

Article

Long-Term Temperature and Precipitation Trends Across South America, Urban Centers, and Brazilian Biomes

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Abstract

This study examines long-term trends in maximum (Tmax) and minimum (Tmin) near-surface air temperatures and precipitation across South America, focusing on Brazilian biomes and national capitals, using ERA5 reanalysis data for 1979–2024. To isolate the underlying climate signal, seasonal cycles were removed using Seasonal-Trend decomposition based on Loess (STL), which effectively separates short-term variability from long-term trends. Temperature trends were quantified using ordinary least squares (OLS) regression, allowing consistent estimation of linear changes over time, while precipitation trends were assessed using the non-parametric Mann–Kendall test combined with Theil–Sen slope estimation, a robust approach that minimizes the influence of outliers and serial correlation in hydroclimatic data. Results indicate widespread but spatially heterogeneous warming, with Tmax increasing faster than Tmin, consistent with reduced cloudiness and evaporative cooling. A meridional precipitation dipole is evident, with drying across the Cerrado, Pantanal, Caatinga, and Pampa, contrasted by rainfall increases in northern South America linked to ITCZ shifts. The Pantanal emerges as the most vulnerable biome, showing strong warming (+0.51 °C decade^{−1}) and the steepest rainfall decline (−10.45 mm decade^{−1}). Satellite-based fire detections (2013–2024) reveal rising wildfire activity in the Amazon, Pantanal, and Cerrado, aligning with the “hotter and drier” climate regime. In the capitals, persistent Tmax increases suggest enhanced urban heat island effects, with implications for public health and energy demand. Although ERA5 provides coherent spatial coverage, regional biases and sparse in situ observations introduce uncertainties, particularly in the Amazon and Andes, these do not alter the principal finding that the magnitude and persistence of the 1979–2024 warming lie well above the range of interdecadal variability typically associated with the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO). This provides strong evidence that the recent warming is not cyclical but reflects the externally forced secular warming signal. These findings underscore growing fire risk, ecosystem stress, and urban vulnerability, highlighting the urgency of targeted adaptation and resilience strategies under accelerating climate change.

Keywords: climate change; ERA5; south America; temperature trends; precipitation trends; Brazilian biomes



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1. Introduction

Meteorological variables such as temperature and precipitation play a critical role in maintaining environmental balance and supporting planetary well-being. Temperature

directly influences key natural processes, including water evaporation [1], plant photosynthesis [2], and ecosystem thermal regulation [3], all of which affect biodiversity and agricultural productivity. Precipitation is equally vital, as it sustains freshwater resources by replenishing rivers, lakes, and aquifers, while also supporting natural vegetation and food systems [4]. Significant changes in these parameters, whether driven by natural variability or anthropogenic forcing, can lead to extreme events such as prolonged droughts and floods, with cascading effects on food security, public health, and ecological stability [5–7]. Consequently, continuous monitoring and in-depth understanding of temperature and precipitation patterns are essential for advancing climate resilience and developing effective responses to global climate change.

Over the years, human activities have significantly altered precipitation and temperature patterns across the globe [8]. The increasing emission of greenhouse gases, driven by the burning of fossil fuels, deforestation, and the intensification of agriculture, has contributed to a rise in global average temperatures and the amplification of extreme weather events [7,9]. These changes have disrupted rainfall regimes, making them more irregular, with prolonged droughts in some regions and intense, unseasonal rainfall in others. Moreover, unplanned urbanization and the degradation of natural ecosystems have diminished the environment's ability to regulate local climate conditions, further exacerbating these impacts [10,11]. Such climatic imbalances pose serious threats to water, food, and energy security, highlighting the urgent need for a global response grounded in scientific understanding, mitigation strategies, and climate adaptation efforts.

Climate change has increasingly manifested through notable shifts in temperature and precipitation patterns over recent decades, significantly affecting ecosystems, economic activities, and human livelihoods [12–15]. Numerous global and regional studies have documented a rising frequency of extreme weather events, including more intense heatwaves, prolonged droughts, and heavy precipitation occurring over shorter durations. These trends provide compelling evidence of an ongoing shift in traditional climate regimes [16–19]. This gap underscores the need, as emphasized by the IPCC [20,21], to deepen our understanding of regional climate patterns, especially within distinct biomes. Each biome possesses unique climatic, ecological, and environmental characteristics, which influence how it responds to changing climate conditions [22–24].

Scientific awareness of long-term climate change began consolidating in the latter half of the 20th century, as meteorological records revealed statistically significant warming trends across multiple regions of the globe [25,26]. Early observational studies, supported by improved temperature and precipitation datasets, provided some of the first consistent evidence that anthropogenic activities were influencing the global climate system beyond natural variability [20]. Since then, multiple high-resolution reanalysis datasets and satellite observations have refined our understanding of spatial and temporal trends, enabling more precise detection of regional climatic shifts and their ecological consequences [27,28]. Long-term assessments of temperature and precipitation trends typically draw upon three complementary categories of climate data: in situ observations, reanalysis products, and satellite-derived measurements. In situ observations, obtained from ground-based meteorological stations, ocean buoys, and radiosonde networks, provide high temporal accuracy and extended historical coverage, yet often suffer from spatial gaps in remote or inaccessible regions [29,30]. Reanalysis datasets, such as ERA5 [28], the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) [31], and Japanese 55-year Reanalysis (JRA-55) [32], integrate heterogeneous observations with numerical weather prediction models to produce spatially and temporally consistent reconstructions of atmospheric and surface variables at the global scale. Satellite observations, including those from Moderate Resolution Imaging Spectrometer (MODIS) [33], Tropical Rainfall Measuring Mis-

sion (TRMM) [34], and Global Precipitation Measurement (GPM) [35], ensure near-global coverage and are particularly valuable for monitoring regions with sparse ground-based data, despite offering shorter time series and relying on indirect retrieval algorithms. The integration of these diverse data sources enhances the robustness of climate variability assessments and supports the reliable detection of long-term trends across multiple spatial scales.

In recent decades, climate science has increasingly emphasized the importance of downscaling global models and observations to better capture the heterogeneity of regional and local climates [36–38]. This is particularly relevant in South America, where climatic patterns are influenced by complex land–atmosphere interactions [39,40], vegetation–climate feedbacks [41,42], teleconnections such as the El Niño–Southern Oscillation (ENSO) [43] and the South Atlantic Convergence Zone (SACZ) [44]. The regional manifestation of global warming in this context includes both gradual trends, such as increasing mean temperatures, and abrupt changes in precipitation regimes that affect the frequency and severity of hydrometeorological extremes [45]. These complex dynamics highlight the need for historical trend analyses based on observational records or reanalysis data, particularly in ecologically sensitive and socioeconomically vulnerable regions like the Brazilian biomes.

Furthermore, Brazil’s biomes, ranging from the humid Amazon rainforest to the semi-arid Caatinga and the seasonally flooded Pantanal, are not only climate-sensitive but also function as global climate regulators through their roles in carbon storage [46], evapotranspiration [47], and albedo dynamics [48]. Recent studies have shown that even modest shifts in climatic patterns can have outsized ecological impacts, including biodiversity loss [49], biome degradation [23], and feedbacks that may accelerate regional climate change. Therefore, understanding the historical climate trajectory of these ecosystems through long-term trend analysis is essential not only for scientific knowledge, but also for informing conservation, land-use planning, and climate adaptation strategies tailored to each biome’s unique vulnerability profile.

The primary objective of this study is to investigate long-term trends in temperature and precipitation from 1979 to 2024, providing a comprehensive assessment of their spatial distribution across South America, including a focused analysis of the capitals to connect large-scale climatic signals with urban contexts. In addition to this continental-scale perspective, the research provides a detailed examination of climatic trends within Brazil, with a specific focus on the country’s biomes. By exploring the distinct responses of the Amazon, Cerrado, Atlantic Forest, Caatinga, Pantanal, and Pampa biomes, the study seeks to enhance understanding of how long-term trends manifest across diverse ecological regions.

2. Materials and Methods

2.1. Study Area

This study focuses on the South American continent, with particular emphasis on Brazil and its six biomes: Amazon, Cerrado, Atlantic Forest, Caatinga, Pantanal, and Pampa (Figure 1). The continental-scale analysis presents the spatial distribution of long-term temperature and precipitation trends, while more detailed temporal and climatic assessments are conducted within each Brazilian biome. In addition, the capitals of all South American countries are investigated to provide an urban perspective on climate variability. The Brazilian biomes were selected for their ecological importance and climatic diversity, offering contrasting natural environments to evaluate ecosystem vulnerability and resilience under climate change. The South American capitals, in turn, were included for their socio-environmental relevance, as they concentrate population, infrastructure, and

economic activity, providing critical insights into the impacts of climate change and the challenges of adaptation in urban settings.

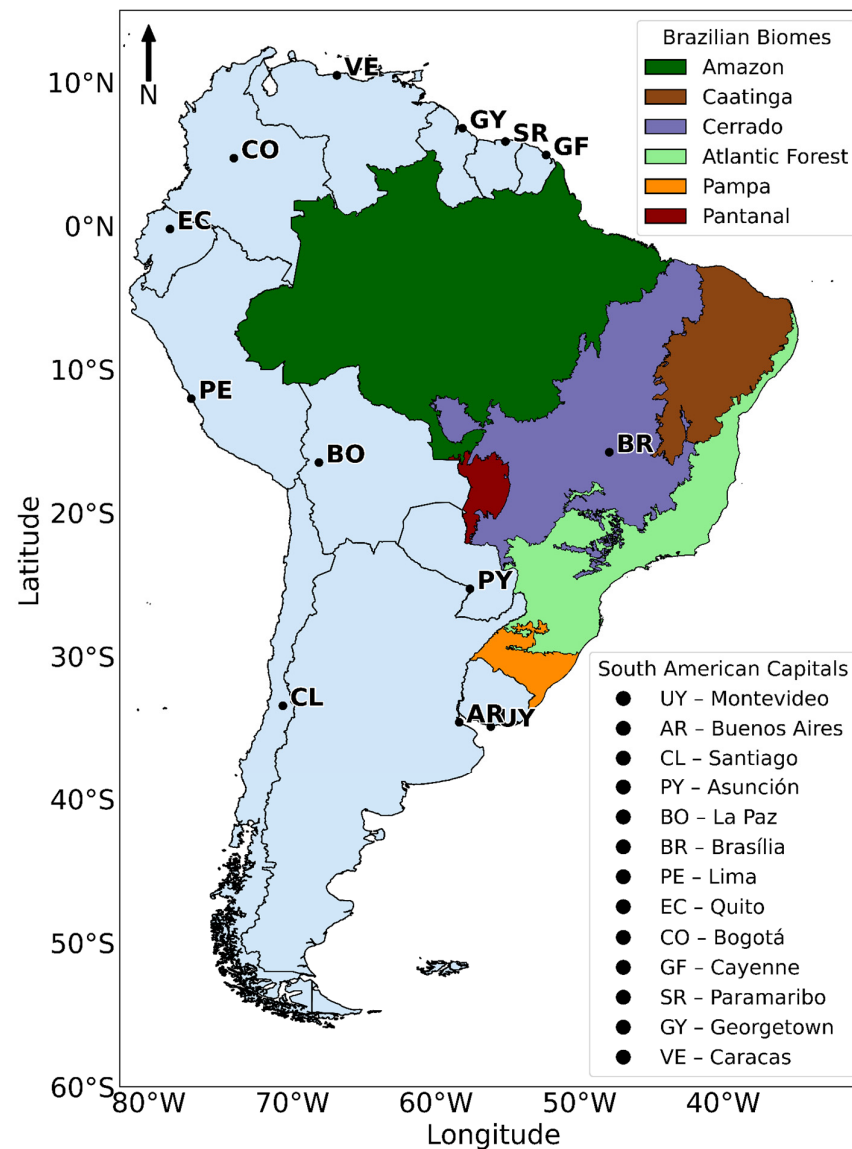


Figure 1. Brazilian biomes across South America (colored areas) and national capitals (black dots with ISO codes).

Figure 1 shows South America along with the boundaries of the Brazilian biomes, and Table 1 presents a summary including other relevant information. The Amazon biome (dark green) is characterized by a hot and humid tropical climate (Af, Am, and Aw under Köppen), with average temperatures between 25 °C and 28 °C and annual precipitation exceeding 2000 mm, supporting one of the most biodiverse ecosystems on Earth. The Atlantic Forest (light green) spans several climatic zones (Af, Am, Aw, Cfa, Cfb, Cwb), with high rainfall (1200–2800 mm/year) and moderate temperatures (20–25 °C), exhibiting strong altitudinal and coastal climatic gradients. The Cerrado (purple), known as the world's most biodiverse savanna, experiences a marked dry-wet seasonal cycle, with annual rainfall between 800 and 2000 mm and average temperatures from 20 °C to 26 °C. The Caatinga (brown), a semi-arid biome, presents low and irregular rainfall (300–800 mm/year), high annual temperatures (23–27 °C), and frequent droughts, being one of the driest regions in Brazil. The Pantanal (red), the world's largest tropical wetland, follows a seasonal flood regime, with mean temperatures around 26.7 °C and precipitation

between 1000 and 1300 mm/year, strongly influencing its aquatic-terrestrial ecosystem dynamics. Finally, the Pampa (orange) is a temperate grassland biome (Cfa), with well-defined seasons, moderate rainfall throughout the year, and average temperatures ranging from 16 °C to 18 °C.

Table 1. Summary of main Brazilian biomes with key climate and ecological characteristics. Includes approximate area, annual rainfall, average temperature, and distinctive environmental features.

Brazilian Biome	Area [km ²]	Annual Precipitation [mm]	Average Temperature [°C]	Other Important Variables
Amazon	~4,196,943	>2000	25 to 28	High biodiversity, humid tropical rainforest, deforestation impact, seasonal dry period (3–5 months)
Atlantic Forest	~1,107,285	1200 to 2800	20 to 25	Dense tropical forest, strong habitat loss, high endemism, humid climate
Cerrado	1,984,554	800 to 2000	20 to 26	Tropical savanna, high fire incidence, biodiversity hotspot, marked wet and dry seasons
Caatinga	~844,453	300 to 800	23 to 27	Semi-arid dry forest, severe drought cycles, water deficit, xerophytic vegetation
Pantanal	~150,000	1000 to 1300	25 to 28	World’s largest tropical wetland, seasonal flooding, rich aquatic biodiversity
Pampa	~176,496	1000–1200	16 to 18	World’s largest tropical wetland, seasonal flooding, rich aquatic biodiversity

2.2. Datasets

Near-surface air temperature at 2 m (T2m) and total precipitation were obtained from the ERA5 reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) [28]. ERA5 provides hourly global atmospheric, oceanic, and land-surface variables at ~31 km horizontal resolution and 137–139 vertical levels, using a four-dimensional variational (4D-Var) data assimilation scheme to optimally combine model forecasts with in situ and satellite observations. The dataset extends from 1940 to the present, is updated daily with a typical five-day latency, and includes uncertainty estimates from a 10-member ensemble at ~63 km and 3-hourly intervals, all publicly available through the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu/datasets> (accessed on 19 March 2025)).

For this study, only data from 1979 to 2024 were used, coinciding with the onset of the satellite era, when observational coverage and reanalysis reliability improved substantially. This choice also avoids temporal inhomogeneities present in the earlier records (1940–1978), affected by limited observational input. ERA5 was selected as the primary dataset due to its high spatiotemporal resolution, temporal homogeneity, and demonstrated ability to represent temperature [50] and precipitation [51] variability in South America. Given the sparse and uneven distribution of meteorological stations across the continent, particularly in remote regions such as the Amazon, using station-only records would lead to substantial spatial biases and incomplete climate characterization. By integrating ground-based measurements, satellite retrievals, and advanced assimilation techniques, ERA5 provides spatially continuous and physically consistent fields, making it particularly suitable for multi-decadal climate trend analysis.

Although ERA5’s horizontal resolution (~31 km) is coarser than the scales of topographic variability in mountainous regions such as the Andes, Serra do Mar, and Mantiqueira, its spatial detail is adequate for regional climate assessments across continental

South America. The purpose of this study is to evaluate large-scale and biome-level climatic trends rather than local microclimatic variations. Therefore, additional downscaling (either dynamical or statistical) was not required, as it would not substantially alter the detection of multi-decadal trends at these spatial scales. Previous studies have shown that ERA5 reliably reproduces temperature and precipitation variability over complex terrains in South America [52,53], particularly when the analysis focuses on regional averages rather than individual mountain sites.

2.3. Data Processing and Seasonal Adjustment

Hourly ERA5 data were retrieved, and daily maximum (Tmax) and minimum (TMin) near-surface air temperatures were derived from the diurnal cycle. For precipitation, 24 h accumulations were computed for each day. Daily temperature records were subsequently averaged to obtain monthly mean values, whereas daily precipitation totals were summed to produce monthly accumulations. This procedure resulted in a fully processed monthly dataset for both variables, suitable for climate analysis.

Decomposing a time series into trend, seasonal, and irregular components is fundamental to uncover underlying variations. The removal of the seasonal component, and when appropriate the irregular one, reduces autocorrelation and enhances model reliability. Several methods are available for time series decomposition, including additive and multiplicative approaches [54], X-11/X-12/X-13-ARIMA-SEATS [55], and Fourier decomposition. In this study, we adopt the Seasonal-Trend decomposition using Loess (STL) [56], chosen for its flexibility in handling non-linear seasonal patterns, robustness to missing data, and ability to separate seasonal, trend, and irregular components with precision.

$$Y_t = T_t + S_t + R_t \quad (1)$$

where Y_t is time series, T_t trend component, S_t seasonal component, and R_t remainder component.

These features are particularly valuable when analyzing climate variables such as temperature and precipitation, whose seasonal cycles evolve over time due to natural variability and external forcings. This approach enables a clearer detection of genuine long-term climate changes, free from predictable seasonal and random irregular influences.

2.4. Trend Analysis Framework

Following the seasonal adjustment process, distinct approaches were adopted for temperature and precipitation trend analysis, reflecting the statistical characteristics of each variable. For temperature, which typically exhibits smoother distributions and is closer to normality, an ordinary least squares (OLS) regression model was fitted to the deseasonalized monthly series. Let the deseasonalized temperature at time $t = 1, 2, \dots, n$ be denoted by T_t . The OLS regression model is formulated as:

$$T_t = \alpha + \beta \cdot t + \varepsilon_t \quad (2)$$

where T_t is the temperature at time t , α the intercept, β is the slope representing the linear trend, and ε_t is the random error term with mean zero and variance σ^2 . The slope β quantifies the rate of change per unit time (e.g., $^{\circ}\text{C decade}^{-1}$). The estimators of α and β are obtained by minimizing the sum of squared residuals:

$$\hat{\alpha}, \hat{\beta} = \operatorname{argmin}_{\alpha, \beta} \sum_{t=1}^n (T_t - \alpha - \beta \cdot t)^2 \quad (3)$$

The residual variance and the standard error of the slope are given by:

$$\hat{\sigma}^2 = \frac{1}{n-2} \sum_{t=1}^n (T_t - \hat{\alpha} - \hat{\beta} \cdot t)^2 \quad (4)$$

$$SE(\hat{\beta}) = \sqrt{\frac{\hat{\sigma}^2}{\sum_{t=1}^n (t - \bar{t})^2}}, \quad \bar{t} = \frac{\sum_{t=1}^n t}{n} \quad (5)$$

To test for the statistical significance of the trend, the null and alternative hypotheses were defined as:

$$H_0 : \beta = 0 \text{ vs. } H_1 : \beta \neq 0$$

The test statistic is:

$$t_s = \frac{\hat{\beta}}{SE(\hat{\beta})}, \quad T_s \sim t_{n-2} \quad (6)$$

Which follows a Student's t-distribution with $n - 2$ degrees of freedom under the null hypothesis. A two-tailed test at the 95% confidence level was applied. The 95% confidence interval for β is:

$$\hat{\beta} \mp t_{0.975, n-2} \cdot SE(\hat{\beta}) \quad (7)$$

where $\hat{\beta}$ is the estimated slope and $SE(\hat{\beta})$ its standard error. This parametric approach is appropriate for temperature because it not only provides the magnitude of the trend but also offers a direct test of whether the observed slope differs significantly from zero [57].

In contrast to temperature, precipitation records typically exhibit high variability, skewed distributions, and frequent zero values, which violate the assumptions of parametric linear regression models. To address these challenges, we employed the non-parametric Mann–Kendall test [58,59], to detect the presence of monotonic trends without requiring normally distributed residuals. Given a time series $\{x_1, x_2, x_3, \dots, x_n\}$, the Mann–Kendall statistic is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (8)$$

$$\text{sgn}(x_j - x_i) = \begin{cases} +1, & \text{if } (x_j - x_i) > 0 \\ 0, & \text{if } (x_j - x_i) = 0 \\ -1, & \text{if } (x_j - x_i) < 0 \end{cases} \quad (9)$$

where $\text{sgn}(\cdot)$ denotes the sign function. The variance of S , assuming no trend, is

$$\text{Var}(S) = \frac{n(n-1) \cdot (2n+5)}{18} \quad (10)$$

For large n , the statistic S approximates a normal distribution, and the standardized Z-score is:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, & \text{if } S < 0 \end{cases} \quad (11)$$

follows a standard normal distribution under the null hypothesis of no trend. Positive values of Z indicate an increasing trend, while negative values indicate a decreasing trend. To estimate the magnitude of the detected trend, we applied the Theil–Sen slope estimator [60], defined as the median of all possible pairwise slopes:

$$\beta = \text{median} \left(\frac{x_j - x_i}{j - i} \right), \quad \forall 1 \leq i < j \leq n \quad (12)$$

This non-parametric estimator is robust against outliers and particularly suitable for skewed or highly variable precipitation data. In this study, significance was evaluated at the 95% confidence level. To minimize the influence of autocorrelation, common in

hydroclimatic time series, trend significance was tested after adjusting for serial dependence following the approach of Yue and Wang (2004) [61].

All statistical calculations, data accumulation procedures, and graphical analyses presented in this study were performed by the authors using the Python programming language (version 3.13.6; <https://www.python.org>, accessed on 25 April 2025). The computational work flow was developed entirely within this environment, employing widely used scientific libraries, including NumPy 2.1.0, Pandas 2.2.3, Matplotlib 3.10, and SciPy 1.15.0.

3. Results

3.1. Spatial Distribution

Figure 2 illustrates the spatial distribution of long-term trends in Tmax and Tmin air temperatures and precipitation, where shaded areas represent the magnitude of the trends and hatched regions denote values not statistically significant at the 95% confidence level. For air temperature, significance is assessed using Student's *t*-test, whereas precipitation trends rely on the Mann–Kendall test combined with Theil–Sen slope estimates. In the case of Tmax (Figure 2a), a pronounced positive trend is evident across much of South America, with the strongest intensification observed over continental regions, particularly the Amazon, Central-West and Southeast Brazil, as well as northern Argentina, Paraguay, and Bolivia, where trends exceed $0.4\text{ }^{\circ}\text{C decade}^{-1}$ and locally surpass $0.6\text{ }^{\circ}\text{C decade}^{-1}$. Notably, the northernmost portion of the continent, including northern Amazonia, Venezuela, and the Guianas, also displays exceptionally strong warming, highlighting the widespread intensification of Tmax across tropical latitudes. Over these continental areas, most positive trends are statistically significant, reinforcing the robustness of the observed warming pattern. Altogether, the results for Tmax reveal a clear and spatially coherent warming signal over the past four decades, consistent with previous studies reporting increased frequency and intensity of heat extremes in South America [62,63]. In contrast, southern South America, particularly Patagonia and the Andes of Chile and Argentina, shows weaker warming signals, generally below $0.2\text{ }^{\circ}\text{C decade}^{-1}$, with large hatched areas indicating lower statistical significance. Coastal regions of northeastern Brazil similarly exhibit weaker or non-significant warming. Negative trends are confined mainly to adjacent oceanic regions, especially along the southeastern Pacific and small portions of the southwestern Atlantic, where most of the trends are not statistically significant, reflecting greater uncertainty in maritime estimates.

The spatial distribution of Tmin trends (Figure 2b) reveals pronounced regional contrasts. Strong and statistically significant warming rates exceeding $0.3\text{ }^{\circ}\text{C decade}^{-1}$ are evident in northern Colombia, northern Chile, and southeastern Bolivia, highlighting areas of robust confidence in the observed trends. Across Brazil, warming signals are more moderate, generally ranging between 0.1 and $0.2\text{ }^{\circ}\text{C decade}^{-1}$. An exception occurs in the state of Rio de Janeiro, where a localized cooling signal is observed; however, this feature coincides with low statistical confidence, limiting its robustness. Over the Atlantic Ocean, weak but spatially coherent positive trends of about $0.1\text{ }^{\circ}\text{C decade}^{-1}$ dominate, while in the southern portion of the basin negative trends emerge, though again with low confidence. In contrast, the tropical to subtropical Pacific south of the equator exhibits weak negative trends, with an extensive region of low statistical significance, suggesting that the signal in this sector remains uncertain. Overall, the results indicate widespread warming of nighttime minimum temperatures over continental South America, punctuated by regional hotspots of stronger trends and oceanic areas where statistical confidence is markedly lower.

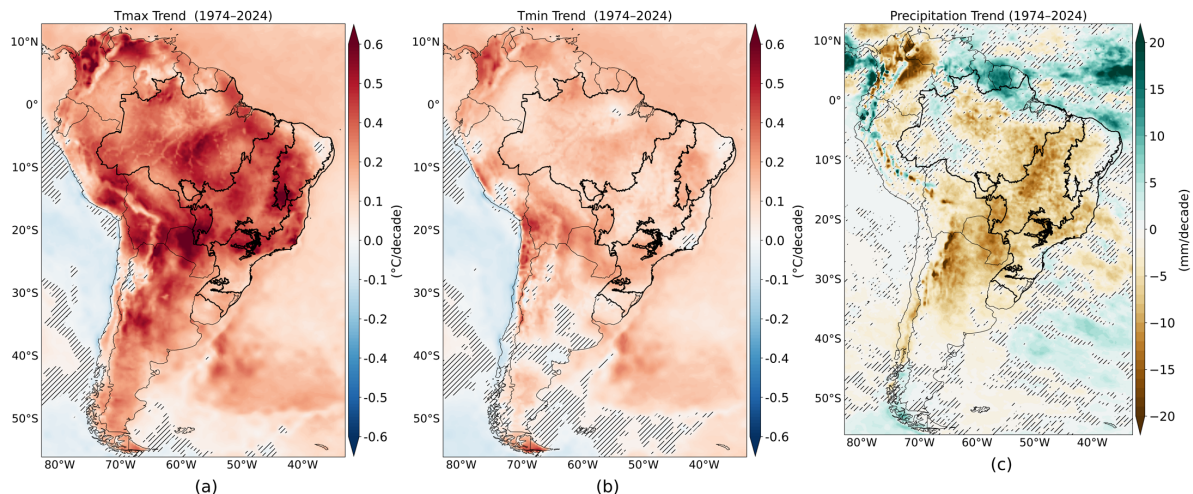


Figure 2. Long-term trends (shaded) and statistical significance (hatched) for Tmax (a), Tmin (b), and precipitation (c). Hatching indicates areas where trends are not significant at the 95% confidence level. Black line contours over Brazil represent the division of biomes.

The analysis of precipitation trends (Figure 2c) reveals a predominantly negative signal, with statistically robust reductions in precipitation over northern Argentina, Paraguay, Bolivia, central Brazil, and parts of the Amazon, extending into Colombia and Venezuela. The strongest declines reach more than $40 \text{ mm decade}^{-1}$ in northern Argentina and along the Colombia–Venezuela border. However, over several other continental regions, negative tendencies are identified but their magnitudes are comparatively weaker and accompanied by low statistical significance, suggesting that these drying signals are less consistent and may be strongly influenced by interannual to decadal variability rather than by long-term climatic forcing. In contrast, positive trends are observed in the northernmost sector of the continent and adjacent oceans, with increases above $20 \text{ mm decade}^{-1}$ in the Intertropical Convergence Zone (ITCZ), around $15 \text{ mm decade}^{-1}$ in Suriname, and exceeding $20 \text{ mm decade}^{-1}$ over the northern Pacific. Additional statistically significant increases extend over Amapá, French Guiana, and northern Venezuela, closely aligned with the mean position of the ITCZ. Over most adjacent oceans, trends are weak and unreliable, except in the equatorial Atlantic near the northern Brazilian coast, where consistent increases are detected. Overall, the spatial pattern indicates a dipole structure, characterized by statistically robust long-term reductions in precipitation across much of the continental interior and enhanced rainfall in the northernmost sector.

This pattern could be partially related to ascent motion near the equator and subsidence to the south. Gomes et al. (2024) [64], analyzing droughts in South America found a meridional circulation with ascent motion over the North Atlantic Ocean and subsidence over the continent. The analyses showed positive Sea Surface Temperature (SST) anomalies in the North Atlantic, favoring ascent motion. The precipitation trend pattern and the temperature trend in the present study are consistent with global warming, which indicates a temperature increase in the atmosphere and oceans [65]. The trends are large in the North Pacific and North Atlantic Oceans (<https://climate.copernicus.eu/climate-indicators/sea-surface-temperature>, accessed on 12 January 2025). The Amazon and Atlantic Forest deforestation could also have contributed to the dry tendency over the continent. An updated vegetation map from PROVEG [66], also discussed in Talamoni et al. (2024) [67] shows a great change in the forested areas, mainly in the Atlantic Forest and Amazon.

Regions lacking statistically significant trends generally coincide with areas of pronounced interannual and decadal variability, which can obscure underlying long-term signals. This variability is strongly influenced by large-scale climate modes such as the El Niño–

Southern Oscillation (ENSO) and the South Atlantic Convergence Zone (SACZ) [43,44,68]. The effect is particularly evident for precipitation, whose skewed distribution and frequent zero values reduce the statistical power to detect monotonic changes. In addition, complex topography, coastal influences, and sparse observations in mountainous or remote regions [53], such as the Andes and Patagonia—introduce localized variability that ERA5's ~31 km resolution cannot fully capture. Collectively, these factors contribute to lower statistical confidence in some areas, despite the robustness of the applied significance tests (Student's *t*-test for temperature and Mann–Kendall with autocorrelation correction for precipitation).

3.2. Trends for Capital Across South America

Capitals concentrate population, infrastructure, and political decision-making, which renders them highly sensitive to variations in precipitation and temperature. Analyzing long-term trends in these urban centers provides policy-relevant insights by linking continental-scale climate signals to urban vulnerability and national adaptation strategies. For this analysis, trend values were extracted from the grid point nearest to each capital. To facilitate interpretation, capitals are ordered from south to north in the figures below, with southern cities on the left and northern cities on the right. In this section, we assess how precipitation and temperature trends manifest across South American capitals.

Temperature and precipitation trends across South American capitals during 1979–2024 reveal a pervasive but spatially heterogeneous signal (Figure 3a,b). For temperature, both Tmax and Tmin exhibit positive and mostly significant trends, though with marked differences in magnitude across cities. Tmax increases are generally stronger, surpassing $0.35\text{ }^{\circ}\text{C decade}^{-1}$ in Asunción, La Paz, Brasília, and Caracas (up to $0.39\text{ }^{\circ}\text{C decade}^{-1}$ in Caracas), while Lima shows the weakest and statistically insignificant Tmax trend ($\sim 0.03\text{ }^{\circ}\text{C decade}^{-1}$) and Bogotá only a modest increase ($\sim 0.05\text{ }^{\circ}\text{C decade}^{-1}$). Tmin trends are positive and significant in nearly all capitals, typically ranging from 0.15 to $0.25\text{ }^{\circ}\text{C decade}^{-1}$, with higher values in La Paz, Quito, Paramaribo, and Georgetown, although Santiago shows a much weaker increase ($\sim 0.04\text{ }^{\circ}\text{C decade}^{-1}$). While many cities display stronger daytime than nighttime warming, exceptions such as Quito suggest that the amplification of Tmax over Tmin is not uniform across the continent. In contrast, precipitation trends reveal a sharper regional contrast: significant declines dominate central and southern capitals, led by Asunción ($-11.32\text{ mm decade}^{-1}$) and Brasília ($-8.66\text{ mm decade}^{-1}$), followed by Santiago, Buenos Aires, and Montevideo. Northern capitals, however, exhibit notable increases, with Paramaribo ($+8.60\text{ mm decade}^{-1}$), Georgetown ($+6.58\text{ mm decade}^{-1}$), and Caracas ($+3.93\text{ mm decade}^{-1}$) standing out, while Lima and Quito display weak and statistically insignificant changes.

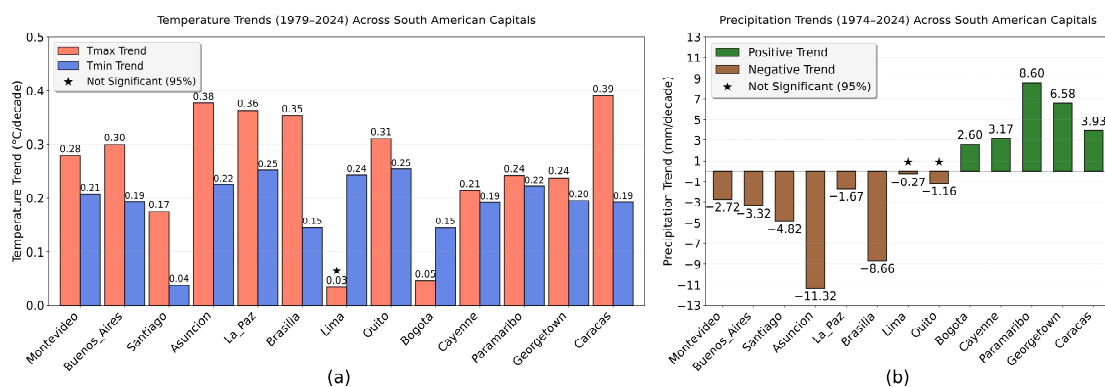


Figure 3. Long-term trends in temperature (a) and precipitation (b) for South American capitals during 1979–2024. The stars (*) indicate the capitals where trends are not statistically significant.

3.3. Trends Across Brazilian Biomes

Figure 4 presents the temporal evolution of spatially averaged Tmax, Tmin, and precipitation across the six Brazilian biomes from 1979 to 2024, considering only grid points with statistical significance.

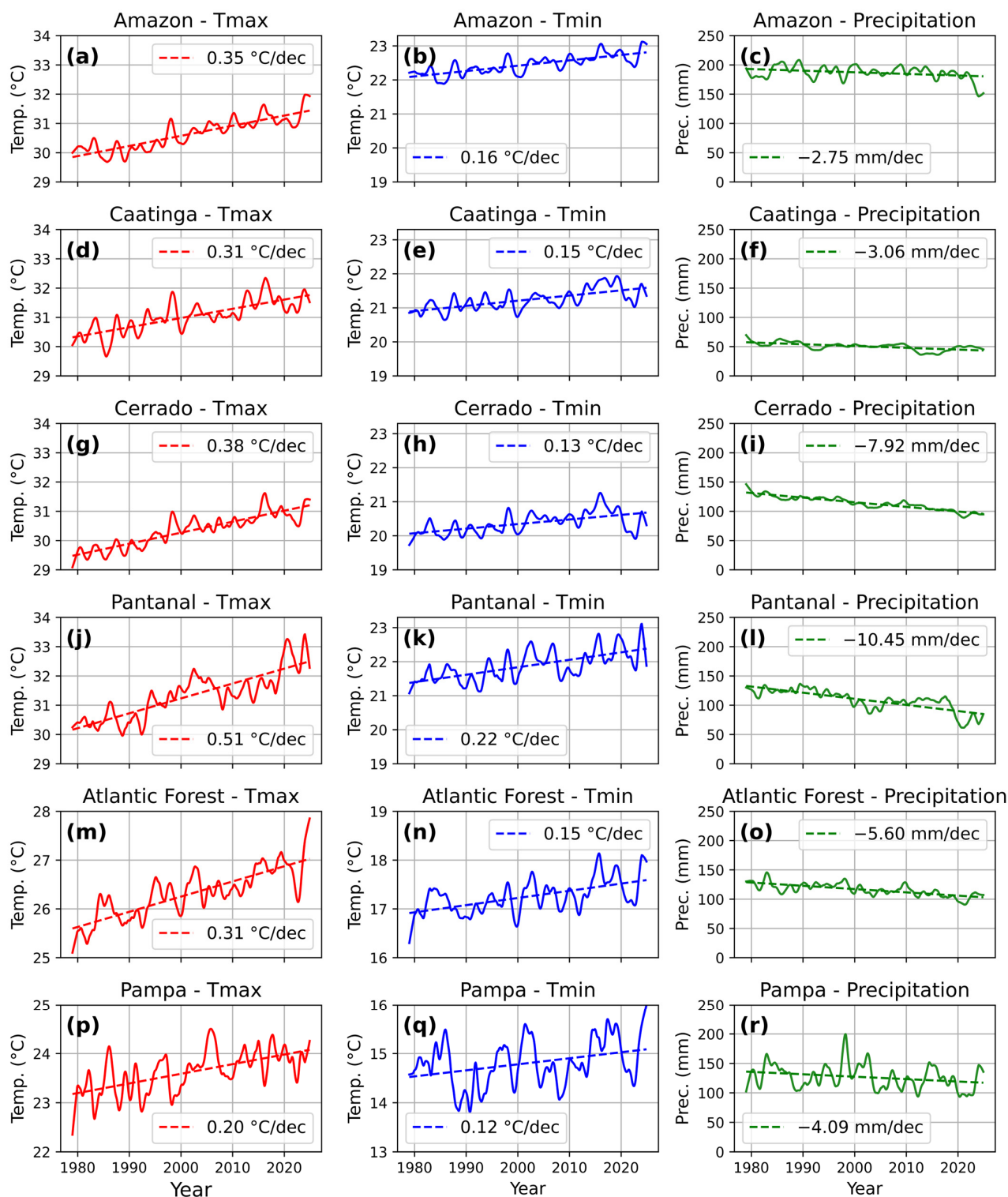


Figure 4. Temporal evolution of spatially averaged Tmax (left column), Tmin (center column), and precipitation (right column) for the six Brazilian biomes: Amazon (a–c), Caatinga (d–f), Cerrado (g–i), Pantanal (j–l), Atlantic Forest (m–o), and Pampa (p–r). Solid lines represent monthly mean values, while dashed lines indicate linear trends fitted to the data.

In the Amazon, T_{max} rose by about $0.35\text{ }^{\circ}\text{C decade}^{-1}$ and T_{min} by $0.16\text{ }^{\circ}\text{C decade}^{-1}$, while rainfall declined by $-2.75\text{ mm decade}^{-1}$ (Figure 4a–c). This combination of warming and drying may exacerbate forest vulnerability to fire (see Figure 5), biodiversity loss, and feedback to regional and global climate systems. Higher temperatures and lower humidity increase evapotranspiration and reduce soil and canopy moisture, creating favorable conditions for drought-induced tree mortality and more frequent and intense wildfires. Such disturbances fragment the forest and accelerate the replacement of closed-canopy rainforest by more open, savanna-like formations, leading to declines in species richness and functional diversity. Additionally, the reduction in vegetation cover and carbon storage weakens the Amazon's role as a continental moisture source and global carbon sink, amplifying regional drying and contributing to positive feedbacks that further reinforce warming and aridification.

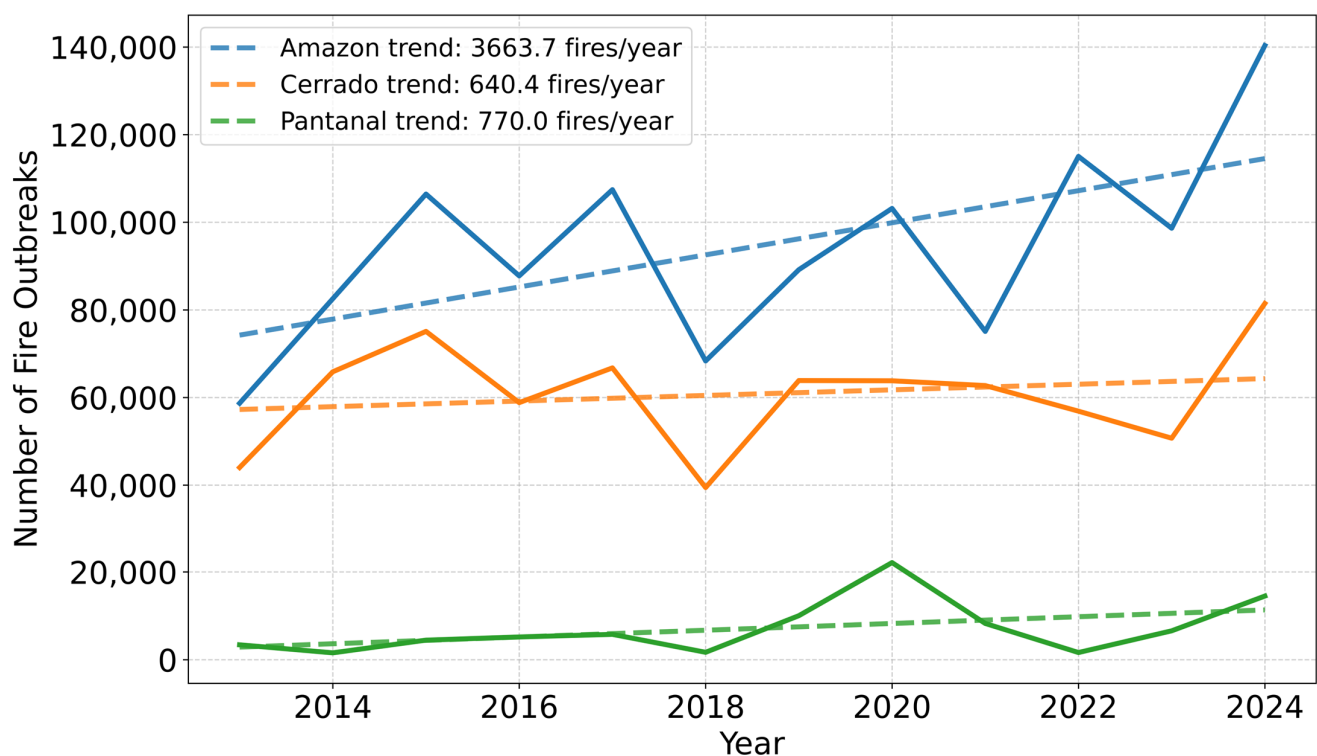


Figure 5. Annual counts of satellite-detected fire outbreaks in the Amazon, Cerrado and Pantanal biomes (2013–2024).

The Caatinga, already characterized by water scarcity, shows similar signals, with T_{max} increasing at $0.31\text{ }^{\circ}\text{C decade}^{-1}$, T_{min} at $0.15\text{ }^{\circ}\text{C decade}^{-1}$, and precipitation decreasing by $-3.06\text{ mm decade}^{-1}$ (Figure 4d–f). These concurrent warming and drying trends heighten evapotranspiration rates and reduce soil moisture and vegetation cover, accelerating land degradation and erosion. Such processes intensify the risk of desertification, particularly in shallow-soil areas with low water retention capacity. As vegetation productivity declines, so does the resilience of local ecosystems and the availability of natural resources, such as forage, timber, and water, on which rural communities depend. Consequently, socioeconomic stress increases through reduced agricultural yields, livestock losses, and migration pressures, reinforcing the vulnerability of populations living in this fragile semi-arid environment.

In the Cerrado, one of the world's great sanctuaries of biodiversity, T_{max} rose at $0.38\text{ }^{\circ}\text{C decade}^{-1}$ and T_{min} at $0.13\text{ }^{\circ}\text{C decade}^{-1}$, while precipitation declined sharply by $-7.92\text{ mm decade}^{-1}$ (Figure 4g–i), posing threats to both ecosystem resilience and the agri-

cultural sector, which is highly dependent on stable rainfall patterns. Rising temperatures and reduced precipitation intensify evapotranspiration, lower soil moisture, and shorten the duration of the wet season, leading to water stress for native vegetation and crops alike. These conditions can favor the replacement of fire-sensitive woody species by more drought- and fire-tolerant grasses, reducing biodiversity and altering carbon and nutrient cycling. In agricultural areas, increased climate variability compromises crop yields, irrigation efficiency, and groundwater recharge, undermining the region's productivity and heightening competition for water resources between human and ecological needs.

The Pantanal, the largest tropical wetland on Earth, stands out as the most vulnerable biome, exhibiting a rise in T_{max} of approximately $0.51\text{ }^{\circ}\text{C decade}^{-1}$ and in T_{min} of $0.22\text{ }^{\circ}\text{C decade}^{-1}$, together with the strongest rainfall reduction of about $-10.45\text{ mm decade}^{-1}$ (Figure 4j–l). This simultaneous warming and drying trend suggests a pronounced hydrological transition that threatens the biome's seasonal flood pulse. Declining rainfall and increasing evaporative demand are projected to reduce both peak inflows and baseflow contributions from the headwaters, thereby diminishing flood magnitude and shortening inundation duration. In addition, soils are expected to dry earlier in the season, while runoff becomes more concentrated during intense rainfall events, disrupting the historically predictable rise-and-fall cycle that supports aquatic and terrestrial communities. These changes, intensified by ongoing land-use conversion and hydrological regulation, may hinder fish recruitment, alter nutrient and sediment dynamics essential for floodplain productivity, increase fire susceptibility (see Figure 5) in previously flooded areas, and weaken the Pantanal's capacity to sustain downstream water supply and quality.

In the Atlantic Forest, where extensive loss of native vegetation has already occurred, T_{max} increased by $0.31\text{ }^{\circ}\text{C decade}^{-1}$ and T_{min} by $0.15\text{ }^{\circ}\text{C decade}^{-1}$, accompanied by a rainfall decrease of $-5.60\text{ mm decade}^{-1}$ (Figure 4m–o). These climatic shifts exacerbate the pressures associated with land-use change, mainly deforestation and agricultural expansion, that have already degraded habitat quality and biodiversity. The combined effects of warming and drying further compromise key ecosystem services such as water regulation, climate stabilization, and soil conservation, which are crucial for sustaining the densely populated regions dependent on this biome. Consequently, these changes intensify the degradation of ecosystem integrity and resilience, amplifying anthropogenic impacts and threatening the long-term functionality of the Atlantic Forest.

The Pampa, though experiencing smaller climatic trends, still shows warming of $0.20\text{ }^{\circ}\text{C decade}^{-1}$ for T_{max} and $0.12\text{ }^{\circ}\text{C decade}^{-1}$ for T_{min} , along with a rainfall reduction of $-4.09\text{ mm decade}^{-1}$ (Figure 4p–r), which may compromise grassland productivity and pastoral systems central to local livelihoods. Even moderate warming can increase evapotranspiration and shorten the growing season of native and cultivated grasses, while reduced rainfall lowers soil moisture and forage availability. These conditions may lead to pasture degradation, favoring invasive or less nutritious species and decreasing carrying capacity for livestock. As the region's economy and cultural identity are deeply linked to extensive cattle ranching, such climatic stressors can undermine both ecological balance and socioeconomic stability, highlighting the need for adaptive rangeland and water management strategies.

Taken together, these results point to a pervasive warming signal across all Brazilian biomes, with T_{max} rising more rapidly than T_{min} , and precipitation showing consistent declines of varying intensity. The combination of hotter days, warmer nights, and diminishing rainfall increases ecosystem stress and heightens the risks of biodiversity loss, water scarcity, and reduced agricultural productivity. Particularly concerning are the trajectories in the Pantanal and Cerrado, where warming and drying trends converge most strongly. Overall, the patterns revealed in Figure 4 underscore the urgency of integrating climate

adaptation strategies into biodiversity conservation, water management, and sustainable land use to safeguard both ecosystems and human well-being in Brazil under ongoing climate change.

Figure 5 presents the annual number of satellite-detected fire outbreaks across the Amazon, Cerrado, and Pantanal biomes, included here to corroborate the manuscript's discussion on the concurrent warming and drying trends and their implications for increasing fire susceptibility in central Brazil. Fire records for the Amazon, Cerrado, and Pantanal were obtained from the INPE through the TerraBrasilis platform (<https://terrabrasilis.dpi.inpe.br/queimadas/portal/>, accessed on 11 April 2025), which provides satellite-based active fire detections derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors onboard the Terra and Aqua satellites and the Visible Infrared Imaging Radiometer Suite (VIIRS) sensors onboard the Suomi-NPP and NOAA-20 satellites. Although this dataset extends back to 1998, we present data only from 2013 onward to ensure temporal consistency. Earlier years exhibit heterogeneity among sensors, particularly in spatial resolution, detection thresholds, and overpass times between the MODIS-only (pre-2012) and combined MODIS+VIIRS (post-2013) eras. Restricting the analysis to 2013–2024 minimizes these artificial discontinuities and provides a homogeneous baseline for assessing recent fire dynamics. The results indicate a marked upward trend in fire occurrences in the Amazon ($+3663.7$ fires yr^{-1}) and moderate positive trends in the Cerrado ($+640.4$ fires yr^{-1}) and Pantanal ($+770.0$ fires yr^{-1}). These patterns are consistent with the climatic findings reported in this study, linking enhanced heat and moisture deficits to the documented increase in fire-prone days across central Brazil.

3.4. Century-Scale Versus Interdecadal Contribution to the 1979–2024 Warming Trend

The analysis presented in this study identified a statistically significant warming trend over South America during the 1979–2024 period. However, because this interval spans only 46 years, it is not sufficient on its own to determine whether the observed trend reflects the long-term global warming signal or whether it is partially influenced by internally generated climate variability operating at interdecadal timescales. Shorter time windows are particularly sensitive to phases of multidecadal oscillations in the climate system, such as the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO), which can temporarily amplify or suppress the underlying secular warming. To address this issue, additional analyses were conducted using the full period available in ERA5, from 1940 to 2024. Although the pre-1979 portion of ERA5 incorporates a higher level of uncertainty due to changes in observational coverage, it remains valuable for distinguishing the nature of the warming signal. Specifically, it allows the identification of whether recent warming rates fall within the envelope of internal interdecadal variability or whether they are consistent with a century-scale externally forced trend.

To clarify whether the recent warming reflects a century-scale externally forced signal or an interdecadal internally generated fluctuation, we performed a set of targeted diagnostic analyses using annual mean near-surface air-temperature anomalies, referenced to the 1981–2010 baseline and calculated exclusively from land grid points over continental South America, with all oceanic areas omitted. First, we estimated trends for the periods 1940–2024 and 1979–2024 using heteroskedasticity- and autocorrelation-consistent (HAC) regression with Newey–West correction [69], providing confidence intervals that remain robust in the presence of serial dependence. Next, to assess the sensitivity of the trend to the length and timing of the observational window, we computed moving-window trends using 46-year intervals. This approach enables a direct comparison between recent warming and the full range of internally generated multidecadal variability captured in the dataset. We further evaluated the statistical distinctiveness of the recent trend using a

bootstrap procedure based on a first-order autoregressive model AR(1) [70] to generate a distribution of internal variability slopes against which the observed trend can be tested. In parallel, we applied one-way analysis of variance (ANOVA) to assess differences between discrete temporal segments and conducted a continuous wavelet transform (CWT) [71] to identify dominant time–frequency patterns and potential interdecadal modes. Together, these diagnostics provide a comprehensive framework to determine whether the 1979–2024 warming is consistent with a persistent century-scale warming trajectory or whether it may be partly modulated by internal interdecadal variability.

Figure 6 presents the evolution of annual surface-air-temperature anomalies over South America from 1940 to 2024, accompanied by linear trends for the full 85-year period and for the satellite-era subset (1979–2024). In addition, trends computed from all possible 46-year moving windows are displayed to quantify the envelope of internally generated multidecadal variability. Several salient features emerge. First, the warming trend over 1940–2024 ($0.155\text{ }^{\circ}\text{C dec}^{-1}$) is statistically robust and persistent over the entire observational record, indicating that the long-term signal is not confined to the recent decades. Second, the warming rate for 1979–2024 ($0.238\text{ }^{\circ}\text{C dec}^{-1}$) is substantially stronger, consistent with the well-documented global acceleration in anthropogenic forcing during the late twentieth and early twenty-first centuries. Third, the 46-year moving-window trends show only positive values throughout the record, including windows starting in the cool 1940s–1950s and those spanning transitional decades. This behavior is incompatible with a quasi-oscillatory mode of variability such as a 40–60-year cycle, which would require alternating periods of cooling and warming of comparable magnitude. Instead, all windows yield warming trends, and the range of slopes closely brackets the full-period trend. Collectively, these diagnostics demonstrate that the observed warming is not an artifact of segment-selection or phase-locking to an internal multidecadal oscillation; rather, it reflects a secular increase that intensifies toward the present.

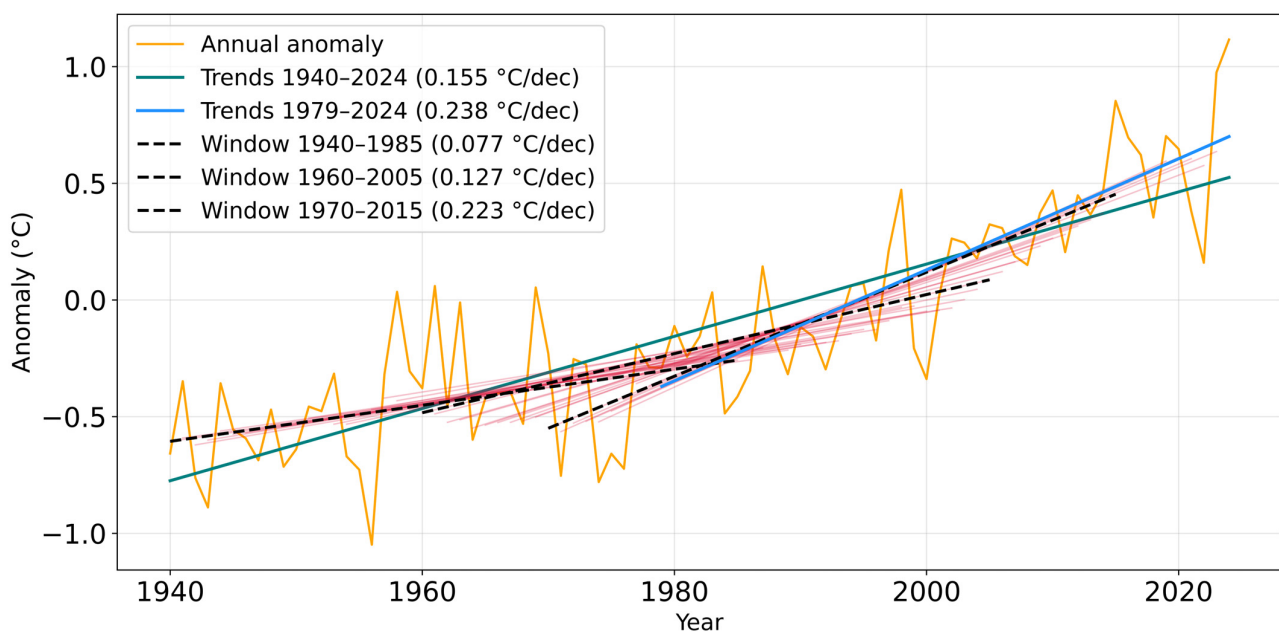


Figure 6. Annual mean near-surface air-temperature anomalies over continental South America from 1940 to 2024 (orange line). The teal and blue lines show the linear trends for 1940–2024 and 1979–2024, respectively. Thin red lines denote all 46-year moving-window trends, illustrating the range of internally generated multidecadal variability. Three representative windows—one from the early part of the record (1940–1985), one from the middle (1960–2005), and one from the later period (1970–2015)—are highlighted with black dashed lines.

The wavelet spectrum in Figure 7 evaluates whether the temperature record exhibits coherent multidecadal oscillatory power that could alias into linear trends when sampled over limited time intervals. If variability of the AMO/PDO type were the primary driver of the recent warming, the transform should reveal alternating warm and cool phases with quasi-periodic expression on 20–60-year scales. However, the CWT reveals no such oscillatory structure. Instead, the dominant feature at multidecadal scales is a monotonic transition from predominantly negative wavelet amplitudes before the mid-1980s to consistently positive values thereafter. This smooth shift in sign, without a subsequent reversal, indicates a long-term trend rather than an oscillation. The absence of repeated cycles at 20–50-year periods argues strongly against a mode of internal variability as the primary driver. In physical terms, the CWT shows a systematic and persistent increase in energy at low frequencies consistent with an externally forced warming signal, not with a recurrent internal mode.

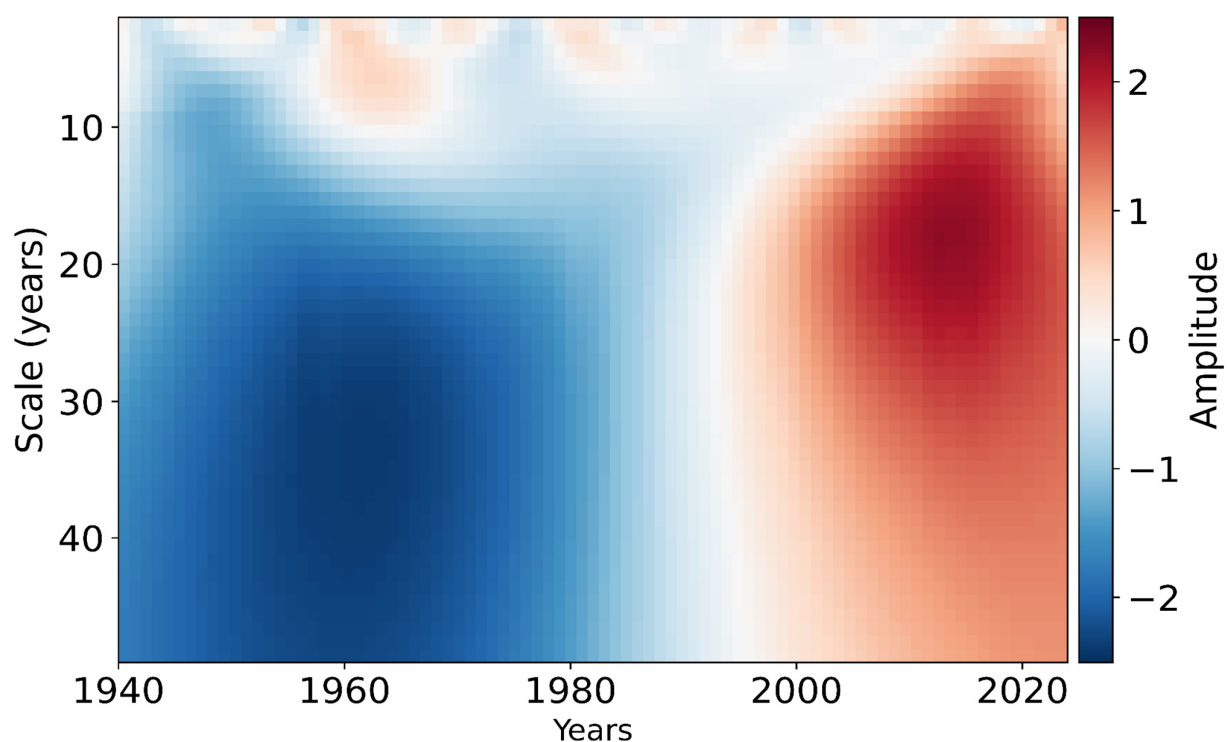


Figure 7. Continuous wavelet transform (CWT) of annual temperature anomalies from 1940 to 2024. The y -axis denotes the characteristic timescale (in years).

Figure 8 quantifies whether the observed 85-year warming trend can plausibly arise from stochastic internal climate variability. A resampling experiment based on an AR(1) null model, selected to approximate the red-noise structure of internal variability, produces a distribution of linear trends that represents the range of slopes expected from internal processes alone. The resulting ensemble is centered near zero, with the 2.5th-to-97.5th percentiles spanning approximately -0.13 to $+0.11$ $^{\circ}\text{C dec}^{-1}$. The observed trend of 0.155 $^{\circ}\text{C dec}^{-1}$ lies far outside this envelope, at the extreme positive tail of the distribution. This result implies that the likelihood of generating the observed warming from internal variability alone is vanishingly small. Moreover, because the satellite-era trend (0.238 $^{\circ}\text{C dec}^{-1}$) is even larger, it is even more inconsistent with an internally generated origin. This provides quantitative, statistically rigorous evidence that the observed multidecadal warming cannot be explained by internal variability alone and thus requires an external forcing component.

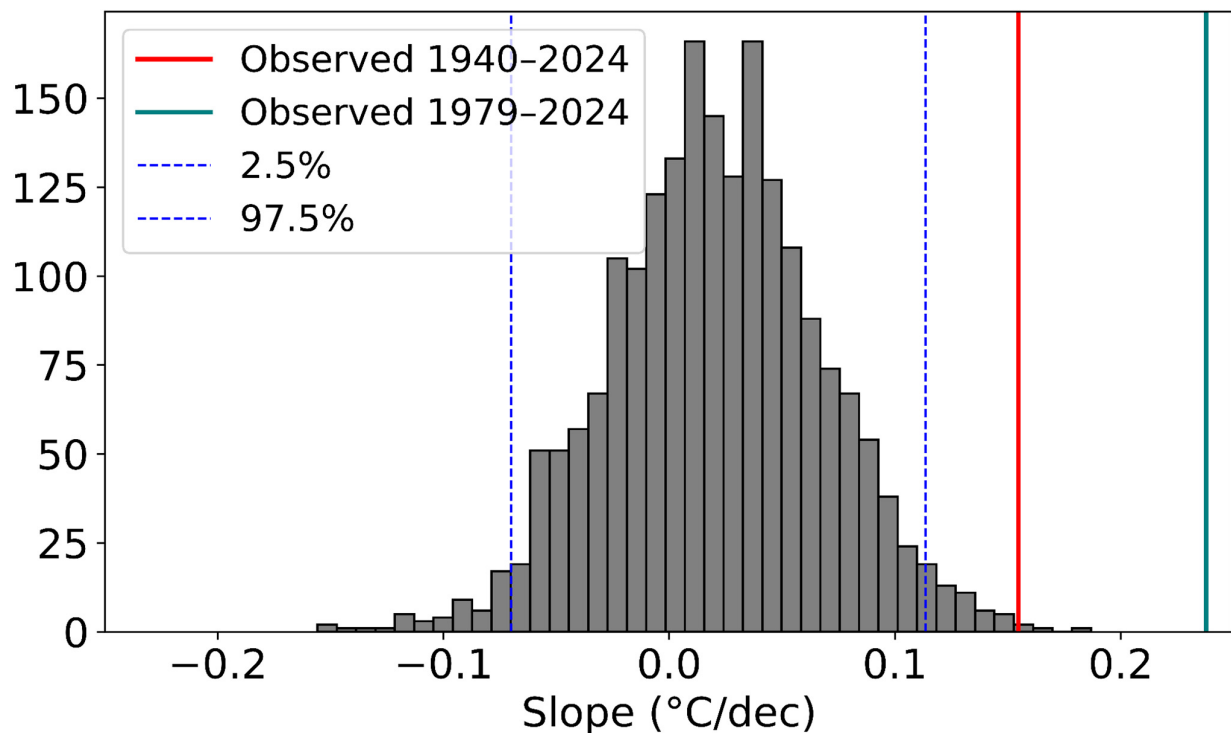


Figure 8. Distribution of linear trends generated from 2000 bootstrap realizations of an AR(1) stochastic model calibrated to the observed 1940–2024 temperature anomalies. The histogram represents the range of trends expected from internal variability alone, with dashed blue vertical lines marking the 2.5th and 97.5th percentiles. The observed 1940–2024 trend is shown by the red vertical line, while the teal vertical line denotes the trend for 1979–2024.

Figure 9 compares the estimated trends for the 1940–2024 and 1979–2024 periods along with their heteroskedasticity- and autocorrelation-consistent confidence intervals. The full-period trend is well constrained and significantly positive, consistent with a century-scale warming trajectory. The satellite-era trend is substantially larger and its confidence interval does not overlap fully with that of the 1940–2024 period, indicating an acceleration in recent decades. Such acceleration is inconsistent with multidecadal internal oscillations, which would not produce sustained and monotonic strengthening of the warming rate. Instead, the pattern is characteristic of increasing external forcing, reflecting the growth of anthropogenic greenhouse gases and the associated intensification of radiative imbalance. The contrast between the two periods thus reinforces that the recent warming does not arise from the positive phase of a natural cycle but is part of a long-term forced response with enhanced rates in the modern era.

Taken together, the four diagnostic approaches form a coherent and mutually reinforcing narrative. The moving-window trends demonstrate that warming is present regardless of the window chosen, contradicting the expectation of alternating warm and cool phases required by an interdecadal oscillation. The wavelet analysis shows no evidence of a recurring multidecadal cycle but instead reveals a persistent, low-frequency increase consistent with a secular trend. The AR(1) bootstrap confirms that internal variability cannot account for the magnitude of the observed warming, rendering a purely internal origin statistically implausible. Finally, the comparison of trends across periods shows a clear acceleration, which is a hallmark of external forcing, not natural oscillatory behavior. Collectively, these results provide strong, multi-method evidence that the 1979–2024 warming over South America reflects a century-scale, externally forced climate change signal rather than an expression of internally generated interdecadal variability.

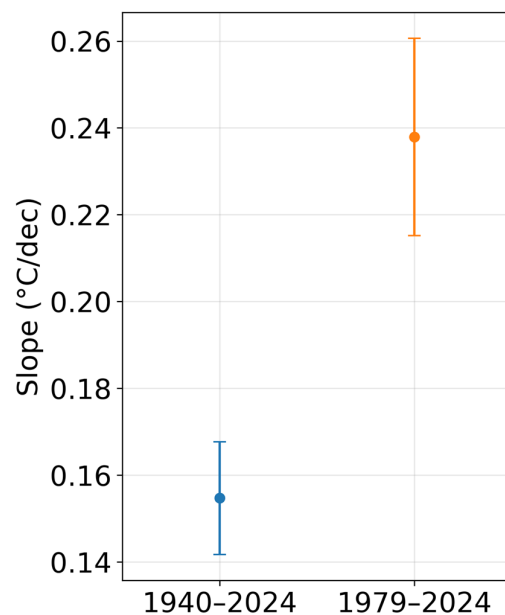


Figure 9. Comparison of linear warming trends and their 95% confidence intervals for the periods 1940–2024 (blue marker) and 1979–2024 (orange marker).

4. Discussion

The stronger warming of T_{max} relative to T_{min} across South America emerges as a consistent signal in both observational records and model-based studies, and can be attributed to coupled declines in precipitation and cloud cover. Reduced cloudiness enhances surface solar radiation during the day, intensifying sensible heat fluxes and accelerating T_{max} increases, while the absence of nocturnal cloud insulation allows for stronger radiative cooling, thereby moderating T_{min} rises. This mechanism is consistent with recent global findings showing that cloud cover is the dominant driver of diurnal temperature range (DTR) variability [72], exerting a strong negative correlation with DTR across more than 80% of land surfaces [73,74]. Additional processes reinforce this asymmetry: reduced precipitation and soil moisture limit evaporative cooling, further amplifying T_{max} under drought conditions [75,76]. Moreover, land-use change and deforestation suppress evapotranspiration and increase sensible heating, leading to enhanced diurnal contrasts [77,78]. Consequently, DTR expands under drier and clearer conditions, reflecting a robust continental-scale mechanism whereby declining precipitation and cloud cover disproportionately amplify daytime warming. This dynamic highlights the interplay of radiation, atmospheric circulation, and land-surface processes in shaping the distinct trajectories of T_{max} and T_{min} trends in South America.

In contrast to the widespread continental warming, the adjacent eastern Pacific exhibits weakly negative trends in near-surface air temperature (2 m), although the signal is relatively small in magnitude and statistically less robust in some regions. This cooling tendency is consistent with mechanisms linked to the Peru–Chile upwelling system, where stronger trade winds can enhance Ekman divergence and promote the upwelling of cold subsurface waters along the coast [79,80]. Such ocean–atmosphere coupling may be further reinforced by a more stable lower troposphere that favors the persistence of stratocumulus decks, increasing surface albedo and amplifying local cooling [81,82]. While these processes provide a plausible explanation for localized cooling adjacent to South America, caution is warranted: the signal is weak, spatially heterogeneous, and may partly reflect internal variability such as decadal modes of Pacific SST fluctuations, in addition to limited observational coverage. This combination reduces confidence in the robustness of the detected trends, in stark contrast to the strong and statistically significant warming observed inland.

The observed declines in precipitation across central and southern South America, particularly over the Amazon, Cerrado, Pantanal, and northern Argentina, are consistent with recent evidence highlighting the intensification of compound extremes in the continent. Feron et al. (2024) [45] demonstrate that such drying and warming trends have translated into a sharp escalation of hot, dry, and high fire-risk days, with a threefold increase in the frequency of compound extremes in key hotspots such as the northern Amazon and the Gran Chaco. Similarly, Marengo et al. (2025) [63] report a growing incidence of heatwaves and prolonged droughts in Brazil, underscoring the combined pressures of rising temperatures and diminishing rainfall on ecological systems and water resources. Together, these convergent findings indicate that South America is not only undergoing gradual climatic changes but is entering a regime of intensified compound extremes that threaten ecosystem resilience, water security, and human well-being.

Our analyses reveal widespread but spatially heterogeneous warming across South American capitals. Both T_{max} and T_{min} increased significantly, although T_{max} trends are generally stronger, exceeding $0.35\text{ }^{\circ}\text{C decade}^{-1}$ in Asunción, La Paz, Brasília, and Caracas. In contrast, Lima and Bogotá display weak or statistically insignificant T_{max} warming, highlighting strong local modulation. This heterogeneity is consistent with continental-scale assessments of temperature extremes [83,84]. A clear diurnal asymmetry is observed, with daytime warming generally stronger than nighttime warming in most cities, consistent with global evidence of a renewed increase in diurnal temperature range since the 1980s [72]. Local controls explain notable exceptions: Lima's subdued T_{max} trend is associated with coastal upwelling and persistent stratus cloud cover [85], whereas Bogotá's modest warming reflects its high elevation and frequent cloudiness. In addition, urbanization further enhances T_{max} through urban heat island effects [86].

To more directly connect our reanalysis-based results for national capitals with the urban climate literature, we explicitly compare our ERA5-derived trends with studies based on in situ and satellite observations and with analyses of social vulnerability. First, the broad warming we detect in most capitals and the stronger increases in daytime maximum temperatures are consistent with documented surface and air urban heat-island (UHI) signals in Brazilian cities derived from both remote sensing and station networks [87]. These observational studies show persistent daytime and nighttime SUHI patterns and highlight heterogeneity within metropolitan regions that cannot be fully resolved at reanalysis grid spacing, which helps explain some of the inter-city differences in trend magnitude we report. Second, city-level epidemiological work demonstrates that even modest increases in ambient temperatures translate into measurable public-health burdens in Latin American capitals, with mortality and morbidity risks concentrated among older adults and socially vulnerable groups [88,89]. Third, cross-city analyses of intra-urban exposure show systematic, socio-spatial inequalities, lower-income neighborhoods frequently experience higher surface and near-surface temperatures and lower access to cooling refuges [90,91]. Taken together, these observation-based findings indicate that (a) our ERA5 trends provide a valuable and consistent continental-scale context for urban change, and (b) fine-scale observational and socio-demographic studies are essential to translate these climatic trends into local heat-risk assessments and adaptation priorities. We therefore recommend that future work couple ERA5 trend detection with higher-resolution surface temperature datasets, dense urban station networks, and social-vulnerability indices to better quantify exposure and adaptive needs at neighborhood scales.

Precipitation exhibits a pronounced meridional dipole. Drying trends dominate central and southern capitals (e.g., $-11.32\text{ mm decade}^{-1}$ in Asunción, -8.66 mm in Brasília), consistent with recent severe droughts in Brazil and the Pantanal [16,92]. In contrast, northern capitals such as Paramaribo, Georgetown, and Caracas display significant increases, reflect-

ing shifts in the Intertropical Convergence Zone (ITCZ) and the South Atlantic Convergence Zone in response to ocean warming and anthropogenic forcing [93]. This spatial pattern represents a temporal shift relative to earlier studies that reported wetter conditions in southern South America during the late 20th century [94]. In sum, South American capitals illustrate the dual fingerprint of climate change: robust yet uneven warming, coupled with a marked reorganization of rainfall patterns, characterized by drying in the tropics and subtropics and increased precipitation near the equator. These shifts carry far-reaching implications for water security, agricultural productivity, and urban resilience.

Across Brazil's biomes, progressive warming has been a pervasive feature during 1979–2024, with Tmax trends varying notably among biomes. The Pantanal exhibits the strongest warming at $0.51\text{ }^{\circ}\text{C decade}^{-1}$, whereas the Pampa shows the weakest trend at $0.20\text{ }^{\circ}\text{C decade}^{-1}$, and the remaining biomes fall between 0.31 and $0.38\text{ }^{\circ}\text{C decade}^{-1}$. This warming pattern, although showing different magnitudes due to variations in data types, analytical methods, and time periods, has also been observed in other studies across various Brazilian biomes [23,95,96]. Precipitation trends, in contrast, reveal marked spatial and temporal heterogeneity. Previous studies also indicate that soil moisture responses are highly uneven, with pronounced drying in regions such as the eastern Amazonia–Cerrado transition, while other areas exhibit stable or even increasing soil moisture [23,92,96]. These findings underscore that long-term hydroclimatic responses are neither uniform nor linear, highlighting the need for biome-specific analyses to disentangle the mechanisms driving regional climate variability and change.

Previous studies indicate that the Amazon has not exhibited a significant long-term trend in precipitation [97], nor have soil moisture data shown consistent trends, although sharp reductions occurred during recent droughts (e.g., 2013–2015) [92,98]. In line with these findings, our results suggest that precipitation trends in the Amazon biome generally remain low (around $-2.75\text{ mm decade}^{-1}$). The minimum precipitation in the Amazon Biome in 2023 reveals the extreme drought that occurred in the region [99], further illustrating the recurrence of severe dry events despite the absence of a clear long-term trend. Evidence from the literature suggests that deforestation and forest degradation can disrupt local hydrology by reducing evapotranspiration and moisture recycling, potentially weakening convective rainfall and increasing drought risk, particularly in the southern and eastern Amazon [96,100–102]. Recent studies further indicate that while deforestation contributes to regional drying, global climate change appears to be the dominant driver of recent hydroclimatic shifts, with deforestation acting as a reinforcing feedback [101].

In the Caatinga, the long-term drying trend of approximately $-3.06\text{ mm decade}^{-1}$ found in our results is consistent with mechanisms described in the literature. Previous studies have shown that rainfall variability in Northeast Brazil is strongly influenced by shifts in tropical Atlantic sea surface temperature gradients, which modulate the position of the Intertropical Convergence Zone [103,104]. While our study does not directly analyze ocean–atmosphere dynamics, the persistence of such mechanisms under global warming provides a plausible explanation for the sustained precipitation deficits observed across the semiarid Caatinga biome.

Our study shows that over the past 4.5 decades, the Pantanal and Cerrado have experienced a concurrent climatic and hydrological trend characterized by warming and aridification. This pattern is marked by reduced water availability, rising temperatures, and intensification of droughts, driven by the interaction between climate change and extensive land-use transformations [16,96]. Deforestation, dam construction, and agricultural expansion have disrupted hydrological connectivity, weakening the seasonal flood pulses that sustain biodiversity in the Pantanal and diminishing the regenerative capacity of Cerrado headwaters that supply its wetlands [105]. These alterations generate reinforcing feedbacks

of vegetation loss, soil desiccation, and fire vulnerability (see Figure 5), leading to habitat degradation, declining agro-pastoral productivity, and the erosion of ecosystem services such as water and climate regulation [106,107]. The resulting socioecological impacts are profound: endemic species face shrinking habitats, traditional communities lose the subsistence tied to natural flood cycles, and regional economies suffer under recurring fires (see Figure 5) and declining agricultural yields [108–110]. Together, these interlinked processes underscore the urgency of coordinated conservation and sustainable management to preserve the ecological integrity and human well-being of these globally significant biomes.

The Atlantic Forest, spanning much of Brazil's coastline and hosting major metropolitan centers such as São Paulo, Rio de Janeiro, Salvador, Recife, and Porto Alegre, concentrates nearly 70% of the country's population [111]. This demographic weight explains why it is also the most studied Brazilian biome, accounting for 39% of research efforts [112]. High population density directly shapes long-term climate trends through multiple pathways, including greenhouse gas emissions, rapid urbanization and heat island effects, loss of native forest, and intensified demand for energy and water [113–117]. For this global biodiversity hotspot, already reduced to a fraction of its original extent, only about 28% of its original vegetation remains [111]. Consistent with previous findings, our results also indicate a pronounced rise in temperatures accompanied by a decline in precipitation across the Atlantic Forest, reinforcing the notion that these climatic shifts act as a threat multiplier [118]. In practice, higher temperatures increase evapotranspiration rates while reduced rainfall limits water recharge, intensifying drought stress in fragmented remnants, heightening wildfire risk, and undermining both carbon storage and hydrological services essential for densely populated regions. In the Pampa biome, our results reveal a consistent warming and drying trend that threatens the productivity of native pastures and the sustainability of local livestock systems, while also posing risks to the region's unique biodiversity.

Recent studies by Braga and Laurini (2024) [23] reinforce this vulnerability, showing that rising temperatures intensify evapotranspiration and plant heat stress, processes likely to disrupt phenological cycles and alter species dynamics with far-reaching ecological and socioeconomic consequences. Beyond this biome-specific evidence, Braga and Laurini (2024) [23] have also made important advances in understanding temperature dynamics across Brazilian biomes through a rigorous Bayesian spatio-temporal decomposition of station records, demonstrating the existence of distinct, biome-specific permanent warming trends. Building upon these valuable contributions, the present study extends the analysis in three key dimensions. First, by employing ERA5 reanalysis data for the entire South American continent, we provide a spatially continuous assessment encompassing both temperature ($T_{\max}$ and $T_{\min}$) and precipitation fields, overcoming limitations related to station coverage. Second, we explicitly evaluate asymmetric warming ($T_{\max}$ increasing faster than $T_{\min}$) and the emergence of a meridional precipitation dipole, offering a broader hydroclimatic perspective that integrates thermal and hydrological variability. Finally, while Braga and Laurini's results revealed heterogeneity of temperature trends among Brazilian biomes, our findings highlight additional regional hotspots of compounded temperature and precipitation change, notably in the Pantanal and central continental regions, thereby linking local heterogeneity with large-scale atmospheric circulation patterns. Together, these complementary studies provide robust and convergent evidence of the intensifying and spatially diverse impacts of climate change across South America.

The use of ERA5, while highly valuable for climate research, involves uncertainties that warrant cautious interpretation. Previous studies Refs. [51,52,119–121] have identified regional biases, particularly in sparsely observed areas such as the Amazon and the Andes, as well as systematic tendencies to overestimate $T_{\min}$ and underestimate $T_{\max}$ across

South America [53]. Furthermore, large-scale spatial averaging may obscure important local variability. Future work should integrate ground-based observations and multiple reanalysis products to better constrain these uncertainties and strengthen the reliability of climate assessments. Building upon these findings, it is important to recognize that ERA5 uncertainties arise from several interconnected sources. A key factor is the sparse and uneven distribution of assimilated observations, particularly across data-scarce regions such as deserts, high mountains, and parts of the tropics [122]. Model physics, parameterization schemes, and gradual changes in the observing system also contribute to variability within the dataset [123]. For example, satellite sensor transitions and updates in data assimilation can introduce subtle temporal inhomogeneities that influence long-term trend estimates [124]. Although ERA5 includes ensemble-based uncertainty information, these values capture only internal model variability and not the full range of observational or structural uncertainty [125]. Therefore, while ERA5 provides a consistent and physically robust representation of climate variability, its trends should be viewed as one plausible realization of regional climate behavior. Future work that combines multiple reanalyses and in situ observations will be essential to more accurately quantify and constrain these uncertainties, thereby strengthening the reliability of climate assessments.

We acknowledge that understanding the physical mechanisms and large-scale circulation patterns that influence the observed temperature and precipitation trends is fundamental to advancing the interpretation of climate variability and change in South America. Although a detailed investigation of atmospheric circulation was beyond the scope of this study, which primarily focused on detecting and characterizing long-term trends across biomes and urban areas, future research should examine how regional and global circulation systems, such as ENSO, the South Atlantic Convergence Zone, and subtropical jet variability, shape these spatial patterns. Integrating such dynamical analyses will be essential to more accurately attribute the detected trends and to enhance projections of climate-related risks in the region.

5. Conclusions

Long-term trends in Tmax and Tmin, as well as precipitation across South America, its capital cities, and Brazilian biomes, were investigated using ERA5 reanalysis from ECMWF for the period 1979–2024. To ensure statistical robustness, seasonal cycles were removed via STL, and trend estimates were derived using ordinary least squares (for temperature) and Mann–Kendall with Theil–Sen slope estimators corrected for autocorrelation following Yue–Wang (for precipitation). Results reveal a pervasive and spatially robust warming across South America, with Tmax increasing more strongly than Tmin. Precipitation exhibits a dipole pattern: drying in the continental interior and southern regions, and rainfall increases in the far north associated with the Intertropical Convergence Zone (ITCZ).

In major capitals, the warming signal is unequivocal though heterogeneous. Significant increases in Tmax exceeding ~ 0.35 °C decade^{−1} are observed in Asunción, La Paz, Brasília, and Caracas, while Lima and Bogotá display weaker trends. Precipitation changes mirror the continental dipole, with drying in central–southern cities (-11.32 mm/decade in Asunción; -8.66 mm/decade in Brasília) and increases in northern capitals such as Paramaribo, Georgetown, and Caracas. The intensifying warming in major capitals, combined with limited green infrastructure and high population density, suggests increasing exposure to urban heat stress and growing inequality in thermal vulnerability.

Among Brazilian biomes, the Pantanal emerges as the most vulnerable hotspot, exhibiting pronounced warming (Tmax ≈ 0.51 °C decade^{−1}) and the steepest rainfall decline (≈ -10.45 mm decade^{−1}). The Cerrado also shows strong concurrent warming and drying (≈ -7.92 mm decade^{−1}), while the Amazon records an increase in Tmax

(~ 0.35 °C decade⁻¹) and T_{min} (~ 0.16 °C decade⁻¹) accompanied by a modest reduction in rainfall (≈ -2.75 mm decade⁻¹). Consistent with these climatic patterns, a significant rise in satellite-detected fire occurrences was observed between 2013 and 2024 across these three biomes, most notably in the Amazon (+3663.7 fires yr⁻¹), followed by the Pantanal (+770.0 fires yr⁻¹) and Cerrado (+640.4 fires yr⁻¹), highlighting the link between increasing heat, declining moisture, and heightened fire susceptibility in central and western Brazil. Both the Caatinga and Atlantic Forest experience rainfall losses (≈ -3.06 and -5.60 mm decade⁻¹, respectively), whereas the Pampa presents the weakest warming (T_{max} ≈ 0.20 °C decade⁻¹) yet still a measurable decline in precipitation (≈ -4.09 mm decade⁻¹).

These patterns indicate mounting risks to ecosystems, water security, and agricultural productivity, with adaptation priorities in the Pantanal and Cerrado. Mechanistically, the asymmetry between T_{max} and T_{min} is consistent with reduced cloudiness and precipitation, enhanced solar radiation, and limited evaporative cooling, leading to an expansion of diurnal temperature range under drier, clearer-sky conditions. The results suggest a transition towards more frequent compound extremes of heat, drought, and fire. This underscores the urgency of integrated adaptation strategies encompassing water management, land use, and biodiversity conservation, alongside sustained mitigation efforts, particularly in regions where warming and drying converge.

The additional diagnostics presented in Section 3.4 strengthen the interpretation that the warming observed across South America during 1979–2024 is embedded within a longer-term, century-scale warming trajectory. Robust trend estimates, the absence of alternating sign in 46-year moving-window slopes, the position of the recent trend outside the AR(1) bootstrap envelope, and CWT evidence—indicating a persistent low-frequency increase—together render a purely internal explanation driven by multidecadal variability (such as AMO or PDO) improbable. Accordingly, the recent acceleration in warming is best understood as the intensification of an externally forced secular signal, with significant implications for national adaptation planning and long-term climate resilience.

While ERA5 offers spatially consistent and physically coherent fields, its accuracy varies regionally due to sparse in situ observations and known model biases, particularly in the Amazon and Andean regions, which may influence the magnitude of the estimated trends. These uncertainties are more pronounced prior to 1979, when observational constraints were substantially weaker. Therefore, continued validation against multiple independent datasets, including ground-based observations, alternative reanalyses, and CMIP6 detection-and-attribution experiments, remains essential for strengthening confidence in the attribution of long-term warming signals.

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