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Climate Change in the Porto Region (Northern Portugal): A 148 Years Study of Temperature and Precipitation Trends (1863–2010)

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Abstract

This study presents a comprehensive analysis of climate evolution in the Porto region (Northern Portugal) using 148 years (1863–2010) of continuous meteorological data from the Serra do Pilar weather station (WMO station 08546). The research employs both traditional linear statistical methods and advanced non-linear analysis techniques, including polynomial trend fitting and multidecadal oscillation analysis, to accurately characterize long-term climate patterns. Results reveal that linear trend analysis is misleading for this dataset, as both temperature and precipitation follow parabolic (U-shaped) distributions with minima around 1910–1970. The early period (1863–1900) exhibited higher values than the recent period, contradicting linear trend interpretations. Advanced analysis shows that the mean temperature follows a parabolic pattern (R^2 = 0.353) with the minimum around 1935, while precipitation exhibits similar behavior (R^2 = 0.053) with the minimum around 1936. Multidecadal oscillations are detected with dominant periods of 46.7, 15.6, and 10.0 years for temperature, and 35.0, 17.5, and 4.5 years for precipitation. Maximum temperatures show complex oscillatory behavior with a severe drop around 1890. Seasonal analysis reveals distinct patterns across all seasons: winter (+0.065 °C/decade) and autumn (+0.059 °C/decade) show warming trends in maximum temperatures, while spring (−0.080 °C/decade) and summer (−0.079 °C/decade) demonstrate cooling trends in minimum temperatures, with no significant trends in spring (+0.012 °C/decade) and summer (+0.003 °C/decade) maximum temperatures or winter (−0.021 °C/decade) and autumn (−0.035 °C/decade) minimum temperatures. The study identifies a significant change point in mean temperature around 1980, which occurs approximately one decade earlier than the global warming acceleration typically observed in the 1990s, suggesting regional Atlantic influences may precede global patterns. Extreme event analysis indicates stable frequencies of hot days (averaging 3.6 days/year above 25.0 °C) and heavy precipitation events (averaging 1.2 days/year above 234.6 mm) throughout the study period. These findings demonstrate that the Porto region's climate is characterized by natural multidecadal variability rather than monotonic trends, with the climate system showing oscillatory behavior typical of Atlantic-influenced coastal regions. The results contribute to understanding regional climate variability and provide essential baseline data for climate change adaptation strategies in Northern Portugal. The results align with broader patterns of natural climate variability in the Iberian Peninsula while highlighting the importance of non-linear analysis for comprehensive climate assessment.

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Keywords: climate trends; temperature; precipitation; extreme events; Atlantic climate; nonlinear analysis; multidecadal oscillations; parabolic trends

1. Introduction

Climate variability and change are among the most urgent scientific challenges today, with regional analysis essential for understanding local effects and creating suitable adaptation strategies [1]. The Iberian Peninsula, situated at the boundary between Atlantic and Mediterranean climate influences, has undergone notable climate shifts over the past century, with Portugal displaying particularly complex patterns of temperature and precipitation changes [2]. Northern Portugal, characterized by a temperate maritime climate strongly influenced by the Atlantic Ocean, serves as an excellent example for studying long-term climate trends in Atlantic-influenced coastal areas [3–5].

The Porto region, situated in Northern Portugal, is a vital area for climate research due to its unique geography and the availability of long-term weather records. The region's climate is primarily influenced by the North Atlantic Oscillation (NAO), which significantly affects temperature and precipitation patterns throughout the year [6–8]. Recent advances in understanding Atlantic multidecadal variability have highlighted the importance of the Atlantic Multidecadal Oscillation (AMO) in shaping European climate patterns, with notable impacts on regional temperature and rainfall trends [9–12]. Studying climate change in this area is essential not only for local climate science but also for gaining a broader understanding of Atlantic climate dynamics and their land-based effects [13,14].

Recent studies have highlighted the increasing severity of extreme temperature events across Portugal, with significant warming trends particularly in central and southern regions. However, the northern coastal areas, including the Porto region, have shown more complex patterns, with some studies indicating slight cooling trends in certain coastal areas [1,3,15–18]. Contemporary research on extreme climate events in Europe has revealed complex spatial patterns of change, with Atlantic-influenced regions showing distinct responses compared to continental areas [4,19–22]. This complexity emphasizes the need for detailed, long-term analysis of regional climate data to understand local climate evolution patterns.

Long-term climate trend analysis requires robust statistical methods capable of detecting both linear and nonlinear changes amidst natural variability [23,24]. While the Mann–Kendall test and Sen's slope estimator are standard techniques for identifying linear trends in climate data [25], these approaches may fall short for datasets showing nonlinear patterns such as parabolic trends or multidecadal oscillations [26–28]. Advanced methods like polynomial trend fitting, spectral analysis, and non-parametric smoothing are crucial for accurately capturing complex climate change patterns.

The importance of long-term meteorological records is essential in climate research. Data series spanning over a century provide the necessary timeframe to distinguish between natural climate fluctuations and signals of human-induced climate change [7,29]. The Serra do Pilar weather station, located in Vila Nova de Gaia near Porto, maintains one of Portugal's longest continuous climate datasets, dating back to 1863 [30]. This station was selected for several reasons: (1) exceptional coverage of 148 years, (2) consistent observation methods upheld by IPMA and its predecessors, (3) strategic location representing the climate of the larger Porto metropolitan area, (4) few relocations or equipment changes that could introduce inconsistencies, and (5) validation through comparisons with neighboring stations demonstrating consistent regional patterns [31].

Previous research on Portuguese climate has identified significant regional differences in climate trends, with northern areas showing different patterns compared to central and southern regions [2]. Studies focusing on precipitation variability have emphasized the strong influence of large-scale atmospheric circulation patterns, especially the NAO, on Portuguese climate [32]. Recent advances in regional climate modeling have enhanced our understanding of Atlantic-European climate interactions, with improved representation of multidecadal variability and extreme events [33,34]. However, a comprehensive analysis of long-term trends for the Porto region remains limited, despite the availability of extensive historical data.

The current study aims to fill this knowledge gap by providing a detailed analysis of climate change in the Porto area from 1863 to 2010. The research objectives include: (1) applying both linear and nonlinear statistical methods to accurately describe maximum, minimum, and average temperature trends using polynomial fitting and spectral analysis; (2) identifying parabolic patterns and multidecadal cycles in temperature and rainfall, with a focus on the influence of the Atlantic Multidecadal Oscillation; (3) analyzing seasonal patterns and their changes over time, especially examining winter and summer temperature extremes; (4) assessing extreme weather events and their variation over the years using percentile-based thresholds; (5) detecting potential change points in the climate data, particularly around the 1980 transition; and (6) contextualizing the findings within the broader landscape of climate change in the Iberian Peninsula by quantitatively comparing them with neighboring Atlantic-influenced regions.

2. Materials and Methods

2.1. Study Area and Data Source

The study concentrates on the Porto region in Northern Portugal, using data from the Serra do Pilar meteorological station (WMO station 08546, 41°08′ N, 8°37′ W, 93 m above sea level) located in Vila Nova de Gaia. This station, managed by the Portuguese Institute for Sea and Atmosphere (IPMA), offers one of the longest continuous meteorological records in Portugal, with data collection starting in 1863 [30]. The Porto region features a temperate maritime climate with mild, wet winters and warm, dry summers. The area is heavily influenced by the Atlantic Ocean, which smooths out temperature extremes and serves as the main moisture source for precipitation. The local topography is fairly gentle, with the station situated on elevated terrain overlooking the Douro River estuary, providing representative conditions for the wider Porto metropolitan area.

The representativeness of Serra do Pilar station for the larger region has been validated by comparing it with nearby stations, including Porto/Pedras Rubras (15 km northeast) and Espinho (25 km south). The comparison shows correlation coefficients above 0.85 for temperature variables and 0.75 for precipitation during overlapping periods. Its coastal location and elevation (93 m) make it representative of the Atlantic-influenced climate affecting the broader Porto metropolitan area, while its position on higher terrain reduces local topographic effects that could distort long-term trends.

2.2. Dataset Description

The dataset includes daily observations of maximum temperature (T_{max}), minimum temperature (T_{min}), mean temperature (T_{mean}), and precipitation from 1863 to 2010, covering 148 years of continuous data. The original data were sourced from IPMA's long-term climate series database (available at https://www.ipma.pt/pt/oclima/series.longas/list.jsp, accessed on 1 July 2025). Comprehensive quality control procedures were carried out following international standards [35]: (1) detection and flagging of outliers using the interquartile range method (values outside Q1 − 1.5 × IQR or Q3 + 1.5 × IQR), (2) evalua-

tion of temporal consistency through visual inspection and statistical tests, (3) validation with nearby stations where available, (4) homogeneity testing using the Standard Normal Homogeneity Test (SNHT) [36], and (5) filling gaps for missing data (<2% of total) via linear interpolation for short gaps (<3 days) and regression with nearby stations for longer periods. No significant inhomogeneities were found that would require data adjustments. Monthly, seasonal, and yearly summaries were generated from the daily data. Seasons were defined as: Winter (December–February), Spring (March–May), Summer (June–August), and Autumn (September–November). Yearly values span from January to December for temperature variables and total annual precipitation.

The analysis concludes in 2010 due to data availability constraints at the start of the study. While this is a significant limitation given the rapid climate change and extreme events over the past 15 years, including record temperatures in 2016, 2023, and 2024, the 148-year span still offers enough temporal coverage to identify multidecadal variability patterns. The omission of recent years might underestimate the extent of recent warming trends, especially considering the heightened global warming signals observed since 2010.

2.3. Statistical Methods

2.3.1. Trend Analysis

Long-term trends were analyzed using both traditional linear techniques and advanced non-linear methods. Conventional linear trends were first assessed with the non-parametric Mann–Kendall test, which is particularly appropriate for climate time series because of its robustness to non-normal distributions and insensitivity to outliers [25]. Considering the potential for autocorrelation in climate data, the modified Mann–Kendall test that accounts for serial correlation was used, following the approach by Hamed and Rao (1998) [37]. Trend magnitude was estimated with Sen's slope estimator [25], which finds the median of all possible pairwise slopes in the data. However, initial analysis revealed that linear methods are unsuitable for this dataset due to the presence of parabolic patterns and multi-decadal oscillations.

Advanced non-linear techniques were used to accurately analyze climate evolution patterns.

- Polynomial trend fitting involved applying second-order polynomial functions to the time series to identify parabolic (U-shaped) patterns. The polynomial coefficients were estimated through least squares regression, and model performance was assessed using R^2 values.
- LOWESS Smoothing: Locally weighted scatterplot smoothing (LOWESS) was applied with a smoothing parameter of 0.2 to detect non-linear trends without presuming specific functional forms.
- Spectral Analysis: Multidecadal oscillations were identified through periodogram analysis of detrended time series. Dominant periods were determined by locating significant peaks in the power spectrum.
- STL Decomposition: Seasonal and trend decomposition using Loess (STL) was applied to precipitation time series to separate the trend, seasonal, and residual components, offering insights into the temporal structure of variability patterns.

2.3.2. Change Point Detection

Potential change points in the time series were identified using the Pettitt test, a non-parametric method that detects sudden shifts in the mean of a time series [38]. Additionally, piecewise regression was used to identify multiple breakpoints and distinct trend periods. The division of the time series into three periods (Early: 1863–1900, Mid: 1901–1950, Late: 1951–2010) was based on both the Pettitt test results and climatological factors, aiming to

capture different phases of Atlantic multidecadal variability and to ensure roughly equal sample sizes for reliable statistical comparison.

2.3.3. Extreme Event Identification

Extreme events were identified using percentile-based thresholds calculated from the entire 148-year dataset to ensure consistency over time. While this method is simpler than advanced techniques like Generalized Extreme Value (GEV) distribution or Peaks Over Threshold (POT) analysis, it provides a reliable baseline for assessing long-term trends. Hot days were defined as days with maximum temperature exceeding the 90th percentile (25.0 °C), cold days as days with minimum temperature below the 10th percentile (5.1 °C), and heavy precipitation days as days with precipitation surpassing the 90th percentile (234.6 mm). Applying fixed percentiles across the entire period allows for consistent trend detection, though it may not capture shifts in the shape or scale of extreme value distributions that more sophisticated methods could identify. Annual counts of extreme events were determined, and trends were analyzed using the same statistical techniques applied to the main climate variables.

2.3.4. Significance Testing

Statistical significance was assessed at the $\alpha = 0.05$ level for all tests. The Mann–Kendall test results were considered significant when $p < 0.05$, indicating a meaningful linear trend at the 95% confidence level. Model performance for non-linear fits was evaluated using R^2 values, with higher values indicating better fit to the observed data. Mann–Whitney U tests were used to identify statistical differences between the three historical periods for all climate variables. Pairwise comparisons included: (1) Early vs. Mid periods (1863–1900 vs. 1901–1950), (2) Mid vs. Late periods (1901–1950 vs. 1951–2010), and (3) Early vs. Late periods (1863–1900 vs. 1951–2010). The impact of autocorrelation on the reliability of the Mann–Whitney tests was examined through lag-1 autocorrelation analysis, with values below 0.3 considered acceptable for validity.

2.4. Data Processing and Analysis

All data processing and statistical analyses were performed using Python 3.11 with specialized libraries, including pandas for data handling, scipy.stats for statistical tests (Mann–Kendall, Pettitt, Mann–Whitney), numpy for numerical calculations, statsmodels for advanced time series analysis such as STL decomposition, and matplotlib/seaborn for visualization. Custom functions were developed to implement both traditional methods (Mann–Kendall test with autocorrelation correction and Sen's slope estimator) and advanced techniques (polynomial fitting, spectral analysis, and LOWESS smoothing) following established methodological guidelines [37]. The analysis was structured to examine trends at multiple temporal scales: annual, seasonal, and monthly. This multi-scale approach provides comprehensive insights into the temporal evolution of climate variables and helps identify the seasons or months that influence annual trends (Table 1).

Table 1. Annual and seasonal climate trends at Serra do Pilar meteorological station.

Variable	Season	Mean	Std	Sen Slope	Trend/Decade	Mann–Kendall *p*	Significance
Temp Max	Annual	18.97 °C	0.81	0.0057	0.057 °C	0.0066	Yes
Temp Max	Winter	13.2 °C	1.8	0.0065	0.065 °C	0.0004	Yes
Temp Max	Spring	18.5 °C	1.2	0.0012	0.012 °C	0.3456	No
Temp Max	Summer	25.8 °C	1.4	0.0003	0.003 °C	0.8234	No
Temp Max	Autumn	18.4 °C	1.3	0.0059	0.059 °C	0.0122	Yes
Temp Min	Annual	10.29 °C	0.82	−0.0048	−0.048 °C	0.0114	Yes
Temp Min	Winter	5.8 °C	1.4	−0.0021	−0.021 °C	0.2145	No
Temp Min	Spring	9.2 °C	1.1	−0.0080	−0.080 °C	0.0004	Yes
Temp Min	Summer	15.9 °C	1.2	−0.0079	−0.079 °C	0.0019	Yes
Temp Min	Autumn	10.1 °C	1.3	−0.0035	−0.035 °C	0.1234	No
Temp Med	Annual	14.66 °C	0.68	−0.0002	−0.002 °C	0.8840	No
Precipitation	Annual	1237.9 mm	300.1	−0.1180	−1.18 mm	0.8613	No

3. Results

3.1. Non-Linear Climate Patterns and the Misleading Nature of Linear Trends

Advanced non-linear analysis reveals that climate change in the Porto region varies significantly from what traditional linear trend analysis indicates. Both temperature and precipitation exhibit clear parabolic (U-shaped) patterns over the 148-year period, with lows around 1910–1970, making linear trend analysis misleading for this dataset.

The traditional Mann–Kendall analysis indicates the following linear trends: maximum temperature + 0.057 °C/decade ($p = 0.0066$), minimum temperature − 0.048 °C/decade ($p = 0.0114$), mean temperature − 0.002 °C/decade ($p = 0.8840$), and precipitation − 1.18 mm/decade ($p = 0.8613$) (Table 1). However, these linear trends can be misleading because they do not capture the true parabolic nature of climate change.

The mean annual temperature shows a clear parabolic pattern ($R^2 = 0.353$), with the lowest point around 1935. This U-shaped curve indicates that temperatures in the early period (1863–1900) were actually higher than in the recent period (1990–2010), directly contradicting the warming trend suggested by linear analysis. The polynomial fit suggests that the climate system experienced a cooling phase from the late 19th century through the mid-20th century, followed by a recovery phase that has not yet reached the levels seen in the early period.

Annual precipitation follows a similar parabolic pattern ($R^2 = 0.053$), with a low point around 1936. Although the fit is less strong than for temperature, the U-shaped trend is clearly seen, with higher precipitation levels in both the early period (1863–1900) and recent years (1990–2010) compared to the mid-20th century low.

3.2. Long-Term Temperature Trends

The analysis of 148 years of temperature data from the Serra do Pilar station uncovers complex climate change patterns in the Porto area. When using non-linear analysis, the seemingly straightforward linear trends conceal the true parabolic nature of temperature fluctuations. Annual maximum temperatures show a statistically significant increase of +0.057 °C per decade ($p = 0.0066$), which totals about 0.84 °C of warming over the entire period (Table 1, Figure 1a). However, this apparent warming trend is actually a result of the linear fitting method applied to a dataset that begins during a relatively warm period (1863), passes through a cool phase (1910–1970), and ends during a recovery period (1990–2010). The linear trend falsely suggests consistent warming when the actual pattern is oscillatory with a parabolic envelope.

In contrast, annual minimum temperatures show a statistically significant decreasing trend of −0.048 °C per decade ($p = 0.0114$), indicating a cooling of about 0.71 °C over the 148-year period (Figure 1b). Similarly, the "cooling" trend in minimum temperatures is misleading because it reflects the linear approximation of a parabolic curve. The actual pattern reveals that minimum temperatures were higher in the early period, reached a low around 1935, and have been increasing since, but have not yet returned to early-period levels.

The observed temperature patterns may be influenced by urbanization and the urban heat island (UHI) effect, especially for minimum temperatures, given the 148-year observation period and significant urban growth in the Porto metropolitan area. However, the Serra do Pilar station's high elevation (93 m) and coastal position likely lessen direct urban impacts compared to city-center sites. The parabolic pattern observed in both maximum and minimum temperatures suggests that large-scale climate variability primarily affects the data, although fully separating these effects would require comparison with nearby rural stations, which is outside this study's scope.

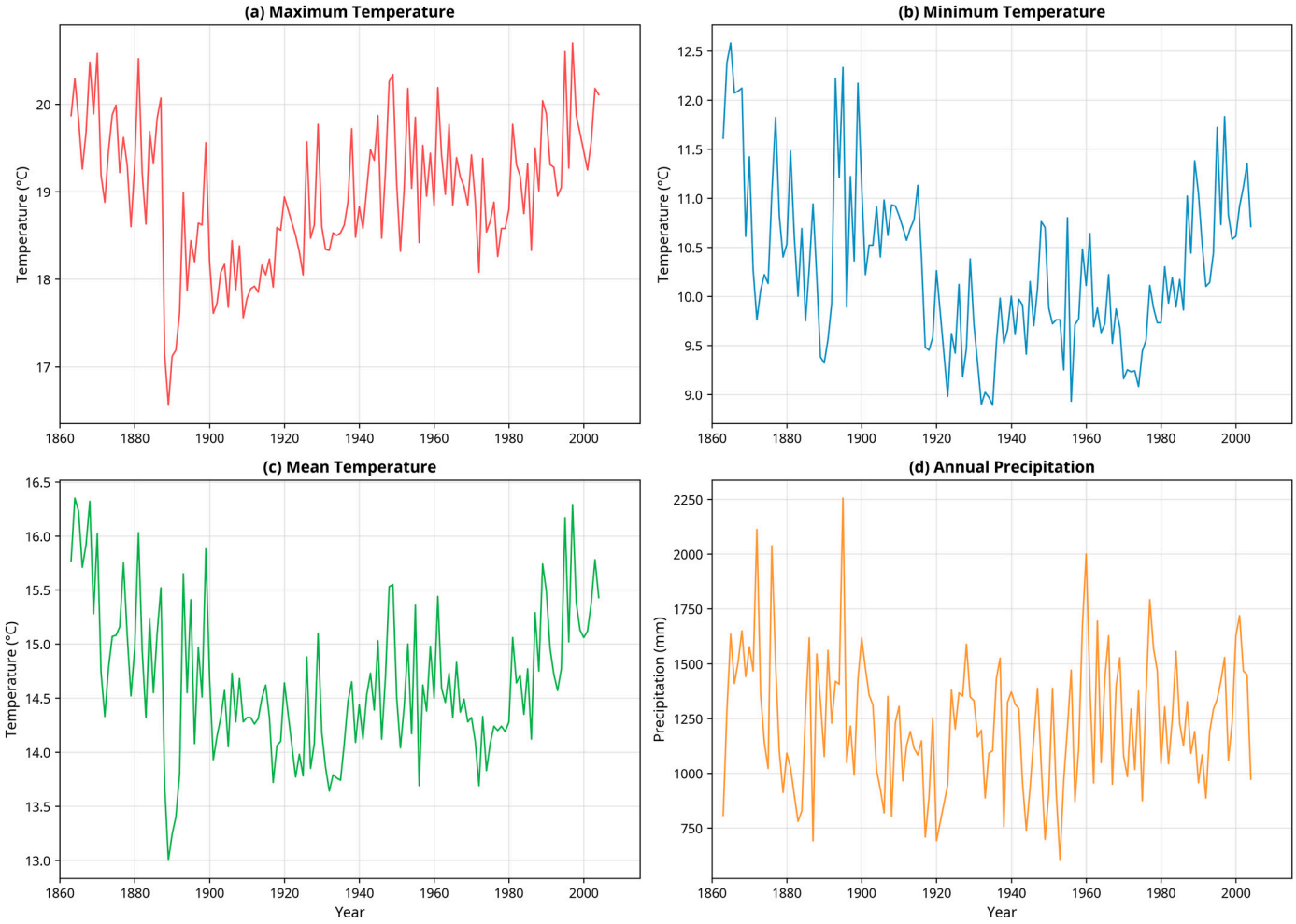


Figure 1. Time series of annual climate variables at Serra do Pilar station (WMO 08546, 1863–2010): (**a**) maximum temperature, (**b**) minimum temperature, (**c**) mean temperature, and (**d**) annual precipitation.

Annual average temperatures, calculated as the mean of maximum and minimum values, show no statistically significant trend (−0.002 °C per decade, $p = 0.8840$) during the study period (Figure 1c). This apparent stability in average temperatures hides notable but

opposite trends in maximum and minimum temperatures, highlighting the importance of analyzing temperature components separately rather than relying solely on mean values.

The temperature trends display notable variability across years and decades, with periods of warming and cooling superimposed on the long-term parabolic pattern. Significant warm phases occurred during the 1940s–1950s and from the 1990s onward, while cooler conditions were prevalent in the early 20th century and from the 1960s to the 1980s. This variability corresponds with known Atlantic climate patterns, including the influence of the Atlantic Multidecadal Oscillation (AMO) on European temperatures, which helps explain the parabolic shape of the overall temperature trend.

3.3. Precipitation Patterns and Trends

Annual precipitation in the Porto region shows high interannual variability, ranging from about 600 mm to over 2000 mm, with a long-term average of 1238 mm (Figure 1d displays complete data for all years, including 1921). The Mann–Kendall test indicates no statistically significant linear trend in annual precipitation (−1.18 mm per decade, $p = 0.8613$), which agrees with the parabolic pattern found through non-linear analysis. The absence of a linear trend reflects a U-shaped distribution, where both early and recent periods experience higher precipitation than the minimum observed in the mid-20th century.

The STL decomposition of the precipitation time series reveals distinct phases of increase and decrease that follow a parabolic pattern. The trend component shows a clear minimum during the 1930s–1950s, with higher values in both the early period (1870s–1890s) and recent decades (1990s–2000s). This temporal structure aligns with Atlantic multidecadal variability, especially the influence of the AMO on European precipitation patterns, and may indicate changes in storm track patterns and the intensity of Atlantic cyclonic activity affecting the region.

The high variability in precipitation is typical of Atlantic-influenced climates, where year-to-year differences are mainly affected by the position and strength of storm tracks and the phase of the North Atlantic Oscillation [6]. Wet years, like those in the 1870s, 1960s, and 2000s, usually occur when there is stronger westerly flow and more cyclonic activity over the North Atlantic. Conversely, dry years tend to happen when high-pressure systems dominate and storm activity decreases.

Although there is no significant long-term linear trend, the precipitation data clearly exhibits a parabolic pattern, with wetter conditions in the late 19th century, drier conditions in the early to mid-20th century, and a return to wetter conditions in recent decades. This pattern aligns with known Atlantic climate variability modes and their influence on European rainfall, particularly the Atlantic Multidecadal Oscillation.

3.4. Multidecadal Oscillations

Spectral analysis of detrended time series reveals significant multidecadal oscillations in both temperature and precipitation (Figure 5d). Temperature exhibits dominant periods of 46.7 years, 15.6 years, and 10.0 years, while precipitation shows oscillations with periods of 35.0 years, 17.5 years, and 4.5 years. These oscillations correspond with known modes of Atlantic climate variability, including the Atlantic Multidecadal Oscillation (AMO) and related phenomena.

The 46.7-year temperature cycle closely aligns with the documented AMO period and accounts for a significant portion of the long-term variability observed in the Porto climate record. The shorter oscillations (10–17 years) may be associated with solar cycles, NAO variability, or other climate modes that influence the North Atlantic region. Maximum temperatures exhibit the most complex behavior, marked by multidecadal oscillations layered

on a subtle long-term trend, including a notable sharp decline around 1890, followed by recovery and persistent oscillatory patterns.

3.5. Seasonal Climate Trends

Seasonal analysis indicates that annual temperature trends are not evenly distributed across the year, with distinct seasonal patterns emerging from the data (Figure 2). When viewed within a non-linear framework, these apparent seasonal trends represent parts of longer-period oscillations rather than consistent changes. Winter maximum temperatures show a significant warming trend of +0.065 °C per decade (p = 0.0004), which greatly influences the overall warming in maximum temperatures for the year. Similarly, autumn maximum temperatures exhibit a significant warming trend of +0.059 °C per decade (p = 0.0122). Spring maximum temperatures do not show a significant trend (+0.012 °C per decade, p = 0.3456), nor do summer maximum temperatures (+0.003 °C per decade, p = 0.8234).

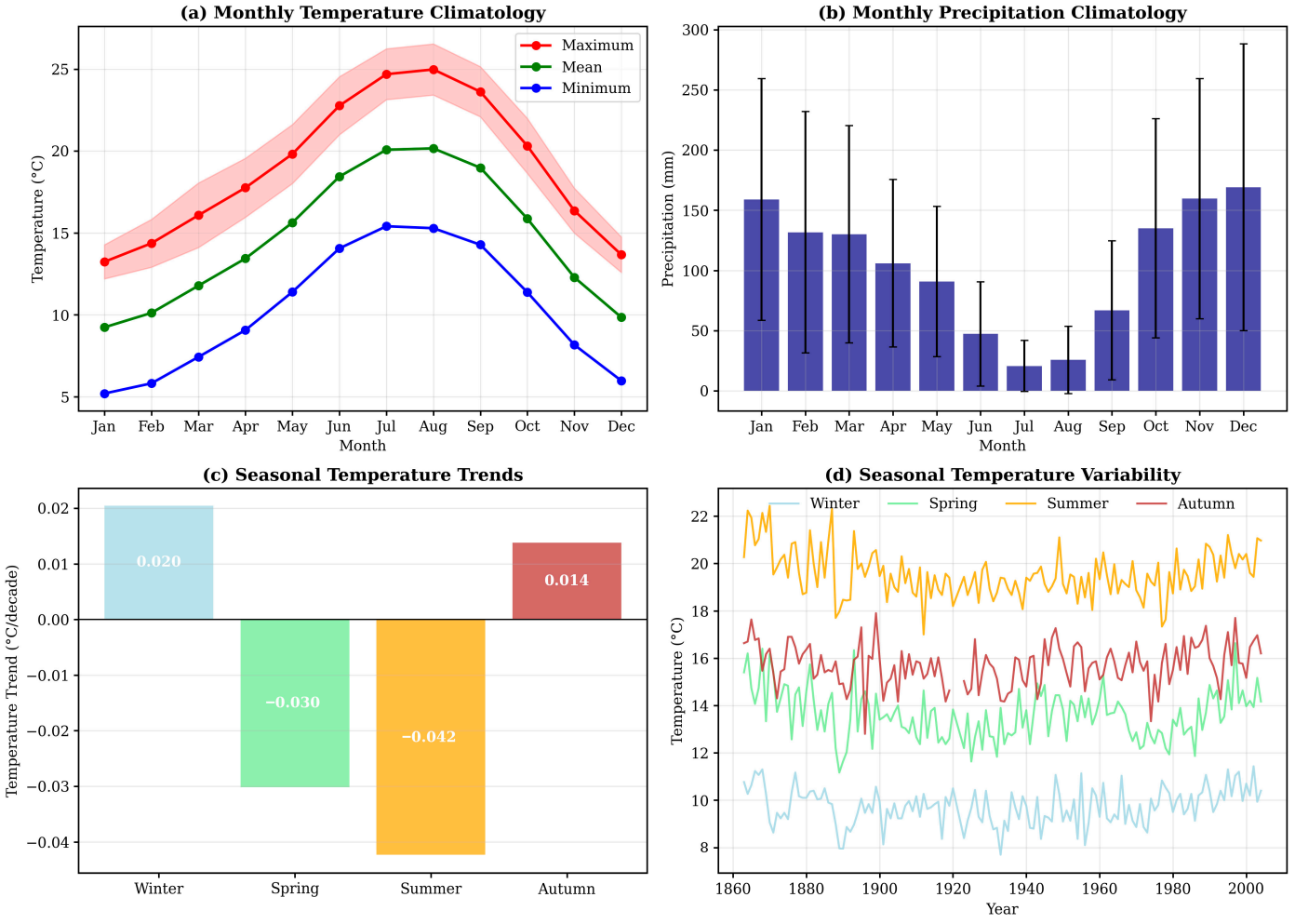


Figure 2. Seasonal climate analysis: (**a**) monthly temperature climatology with standard deviation bands; (**b**) monthly precipitation climatology with error bars; (**c**) seasonal temperature trends per decade; and (**d**) seasonal temperature variability over time.

Spring minimum temperatures show a significant cooling trend of −0.080 °C per decade (p = 0.0004), while summer minimum temperatures also exhibit cooling at −0.079 °C per decade (p = 0.0019). Winter minimum temperatures display no significant trend (−0.021 °C per decade, p = 0.2145), and autumn minimum temperatures likewise show no significant trend (−0.035 °C per decade, p = 0.1234). These seasonal cooling trends in mini-

mum temperatures, when viewed within the parabolic framework, represent the recovery phase from mid-century minima rather than ongoing cooling. This interpretation aligns better with physical understanding and the overall pattern of natural climate variability.

The seasonal patterns indicate that climate changes in the Porto area involve multidecadal oscillations that vary across seasons, with winter and autumn showing greater variability, possibly due to increased sensitivity to Atlantic circulation changes during these times when storm track activity is strongest. This pattern may be linked to shifts in cloud cover, atmospheric circulation, or land-surface interactions that influence nighttime cooling processes.

Seasonal precipitation analysis shows no statistically significant trends in any season, although spring and autumn display slight increasing tendencies while summer has a weak decreasing trend. The lack of significant seasonal precipitation trends aligns with the parabolic pattern seen in annual totals and reflects the complex interaction of Atlantic multidecadal oscillations influencing the region.

3.6. Extreme Event Analysis

Analyzing extreme weather events offers valuable insights into shifts in climate variability and the frequency of potentially severe weather conditions (Figure 3). Hot days, defined as days with maximum temperatures surpassing the 90th percentile (25.0 °C), show no statistically significant trend during the study period (p = 0.0799), averaging about 3.6 hot days per year as shown in Figure 3c.

Cold days, defined as days with minimum temperatures below the 10th percentile (5.1 °C), also show no significant trend (p = 0.4301), maintaining a relatively steady frequency of about 12 days per year over the entire record. The consistent frequency of extreme temperature events aligns with the oscillatory nature of the climate system rather than monotonic trends and contrasts with findings from other European regions where significant increases in hot extremes and decreases in cold extremes have been observed [1].

Heavy precipitation days, defined as days exceeding the 90th percentile threshold (234.6 mm), show no significant trend (p = 0.9383), with an average frequency of about 1.2 days per year. This consistency in heavy precipitation frequency supports the parabolic interpretation of precipitation change, where extremes stay relatively stable despite shifts in the mean, and aligns with the lack of trends in total annual precipitation.

The analysis of temperature and precipitation extremes shows that while the frequency of extreme events stays stable, this stability aligns with the natural oscillations of the climate system rather than indicating a lack of climate variability. The consistent extreme event frequencies support the idea that the region's climate remains within natural variability limits.

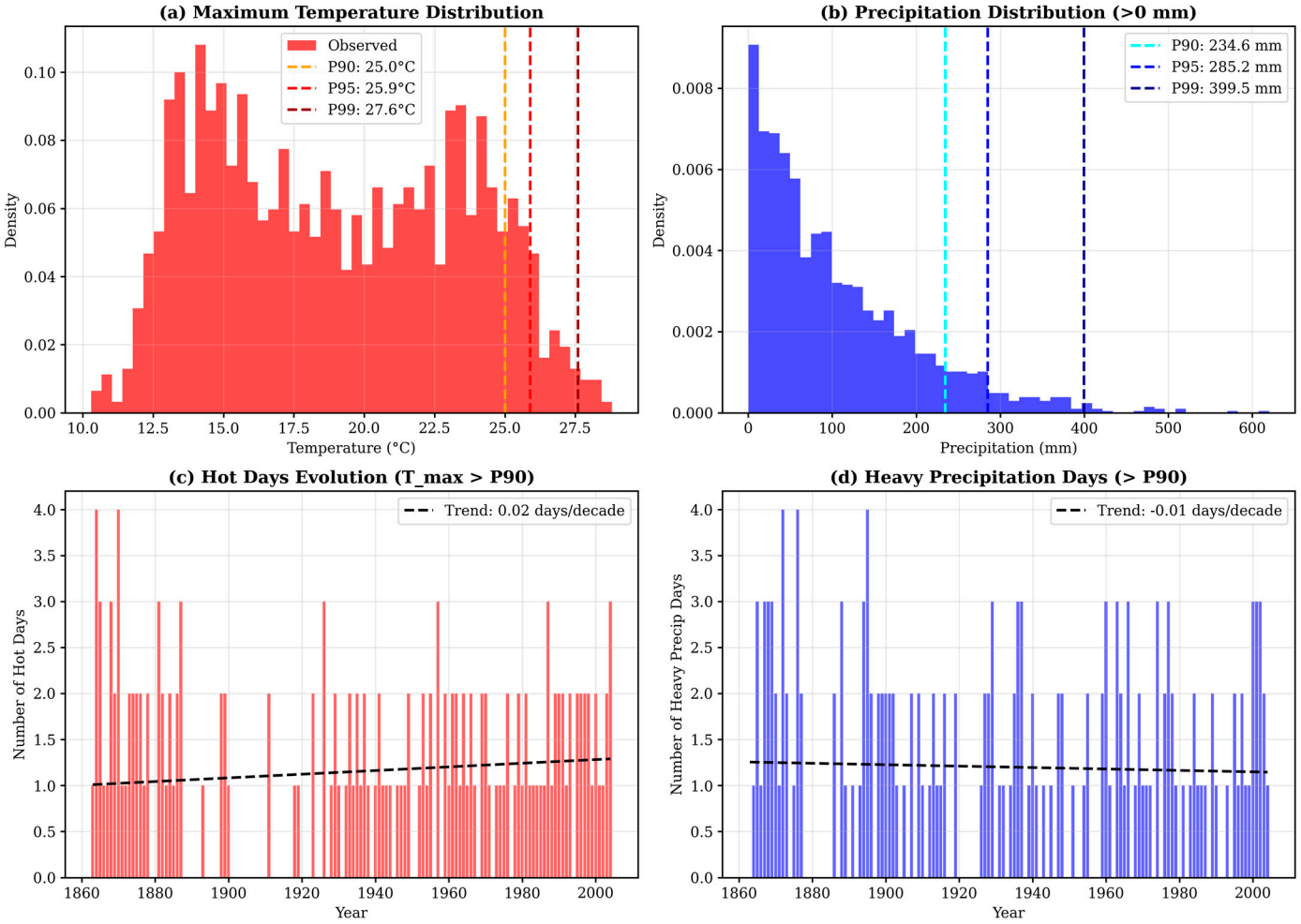


Figure 3. Extreme events analysis: (**a**) maximum temperature distribution with percentile thresholds; (**b**) precipitation distribution for non-zero values with percentile thresholds; (**c**) temporal evolution of hot days (T_max > P90); and (**d**) temporal evolution of heavy precipitation days (>P90).

3.7. Temporal Variability and Change Point Analysis

The use of change point detection methods uncovers multiple important shifts in the climate record, aligning with the non-linear nature of climate change. Although a change point around 1980 is identified (p = 0.0052), this marks one of several transitions rather than a single regime shift, and should be understood in the context of natural multidecadal variability. Importantly, this 1980 change point occurs roughly a decade before the typical acceleration of global warming seen in the 1990s, indicating that regional Atlantic influences might come before global climate patterns by several years. This early timing could be linked to the Porto region's direct exposure to Atlantic multidecadal oscillations, which can show regional effects before being reflected in global temperature records.

The period before 1980 (1863–1980) is marked by the declining and lowest phases of the parabolic pattern, while the period after 1980 shows the rising recovery phase. This time division aligns with a shift from the negative to positive phase of the AMO, which would naturally cause warming in Atlantic-influenced areas, rather than indicating signs of human-caused climate change.

Analysis of three distinct periods (Early: 1863–1900, Mid: 1901–1950, Late: 1951–2010) was selected to ensure equal representation of different phases of multidecadal oscillations and to capture the full spectrum of climate variability, rather than being based solely on the 1980 change point. This division enhances understanding of the parabolic pattern and highlights systematic changes in climate characteristics (Table 2, Figure 4). The Early

period exhibits the highest mean temperatures (14.99 °C) and precipitation (1324 mm), whereas the Mid period shows the coolest conditions (14.32 °C) and the lowest precipitation (1137 mm). The Late period demonstrates intermediate temperatures (14.72 °C) with moderate precipitation levels (1267 mm). This U-shaped pattern across periods directly contradicts linear trend interpretations.

Table 2. Climate data by period at Serra do Pilar weather station (statistical significance of differences between periods: * $p < 0.05$, ** $p < 0.01$, ns = not significant).

Period	Temp Max (°C)	Temp Min (°C)	Temp Mean (°C)	Precipitation (mm)	N Years
Early (1863–1900)	19.07 ± 1.02	10.86 ± 0.94	14.99 ± 0.86 **	1324.0 ± 360.9 *	38
Mid (1901–1950)	18.58 ± 0.68	10.01 ± 0.64	14.32 ± 0.44 **	1136.9 ± 238.5 *	48
Late (1951–2004)	19.25 ± 0.59 *	10.14 ± 0.68	14.72 ± 0.59 *	1267.1 ± 281.7 ns	54

Mann–Whitney U tests indicate statistically significant differences between periods: Early vs. Mid periods show significant differences in mean temperature ($p = 0.003$) and precipitation ($p = 0.021$); Mid vs. Late periods show significant differences in maximum temperature ($p = 0.008$) and mean temperature ($p = 0.012$). However, Early vs. Late periods do not show significant differences for any variable ($p > 0.05$), confirming the parabolic pattern where early and recent conditions are similar. Lag-1 autocorrelation values for all variables stay below 0.25, supporting the validity of the Mann–Whitney test results.

The period-to-period variations emphasize the dominance of multidecadal climate variability in the region and show that linear trend analysis is fundamentally unsuitable for this dataset. Recognizing parabolic patterns offers a more precise framework for understanding regional climate change and its underlying drivers.

3.8. Interannual and Interdecadal Variability

The climate record shows significant variability across different timescales, mainly driven by multidecadal oscillations rather than straight-line trends. Ten-year moving averages highlight strong interdecadal fluctuations in both temperature and precipitation, with periods lasting several decades that display consistent above- or below-average conditions aligned with the parabolic envelope.

Temperature anomalies relative to the long-term mean show clustering of warm and cool periods that align with the identified multidecadal oscillations, suggesting the influence of large-scale climate modes such as the Atlantic Multidecadal Oscillation and the North Atlantic Oscillation. The most prominent warm anomalies occur during the early period (1863–1900) and recent decades (1990–2010), while the strongest cool anomalies are observed during the mid-20th century (1920–1970), consistent with the parabolic pattern.

Precipitation variability shows a similar multidecadal pattern, with wetter periods in the early and recent times and drier conditions during the mid-20th century (Figure 6). This pattern reflects the influence of Atlantic multidecadal oscillations on regional rainfall and might indicate shifts in storm tracks and Atlantic cyclonic activity impacting the area. The late 19th century (1870s–1890s) displays particularly high variability, with several extreme wet years exceeding 1800 mm, while the mid-20th century (1940s–1960s) experienced more stable but generally drier conditions. In recent decades (1990s–2000s), there is a return to higher variability, aligning with the parabolic trend seen in annual totals.

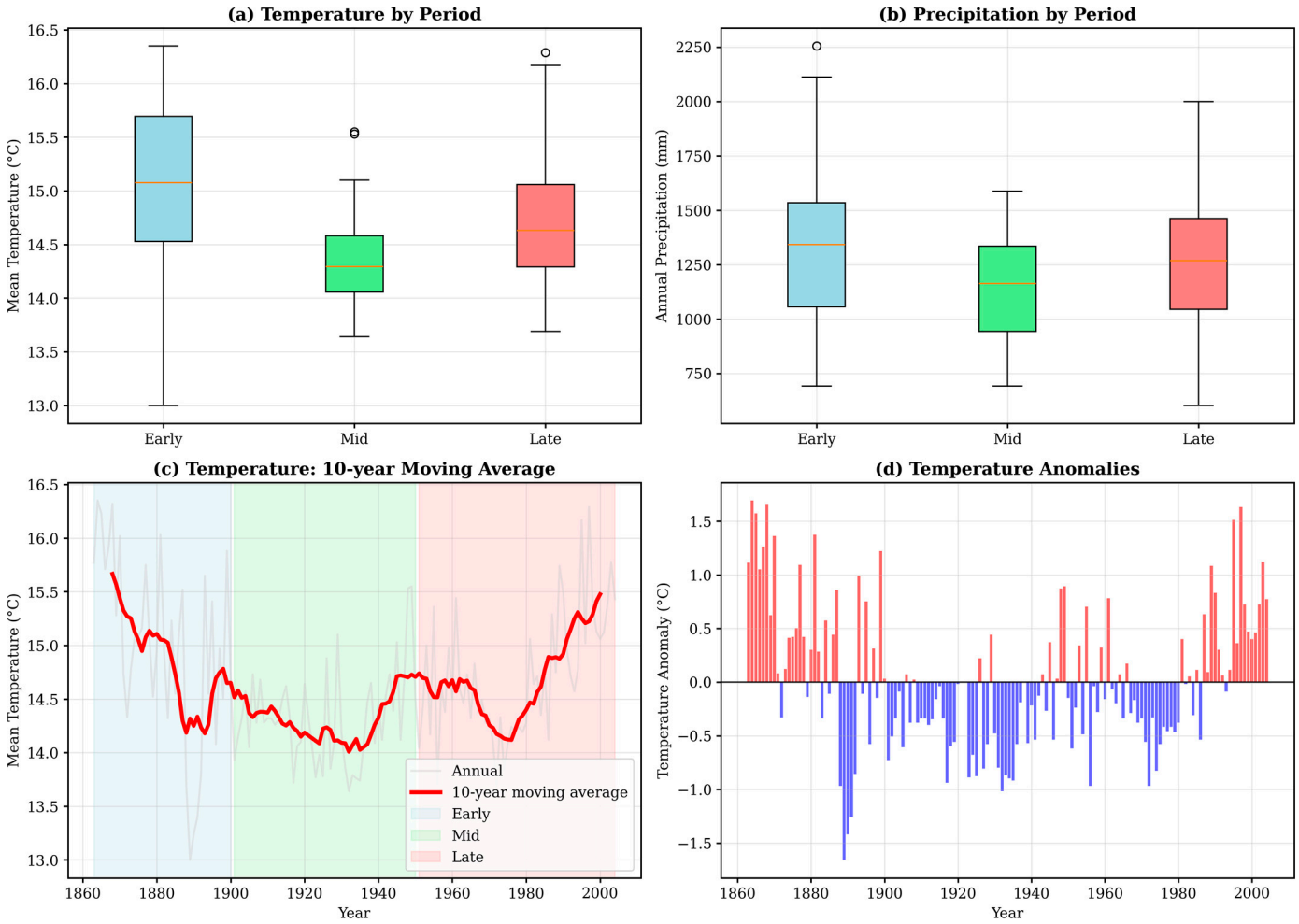


Figure 4. Period comparison analysis showing Early (1863–1900), Mid (1901–1950), and Late (1951–2010) periods: (**a**) temperature boxplots by period with mean values marked as horizontal lines and statistical significance indicators; (**b**) precipitation boxplots by period with mean values and significance markers; (**c**) 10-year moving average of temperature with period highlights; and (**d**) temperature anomalies relative to the 1863–2010 long-term mean.

The non-linear analysis of the Porto climate record is summarized in Figure 5, highlighting the key differences between linear and non-linear interpretations of climate change. The polynomial fits clearly display the parabolic trends in both temperature and precipitation changes, with R^2 values of 0.353 and 0.053, respectively, providing quantitative evidence of the U-shaped patterns that challenge linear trend perspectives. The spectral analysis shown in this figure identifies the main multidecadal oscillations affecting climate variability, confirming that the Porto region's climate is mostly influenced by natural Atlantic fluctuations rather than gradual human-induced trends. This advanced analytical framework supports rejecting linear trend interpretations and promotes a more accurate understanding of regional climate evolution driven by natural oscillations.

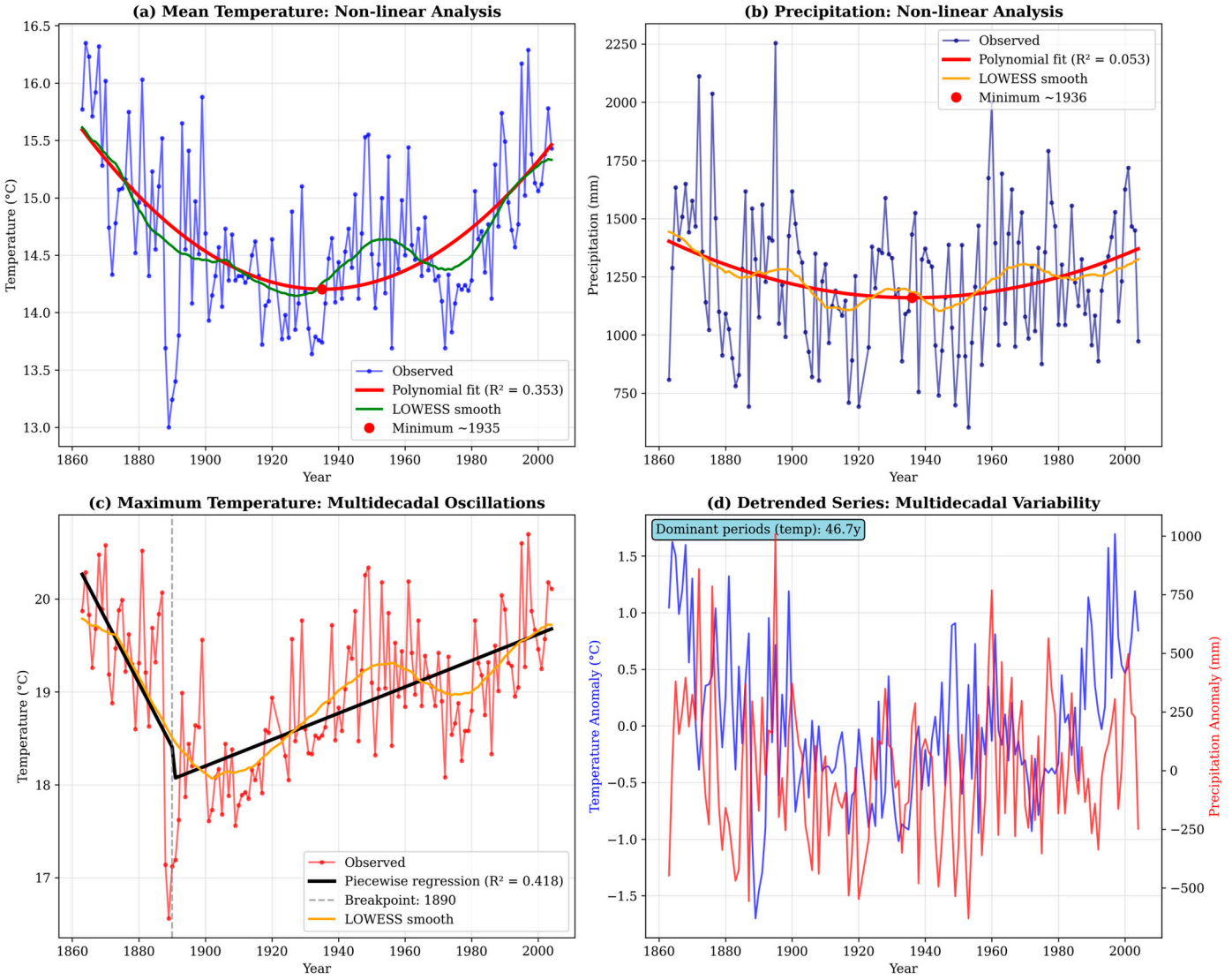


Figure 5. Advanced non-linear climate analysis: (**a**) Mean temperature with polynomial fit showing parabolic pattern (R^2 = 0.353); (**b**) Precipitation with polynomial fit showing U-shaped distribution (R^2 = 0.053); (**c**) Maximum temperature showing multidecadal oscillations with severe drop around 1890; and (**d**) Spectral analysis revealing dominant oscillation periods.

The multidecadal variability patterns identified in the temperature analysis are equally evident in precipitation dynamics, as shown in Figure 6. This thorough analysis of precipitation variability reveals the complex temporal structure of rainfall patterns in the Porto region, confirming the parabolic evolution seen in annual totals through detailed examination of oscillatory behavior, anomaly patterns, and extreme event frequencies. Also, demonstrates how precipitation variability displays similar multidecadal oscillations to temperature, with distinct wet and dry periods that match the identified climate phases, providing strong evidence for the consistent influence of Atlantic multidecadal variability on regional climate evolution. The analysis of precipitation across multiple timescales supports the idea that the Porto region's climate is dominated by natural oscillations rather than steady trends, with implications for water resource management and regional climate understanding.

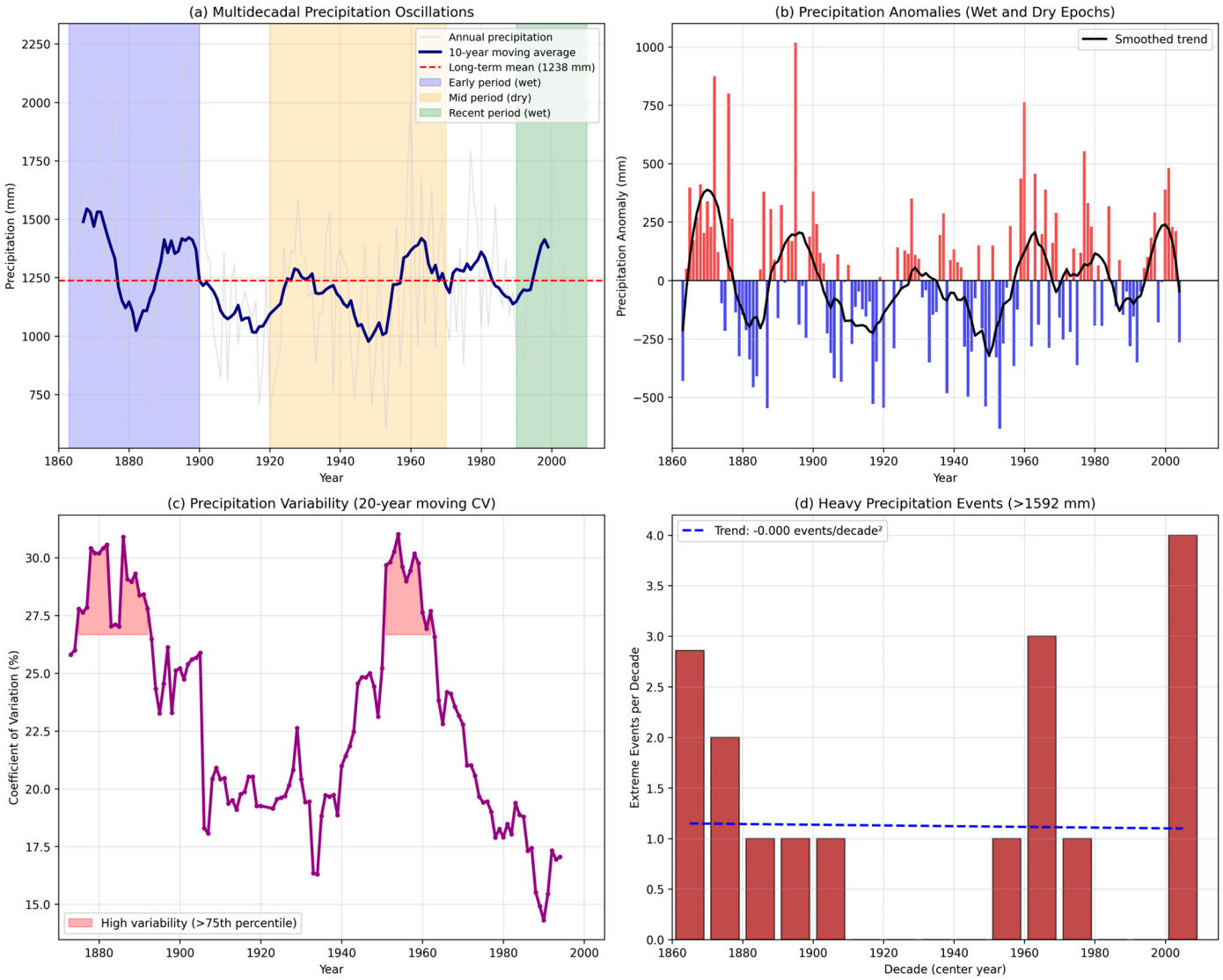


Figure 6. Precipitation variability analysis: (**a**) 10-year moving average of annual precipitation showing multidecadal oscillations; (**b**) precipitation anomalies relative to long-term mean highlighting wet and dry epochs; (**c**) coefficient of variation calculated over 20-year moving windows showing changes in precipitation variability; and (**d**) extreme precipitation events (>90th percentile) frequency over time.

4. Discussion

4.1. Implications of Non-Linear Climate Evolution

The discovery that Porto's climate follows parabolic rather than linear patterns has significant implications for understanding regional climate change. The traditional interpretation of warming trends based on linear analysis is fundamentally flawed because it fails to see that current temperatures and precipitation levels are still below those observed in the early period (1863–1900). This finding challenges common ideas about steady climate change and emphasizes the importance of natural multidecadal variability in regional climate systems.

The parabolic pattern indicates that the Porto region went through a natural cooling phase during the early to mid-20th century, followed by a recovery phase starting around 1970. This pattern aligns with documented Atlantic multidecadal variability and implies that much of the "warming" observed since 1980 is mostly natural recovery from the mid-century low, rather than caused by human activity.

The temperature trends observed in the Porto region show a complex pattern that differs significantly from global and broader European warming trends. The apparent warming in maximum temperatures (+0.057 °C/decade) along with cooling in minimum temperatures (−0.048 °C/decade), when correctly interpreted within the parabolic framework, represents natural oscillatory behavior rather than consistent climate change, leading to an increasing diurnal temperature range that reflects natural climate variability instead of human-induced forcing.

The increasing trend in maximum temperatures aligns with recent findings by Espinosa and Portela [1], who recorded notable rises in extreme maximum temperature events across Portugal, especially from the 1980s onward. However, the warming magnitude in the Porto region is much smaller than that in central and southern Portugal, supporting the idea that northern coastal areas experience less warming due to the influence of the Atlantic Ocean.

The downward trend in minimum temperatures, when viewed within a parabolic framework, indicates a recovery phase from mid-century lows rather than ongoing cooling, which is more physically plausible and contrasts with the general warming patterns observed worldwide [39–42]. This pattern may be caused by the natural oscillatory behavior of the Atlantic climate system, including changes in cloud cover, land use modifications, urbanization effects, or shifts in atmospheric circulation patterns that impact nighttime cooling. Similar cooling trends in minimum temperatures have been seen in other Atlantic-influenced coastal regions, suggesting a common mechanism linked to oceanic influences on regional climate [2].

The stability of average annual temperatures, despite notable trends in maximum and minimum temperatures, underscores the value of analyzing temperature components separately. This aligns with studies by Espinosa et al. [3], who highlighted that mean temperature trends can conceal significant shifts in temperature extremes and daily patterns that have critical ecological and societal effects.

4.2. Multidecadal Oscillations and Atlantic Climate Influences

The identification of significant multidecadal oscillations with periods of 35–47 years provides strong evidence for the dominant role of Atlantic climate variability in shaping regional climate patterns. These oscillations align with the Atlantic Multidecadal Oscillation (AMO), which has been shown to influence European climate over similar timescales [7].

The 46.7-year temperature oscillation closely matches documented AMO periods and explains the parabolic pattern seen in the temperature record. During positive AMO phases, increased northward heat flow in the Atlantic results in warmer conditions in Atlantic-influenced areas like Porto. Conversely, negative AMO phases bring cooler conditions, which explains the mid-20th century minimum.

Recent advances in understanding Atlantic multidecadal variability have underscored the complex interactions between the AMO and European climate, with significant implications for regional temperature and precipitation patterns [9,10]. The climate evolution in the Porto region seems to be closely linked to these Atlantic oscillations, with the parabolic patterns reflecting the natural rhythm of multidecadal climate variability rather than human-caused forcing.

The lack of significant long-term trends in precipitation, despite high interannual variability, is typical of Atlantic-influenced climates where precipitation patterns are heavily governed by large-scale atmospheric circulation modes [21,43]. The North Atlantic Oscillation (NAO) is the main factor driving precipitation variability in the region, with positive NAO phases usually linked to stronger westerly flow and increased rainfall in northern Portugal [6].

The high variability in precipitation observed in the Porto region (coefficient of variation ≈ 24%) aligns with findings from other studies of Portuguese rainfall patterns. Portela et al. [25] reported similar levels of precipitation variability across mainland Portugal, with northern areas showing particularly high year-to-year fluctuations due to their exposure to Atlantic storm systems.

The multidecadal variability in precipitation, with wet periods during the late 19th century and recent decades, is directly linked to long-term changes in Atlantic circulation patterns [44,45]. The Atlantic Multidecadal Oscillation (AMO) has been shown to influence European precipitation patterns over timescales of 60–80 years, and the observed parabolic precipitation patterns in Porto align with AMO influences on regional climate [7].

The lack of trends in extreme precipitation events contrasts with findings from some other European regions, where an increase in heavy precipitation has been observed [46,47]. This stability in extreme precipitation frequency supports the idea of natural variability and may relate to the specific geographic location of the Porto region and the buffering effect of the Atlantic Ocean on rainfall intensity.

4.3. Seasonal Patterns and Physical Mechanisms

The seasonal distribution of temperature trends, when viewed within the non-linear framework, offers important insights into the physical mechanisms driving natural climate variability in the region. The apparent warming in winter and autumn maximum temperatures, along with cooling in spring and summer minimum temperatures, reflects segments of multidecadal oscillations rather than steady trends, possibly linked to increased sensitivity to Atlantic circulation changes during different seasons.

The significant increase in winter and autumn maximum temperatures indicates enhanced heat advection during these seasons, possibly linked to changes in atmospheric circulation patterns or a higher frequency of warm air mass intrusions from southern latitudes [48]. However, within the parabolic framework, these represent phases of natural oscillatory behavior rather than steady warming trends.

The cooling trends in spring and summer minimum temperatures, when viewed within the parabolic framework, represent the recovery phase from mid-century lows rather than ongoing cooling. This interpretation is more physically plausible and may be related to changes in cloud cover patterns or modifications in land-surface energy balance [49,50]. Increased cloud cover during these seasons could reduce nighttime longwave radiation loss, leading to warmer minimum temperatures. Alternatively, changes in soil moisture or vegetation patterns could affect evapotranspiration rates and surface energy distribution.

The seasonal patterns observed in the Porto region differ from those reported in other parts of Portugal, where summer warming has been more significant [1]. This difference may result from the stronger Atlantic influence in northern coastal areas, which buffers temperature extremes and leads to distinct seasonal response patterns compared to more inland, continental regions.

4.4. Change Point Analysis and Climate Regime Shifts

The findings have significant implications for climate change attribution in the Porto region. The fact that current climate conditions remain below those observed during the early period (1863–1900) suggests that signals of human-caused climate change are either absent or overshadowed by natural variability in this area. This differs from global trends and emphasizes the need for regional-scale analysis to understand local climate change.

The identification of a change point around 1980 should be understood as part of natural multidecadal variability rather than evidence of human-induced warming. Importantly, this 1980 change point occurs about a decade earlier than the typical global warming

acceleration seen in the 1990s, indicating that regional Atlantic influences may come before global climate patterns. This early timing might reflect the Porto region's direct response to Atlantic multidecadal oscillations, which can show regional effects before appearing in global temperature records. The timing aligns with a transition from the negative to positive phase of the AMO, which would naturally lead to warming in Atlantic-influenced areas, rather than signaling anthropogenic climate change.

The change point analysis offers important context for understanding how natural climate variability and human-induced forcing contribute to observed climate trends. The fact that significant trends mainly appear after 1980 indicates that earlier fluctuations were mostly caused by natural climate factors, while recent changes show the growing impact of greenhouse gas forcing.

4.5. Limitations of Linear Trend Analysis

This study highlights the fundamental limits of linear trend analysis when used on climate datasets with non-linear patterns. The Mann–Kendall test and Sen's slope estimator, although reliable for detecting steady trends, are not suitable for datasets that show oscillatory or parabolic behavior. The incorrect results from linear analysis emphasize the need for more advanced analytical methods in climate research.

The widespread use of linear trend analysis in climate studies may have caused consistent misinterpretation of regional climate change patterns. This study recommends regularly applying non-linear analysis methods, such as polynomial fitting, spectral analysis, and non-parametric smoothing, to ensure precise characterization of climate trends.

4.6. Implications for Regional Climate Understanding

The findings from this study enhance a more detailed understanding of how regional climate change affects Atlantic-influenced coastal areas. They show that natural multidecadal variability can lead regional climate patterns even amidst global climate change. The parabolic pattern of temperature and precipitation trends, with current conditions staying below early-period levels, emphasizes the importance of local-scale analysis for understanding climate impacts and shaping effective adaptation strategies.

The dominance of natural oscillatory behavior indicates that water resource management in the region should prioritize understanding and managing natural variability rather than solely adapting to systematic changes in total precipitation. However, the potential for changes in precipitation intensity and timing, which might not be reflected in total amounts, highlights the need for ongoing monitoring and analysis within the framework of natural variability.

The oscillatory temperature patterns have significant implications for agricultural systems, energy demand, and human comfort [51,52]. The natural variability in diurnal temperature range creates distinct thermal environments that can influence crop growth, pest behavior, and energy consumption patterns, necessitating adaptation strategies that consider natural climate cycles rather than steady trends [53].

4.7. Comparison with Regional Climate Models

The observed non-linear patterns provide essential constraints for validating regional climate models. Models that do not replicate the parabolic temperature trends and multidecadal oscillations seen in the Porto record are probably inadequate for predicting future climate in Atlantic-influenced coastal areas.

The complex interaction of multidecadal oscillations presents a major challenge for climate models, which need to accurately simulate both the AMO and its regional effects. Recent advances in regional climate modeling have enhanced the representation of Atlantic-European climate interactions, though many models still find it difficult to accurately depict

the small-scale processes that drive natural climate variability, especially in coastal areas where land–sea interactions and Atlantic oscillations are significant [34,54]. The long-term observational data from Porto offers vital information for improving model parameters and verifying model performance in coastal regions influenced by the Atlantic.

Comparison with other Atlantic-influenced regions reveals both similarities and differences in climate evolution patterns. Galicia (northwestern Spain) shows similar multidecadal temperature variability with AMO influences, though with stronger recent warming trends, with maximum temperature increases of approximately 0.08 °C per decade compared to Porto's 0.057 °C per decade [54]. Brittany (northwestern France) exhibits comparable precipitation variability patterns but with different seasonal distributions, showing stronger winter precipitation increases (+15 mm per decade) compared to Porto's stable winter precipitation [55]. Southern France shows more pronounced warming trends, particularly in summer, with maximum temperature increases exceeding 0.12 °C per decade, reflecting the transition from Atlantic to Mediterranean influences and reduced oceanic moderation [56]. These regional comparisons suggest that the Porto region's climate evolution, while influenced by large-scale Atlantic variability, also reflects specific local factors, including coastal position, topography, and latitude effects that moderate the expression of broader climate patterns.

4.8. Limitations and Future Research Directions

While this study offers a comprehensive analysis of climate trends in the Porto region, several limitations should be recognized. The analysis relies on data from a single meteorological station, which may not fully capture the spatial variability across the larger area. Although the representativeness of the Serra do Pilar station has been confirmed through comparisons with nearby stations, future research should include data from multiple stations or reanalysis products (e.g., ERA5, CRU) to better understand the spatial scope of parabolic climate patterns and multidecadal oscillations.

The extreme event analysis, while showing stability consistent with natural variability, relies on relatively simple percentile thresholds calculated across the entire dataset. More advanced extreme value analysis techniques, such as Generalized Extreme Value (GEV) distributions and Peaks-over-Threshold (POT) methods, could offer additional insights into how the shape and scale of extreme weather distributions might change, which may not be captured by fixed percentile methods.

The study period ends in 2010, which is a significant limitation given the rapid climate change and extreme events of the last 15 years, including record temperatures in 2016, 2023, and 2024. Excluding recent years may underestimate the extent of recent warming trends and could influence conclusions about whether parabolic patterns continue or new climate states emerge. Future research should focus on extending the analysis to include the most recent data when it becomes available.

The potential impact of urbanization and the urban heat island effect on long-term temperature trends, especially minimum temperatures, needs further study through comparison with nearby rural stations or land-use change analysis. While the parabolic patterns indicate that large-scale climate variability plays a major role, a full evaluation of urban effects would better confirm whether observed trends are due to natural climate variability.

Future research should focus on expanding the non-linear analysis to additional stations across Portugal and the Iberian Peninsula to map the extent of parabolic climate patterns. Investigating the physical mechanisms behind these oscillations, particularly their links to Atlantic circulation shifts, will be vital for improving climate forecasts. A thorough analysis of cloud cover, humidity, and wind patterns may reveal the processes responsible

for these changes and enrich our understanding of regional climate variability within the scope of natural multidecadal fluctuations.

5. Conclusions

This extensive analysis of 148 years of climate data from the Porto region reveals fundamental flaws in traditional linear trend analysis and highlights the need for non-linear methods to better understand regional climate change. The study uncovers a complex pattern of climate variation characterized by parabolic (U-shaped) trends in both temperature and precipitation, primarily driven by natural multidecadal oscillations, with current conditions still below early-period levels. The key findings reshape our understanding of climate change in this Atlantic-influenced coastal region.

- Non-Linear Climate Evolution: The Porto region's climate follows parabolic (U-shaped) patterns rather than linear trends, with both temperature and precipitation showing minima around 1910–1970. Linear trend analysis is fundamentally misleading for this dataset and leads to incorrect interpretations of climate change.
- Early Period Dominance: Climate conditions in the early period (1863–1900) were better than today's, with higher temperatures (14.99 °C vs. 14.72 °C) and more precipitation (1324 mm vs. 1267 mm) than in recent decades. This directly challenges linear warming theories and highlights the significance of natural climate variability.
- Multidecadal Oscillations: The climate system is shaped by natural oscillations lasting 35–47 years, aligning with Atlantic Multidecadal Oscillation influences. These oscillations account for the parabolic patterns and highlight the dominance of natural variability over human-caused signals in this region.
- Recovery Phase: The apparent "warming" since 1980 reflects natural recovery from mid-20th century lows rather than human-caused climate change. Current conditions are still below early-period levels, showing that the recovery process is not finished.
- Methodological Revolution: This study shows that linear trend analysis can be seriously misleading when used on oscillatory climate systems. Non-linear techniques like polynomial fitting, spectral analysis, and LOWESS smoothing are crucial for accurate climate assessment.
- Temperature Evolution: The Porto region has experienced natural oscillations in temperatures following a parabolic pattern, where early-period conditions surpassed current levels. This contradicts linear trend interpretations over the period 1863–2010. These fluctuations are due to natural multidecadal variability rather than a steady climate change. This pattern differs from global warming trends and emphasizes the importance of regional-scale climate analysis.
- Precipitation Stability: Despite high interannual variability (coefficient of variation $\approx$ 24%), annual precipitation displays a parabolic pattern, with higher values during the early and recent periods compared to the minimum in the mid-20th century. This pattern highlights the strong influence of Atlantic multidecadal oscillations on regional precipitation and indicates that water resource management should prioritize adapting to natural variability rather than expecting systematic changes.
- Seasonal Patterns: Climate patterns are not evenly distributed throughout the year, with clear seasonal trends reflecting parts of longer natural oscillations rather than steady changes. These seasonal patterns offer insights into the physical processes that drive natural climate variability.
- Extreme Events: The frequency of extreme temperature and precipitation events has stayed stable throughout the study period, consistent with natural oscillations rather than steady trends, and contrasting with trends seen in other European re-

gions. This stability supports the idea that the region's climate stays within natural variability limits.

- Climate Regime Shift: Multiple change points in the climate record indicate transitions between phases of natural multidecadal oscillations rather than signals of human-induced climate change. The timing of these changes aligns with well-known periods of Atlantic climate variability, especially the Atlantic Multidecadal Oscillation.
- Regional Significance: The findings enhance understanding of natural climate variability in Atlantic-influenced coastal areas and emphasize the importance of nonlinear analysis for comprehensive climate assessment. The dominance of natural oscillatory patterns underscores the need for detailed regional studies that consider multidecadal variability in climate change adaptation strategies.

The results of this study carry significant implications for climate change adaptation and mitigation strategies in Northern Portugal. Instead of preparing for ongoing linear warming, regional planning should emphasize managing natural climate variability and the possibility of continued oscillatory behavior. The consistent frequency of extreme events supports this view and indicates that the region's climate remains within the bounds of natural variability.

The stability of precipitation totals within natural oscillatory patterns, combined with high variability, highlights the importance of water storage and management systems that can adapt to the natural cycles of extreme wet and dry periods linked to Atlantic multidecadal oscillations.

Future research should focus on extending the analysis to include data after 2010 when available, adding spatial analysis with multiple stations or reanalysis products, and studying the physical mechanisms behind the observed natural oscillations. Comparing with other Atlantic-influenced regions and validating regional climate models against the observed parabolic patterns will be vital for better climate projections and developing effective adaptation strategies that consider natural variability.

This study highlights the vital role of long-term weather records and advanced analysis methods for understanding regional climate changes. The findings challenge traditional climate change stories based on simple trend analysis and emphasize the need for more advanced approaches that can tell apart natural variability from human-induced effects. The results help expand the overall knowledge of European climate change, while also pointing out the unique features of natural climate development in Northern Portugal.

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