

Climatological aspects of extreme precipitation in Europe, related to mid-latitude cyclonic systems

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Abstract Climatic aspects of extreme European precipitation are studied. Daily pluviometric data from 280 stations across Europe, covering the period from 1958 to 2000, are used. First, the criteria for extreme precipitation cases and episodes are communicated using threshold and spatial definitions. The cases and episodes meeting these criteria are grouped according to their area of appearance. Most of them are located in three major areas: Greece, the Alps, and the Iberian Peninsula. The existence of trends in the annual and seasonal time series of these extreme events is examined. Decreasing trends are found in most of the cases, for Greece, the Iberian Peninsula, and Europe, as a whole. The Alps present a different behavior, with no trend at all in the southern part, and a possible increasing trend in the northern part. Finally, the positive impact of altitude in the frequency of occurrence of extreme precipitation episodes in Europe is discussed.

1 Introduction

Extreme precipitation has always been an issue of great scientific interest, due to its enormous effect on humans, their properties, and the environment. Numerous catastrophic events, produced by episodes of torrential or prolonged rainfall, can be found throughout history. A lot of research is already been done, in an effort to better understand the mechanisms and physical laws that govern

such phenomena. Equally significant work is been done in examining their climatological aspects around the globe. The 4th IPCC Assessment Report (IPCC et al. 2007) provides an updated description of this work.

Many researchers have investigated the extreme precipitation of the European continent for the existence of possible trends. The conclusions may vary, according to the scope, methodology, and database of each study. For example, Mudelsee et al. (2003) and New et al. (2001) reported decreasing trends in the second half of the twentieth century. On the other hand, Moberg and Jones (2005) and Klein Tank and Können (2003) found evidence of increasing trends. Research was performed on the precipitation on specific European sub-regions. For example, Nastos and Zerefos (2007) dealt with the Greek area, Frei and Schär (2000) and Schmidli and Frei (2005) with the Alpine region, and González Hidalgo et al. (2003) and Costa and Soares (2009) with the Iberian Peninsula. The conclusions of these studies are not always in complete agreement with each other.

Sevruk (1997), Frei and Schär (1998), Alpert (1986), Prudhomme and Reed (1998), and Brunsdon et al. (2001) studied the relation between orography and precipitation. They have shown that the orography affects substantially the spatial characteristics and the amount of precipitation. A general increase of precipitation with altitude was reported, although the geomorphology of each different area can affect precipitation in a unique way.

Although bibliography seems to be extensive on the subjects of extreme precipitation, very few studies examined the climatic characteristics of extreme precipitation that was produced by mid-latitude cyclonic systems only. In this study, some climatological aspects of extreme precipitation related to mid-latitude cyclonic systems are investigated.

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In order to study the extreme precipitation related to cyclonic systems, thermally induced thunderstorms should be excluded. A criterion based on the different characteristics of these two processes of precipitation is set. This criterion also defines and distinguishes the “case” and “episode” of extreme precipitation. After the identification of all the cases and episodes of extreme precipitation produced by mid-latitude cyclonic systems, they are grouped according to their area of occurrence. Europe, as a whole, and specific sub-regions are investigated for possible trends, using the non-parametric Mann–Kendall test and the linear regression theory.

The effect of orography on the frequency of appearance of extreme precipitation is also examined. The pluviometric stations are clustered into nine classes, according to their altitude. The number of stations of each class is compared to the number of cases of extreme precipitation recorded at the stations of the class, in order to reveal the positive relation between the increase of extreme precipitation and the altitude.

2 Data

Daily precipitation data, from 280 pluviometric stations across Europe, are used in the present study. The covered period extends from 1958 to 2000. These data were obtained from European Climate Assessment & Dataset and the Meteorological Services and Institutes shown in Table 1, through the Statistical and Regional dynamical Downscaling of Extremes for European Regions (STARDEX) program, after its completion.

The spatial distribution of the stations used in the present study is shown in Fig 1. They cover the continental Europe, up to 30° E longitude, and the British Islands and Ireland. Western Europe, the UK, Ireland, Czech Republic, Hungary, Romania, and Greece are covered quite satisfactorily by the pluviometric network. The Balkan area (except Greece and Romania), Poland, and central and southern Italy present a rather sparse network coverage, which may lead to partial “loss” of episodes of extreme precipitation in these areas. However, this problem does not affect the study substantially, since the objective is not to record every single extreme precipitation episode but to investigate specific climatological features of them.

The total number of pluviometric stations of each country is indicated in Table 2. Most of them belong to six countries: France, Germany, Greece, Spain, Switzerland, and the UK.

The definition of “hydrological day” differs among different countries. However, most of the stations mentioned before (169 out of 280) use the definition proposed by WMO, according to which the hydrological day starts at 06:00 UTC and ends at 06:00 UTC of the next day. For uniformity reasons, this definition was considered to apply for all of the stations used here.

Thermal thunderstorms, along with “weak cyclones of thermal origin” (Maheras et al. 2001), tend to develop mainly in the warm season of the year and the southern parts of Europe. They are associated with high intensity and significant amount of rainfall. The majority of them are local and limited area systems, in contrast to mid-latitude cyclonic systems which extend to much wider areas, and they usually take place during the passing of short wave

Table 1 Meteorological services that contributed data to the STARDEX program

Country	Meteorological service
Austria	<i>ZentralAnstalt für Meteorologie und Geodynamik</i>
Czech Republic	<i>Ěeský Hydrometeorologický Ústav</i>
Denmark	<i>Danmarks Meteorologiske Institut</i>
Finland	<i>Ilmatieteen Laitos</i>
France	<i>Meteo France</i>
Germany	<i>Deutscher Wetterdienst</i>
Great Britain	Climatic Research Unit University of East Anglia
Greece	Department of Meteorology and Climatology, Aristotle University of Thessaloniki
Hungary	<i>Országos Meteorológiai Szolgálat</i>
Italy	<i>Servizio Meteorologico Regional, ARPA-Emilia Romagna</i>
Norway	<i>Meteorologisk Institutt</i>
Portugal	<i>Instituto de Meteorologia</i>
Russia (former Soviet Union)	Russian Meteorological and Hydrological Institute
Spain	<i>Instituto Nacional de Meteorología</i>
Sweden	<i>Sveriges Meteorologiska Och Hydrologiska Institut</i>
Switzerland	<i>MeteoSchweiz</i>
The Netherlands	<i>Koninklijk Nederlands Meteorologisch Instituut</i>

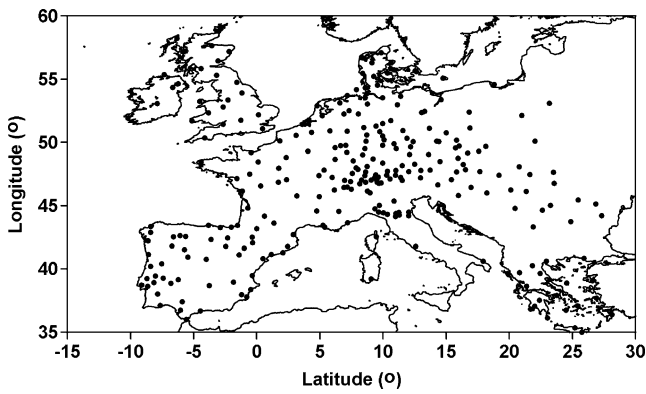


Fig. 1 Spatial distribution of the pluviometric stations used

disturbances of the middle and upper troposphere or even days of anticyclonic circulation. In order to avoid such events and not to incorporate within the sample, summer months (June, July, and August) were excluded from this study.

3 Definitions of “case” and “episode” of extreme precipitation

Although thermal thunderstorms tend to develop during summer, they can also occur during spring or autumn. In order to completely eliminate them from the study, a strict criterion is set and applied. This criterion defines the case and episode of extreme precipitation. The case of extreme precipitation

Table 2 Total number of pluviometric stations of each country

Country	NPS
Austria	14
Belgium	1
Czech Republic	11
Croatia	1
Denmark	12
France	33
Germany	49
Greece	20
Hungary	7
Ireland	3
Italy	15
Luxemburg	1
The Netherlands	6
Poland	7
Portugal	12
Romania	9
Spain	35
Switzerland	21
UK	21
Yugoslavia	2

NPS number of pluviometric stations

applies to a single station and is defined as the recording of over 60 mm/day of precipitation at a single station.

The extreme precipitation episode applies to two or more neighboring stations and is defined as the event that fulfills the two following rules:

- (a) Precipitation recordings exceed 60 mm in the same day at two at least neighboring stations ($d_{max}=550$ km).
- (b) During the previous or the next day, precipitation recordings exceed 60 mm/day at one or more of the stations of rule (a) or another station, situated within a 550-km radius from them.

It should be mentioned that if one or both of the rules of the criterion are satisfied for three or more consecutive days, then these days are considered to be part of the same episode.

The precipitation threshold value of 60 mm/day and the maximum distance between neighboring stations ($d_{max}=500$ km) are not set arbitrarily. Their setting is based on the different spatial and temporal characteristics of thermally induced and synoptic scale precipitation events.

Firstly, the threshold value of the case and the episode have to be set. Two significant problems become evident:

- The climatic diversity of the European continent
- The subjectivity of the term “extreme”

It is a fact that the various regions of Europe present different precipitation regimes. Rainfall amount, intensity, and seasonal distribution differ widely from one site to another, making the selection of a common threshold quite a difficult task.

The term “extreme” can acquire a lot of different meanings, depending on the scope of the study, the database and methodology used, and the personal judgment of the researcher. It is stated by New et al. (2001) that “most studies have differing definitions of intense precipitation, which makes comparison of results problematic.” Schmidli and Frei (2005) examined the possible trends of extreme precipitation and wet and dry days sequences with the aid of a series of indices. It was found that not all indices agree at all times, a fact that can be attributed to the subjectivity of the definition of each index and the term “extreme precipitation.”

In order to overcome those two problems, the threshold value is set at a relatively high value. The risk of characterizing an episode as “extreme,” without actually being such, is decreased substantially by increasing the threshold value. Moreover, the increase of the threshold increases the “extremity” of the episodes. After an extensive investigation, the threshold value is set at 60 mm/day, according to the following arguments:

- (a) It can definitely be characterized as “extreme,” since it equals to almost 8 h of continuous “heavy” rain, according to *Glossary of Meteorology* (Huschke 1959).

(b) It exceeds many analogous threshold values found in the literature (Groisman et al. 1999; Kothavala 1997; Twardosz and Niedźwiedź 2001; Ulbrich and Fink 1996; González Hidalgo et al. 2003).

The threshold value is not set higher because, as it can be seen in Fig. 2, the total number of cases of extreme precipitation decreases rapidly with the increase of the threshold. Values over 60 mm/day reduce the number of cases by such high percentage that makes the statistical analysis of their characteristics rather problematic. Conclusively, an “extreme precipitation case” is defined as the recording of over 60 mm/day of precipitation at a single station. Three thousand two hundred thirty-three cases of extreme precipitation are found across the examined area, during the period 1958–2000.

As mentioned before, two stations can be affected by the same cyclonic system only if they are relatively close to each other (neighboring stations). A statistical approach is followed to define the maximum distance between two neighboring stations (d_{max}). The 3,233 extreme precipitation cases are used to form episodes of extreme precipitation. The stations of every episode have recorded over 60 mm/day on two or more consecutive days and range no more than the maximum distance between neighboring stations (d_{max}) from each other. By increasing d_{max} from 100 to 650 km with a step of 50 km, 12 groups of extreme precipitation episodes were made, one for every different d_{max} . Table 3 shows the total number of episodes (TNE) for each d_{max} , while the graph of TNE as a function of d_{max} is depicted in Fig. 3.

The increase of the d_{max} results in an increase of the TNE up to the distance of 550 km. After this distance, TNE remains practically unaffected, a fact which implies that further increase of the d_{max} does not “produce” new episodes. Moreover, a detailed episode-to-episode investigation showed that, beside this distance, no significant addition of stations is observed, in the already existing episodes. Therefore, the

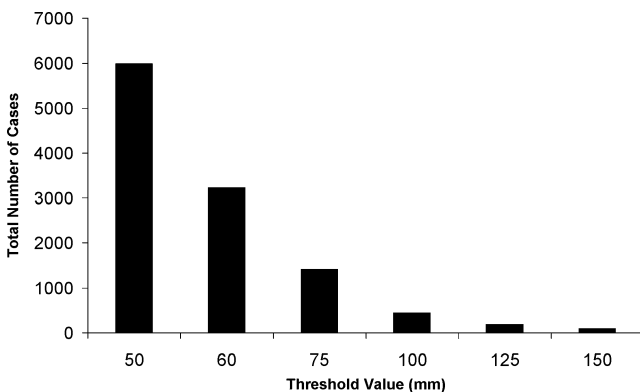


Fig. 2 Total number of extreme precipitation cases which appear above the specified threshold values

Table 3 Total number of episodes for different values of maximum distance between neighboring stations (d_{max})

d_{max} (km)	TNE
100	71
150	98
200	129
250	143
300	148
350	166
400	182
450	188
500	193
550	204
600	204
650	206

TNE total number of episodes

distance of 550 km is adopted as the maximum distance between two neighboring stations (d_{max}).

4 Methodology

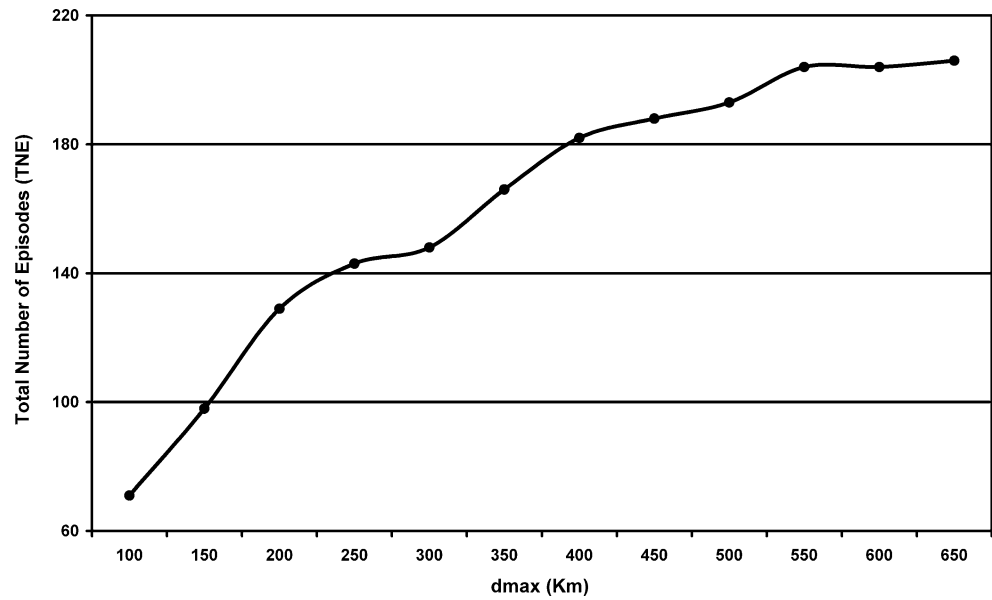
In order to investigate the linear trends that may exist in extreme precipitation, linear regression analysis (Acton 1959; Farebrother 1999) is used. The least squares line (Wilks 1995) of each time series is calculated. The slope of this line represents the linear trend of the series. Then, the Kendall-tau statistic (Press et al. 1996) is applied to the linear trend, in order to determine its level of significance. This test calculates the τ -parameter, according to the formula:

$$\tau = \frac{c - d}{\sqrt{c + d + \text{extra-}y} \cdot \sqrt{c + d + \text{extra-}x}} \tag{1}$$

where c (concordant) is considered any pair of two consequent x values, whose relative rank is the same to the relative rank of their respective y values, and d (discordant) is characterized as any pair of two consequent x values, whose relative rank is opposite to the relative rank of their respective y values. When two consequent x values are equal, they consist an extra- x pair, and when two consequent y values are equal, they consist an extra- y pair. The τ -parameter is checked against the value $(\tau)_t = \pm 1.96 \cdot \sqrt{\frac{4N+10}{9N(N-1)}}$, where N is the total number of the time series observations. In the case where $|\tau| \geq |(\tau)_t|$, the linear trend of the examined time series is considered to be statistically significant at a 95% level of confidence.

The graphic version of the non-parametric Mann–Kendall test (Goossens and Berger 1986; Sneyers 1990) is applied to the series, in order to identify specific sub-periods, where possible trends exist. The normal and retrograde curve

Fig. 3 Total number of episodes of extreme precipitation (*TNE*) as a function of the maximum distance between neighboring stations (d_{max})



of the test are calculated and drawn. The time of their intersection marks the start of a trend, provided that the two curves follow opposite directions. In the case that the normal curve exceeds the 95% confidence level, the trend is considered to be statistically significant.

5 Trends of extreme precipitation

Two kinds of time series are examined. Those which consist of the number of extreme precipitation cases for the period from September to May and will be called “all-months” time series and those which consist of the number of extreme precipitation cases for each of the seasons: autumn (September to November), winter (December to February), and spring (April to May).

All-months and seasonal time series of extreme precipitation cases, for the whole European continent and three specific sub-regions of it, are subjected to linear regression analysis, the Kendall-tau test, and the non-parametric Mann–Kendall test, in order to reveal any possible trends. The sub-regions, which were selected because they accumulated most of the extreme precipitation episodes, are Greece, the Alpine Region, and the Iberian Peninsula.

5.1 Europe

The use of the analysis procedures mentioned in the Section 4 produced a series of graphs like those presented in Fig. 4a, b. The rest of the graphs are not shown here.

Figure 4a depicts the time variation of the total number of spring extreme precipitation cases for Europe as a whole. The least squares regression line is also drawn, and its slope is calculated. In Fig. 4b, the normal and retrograde curve of

the non-parametric Mann–Kendall test and also the 95% confidence limits are shown. These two figures combined with the application of the Kendall-tau test (Table 5) reveal a negative trend, which becomes statistically significant during the period 1980–1997. It should be reminded that

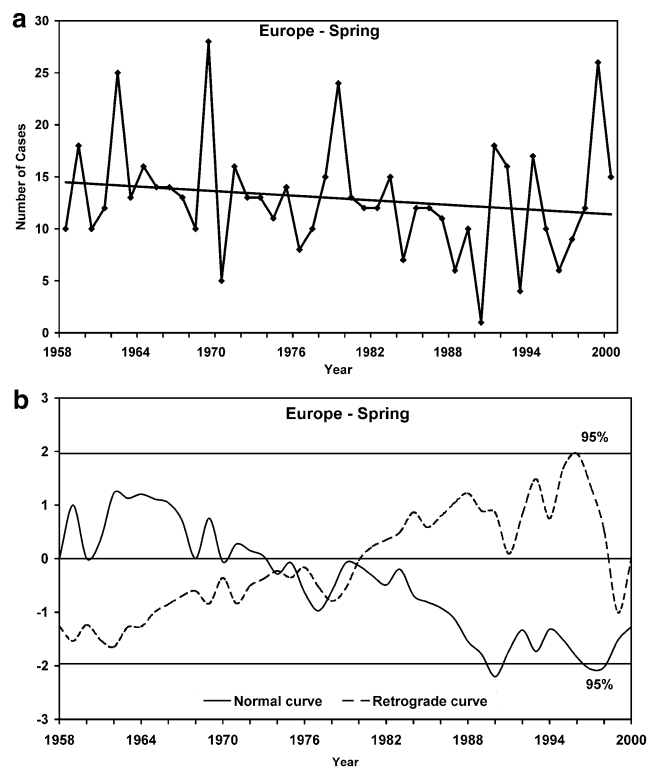


Fig. 4 **a** Total number of spring extreme precipitation cases per year with time and least squares regression line for the period 1958–2000 for Europe as a whole. **b** Normal and retrograde curve of the Mann–Kendall test for the same series

this conclusion is valid only for the continental Europe, the British Islands, and Ireland.

Table 4 summarizes the results of the application of linear regression analysis and Kendall-tau test on all the examined time series, while Table 5 summarizes the results of the application of the non-parametric Mann–Kendall test. As it can be seen in Table 4, Europe presents statistically non-significant negative linear trends, when the full length of the series is examined. Non-significant negative trends are also evident for all the seasonal time series. However, the Mann–Kendall test (Table 5) shows short periods of statistically significant negative trends for all-months, winter, and spring and a non-significant negative trend for autumn.

Maheras et al. (2004) found a decreasing trend in the frequency of appearance of mid-latitude cyclonic systems. This is in absolute agreement with the decrease of extreme precipitation cases that is found in the present paper. According to the 4th IPCC Assessment Report (IPCC et al. 2007), Mediterranean precipitation diminishes, although northern European precipitation increases. Karagiannidis et al. (2009) have shown that an overall negative trend of 0.38 episodes per year is evident in the all-months time series for the whole Europe. With the use of the non-parametric Mann–Kendall test, the trend was localized in a period that starts in the middle 1970s and continues until 2000. A possible decreasing trend of the occurrence of extreme floods in the central Europe was found by Mudelsee et al. (2003). Moreover, a decrease of the mean monthly amount of precipitation during the winter for some European regions was revealed. In a study of the global precipitation, New et al. (2001) concluded that annual precipitation values presented a maximum in the 1950s and a decreasing trend followed up. No trend of the extreme precipitation cases in Europe were revealed, except an increasing one for summer in Poland. Utilizing a series of appropriate indices, Moberg and Jones (2005) revealed an increasing trend for the average precipitation intensity and moderately strong events. Finally, Klein Tank

and Können (2003) showed an increasing trend of the total precipitation and the precipitation of “moderate” and “very wet” days in Europe during the period 1946–1999. However, these trends were observed mainly at stations of high latitudes.

The different areas and periods of examination, along with the various methodologies used in the studies mentioned before, make the comparison of the findings of the present study a difficult task. Moreover, the exclusion of the summer months is a justified parameter of discrepancy between the conclusions of this study and those of other ones that do not exclude summer months. Nevertheless, a general agreement, at least with the 4th IPCC Assessment Report, seems to exist.

5.2 Greece

Regarding the Greek area, as can be seen in Table 4, a general decreasing trend is evident, when linear regression analysis is applied in the autumn, winter, and all-months time series. The spring trend, however, is not statistically significant. The application of Mann–Kendall test (Table 5) reveals statistically significant negative trends for the same time series. Autumn and all-months extreme precipitation decrease during the last decade of the examined period, while winter extreme precipitation during the 1980s and early 1990s. Again, the spring extreme precipitation presents no significant trend.

Bibliography includes numerous studies on the trends of precipitation over the Greek area. According to the STARDEX program (STARDEX 2005), extreme precipitation presents trends of varying signs and levels of significance in the greater Greek area. A statistically non-significant negative trend in the annual precipitation amount of Athens was reported by Nastos and Zerefos (2007). Statistically significant increase of the wet days was also found after 1968. The overall conclusion was that extreme precipitation increased in the greater Athens area. Katsoulis and Kambetidis (1989) reported varying trends

Table 4 Linear regression analyses trends for seasonal and all-months (September to May) time series of Europe and specific sub-regions, for the period 1958–2000

Area	Autumn	Winter	Spring	All-months
Europe	−0.168	−0.138	−0.073	−0.379
Greece	−0.077	−0.073	−0.003	−0.165
Iberian	−0.155	−0.149	−0.115	−0.428
Spain	−0.118	−0.078	−0.085	−0.283
Portugal	−0.037	−0.071	Insufficient data	−0.145
Alps	+0.070	+0.076	+0.020	+0.150
Switzerland	+0.061	+0.080	+0.069	+0.205
Northern Italy	−0.010	−0.004	−0.049	−0.056

The slopes of the least squares lines are measured in extreme precipitation cases per year. Bold are marked the trends which were found (Kendall-tau test) to be statistically significant at 95% level of confidence

Table 5 Trends found with the use of the non-parametric Mann–Kendall test on seasonal and all-months (September to May) time series of Europe and specific sub-regions, for the period 1958–2000

Area	Autumn	Winter	Spring	All-months
Europe	(-)1969–1978	(-)1962–1967	(-)1980–1997	(-)1969–2000
Greece	(-)1995–2000	(-)1979–1994	NT	(-)1998–2000
Iberian	(-)1990–2000	(-)1999–2000	(-)1981–2000	(-)1983–2000
Spain	(-)1970–1983	NT	(-)1981–2000	(-)1983–2000
Portugal	NT	(-)1992–2000	Insufficient data	(-)1995–2000
Alps	NT	NT	NT	NT
Switzerland	NT	NT	NT	(+)1989–2000
Northern Italy	NT	NT	(-)1980–2000	NT

The sign defines the positive or negative trend, and the approximate time period of the trend follows. Bold are marked the trends which were found to be statistically significant at 95% level of confidence

NT the absence of trend in the examined time series

in seasonal precipitation in Athens. No trend was found in mean annual precipitation intensity in Athens since 1958, while no significant trend was found in annual precipitation amount too. Finally, a statistically significant negative trend in winter precipitation was identified by Maheras et al. (2004). Negative trend was found for spring and autumn too but at a lower significance level. These trends were attributed to the decreasing trend in the frequency of appearance of cyclonic weather types.

The decreasing trend that was found for all-months, winter, and autumn extreme precipitation times series is in good agreement with most of the trends, reported in the studies mentioned before. This agreement also demonstrates the fact that total precipitation and extreme precipitation related to mid-latitude cyclonic systems present similar trends.

5.3 Alpine region

No significant trends are observed for the examined time series of the Alpine region, as it can be seen in Tables 4 and 5. Only small fluctuations of extreme precipitation are noted, and they do not constitute abrupt climatic changes or statistically significant trends.

Switzerland is considered to be representative of the northern part of the Alpine region, while northern Italy is considered to be representative of the southern part. Therefore, the Alpine region could also be examined as two separate parts.

The northern part, represented by Switzerland, presents an upward trend for all-months time series. As it can be seen in Tables 4 and 5, a statistically significant positive linear trend is found for the period 1958–2000, while the implementation of the Mann–Kendall test localizes the trend during the years 1989–2000. The investigation of the seasonal time series shows no linear trends but only statistically non-significant positive trends for winter and spring extreme precipitation. Northern Italy, on the other

hand, presents no statistically significant trend in the seasonal and all-months time series.

Frei and Schär (2000) developed a methodology for the computation of the probability of rare events and studied the extreme precipitation trends in the Alps. The number of the stations presenting significant trends was very small for all seasons. They concluded that there is no significant trend in the Alpine precipitation for the period 1901–1994. Schmidli and Frei (2005) implemented two different methodologies for analyzing trends and investigating their statistical significance. They found a positive statistically significant trend in extreme winter precipitation in many stations of the northern and northwestern side of the Alps during the period 1901–2000. A negative trend was found in the southern and southeastern side, but it was not statistically significant. A statistically significant negative trend was found in the autumn in the southern side only. Brunetti et al. (2001), studying northeastern Italy time series, concluded that there is no trend in extreme precipitation cases. However, mean intensity, defined as mean precipitation amount per day, was found to be increasing, but not at a significant level. Using daily precipitation amount time series for a great number of Italian stations, Brunetti et al. (2002) found no significant trend in the extreme precipitation. In their paper, precipitation was considered as extreme, when it exceeded 10% of the mean annual amount in a series of five consecutive days. Most of the studies mentioned before agree with the conclusions of the present one, verifying, among others, the interesting differentiation between the northern and the southern Alpine region.

5.4 Iberian Peninsula

The Iberian Peninsula time series show a distinct negative trend. As it can be seen in Table 4, a statistically significant negative linear trend exists in the series of winter, spring, and all-months. Mann–Kendall non-parametric test (Table 5)

localizes the trend during the last two decades in the spring and all-months time series and the last 3 years in the winter time series. The negative trend of the last decade of the autumn extreme precipitation is not statistically significant.

The time series of the Portuguese stations are examined separately from those of Spain. This distinction is made because Portugal is clearly influenced by the Atlantic Ocean, while Spain is mainly influenced by the Mediterranean Sea.

From the application of the linear regression analysis and the Mann–Kendal test on the Spanish stations time series, a definite negative trend was found for all-months and spring, which can be localized in the last two decades. Autumn presents a negative trend during the 1970s and early 1980s, while a non-significant linear negative trend was found for winter.

Portugal experiences very few extreme precipitation cases during spring. For this reason, no trend analysis was performed for this time series. Winter and all-months extreme precipitation present a statistically significant negative trend localized in the 1980s and 1990s. A non-significant linear negative trend is recorded for autumn.

García et al (2007) examining the possible trends in block-seasonal extreme rainfall over the Iberian Peninsula in the second half of the twentieth century found mostly negative trends for spring and winter and varying trends for autumn. González Hidalgo et al. (2003) searched for possible trends of the daily amount of precipitation of the “higher/highest events” for the second half of the twentieth century in the Valencia area and found a statistically significant negative trend. Ramos and Martínez-Casasnovas (2006), studying the trends in precipitation in NE Spain during the last half of the twentieth century, showed an increase in the fraction of total rainfall accumulated in extreme events, especially during autumn, where the strength of the events also increased. Costa and Soares (2009) using a series of wetness indices, for Portuguese pluviometric stations, showed that the frequency of extremely high precipitation events has cyclic patterns and different trend signals at the period 1955–1999.

The conclusions of the studies mentioned before are not in agreement with each other. However, the findings of at least half of them support the conclusions of the present study.

6 The effect of altitude on extreme precipitation

Europe is a continent which, despite its relatively small size, has a remarkable number of mountains, some of them having peaks over 3,000 m. In the present paper, a study of the effect of altitude to the precipitation is attempted. The frequency of occurrence of extreme precipitation as a function of the altitude is examined. The pluviometric stations are divided in nine classes, according to the station’s altitude. Those classes are shown in the first

column of Table 6. In the same table, the total number of stations of each class and its percentage, the total number of extreme precipitation cases recorded in these stations and its percentage, and finally the difference between these two percentages are also shown.

As it can be seen in the last column of Table 6 and in Fig. 5, the difference between the percentage of the number of cases and the percentage of the number of stations increases with the increase of the altitude. This difference is -6% for the 0–100 m class and -11% for the 100–200 m class. For the three next classes (200–300, 300–500, and 500–700 m), the difference is around zero (1%, 1%, and -1% , respectively), while for the last four classes is positive. For the 700–1,000 m class, the difference is 6%, for the class 1,000–1,500 m is 3%, for the 1,500–2,000 m is 5%, and finally for the class over 2,000 m is 3%.

The above show that the increase of the station altitude results in an increase of the number of extreme precipitation cases. Up to 700 m, elevation seems to play a minor role, while a distinct increase of extreme precipitation is observed at altitudes over 700 m.

This effect of the orography to the volume and spatial characteristics of precipitation has already been examined by many researchers. Sevruck (1997) studied the relation between the altitude, topography, and the precipitation in the Alpine region. He concluded that although a definite effect of altitude on precipitation exists, it is significantly influenced by parameters like the topography and prevailing wind direction. Frei and Schär (1998) showed that, besides the altitude, topography and the general atmospheric circulation also affect precipitation. Prudhomme and Reed (1998), discussing the relation between extreme daily precipitation and topography in a case study in Scotland, confirmed the remarkable influence of altitude, declination, and proximity to the sea on the precipitation of mountainous areas. Brunson et al. (2001) showed the relation between the characteristics of precipitation and the altitude, which, however, vary among different areas.

All the studies mentioned before concluded that there is a definite influence of the altitude to precipitation. However, due to the great variety of parameters that contribute to the final manifestation of this influence, most of the studies are spatially limited to a specific mountainous area. Nevertheless, the agreement between the general conclusions of the present study and those of the ones mentioned before proves the clear positive influence of the altitude in extreme precipitation.

7 Conclusions and discussion

Linear regression analysis and the non-parametric Mann–Kendall test are used to examine the possible trends of

Table 6 First column shows the altitude class

Altitude class (m)	Total number of stations	Percentage P1 (%)	Total number of cases	Percentage P2 (%)	P2–P1 (%)
0–100	122	44	1,216	38	–6
100–200	36	13	71	2	–11
200–300	26	9	320	10	1
300–500	38	14	456	14	1
500–700	21	8	219	7	–1
700–1,000	22	8	432	13	6
1,000–1,500	6	2	167	5	3
1,500–2,000	6	2	224	7	5
2,000+	3	1	128	4	3
Total	280	100	3,294	100	

Second and third column show the total number of stations and their percentage of each class. Fourth and fifth column show the total number of cases of extreme precipitation and their percentage for the stations of each class. Sixth column shows the difference between the two percentages

extreme precipitation in Europe and specific sub-regions of it. The effect of altitude increase in extreme precipitation is also examined.

- Continental Europe as a whole, together with Great Britain and Ireland, do not present any statistically significant linear trends for the total of the examined period. However, short-term but statistically significant negative trends are revealed for the all-months, winter, and spring time series. The time period that hosts these trends varies between the different series. In the case of all-months time series, the negative trend starts in the late 1960s and reaches 2000. This trend could be associated to an analogous decrease of mid-latitude cyclonic systems in Europe.
- The negative trend that is recorded when the continent was examined as a whole is not manifested in exactly the same form in the sub-regions which were examined. Therefore, the climatic change that could be associated to this trend is not manifested in the same way or severity in the whole continent.
- Greece presents linear negative trends in extreme precipitation cases of all-months, autumn, and winter. The application of the Mann–Kendall test showed that these trends become statistically significant during the

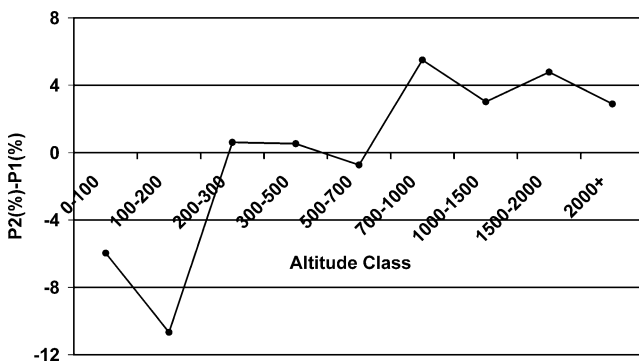


Fig. 5 Percentage difference (P2–P1) change with altitude class, as shown in Table 6

last decade, or the last two decades, if the winter time series is considered.

- No trend is found in the extreme precipitation of the Alpine region as a whole. Lack of trend is also observed in the northern Italy, which is representative of the southern side of the Alps. On the contrary, in Switzerland, which is considered to represent the northern side of Alps, a positive trend was revealed in the all-months time series. With the application of Mann–Kendall test, this positive trend was found to be statistically significant, throughout the last decade.
- An almost monotonous linear decrease in extreme precipitation was revealed for the Iberian Peninsula, when all-months, winter, and spring time series were examined. This decrease is statistically significant during the last two decades, with the exception of winter time series where the trend is constrained in the last 2 years of the examined period. Portugal, which is influenced by the Atlantic Ocean, presents analogous negative trends, which become significant during the last decade. Spain, mainly influenced by the Mediterranean, presents a similar negative trend. With the aid of the Mann–Kendall test, the trend is found to be statistically significant during the last two decades.
- Extreme precipitation trends seem to vary according to the change of geographic latitude. Regions of northern geographic latitude lower than 43° (Iberian Peninsula and Greece) present a decrease of the extreme precipitation associated to mid-latitude cyclonic systems. In northern regions, specifically in the southern side of the Alps (northern latitude 43–45°), no significant trend was found. Finally, in the northern side of the Alps (northern latitude 45–47°), a statistically significant positive trend was revealed. These conclusions are similar to the ones presented by the STARDEX program (STARDEX 2005).
- The comparison between the trends of total precipitation and those found in the present investigation shows

that they are similar enough in sign and period of appearance. This fact confirms the hypothesis that extreme precipitation associated to mid-latitude cyclonic systems changes with time in patterns analogous to those of total precipitation.

- Finally, it was shown that the increase of the altitude, especially over 700 m, increases the number of extreme precipitation cases recorded. This fact demonstrates the definite and positive in general effect of the altitude in extreme precipitation.

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