RESEARCH ARTICLE OPEN ACCESS

Spatio-Temporal Trends in Precipitation Indices Over Mediterranean Using ERA5-Land Data (1950–2024)

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Received: 7 May 2024 | **Revised:** 18 April 2025 | **Accepted:** 19 July 2025

Funding: The author received no specific funding for this work.

Keywords: climate extremes analysis | long-term precipitation trends | mediterranean climate | precipitation indices

ABSTRACT

The Mediterranean region is a climate hotspot, where precipitation patterns play a crucial role in the hydrological cycle, influencing water resources, agriculture, and socio-economic aspects. This study aims to analyse the long-term trends in precipitation indices over the Mediterranean using the high-resolution ERA5-Land dataset from 1950 to 2024. A suite of precipitation indices was calculated, including frequency, intensity, and persistence metrics, to provide a comprehensive assessment of the region's precipitation dynamics. The Mann-Kendall test and Sen's slope estimator were employed to detect and quantify statistically significant trends. Notably, our analysis indicates that heavy precipitation days (R10 mm) decreased by approximately 2 days per decade in the western Mediterranean while increasing by about 0.5 days per decade in the northeastern Mediterranean. In addition, total annual precipitation (PRCPTOT) showed declines of up to 60 mm per decade in specific areas, and the maximum one-day precipitation (Rx1day) increased by up to 3 mm per decade in localised regions. This study contributes to the growing body of literature on the impacts of climate change on precipitation patterns, particularly in the context of the Mediterranean, a region known for its sensitivity to environmental shifts.

1 | Introduction

The hydrological cycle is expected to accelerate as the climate warms, potentially leading to significant hydrological changes worldwide (Allen and Ingram 2002). Indeed, as global temperatures rise, the intensification of the hydrological cycle is anticipated to bring about profound alterations in precipitation patterns across the globe (IPCC 2021). Although changes in global mean precipitation are not statistically significant (Donat et al. 2016; Trenberth 2011), an increase in extreme precipitation events on a global scale is detectable (Alexander et al. 2006; Asadieh and Krakauer 2015; Fischer and Knutti 2016; Min et al. 2011; Sun et al. 2021; Westra et al. 2013). These changes can lead to a higher likelihood of extreme precipitation events in regions projected to experience a decrease in average precipitation, such as the Mediterranean. The Mediterranean region, with its unique climate dynamics, serves as a barometer for climate change, serving as a climatic hotspot (Giorgi 2006; Tuel and Eltahir 2020), making the study of precipitation indices not only a regional concern but also of global interest.

One hallmark of the Mediterranean climate is its pronounced interannual variability in precipitation (Lionello 2012). Annual precipitation trends are stationary over time, with significant variations observed only in specific areas or periods, and these trends are not uniform across the Mediterranean (Ali et al., Ali et al. 2022; Cherif et al. 2020). Recent studies have also noted that while extreme events are increasing, total rainfall may be declining in several sub-regions (Alpert et al. 2002; Wang et al. 2017). Studies have shown that these trends are more pronounced in certain sub-regions, with the eastern and southern Mediterranean experiencing distinct patterns due to their unique climatic and topographical features (Hochman et al. 2022; Hamitouche et al. 2024). Specifically, the intensification of extreme precipitation coupled with declining total rainfall poses significant challenges for water resource management and drought/flood preparedness in the Mediterranean.

The eastern Mediterranean, for instance, has been identified as a region where extreme weather events have significant societal impacts. Hochman et al. (2022) documented the increase in frequency and intensity of extreme precipitation events in this region, attributing these changes to shifts in large-scale atmospheric circulation patterns. Similarly, in Algeria, changes in extreme precipitation indices across different climate zones have been observed, highlighting regional disparities (Hamitouche et al. 2024). Taken together, these studies emphasise the need to focus on the eastern and southern parts of the Mediterranean, which have been underrepresented in previous research.

Research has systematically analysed daily precipitation data, revealing significant trends in moderate and heavy precipitation events across Europe (Klein Tank and Können 2003) and the Mediterranean basin (Nastos et al. 2013). However, many of these studies have focused on the northern Mediterranean, with less emphasis on the eastern and southern regions, where data scarcity and complex terrain pose challenges (Hernández et al. 2015; Hamitouche et al. 2024). This gap highlights the need for comprehensive studies that encompass the entire Mediterranean basin to better understand regional differences in precipitation trends. Thus, a comprehensive analysis that includes the eastern and southern Mediterranean is crucial to fully understand the regional nuances of precipitation trends.

The intensity of extreme precipitation events, as measured by indices like Rx1day and Rx5day, is increasing, particularly for extremes that surpass historical norms (Trigo et al., Trigo 2013). Recent studies in Türkiye have shown variability in temperature and precipitation extremes, indicating significant trends in extreme precipitation indices (Ciftci and Sahin 2023). Similarly, in the Pyrenees, a detailed analysis of climate extremes has revealed long-term trends that are crucial for understanding regional climate dynamics (Cuadrat et al. 2024). Collectively, these findings suggest that while some regions are experiencing increases in extreme precipitation, others may not exhibit the same patterns, underscoring the heterogeneous nature of climate change impacts in the Mediterranean.

Extreme precipitation is a key driver of hydrological hazards like landslides, floods, and flash floods, significantly impacting soil erosion and agriculture. Between 2000 and 2023, Mediterranean countries faced numerous disasters due to such weather, resulting in over 3000 deaths and affecting more than 3.5 million people, with damages estimated at $47 billion (EM-DAT, 2023). Under global warming conditions, studies have shown an increase in the frequency and intensity of extreme events like R95p and R99p (Kunkel et al. 2003; Zolina et al. 2013). However, inconsistencies or uncertainties in observed trends may arise from dataset limitations, serial correlations in long series, or regional climatic variability (Hernández et al. 2015; Tramblay et al. 2013).

Research highlighted varied extreme precipitation trends across the Mediterranean, with the northern areas experiencing increases, in contrast to more static conditions in the south (Ali et al., Ali et al. 2022). Western regions have seen more rainfall, while the east trends drier (Kostopoulou and Jones 2005). Elevation affects precipitation variability, with significant disparities in indices like R95p and R99p (Nastos et al. 2013). In the Eastern Mediterranean, there is a rising trend in heavy rainfall events, particularly evident in the Rx5day index in Türkiye and Greece (Mathbout et al. 2018). Conversely, in Portugal, a decrease in annual precipitation aligns with a positive NAO index, influencing dry conditions (Santos et al. 2019). These trends underscore the need for comprehensive climate adaptation strategies, particularly in regions like the Southern Levant, where decreasing extreme rainfall indices signal increased rainfall intensity, impacting agricultural and water resource planning (Salameh et al. 2022).

The Mediterranean region's complex topography and varied climate make it particularly challenging to model and analyse precipitation trends accurately. Hence, high-resolution, long-term datasets become crucial for capturing local-scale dynamics and improving model accuracy. The ERA5-Land dataset, with its fine spatial ($0.1° \times 0.1°$) and temporal (hourly) resolution, provides an unprecedented opportunity to address these gaps and enhance our understanding of precipitation dynamics in the Mediterranean region (Muñoz Sabater 2019). While reanalysis datasets like ERA5-Land have been shown to perform well in extratropical regions with dense observational networks, their accuracy can vary depending on factors such as station density and topography (Lavers et al. 2022; Bandhauer et al. 2021). Recent studies indicate that ERA5-Land tends to overestimate mean precipitation and wet-day frequency while underestimating extreme precipitation events in certain regions (Rivoire et al. 2021; Gomis-Cebolla et al. 2023). Therefore, it is crucial to assess the reliability of ERA5-Land data against observational datasets, especially in regions with complex terrain like the Mediterranean.

To address these uncertainties, some studies have validated ERA5-Land data against high-resolution gridded datasets and observational records in the Mediterranean region. For example, Gomis-Cebolla et al. (2023) assessed the reliability of ERA5 and ERA5-Land precipitation data for simulating Mediterranean extreme flash-flood events, finding that while ERA5-Land provides valuable insights, caution must be exercised due to potential biases. Similarly, Bandhauer et al. (2021) evaluated the spatial and temporal precipitation biases of CORDEX models in comparison to ERA5 and E-OBS, highlighting the importance of dataset selection in climate studies.

While the exinature of precipitation changes in the Mediterranean, several gaps remain to be addressed—particularly in understanding the different precipitation indices over long-term periods and across all sub-regions. Additionally, previous studies often lack a comprehensive approach that combines multiple indices to assess the cumulative effects of changes in precipitation (Paxian et al. 2015; Hochman et al. 2022). This study aims to build on the existing literature by conducting a detailed analysis of the ERA5-Land dataset,

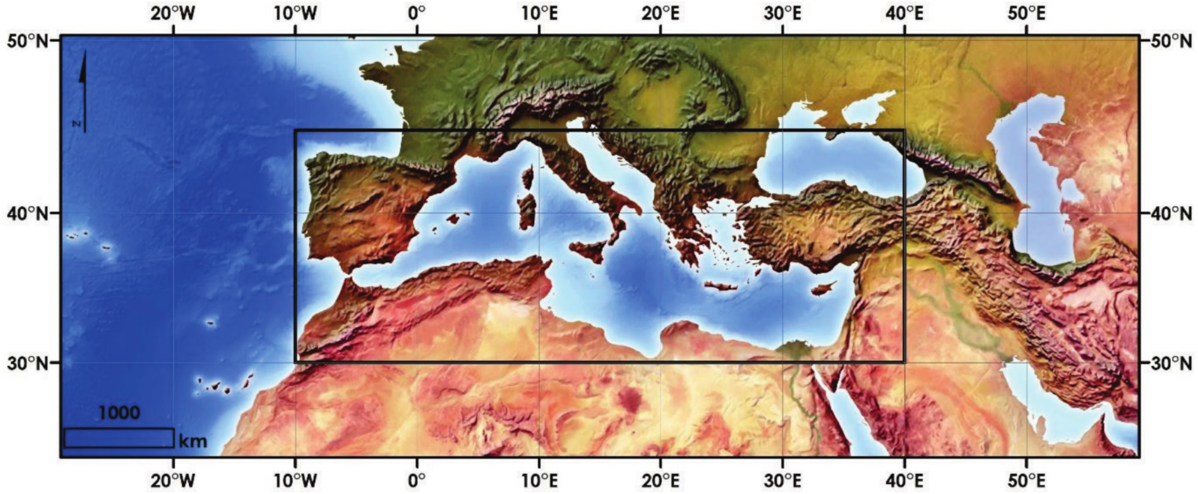

FIGURE 1 | Study area. [Colour figure can be viewed at wileyonlinelibrary.com]

covering the period from 1950 to 2024, to explore long-term trends and variability in precipitation indices across the Mediterranean region.

We investigate a suite of precipitation indices, including precipitation frequency, intensity, and persistence, across the entire Mediterranean basin, with particular attention to the often underrepresented eastern and southern areas. Spanning 1950–2024, our analysis offers comprehensive temporal coverage and includes a seasonal component, thus capturing both spatial and temporal nuances in precipitation patterns. Additionally, the study incorporates a seasonal analysis to explore the temporal dimensions of precipitation patterns. By addressing the spatial and temporal inconsistencies and uncertainties in observed trends, this research is expected to offer valuable contributions to the field of climate science.

The implications of this study are significant, as it provides valuable insights for policymakers and stakeholders in the region. With a more detailed understanding of precipitation patterns and their drivers, more effective adaptation and mitigation strategies can be developed to manage the risks associated with climate variability and change. Furthermore, our basin-wide focus and use of observational validation serve to enhance the reliability of the conclusions and lay a robust foundation for future research in this critical climatic hotspot.

2 | Study Area

The Mediterranean region is a vast and diverse geographical area stretching from the Iberian Peninsula in the west to the Levantine basin in the east, delimited longitudinally from 10° W to 40° E and latitudinally from 30° N to 45° N (Figure 1). Key boundaries include the Atlantic Ocean in the west and the Mediterranean Sea, which acts as a vital moisture source influencing regional climate. The region's complex topography, exemplified by major ranges like the Pyrenees and the Alps, modulates precipitation patterns by generating significant spatial variability.

The Mediterranean climate is characterised by hot, dry summers and mild, wet winters, a pattern heavily influenced by the subtropical high-pressure systems and the polar front, making it a unique climatic region (Ulbrich et al. 2012). These seasonal dynamics result in pronounced differences in rainfall both spatially and temporally (Figure 2). The region's complex topography, exemplified by major ranges like the Pyrenees and the Alps, modulates precipitation patterns by generating significant spatial variability. Given the region's limited and uneven water resources, precipitation variability directly affects hydrological processes and regional water security.

3 | Data and Methods

Recognising the necessity for comprehensive hydroclimatic analysis, this study harnesses the ERA5-Land dataset, accessed through the Climate Data Store (CDS) service, which provides a granular, daily total precipitation measure spanning from January 1, 1950, to December 31, 2024. The ERA5-Land dataset offers a high spatial resolution of $0.1° \times 0.1°$ (approximately $9\,km \times 9\,km$), which is essential for capturing local precipitation patterns and finer-scale dynamics (Muñoz Sabater 2019). This high-resolution dataset enables an in-depth examination of precipitation patterns over the Mediterranean, offering valuable insights into the long-term climatic trends and their variabilities within the region.

While ERA5-Land provides comprehensive coverage, it is important to note that reanalysis datasets may have limitations in representing extreme precipitation events and regional precipitation patterns due to factors such as station density and complex topography (Lavers et al. 2022; Bandhauer et al. 2021). Studies have indicated that ERA5-Land tends to overestimate mean precipitation and wet-day frequency while underestimating extreme precipitation events (Rivoire et al. 2021; Gomis-Cebolla et al. 2023). However, given the scarcity of long-term observational data across the Mediterranean, particularly in the eastern and southern regions, ERA5-Land remains a valuable resource for analysing precipitation trends over extended periods.

To dissect the complexity of precipitation behaviour, this study adopts a classification schema for precipitation indices that allows for a multi-faceted analysis of precipitation characteristics, including frequency, intensity, and extreme weather events. The indices, as described in the provided table (Table 1), include the count of heavy precipitation days (R10 mm, R20 mm, R30 mm), maximum daily precipitation (Rx1day), and maximum five-day precipitation (Rx5day), among others. The indices are categorised into three groups: 'Precipitation Frequenc', 'Precipitation Intensit', and 'Precipitation Persistence'; each with its respective units of measurement. The calculation of these indices follows the standard definitions as set by the Expert Team on Climate Change Detection and Indices (ETCCDI). These indices are not arbitrarily chosen; rather, they are carefully selected to encapsulate the broad spectrum of precipitation dynamics, from moderate rainfall events that replenish soil moisture to extreme events that may lead to flooding or droughts. For instance, Rx1day provides insights into the peak intensity of rainfall that could lead to flash flooding, while PRCPTOT reflects the overall water availability and is a vital parameter for agricultural and water resource management. The seasons are defined according to the meteorological convention: Winter (December, January, February), Spring (March, April, May), Summer (June, July, August), and Autumn (September, October, November).

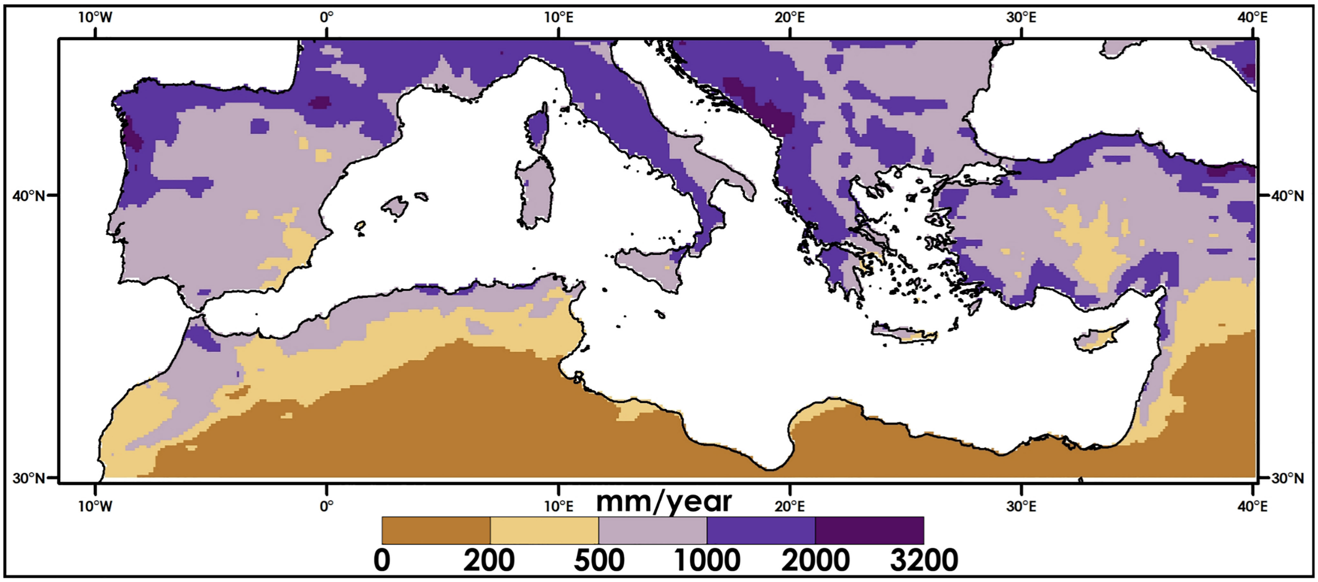

FIGURE 2 | Long-term average annual precipitation distribution in the mediterranean region (1950–2024). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 | Classification of precipitation indices used in the assessment of Mediterranean precipitation patterns.

Classification	Extreme climate indices	Description	Unit
Precipitation frequency	R10 mm	Number of heavy precipitation days ≥ 10 mm	Days
	R20 mm	Number of very heavy precipitation days ≥ 20 mm	Days
	R30 mm	Number of extremely heavy precipitation days ≥ 30 mm	Days
Precipitation intensity	Rx1day	Maximum precipitation on 1-day intervals	mm
	Rx5day	Maximum precipitation on 5-day intervals	mm
	PRCPTOT	Annual total precipitation	mm
	SDII	Simple daily intensity index	mm/day
	R95p	Daily precipitation ≥ 95th percentile	mm
	R99p	Daily precipitation ≥ 99th percentile	mm
Precipitation persistence	CDD	Consecutive dry days (the maximum number of consecutive days with daily precipitation less than 1 mm.)	Days
	CWD	Consecutive wet days (the maximum number of consecutive days with daily precipitation equal to or greater than 1 mm)	Days

Upon the computation of the indices, a robust statistical analysis was performed to discern trends and detect significant changes over the study period. The Mann-Kendall test, a non-parametric method, was employed to analyse the time series data for monotonic trends, which is essential in the context of climate studies due to its minimal assumptions about the data distribution. The significance of the Mann-Kendall test lies in its ability to handle non-linear trends and its robustness against abrupt changes, which are common in climatic time series data (Hirsch et al. 1982; Gilbert 1987). Prior to applying the Mann-Kendall test, the data series were tested for serial correlation to ensure the validity of the test results, following the method proposed by Hamed and Rao (1998).

Complementing the Mann-Kendall test, Sen's slope estimator was utilised to quantify the magnitude of the trend. This method provides a median-based slope estimate, which is particularly resistant to outliers, thereby offering a more reliable measure of change over time (Sen 1968). The slope is interpreted as the change per year or decade, depending on the context, offering an intuitive understanding of the trend's practical significance.

For the spatial representation of these trends, the study devised a series of maps delineating the decadal changes in precipitation patterns. These maps are constructed to differentiate statistically significant areas at the 95% confidence level, ensuring that only meaningful trends are highlighted. The regions marked with shaded patterns indicate areas where changes in precipitation indices are significant, thereby providing a clear visual demarcation of where climate change impacts are most pronounced.

While direct validation of ERA5-Land data against observational datasets like E-OBS was not performed due to the lack of consistent long-term observational data across the entire Mediterranean region, the reliability of ERA5-Land for analysing precipitation trends is supported by previous studies (Muñoz Sabater 2019; Tarek et al. 2020). However, it is acknowledged that the dataset's accuracy may vary regionally, and the results should be interpreted with consideration of these potential limitations.

4 | Results

4.1 | Precipitation Frequency Indices

Precipitation Frequency indices (R10 mm, R20 mm, R30 mm), which measure the frequency of heavy, very heavy, and extremely heavy precipitation days respectively, reveal a complex picture across the Mediterranean with generally low proportions of statistically significant trends (Figure 3). Overall, Figure 4 indicates that fewer than 5% of grid cells across the Mediterranean show statistically significant trends for these frequency indices, suggesting that robust long-term changes in the frequency of heavy precipitation are not widespread. However, where significant trends are detected, they highlight regional nuances. Analysis of annual trends indicates a general decline in heavy precipitation days across the western Mediterranean, particularly along the Iberian Peninsula and northern Maghreb including Morocco. This drying trend is most pronounced for heavy (R10 mm) and very heavy (R20 mm) precipitation, with decreases reaching −2 days and −1 day per decade, respectively. In contrast, the eastern Mediterranean shows a different pattern. Extremely heavy precipitation days (R30 mm) show no coherent inland signal; significant negative trends are confined mainly to the southwestern Maghreb and parts of the Iberian Peninsula (Figure 3), while notable increases are observed along parts of the eastern Mediterranean coast, with frequencies rising by up to 0.9 days per decade along the northern Adriatic coast (Croatia–Slovenia) and in pockets of western Greece. For moderate and heavy precipitation events (R20 mm and R30 mm), negative trends tend to dominate; however, statistically significant positive clusters occur over the western Balkans (Bosnia-Herzegovina, Croatia, Albania) and along parts of the northern Aegean, highlighting the spatially heterogeneous behaviour of very heavy precipitation frequency. Across the three frequency indices, the proportion of significant positive trends rises from R10 mm (~20%) to R30 mm (~64%); yet the area affected shrinks markedly, with only ≈1% of all grid cells showing any significant R30 mm change (Figure 3). This means the most extreme daily rainfall threshold intensifies, but only in very localised hotspots (the northern Adriatic and northern Aegean), whereas lower threshold events display broader but more mixed tendencies across the basin. These results point to a redistribution rather than a basin-wide intensification: very heavy rainfall days (R30 mm) are becoming more frequent, but only in a few localised hotspots (≈1% of the domain), while moderate heavy rainfall events (R10 mm) show broader declines across the western basin, with only limited pockets of increase in the eastern Adriatic and northern Aegean. These findings underscore a heterogeneous pattern of changes in the frequency of heavy precipitation events across the Mediterranean, with a general drying tendency in the west contrasted by localised increases and a complex shift in the intensity distribution of these events.

Seasonal variations in heavy precipitation frequency reveal further complexities (Figures S1–S3). While annual trends show a general drying in the west, seasonal analyses provide a more detailed view. For R10 mm, seasonal variations show diverse trends: winter features marked declines in North Africa, while spring presents mixed fluctuations across the region. Summer and autumn exhibit increases, particularly in the eastern Adriatic and northern Aegean, while pronounced declines over the Iberian Peninsula underscore a marked longitudinal contrast across the basin. Significant changes in autumn, especially in the northern Mediterranean, underscore the variable climatic influences and the complex dynamics of atmospheric patterns impacting seasonal precipitation distribution. During winter, the southern Mediterranean, particularly North Africa, experiences significant declines in heavy precipitation days, echoing the R10 mm trends. These reductions are marked by significant clusters; in winter, most northern sub-basins likewise show decreases, confirming a basin-wide contraction of heavy-rainfall days during the cool season. Spring shows pronounced variability across the Mediterranean with no clear directional trends, indicating a transitional period with scattered heavy precipitation days. Summer exhibits virtually no statistically significant change in R10 mm frequency across the basin, apart from small positive clusters along the eastern Adriatic coast (Croatia–Bosnia) and the eastern Black-Sea littoral of Türkiye. By contrast, autumn (F) displays the widest-ranging wetting signal: significant increases stretch from north-west Iberia and the Cantabrian coast, across northern

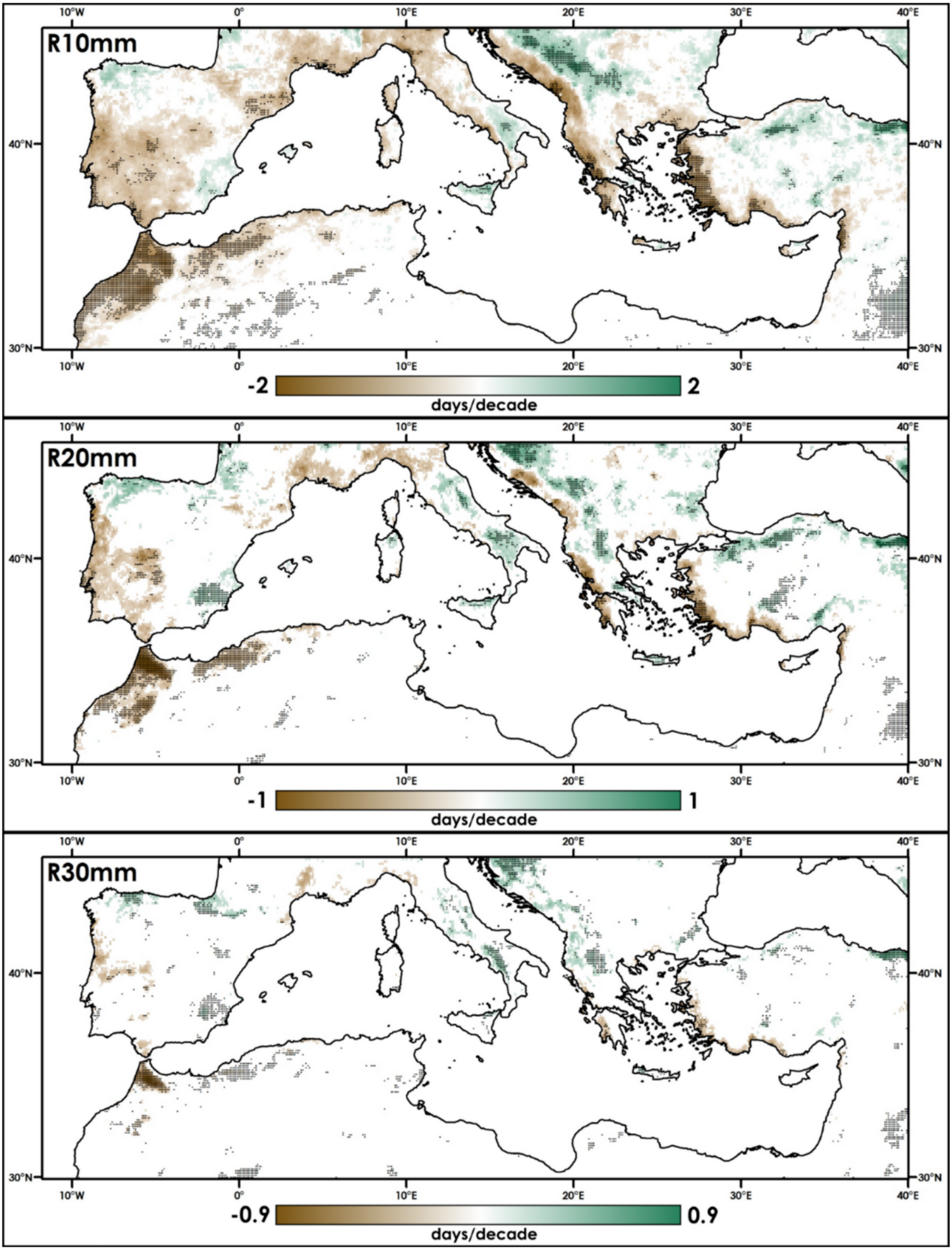

FIGURE 3 | Geographical distribution of the trend in the number of heavy precipitation days (R10 mm), very heavy precipitation days (R20 mm) and extremely heavy precipitation days (R30 mm) across the Mediterranean region for the period 1950–2024. Shaded areas indicate regions where the trend is statistically significant at the 95% confidence level based on the Mann-Kendall test. [Colour figure can be viewed at wileyonlinelibrary.com]

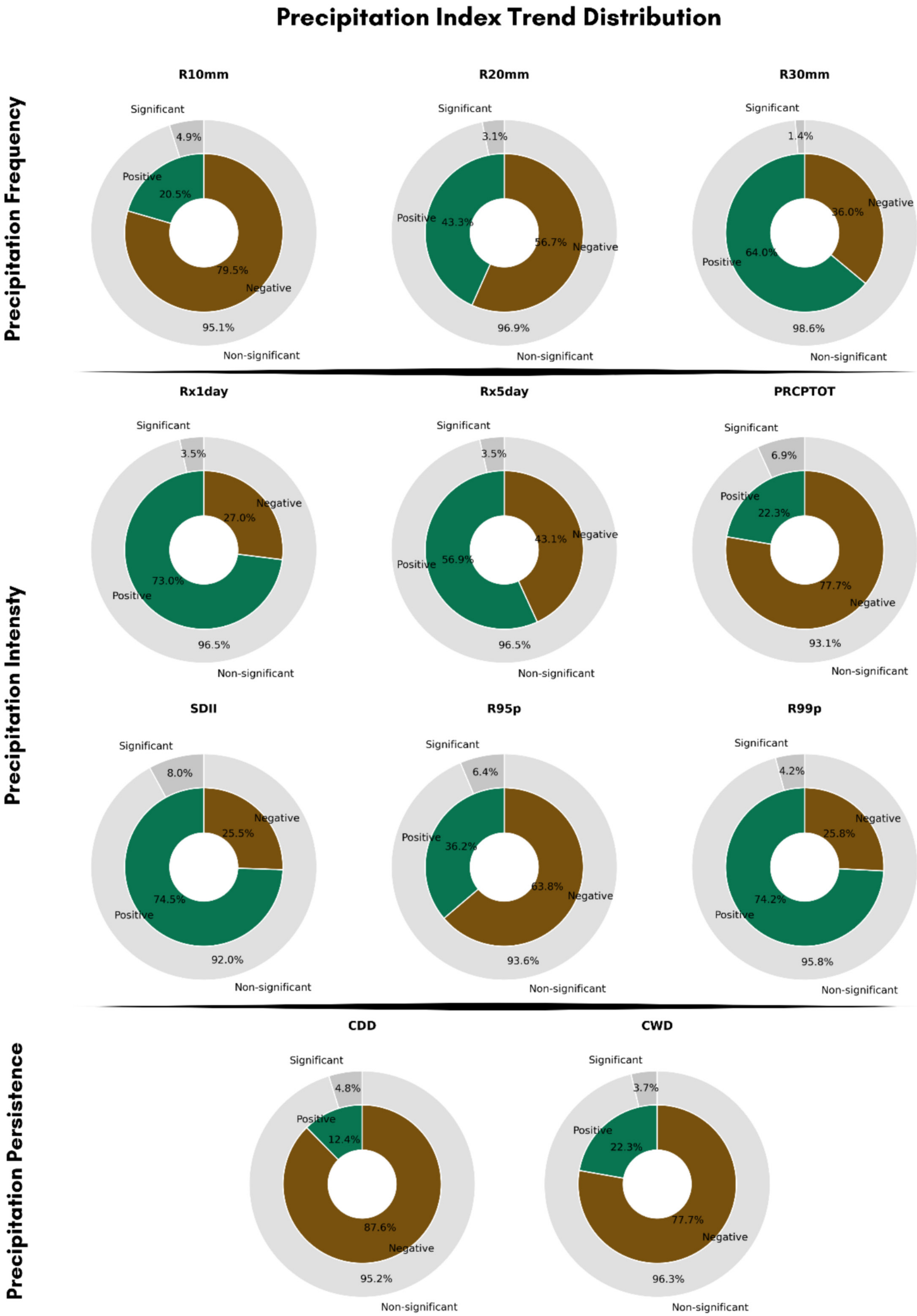

FIGURE 4 | Legend on next page.

FIGURE 4 | Distribution of trend significance and direction for each precipitation index. In each donut chart, the outer grey ring indicates the proportion of grid cells across the Mediterranean region exhibiting statistically significant versus non-significant trends at the 95% confidence level. The inner ring shows, within the cells, that are significant, the percentage of positive (green) and negative (brown) trends. [Colour figure can be viewed at wileyonlinelibrary.com]

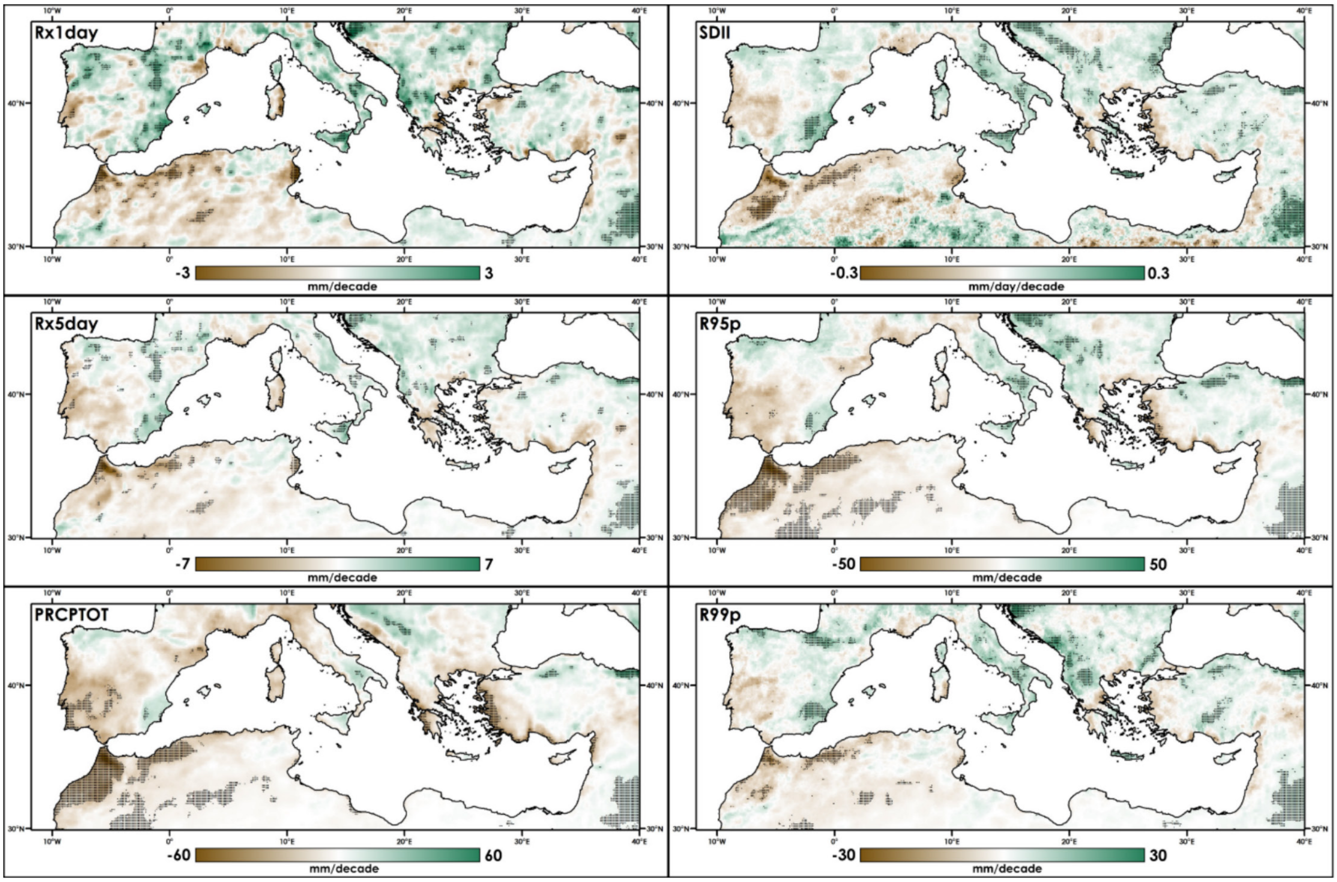

FIGURE 5 | Geographical distribution of the trend in the maximum 1-day precipitation (Rx1day), maximum 5-day precipitation (Rx5day), annual total precipitation (PRCPTOT), the Simple Daily Intensity Index (SDII), the daily precipitation at the 95th percentile (R95p) and the daily precipitation at the 99th percentile (R99p) across the Mediterranean region for the period 1950–2024. Shaded areas indicate regions where the trend is statistically significant at the 95% confidence level based on the Mann-Kendall test. [Colour figure can be viewed at wileyonlinelibrary.com]

Italy and the northern Adriatic, to western Greece, whereas negative pockets persist over interior North Africa. Seasonally, the R30 mm maps are characterised by a predominance of white or lightly shaded areas across the Mediterranean, signalling minimal decade-by-decade changes in the frequency of days with at least 30 mm of precipitation. This general lack of significant trends across many areas during most seasons suggests relative stability in the occurrence of these heavy precipitation events. Winter exhibits localised changes: statistically significant decreases in R30 mm days concentrate over the north-west Iberian Peninsula and northern Morocco, while very small positive clusters arise along the eastern Adriatic and northern Aegean coasts. Summer likewise shows coherent signals, with notable declines across western Iberia and the western Maghreb, whereas the rest of the basin remains largely trend-neutral. The few localised significant changes underscore the influence of regional climatic factors over broader shifts in climate patterns. Conversely, the spring season reveals a patchwork of slight increases and decreases, yet these changes are not statistically significant. In the autumn, however, there is a noticeable increase in heavy precipitation days in the northern Adriatic, western Greece, and the southeast Black-Sea coast of Türkiye, suggesting a seasonal intensification of rainfall events. In summary, seasonal trends indicate a complex interplay, with winter drying in North Africa being a consistent feature across R10 mm and R20 mm indices, while other seasons and regions exhibit more variable and less pronounced changes in heavy precipitation frequency.

4.2 | Precipitation Intensity Indices

Precipitation Intensity indices (Rx1day, Rx5day, PRCPTOT, SDII, R95p, and R99p) reveal a nuanced and seasonally variable picture of changes in rainfall severity across the Mediterranean (Figure 5). These intensity indices collectively suggest a complex pattern with significant seasonal and regional variations in both intensification and attenuation of rainfall extremes across the region.

Analysing the intensity indices, Rx1day and Rx5day, which quantify maximum daily and 5-day precipitation, reveals mixed annual trends characterised by spatial heterogeneity. As highlighted in Figure 4, Rx1day shows a predominance of positive trends (≈73% of significant cells), especially over the Balkans and northeastern Türkiye, whereas Rx5day presents a more balanced mix, emphasising the localised nature of extreme rainfall intensification. Specifically, annually, regions like the northern Dinaric Alps, northeastern Türkiye, and the Levant show increases in maximum daily and 5-day precipitation, indicating localised intensification of extreme rainfall episodes. In contrast, the western and southern Mediterranean, including North Africa and the Iberian Peninsula, exhibit spatially complex trends. While declines prevail over several indices across large areas, particularly in Northwest Africa and southern/western Iberia (e.g., for PRCPTOT, Rx5day, R95p), notable significant positive trends are also observed in specific locations, especially for Rx1day and R99p in northeastern Iberia. Seasonally, Rx1day maps (Figure S4) illustrate that winter months show significant declines in maximum daily precipitation along the southern Mediterranean coast, particularly in North Africa and the Iberian Peninsula, while spring reveals a mixed pattern with increases in regions like the Balkans and the Aegean Sea. Summer shows predominant declines across the western Mediterranean and variable patterns in the eastern Mediterranean. Autumn exhibits increased precipitation across northern Mediterranean areas, particularly around the Italian Peninsula and the Adriatic region, and in some coastal areas of North Africa. For Rx5day, seasonal breakdowns underscore distinct patterns: winter displays marked decreases along the southern Mediterranean shores and slight increases along the Adriatic coast and western Mediterranean (Figure S5). Spring reveals increases in the Balkans and Greece and declines in the western Iberian Peninsula. Summer shows contrasting trends between the eastern Balkan Peninsula and Türkiye (increases) and the Iberian Peninsula (decreases).

PRCPTOT, representing annual total precipitation, presents significant negative trends in specific areas of the western Mediterranean, particularly in northern Africa, the southwest of the Iberian Peninsula, and the west coast of Türkiye, with decreases of up to −60 mm per decade (Figure 5). Despite this drying signal, Figure 4 also shows that a considerable portion (~22.3%) of grid cells for PRCPTOT exhibit significant positive trends, indicating regional variability in annual precipitation changes. Increases in annual precipitation are noted in the Dinaric Alps and parts of northeastern Türkiye. Seasonal analyses of PRCPTOT further highlight these dynamics (Figure S6). Winter months show widespread and statistically significant decreases in total precipitation across large areas of the southern Mediterranean (including North Africa, the southern Iberian Peninsula, and the Levant), with declines reaching up to 30 mm/decade. These winter trends appear to be a primary driver of the observed negative annual precipitation trends in these regions. Spring displays varied trends with significant decreases along the western coasts of the Iberian Peninsula and North Africa. Conversely, summer and fall exhibit some regions of increase, particularly in the northern Mediterranean.

The Simple Daily Intensity Index (SDII) indicates that, on an annual basis, where changes in intensity are significant, they are more frequently increases rather than decreases. Indeed, Figure 4 reveals that over 70% of grid cells with significant SDII trends are positive. The annual spatial distribution of SDII trends shows intensification particularly in the eastern Mediterranean and decreases predominantly in Northwest Africa and parts of the Iberian Peninsula (Figure 5). Seasonally, SDII maps present a nuanced view (Figure S7). Winter shows marked decreases in rainfall intensity in the southern Mediterranean, especially North Africa's northern coast. Spring sees slight decreases in the central Mediterranean and parts of the Iberian Peninsula. Summer displays complex patterns with no dominant trends. Fall, however, shows significant increases in rainfall intensity across the northern Mediterranean.

For the extreme intensity indices, R95p and R99p, a balanced distribution of positive and negative annual trends is observed among the significant grid cells, indicating a heterogeneous pattern of extreme precipitation intensity changes across the basin. Annual maps for R95p and R99p illustrate this, showing areas of increased intensity in the central and eastern Mediterranean and mixed or decreasing trends in the western Mediterranean. Seasonal analysis of R95p reveals winter decreases in precipitation intensity along the western part of the southern Mediterranean coasts (including Northwest Africa and southern Iberia), and spring shows an east–west disparity with increases in the Balkans and Southern Italy and decreases mainly in the west of the Iberian Peninsula (Figure S8). Summer shows widespread significant decreases across the Iberian Peninsula and Northwest Africa, while autumn reveals significant increases in precipitation intensity across extensive areas of the northern Mediterranean. Seasonal R99p maps show generally less intense changes, with winter exhibiting sparse significant changes and slight decreases over parts of Northwestern Africa and the southern Iberian Peninsula (Figure S9).

In summary, the analysis of Precipitation Intensity indices reveals a distinct contrast across the Mediterranean basin. A pattern of general intensification is observed in parts of the eastern Mediterranean (e.g., Balkans, Türkiye, Levant showing positive trends for Rx1day, Rx5day, SDII), while predominantly decreasing trends or mixed signals characterise the western Mediterranean (e.g., Iberian Peninsula, Northwest Africa showing negative trends for PRCPTOT, SDII, Rx5day, but mixed signals for Rx1day). Seasonally, notable features include winter drying (decreased intensity) in western and southern regions (e.g., Iberia, North Africa for several indices including Rx1day, Rx5day, SDII, R95p) and increased intensity during autumn, particularly across northern Mediterranean areas (e.g., for Rx1day, SDII, R95p). The most extreme intensity indices (R95p, R99p) display a heterogeneous pattern annually, reinforcing the overall spatial variability but also reflecting the key seasonal signals like autumn intensification in the north and winter decreases in the south/west.

4.3 | Precipitation Persistence Indices

Precipitation Persistence indices, CDD (consecutive dry days) and CWD (consecutive wet days), provide insights into the duration of dry and wet periods, which are critical for understanding drought and flood risks across the Mediterranean. Figure 4

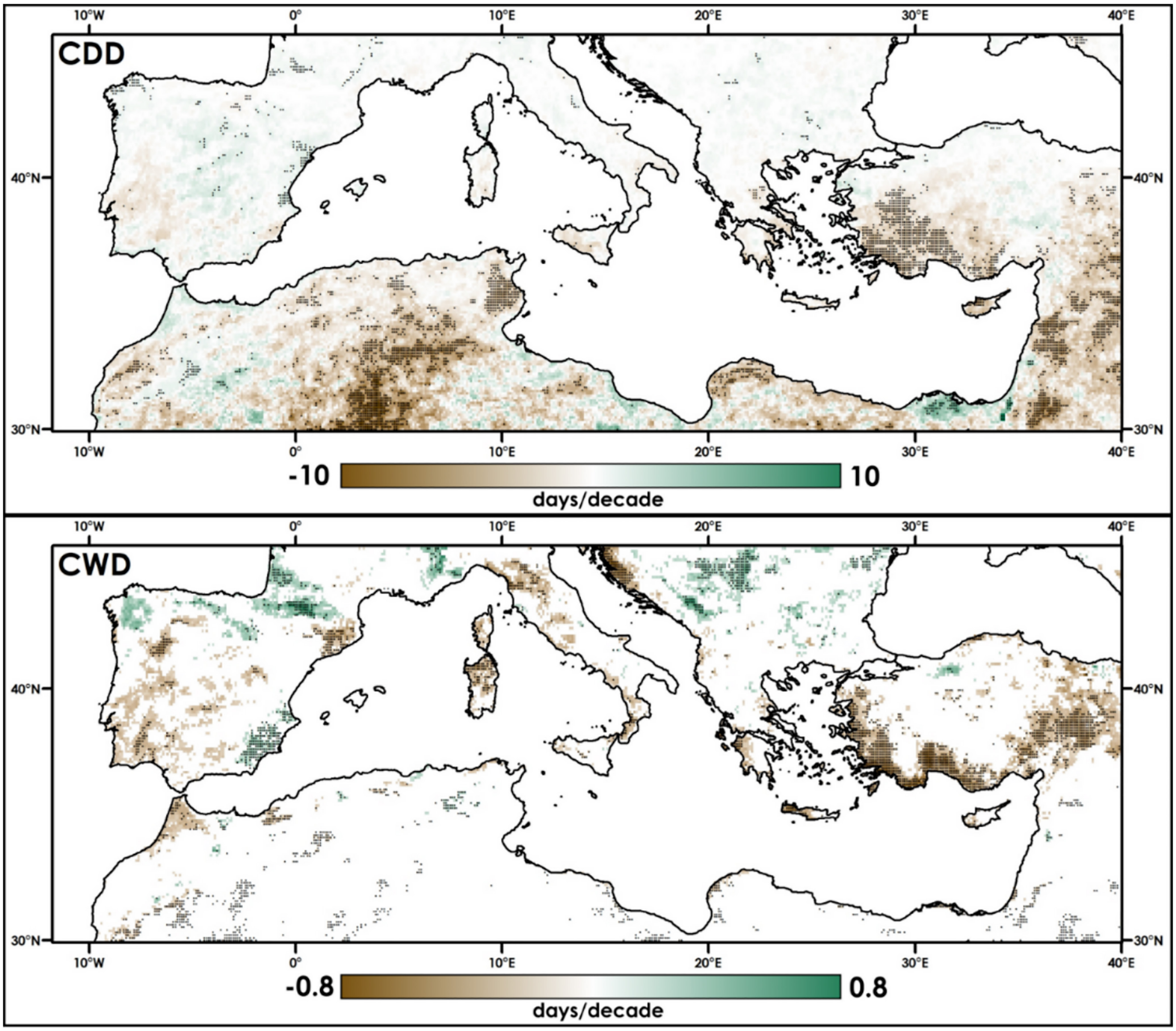

FIGURE 6 | Geographical distribution of the trend in the maximum number of consecutive dry days (CDD) and the maximum number of consecutive wet days (CWD) across the Mediterranean region for the period 1950–2024. Shaded areas indicate regions where the trend is statistically significant at the 95% confidence level based on the Mann-Kendall test. [Colour figure can be viewed at wileyonlinelibrary.com]

indicates that both CDD (4.8% significant) and CWD (3.7% significant) show significant trends across the Mediterranean domain, highlighting that changes in precipitation persistence are spatially limited. Where significant trends are observed, they predominantly indicate a reduction in the persistence of both dry and wet spells.

Analysing annual trends, the CDD index (Figure 6) reveals a significant reduction in consecutive dry days across the eastern Mediterranean, particularly in the Levant and parts of the northern Middle East. This suggests a shift towards milder dry periods in these regions annually, characterised by less prolonged dry spells. Conversely, while some parts of the Iberian Peninsula show increases in consecutive dry days (CDD), large areas across Northwest Africa exhibit significant declining trends, indicating shorter dry spells annually in these regions (Figure 6). The CWD index annually illustrates a decreasing trend (shorter wet spells) in maximum consecutive wet days in the northeastern Mediterranean, particularly the Balkans and western Türkiye, suggesting a shift towards longer dry spells in this region and potentially complicating water resource management (Figure 6). Areas like the Iberian Peninsula and the northwest coast of Africa, however, show significant decreasing trends in CWD in many areas, particularly southern/eastern Iberia and the Maghreb coast, although some northern parts of Iberia show increasing trends, indicating changes in wet day frequencies. According to Figure 4, where significant trends in persistence indices do appear, negative trends (indicating a decrease in the persistence of dry and wet spells) are dominant for both CDD and CWD. Specifically, for CDD, approximately 87.6% of the significant cells show negative trends, suggesting that areas experiencing significant changes in dryness persistence are mostly seeing shorter prolonged dry spells over time. CWD also exhibits a majority negative trend direction within its significant cells, indicating shorter prolonged consecutive wet periods in regions with significant trends. Thus, annual persistence-related changes appear to be concentrated in limited pockets of the Mediterranean, reflecting the spatial heterogeneity of its climate.

Seasonal variations further elucidate these persistence trends. For CDD, seasonal maps (Figure S10) reveal distinct trends: winter shows substantial increases in consecutive dry days across significant areas of the Iberian Peninsula, North Africa, and Northern Italy, suggesting a potential intensification of dry conditions during winter in these regions. In contrast, the southeastern Mediterranean coast, including Egypt, shows slight decreases in winter CDD. Other seasons exhibit less significant or clear CDD trends, indicating more complex seasonal patterns. Seasonal variations in CWD, detailed in Figure S11, underline pronounced winter declines along the northern African coast and parts of the Iberian Peninsula, suggesting drier winters which could impact regions typically reliant on this season's rainfall. This pattern aligns with the observed winter trends in total precipitation. Spring shows similar trends with slight increases in some areas but lacks the widespread significance seen in winter. Summer and fall do exhibit some increases, particularly in northeastern Türkiye, although with limited statistical significance, indicating subtle shifts in seasonal precipitation patterns.

The apparent contradiction observed, where northern Africa experiences a decrease in annual CDD but an increase during winter, can be attributed to seasonal shifts in precipitation patterns. Enhanced precipitation during spring and summer months reduces the annual CDD by shortening dry spells in those seasons. Conversely, decreased precipitation during winter and autumn extends dry spells in these seasons, leading to increased CDD. This seasonal redistribution of rainfall, influenced by changes in atmospheric circulation patterns and climate change effects, results in complex regional precipitation dynamics. These combined annual and seasonal findings highlight the complexity of climatic systems, emphasising the importance of considering multiple temporal scales in trend analysis, particularly for persistence indices. The winter months becoming increasingly dry in parts of the Mediterranean, despite a general annual trend towards shorter dry days in some eastern areas (CDD), and the winter declines in wet day persistence along the northern African coast and Iberian Peninsula (CWD), highlight significant shifts in the seasonality of both dry and wet spells across the Mediterranean. These seasonal shifts necessitate detailed regional analyses to adapt water management strategies to these changing precipitation patterns effectively.

4.4 | Correlation Analysis of Precipitation Indices

To further understand the relationships and interconnectedness among various precipitation indices across the Mediterranean region, a correlation matrix analysis was conducted using the ERA5-Land dataset for the period 1950–2024 (Figure 7). Figure 7 depicts the spatial pattern correlations between pairs of precipitation indices, calculated by correlating their respective trend maps (Sen's slope values) across all grid points within the study domain. This analysis provides insights into the spatial pattern correlation of extreme precipitation events and their influence on the overall precipitation regime in the Mediterranean.

The correlation matrix reveals that the indices representing the frequency of heavy precipitation events (R10 mm, R20 mm, R30 mm, R95p, and R99p) exhibit exceptionally high correlations ($r > 0.9$) with each other. This strong interdependence indicates a notable consistency in their spatial trend patterns across the Mediterranean. Moreover, indices measuring maximum daily precipitation over one day (Rx1day) and five-day periods (Rx5day) also show strong correlations with these frequency indices, reinforcing that the intensity and persistence of extreme events are spatially consistently trending across the region.

The total annual precipitation (PRCPTOT) exhibits a high correlation with several of the extreme precipitation indices, particularly with R10 mm ($r = 0.95$), R20 mm ($r = 0.96$), R95p ($r = 0.98$), and R99p ($r = 0.88$). This indicates that the annual precipitation totals in the Mediterranean are significantly influenced by extreme precipitation events. These results support the idea that extreme events contribute disproportionately to annual totals, a trend observed in previous studies focusing on the Mediterranean (Alpert et al. 2002; Tramblay et al. 2013).

The Simple Daily Intensity Index (SDII), representing the average intensity of precipitation on wet days, demonstrates moderate to strong correlations with indices such as R95p ($r = 0.66$), R99p ($r = 0.74$) and Rx1day ($r = 0.75$). This indicates that the overall intensity of daily precipitation exhibits spatially consistent increases alongside extreme events, further reinforcing the notion that the Mediterranean region is experiencing more intense rainfall patterns, consistent with observations from Fischer and Knutti (2016).

The precipitation persistence indices, CDD (maximum length of dry spell) and CWD (maximum length of wet spell), behave differently compared to the other indices. CDD shows very weak correlations with all other indices (ranging from 0.02 to 0.07), suggesting that based on the annual scale correlations analysed (Figure 7), dry spells operate independently of precipitation extremes or intensity, likely driven by different atmospheric mechanisms governing annual persistence. In contrast, CWD has moderate correlations with indices such as PRCPTOT ($r = 0.67$) and R10 mm ($r = 0.66$), indicating that areas experiencing more consecutive wet days tend to have higher annual precipitation totals and a greater number of heavy precipitation events.

Overall, the high correlation among most extreme precipitation indices suggests a spatial consistency in their trend patterns across the Mediterranean in terms of how these indices evolve over time. This highlights that extreme precipitation events may be influenced by regional atmospheric circulation patterns, sea surface temperature anomalies, and teleconnection influences like the North Atlantic Oscillation (NAO) and East Atlantic/Western Russia (EA/WRNCP) patterns (Trigo et al. 2002; Mastrantonas et al. 2021). Further research, including analysis of trends in these climatic drivers, is needed to confirm these potential linkages.

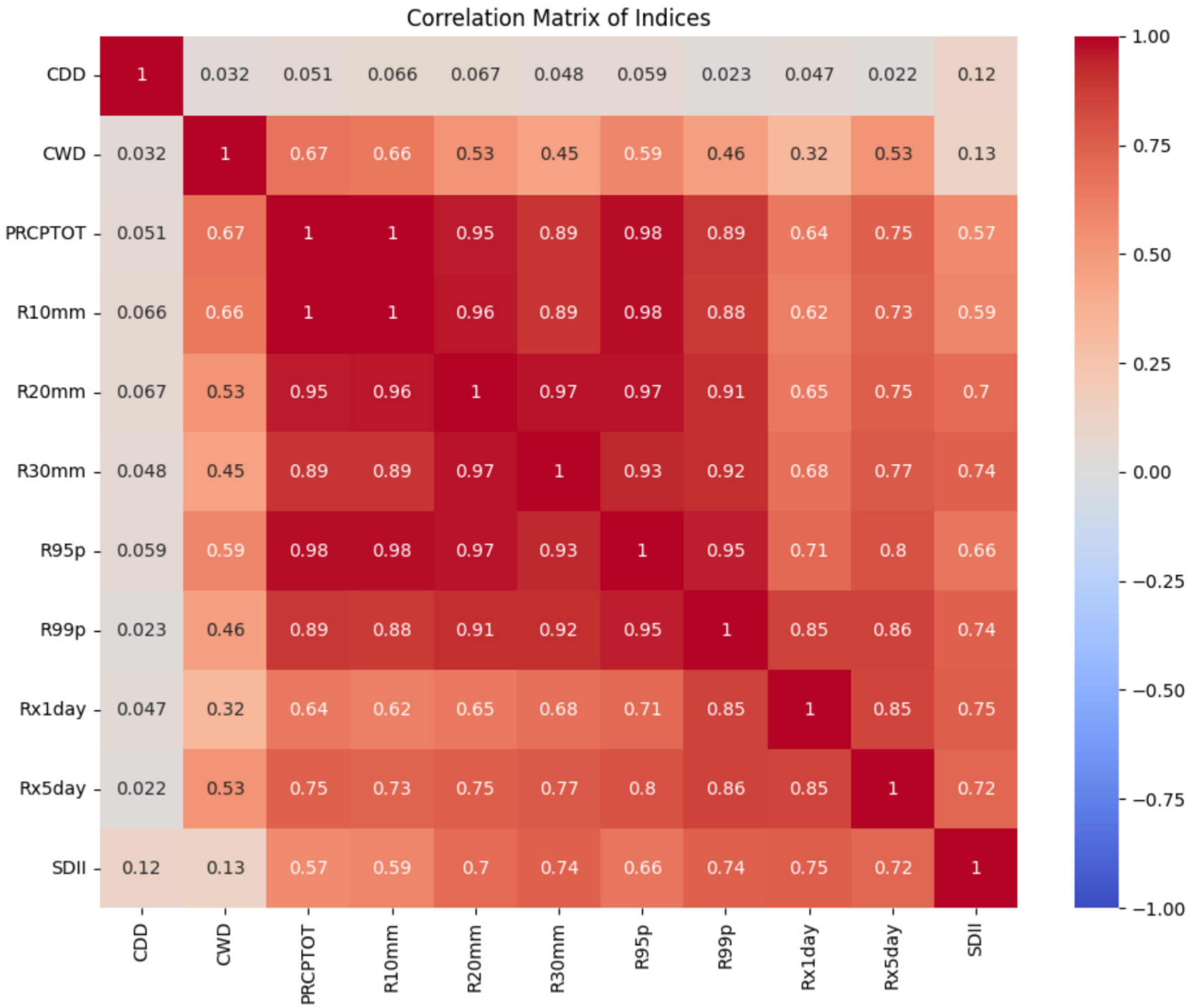

FIGURE 7 | Correlation matrix of precipitation indices across the mediterranean region (1950–2024). [Colour figure can be viewed at wileyonlinelibrary.com]

5 | Discussion

This study provides a comprehensive assessment of precipitation trends across the Mediterranean, revealing significant spatial heterogeneity in precipitation changes. Notably, a clear west–east dipole pattern emerges, characterised by decreasing precipitation trends in the western Mediterranean and increasing trends in the eastern Mediterranean. This spatial contrast is evident across various precipitation indices, including heavy precipitation frequency, intensity, and total annual precipitation. This observed spatial variability emphasises the complex regional climate dynamics and the need for spatially differentiated climate adaptation strategies across the Mediterranean.

The observed west–east dipole in precipitation trends is further supported by existing literature, particularly regarding the intensification of extreme precipitation in the Eastern Mediterranean. For instance, Ciftci and Sahin (2023) observed an upward trend in precipitation extremes in Türkiye, which supports our findings of increased heavy precipitation indices in the northeastern Mediterranean. Similarly, Hamitouche et al. (2024) reported changes in extreme precipitation indices across Algeria, noting regional variations reveal a drying trend in the Western Mediterranean, consistent with our findings. While Hamitouche et al. (2024) focused on Algeria, their findings of decreasing precipitation indices in certain Algerian climate zones resonate with our broader observation of a drying trend across the Western Mediterranean. Moreover, our seasonal analysis, particularly the pronounced summer drying in the Iberian Peninsula and North Africa (Figures S1–S11), reinforces concerns about water scarcity during critical growing seasons, as highlighted by Abrantes et al. (2017). The contrasting wetting trend along the Adriatic coast and northeastern Türkiye during winter and spring further underscores the complex spatial and temporal heterogeneity of precipitation changes in the Mediterranean.

Our seasonal analysis further highlights the nuanced nature of precipitation changes, with distinct seasonal patterns emerging across the Mediterranean. The pronounced decrease in total annual precipitation (PRCPTOT) during summer, particularly across the Iberian Peninsula and North Africa, directly intensifies concerns about water scarcity during the already dry summer months and critical agricultural growing seasons (Abrantes et al. 2017). Conversely, the observed increases in PRCPTOT during winter and spring along the Adriatic coast and northeastern Türkiye may indicate a potential shift towards wetter shoulder seasons in these subregions. These contrasting seasonal trends have significant implications for water resource management, agricultural planning, and drought/flood preparedness across the diverse Mediterranean landscape.

The spatial dipole pattern is further evident when examining heavy precipitation days (R10 mm, R20 mm, R30 mm) and extreme precipitation intensity (R99p). Our analysis of heavy precipitation frequency indices (R10 mm, R20 mm, R30 mm) clearly delineates a geographical divergence: decreasing trends across the Western Mediterranean and increasing trends over the Eastern Mediterranean (Figure 3). This geographical split implies a heightened risk of flooding in the Eastern Mediterranean, particularly during autumn and winter (Figures S1–S3). This pattern supports broader observations of climatic shifts, including increased drought frequency in the Mediterranean as documented by Hoerling et al. (2012) and a drying trend noted by Mariotti et al. (2008). Indeed, these trends align with broader climate change projections for the Mediterranean, indicating an increased frequency of droughts in the west (Hoerling et al. 2012; Mariotti et al. 2008) and a potential intensification of flood risk in the east. These findings highlight significant regional shifts; however, it is crucial to consider them within the context of the data and methods used.

While our study provides valuable insights into Mediterranean precipitation trends, it is crucial to acknowledge potential limitations inherent in the ERA5-Land dataset. ERA5-Land, while offering high spatial resolution and extensive coverage, is a reanalysis product and therefore has inherent uncertainties, particularly in regions with complex topography and limited observational data, such as parts of the Mediterranean basin (Bandhauer et al. 2021; Lavers et al. 2022). Indeed, studies suggest that ERA5-Land can exhibit biases, including overestimation of mean precipitation and underestimation of extreme precipitation intensities (Rivoire et al. 2021; Gomis-Cebolla et al. 2023). To address the potential influence of serial correlation on trend significance (Yue & Wang, 2004), we employed the Hamed and Rao (1998) modified Mann-Kendall test, which is robust against autocorrelation. However, while this method mitigates the impact of autocorrelation, uncertainties related to data limitations and potential biases in ERA5-Land should be considered when interpreting the observed trends. Further validation with observational datasets is recommended for future studies to enhance the robustness of these findings.

Large-scale atmospheric circulation patterns and sea surface temperatures (SSTs) are recognised as key modulators of precipitation variability in the Mediterranean region. While this study does not delve into a detailed analysis of these driving factors, it is plausible that shifts in patterns such as the North Atlantic Oscillation (NAO) and Mediterranean Oscillation (MO) contribute to the observed precipitation trends. For instance, positive NAO phases are typically linked to drier conditions in the southern Mediterranean and wetter conditions in the north (Trigo et al. 2002). However, the complex and potentially non-stationary relationship between these large-scale patterns and regional precipitation necessitates further dedicated research. Besides NAO and SSTs, other regional atmospheric patterns may also play a role in modulating Mediterranean precipitation, although their specific contributions require further dedicated investigation.

Shifts in precipitation persistence are also evident across the Mediterranean. In the northeastern Mediterranean, we observe a trend towards longer wet periods, particularly during winter. This increase in consecutive wet days (CWD) may exacerbate flood risks in this region, consistent with findings on precipitation variability in the Mediterranean (Lionello 2012). Conversely, the Western Mediterranean exhibits an increasing trend in consecutive dry days (CDD) during summer, indicating a heightened drought risk during already dry summers. This elevated drought risk underscores the need for Mediterranean-specific measures highlighted in the IPCC AR6 (WG II Ch. 13), including integrated drought-management plans, demand-side water conservation, expansion of early-warning systems, and adoption of drought-resilient crop varieties (IPCC 2021).

The observed precipitation trends are likely driven by a complex interplay of climatic and regional factors. Large-scale atmospheric circulation patterns, such as the NAO, and sea surface temperatures (SSTs) are undoubtedly important factors influencing precipitation regimes (Trigo et al. 2002). The Mediterranean's complex topography also plays a crucial role in shaping regional precipitation patterns, creating diverse microclimates and orographic effects (Norrant-Ritz & Douguédroit, Norrant and Douguédroit 2006). While land-use changes and urbanisation can modify local climates, their impact on basin-scale precipitation trends is likely secondary compared to these broader climatic drivers.

Our findings, particularly the increasing trends in extreme precipitation indices in the Eastern Mediterranean, are consistent with recent studies indicating a strengthening of precipitation extremes in certain parts of the Mediterranean region (Ciftci and Sahin 2023; Hamitouche et al. 2024). This suggests that the intensification of precipitation extremes, especially in the Eastern Mediterranean, may be an ongoing and potentially accelerating trend.

In conclusion, our findings underscore the critical importance of considering spatial and temporal variability when analysing precipitation trends in the Mediterranean region. The identified west–east dipole and seasonal contrasts in precipitation indices highlight the complex regional climate dynamics and have significant implications for water resource management and climate change adaptation strategies. Furthermore, future studies should prioritise the validation of reanalysis datasets like ERA5-Land with high-resolution observational data, where available, to enhance the robustness of precipitation trend analyses. Investigating the socio-economic impacts of these changing precipitation patterns is also crucial for developing effective and region-specific adaptation measures.

6 | Conclusions

Our study has demonstrated spatially heterogeneous trends in precipitation extremes across the Mediterranean region, revealing a distinct west–east dipole pattern. Specifically, we identified decreasing trends in total and heavy precipitation indices in the Western Mediterranean, contrasting with increasing trends, particularly in extreme precipitation, in the Eastern Mediterranean. The observed divergence between the western and eastern Mediterranean in terms of precipitation trends underscores the complex spatial and temporal climatic dynamics of the region. The findings highlight the need for tailored, region-specific climate adaptation strategies to manage the implications of these changes on water resources, agriculture, and flood risk. As the climate continues to warm, it is imperative that Mediterranean countries enhance their adaptive capacity to navigate the challenges posed by more variable and extreme precipitation patterns. Even though the majority of grid cells across the Mediterranean region do not exhibit statistically significant trends in precipitation indices, the observed significant changes, though limited in spatial extent, are concentrated in key areas such as the western Mediterranean and the northeastern Mediterranean. These localised trends, including decreases in heavy precipitation frequency in the west and increases in extreme precipitation in the east, highlight the region's vulnerability to climate change and underscore the need for targeted adaptation strategies.

While our study is extensive, its limitations include the spatial resolution of the ERA5-Land dataset, which may obscure finer-scale dynamics, suggesting the necessity for high-resolution observational data in future research. Further studies should also enhance climate models to better predict precipitation extremes and develop more effective climate adaptation strategies. Moreover, exploring the socio-economic impacts of precipitation changes, such as on agriculture, urban water management, tourism, and public health will be crucial for devising comprehensive adaptation strategies.

To address these evolving challenges, we recommend policymakers and practitioners develop action-oriented, integrated water resource management strategies that are adaptable to changing precipitation patterns and invest in climate-resilient infrastructure. Furthermore, strengthening enhanced regional cooperation on water management could also strengthen resilience to climate change impacts and facilitate knowledge sharing and coordinated adaptation efforts across the Mediterranean basin.

Author Contributions

Doğukan Doğu Yavaşlı: conceptualization, investigation, writing – original draft, methodology, visualization, validation, writing – review and editing, software, project administration, data curation, supervision, resources.

Conflicts of Interest

The author declares no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supplementary Information.