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Study of the Seasonality of Extreme Precipitation Events over the Mediterranean for the Future Period 2081–2100 †

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Abstract: This study examines extreme precipitation seasonality in the Mediterranean for the future period 2081–2100, based on the climate scenario SSP5-8.5. Using data from the CNRM-CM6-1-HR, the study determines the dates of extreme precipitation events using the circular statistics method. The results indicate that almost 50% of grid points experienced the first extreme event of the year between January and February during the reference period. In the future period, there will be an increase in the percentage of grid points experiencing events during the cold period, meaning that there will be a seasonal shift of extreme events to colder months mainly affecting the west and east Mediterranean.

Keywords: extreme; precipitation; seasonality; circular statistics; Mediterranean; SSP5-8.5; CMIP6; CNRM; climate change; ERA5

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1. Introduction

Precipitation is a crucial component of the hydrological cycle and understanding its distribution and the seasonal patterns of its extreme events is essential for water resource management, agricultural planning, and flood risk assessment [1]. This study aims to provide a thorough analysis of the seasonal patterns of future extreme precipitation events over the Mediterranean using circular statistics. Circular statistics is a method used to analyse data that has directional characteristics, such as time or direction, and is commonly used in climate and environmental studies to analyse seasonal patterns [2]. Climate change has increased extreme precipitation events in the region, which can disrupt the timing and duration of seasonal events and impact the structure and function of entire ecosystems [3]. While most studies aim to investigate extreme precipitation spatially and quantitatively [4–6], this study will further analyse the temporal and intra-annual distribution of the phenomenon. The results will have significant implications for understanding the impacts of climate change and will contribute to developing effective mitigation and adaptation strategies.

2. Materials and Methods

In the present study, total precipitation data from the Climate Data Store (C3S) on the Copernicus platform were used. Specifically, two datasets were used: the first is the ERA5 (ECMWF Reanalysis v5) dataset for the reference period 1986–2005 [7], and the second is the global climate model CNRM-CM6-1-HR from the French research institute Centre National de Recherches Météorologiques (CNRM), which was selected after an evaluation of its performance for the Mediterranean region. The global climate model data were taken for the same reference period of 1986–2005 but also for the future study period of 2081–2100 under the SSP5-8.5 climate scenario. This future period was chosen to evaluate the long-term impacts of climate change on extreme precipitation events, especially on a planet with continuously increasing greenhouse gas emissions, as defined by the SSP5-8.5 scenario. Initially, the CNRM historical data were evaluated against the reanalysis ERA5 data. The spatial resolution of the ERA5 data is approximately 25 × 25 km, while the model's spatial resolution is 100 × 100 km. Finally, the temporal resolution of the data retrieved from the C3S platform was, in each case, daily.

For the extreme precipitation index, cumulative daily precipitation data in millimetre (mm) units were used, for which the 99th percentile was then calculated using the Climate Data Operator (CDO). It is worth noting that, mainly due to the low spatial resolution, global climate models usually produce too many days with little total precipitation, sometimes known as the "drizzle problem" [8]. Days with precipitation below 0.1 mm were defined as days with no precipitation (equal to 0 mm).

For this study, the methodology was based on circular statistics [9,10] in order to analyse the average seasonality of annual extreme precipitation events [11]. Thus, to calculate the average occurrence date (day of the year) of the extreme event for a given grid point, the occurrence date of the extreme event D_i for the year i is converted to an angular value θ_i in radians through the relation:

$$\theta_i = D_i \times 2\pi \times m_i \; 0 \leq \theta_i \leq 2\pi \tag{1}$$

where D_i = 1 corresponds to 1 January and D_i = m_i to 31 December, and where mi is the number of days in the year (365 or 366 for leap years). The average date of occurrence of the extreme event, $\overline{D}$, at a given grid point, is then obtained by the relation:

$$\bar{D} = \begin{cases} \left(\tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right)\right) \cdot \frac{\bar{m}}{2\pi} & \text{if } \bar{x} > 0, \bar{y} \geq 0 \\ \left(\tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right) + \pi\right) \cdot \frac{\bar{m}}{2\pi} & \text{if } \bar{x} < 0 \\ \left(\tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right) + 2\pi\right) \cdot \frac{\bar{m}}{2\pi} & \text{if } \bar{x} > 0, \bar{y} < 0 \\ \frac{\bar{m}}{4} & \text{if } \bar{x} = 0, \bar{y} > 0 \\ \frac{3\bar{m}}{4} & \text{if } \bar{x} = 0, \bar{y} < 0 \\ \text{undefined} & \text{if } \bar{x} = 0, \bar{y} = 0 \end{cases} \tag{2}$$

$$\text{with } \bar{x} = \frac{1}{n}\sum\nolimits_{i=1}^{n} cos\theta_i \tag{3}$$

$$\bar{y} = \frac{1}{n}\sum\nolimits_{i=1}^{n} sin\theta_i \tag{4}$$

where $\overline{m}$ is the mean number of days per year (365.25), and n = 20, i.e., the total number of years studied.

Note that within a year, the value exactly in the percentile where the extreme event occurs may occur more than once; however, in this study, only the first time it occurred was considered.

3. Results

The results of the seasonal distribution of extreme precipitation are presented and discussed. Firstly, the results of the ERA5 dataset for the reference period 1986–2005 are given, in order to validate the results of the CNRM-CM6-1-HR model. Maps of the extreme precipitation seasonal distribution (Figure 1) reveal that both the CNRM model and ERA5 reproduce the spatial and temporal extreme precipitation patterns well despite the different spatial resolution. The results of the future period are also presented and compared with those of the reference period. The extreme precipitation calendar was created with the first day of the extreme value per year.

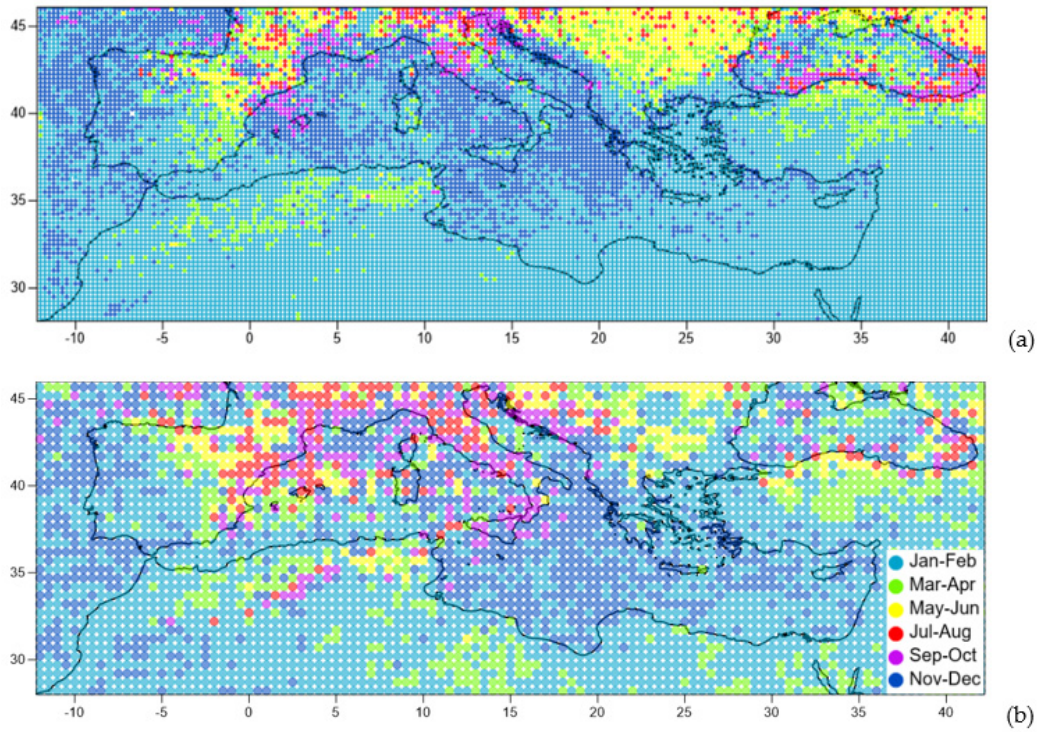

Figure 1. Seasonal distribution of extreme precipitation during the reference period 1986–2005, ERA5 reanalysis data (**a**) and CNRM-CM6-1-HR model (**b**).

Figure 1 shows the temporal distribution of extreme precipitation from January to December, in classes of two months, for the reference period. The two datasets (ERA5 and climate model) show a similar spatial distribution over most of the study area, including the Iberian Peninsula, France, Greece, and Turkey, while the distribution is similar in the Balkan Peninsula but without the scattered grid points for the months of July–August identified in the case of the ERA5 data. In particular, extreme precipitation occurs during the winter months throughout the Mediterranean Sea and the Atlantic Ocean. It was observed that in Portugal up to central Spain, extreme events occur between November and February. In eastern Spain, the episodes occur a little later, mainly from March to June and, in some cases, from July to October. Indeed, in the Balearic Islands and the Iberian Sea, extreme precipitation episodes occur in the autumn months of September to October. In the coastal areas of southern France, the episodes are mainly concentrated in November–December, while in the inland areas, the distribution of precipitation occurs between the warmer months, from March to October.

The northern part of the Italian peninsula, including the northern Adriatic Sea, experiences the majority of extreme precipitation in September–October, with scattered grid points in the region distributed throughout the year. In southern Italy, the phenomena are recorded during the winter months, as well as on the eastern shores of the Adriatic Sea and more specifically in Croatia, where the windward side of the Dinaric Alps is located. In the case of the global model, the extreme episodes start to appear earlier compared to ERA5 data, from July–August in northern Italy and September–October in southern Italy. The distribution of extreme precipitation episodes in the Balkan region is characteristic, with most grid points showing extreme precipitation in May and June, followed by the March–April period. During these two months, extreme precipitation episodes are also found in northern Greece, while in the rest of the mainland and islands, the winter months, especially January and February, predominate as the months of extreme precipitation. The intra-annual distribution in the area over the Black Sea is quite uneven, with episodes occurring throughout the year with no clear seasonal pattern. Northeast of this, the distribution of extreme precipitation occurrences is similar to that of the Balkan Peninsula, with the months of May–June predominating. In Turkey, extreme precipitation episodes are found from January to April. Finally, on the African continent, the episodes occur in the first two months of the year, apart from the Atlas Mountains, where they occur in March and April.

After comparing the two datasets for the precipitation variable, it can be concluded that the CNRM-CM6-1-HR model realistically reflects the precipitation in the Mediterranean region for the period 1986–2005 and can be used in the present analysis.

The spatial intra-annual distribution of extreme precipitation episodes for the period 2081–2100 under the very-high-emissions scenario SSP5-8.5 is shown in Figure 2. In the western and central Mediterranean, November and December are estimated to be the most frequent months of extreme precipitation. Therefore, in this region, it seems that the events will shift to the beginning of the cold season compared to the reference period. In the eastern Mediterranean Sea, the data show that the dominant months of occurrence will be January–February, while in the reference period, they were November–December, but the events remain in the cold season of the year. Moving on to the continental western Mediterranean, it is observed that in the eastern Iberian Peninsula, extreme precipitation episodes, instead of occurring in spring (March–June), are expected to occur in winter, namely in January and February. Similarly, in both southern France and Italy, where in many parts of the grid extreme precipitation events occurred in the summer months of July and August, it is expected that these events will occur in November and December. It is noticeable that, in central Italy, the extreme precipitation events are projected later, in November–December. In the western Balkan Peninsula, including Greece, the months of extreme precipitation are dominated by November and December. In the central Balkans and northern Turkey, no grid points are observed in the future period where extreme precipitation occurs in the months May–June, as in the case of the reference period, while for the months March–April, several points also occur in the future study period. The shifted extreme precipitation occurrence season is expected to be towards the winter months in the Black Sea region and also in Africa, where grid points for the months March–April are significantly reduced compared to the reference period.

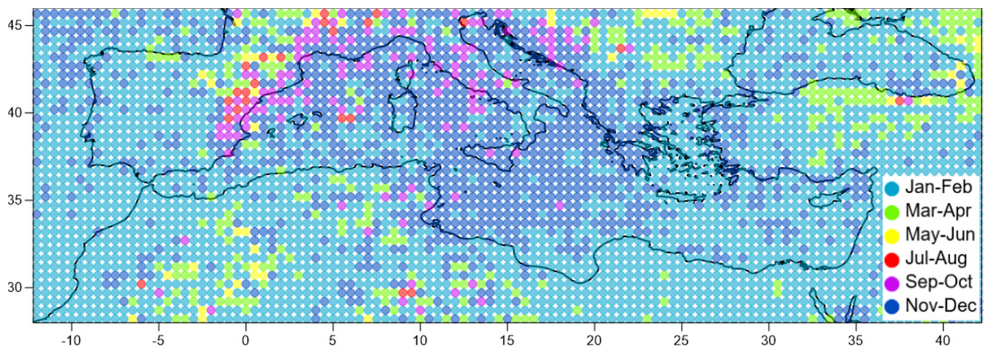

Figure 2. Seasonal distribution of extreme precipitation for the future period 2081–2100, based on SSP5-8.5.

The percentage distribution of grid points corresponding to the different months of the year is shown in Table 1. In comparison with the ERA5 data, it can be seen that the climate model underestimates the grid points that experience the extreme precipitation episode in the winter months and slightly overestimates it in the other seasons of the year. The data show some significant changes in extreme precipitation patterns between the reference period and the future period. For example, the percentage of grid points with extreme rainfall in January–February increased from 50.4% in the reference period to 59.1% in the future period, an increase of 8.7%. In contrast, the percentage of grid points with extreme rainfall events in May–June decreased from 4.4% in the reference period to 1% in the future period, a decrease of 3.4%. Overall, the data show an increase in extreme precipitation events during the cold season (January–February and November–December), with a decrease in all other months of the year, with the largest decrease (−5.7%) occurring in March–April.

Table 1. Percentage of grid points belonging to each different time interval of the year for the extreme precipitation indicator for the periods 1986–2005 and 2081–2100.

Time Interval	Percentage of Grid Points 1986–2005, ERA5	Percentage of Grid Points 1986–2005, Historical	Percentage of Grid Points 2081–2100
January–February	60.7%	50.4%	59.1%
March–April	8.2%	12.7%	7%
May–June	5.2%	4.4%	1%
July–August	2.2%	4.0%	0.6%
September–October	3.1%	5.4%	3.2%
November–December	20.4%	23.2%	29%

4. Conclusions

This study presents a detailed analysis of the seasonality characteristics of precipitation extremes in the Mediterranean in an attempt to identify the geographical regions with similar temporal extreme precipitation characteristics. From the analysis of the results obtained, it can be seen that the climate model underestimates the percentage of grid points that experience extreme precipitation episodes in the winter months and slightly overestimates it during the other seasons of the year for the reference period. Generally, in January and February, extreme rainfall occurs in the eastern Mediterranean and in particular western and southern Turkey, Israel, Syria, Lebanon, and northern Africa. In March–April, some areas in north-west Africa, Spain, the central Balkan Peninsula, and central and northern Turkey face extreme precipitation events, while later in May–June, only in north-east Spain, France, the majority of grid points in Balkan Peninsula and the Black Sea do the episodes occur. In the warmer season from July to October, the episodes occur in continental Europe, especially in the Gulf of Geneva and the eastern Black Sea.

These results are in agreement with the findings of Alpert et al. [12], which showed that the highest frequency of extreme precipitation was observed during January and February in the eastern Mediterranean. Moreover, the results reflect those of Rajczak et al. [6] from the southern Alps to the Gulf of Genoa, who also found that extreme precipitation was also present during the winter months (January—February), while Petrucci et al. [13] also concluded that the extreme precipitation events in southern Italy occur mostly in September–October.

In the future, an increase in extreme precipitation events during the cold season is expected for the period 2081–2100 under SSP5-8.5. The extreme precipitation shifts forward to the winter season, for the majority of the Mediterranean regions, while some areas in east Spain and north France, central Italy, and Croatia are expected to experience these episodes in the warmer season of the year, from July to October. A study by Marelle et al. [14] also showed that by the end of the 21st century, for the RCP8.5 scenario, extreme precipitation could shift to significantly later in the year in most regions from summer and early autumn to autumn and winter.

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