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Spatial and Temporal Trend Analysis of Extreme Daily Precipitation in the Western Black Sea Region Using ERA5 Data

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Research Article

Keywords: Extreme precipitation, ERA5, Mann–Kendall test, Sen's slope coefficient, Spatial analysis

Posted Date: April 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9381350/v1

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Additional Declarations: No competing interests reported.

Abstract

This study investigates the temporal and spatial variability of extreme daily precipitation in the Western Black Sea Region of Türkiye over the period 1991–2025 using ERA5 reanalysis data. Annual maximum daily precipitation series were derived for each grid cell, and trends were assessed using the non-parametric Mann-Kendall test and Sen's slope estimator.

The results indicate that the regional annual maximum daily precipitation exhibits a weak increasing trend, with a Sen's slope of 0.28 mm/year; however, this trend is not statistically significant at the 95% confidence level ($p = 0.164$). Similarly, the sample grid cell analysis reveals no significant trend ($p = 0.589$), despite minor positive tendencies.

Spatial analysis shows a heterogeneous distribution of trends across the study area, with positive trends concentrated in central parts of the region and weak negative trends observed in some coastal and eastern areas. Nevertheless, the majority of grid cells do not exhibit statistically significant trends ($p > 0.05$), indicating that the observed variations are largely driven by natural climate variability rather than a clear long-term trend.

Overall, the findings highlight the importance of considering spatial heterogeneity when assessing extreme precipitation changes at the regional scale. The study provides a comprehensive and up-to-date assessment of extreme precipitation patterns in the Western Black Sea Region and contributes to a better understanding of regional hydroclimatic variability under changing climate conditions.

1. Introduction

Climate change is widely recognized as one of the most critical environmental challenges due to its impacts on hydrometeorological processes. In particular, changes in the frequency and intensity of extreme weather events have significant consequences for both natural systems and human activities. In this context, extreme precipitation events have become a critical research topic in the fields of hydrology and disaster management due to their impacts, such as flooding, increased surface runoff, soil erosion, and infrastructure damage.

Studies conducted on a global scale have revealed that extreme precipitation events are showing an increasing trend in many regions, while also emphasizing that these changes are highly spatially heterogeneous. Regional climate dynamics, topographic features, and atmospheric circulation systems are among the key factors determining the distribution of extreme precipitation. Therefore, it is essential to assess extreme precipitation not only temporally but also spatially (Westra et al., 2013; Fischer and Knutti, 2016; Yadav, 2022; Kassaye et al., 2024; Sham et al., 2025).

Among the data sources used in extreme precipitation analyses, observation stations and reanalysis datasets stand out. However, the limited spatial distribution of station data poses a significant constraint, particularly in regional analyses. In this context, the ERA5 reanalysis dataset, developed by

the European Centre for Medium-Range Weather Forecasts, has been widely used in recent years due to its high spatial and temporal resolution (Muñoz-Sabater et al., 2021). ERA5 data offers the advantage of providing homogeneous data over large areas, enabling a more detailed examination of extreme precipitation.

Non-parametric tests play a significant role among the methods used to identify trends in extreme precipitation. In this context, the Mann–Kendall test is one of the most widely used methods for trend detection in hydro-meteorological time series (Abdulfattah, 2025; Monir et al., 2025; Zhang et al., 2025). This test is typically applied in conjunction with Sen's slope coefficient, allowing for the determination of both the direction and magnitude of the trend. The primary reason for preferring these methods is that they do not require assumptions regarding data distribution and are less affected by outliers.

A review of studies on extreme precipitation in Türkiye reveals that the Black Sea Region is particularly susceptible to flooding and heavy rainfall events, primarily due to its topographic structure and humid climatic conditions (Aksu et al., 2022; Halis et al., 2022). Flood events that have occurred in the region in recent years have further underscored the importance of analyzing extreme precipitation. However, a significant portion of existing studies relies on data from a limited number of meteorological stations, which makes it difficult to conduct detailed spatial analyses. Furthermore, while the number of studies utilizing reanalysis datasets is increasing, there remains a limited number of studies focused on the Western Black Sea Region that examine long-term trends on a grid based scale.

The primary objective of this study is to comprehensively examine the temporal and spatial variations in extreme daily precipitation in the Western Black Sea Region using high resolution ERA5 data. In this context, annual maximum daily precipitation series were generated using daily total precipitation data from 1991 to 2025, and the Mann–Kendall test and Sen's slope coefficient method were applied to these series. The original contribution of this study lies in its detailed presentation of not only the temporal trends but also the spatial distribution of extreme precipitation at the grid level, thereby providing a high-resolution assessment for the Western Black Sea Region. In this regard, the study aims to contribute to a better understanding of the effects of regional climate change and the assessment of disaster risks.

2. Material and methods

2.1 Study area

This study covers the Western Black Sea Region, located in northern Türkiye. The study area is situated approximately between 29.5°E and 34.0°E longitude and 40.3°N and 42.7°N latitude, and features a heterogeneous topographic structure that encompasses both the Black Sea coastal zone and the inland regions.

The study area includes the provinces of Zonguldak, Bartın, Karabük, Kastamonu, and Düzce as well as a broad region encompassing the coastal and inland areas of these provinces. Additionally, the region

represents a significant portion of the Western Black Sea Basin and is one of the areas in Türkiye where extreme precipitation events are frequently observed.

The region's climate is influenced by the humid air masses of the Black Sea and exhibits a rainy character throughout the year. In particular, while precipitation amounts increase in coastal areas due to orographic elevation effects, distinct spatial variations in precipitation patterns are observed in inland areas due to topographic shading and elevation differences. This situation necessitates the analysis of extreme precipitation events both temporally and spatially.

The Western Black Sea Region has also drawn attention due to flood events in recent years, making it a critical area of study for understanding the effects of extreme precipitation on disaster risks. Therefore, a detailed examination of the region using high-resolution datasets is of great importance for identifying the local impacts of climate change.

2.2 Data Sets

In this study, the ERA5 reanalysis data set provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) was used. ERA5 has an hourly temporal resolution and a spatial resolution of approximately 0.25° × 0.25°, enabling the long-term and homogeneous analysis of atmospheric variables (Hersbach et al., 2020).

Within the scope of this study, daily total precipitation (tp) data from 1991 to 2025 were evaluated. During the data download process, the coordinate boundaries representing the study area were used as a basis, and daily precipitation series were generated for all grid cells within the region. Since total precipitation values in the ERA5 dataset are given in meters, these values were converted into millimeters prior to analysis. This conversion is expressed by the following equation (Eq. 1):

$$P_{mm} = P_m \times 1000 \quad (1)$$

Here, P_{mm} represents the daily precipitation amount in millimeters, while P_m denotes the total precipitation value in meters. Thus, all analyses were conducted in the unit of mm/day.

The use of reanalysis datasets offers significant advantages, particularly in areas where the station network is sparse or spatial representation is limited. From the perspective of this study, the primary advantage of ERA5 data is that it enables the assessment of the spatial distribution of extreme precipitation on a grid basis in a topographically and climatically heterogeneous region such as the Western Black Sea Region.

2.3. Determination of the Extreme Precipitation Index

Although various indices can be used to identify extreme precipitation events, this study has opted for the annual maximum daily precipitation approach. This approach represents the highest daily precipitation value within a given year and is widely used in the assessment of hydro-meteorological risks (Katz et al., 2002; Chen et al., 2022; Jiang et al., 2025).

When the daily precipitation series for a given year is denoted by P_t, the maximum daily precipitation for that year is defined as follows (Eq. 2):

$$P_{max}^{(y)} = \max(P_t),\ t = 1, 2, \ldots, n \quad (2)$$

Here, $P_{max}^{(y)}$ represents the maximum daily precipitation value for year y; n denotes the total number of days in that year.

This process was applied separately for each grid cell in the study area. Thus, annual maximum daily precipitation series covering the 1991–2025 period were obtained for each grid cell. The use of annual maximum series facilitates the identification of short-duration, high-intensity precipitation events and provides a meaningful indicator, particularly for flood risk assessment.

Additionally, to assess the general trend at the regional scale, the highest daily precipitation value observed across all grid cells within the study area for each year was also determined. Thus, both grid-based spatial analysis and regional time series analysis were conducted.

2.4. Trend Analysis

Non-parametric methods were preferred for identifying trends in extreme precipitation series. In this context, the Mann–Kendall trend test was used to determine the presence of a trend, and Sen's slope coefficient method was used to determine the magnitude of the trend (Acquaah, 2025). The primary reason for choosing these non-parametric methods is that hydro-meteorological time series often do not follow a normal distribution and can be influenced by outliers.

2.4.1. Mann–Kendall Trend Test

The Mann–Kendall test is a widely used non-parametric method for determining whether a time series exhibits a monotonically increasing or decreasing trend (Mann, 1945; Kendall, 1975; Yue et al., 2002; Al Mashoudi et al., 2025; Islam et al., 2025; Yaméogo, 2025). The basic logic of the test is based on comparing all pairs of observations in the time series. The test statistic S is calculated as follows (Eq. 3):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(x_j - x_k) \quad (3)$$

Here, x_j and x_k represent the observation values in the time series, and n denotes the total number of observations. The sign function $\mathrm{sgn}(x_j - x_k)$ used in the equation is defined as follows (Eq. 4):

$$\mathrm{sgn}(x) = 1,\ x > 0 \quad (4)$$

$$\mathrm{sgn}(x) = 0,\ x = 0$$

$$\mathrm{sgn}(x) = -1,\ x < 0$$

In this test, a positive value of S indicates an upward trend, while a negative value indicates a downward trend. The variance of the S statistic is calculated using the following equation (Eq. 5):

$$Var(S) = n(n-1)(2n + 5) / 18 \quad (5)$$

The standardized Z-test statistic is then obtained using the S and Var(S) values (Eq. 6):

$$Z = (S - 1) / \sqrt{Var(S)}, S > 0 \quad (6)$$

$$Z = 0, S = 0$$

$$Z = (S + 1) / \sqrt{Var(S)}, S < 0$$

The statistical significance of the trend is assessed using the calculated Z value. In this study, significance was evaluated based on a 95% confidence interval, and the corresponding $p < 0.05$ criterion was accepted as the standard for statistical significance.

2.4.2. Sen's Slope Coefficient

While the Mann–Kendall test indicates the presence of a trend, Sen's slope coefficient method was applied to quantitatively determine the magnitude and direction of the trend (Sen, 1968; Frimpong et al., 2022; Sudarsan and Lasitha, 2023; Kumar and Attri, 2025). In this method, slope values are calculated for all observation pairs in the time series, and the median of these values is then taken.

The slope value Q_i for each observation pair is calculated using the following equation (Eq. 7):

$$Q_i = (x_j - x_k) / (j - k), j > k \quad (7)$$

Here, x_j and x_k represent the observation values, and $j-k$ denotes the time difference. Sen's slope coefficient is obtained by taking the median of all Q_i values (Eq. 8):

$$Q_{med} = median(Q_i) \quad (8)$$

The resulting Q_{med} value provides information about the direction and magnitude of the trend. A $Q_{med} > 0$ indicates an increasing trend, while a $Q_{med} < 0$ indicates a decreasing trend. The absolute magnitude of the value is interpreted as a quantitative measure of the annual rate of change.

2.4.3. Spatial Analysis

In this study, the Mann–Kendall test and Sen's slope coefficient method were applied separately to each grid cell in the study area. This allowed us to identify not only the temporal trends of extreme daily precipitation in the Western Black Sea Region but also the spatial distribution of these trends.

First, annual maximum daily precipitation series covering the 1991–2025 period were generated for each grid cell. Subsequently, the Mann–Kendall test was applied to these series to determine the statistical significance of the trends, and the magnitude of the trends was calculated using Sen's slope coefficient. The results were mapped to assess the spatial patterns of increasing and decreasing trends within the study area.

In addition, the same analyses were conducted for the regional annual maximum series representing the entire study area. Thus, both a detailed spatial analysis at the grid level and a time-series assessment reflecting the general trend at the regional scale are presented together.

3. Results

The temporal variability of extreme daily precipitation in the Western Black Sea Region was assessed using the annual maximum precipitation series for the 1991–2025 period. The results reveal a pronounced interannual variability, characterized by distinct peaks in specific years, indicating the episodic nature of extreme precipitation events.

Although fluctuations are evident throughout the time series, no consistent long-term trend is observed. This suggests that extreme precipitation in the region is dominated by short-term variability rather than a persistent directional change. The absence of a clear monotonic trend is further supported by the irregular clustering of extreme events in certain years (Fig. 1).

These findings highlight that extreme precipitation behavior in the study area is highly variable and potentially influenced by transient atmospheric circulation patterns rather than a sustained climatic signal.

3.2. Descriptive Statistics

Descriptive statistics of the regional maximum series and a representative grid cell reveal substantial differences in both magnitude and variability (Table 1). The regional series exhibits higher maximum values and greater standard deviation, indicating a broader range of extreme precipitation events across the study area.

This disparity clearly demonstrates that extreme precipitation is not uniformly distributed but instead exhibits strong spatial heterogeneity. The higher variability observed at the regional scale suggests that localized extreme events significantly influence the overall precipitation regime.

These findings emphasize the importance of spatially explicit analyses when assessing extreme precipitation, as single-point evaluations may underestimate the true variability and intensity of extreme events.

Table 1
Descriptive statistics

Parameter	Regional Series (mm)	Sample Point (mm)
Minimum	42.00	23.11
Maximum	179.00	83.38
Mean	72.80	39.88
Standard Deviation	24.17	13.58

Based on these results, it is observed that regional maximum precipitation values are higher and more variable than those at the sample point. This clearly demonstrates that extreme precipitation exhibits a spatially heterogeneous pattern.

3.3. Results of Regional Trend Analysis

The results of the Mann–Kendall test applied to the annual maximum daily precipitation series indicate that there is no statistically significant trend in the time series. According to the test results, while the trend direction points to a weak upward trend, this trend is not significant at the 95% confidence level.

Sen's slope coefficient results also support this finding, indicating a low-magnitude upward trend in annual maximum daily precipitation (Table 2).

Table 2
Trend analysis results

Series	Trend	p value	Kendall's Tau	Sen's slope (mm/year)
Regional	No trend	0.1640	0.1664	0.2810
Sample Point	No trend	0.5894	0.0655	0.0810

These results indicate that long-term changes in extreme precipitation do not show a statistically significant trend and that the observed changes may largely be attributed to natural variability.

3.4. Spatial Distribution of Trends

The spatial distribution of trends reveals a markedly heterogeneous pattern across the study area (Fig. 2). Positive trends are predominantly observed in the central regions, whereas weak negative trends are identified in certain eastern and coastal areas.

This spatial contrast suggests that extreme precipitation dynamics are strongly influenced by local factors such as topography, elevation, and proximity to the Black Sea. In particular, the observed increase in central areas may be associated with orographic enhancement and localized atmospheric instability.

Conversely, the weak decreasing trends in coastal regions may reflect changes in moisture transport pathways or alterations in regional circulation patterns. These spatially contrasting trends highlight the complex interplay between regional climate dynamics and local geographic conditions.

3.5. Statistical Significance Analysis

The statistical significance analysis indicates that the majority of grid cells do not exhibit significant trends at the 95% confidence level (Fig. 3). Only a very limited number of cells show statistically meaningful changes, and these are spatially scattered.

This lack of statistical significance suggests that the detected spatial patterns should be interpreted with caution. While certain areas exhibit increasing or decreasing tendencies, these patterns do not represent a consistent or dominant regional signal.

The results further reinforce the notion that extreme precipitation variability in the Western Black Sea Region is primarily governed by stochastic processes rather than systematic long-term changes.

3.6. Analysis of the Most Extreme Years

Regional maximum values were analyzed to determine the highest daily precipitation values observed during the study period. The results indicate that extreme precipitation events were concentrated in certain years (Table 3).

Table 3
The years in which the highest extreme precipitation values were recorded

Year	Max. Precip. (mm)	Latitude	Longitude
2004	179.00	40.50	30.00
2015	146.20	41.25	31.25
2024	138.70	41.75	33.50
2008	132.40	40.75	30.00
2023	128.90	41.50	31.75

These results indicate that extreme precipitation exhibits an irregular temporal distribution and may intensify in certain years, thereby increasing the risk of regional disasters

4. Discussion

This study examines the temporal and spatial variation of extreme daily precipitation in the Western Black Sea Region for the period 1991–2025. The findings indicate that, although there is a weak upward trend in annual maximum daily precipitation values across the region, this trend is not statistically

significant. However, the results of the spatial analysis reveal that extreme precipitation does not exhibit a homogeneous distribution across the region and that different trends emerge in specific areas.

These findings are consistent with a substantial body of literature. Studies conducted on a global scale have shown that extreme precipitation events may exhibit an increasing trend in some regions, but these increases are spatially heterogeneous (Alexander et al., 2006; Donat et al., 2013). These studies emphasize that changes observed in extreme precipitation indices vary depending on regional climate dynamics. In this context, the heterogeneous spatial patterns observed in the Western Black Sea Region are consistent with the trends observed on a global scale.

Studies conducted at the national level also support these findings. Analyses of precipitation series across Türkiye indicate that trends vary from region to region and do not exhibit a homogeneous pattern (Partal & Kahya, 2006). In studies focusing specifically on the Black Sea basins, it has been reported that no distinct trend was observed in the Western Black Sea Region, whereas some increasing trends were observed in the Eastern Black Sea. This situation highlights that extreme precipitation in Türkiye exhibits regionally distinct behaviors.

The spatial trend patterns obtained in this study are notable for the increasing trends observed particularly in the central parts of the study area and the weak decreasing trends in some coastal/eastern sections. This heterogeneous structure is closely related to the region's topographic features and atmospheric circulation systems. The ascent and condensation of moist air masses transported over the Black Sea along the coast lead to increased precipitation in certain areas, while the topographic shadowing effect in inland regions can result in distinct precipitation patterns.

However, the fact that the results of the Mann–Kendall test do not reveal a statistically significant trend indicates that the long-term change in extreme precipitation has not yet exhibited a statistically robust direction. This can be attributed to the inherently high variability of extreme precipitation and the fact that it occurs in intermittent, irregular patterns. Furthermore, although the study period covers a long timeframe, the irregular nature of extreme events may contribute to the low statistical significance observed.

The findings suggest that careful interpretation is necessary when assessing the regional impacts of climate change. Although strong evidence suggests an increase in extreme precipitation at the global scale, this effect does not manifest uniformly across regions. Specifically in the Western Black Sea Region, the observed trends toward increased extreme precipitation have not yet translated into a strong and statistically significant change.

In conclusion, this study demonstrates that extreme precipitation in the Western Black Sea Region exhibits a spatially heterogeneous pattern and that, overall, no statistically significant trend was observed. These findings emphasize the need to consider not only temporal trend analyses but also spatial variability when assessing disaster risks at the regional scale.

5. Conclusion

In this study, the temporal and spatial variations in extreme daily precipitation in the Western Black Sea Region for the period 1991–2025 were examined using ERA5 reanalysis data. Analyses conducted on annual maximum daily precipitation series revealed that extreme precipitation exhibited a weak increasing trend across the region, although this trend was not statistically significant.

The findings reveal that extreme precipitation in the Western Black Sea Region exhibits a spatially heterogeneous pattern and that the observed changes have largely occurred within the context of natural climate variability. This indicates that, when assessing the impacts of climate change at the regional scale, it is necessary to consider not only general trends but also spatial variations.

From an applied perspective, the results suggest that risk assessments and adaptation strategies in the region should focus on low-frequency, high-impact events rather than assuming steady increases in precipitation extremes. This has direct relevance for flood risk management, infrastructure planning, and climate resilience policies.

This study demonstrates that high-resolution reanalysis data can be effectively utilized in extreme precipitation analyses and provides a current and comprehensive assessment for the Western Black Sea Region. Future studies involving the use of longer time series, the evaluation of different extreme precipitation indices, and the inclusion of climate model projections in the analysis will contribute to a clearer understanding of the changes in the region.

Declarations

Author Contribution

Uzun, Ömer Faruk. He handled all aspects of the project, including data analysis, copywriting, and mapping.

Data Availability

The study includes a step that utilizes freely available ERA5 precipitation data.

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Figures

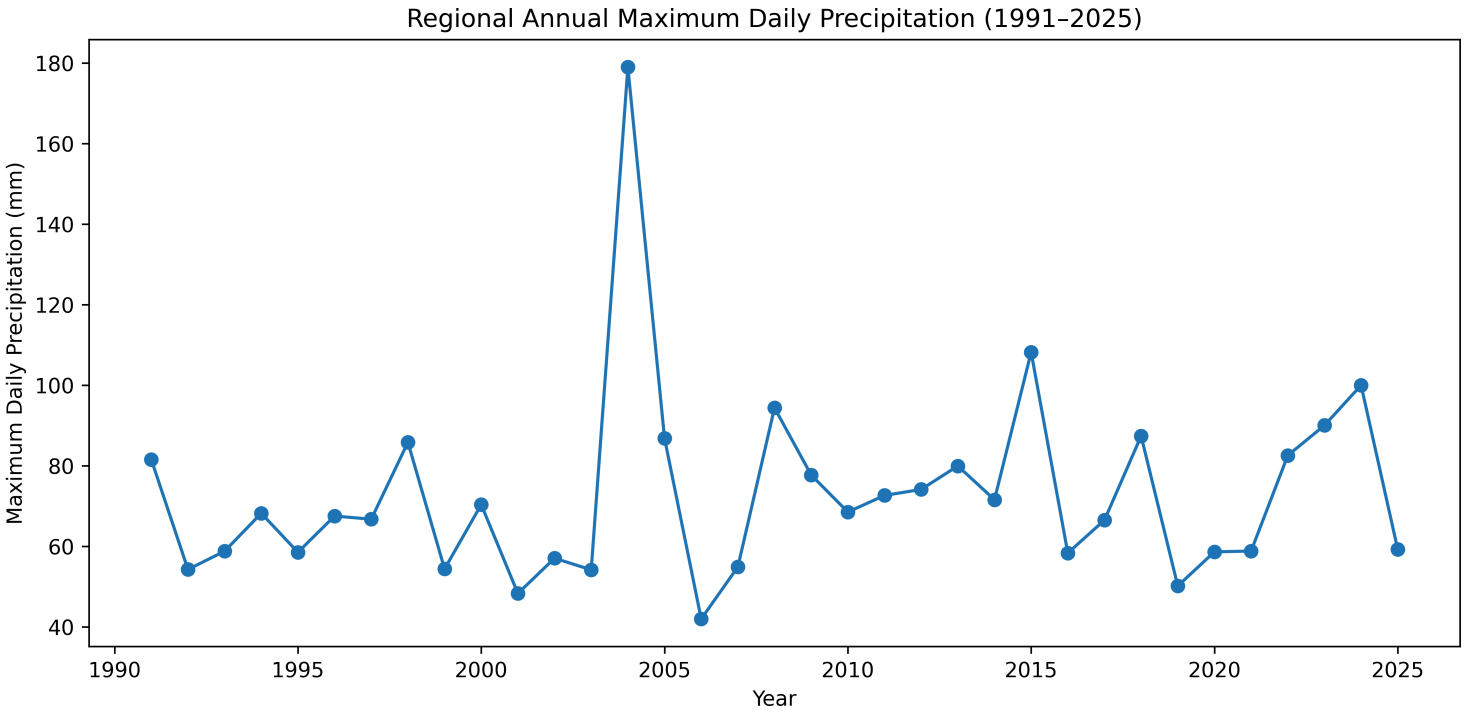


Figure 1

Annual maximum daily precipitation series for the Western Black Sea Region for the period 1991–2025

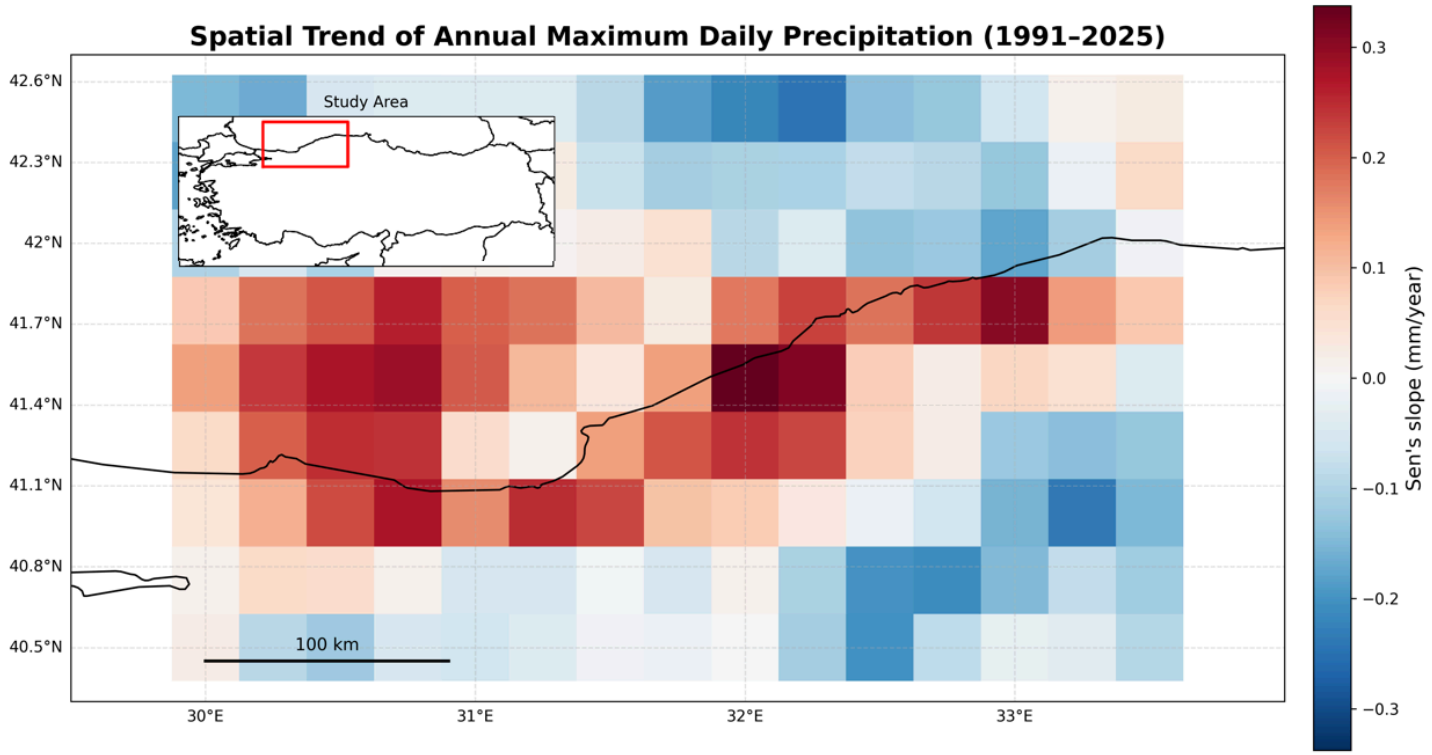


Figure 2

Spatial distribution of annual maximum daily precipitation in the Western Black Sea Region according to Sen’s slope coefficient (1991–2025)

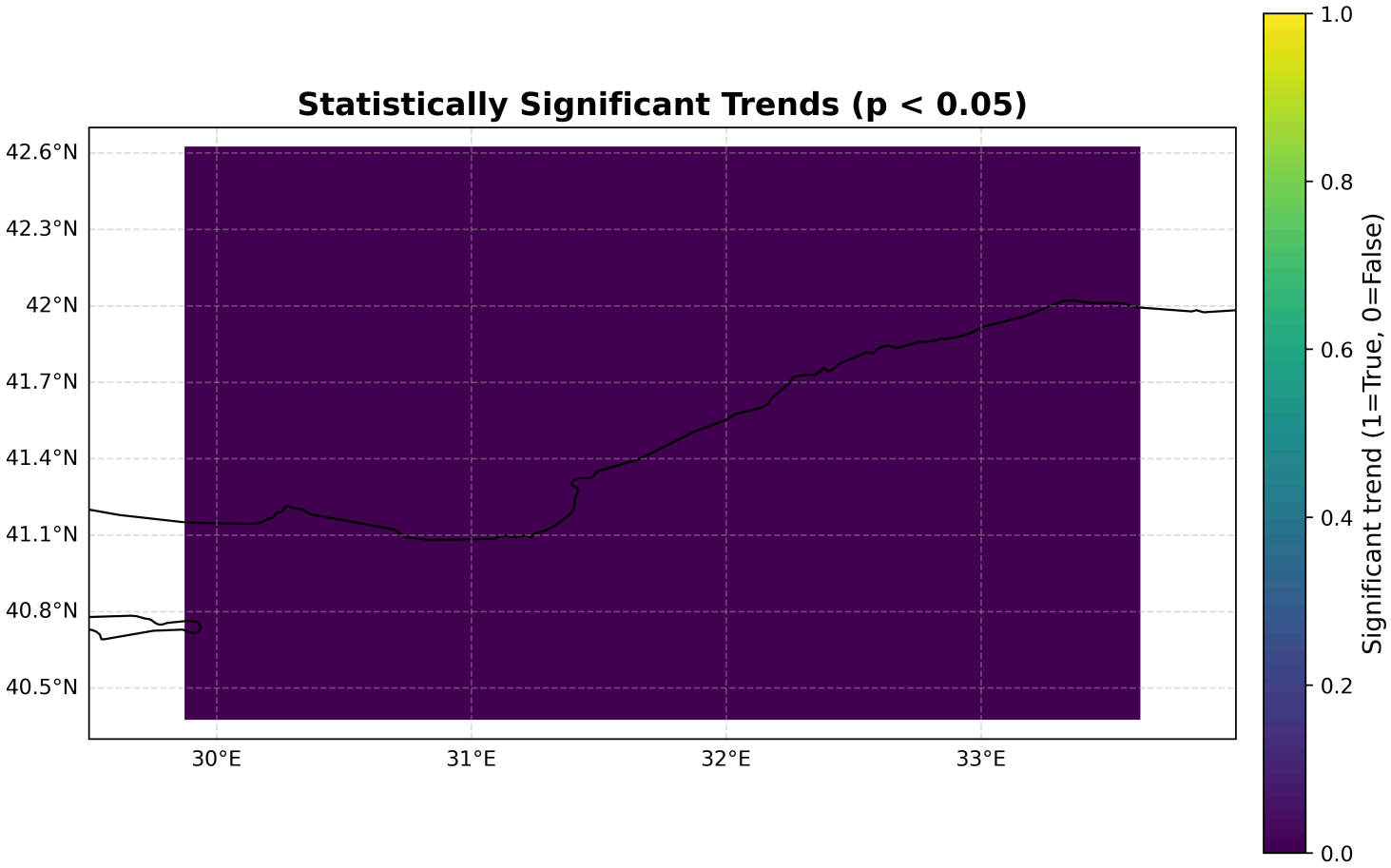


Figure 3

Spatial distribution of statistically significant trends at the 95% confidence level