



Review Article

Is daily extreme rainfall increasing in the Mediterranean basin? A critical review of the evidence

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ABSTRACT

This article reviews published research on trends in extreme precipitation events across the Mediterranean basin between 1980 and 2025. A total of 175 peer-reviewed studies were compiled using standardized search criteria across major bibliographic databases. The review focuses on reporting the diversity of findings as presented by their authors, while it does not assess the quality of data, methods, or definitions used in individual studies. To avoid misinterpretation, and ensure traceability of our research, key statements regarding trends transcribed directly from each paper's abstract, main text, or conclusions are compiled. The results highlight substantial spatial and temporal heterogeneity in reported trends, with few statistically significant and regionally consistent patterns. While in some subregions (particularly parts of Italy, southern France, some areas of Spanish east-coastland and North-Western Africa coastland) localized increases in high-magnitude rainfall events have been found, many areas show either no trend or statistically insignificant changes. The evidence does not support a basin-wide intensification of extreme precipitation, and observed trends appear more strongly influenced by local geographic and synoptic factors, or linked to specific analysis time windows, than by a coherent signal of global climate forcing. These findings underscore the importance of continued observation, high-resolution analysis, and cautious interpretation of regional extremes in a climate change context. A more unified methodological framework is needed to improve comparability across studies and support effective risk management and adaptation strategies in this highly exposed region.

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"... people's beliefs and convictions are in almost every case gotten at second-hand, and without examination, from authorities who have not themselves examined the questions at issue but have taken them at second-hand from other non-examiners, whose opinions about them were not worth a brass farthing." Mark Twain (in Laframboise 2011, *The delinquent teenager*, p. 4).

1. Introduction

Global assessments have identified increases in heavy precipitation events over several regions especially at higher latitudes. This observation was initially established in seminal studies (Katz and Brown, 1992; Groisman and Legates, 1995), and subsequently reinforced by further research (Groisman et al., 2005; Moberg and Jones, 2005; Zolina et al., 2005). The robustness of this trend has been confirmed by later multi-regional analyses (Westra et al., 2013; Donat et al., 2016; Sippel et al., 2017), and has been consistently recognized in successive IPCC assessment reports.

However, the spatial distribution of these trends remains highly variable, and the evidence is often ambiguous or inconsistent across regions (Myhre et al., 2019; Sun et al., 2021; Kelebek et al., 2021). While some studies report localized increases in high-magnitude rainfall events, others find no statistically significant trends—or even declines—depending on factors such as the region analyzed, the time period considered, the quality and resolution of the data, and the methodological approach used (Alexander et al., 2006; Alexander, 2016; Papalixiou and Montanari, 2019).

The Mediterranean basin, which spans parts of Europe, North Africa, and the Middle East, presents a particularly complex case. The region is characterized by high climatic and geographic heterogeneity, significant variations in data availability and accessibility, and a marked seasonality in precipitation regimes. Extreme precipitation events are among the most impactful hydrometeorological hazards in the region, frequently leading to flash floods, landslides, infrastructure damage, and human casualties. Given the region's complex topography, densely populated coastal zones, and exposure to rapid atmospheric changes, understanding trends in extreme rainfall is essential for effective risk management and climate adaptation.

Despite the growing number of studies addressing precipitation in this region (see Vicente et al., 2025), until present no comprehensive synthesis has yet been introduced on extreme precipitation. Even classical research such as Alpert et al. (2002), have not succeeded in resolving the inconsistencies between regional observations and broader global trends. Moreover, the heterogeneity of definitions, indices, thresholds, and statistical approaches across the literature significantly complicates cross-study comparison and generalization. This review aims to assess the state of knowledge on observed trends in daily extreme precipitation across the Mediterranean basin between 1980 and 2024. We compile and report key conclusions from 175 peer-reviewed studies, avoiding reinterpretation or reanalysis of results. Our goal is not to re-evaluate the quality of data or methods, but to systematically document what has been reported, identify spatial and temporal

patterns, and highlight areas of consensus and disagreement. In doing so, we aim to support future research efforts and inform ongoing discussions about climate change impacts in the Mediterranean.

The article is organized as follows: Section 2 discusses how extreme precipitation events are defined and measured. Section 3 describes our data compilation strategy. Section 4 presents the regional synthesis of findings. Section 5 offers a general discussion of overarching patterns and uncertainties. Section 6 concludes with final remarks.

2. Methods and Scope of the Review

This review is based on a systematic compilation of 175 peer-reviewed studies published that examine trends in daily extreme precipitation events across the Mediterranean basin. The literature was identified using standardized keyword searches in major bibliographic databases, including Scopus and the Web of Science. Search terms combined descriptors such as "extreme rainfall," "precipitation," "Mediterranean," "trend," and individual country names. Only studies based on observed daily data were included; analyses based exclusively on sub-daily (e.g., hourly) data, simulations, or projections were excluded to ensure comparability across historical timeframes. The search covered publications from 1980 to 2024, although the earliest study meeting the inclusion criteria was published in 1997.

It should be noted that the bibliographic search was conducted primarily in English-language databases, which may have led to the underrepresentation of studies published in other languages. This potential language bias is a common limitation in global and regional reviews and may partly explain the limited visibility of some national or local studies.

The studies vary widely in their geographic coverage, data periods, and methodological approaches, and the selected thresholds may vary (see next section).

To avoid interpretative bias, no subjective assessment of data quality, methodology, or significance thresholds was undertaken and the review relies on direct quotations from the abstract, main text, or conclusions of each paper—specifically those passages in which the authors report trends in extreme precipitation events. Verbatim quotes from the studies analyzed are provided in the Supplement File Appendix to aid traceability and promote transparency; excerpts were lightly edited for brevity using ellipses (...) and supplemented with clarifications in brackets [...] where needed. In the main text they are summarized in tables and figures to indicate the direction and significance of trends reported in each region, the length period analyzed and the number of observatories used.

While no meta-analysis or standardization was performed, the review organizes findings by sub-region to highlight spatial patterns and variability. The resulting compilation serves as a reference for identifying consistent signals—or lack thereof—across a diverse body of regional and national studies.

3. Defining Extreme Rainfall events

There is no universally accepted definition of an extreme rainfall event, as it depends on the local climate, impacts of interest, and methodological approach. In most climatological studies, extremes are operationalized based on one of the following:

- **Fixed thresholds:** Events exceeding absolute values, such as 10 mm/day or 50 mm/day.
- **Percentile-based indices:** Events above the 90th, 95th, or 99th percentile of the historical daily rainfall distribution (e.g., R95p, R99p).
- **Return-level based metrics:** Statistically modeled recurrence intervals (e.g., RX1day or annual maximum daily precipitation).
- **Impact-based thresholds:** Precipitation levels historically associated with documented societal or environmental impacts.

These approaches are not mutually exclusive and are often combined. For example, several studies calculate the contribution of events

Table 1
Common indices of extreme precipitation and their frequency of use in the reviewed studies.

Index	Name	Definition	Unit	Frequency
R10mm	Heavy precipitation days	Number of days with precipitation ≥ 10 mm	days	38
R20mm	Very heavy precipitation days	Number of days with precipitation ≥ 20 mm	days	37
R25mm / R30mm / ...	Extremely heavy precipitation days	Number of days with precipitation ≥ 25 mm or 30 mm (depending on region/study)	days	27
RX1day	Max 1-day precipitation amount	Annual maximum 1-day precipitation	mm	52
RX5day	Max 5-day precipitation amount	Annual maximum consecutive 5-day precipitation	mm	18
PRCPTOT	Annual total wet-day precipitation	Total precipitation from days with ≥ 1 mm (wet days)	mm	8
43R95p	Very wet days (percentile)	Precipitation from days above the 95th percentile of wet-day distribution	mm	31
R99p	Extremely wet days (percentile)	Precipitation from days above the 99th percentile of wet-day distribution	mm	16
R95pTOT	Contribution from very wet days	Percentage of annual precipitation from days above the 95th percentile	%	8
SDII	Simple daily intensity index	Mean precipitation per wet day (total precipitation / number of wet days)	mm	17
CDD	Consecutive dry days	Maximum number of consecutive days with precipitation < 1 mm	days	0
CWD	Consecutive wet days	Maximum number of consecutive days with precipitation ≥ 1 mm	days	8
DPCI	Daily precipitation concentration index	Concentration of daily precipitation events	%	2
RPx	Return period exceedance	Number of events exceeding a return period threshold (e.g., 10-year, 20-year rainfall)	varies	17

exceeding the 95th percentile to seasonal or annual totals. Others use the frequency of days with rainfall above 20 mm/day (R20) as a proxy for extremes. The specific method chosen influences trend detection and comparability across studies. As example in the Mediterranean region, local thresholds vary widely. For example, [Anagnostopoulou and Tolika \(2012\)](#) note that the 95th percentile exceeds 30 mm/day in parts of the eastern Mediterranean and reaches over 45 mm/day along main cyclone pathways.

In the present review, most studies defined precipitation extremes using standardized indices and percentile-based thresholds (e.g., R95p, R99p), fixed daily rainfall amounts (e.g., R20mm), or maximum accumulation metrics (e.g., RX1day, RX5day). These follow the internationally harmonized definitions established by the Expert Team on Climate Change Detection and Indices (ETCCDI; see [Moberg et al., 2006; de Lima et al., 2015](#)) and are summarized in [Table 1](#), along with their frequency within the reviewed studies. Many of these studies rely on multiple ETCCDI indices simultaneously to capture different facets of rainfall variability and extremes, such as frequency, intensity, and duration.

In addition, several works employed other indices that extend beyond the ETCCDI framework. One example is the Daily Precipitation Concentration Index (DPCI), which quantifies whether rainfall is evenly spread or concentrated in a few intense events ([Martín-Vide, 2004](#)). Other studies adopted indices derived from extreme value analysis (EVA), such as the number of exceedances above return period thresholds (RPx). These EVA-based metrics, sometimes implemented under non-stationary frameworks using moving windows or time-varying parameters, are particularly useful for assessing changes in the frequency of rare, high-impact precipitation events.

4. Regional patterns in Extreme Rainfall Trends

This section synthesizes findings from 175 peer-reviewed studies reporting trends in daily extreme precipitation across the Mediterranean basin, published between 1997 and 2024. To facilitate interpretation, results are presented from global and basin-wide studies to national and sub-national analyses. Each regional section begins with a concise overview of the studies available for that area, including general characteristics such as time periods, spatial coverage, and methods used. This is followed by a summary table highlighting key studies, periods of analysis, geographic focus, and reported trends. To maintain clarity in the main text while ensuring full traceability, an extensive selection of direct quotations from the original sources is provided in the Supplement File in the appendix.

It is important to emphasize that the studies included in this compilation differ substantially in their data sources, period lengths, station density, thresholds, and statistical approaches. As a result, direct comparison between individual studies is not always possible. However, by grouping studies geographically and focusing on reported conclusions, we aim to provide a coherent synthesis of emerging patterns, contradictions, and research gaps across the Mediterranean basin.

To contextualize the evolution and geographic scope of published research on extreme rainfall in the Mediterranean, [Fig. 1](#) shows the number of articles published per year between 1997 and 2024. The volume of publications increased markedly from the early 2000s, peaking around 2019, before showing a slight decline in more recent years. This trend reflects the growing scientific and societal interest in climate extremes, as well as the increasing availability of high-resolution datasets and computational methods.

In general, the studies included in this review span from the second half of the 20th century to the present decade, with most beginning after 1950. A smaller subset of studies extends further back in time, primarily in the western Mediterranean, where longer meteorological records are more readily available, in some cases dating to the late 19th or early 20th century. [Fig. 2](#) illustrates these patterns by showing the starting and ending years of the periods analyzed in each study, effectively capturing

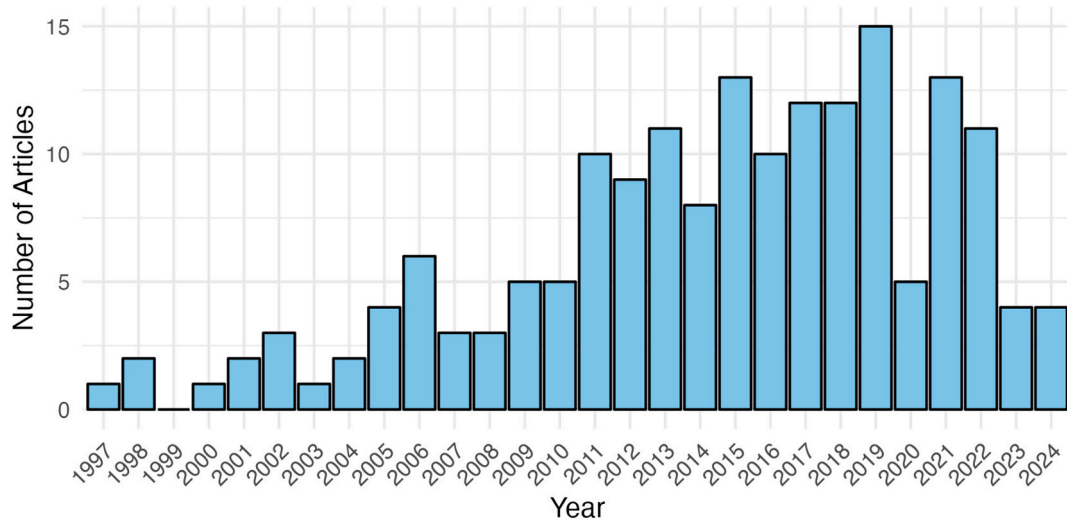


Fig. 1. Number of peer-reviewed articles published annually (1997–2024) addressing extreme precipitation across the Mediterranean basin.

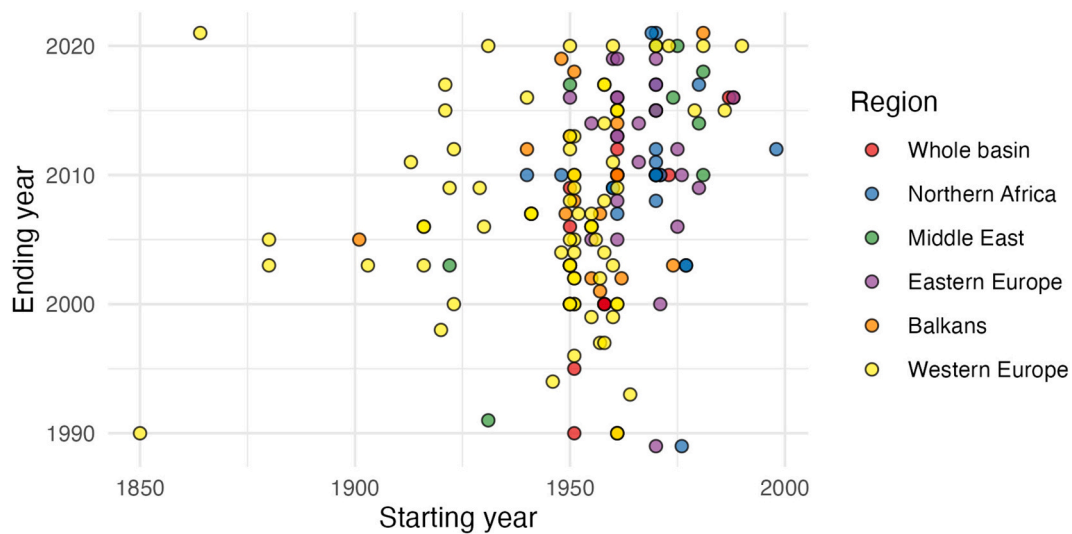


Fig. 2. Starting and ending years of the periods analyzed in the reviewed studies. Each point represents the temporal coverage of one study, with colours indicating the corresponding Mediterranean subregion.

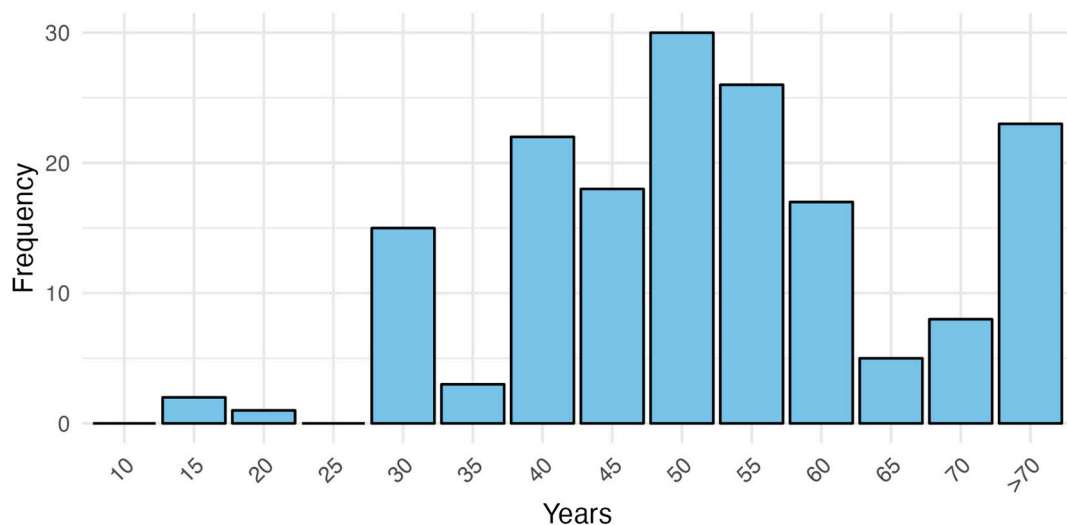


Fig. 3. Histogram of the duration (in years) of the periods analyzed in the reviewed studies on extreme daily precipitation across the Mediterranean.



Fig. 4. Geographic distribution of reviewed studies on extreme daily precipitation across the Mediterranean basin.

Table 2
Number of reviewed studies by geographic coverage.

Region / Country	Number of Studies
Global / Mediterranean-wide	17
Morocco	9
Algeria	10
Tunisia, Libya, Egypt	6
Middle East (Israel, Palestine, Syria, Jordan, Cyprus)	11
Türkiye	13
Bulgaria, Romania, Moldova, Ukraine	11
Greece	4
Albania, Bosnia-Herzegovina, Montenegro	4
Croatia, Slovenia	5
Serbia	5
Italy	34
France	9
Portugal	10
Spain	25

their temporal coverage. Regional differences are clearly visible in the distribution of time spans: studies conducted in western countries, such as Spain, France, and Italy, tend to draw from longer-term datasets, whereas those from North Africa and the Eastern Mediterranean typically begin in the 1970s or later, reflecting more limited historical data availability. Eastern European and Balkan studies often begin in the mid-20th century, occupying an intermediate position in terms of temporal depth. Overall, the figure highlights the temporal heterogeneity of the evidence base and reveals clear disparities in data availability across Mediterranean countries, which have important implications for detecting and comparing trends in extreme precipitation.

Finally, the duration of the analyzed period ranges from 13 to 157 years, with a modal value of 49; the temporal duration analyzed remains consistent over time, between 30 and 60 years. Fig. 3 complements this information by showing the distribution of the duration (in years) of the analyzed periods. Notably, a substantial number of studies cover more than 70 years, again reflecting the presence of long-term records in Western Mediterranean countries. At the other end of the spectrum, a small number of studies fall below the commonly recommended minimum of 30 years for climate trend analysis, which may limit their reliability in detecting robust signals.

The map in Fig. 4 shows the number of studies conducted in each country, based on the primary geographic focus of the analysis. The majority of studies are concentrated in Italy, Spain, and Türkiye, which together account for over 40% of the total sample (Table 2), reflecting the availability of long-term observational data and the existence of active national research communities. In contrast, coverage is more limited in Portugal, France, parts of North Africa, the Levant, and the easternmost sectors of the basin, where restricted data access, institutional fragmentation, and language barriers may hinder scientific output and international visibility. Approximately 10% of the studies are global

Table 3
Summary table: global / mediterranean-wide studies.

Study	Period	Coverage	Trend Summary
Piervitali et al. (1997)	1951–1990	Whole basin, 59 stations	Decrease in “meteorological bombs” (extreme events)
Alpert et al. (2002)	1951–1995	Whole basin, 265 stations	Increase in torrential/heavy events; decrease in moderate/light precipitation
Haylock and Goodes (2004)	1958–2000	Pan-Europe, 347 stations	South shows decreasing trend in R90N (wet days above 90th percentile)
Zhang et al. (2005)	1950–2003	Middle East, 52 stations	Weak, incoherent trends; high interannual variability
Kostopoulou and Jones (2005)	1958–2000	Central/East, 84 stations	Mixed trends: increases in central Med, decreases in eastern 90th and R10mm
Narrant and Douguedroit (2006)	1950–2000	Whole basin, 63 stations	No significant trend in RD >10 mm
Toreti et al. (2010)	1950–2006	Coastal Med, 20 stations	Mostly non-significant changes; some decreasing trends
Cortesi et al. (2012)	1971–2010	Pan-Europe, 530 stations	No significant change in daily precipitation distribution
Karagiannidis et al. (2012)	1958–2000	Pan-Europe, 280 stations	Decreasing trends in most areas; no trend in southern Alps
Tramblay et al. (2013a)	1950–2009	NW Africa, 22 stations	No clear trend; stationarity hypothesis remains valid related to 95th
Donat et al. (2014)	1961–2010	N Africa, 27 stations	Trends in extremes inconsistent and mostly not significant
Marani and Parisi (2014)	1973–2010	Whole basin, 135 stations	Slight increase in moderate events in east; decrease in strong events in west >100 mm/day
Raymond et al. (2016)	1950–2013	Whole basin, grid	No clear trend due to localized nature of extremes
Mathbout et al. (2017)	1961–2012	East Med, 70 stations	Significant decrease in extreme/heavy events
Zittis (2018)	1988–2016	MENA, 5 grids	Weak or inconsistent trends, except R20mm increases in Balkans
Benabdellouahab et al. (2020)	1987–2016	W. Med / Maghreb, 25 stations	Increase in Q95 and Q99 exceedances since late 1990s
Salhi et al. (2022)	1970–2021	NW Africa, 45 stations	Seasonal shifts in precipitation ≥10 mm; spring increase, autumn/winter decrease

or Mediterranean-wide in scope, and are discussed separately in the following section.

Table 4
Summary Table: North Africa. By chronological order in countries.

Study	Period	Coverage	Trend Summary
Tramblay et al. (2012)	1961–2007	Morocco, 10 stations	No significant trends in winter extremes
Khomsi et al. (2015)	1977–2003	Morocco, 2 basins, 8 stations	Positive but weak and non-significant trends
Filahi et al. (2016)	1970–2012	Morocco, 20 stations	No significant trends except some in north and central regions in Q95 and Q99
Khomsi et al. (2016)	1977–2003	North and South Morocco, 19 stations	No significant generalized trends in extreme rainfall
Moujahid et al. (2018)	1970–2015	Northern Morocco, 7 stations	Increase up to 9% in extreme rainfall quantiles
Hadria et al. (2019)	1998–2012	Morocco, 23 stations	Increase in Q99 in northern Morocco, mainly in summer
Ouatiki et al. (2019)	1970–2010	Central Morocco, 15 stations	Positive trend in wet days >50 mm/day
Driouech et al. (2021)	1960–2009	Morocco, 30 stations	Predominantly non-significant trends
Hadri et al. (2021)	1970–2017	Morocco	Non-significant downward trends in >10/20 mm events
Taïbi et al. (2015)	1971–2010	Western High Atlas, 4 stations	Algeria Chélif basin, 13 stations
Ghenim and Megnounif (2016)	1970–2011	Northern Algeria, 35 stations	Negative trend in P90–P99.5, not significant
Taïbi et al. (2017)	1940–2010	Northern Algeria, 95 stations	Annual Maximum Daily Rainfall increased contribution to annual totals in few stations
Taïbi et al. (2019)	1961–1990	Algerian coast, 5 stations	No significant change in extreme event percentiles 95th, 99th
Benzater et al. (2019)	1970–2010	Algeria Macta basin, 41 stations	Decrease in frequency > 50 mm/day in some stations
Benzater et al. (2021)	1970–2010	Algeria, Macta basin, 41 stations	Downward trend in 1970–1992, upward trend 1992–2010
Bessaklia et al. (2021)	1970–2010	Algeria, Macta basin, 41 stations	Migration toward higher categories of extreme rainfall
Boulmaiz and Boutaghane (2022)	1970–2008	Northeast Algeria, 16 stations	Mostly non-significant upward trends in multiple indices
Benzater et al. (2023)	1970–2010	Northeast Algeria, 16 stations	Increase in extreme rainfall in many areas
Hamitouche et al. (2024)	1969–2021	Algeria, 16 stations	Decrease in 1970–1992; significant increase post-1993
Kingumbi et al. (2005)	1976–1989	Tunisia, Merguellig basin, 8 stations	Significant increase in extreme variability in warm Mediterranean zone
Driouech et al. (2013)	1960–2009	Tunisia, 5 stations	Decrease in daily rains >30 mm
Haktanir et al. (2013)	79 & 61 years	Alexandria, Egypt, Antalya, Türkiye	Negative trends in winter and spring
Gado et al. (2019)	From 1909	Egypt, 31 stations	Significant increase in Alexandria; no trend in Antalya
Mostafa et al. (2019)	1980–2017	Northern Egypt, 8 stations	Negative seasonal trends in maximum daily rainfall
Nashwan et al. (2019)	1948–2010	Egypt (0.25° × 0.25° grid)	No significant trend in RX5day
			No change in rainfall and extremes

4.1. Global and regional studies

A total of 17 studies in the reviewed sample provide Mediterranean-wide or pan-European analyses of extreme precipitation trends (Table 3). These studies typically rely on large-scale gridded datasets or

multi-country station compilations, covering time periods from the 1950s to the 2010s. Many adopt standardized indices (e.g., R95p, R99p, RX1day). While a number of studies report increases in extreme precipitation over parts of the Mediterranean—particularly in the west and north—others find spatially inconsistent or non-significant patterns. Overall, the basin is frequently characterized by a high degree of spatial variability and limited agreement across subregions, with several studies explicitly stating the difficulty of identifying a coherent signal.

4.2. North Africa

Nine studies in the review address extreme precipitation trends in Morocco, ten in Algeria, and six collectively in Tunisia, Libya, and Egypt (Table 4). Most datasets begin in the 1960s or 1970s and extend into the early 2010s, with several analyses focusing on individual basins or specific climate zones. Threshold-based indices (e.g., >10 mm, Q95, R20mm) are commonly used, along with annual daily maximum rainfall series. Across the region, extreme rainfall trends are generally weak, statistically non-significant, and spatially heterogeneous. A few localized increases are observed in coastal and northern areas—particularly in Morocco and parts of Algeria—while Tunisia and Egypt mostly exhibit stable or decreasing trends in extreme rainfall indices.

The majority of these studies show no statistically significant trends in extreme rainfall over the past five to six decades. Where trends are detected, they tend to be localized—such as in northern Morocco or the coastal strip of Algeria—and often limited to particular thresholds (e.g., >50 mm/day, Q99) or seasons. In contrast, Tunisia and Egypt exhibit predominantly neutral to negative trends, especially during winter and spring. Most datasets span from the 1960s to the early 2010s, and the general conclusion is that extreme precipitation patterns in this region remain stable, with any emerging changes being recent, weak, and often non-significant.

A common theme across studies is the lack of trend robustness, which may be related to short time series, low station density, or strong interannual variability. Nevertheless, several authors note the growing

Table 5
Summary table: Eastern Mediterranean (Levant and Cyprus).

Study	Period	Coverage	Trend Summary
Ben-Gai et al. (1998)	1931–1991	Israel, 60 stations	Changes in gamma distribution tail; implications for increased extreme frequency
Smadi and Zghouç (2006)	1922–2003	Jordan, 3 stations	Increasing intensity, especially in March; fewer rain days
Freiwan and Kadioğlu (2008)	1950–2000	Jordan, 14 stations	Higher probability of short-term heavy showers in south/east
Zaifoğlu et al. (2017)	1970–2015	Cyprus, 36 stations	Mostly increasing trends, but not statistically significant
Katsanos et al. (2017)	1981–2010	Cyprus, 150 stations	Increase in daily max; decrease in R10 and R20 thresholds
Al Qatarneh et al. (2018)	1980–2014	Jordan, 8 stations	Insignificant trends across all precipitation indices
Yosef et al. (2019)	1950–2017	Israel, 60 stations	Decrease in R10mm; most trends not statistically significant
Ajjur and Riffi (2016)	1974–2016	Gaza, 8 stations	Non-significant increase in R10 and R20; rising contribution to annual totals
Drori et al. (2021)	1975–2020	Israel, 51 stations	Increase in average daily rainfall intensity in 8 of 9 regions
Salameh et al. (2022)	1970–2020	Israel and Palestine, 66 stations	Substantial decreasing trends in R10, R20, especially in spring/autumn
Lazoglou et al. (2024)	1981–2018	Cyprus (gridded 1 × 1 km)	Observed trends in extremes not significant

influence of high-magnitude events in annual rainfall budgets suggesting that, even in the absence of clear frequency trends, the relative importance of extremes may be increasing in some locations.

4.3. Eastern Mediterranean (Levant and Cyprus)

Eleven studies cover the Eastern Mediterranean region, focusing on Israel, the Palestinian territories, Jordan, and Cyprus (Table 5). The periods analyzed range from the 1930s to the 2020s, with some of the longest time series in the entire Mediterranean compilation. Most studies employ percentile-based indices (R10mm, R20mm, R95p), while others analyze daily annual maximum precipitation or simple rain day thresholds. Overall, trends are inconsistent and rarely statistically significant, though some studies suggest localized increases in precipitation intensity or in the contribution of heavy events to annual totals. Notably, Israel and the West Bank show both increases in intensity and decreases in frequency, depending on season and station. For Syria and Lebanon, no long-term studies could be identified.

Studies in the Eastern Mediterranean point to a high degree of spatial and seasonal variability in extreme rainfall trends. While some long-term records (e.g., Israel, Jordan) show increases in intensity or changes in the distribution tails of precipitation events, most trends in frequency-based indices (e.g., R10mm, R20mm) are not statistically significant. Seasonal differences are often noted -such as decreases in spring/autumn in Israel or intensification in March in Jordan- but these are not consistently replicated across studies. In Cyprus, while some increases in daily maxima are observed, they are generally not significant.

Overall, this region appears to be undergoing subtle shifts in the character of precipitation (e.g., intensity, contribution to annual totals) rather than in the frequency of extreme events. The results also reinforce the localized nature of extremes and the challenges in drawing generalizations without high-density, high-resolution observations.

4.4. Eastern Mediterranean (Europe)

Twenty-seven papers were compiled from Eastern Mediterranean Europe predominately from Türkiye (16), both at national (6 cases) or subregional scale (10 papers), followed by Romania (6 papers); same supranational analyses give a comprehensive spatial picture in the area (Table 6). Spatial density varies from few stations to hundred, and usually period start around middle of the 20th century.

Across Türkiye and Eastern European countries, studies consistently show strong spatial contrasts in extreme rainfall trends. In Türkiye, the coastal regions (e.g., Black Sea, southern Mediterranean) exhibit weak to moderate increases, while interior zones show declining or stable trends. These patterns are not always statistically significant, and the results vary by season.

In Romania and Bulgaria, some stations—particularly in intra-Carpathian and mountainous areas—show increased contributions from heavy rainfall events, even as total rainfall or light rain days may be declining. However, most trends are not significant, and multi-decadal variability and diverse topography complicate the attribution of observed changes. In Moldova and Ukraine, data is sparse, but trends suggest a similar intensification pattern in select areas.

Overall, while no unified regional signal emerges, localized increases in intensity and disproportionate contributions of heavy rainfall to annual totals are frequently reported, especially in high-relief areas.

4.5. Balkans

The Balkans are represented by 19 studies in the review, with data primarily from Greece, Serbia, Montenegro, Croatia, and Slovenia (Table 7). The period of analysis generally spans from the 1950s to the 2010s, with a few longer series extending back to the early 20th century. Most studies use percentile-based indices (R95p, R99p), fixed daily

Table 6
Summary Table: Eastern Mediterranean (Europe). By chronological order in countries.

Study	Period	Coverage	Trend Summary
Cukur (2011)	1975–2006	Türkiye inland and southern areas, 40 stations	Precipitation more than 100 mm have increased
Acar and Senocak (2012)	1955–2005	Türkiye, 7 stations	General upward trend in annual extremes
Yilmaz (2015)	1970–1989	Türkiye Antalya, southern coast, 7 stations	Significant increasing trends for at least one extreme rainfall index Increase in heavy precipitation events, although mostly not significant
Abbasnia and Toros (2018)	1961–2016	Türkiye Marmara region, 7 stations	No clear pattern in the trend
Duzenli et al. (2018)	1955–2014	Türkiye Black Sea region, Turkey, 65 stations	Significant increase in the number of heavy precipitation days in the last 30 years
Balov and Altunkaynak (2019)	1971–2000	Türkiye Coastland of Black Sea, 9 stations	Spatial and temporal variability of extreme precipitation indices
Tongal (2019)	1970–2017	Türkiye Antalya basin (south coast), 7 stations	General decreasing trends in all extreme indices
Abbasnia and Toros (2020)	1976–2010	Türkiye, 71 stations	Coastal and NE Black Sea regions prone to more extremes
Sarış (2020)	1975–2012	Türkiye, 98 stations	Positive trend is found in the R10mm, R20mm and + R30mm indices
Oruc and Yalcin (2021)	1950–2016	Türkiye Thrace region, 4 stations	No statistically significant trend
Ay (2021)	1960–2019	Türkiye Aegean region, 8 stations	Decreasing trends inland; increasing in coastal areas for shorter durations
Albayrak et al. (2022)	1970–2015	Türkiye, 63 stations	Mostly decreasing trends >10 mm/day; some significant increases in SE
Acar and Gönençgil (2022)	1966–2014	Türkiye, 166 stations	No significant trends overall; increase in heavy events post-1990 in some regions
Bocheva et al. (2009)	1961–2005	Bulgaria, 26 stations	Only 3 Romanian stations show significant trends
Villarini (2012)	up to 2012	Bulgaria, Romania, Ukraine 44 stations	Positive trend not significant in extreme event
Croitoru et al. (2013)	1961–2008	Bulgaria, Romania, 13 stations	Increase daily 50 mm and 100 mm events
Stefanescu et al. (2014)	1980–2009	Romania 230 stations	Mixed signals; most stations show no significant trends
Dumitrescu et al. (2015)	1961–2013	Romania, 150 stations	Signal not clear
Busuioc et al. (2015)	1961–2010	Romania, 98 stations	Increase R5, R10 in isolated areas
Croitoru et al. (2016)	1961–2013	Romania, 34 stations	No significant change in maximum daily amounts
Busuioc et al. (2016)	1961–2010	Romania, 81 stations	Increase R30
Machidon (2017)	1961–2016	Romania, Moldova, 8 stations	Convective precipitation ≥60 mm/day increased in many areas
Marinova et al. (2017)	1988–2016	Bulgaria, 115 stations	No clear pattern; increases in convective areas, low significance
Micu et al. (2021)	1961–2019	Romanian Carpathians, 13 stations	

Table 7
Summary Table: Balkans. By chronological order in countries.

Study	Period	Coverage	Trend Summary
Nastos and Zerefos (2008)	1957–2001	Greece, 21 stations	Positive but non-significant trends >30 mm and > 50 mm/day Increased variability;
Kioutsoukis et al. (2010)	1955–2002	Greece, 40 stations	R95p and R99p show mixed, mostly negative trends Significant positive trends in Athens; negative trends elsewhere
Kambezidis et al. (2010)	1962–2002	Greece, 32 stations	No clear regional pattern; western Greece has highest observed maxima
Markonis et al. (2017)	1940–2012	Greece, 136 stations	Decrease R95, not significant Decreasing number of rain days; slight increases in heavy events in NE
Ducić et al. (2012)	1957–2007	Montenegro, 2 stations	Increase >50 mm, but not statistically significant
Burić et al. (2015)	1951–2010	Montenegro, 23 stations	Increase R40 and R50
Doderović et al. (2020)	1951–2008	N Montenegro, Kolašin	No changes in R95%
Burić and Doderović (2021)	1951–2018	Montenegro, 1 Stations	No Changes in R95, R95T
Gajić-Čapka and Cindrić (2011)	1901–2005	Croatia whole country, 5 stations.	Mostly weak trends; some regional increases in extremes
Patarčić et al. (2014)	1961–1990	Croatian Adriatic region, 19 stations	More frequent >32 mm/day events; not statistically significant
Gajić-Čapka et al. (2015)	1961–2010	Croatia, 132 stations	Increase occurrence of extreme
Bonacci et al. (2021)	1948–2019	Croatia, 4 stations	Increases in R20 and R95T at end of 20th century
Vrsalović et al. (2023)	1981–2021	Imotski area, Croatia, 2 stations	Observed clear signal Rx1day
Unkašević and Tosić (2011)	1949–2007	Serbia, 10 stations	Not significant changes in consecutive wet days
Milanović et al. (2015)	1974–2003	Nis and Belgrado stations, Serbia, 2 stations.	Positive but non-significant trends in R10mm and R20mm
Malinovic-Milicevic et al. (2016)	1961–2010	Serbia, 10 stations	Increase in maximum daily precipitation
Tosić et al. (2017)	1961–2014	Serbia, 16 stations	
Andelković et al. (2018)	1961–2015	Serbia, 28 stations	

thresholds (e.g., >30 mm), or annual maxima. Across the region, the prevailing result is a lack of statistically significant trends in extreme precipitation frequency. Nonetheless, some areas show increasing intensity (especially in Serbia and parts of Croatia), or a growing share of annual precipitation falling in extreme events, even if frequency does not increase

Across the Balkans, no coherent regional trend in extreme rainfall emerges from the literature. The most common result is a lack of statistically significant changes, particularly in frequency-based indices like R10mm, R20mm, and R95p. However, there are repeated indications of increasing event intensity in select areas, especially in Serbia and Croatia, where daily maxima and the frequency of high-magnitude events have shown upward tendencies since the late 20th century. Montenegro exhibits a potential shift in the spatial distribution of heavy events (more in NE than SW), although most results remain non-significant. On the contrary Greece stands out for its high variability and lack of agreement between stations, with some positive trends in

urban areas like Athens but declines elsewhere.

The data suggest that while frequency trends are unclear, there may be a growing dependence of annual totals on high magnitude events, a finding echoed in other Mediterranean regions. More spatially consistent monitoring and longer records would help clarify these emerging signals.

4.6. Western Mediterranean Europe

The Western Mediterranean is the best-studied part of the basin, with over 75 studies—34 from Italy, 25 from Spain, 10 from Portugal, and 9 from France. These studies feature some of the longest and densest datasets available, with several exceeding 100 years of observations and station networks of >1000 series. Most analyses rely on both absolute thresholds (e.g., >30 mm, >100 mm/day) and percentile-based indices (R95p, RX1day). Due to the large number of studies, we will describe the main results country-wise.

4.6.1. Italy

Italy offers one of the richest and most spatially and temporally extensive datasets on extreme precipitation in the Mediterranean basin (Table 8). Several studies, particularly those by Brunetti and colleagues, include data series dating back to the late 19th century and demonstrate consistent trends across decades and regions. A widespread decline in the number of wet days has been observed across the country, especially since the 1970s. However, this reduction in frequency is often accompanied by a rise in precipitation intensity, with notable increases in the 90th percentile, annual maxima, and daily totals exceeding 25–50 mm, particularly in northern and central Italy.

In the Po Valley and Alpine regions, evidence for an intensification of extreme rainfall events is strong and supported by both long-term and high-density station data. The 1930–1945 and 1975–1995 periods stand out as decades of increasing extremes in these areas. In central regions like Tuscany, Umbria, and the Marche, results are more heterogeneous: some stations show increases in spring and autumn extremes, while others reveal declines or no trends, especially in longer time series.

By contrast, studies in southern Italy, including Calabria, Basilicata, and Apulia, generally report stable or declining trends in the frequency and magnitude of extreme events. A similar pattern holds for Sardinia and parts of Sicily, although localized increases in storm intensity have been observed in western Sicily. Interestingly, some of the southern regions also report increases in less intense rainfall categories, suggesting a redistribution rather than a true intensification of extremes.

Overall, Italy shows a divergent spatial pattern: the north and central areas are experiencing a rise in the severity of extreme precipitation events, even as the number of rain days' declines, while southern regions are characterized by mixed or negative trends. The country's exceptional station density and long time series make its evidence base among the most robust in the Mediterranean.

4.6.2. France

Studies on extreme precipitation in France focus primarily on the southern and Mediterranean regions, particularly Languedoc-Roussillon, the southern Alps, and the Provence–Alpes–Côte d'Azur region (Table 9). Although fewer in number than those for neighboring Italy or Spain, the reviewed studies are rich in spatial detail and increasingly benefit from high-resolution station and gridded datasets.

The earliest studies (e.g., Pujol et al., 2007) detect seasonal shifts in monthly maxima, such as decreases in March and increases in April, which may reflect intra-seasonal redistribution rather than true intensification. More recent work, especially since 2015, identifies clear upward trends in the magnitude and frequency of high-threshold events, particularly post-1980 and with greater confidence after the year 2000. For example, Ribes et al. (2019) and Blanchet et al. (2021); Blanchet and Creutin (2022) indicate that 200 mm/day events have become significantly more frequent, while return periods for intense rainfall have

Table 8
Summary table: Italy.

Study	Period	Coverage	Trend Summary
Brunetti et al. (2001a)	1951–1996	Whole Italy, 67 stations	Significant decrease in wet days; increase in intensity, especially in the north
Brunetti et al. (2004a)	1880–2003	Regional series, 45 stations	Fewer wet days across Italy; northern regions show intensity increases
Colombo et al. (2007)	1961–2000	Whole Italy, 50 stations	No trend in events >30 mm/day
Iannuccilli et al. (2021)	1979–2015	Whole Italy, 46 stations	Significant increases in 90th percentile events in winter/spring
Northern Italy			
Brunetti et al. (2000)	1850–1990s	Po Plain, 5 stations	Positive trend in precipitation >25 mm and > 50 mm/day
Brunetti et al. (2001b)	1920–1998	NE Italy, 7 stations	Increase in decile 10 events; decrease in moderate events
Pavan et al. (2008)	1951–2004	Emilia-Romagna	Decrease in rain days; summer increase in mountain extremes
Todeschini (2011)	1880–2005	Lombardy, 6 stations	Significant increase in daily precipitation maxima
Acquaotta and Fratianni (2013)	1913–2011	Piedmont, 13 stations	No clear trends in heavy precipitation or wet period duration
Parisi et al. (2014)	1951–2005	Lombardy, 30 stations	No significant trend in extreme event frequency
Saidi and Ciampittiello (2015)	From 1927	Piedmont, 4 stations	No uniform trend; increase in short-duration extremes at some sites
Brugnara and Maugeri (2019)	1922–2009	Trentino-South Tyrol, 200 series	Increase in annual maxima in west; decrease in spring extremes in east
Pavan et al. (2019)	1961–2015	North-Central Italy, 1762 stations	Decline in wet days; increase in 90th percentile precipitation
Central Italy			
Crisci et al. (2002)	1946–1994	Tuscany, 81 stations	No significant trend overall; extremes increased post-1970 at some sites
Testa et al. (2006)	1951–2000	Lazio, 31 stations	No significant trends in rainfall class frequencies
Faticchi and Caporali (2009)	1916–2003	Central Tuscany, 60 stations	Decrease in wet days, including >10 mm events
Romano and Preziosi (2013)	1952–2007	Tiber River Basin, 102 stations	Annual/winter totals decreased; no clear trend in intensity indices
Bartolini et al. (2014)	1955–2007	Tuscany, 21 stations	Decrease in annual extremes in NW areas
Cifrodelli et al. (2015)	1923–2012	Umbria, 3 stations	No substantial change in rainfall maxima or intensity
Pieri et al. (2017)	1986–2015	Italian Apennines, 308 stations	Increase in extremes >20 mm/year, especially in spring and autumn
Soldini and Darvini (2017)	1951–2013	Marche, 54 stations	Most maxima stable; R20mm and R95pTOT declining
Morbidelli et al. (2018)	1921–2015	Umbria, 10 stations	North shows positive trends; south negative
Gentilucci et al. (2019)	1921–2017	Marche, 128 series	Significant increase in extreme events in southern part of region
Southern-Island Italy			
Brunetti et al. (2012)	1916–2006	Southern Italy, 129 stations	Daily intensity declining in upper categories

Table 8 (continued)

Study	Period	Coverage	Trend Summary
Arnone et al. (2013)	1956–2005	Sicily, 57 stations	Increase in short-duration extremes; weaker trends at longer durations
Piccarreta et al. (2013)	1951–2010	Basilicata, 55 stations	Summer decrease in daily extremes; multi-day sequences increasing
Liuzzo et al. (2015)	1950–2008	Sicily, 65 stations	Mixed trends; both positive and negative
Bonaccorso and Aronica (2016)	1929–2009	Sicily, 204 stations	Increased storm intensity in western Sicily; localized in others
Caloiero et al. (2017)	1916–2006	Calabria, 129 stations	Decline in >30 mm/day events; increase in weaker rainfall
Boi (2018)	1951–2000	Sardinia, 13 stations	No significant changes, except slight March increase
Roseto et al. (2023)	1931–2020	Apulia, 90 stations	Daily extremes declining; slight hourly increase
Prete et al. (2023)	1990–2020	Calabria, 38 stations	Increase in daily extremes; up to 500 mm/day predicted for return period
Avino et al. (2024)	1970–2020	Southern Italy, 907 stations	Mostly non-significant trends; increases in short-duration extremes
Caporali et al. (2020)	–	Southern Italy (review of 54 studies)	Contrasting findings; generalization not possible

Table 9
Summary table: France.

Study	Period	Coverage	Trend Summary
Pujol et al. (2007)	1948–2004	Languedoc-Roussillon, 92 stations	Monthly maxima decreased in March, increased in April (possible seasonal shift)
Cantet et al. (2011)	1960–2003	France, 139 stations	Rainfall occurrence increased except in Mediterranean area
Tramblay et al. (2013b)	1958–2008	Southern France, 44 stations	Slight increase in most extreme events post-1980; not statistically significant
Soubeyroux et al. (2015)	1950–2005	France, 900 series	Most series show upward but non-significant trends in extremes
Blanchet et al. (2018)	1958–2014	Southern France, SAFRAN grid	Local increases; weak or negative trends west of Montpellier and Massif Central
Ribes et al. (2019)	1961–2015	Southern France, 96 stations	Significant increase in intensity and frequency of high-threshold events
Blanchet et al. (2021)	1958–2017	Southwestern Alps	Significant increase in 20-year return levels in autumn
Nouaceur et al. (2022)	1973–2020	Southern France, 9 stations	More frequent rainfall events >100 mm in 24–48 h intervals
Blanchet and Creutin (2022)	1960–2020	French Mediterranean, 1180 stations	20-year events now occur every 8 years; clear shift in return periods

shortened: in many locations, what was once a 20-year event now occurs every 8 years. The autumn season is especially prone to this intensification, consistent with warming sea surface temperatures and favorable atmospheric dynamics.

Despite this general increase, not all locations show the same pattern. Some parts of southern France, such as the area west of Montpellier and certain mountainous zones in the Massif Central, show weak or even declining trends in extremes. These local discrepancies highlight the influence of topography, mesoscale convection, and station

Table 10
Summary table: Spain.

Study	Period	Coverage	Trend Summary
Goodess and Jones (2002)	1957–1997	Whole Spain, 18 stations	Fewer, more intense rain days along SE coast; lighter rain increasing inland
Gallego et al. (2006)	1958–1997	Iberian Peninsula, 35 stations	Decrease in intense events; increase in light rainfall
Rodrigo (2010)	1951–2002	Iberian Peninsula, 22 stations	Negative trend in probability of rainfall >95th percentile
Acero et al. (2011)	1958–2004	Iberian Peninsula, 52 stations	High spatial variability; positive trend in 20-year return levels in autumn SE
García et al. (2007)	1958–2017	Spain, 35 stations	Decreasing seasonal extreme precipitation
Gallego et al. (2011)	1903–2003	Spain, 27 stations	Increase in light rainfall, decrease in heavy events except Mediterranean coast
Fernandez-Montes et al. (2012)	1950–2003	Whole Spain, 44 stations	Few trends; winter extremes increased in east, decreased in west
Fernandez-Montes et al. (2014)	1950–2003	Whole Spain, 44 stations	Spring extremes declined in west/south; autumn extremes increased in NW
Merino et al. (2016)	1960–2011	Spain, 45 stations	Slightly significant trends in RX1day, R95p; no consistent pattern
Serrano-Notivoli et al. (2018)	1950–2012	Spain, 12,858 stations	Low and moderate events increased inland; extremes increased along SE coast
Miró et al. (2022)	1950–2020	Spain, unspecified stations	ESE components showed significant increases >150 mm/day
Senent-Aparicio et al. (2023)	1951–2009	Peninsular Spain, 3236 grid points	Rain days decreased; intensity slightly increased
Regional studies			
Romero et al. (1998)	1964–1993	Mediterranean coast, 410 stations	Increase in coastal extremes (>100 mm/day); inland decrease in wet days
González-Hidalgo et al. (2003)	1961–1990	Valencia region, 96 stations	Increase in annual contribution of higher events despite negative trend
Burgueño et al. (2005)	1950–2000	NE Spain, 75 stations	Large rainfall shares from few daily episodes; unclear trends
Ramos and Martínez-Casasnovas (2006)	1923–2000	NE Spain, 5 stations	Significant increase in daily and 5-day maxima; not uniform seasonally
Lopez-Moreno et al. (2010)	1955–2006	NE Spain, 217 stations	Decrease or no trend in moderate/heavy events
Beguería et al. (2011)	1930–2006	NE Spain, 64 stations	No generalized trend in extreme precipitation
Hidalgo-Muñoz et al. (2011)	1955–2006	Andalusia, 86 stations	Winter decrease in western/central Andalusia; positive trend SE
Valencia et al. (2012)	1957–2002	Ebro Basin, 14 stations	Negative trends in all indices; few statistically significant
Valdes-Abellan et al. (2017)	1940–2016	SE Spain, 5 stations	Rainy days decreased, especially for higher daily values
Vicente et al. (2017)	1950–2013	Segre Basin, 8 stations	General reduction in extreme event occurrence
Miró et al. (2018)	1955–2006	Júcar and Segura basins, 890 stations	Increase in coastal extremes; decline in moderate events inland

Table 10 (continued)

Study	Period	Coverage	Trend Summary
García et al. (2018)	1961–2009	Extremadura, SW Spain	Decrease in winter/spring extremes; slight autumn increase
Sánchez-Almodóvar (2022)	1981–2020	SE Spain, 26 stations	No statistically significant trend in >100 mm/day events

distribution on trend detection.

In summary, in the southern Mediterranean region of France recent high-resolution studies provide compelling evidence for increasing frequency and magnitude of extreme daily precipitation, especially in autumn and during exceptional convective events, while spatial variability persists.

4.6.3. Spain

Spain presents a highly heterogeneous picture of extreme precipitation trends, shaped by sharp climatic gradients, complex topography, and strong seasonal variability (Table 10). The reviewed studies cover both national-scale datasets, some spanning more than a century and dense regional networks, especially in eastern and northeastern Spain, where torrential events are of particular concern.

At the national level, the most robust finding is a decline in moderate to heavy rainfall events across much of the interior and western Iberian Peninsula, coupled with an increase in lighter rain and the number of dry days. This trend is reported consistently in studies such as Gallego et al. (2006, 2011), Rodrigo (2010), and Serrano-Notivoli et al. (2018), with some suggesting that annual precipitation is increasingly reliant on a smaller number of intense events.

In contrast, the eastern and southeastern coastal regions (e.g., Valencia, Murcia, eastern Andalusia, Catalonia) show localized increases in extreme precipitation, particularly for high daily thresholds (e.g., >100 mm/day). These findings are supported by both gridded analyses (e.g., Senent-Aparicio et al., 2023; Miró et al., 2022) and dense

Table 11
Summary table: Portugal.

Study	Period	Coverage	Trend Summary
Rodrigo and Trigo (2007)	1951–2002	Iberian Peninsula, 22 stations	Daily intensity decreased; extreme events mostly stable, few significant trends
Costa and Soares (2009)	1955–1999	Southern Portugal, 106 stations	No significant trends; short-term intensity increased in late 20th century
Durão et al. (2009)	1960–1999	Southern Portugal, 105 stations	No significant trend in R30 (extremely heavy precipitation)
Durão et al. (2010)	1961–2000	Southern Portugal, 105 stations	Spatial continuity of extremes increased; more homogeneous extremes
de Lima et al. (2013)	1941–2007	Mainland Portugal, 23 stations	Decrease in total wet-day and extreme precipitation; R20 increased in autumn
Santos and Fragoso (2013)	1950–2000	Northern Portugal, 39 stations	Decrease in extremes in most seasons; slight autumn increase
Espírito Santo et al. (2014)	1941–2007	Mainland Portugal, 57 stations	Decline in R10/R20 in spring/summer; autumn/winter trends mostly not significant
De Lima et al. (2015)	1941–2007	Mainland Portugal, 57 stations	>65% of stations show decreasing R10, R20, R25; mostly non-significant
Santos et al. (2019)	1950–2003	Mainland Portugal, 0.2° grid from PT02	Decrease in spring extremes in central Portugal; slight autumn increase in north
Espinosa et al. (2022)	1864–2021	Lisbon, Geofísico station	Annual maxima more frequent and intense in recent decades

observational studies (e.g., Romero et al., 1998; Miró et al., 2018), which attribute the rise in intensity to coastal convective events, often tied to sea-land interactions and cut-off lows.

In northeastern Spain, long-term studies (e.g., Beguería et al., 2011; Vicente et al., 2017) find no clear or consistent trends, although some note a decrease in the number of days with intense rainfall, even as their share of annual totals increases. Similar patterns are observed in southern inland Spain (e.g., Extremadura and parts of Andalusia), where intensity has remained stable or declined.

In summary, compilation of researches shows a spatial dipole: while much of the country, particularly inland and western areas, has seen stable or declining trends, in the Mediterranean coastal zones an increasing frequency and/or severity of extremes has been reported, particularly in the last two to three decades. Nevertheless, recent analyses (e.g., González-Hidalgo et al., 2025) using long-term, high-density national networks conclude that there is no temporal trend in the frequency of extraordinary events (e.g., >100 mm/day or > 200 mm/day) across mainland Spain over the last century. Also, Beguería et al. (2025) indicated in a daily dataset of 341 stations (period 1951–2020) that “more stations displaying significant decreases than increases in extreme precipitation event attributes”.

4.6.4. Portugal

Portugal presents a relatively consistent picture of stable or declining trends in extreme daily precipitation over the past 60–80 years (Table 11). Most studies cover the mid-20th century to early 2000s, and rely on dense station networks in southern and central regions, with a few extending to the north or focusing on long-term records (e.g., Lisbon).

A large proportion of studies (e.g., De Lima et al., 2015; Espírito Santo et al., 2014; Santos and Fragoso, 2013) report declines in the frequency of heavy precipitation days, using indices such as R10mm, R20mm, and R25mm. These decreasing trends are generally not statistically significant at most stations, but the signal is coherent across the country. In particular, spring and summer show the clearest signs of decline, while autumn and winter trends are more variable.

At the same time, some studies note a slight increase in precipitation intensity or spatial coherence of extremes—particularly in the southern regions—during the late 20th century. For instance, Durão et al. (2010) report increasing spatial homogeneity of R30 events in southern Portugal, suggesting broader-scale control of extreme event dynamics, possibly linked to atmospheric circulation changes.

One long-term series from Lisbon (Espinosa et al., 2022) reveals an increase in the frequency and intensity of annual maxima in recent decades, potentially pointing to an emerging signal not yet detectable in shorter or regionally averaged series.

Overall, Portugal stands out as a region where no consistent intensification of daily extreme precipitation has been detected. Most trends in frequency and magnitude are flat or negative, especially when analyzed over the full observational period. Nonetheless, some regional and recent shifts—particularly in southern and urban areas—warrant closer monitoring in light of possible nonlinear responses to climate forcing.

* * * * *

Summarizing, published research shows signals of intensifying extreme rainfall in Western Mediterranean basin, though these signals are geographically concentrated. In northern and central Italy, southern France, and the eastern Spanish Mediterranean coast, studies consistently report increases in extreme magnitudes (e.g., RX1day, R100mm), particularly since the 1980s. These changes often coincide with decreases in the number of rainy days, suggesting a shift toward fewer but more intense events.

In contrast, southern Italy, inland Spain, and much of Portugal exhibit no significant trends or even declines in frequency-based indices lower in magnitude like R10mm or R20mm. Yet, even in these regions, some studies note an increased share of annual precipitation falling in

extremes, which may reflect changing precipitation distribution rather than absolute increases in extremes. These contrasting results illustrate the difficulty of comparing trends that refer to such diverse magnitudes.

Overall, our compilation indicates that this region provides observational evidence for increasing rainfall extremes in the last decades in specific subregions of the Mediterranean, particularly coastal zones exposed to warm sea-surface temperatures and favorable synoptic conditions.

5. Critical synthesis and discussion

5.1. Mediterranean-wide synthesis

The question of whether extreme precipitation is increasing globally has been the subject of active debate since the 1990s. From seminal papers such those by Katz and Brown (1992) and Groisman and Legates (1995) a widespread increase in the frequency of very heavy precipitation across the mid-latitudes has been stressed. This can be summarized by Groisman et al. (2005) stating that “in the mid-latitudes, a widespread increase in the frequency of very heavy precipitation during the past 50 to 100 years [occurred]”. Subsequent studies followed the same premise: Moberg and Jones (2005) highlighted a significant increase in both the intensity and frequency of “moderately strong” rainfall events; Zolina et al. (2005) observed significant trends in Europe, noting “... positive centennial-scale changes in heavy and very heavy precipitation (...) [were detected] in Eastern Europe”; similar results were reported by Min et al. (2009), who analyzed annual maximum daily precipitation. Meanwhile, Alexander et al. (2006) stated: “Trends computed on the grids show little significance”, and years later added: “...a number of studies have shown differences between precipitation datasets, including their representation of extremes (...)” (Alexander, 2016). This narrative has become increasingly entrenched in the most recent contribution, with studies such as:

Westra et al. (2013) stating: “Statistically significant increasing trends can be detected on a global scale, with nearly two-thirds of stations showing increases” [although only 7% were statistically significant].

Donat et al. (2016): “Despite uncertainties in total precipitation changes, extreme daily precipitation averaged over both dry and wet regimes shows robust increases in (...) observations (...) over the past six decades”.

Sippel et al. (2017). Commenting the paper of Donat et al. (2016): “We find that (a) statistical artefacts introduced by data pre-processing based on a time-invariant reference period lead to an overestimation of the reported trends by up to 40%, and that (b) the reported trends of globally aggregated extremes and annual totals are highly sensitive to the definition of a dry region of the globe”.

Papalexioiu and Montanari (2019) reporting “increasing trends... detected in large parts of Eurasia, including parts of the northern Mediterranean basin,” but cautioning that “changes in magnitude are not in general correlated with changes in frequency”.

Myhre et al. (2019): “The intensity of the heaviest extreme precipitation events is known to increase with global warming. How often such events occur in a warmer world is however less well established, and the combined effect of changes in frequency and intensity on the total amount of rain falling as extreme precipitation is much less explored, in spite of potentially large societal impacts”.

Sun et al. (2021) concluding that “Extreme precipitation over land has intensified on average... although the spatial distribution of stations with significant trends is largely random”.

While most of these such studies support a broad global trend, this review reveals that the signal breaks down at regional and sub-regional scales, particularly in the Mediterranean basin.

Across the 175 reviewed studies, no statistically robust or spatially consistent trend in extreme precipitation emerges for the Mediterranean basin as a whole, with roughly one-third of the analyses ($n = 57$) reporting increases, another third indicating no significant change ($n = 43$) or mixed ($n = 43$) results, and a smaller fraction showing decreases

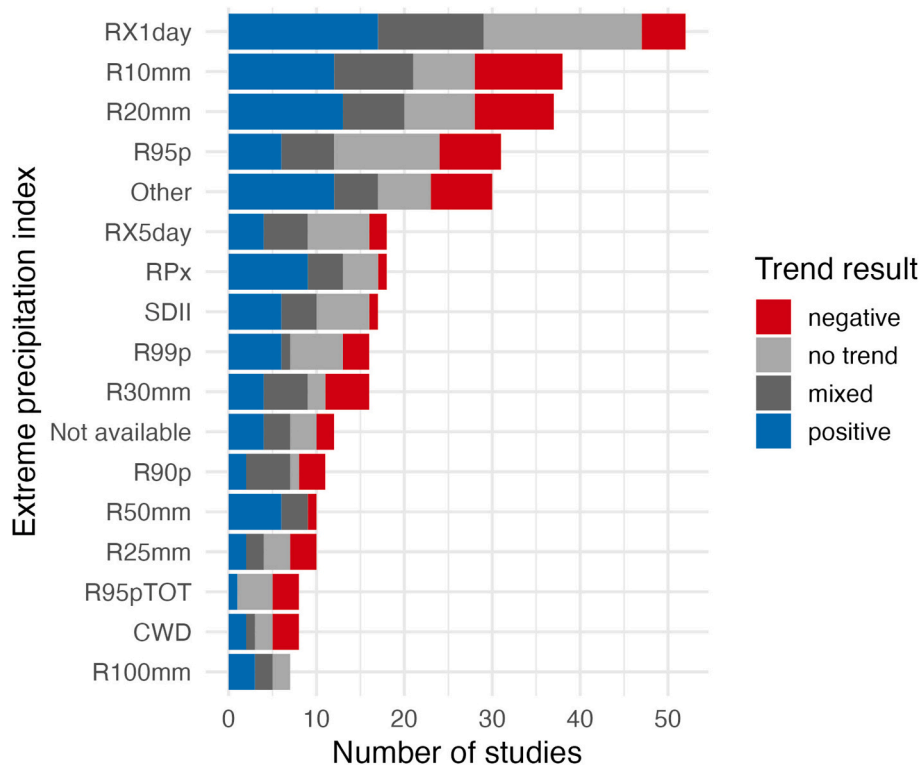


Fig. 5. Frequency of reported trends in extreme precipitation across the Mediterranean region, classified by index type.

($n = 32$).

Spatial heterogeneity dominates. In the western basin, including northern Italy, southern France, and parts of eastern Spain and Morocco, it is suggested increasing trends in daily maxima and high-threshold events (>100 mm/day), especially since the 1980s. In contrast, eastern Mediterranean, some inland areas of northwest Africa (Morocco), and interior Iberia often exhibit weak, negative, or non-significant trends, nevertheless in eastern was indicated positive trend of these extreme events years ago (Marani and Parisi, 2014).

Temporal variability is also high. Where positive trends exist, they often appear only in specific seasons (autumn) or recent decades, and may be limited to coastal or mountainous zones. A recurring finding is that the number of wet days is decreasing, while the contribution of extreme events to total precipitation is increasing, suggesting a redistribution rather than a basin-wide intensification.

5.2. Methodological and data challenges

This review underscores a critical challenge in understanding Mediterranean extremes: heterogeneity in data, definitions, and methods. While some studies use fixed thresholds (e.g., R20mm), others rely on percentiles (e.g., R95p, R99p), return periods (e.g., RPx), or other indicators. These methodological choices influence trend detectability and limit comparability across studies. Fig. 5 shows that the overall distribution of positive, negative, and non-significant trends does not appear to depend systematically on the index used. In other words, the lack of a robust or spatially coherent signal is not explained by the type of indicator employed. Even so, comparisons between studies must be approached with caution, as the indices reflect very different physical conditions—for example, those based on fixed thresholds (e.g., R20mm vs. R100mm) refer to events of widely varying magnitude.

A more detailed analysis of the periods covered by each study might reveal whether temporal shifts in the distribution exist, although such an approach is limited by the lack of directly comparable time spans. Similarly, geographic stratification would not necessarily yield

consistent conclusions, given the uneven spatial coverage of studies, differences in station density, and the diversity of analyzed periods.

Other methodological challenges include:

- Varying station density and record lengths, ranging from a few decades to over a century.
- Inconsistent statistical approaches to significance testing, homogeneity corrections, and spatial aggregation.
- Underrepresentation of some regions (e.g., Libya, Syria, Lebanon), due to limited data access or language barriers.

These factors highlight the need for harmonized indices, basin-wide collaborative data efforts, and greater use of gridded or reanalysis-based high-resolution datasets.

5.3. Global framing vs. regional realities

The present review finds no coherent or statistically robust trend in extreme daily precipitation across the Mediterranean as a whole. Instead, trends are found to be highly spatially variable, and significant changes—whether positive or negative—tend to be localized and dependent on data availability, period of analysis, and choice of indices.

These nuanced and regionally grounded assessments align well with recent Intergovernmental Panel on Climate Change (IPCC, 2021a) regarding the Mediterranean basin. In particular, the detailed chapters of the Sixth Assessment Report (AR6) emphasize the spatial and temporal variability of observed trends in heavy precipitation across the region. Chapter 11 notes that “*trends in the Mediterranean region are in general not spatially consistent, with decreases in the western Mediterranean and some increases in the eastern Mediterranean*” (IPCC AR6, 2021b, p. 1559). The same chapter acknowledges that, although there may be an overall tendency for heavy precipitation to increase in more regions than it decreases, “*trends in many locations were not statistically significant*” and that “*there were wide regional and seasonal variations*” (p. 1557–1558). Similarly, Chapter 12 assigns low confidence to changes in heavy precipitation over northern Africa (Table 12.3, p. 1797) and reports insufficient evidence for robust trends in Mediterranean extremes

(Table 12.12, p. 1856).

In addition, it is important to recognize the different scales of assessment in the IPCC AR6. The Summary for Policymakers provides a global synthesis, stating with high confidence that ‘*the frequency and intensity of heavy precipitation events have increased since the 1950s over most land areas for which observational data are sufficient for trend analysis*’ (AR6 SPM A.3.2, p. 8). This global perspective necessarily abstracts from regional complexities. By contrast, the regional chapters emphasize that for the Mediterranean basin evidence of consistent changes is weak, spatially heterogeneous, and often not statistically significant. Our findings are therefore consistent with the AR6 regional assessment, and they underscore the need to move beyond global generalizations when considering Mediterranean (or, in general, regional) hydroclimatic risks.

Even more problematic is the widespread tendency in introductory sections of scientific papers to repeat the claim that extreme precipitation is increasing in the Mediterranean, often without citing region-specific evidence or critically engaging with the existing body of literature. This review shows that such claims are rarely substantiated by the available observational record and that more caution is warranted in asserting general trends for this highly heterogeneous region.

5.4. Implications and future research needs

The Mediterranean basin's complexity—its steep climate gradients, rugged topography, localized convection, and strong sea-atmosphere interactions—makes it unlikely that a single trend or driver governs all observed changes in extremes.

From a scientific and policy perspective, the following implications emerge:

- Global generalizations about climate trends, while often necessary for communication and policy, should be made with caution. As this review illustrates, substantial discrepancies can exist at the regional level—even in areas frequently described as climate change hotspots, such as the Mediterranean. Assertions of widespread intensification of extreme precipitation must therefore be critically examined in light of region-specific evidence.
- Local-scale dynamics are key: Coastal convection, topographic enhancement, and mesoscale phenomena may dominate the occurrence of extreme rainfall more than large-scale forcing.
- Basin-wide trend detection requires harmonization: A standardized suite of indices (e.g., ETCCDI) and shared methodological protocols would enhance comparability.
- Emerging signals if confirmed in future should be tracked: Some regions (e.g., SE Spain, southern France, NE Italy, N Morocco) may be early indicators of future changes.

There is also a need for integrated approaches that combine observational records, high-resolution climate models, and hydrological impact assessments to improve our understanding of future extreme precipitation risks. Importantly, studies based solely on model outputs should not be treated as conclusive evidence of temporal changes in precipitation extremes unless they are explicitly evaluated against observational data. The link between modeled trends and real-world measurements remains essential for ensuring credibility and relevance in regional climate impact assessments.

6. Conclusions

This review synthesized the findings of 175 peer-reviewed studies on trends in extreme daily precipitation across the Mediterranean basin from 1997 to 2024. Despite a widely held belief that heavy rainfall is intensifying everywhere due to global warming, the evidence compiled here reveals a far more complex and regionally differentiated picture. The following synthesis summarizes the results reported in the reviewed studies, highlighting the prevailing spatial and temporal patterns of change:

- No generalized basin-wide intensification of extreme

precipitation events has been observed. Trends in the Mediterranean are spatially heterogeneous and often statistically insignificant, with non-significant results prevailing in inland and many southern regions, although localized signals of change do exist in certain regions and time periods. These findings are consistent with the regional assessment presented in the IPCC AR6, which likewise emphasize uncertainty and spatial fragmentation in Mediterranean extremes.

- Positive trends published are regionally concentrated, particularly in northern Italy, southern France, and the eastern Spanish Mediterranean coast and some areas of northern Maghreb, where increases in daily maxima and high-threshold events have been documented, often since the 1980s. Notwithstanding, no long-term trend has been observed.
- In much of North Africa, Eastern Europe, and the Eastern Mediterranean, trends are flat or decreasing, and rarely statistically significant, with many studies pointing to stationarity in extreme rainfall indicators.
- A decline in the number of wet days is observed in many parts of the basin, especially in Italy and Spain. This decline is sometimes accompanied by an increase in precipitation intensity, suggesting a shift toward fewer but more intense events.
- The definition of “extreme” varies largely across studies, complicating comparison. Index selection (e.g., absolute vs. percentile-based thresholds) and record length may affect trend detection. Nevertheless, there are no substantial differences in reported results depending on the extreme index used, as studies based on different thresholds or definitions yield broadly consistent conclusions.
- Future assessments should prioritize harmonized indices, basin-wide coordination, and multiple resolution (including sub-daily) analyses

Disclaimer: use of AI tools

Some portions of this manuscript were edited and translated with the assistance of AI-based language tools to improve clarity and consistency. Final content and interpretations are solely the responsibility of the authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.earscirev.2026.105409>.

Data availability

No data was used for the research described in the article.

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