts of Teleconnection Patterns on South America Climate. **Annals of the New York Academy of Sciences**, v. 1504, n. 1, p. 116–153, 2021b.

- REBOITA, M. S.; AMBRIZZI, T.; SILVA, B. A.; PINHEIRO, R. F.; DA ROCHA, R. P. The South Atlantic Subtropical Anticyclone: Present and Future Climate. **Frontiers in Earth Science**, v. 7, 2019. Disponível em: <<https://www.frontiersin.org/articles/10.3389/feart.2019.00008>>. Acesso em: 18 abr. 2023.
- REBOITA, M. S.; DA ROCHA, R. P.; SOUZA, C. A. de; BALDONI, T. C.; SILVA, P. L. L. da S.; FERREIRA, G. W. S. Future Projections of Extreme Precipitation Climate Indices over South America Based on CORDEX-CORE Multimodel Ensemble. **Atmosphere**, v. 13, n. 9, p. 1463, set. 2022a.
- REBOITA, M. S.; KUKI, C. A. C.; MARRAFON, V. H.; DE SOUZA, C. A.; FERREIRA, G. W. S.; TEODORO, T.; LIMA, J. W. M. South America Climate Change Revealed through Climate Indices Projected by GCMs and Eta-RCM Ensembles. **Climate Dynamics**, v. 58, n. 1, p. 459–485, 1 jan. 2022b.
- REBOITA, M. S.; KUKI, C. A. C.; MARRAFON, V. H.; DE SOUZA, C. A.; FERREIRA, G. W. S.; TEODORO, T.; LIMA, J. W. M. South America Climate Change Revealed through Climate Indices Projected by GCMs and Eta-RCM Ensembles. **Climate Dynamics**, v. 58, n. 1, p. 459–485, 1 jan. 2022c.
- REBOITA, M. S.; SANTOS, I. INFLUÊNCIA DE ALGUNS PADRÕES DE TELECONEXÃO NA PRECIPITAÇÃO NO NORTE E NORDESTE DO BRASIL. **Revista Brasileira de Climatologia**, v. 15, 15 abr. 2015. Disponível em: <<https://revistas.ufpr.br/revistaabclima/article/view/37686>>. Acesso em: 3 jul. 2025.
- REHBEIN, A.; AMBRIZZI, T. ENSO Teleconnections Pathways in South America. **Climate Dynamics**, v. 61, n. 3, p. 1277–1292, 1 ago. 2023.
- RUIZ-VÁSQUEZ, M.; ARIAS, P. A.; MARTÍNEZ, J. A.; ESPINOZA, J. C. Effects of Amazon Basin Deforestation on Regional Atmospheric Circulation and Water Vapor Transport towards Tropical South America. **Climate Dynamics**, v. 54, n. 9, p. 4169–4189, 1 maio 2020.
- SALAZAR, A.; BALDI, G.; HIROTA, M.; SYKTUS, J.; MCALPINE, C. Land Use and Land Cover Change Impacts on the Regional Climate of Non-Amazonian South America: A Review. **Global and Planetary Change**, v. 128, p. 103–119, 1 maio 2015.
- SANTOS, C. A. C. dos; MELO, M. M. M. S.; BRITO, J. I. B. de. Tendências de Índices de Extremos Climáticos para o Estado do Amazonas e suas Relações com a TSM dos Oceanos Tropicais. **Revista Brasileira de Meteorologia**, v. 31, p. 1–10, mar. 2016.
- SASAKI, W.; DOI, T.; RICHARDS, K. J.; MASUMOTO, Y. The Influence of ENSO on the Equatorial Atlantic Precipitation through the Walker Circulation in a CGCM. **Climate Dynamics**, v. 44, n. 1, p. 191–202, 1 jan. 2015.
- SEGURA, H.; JUNQUAS, C.; ESPINOZA, J. C.; VUILLE, M.; JAUREGUI, Y. R.; RABATEL, A.; CONDOM, T.; LEBEL, T. New Insights into the Rainfall Variability in the Tropical Andes on Seasonal and Interannual Time Scales. **Climate Dynamics**, v. 53, n. 1, p. 405–426, 1 jul. 2019.

SENEVIRATNE, S. I.; HAUSER, M. Regional Climate Sensitivity of Climate Extremes in CMIP6 Versus CMIP5 Multimodel Ensembles. **Earth's Future**, v. 8, n. 9, p. e2019EF001474, 2020.

SIERRA, J. P.; JUNQUAS, C.; ESPINOZA, J. C.; SEGURA, H.; CONDOM, T.; ANDRADE, M.; MOLINA-CARPIO, J.; TICONA, L.; MARDONEZ, V.; BLACUTT, L.; POLCHER, J.; RABATEL, A.; SICART, J. E. Deforestation Impacts on Amazon-Andes Hydroclimatic Connectivity. **Climate Dynamics**, v. 58, n. 9, p. 2609–2636, 1 maio 2022.

SILVA, P. S.; GEIRINHAS, J. L.; LAPERE, R.; LAURA, W.; CASSAIN, D.; ALEGRÍA, A.; CAMPBELL, J. Heatwaves and fire in Pantanal: Historical and future perspectives from CORDEX-CORE. **Journal of Environmental Management**, v. 323, p. 116193, 1 dez. 2022.

SKANSI, M. de los M.; BRUNET, M.; SIGRÓ, J.; AGUILAR, E.; AREVALO GROENING, J. A.; BENTANCUR, O. J.; CASTELLÓN GEIER, Y. R.; CORREA AMAYA, R. L.; JÁCOME, H.; MALHEIROS RAMOS, A.; ORIA ROJAS, C.; PASTEN, A. M.; SALLONS MITRO, S.; VILLAROEEL JIMÉNEZ, C.; MARTÍNEZ, R.; ALEXANDER, L. V.; JONES, P. D. Warming and wetting signals emerging from analysis of changes in climate extreme indices over South America. **Global and Planetary Change**, v. 100, p. 295–307, 1 jan. 2013.

SOMOROWSKA, U. Amplified signals of soil moisture and evaporative stresses across Poland in the twenty-first century. **Science of The Total Environment**, v. 812, p. 151465, 15 mar. 2022.

STATEN, P. W.; GRISE, K. M.; DAVIS, S. M.; KARNAUSKAS, K. B.; WAUGH, D. W.; MAYCOCK, A. C.; FU, Q.; COOK, K.; ADAM, O.; SIMPSON, I. R.; ALLEN, R. J.; ROSENLOF, K.; CHEN, G.; UMMENHOFER, C. C.; QUAN, X.-W.; KOSSIN, J. P.; DAVIS, N. A.; SON, S.-W. Tropical Widening: From Global Variations to Regional Impacts. 30 jun. 2020. Disponível em: <<https://journals.ametsoc.org/view/journals/bams/101/6/BAMS-D-19-0047.1.xml>>. Acesso em: 11 ago. 2025.

SUN, C.; ZHU, L.; LIU, Y.; HAO, Z.; ZHANG, J. Changes in the drought condition over northern East Asia and the connections with extreme temperature and precipitation indices. **Global and Planetary Change**, v. 207, p. 103645, 1 dez. 2021a.

SUN, Q.; MIAO, C.; DUAN, Q.; ASHOURI, H.; SOROOSHIAN, S.; HSU, K.-L. A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons. **Reviews of Geophysics**, v. 56, n. 1, p. 79–107, 2018.

SUN, Q.; ZHANG, X.; ZWIERS, F.; WESTRA, S.; ALEXANDER, L. V. A Global, Continental, and Regional Analysis of Changes in Extreme Precipitation. **Journal of Climate**, v. 34, n. 1, p. 243–258, jan. 2021b.

SUN, Q.; ZHANG, X.; ZWIERS, F.; WESTRA, S.; ALEXANDER, L. V. A Global, Continental, and Regional Analysis of Changes in Extreme Precipitation. 1 jan. 2021c. Disponível em: <<https://journals.ametsoc.org/view/journals/clim/34/1/jcliD190892.xml>>. Acesso em: 3 jul. 2025.

TABARI, H. Climate Change Impact on Flood and Extreme Precipitation Increases with Water Availability. **Scientific Reports**, v. 10, n. 1, p. 13768, 13 ago. 2020.

TAN, M. L.; JUNENG, L.; TANGANG, F. T.; CHUNG, J. X.; RADIN FIRDAUS, R. B. Changes in Temperature Extremes and Their Relationship with ENSO in Malaysia from 1985 to 2018. **International Journal of Climatology**, v. 41, n. S1, p. E2564–E2580, 2021.

TASCHETTO, A. S.; RODRIGUES, R. R.; MEEHL, G. A.; MCGREGOR, S.; ENGLAND, M. H. How Sensitive Are the Pacific–Tropical North Atlantic Teleconnections to the Position and Intensity of El Niño-Related Warming? **Climate Dynamics**, v. 46, n. 5, p. 1841–1860, 1 mar. 2016.

TASCHETTO, A. S.; UMMENHOFER, C. C.; STUECKER, M. F.; DOMMENGET, D.; ASHOK, K.; RODRIGUES, R. R.; YEH, S.-W. ENSO Atmospheric Teleconnections. *Em: El Niño Southern Oscillation in a Changing Climate*. [s.l.] American Geophysical Union (AGU), 2020. p. 309–335.

TE WIERIK, S. A.; CAMMERAAAT, E. L. H.; GUPTA, J.; ARTZY-RANDRUP, Y. A. Reviewing the Impact of Land Use and Land-Use Change on Moisture Recycling and Precipitation Patterns. **Water Resources Research**, v. 57, n. 7, p. e2020WR029234, 2021.

TEDESCHI, R. G.; CAVALCANTI, I. F. A.; GRIMM, A. M. Influences of Two Types of ENSO on South American Precipitation. **International Journal of Climatology**, v. 33, n. 6, p. 1382–1400, 2013.

THIELEN, D.; RAMONI-PERAZZI, P.; PUCHE, M. L.; MÁRQUEZ, M.; QUINTERO, J. I.; ROJAS, W.; SOTO-WERSCHITZ, A.; THIELEN, K.; NUNES, A.; LIBONATI, R. The Pantanal under Siege—On the Origin, Dynamics and Forecast of the Megadrought Severely Affecting the Largest Wetland in the World. **Water**, v. 13, n. 21, p. 3034, jan. 2021.

THIELEN, D.; SCHUCHMANN, K.-L.; RAMONI-PERAZZI, P.; MARQUEZ, M.; ROJAS, W.; QUINTERO, J. I.; MARQUES, M. I. Quo Vadis Pantanal? Expected Precipitation Extremes and Drought Dynamics from Changing Sea Surface Temperature. **PLOS ONE**, v. 15, n. 1, p. e0227437, 7 jan. 2020.

TRENBERTH, K. E. ENSO in the Global Climate System. *Em: El Niño Southern Oscillation in a Changing Climate*. [s.l.] American Geophysical Union (AGU), 2020. p. 21–37.

TRENBERTH, K. E.; SHEA, D. J. Atlantic Hurricanes and Natural Variability in 2005. **Geophysical Research Letters**, v. 33, n. 12, 2006. Disponível em: <<https://onlinelibrary.wiley.com/doi/abs/10.1029/2006GL026894>>. Acesso em: 3 jul. 2025.

VALLÈS-CASANOVA, I.; LEE, S.-K.; FOLTZ, G. R.; PELEGRÍ, J. L. On the Spatiotemporal Diversity of Atlantic Niño and Associated Rainfall Variability Over West Africa and South America. **Geophysical Research Letters**, v. 47, n. 8, p. e2020GL087108, 2020.

VAN LOON, A. F. Hydrological Drought Explained. **WIREs Water**, v. 2, n. 4, p. 359–392, 2015.

VICENTE-SERRANO, S. M.; BEGUERÍA, S.; LÓPEZ-MORENO, J. I. A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. **Journal of Climate**, v. 23, n. 7, p. 1696–1718, 1 abr. 2010.

VICENTE-SERRANO, S. M.; MCVICAR, T. R.; MIRALLES, D. G.; YANG, Y.; TOMAS-BURGUERA, M. Unraveling the Influence of Atmospheric Evaporative Demand on Drought and Its Response to Climate Change. **WIREs Climate Change**, v. 11, n. 2, p. e632, 2020.

WAINER, I.; PRADO, L. F.; KHODRI, M.; OTTO-BLIESNER, B. The South Atlantic Sub-Tropical Dipole Mode since the Last Deglaciation and Changes in Rainfall. **Climate Dynamics**, v. 56, n. 1, p. 109–122, 1 jan. 2021a.

WAINER, I.; PRADO, L. F.; KHODRI, M.; OTTO-BLIESNER, B. The South Atlantic Sub-Tropical Dipole Mode since the Last Deglaciation and Changes in Rainfall. **Climate Dynamics**, v. 56, n. 1, p. 109–122, 1 jan. 2021b.

WESTRA, S.; ALEXANDER, L. V.; ZWIERS, F. W. Global Increasing Trends in Annual Maximum Daily Precipitation. **Journal of Climate**, v. 26, n. 11, p. 3904–3918, 1 jun. 2013.

WONG, A. P. S.; WIJFFELS, S. E.; RISER, S. C.; POULIQUEN, S.; HOSODA, S.; ROEMMICH, D.; GILSON, J.; JOHNSON, G. C.; MARTINI, K.; MURPHY, D. J.; SCANDERBEG, M.; BHASKAR, T. V. S. U.; BUCK, J. J. H.; MERCEUR, F.; CARVAL, T.; MAZE, G.; CABANES, C.; ANDRÉ, X.; POFFA, N.; YASHAYAEV, I.; BARKER, P. M.; GUINEHUT, S.; BELBÉOCH, M.; IGNASZEWSKI, M.; BARINGER, M. O.; SCHMID, C.; LYMAN, J. M.; MCTAGGART, K. E.; PURKEY, S. G.; ZILBERMAN, N.; ALKIRE, M. B.; SWIFT, D.; OWENS, W. B.; JAYNE, S. R.; HERSH, C.; ROBBINS, P.; WEST-MACK, D.; BAHR, F.; YOSHIDA, S.; SUTTON, P. J. H.; CANCOUËT, R.; COATANOAN, C.; DOBBLER, D.; JUAN, A. G.; GOURRION, J.; KOŁODZIEJCZYK, N.; BERNARD, V.; BOURLÈS, B.; CLAUSTRE, H.; D'ORTENZIO, F.; LE RESTE, S.; LE TRAON, P.-Y.; RANNOU, J.-P.; SAOUT-GRIT, C.; SPEICH, S.; THIERRY, V.; VERBRUGGE, N.; ANGEL-BENAVIDES, I. M.; KLEIN, B.; NOTARSTEFANO, G.; POULAIN, P.-M.; VÉLEZ-BELCHÍ, P.; SUGA, T.; ANDO, K.; IWASASKA, N.; KOBAYASHI, T.; MASUDA, S.; OKA, E.; SATO, K.; NAKAMURA, T.; SATO, K.; TAKATSUKI, Y.; YOSHIDA, T.; COWLEY, R.; LOVELL, J. L.; OKE, P. R.; VAN WIJK, E. M.; CARSE, F.; DONNELLY, M.; GOULD, W. J.; GOWERS, K.; KING, B. A.; LOCH, S. G.; MOWAT, M.; TURTON, J.; RAMA RAO, E. P.; RAVICHANDRAN, M.; FREELAND, H. J.; GABOURY, I.; GILBERT, D.; GREENAN, B. J. W.; OUELLET, M.; ROSS, T.; TRAN, A.; DONG, M.; LIU, Z.; XU, J.; KANG, K.; JO, H.; KIM, S.-D.; PARK, H.-M. Argo Data 1999–2019: Two Million Temperature-Salinity Profiles and Subsurface Velocity Observations From a Global Array of Profiling Floats. **Frontiers in Marine Science**, v. 7, 2020. Disponível em: <<https://www.frontiersin.org/articles/10.3389/fmars.2020.00700>>. Acesso em: 5 dez. 2022.

WONG, M. L.; WANG, X.; LATRUBESSE, E. M.; HE, S.; BAYER, M. Variations in the South Atlantic Convergence Zone over the mid-to-late Holocene inferred from speleothem $\delta^{18}\text{O}$ in central Brazil. **Quaternary Science Reviews**, v. 270, p. 107178, 15 out. 2021.

XU, J.; MA, Z.; YAN, S.; PENG, J. Do ERA5 and ERA5-Land Precipitation Estimates Outperform Satellite-Based Precipitation Products? A Comprehensive Comparison between State-of-the-Art Model-Based and Satellite-Based Precipitation Products over Mainland China. **Journal of Hydrology**, v. 605, p. 127353, 1 fev. 2022.

YOON, J.-H.; ZENG, N. An Atlantic Influence on Amazon Rainfall. **Climate Dynamics**, v. 34, n. 2, p. 249–264, 1 fev. 2010.

- YU, Y.; SCHNEIDER, U.; YANG, S.; BECKER, A.; REN, Z. Evaluating the GPCC Full Data Daily Analysis Version 2018 through ETCCDI Indices and Comparison with Station Observations over Mainland of China. **Theoretical and Applied Climatology**, v. 142, n. 3, p. 835–845, 1 nov. 2020.
- YUAN, Z.; QIN, J.; LI, S.; HUANG, S.; MBULULO, Y.; REHMAN, A. Impact of Boreal Autumn Antarctic Oscillation on Winter Wet-Cold Weather in the Middle-Lower Reaches of Yangtze River Basin. **Climate Dynamics**, v. 58, n. 1, p. 329–349, 1 jan. 2022.
- YUE, S.; WANG, C. The Mann-Kendall Test Modified by Effective Sample Size to Detect Trend in Serially Correlated Hydrological Series. **Water Resources Management**, v. 18, n. 3, p. 201–218, 1 jun. 2004.
- ZANIN, P. R.; SATYAMURTY, P. Hydrological Processes Interconnecting the Two Largest Watersheds of South America from Seasonal to Intra-Monthly Time Scales: A Critical Review. **International Journal of Climatology**, v. 40, n. 9, p. 3971–4005, 2020.
- ZARGAR, A.; SADIQ, R.; NASER, B.; KHAN, F. I. A review of drought indices. **Environmental Reviews**, v. 19, n. NA, p. 333–349, dez. 2011.
- ZEMP, D. C.; SCHLEUSSNER, C.-F.; BARBOSA, H. M. J.; RAMMIG, A. Deforestation Effects on Amazon Forest Resilience. **Geophysical Research Letters**, v. 44, n. 12, p. 6182–6190, 2017.
- ZHANG, F.; QUAN, Q.; MA, F.; TIAN, D.; HOOVER, D. L.; ZHOU, Q.; NIU, S. When Does Extreme Drought Elicit Extreme Ecological Responses? **Journal of Ecology**, v. 107, n. 6, p. 2553–2563, 2019.
- ZILLI, M. T.; CARVALHO, L. M. V.; LINTNER, B. R. The Poleward Shift of South Atlantic Convergence Zone in Recent Decades. **Climate Dynamics**, v. 52, n. 5, p. 2545–2563, 1 mar. 2019.