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Catalogue and Analysis of Extraordinary Precipitation Events in the Spanish Mainland, 1916–2022

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ABSTRACT

Catalogues of past hazardous events are essential for understanding their magnitude, frequency, geographical distribution and underlying mechanisms. Such compilations provide critical data for identifying patterns, improving predictive models, and enhancing preparedness, thereby contributing to the mitigation of future risks and facilitating effective adaptation to climate-related hazards. In this article, we present the first comprehensive catalogue of extraordinary precipitation over the Spanish mainland, spanning more than a century. This work provides valuable insights into spatial and temporal patterns of these events. We compiled monthly maxima of daily precipitation (Rx1day) exceeding 100 and 200 mm by combining the documentary collections of the AEMET National Climate Data Bank (1916–2022) with newly digitised data from the Annual Summaries of Observation Books (1916–1950). As a result, this dataset represents the most extensive and detailed collection of extraordinary precipitation events in the region. It includes 19,184 monthly maxima records above 100 mm from 4325 observatories, occurring across 4814 days (events). Additionally, there are 1130 records exceeding 200 mm, grouped into 530 days and recorded in 664 observatories. As anticipated, extraordinary rainfalls were most frequent in autumn, while summer recorded the lowest number of events. These events occurred across nearly all regions, although a higher concentration were observed near coastlines. This is particularly the case of records and events over 200 mm, which concentrated along the Mediterranean arc. We identified five spatial patterns that correspond with specific weather types. Beyond atmospheric circulation, the topography played a critical role in determining the spatial extension of extraordinary precipitations. The newly digitised dataset is available at <https://digit.al.csic.es/handle/10261/354840>, accompanied by a collection of maps of daily events. Raw data from the AEMET's National Climate Data Bank are subject to a licenced agreement.

1 | Introduction

The study of extraordinary daily rainfall events is of critical importance, not only for engineering applications such as drainage and flood management (Senent-Aparicio et al. 2023) but also due to their frequent role in causing property damage and loss of life. Two concepts are intertwined in this analysis: daily maximum

precipitation and extreme events, which should be distinguished. Daily maximum precipitation refers to the highest observed rainfall within a specified time period, such as a month or a year, and is usually expressed as Rx1day. In Mediterranean climates, its significance is substantial, with daily maxima contributing, on average, 30% of the monthly total, a value that rises to 70% during the summer months when an entire

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month's precipitation can fall in a single day (González-Hidalgo et al. 2011). In Spain, Font-Tullot (1983) noted that the absolute daily maximum can represent between 10% and 20% of the annual total in northern regions and up to 40% in Mediterranean areas, where in the warm months, it can exceed 60%–70%. Claro et al. (2023) reported that such events account for 24%–28% of annual rainfall, with higher values in the summer and along Mediterranean coastal windward zones. These values underscore the fact that, in Mediterranean climates, annual and monthly totals often depend on just a few days of rainfall (Martín-Vide 2004).

Extreme events are, by definition, rare, and their thresholds are difficult to define, often determined by estimates of past events, return periods, deviations from the mean, or interquartile ranges (see Insua-Costa et al. 2021). Overall, the analysis of extreme events typically focuses on high-magnitude thresholds over 24-h periods and different return intervals. For example, in the eastern Spanish Mediterranean, Casas et al. (2004) classified extreme events as those corresponding to five-year return periods, while Pérez-Zanón et al. (2016) used the 10-year event. Pino et al. (2016) used synoptic conditions from historical floods, while Sillero-Medina et al. (2022) adopted 100 mm/day as the threshold for torrential rainfall. Beneto and Khodayar (2023) analysed events above 50 and 100 mm/day, while Lázaro et al. (2001) used a 100 mm/day threshold in south-eastern Spain, associated with return periods of approximately 30 years. In the Pyrenees, Lemus-Cánovas et al. (2021) found that this threshold was reached at most observatories within a return period of less than 10 years. In the north-eastern coastal areas, Lana et al. (1995) reported high probabilities of extreme precipitation exceeding 200 mm/day. Claro et al. (2023) applied thresholds of 20 mm/day and the 95th percentile across the entire Iberian Peninsula (Portugal and Spain), while Merino et al. (2016) used percentile-based analyses for the Iberian Peninsula and Balearic Islands. Similarly, Sanuy et al. (2024) employed thresholds of 100 mm/day and 200 mm/day to examine maritime storms linked to atmospheric patterns. This review highlights the wide variety of criteria in defining what is an extraordinary precipitation event.

2 | From Global to Regional Perspective of Extraordinary Precipitation Events

In regions of the world with a Mediterranean climate (Cs in the Köppen classification), it is generally assumed that rainfall is decreasing (Deitch et al. 2017; Seager et al. 2019), particularly during the winter months (Hoerling et al. 2012). Simultaneously, projections indicate an increase in extreme precipitation events (Pereira et al. 2021). However, a review of recent studies based on rainfall records paints a more nuanced picture. While a positive trend in extreme precipitation events has been suggested at a global scale (Alexander et al. 2006; Westra et al. 2013; Donat et al. 2016; Papalexiou and Montanari 2019; Myhre et al. 2019; Sun et al. 2021), these trends are neither consistently significant nor uniformly observed across the Mediterranean region. For instance, using annual maximum 1-day precipitation (Rx1day), Alexander et al. (2006) reported significant positive trends at only 7% of

824 stations and significant negative trends at 2.7% of stations for the period 1951–2003. Similarly, Sun et al. (2021), analysing 343 observatories between 1950 and 2018, found 54.2% of stations showing positive trends and 45.8% showing negative trends; however, in both cases, statistically significant trends were observed at fewer than 5% of the stations. Over a longer period (1900–2018), their analysis of 82 stations detected significant positive trends at 12.2% of sites (with global trends showing 57.3% and 42.7% of stations having positive and negative trends, respectively).

Furthermore, several challenges related to data availability and methodological approaches remain unresolved, as highlighted by Sippel et al. (2017) and Alexander (2016). These issues underscore the complexity and variability of precipitation trends in the Mediterranean climate areas and highlight the need for further detailed investigations.

Focusing on the Mediterranean basin, the behaviour of extreme precipitation events remains unclear. In a seminal study, Alpert et al. (2002) suggested an increase in extreme daily rainfall, “in spite of the fact that total rainfall generally decreases.” However, this observation is not consistently supported by more generalised findings, as several studies have reported no significant trends in various indicators of extreme events across the entire basin. For instance, no significant trends have been identified in the broader Mediterranean region (Piervitali et al. 1997; Norrant and Douguedroit 2006; Karagiannidis et al. 2012; Marani and Parisi 2014), the Middle East and North Africa (Zittis 2018), the Middle East (Zhang et al. 2005), central-eastern Mediterranean areas (Kostopoulou and Jones 2005), the eastern basin (Mathbout et al. 2017), the northern Mediterranean coastline (Toreti et al. 2010), the Maghreb (Tramblay et al. 2013a; Salhi et al. 2022), and northern Africa from Morocco to Egypt (Donat et al. 2014). Conversely, a recent study by Benabdelouhab et al. (2020) identified a positive trend in extreme precipitation within the western Mediterranean basin.

At a finer spatial scale, some significant signals have been detected in specific subregions of the western Mediterranean. These include the Mediterranean coast of France (Tramblay et al. 2013b; Ribes et al. 2019; Blanchet et al. 2021; Nouaceur et al. 2022; Blanchet and Creutin 2022), the eastern coastline of the Iberian Peninsula, particularly during autumn (Romero et al. 1999; Goodess and Jones 2002; Acero et al. 2011; Fernández-Montes et al. 2012; Miró et al. 2018, 2022), and Morocco (Khomsi et al. 2015; Ouatiki et al. 2019; Hadria et al. 2019).

A classical study by Rodrigo and Trigo (2007) did not detect significant trends in extreme precipitation events across the Iberian Peninsula. Similarly, in Portugal, no significant trends—or in some cases, negative trends—were observed in the northern regions (Santos and Frago 2013), southern areas (Durão et al. 2009), and the country as a whole (Costa and Soares 2009; Espírito Santo et al. 2014; de Lima et al. 2013, 2015; Santos et al. 2019). However, some studies have identified positive trends in southern Portugal (Durão et al. 2010) and across the entire country (Espinosa et al. 2022).

On the Spanish mainland, global analyses similarly show no significant overall trends (Gallego et al. 2006, 2011; García

et al. 2007; Rodrigo 2010; Merino et al. 2016; Serrano-Notivoli et al. 2018). Regional analyses also fail to reveal a generalised significant trend, with some areas even showing negative trends depending on the indicator used. For example, no consistent trends were detected in northeastern Spain (Burgueño et al. 2005; López-Moreno et al. 2009; Beguería et al. 2011; Valencia et al. 2012; Vicente-Serrano et al. 2017), southeastern Spain (Sánchez-Almodóvar et al. 2022), southern regions (Hidalgo-Muñoz et al. 2011; Valdéz-Abellán et al. 2017), and Extremadura in the southwest (García et al. 2018).

In northern Africa, including Morocco, the findings are consistent with those from the Iberian Peninsula, showing no significant trends in extreme precipitation (Tramblay et al. 2012; Filahi et al. 2016; Khomsi et al. 2016; Driouech et al. 2021; Hadri et al. 2021).

Overall, these studies vary in temporal coverage and data density, yet they consistently highlight the lack of a clear pattern in extreme precipitation events across the western Mediterranean basin. The digitisation of monthly maximum daily precipitation records (1916–1950) from the Annual Summaries of Observations Books, combined with data from the National Climate Data Bank (BNDC) of the Spanish Meteorological Agency (AEMET) (1951–2022), has facilitated a comprehensive study of extraordinary daily rainfall events across mainland Spain. This dataset offers high spatial resolution and extensive temporal coverage, providing an invaluable resource for analysing these events.

The objectives of this study are threefold:

- i. To identify daily events in which specific rainfall thresholds were exceeded.
- ii. To analyse the temporal and spatial variability of these events across mainland Spain (Iberian Peninsula).
- iii. To examine the atmospheric conditions associated with these events.

3 | Data and Methods

3.1 | Documentary Sources

The documentary sources employed in this study comprise two primary datasets: (i) the National Climate Data Bank (NCDB) provided by the Spanish National Meteorological Agency (AEMET), and (ii) recently digitised time series of monthly maxima records of daily precipitation, that is, the highest daily values for each month, from the Annual Summaries of Observations (AOS) books covering 1915–1950 (González-Hidalgo et al. 2024). This information serves as a key indicator in analysing extraordinary precipitation, commonly referred to as Rx1day (monthly maximum 1-day precipitation in this research), measured in mm, as defined by the Expert Team on Climate Change Detection and Indices (de Lima et al. 2015).

This analysis spans the period from 1916 to 2022, during which AOS contributes approximately 40% of the total data for the

years 1916–1950, highlighting the significance of historical paper records in supplementing existing datasets. From 1951 onwards, the National Climate Data Bank (BNDC) serves as the sole source of information, as the ASO publications from 1951 to 1960 lack these specific data.

3.2 | Extraordinary Precipitation Thresholds

Given the extensive period under analysis, the high density of data, and the focus on extraordinary events, we have selected two thresholds for analysing the monthly Rx1day: 100 mm (Rx1day_100), designated as extraordinary rainfall, and 200 mm (Rx1day_200), designated as very extraordinary rainfall. These thresholds were chosen because they represent very high rainfall amounts, which are theoretically rare in mid-latitude continental areas, and are likely to indicate potentially hazardous situations. Additionally, these thresholds have been used in numerous prior studies (Sillero-Medina et al. 2022; Beneto and Khodayar 2023; Lázaro et al. 2001; among many others, see introduction and also Section 5.1.), facilitating comparative analysis.

For each month and date on which Rx1day at any observatory exceeded the 100 or 200 mm thresholds, we identified all observatories that recorded their Rx1day on that same day, irrespective of the precipitation amount. The daily records of Rx1day that surpassed these thresholds were counted as frequencies, and termed “extraordinary records” and “very extraordinary records”, respectively, while the dates of occurrence were registered and termed as “events.” The first approach provides insights into the spatial distribution of precipitation during the event, while the second allows to assess the temporal occurrence of the events.

3.3 | Temporal and Spatial Distribution of Extraordinary Precipitation

Utilising these data, we generated cartographic representations of each event, depicting the spatial distribution of monthly Rx1day values that occurred on the respective day. These maps selectively display the maximum daily precipitation records that coincided with the event date, excluding observatories that reported their monthly maxima on different dates. Consequently, the maps effectively capture the precipitation patterns during each event, providing a reasonable approximation of its spatial extent, while the catalogue of events offers insight into the temporal evolution of extraordinary rainfall episodes.

Furthermore, the event mapping was expanded to encompass a three-day window, spanning from the day preceding to the day following the event. This approach facilitates identifying potential data collection anomalies, such as delayed recording of precipitation amounts, particularly in manual observatories following large storms. It also allows for the detection of extraordinary precipitation events that may persist beyond a 24-h period, providing a more comprehensive understanding of the spatial and temporal characteristics of these events.

3.4 | The Synoptic Conditions of the Event

The analysis of atmospheric conditions associated with extraordinary precipitation events was conducted by identifying the synoptic situations described by their daily weather types, following the classification scheme of Jenkinson and Collison (1977), which automates Lamb's manual classification and builds upon the processing and calculations by Trigo and DaCamara (2000). This classification has been effectively applied to precipitation and temperature data across the Iberian Peninsula, demonstrating optimal results in the analyses of extreme events along the Mediterranean coast (Llop-Garau and Alomar-Garau 2012a, 2012b; Gilibert and Llasat 2018; Cordobilla and Martín Vide 2018; Miro et al. 2020; Sánchez-Almodóvar et al. 2022).

To leverage the full potential of the available database, we utilised the surface pressure grid from the 20th Century Reanalysis (period 1836–2015; Slivinski et al. 2019), which has been recently validated for this purpose (Fernández-Granja et al. 2023). The classification node selected was the central grid point over the Iberian Peninsula (40°N, 357°E), and the analysis was restricted to the 1916–2015 reanalysis period. The resulting dataset is the WETYDAS v.2.0.0 database (Cortesi and Peña-Angulo 2024). After classifying the daily events by their weather type, we analysed their temporal frequencies and spatial distribution.

4 | Results

4.1 | Frequency of Observations and Daily Events

Throughout the analysed period, a total of 19,184 records of monthly Rx1day_100, as recorded by 4325 observatories over 4814 events (Table 1). October and November exhibit the highest frequency, with over 3000 observations each, followed by September and December with more than 2000 observations. January, February, and March also each have over 1000 records. Conversely, July shows the fewest instances, with only 294 daily observations of rainfall exceeding 100 mm. Between September and December, more than 500 days were identified where at least one observatory recorded their Rx1day_100, peaking in November with 687 events. The months with the fewest events are July (132), June (212), and August (242). Thus, from 1916 to 2022, daily rainfall exceeding 100 mm was observed in every month, averaging at least 3.78 days per month, and simultaneous occurrences across multiple observatories were not uncommon.

To illustrate the inter-annual variability of extraordinary precipitation, the ratio of the month with the highest number of records (October, with 3820) to the lowest (July, with 294) is approximately 13:1, while the ratio of the highest number of events (November, with 687 days) to the lowest (July, with 136 days) is around 5:2.

The dataset includes 1130 records of very extraordinary daily rainfall events Rx1day_200, distributed over 530 days from 664 observatories. These numbers demonstrate that such extreme rainfall events have occurred on multiple occasions in more than one observatory, with a notable concentration in September (196 records), October (349 records) and November

TABLE 1 | Total monthly records (Rx1day) and daily events > 100 and > 200 mm. Period 1916–2022.

	> 100 mm		> 200 mm	
	Records	Days	Records	Days
January	1616	477	51	32
February	1354	398	51	34
March	1092	375	43	31
April	789	273	41	29
May	615	239	28	18
June	523	212	20	13
July	294	132	18	14
August	577	242	18	13
September	2427	522	196	62
October	3820	659	349	138
November	3354	687	231	87
December	2723	598	84	59
Total	19,184	4814	1130	530

(231 records). Conversely, significantly less concentration of records is observed during the spring and summer months (fewer than 50 records). The lowest number of records corresponds to July and August (18 records each).

When examining the events temporal distribution, October is the month with the highest number of events Rx1day_200 (138 days), followed by November (87 days), September (62 days) and December (59 days). No month is devoid of such events, with the lowest event concentration occurring between May to August, with less than 20 events. The ratio between the months with the highest and lowest number of records exceeding 200 mm is 19:1, and the ratio for the number of events is around 10:1.

These results mean that, between 1916 and 2022, around 12% of days recorded precipitation exceeding 100 mm in at least one observatory, and around 1.4% of days saw rainfall over 200 mm.

Among the records exceeding 100 mm, a significant proportion also surpassed the 200 mm threshold. In October, 9% of observations exceeding 100 mm recorded values over 200 mm, while in September and November, the percentages were 8% and 7%, respectively. The lowest percentages are observed in the colder months, ranging from 3% to 5%.

The most remarkable events in terms of the number of stations recording values above the thresholds occurred on 06/11/1982, 04/09/1989, 17/12/1997 and 23/10/2000. In all of them, more than 100 observatories (more than 3% of the operational network stations) recorded rainfall greater than 100 mm/day. Furthermore, in the first case, 200 mm/day were exceeded in 12 observatories, 16 stations in the second, and 14 stations in the fourth case. In observations greater than 200 mm, the most extensive case is the event 04/11/1987, when 67 observatories

recorded more than 100 mm, the precipitation in 24 being more than 200 mm. In summary, the findings reveal that multiple observatories can record rainfall exceeding the established thresholds on the same day, and the likelihood of exceeding these thresholds varies by month.

Figure 1 illustrates the spatial distribution of stations recording monthly Rx1day_100 and Rx1day_200 between 1916 and 2022. In general, extraordinary daily rainfall events occurred more frequently along coastal areas and mountainous regions, with a clear concentration in specific sectors in the northern and central mountain ranges, the extreme south, and the eastern coast. However, extraordinary rainfalls were also recorded in inland areas, sometimes with a high spatial frequency of occurrence. Two regions are particularly notable for records exceeding 200 mm: the southwestern Mediterranean coast, close to the Strait of Gibraltar, and the central and northeastern Mediterranean coastline. Additionally, the occurrence of rainfall exceeding 100 mm/day was very high along the northern coast.

Some notable records from the dataset include:

- The day of the year with the highest number of records over 100 mm was November 5th, with 262 records, followed by November 6th, with 248 records.
- The day of the year with the highest number of records over 200 mm was October 19th with 34 records, followed by September 11th with 31 observations.
- The event with the highest number of records above 100 mm was December 17th 1997, with 116 records.
- November 4th 1987 was the event with the highest number of records over 200 mm, totalling 24.
- Accordingly Spanish Meteorological Agency (AEMET) absolute maximum is 814 mm at Olive S.E. Agraria station (code 8058A) in November, 3rd, 1987. In the ASO there is a higher value from Montcada i Reixac Soc. Geografica

station (code 0231) recorded in November, 29th of 1941, with 859 mm; this value is not officially accepted accordingly Spanish Meteorological Agency (AEMET).

4.2 | Temporal Variability of Extraordinary Precipitation Records

This section examines the temporal distribution of events and explores the presence of discernible trends. Figure 2 illustrates the annual frequency of monthly Rx1day_100 and Rx1day_200, alongside the total number of reporting stations. The number of reporting stations is a crucial factor, as it has undergone significant changes throughout the study period, potentially influencing the likelihood of detecting extraordinary precipitation events. The temporal evolution in the number of reporting stations is characterised by a pronounced increase since around 1940 up to 1975, followed by a gradual decline thereafter. Notably, three distinct discontinuities on this general trend are apparent around 1939–1940, 1952 and 1982. The first discontinuity is attributed to the Spanish Civil War, while the causes of the second and third remain unclear (Beguiria et al. 2023; González-Hidalgo et al. 2023), although the most recent one may be related to the automatization of the observational network.

The temporal evolution of records Rx1day_100 shows an increase starting in the mid-1940s, following a prolonged period with fewer than 100 cases per year. This upward trend reached its peak in 1989 with 565 records, concurrent with the expansion of the observatory network. Subsequently, the frequency decreased, only to experience a rebound in 2019 when there were 420 records. This pattern seems to be influenced by the evolution of the observatory network.

In contrast, the pattern for records Rx1day_200 appears to be less influenced by the evolution of the observatory network. The number of records remains relatively stable between 10 and 20 per year, with a certain increase during the 1980s and 1990s,

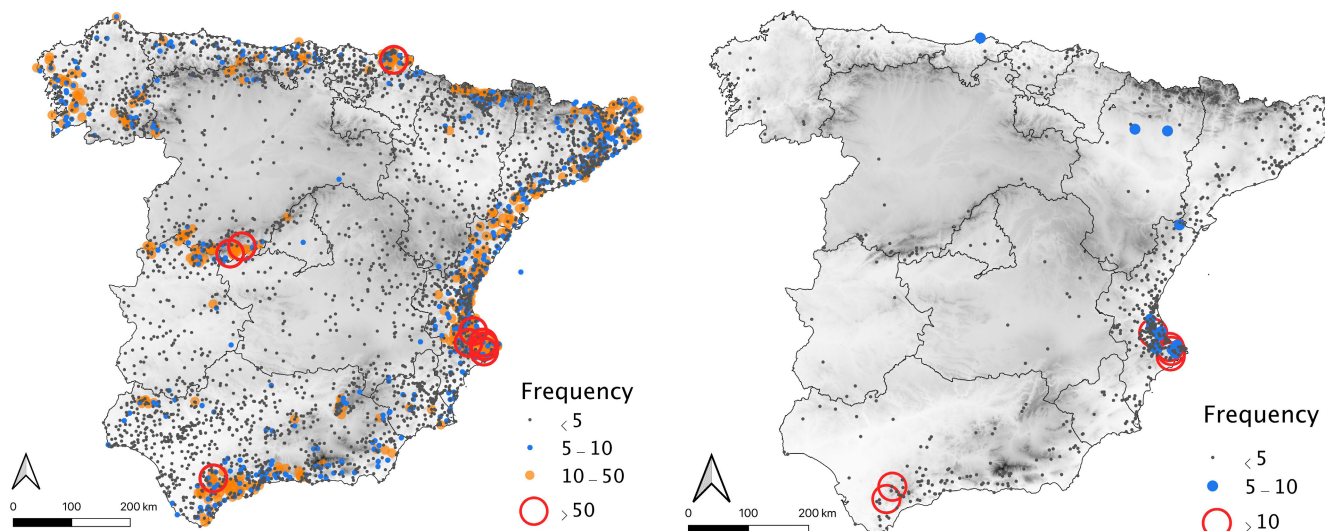


FIGURE 1 | Number of daily events where monthly Rx1day_100 (left) and Rx1day_200 (right) was recorded at each station. Period 1916–2022. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

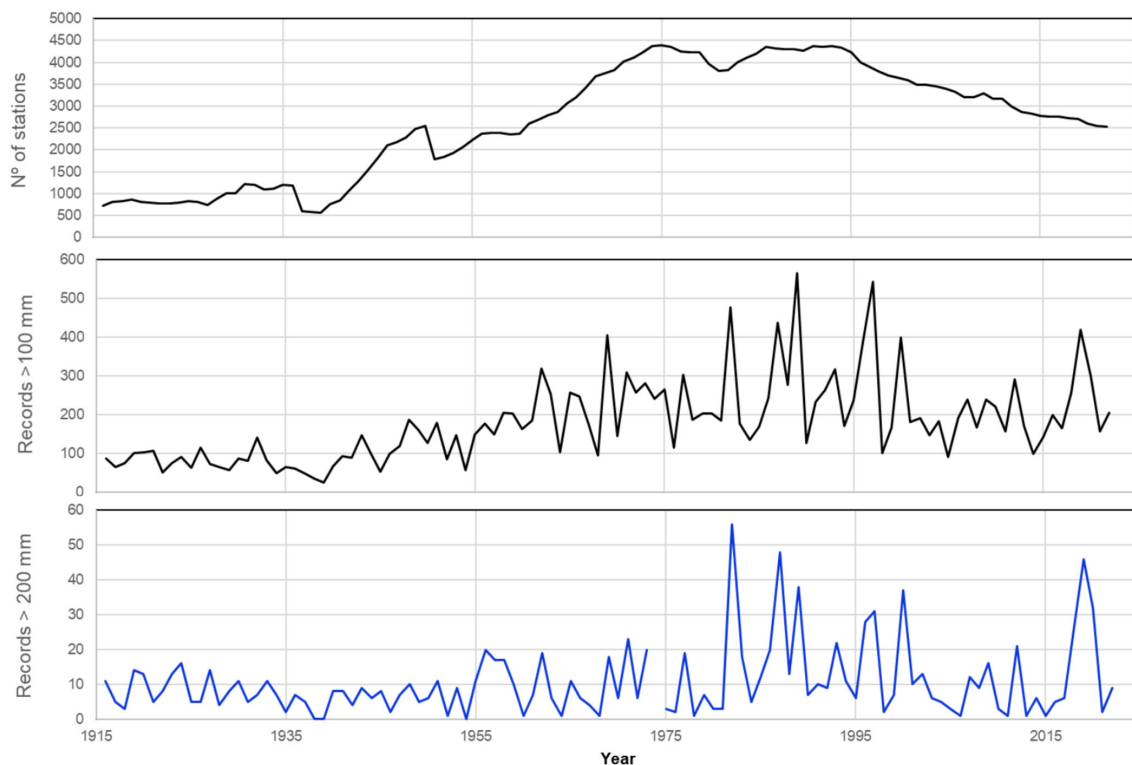


FIGURE 2 | Annual frequency (N°) of monthly Rx1day_100 (Note: Values divided by 10 for comparative purpose), and Rx1day_200 records and total number of operational stations. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

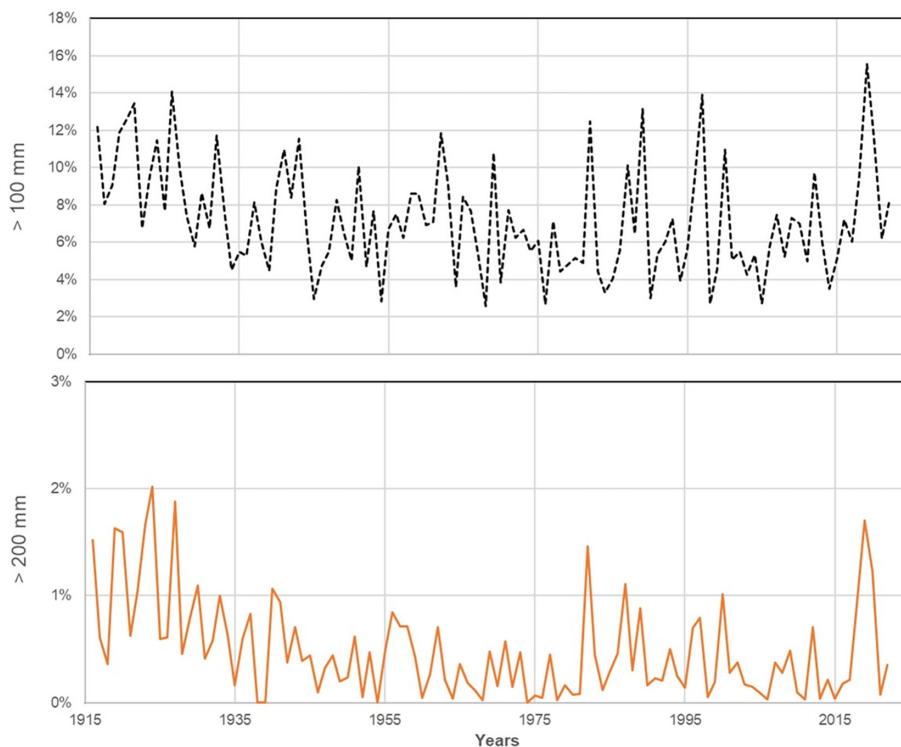


FIGURE 3 | Percentage of monthly Rx1day_100 and Rx1day_200 records relative to the operational stations. Period 1916–2022. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

followed by a decline in recent decades. Notable exceptions include 2019, which saw 46 records, and 1982, which holds the record with 56 observations of monthly Rx1day above 200 mm.

To make these values independent of the number of stations, Figure 3 presents the percentage of observatories that recorded monthly Rx1day_100. When examining the relative occurrence

of extraordinary records, the temporal pattern reveals a reversal compared to the previous one. A decline in the percentage of extraordinary records is observed until around the 1990s, followed by an increase thereafter. Notably, no evidence of a sustained linear trend in the frequency of records is detected.

The dataset enables extracting other statistics, such as the highest records of each year. Figure 4 shows the temporal evolution of the annual absolute maximum daily records. The figure suggests that the magnitude of the annual maximum rainfall typically averages 300 mm/day. There appears to be no discernible long-term trend of increase or decrease, and recent decades do not exhibit notable changes in this regard. This finding is

consistent with earlier studies (Font-Tullot 1983), confirming that 300 mm/day is a typical amount of very high annual daily rainfall in the Spanish meteorological network.

4.3 | Temporal Variability Extraordinary Precipitation Events

The extraordinary precipitation events (days with at least one observation of Rx1dayexceeding 100 and 200 mm) exhibit distinct temporal patterns that go beyond simple frequency counts of records at observatories. Figure 5 shows the annual number of events, alongside the number of operational observatories.

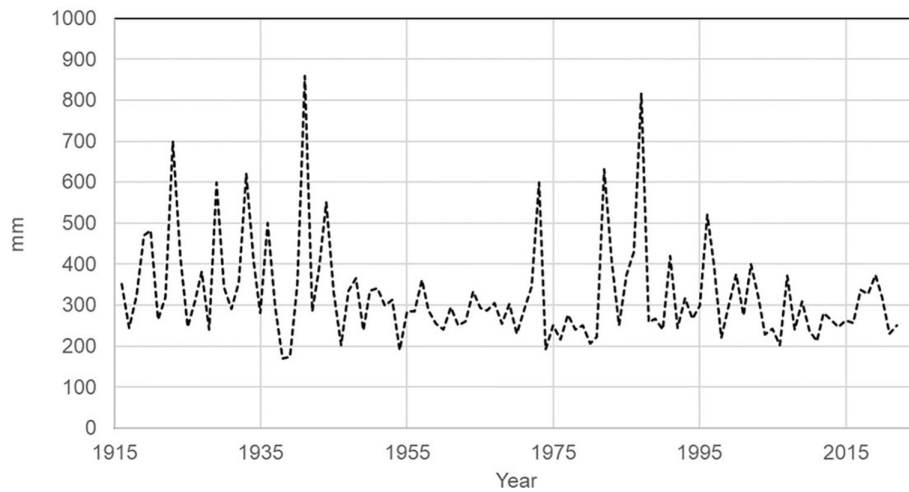


FIGURE 4 | Absolute annual maximum daily amount (mm). Period 1916–2022.

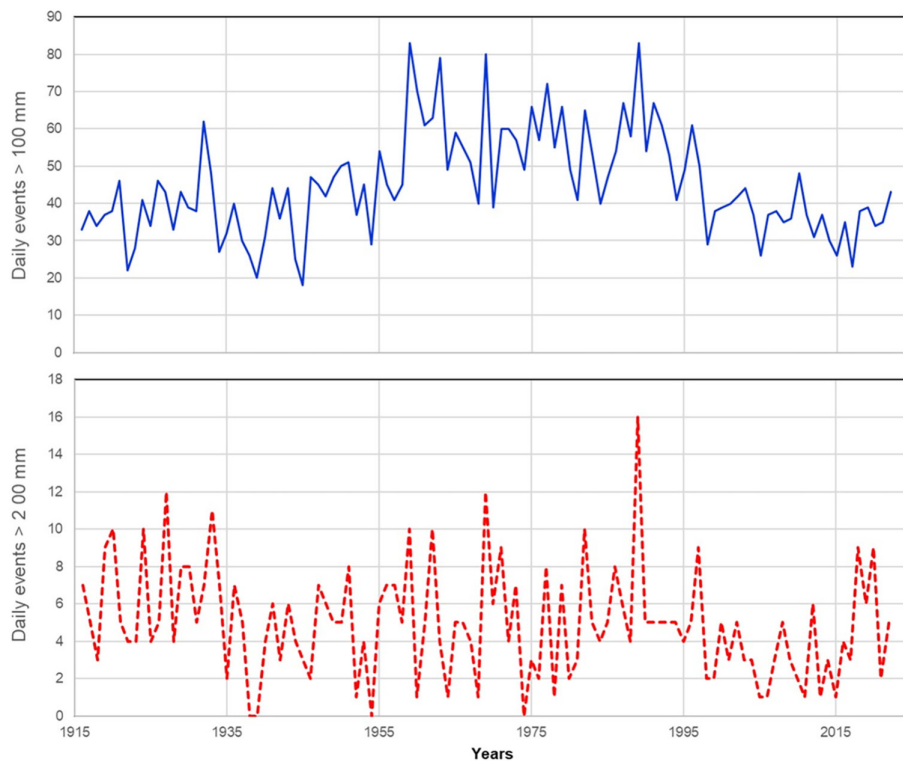


FIGURE 5 | Number of annual daily events greater than 100 and 200 mm. Period 1916–2022. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/terms-and-conditions)]

This approach reveals a dynamic that is less dependent on the network density than the frequency of records discussed earlier.

The number of events above 100 mm shows values between 30 and 40 days per year until the mid-20th century. However, between 1955 and 1990, there was a notable increase, peaking at around 50 days per year. After 1990, the frequency of these events decreased, returning to earlier levels of around 30–40 days per year. The peak years were 1959 and 1989, each with 83 days recording rainfall above 100 mm, followed closely by 1969 with 80 days and 1963 with 79 days. Over recent decades, it appears that on average, 10% of days in any given year experience rainfall above 100 mm somewhere in Spain.

In contrast, the annual number of days with rainfall exceeding 200 mm shows no clear pattern of increase or decrease over time. While fewer days each year register these extreme quantities compared to the 100 mm threshold, their occurrence remains relatively stable, averaging around 3–5 days per year. The years with the highest number of such events were 1989 (16 days)

and 1969 (12 days). In certain years, such as 1954, 1979, 1938, and 1939, no observatory recorded rainfall exceeding 200 mm. However, it should be kept in mind that the years 1938 and 1939 notably coincide with the final phase of the Spanish Civil War, during which observational coverage was greatly reduced.

The irregularity in the density and distribution of observatories over the study period complicates any conclusions about long-term trends in the frequency of these extraordinary rainfall events. However, it appears that the occurrences of both extraordinary precipitation events have remained relatively stable.

4.4 | Spatial Variations

The spatial distribution of monthly Rx1day records exceeding 100 mm, illustrated in Figure 6, reveals important geographic and topographic patterns. These records are organised into hexagonal spatial units, where the frequency of rainfall events is counted regardless of how many observatories are located within

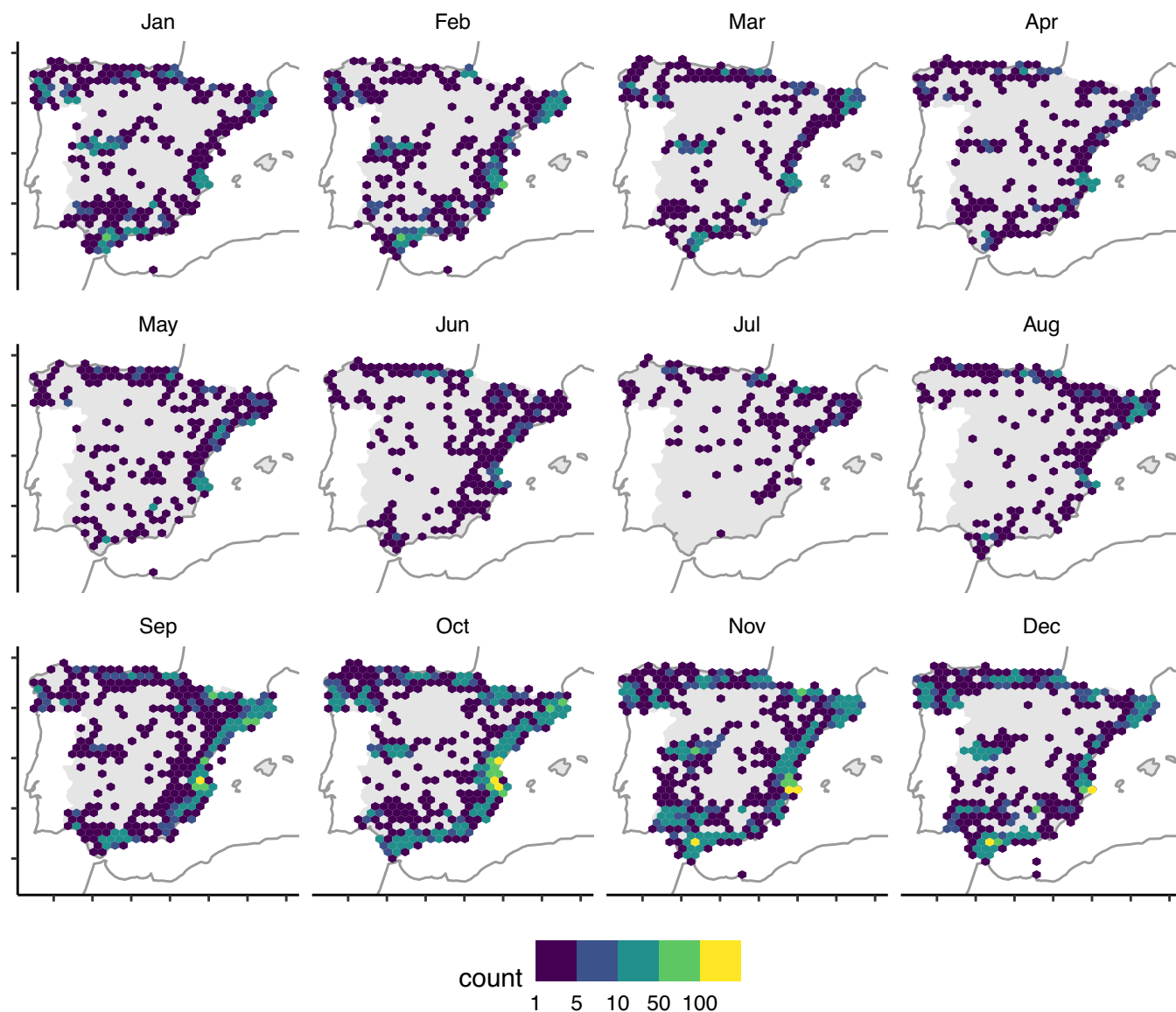


FIGURE 6 | Monthly distribution frequency of Rx1day₁₀₀. Period 1916–2015. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/joc.8785)]

each hexagon. Rainfall exceeding 100mm tends to form bands that run parallel to the coastline and along the main mountain ranges, with frequency increasing notably during autumn and the beginning of winter. The highest values are typically observed near, though not directly on, coastal regions, indicating a clear influence of the surrounding topography. Mountain ranges seem to play a crucial role, with rainfall intensifying due to orographic effects, which suggest a significant role of relief in concentrating precipitation in these areas.

Unlike the previous case, monthly Rx1day_200 shows a greater concentration in time between the months of September and November, and in space on the eastern side of the Iberian Peninsula (Figure 7). These events occur predominantly between September and November, indicating a seasonal concentration in autumn. The Mediterranean coastline and adjacent inland regions show the highest frequency of these intense rainfall events, further supporting the idea that orographic lifting in these regions, combined with seasonal weather

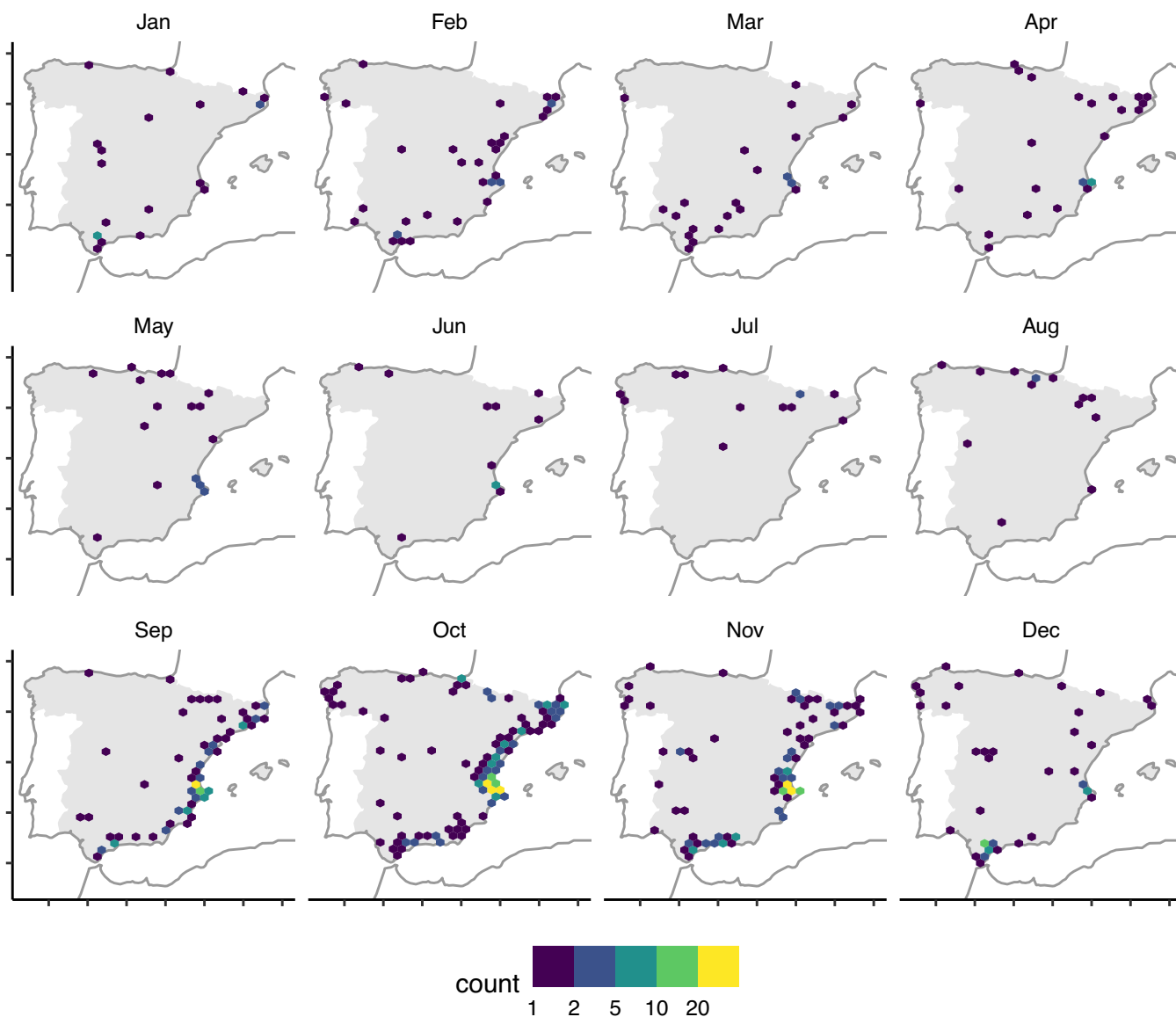


FIGURE 7 | Monthly distribution frequency of Rx1day_200 records. Period 1916–2015. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

TABLE 2 | Monthly percentage distribution of the monthly Rx1day records (Station) and events (days) on which they occurred. Period 1916–2022.

	J	F	M	Ap	My	Jn	Jl	Ag	S	O	N	D
100mm Stations	8.4	7.1	5.7	4.1	3.2	2.7	1.5	3.0	12.7	19.9	17.5	14.2
200mm Stations	4.5	4.5	3.8	3.6	2.5	1.8	1.6	1.6	17.3	30.9	20.4	7.4
100mm Events	9.9	8.3	7.8	5.7	5.0	4.4	2.7	5.0	10.8	13.7	14.3	12.4
200mm Events	6.0	6.4	5.8	5.5	3.4	2.5	2.6	2.5	11.7	26.0	16.4	11.1

patterns, plays a significant role in producing such extraordinary rainfalls.

Table 2 summarises the monthly frequency of events in which both thresholds were exceeded. The period between September and December accumulates more than 64% of the records greater than 100 mm and 75% of those of 200 mm, although the proportion in December decreases. By daily events, the proportion drops in both cases to 50% and 60%, respectively. The results show that extraordinary and very extraordinary daily rainfall is likely to occur in all months, although it tends to be concentrated in some months more than in others, with a clear preference for autumn, followed by the winter months. In the case of rainfall greater than 200 mm, these rainfalls tend to concentrate on the Mediterranean façade and in the autumn months.

TABLE 3 | Frequency of events (days) with precipitation > 100 mm and 200 mm according to the weather type (WT). Period 1916–2015.

WT Type	WT code	> 100 mm		> 200 mm	
		Total	%	Total	%
Anticyclonic	A	247	5.4	15	3.0
Cyclonic	C	744	16.3	87	17.7
North	N	350	7.7	30	6.1
North East	NE	433	9.5	44	8.9
East	E	718	15.7	107	21.7
South East	SE	388	8.5	69	14.0
South	S	227	5.0	28	5.7
South West	SW	497	10.9	42	8.5
West	W	617	13.5	43	8.7
North West	NW	345	7.6	27	5.5

TABLE 4 | Monthly frequency of daily events > 100 mm according to weather types. Period 1916–2015.

	J	F	M	Ap	My	Jn	Jl	Ag	S	O	N	D	Total
A	31	19	17	12	9	13	8	15	21	34	40	28	247
C	61	55	56	68	40	25	12	27	75	101	132	92	744
NW	48	31	35	29	22	19	9	6	17	27	44	58	345
N	21	18	25	22	48	28	16	24	26	40	47	35	350
NE	19	18	23	24	44	44	43	50	52	55	34	27	433
E	40	46	28	32	24	54	32	83	142	106	69	62	718
SE	25	27	26	11	14	6	6	19	73	80	60	41	388
S	29	20	24	5	3	1		1	21	48	50	25	227
W	96	96	70	27	19	10	3	3	35	64	80	114	617
SW	77	52	41	26	9	4		1	34	75	96	82	497
Total	447	382	345	256	232	204	129	229	496	630	652	564	4566

4.5 | Relationship With Synoptic Situations

The preceding findings suggest that extraordinary precipitation events may stem from diverse atmospheric mechanisms, distinguishing between the western and eastern peninsular environments due to differences in Atlantic and Mediterranean air masses, combined with major mountain alignments. In this section we analyse the relationship between these events and a weather types classification following Jenkinson and Collison (1977).

As Table 3 shows, extraordinary precipitation has been observed across all weather types, but a notable concentration is found in the C (cyclonic 16.3%), E (East 15.7%), SW (Southwest 10.9%) and W (West 13.5%) types, which together account for more than 56% of the total daily events. For events of precipitation exceeding 200 mm, this is reduced to three main weather types: C (17.7%), E (21.7%) and SE (14.0%).

These distinctions in weather patterns suggest that different areas might be affected by varying weather types, and the spatial distribution of extreme events is correspondingly diverse. Moreover, the timing of these events also varies, as C and E types are more common in autumn and December, while SW and W types are predominant from mid-autumn to March (Table 4).

We illustrate this concept with an example by presenting the monthly frequency distribution of Rx1day_100 records under E (East) and SW (Southwest) (Figure 8). This figure not only showcases spatial variations but also temporal differences in extraordinary events, highlighting the influence of Atlantic or Mediterranean air masses. For example, the SW type is absent in July, as no events have been recorded under this weather type during that month. This visualisation highlights the complex interplay between atmospheric patterns and the occurrence of extreme rainfall across different regions and months.

A large part of Rx1day_200 records occur under three main weather types: C (Cyclonic), E (East), and SE (Southeast).

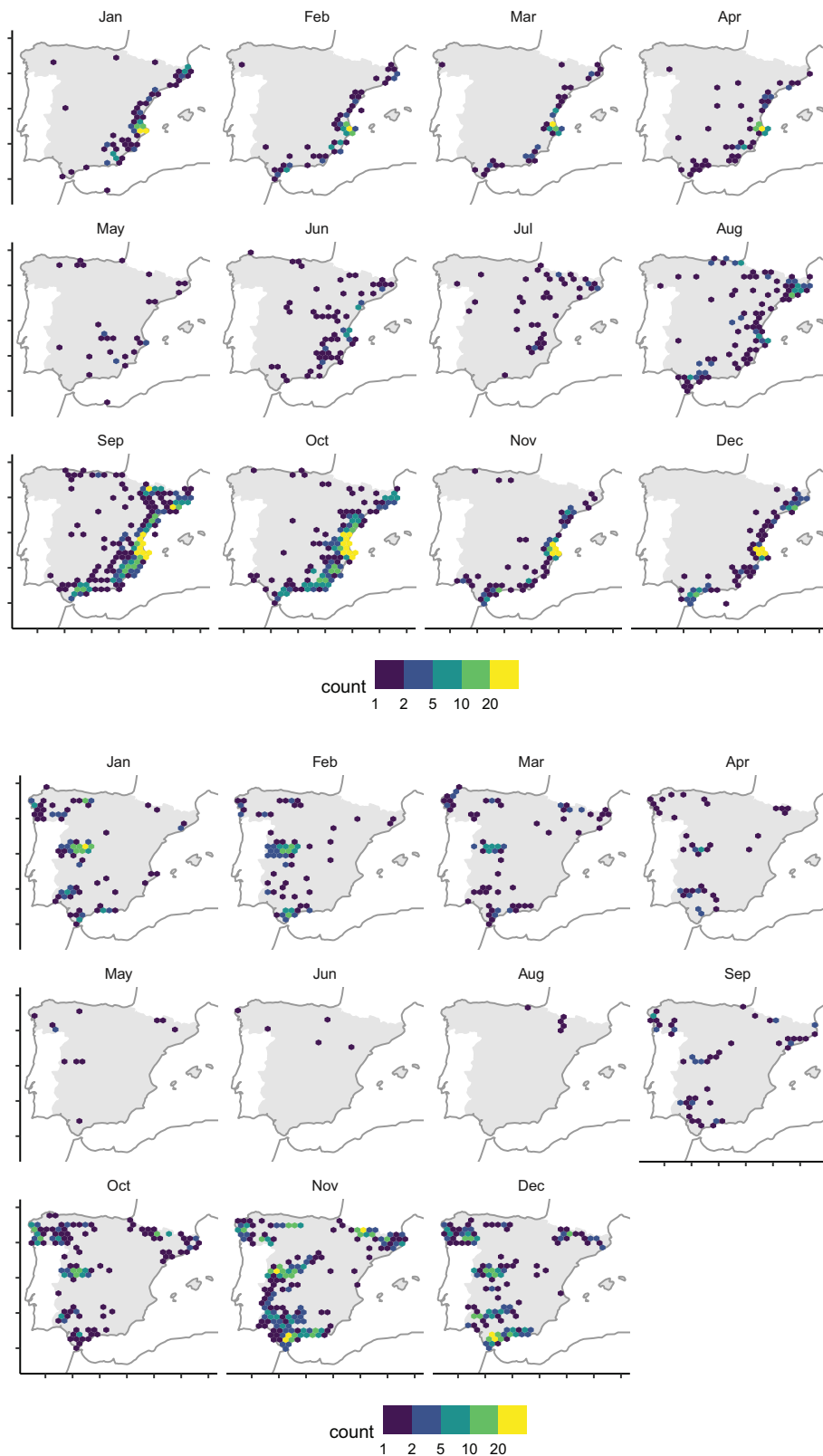


FIGURE 8 | Monthly distribution of the frequency of Rx1day_100 records in East (E) (top) and South-west (SW) (bottom) weather type conditions. Period 1916–2015. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

These three weather types account for more than 50% of the records, with each contributing over 10%. Additionally, the frequency of cyclonic and East weather types increases particularly

during autumn, while the frequency of Southwest and West types diminishes. This might be related to air flows of Atlantic origin that predominate in autumn and winter, which seem to

be less capable of producing such high precipitation intensities. Figure 9 illustrates the distribution of records under the E type, notably showing that there are no records in June and July, and their absence in northern and western areas.

4.6 | Spatial Patterns of Extraordinary Precipitation Events

The comprehensive analysis allows us to identify several distinct spatial patterns of extraordinary precipitation across the Iberian Peninsula, which are shown in Figure 10 categorised as the North, West, Southwest, South, East, and Northeast. For each pattern, we show one example from the catalogue. Each pattern exhibits unique characteristics regarding the frequency and distribution of intense rainfall events, which can be linked to the prevailing weather types and their seasonal variability. These patterns provide valuable insights into how different parts of the Peninsula are affected by intense precipitation under specific synoptic conditions.

The spatial distribution of extraordinary precipitation is closely related to the topography in all patterns. For instance, in the

northern pattern and along the Mediterranean coast, extraordinary records tend to occur near the coastline, with inland areas often not being affected. In contrast, the southwestern pattern reveals that the alignment of relief in the Guadalquivir basin (southwest-northeast) enables Atlantic air flows to penetrate further inland along the valley. Similarly, in the western pattern, the extraordinary records occur further inland due to the west–east alignment of mountains, which does not obstruct Atlantic air flows. However, it is noted that Rx1day records are often linked to local conditions dominated by topography, highlighting the complex interplay between atmospheric and geographic factors.

5 | Discussion

5.1 | Previous Studies and the Need for a Comprehensive Catalogue of Extraordinary Precipitation Events

There is a vast literature concerning intense, extraordinary, and extreme precipitation events in the Mediterranean basin. Poesen and Hooke's (1997) seminal review includes data and

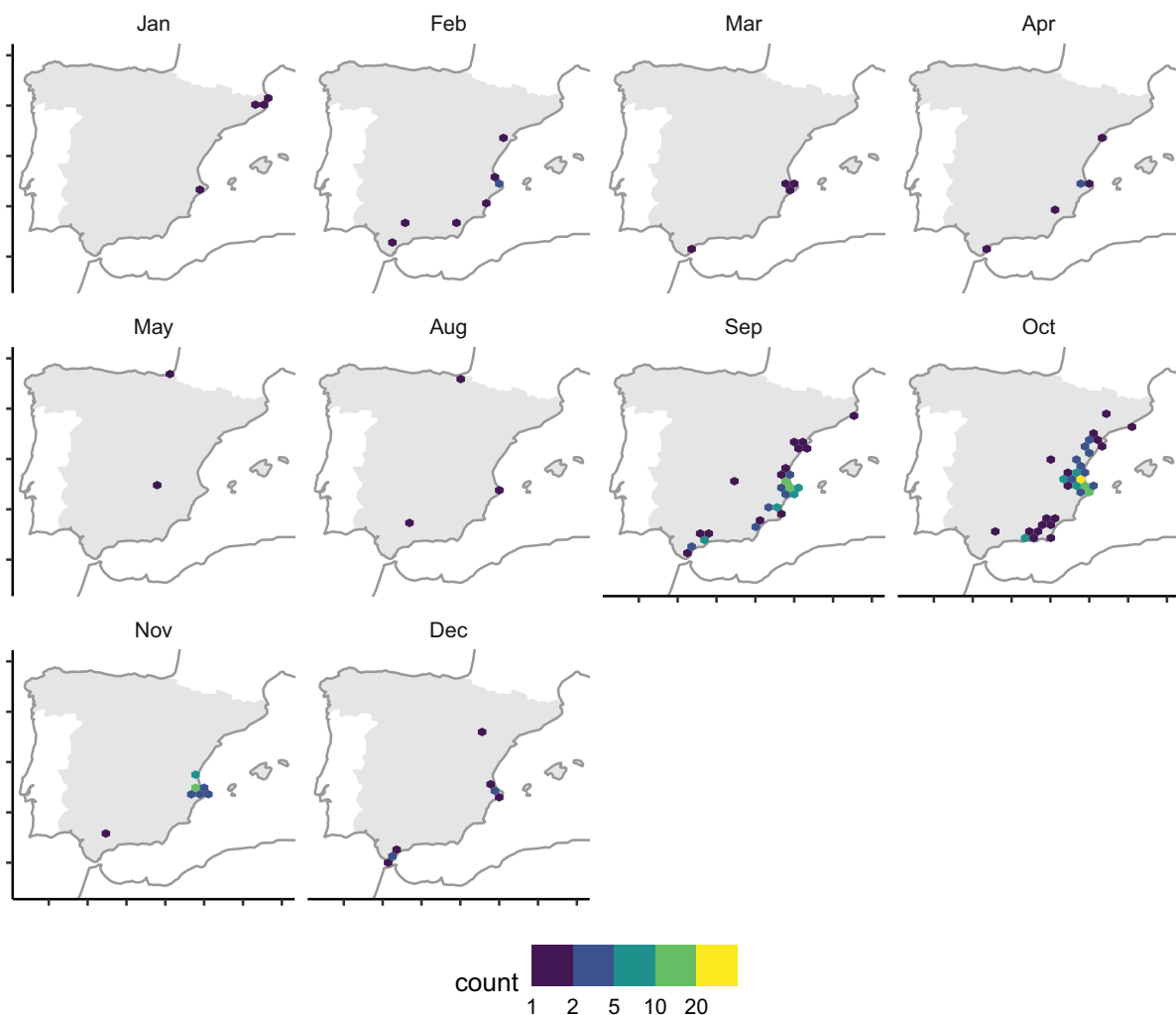


FIGURE 9 | Monthly distribution of the Rx1day₂₀₀ records. Weather Type East (E). Period 1916–2015. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

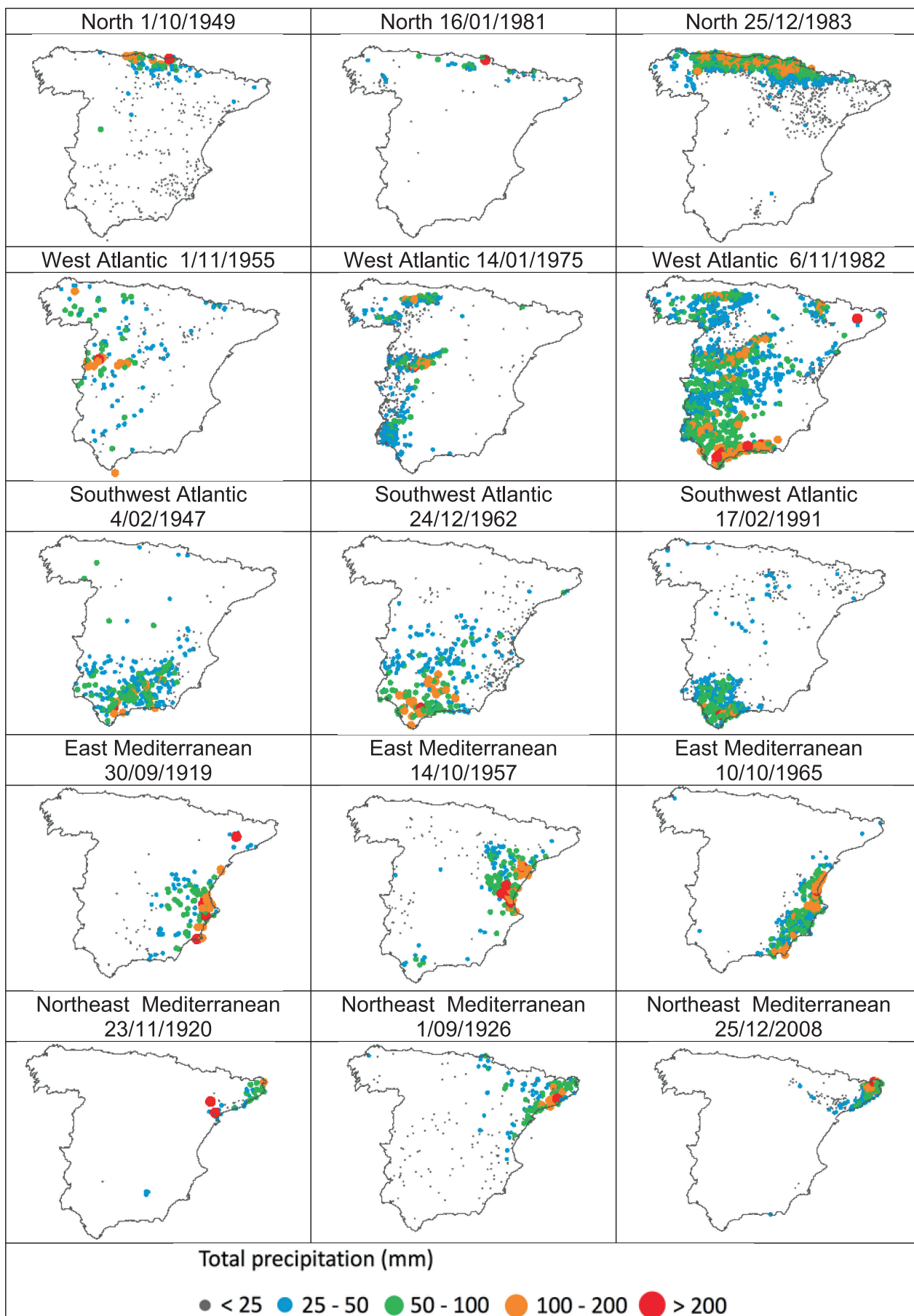


FIGURE 10 | Examples of spatial patterns of monthly Rx1day_200 mm events. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

maps documenting rainfall amounts of several hundred millimetres within a 24-h period, with absolute maxima surpassing 900 mm/day in some Italian observatories. These values are comparable to the highest records in Spain, where maximum rainfall events have exceeded 800 mm/day. Numerous studies have analysed these extreme precipitation events along the Spanish Mediterranean coast, underscoring their high frequency. A summary of some of these findings is provided in Table 5.

This predominance of extreme rainfall along the eastern coast of the Iberian Peninsula has been highlighted in numerous works including Pérez-Cueva (1983), Llasat (1987), Olcina (1994a, 1994b), Martín-Vide (1994), López-Bermúdez and Romero (1993), Insua-Costa et al. (2021), Martín-Vide et al. (2021), Sánchez-Almodóvar et al. (2022), and Beneto and Khodayar (2023). These studies collectively emphasise the vulnerability of the Spanish Mediterranean façade to intense rainfall events, driven by both regional climatology and synoptic-scale weather patterns.

The available information on extreme rainfall events along the Mediterranean margin contrasts with the scarcity of studies covering other regions of the Iberian Peninsula or with those conducted at a peninsular scale. In the former case, research often focuses on localised extraordinary rainfall events, usually tied to incidents such as floods, landslides, and the resulting loss of life and property. These studies, however, do not offer a comprehensive view of extraordinary rainfall patterns across the entire peninsula, and there are relatively few examples. Notable exceptions include Queralt et al. (2009), who examined 102 torrential rain episodes from 1997 to 2006, albeit using a limited observational network. Similarly, Merino et al. (2016) analysed data from 45 stations across mainland Spain and the Balearic Islands, identifying 1175 extreme precipitation events between 1960 and 2011. Their study highlighted the significant influence of topography and convective synoptic conditions, which were closely linked to indices such as the North Atlantic Oscillation index (NAOi) and the Western Mediterranean Oscillation index

(WeMOi), particularly in the eastern mainland. Finally, Ramos et al. (2018) analysed summer extreme events related to atmospheric rivers across the Iberian Peninsula.

Classical texts by Elías-Castillo and Ruiz-Beltrán (1979) on maximum rainfall in Spain (for the period 1940–1970), and Font-Tullos's (1983) analysis of the climate of Spain and Portugal (for 1940–1980), offer valuable historical insights. These works include maps illustrating the probabilities of surpassing certain rainfall thresholds (Elías-Castillo and Ruiz-Beltrán 1979), and records of observed maxima (Font-Tullos 1983). Both works illustrate that daily rainfall exceeding 100 mm has been recorded across most coastal areas of the peninsula, and that such events occur with a relatively short return period. Moreover, daily totals above 200 mm are not uncommon, with the observed maxima often closely linked to the region's complex topography.

The need to update historical data from the early 20th century and to conduct a more detailed analysis of extreme precipitation events served as primary motivation for compiling the present catalogue and analysis. Thanks to this new catalogue, it has been possible to offer novel insights into the spatial and temporal dynamics of extraordinary precipitation across the Iberian Peninsula, particularly in regions where analyses of such events is limited, including the southwest, west and northern areas. Additionally, it enabled a first-ever look at the occurrence of these events during the early decades of the 20th century, filling significant gaps in our understanding of extreme precipitation patterns in these regions.

Some important caveats are necessary when interpreting the results of this study. The new catalogue is not exhaustive from a spatial perspective, as it currently omits data from the Spanish archipelagos (Balearic and Canary Islands). Additionally, the catalogue's focus on monthly Rx1day means that other extraordinary daily precipitation events below the monthly maximum are not included in the dataset. Furthermore, the use of 100 and 200 mm as thresholds for extraordinary events may

TABLE 5 | List of studies of extraordinary rainfall in Spain.

Author	Threshold mm/day	Events	Period	Area
Peñarrocha et al. (2002)	> 250	57	1971–1995	Valencia
	> 350	19	1971–1995	Valencia
Martín-Vide et al. (2008)	> 100	304	1950–2006	Cataluña
Llop-Garau and Alomar-Garau (2012a)	> 100	304	1950–2005	Cataluña
		387	1950–2005	Mallorca
Llop-Garau and Alomar-Garau (2012b)	> 200	49	1931–2001	Mallorca
Gilabert and Llasat (2018)	> 100	261	1900–2010	Cataluña
Riesco-Martín et al. (2014)	> 100	63	2006–2010	Southern coastland
Meseguer-Ruiz et al. (2018)	> 200	239	1950–2016	Júcar and Segura basins
López-Bustins et al. (2020)	> 200	50	1956–2016	Cataluña
Martín-Vide et al. (2021)	> 200	68	1941–2017	Murcia and Alicante
Sánchez-Almodóvar et al. (2022)	> 100	129	1981–2020	Alicante

overlook other significant precipitation events with severe impacts at subregional or local scales. As noted by Merino et al. (2018), rainfall events below these thresholds can still have devastating consequences that are not reflected in the catalogue.

Several notable examples illustrate these limitations. For instance, the Aguilón flood in Zaragoza on September 20, 1921, resulted in 18 fatalities despite a recorded rainfall of only 79.2 mm at a nearby observatory, which is not highlighted in the catalogue. Similarly, intense storms with lower rainfall amounts, such as the summer 2023 storm in Zaragoza that inundated parts of the city with 60 mm of precipitation in a short period, will not be captured in future updates due to not meeting the established thresholds. These examples underscore the importance of considering multiple sources and perspectives when assessing extreme weather events and their impacts.

5.2 | Spatial Patterns and Explanatory Mechanisms

The unique geography of the Iberian Peninsula, situated between the Atlantic and Mediterranean air masses, creates a diverse range of rainfall regimes influenced by the contrasting characteristics of these bodies of water. The complex topography of the peninsula plays a significant role in shaping the spatial distribution of rainfall, with the alignment of mountain ranges having a profound impact on the influence of different air masses and related extreme events. As shown in this paper, Atlantic advections from the west can lead to heavy rainfall events well inland, whereas Mediterranean advections from the east typically result in maximum rainfall along the coastal strip due to the barrier effect of surrounding mountain ranges. In northern regions, the influence of Atlantic advections is also limited to the coastline due to mountainous barriers.

Notably, extreme rainfall events exceeding 200 mm/day are mostly restricted to coastal areas, with notable occurrences near transverse barriers associated with maritime advections, particularly along the Mediterranean and in southwestern regions. However, extreme events exhibit high spatial variability across the Iberian Peninsula.

The frequency of monthly Rx1day exceeding 100 and 200 mm varies significantly across different regions, with distinct calendar patterns. This suggests that the water-holding capacity of easterly and westerly advections differs, implying that the origin of air masses controls the magnitude of extreme events. In other words, the source of the air mass plays a crucial role in determining the severity of rainfall events in different parts of the peninsula.

Diverse mechanisms have been identified as triggers for extreme rainfall episodes; Llasat (1987) particularly in north-eastern Spain, highlighted the role of cut-off lows, also known as DANAs (Spanish acronym), and convective processes (Llasat et al. 2021). Martín-Vide (1989) expanded this by including cold storms, western cold fronts, and mesoscale disturbances. Castillo-Requena (1978) proposed specific pathways for these cut-off lows that align with patterns observed

in this study. The different effects of weather types have been explored by Romero et al. (1999), Sánchez-Almodóvar et al. (2022) and Riesco-Martín et al. (2014) who linked extreme rainfall as a triggering factor of Mediterranean coastland and southern Spain to eastern and north-eastern weather advection, emphasised the role of relief and convective synoptic conditions in torrential rainfall. Pérez-Zanón et al. (2016) in their analyses of the Ebro Observatory records (1905–2003), suggest that the presence of a depression southwest of the Iberian Peninsula, combined with a blocking anticyclone over Europe, typically results in moist and warm Mediterranean advection. This leads to prolonged advective precipitation and extremely intense rainfall from associated convective phenomena. Under the aforementioned conditions, the maximum daily rainfall recorded at this station was 257.6 mm. In Mallorca, Llop-Garau and Alomar-Garau (2012b) link the events exceeding 100 mm per day with cyclonic weather types and easterly and northerly flows, with similar findings in other Mediterranean regions. In the central sector of the Mediterranean coast, Peñarrocha et al. (2002) identified an enhancing relief effect with eastern flows, a similar conclusion found by Martín-Vide et al. (2021) in the provinces of Alicante and Murcia for events of > 200 mm/day.

Other approaches have explored the connections between extreme precipitation and teleconnection indices. For example, Gilabert and Llasat (2018) differentiated between weather types that are effective in extreme events on the Mediterranean coast, noting the influence of maritime flows and cyclonic conditions. In the Pyrenees, Vicente-Serrano et al. (2009) and Lemus-Cánovas et al. (2021) identified correlations with the NAOi and WeMOi indices, while López-Bustins et al. (2020) and Meseguer-Ruiz et al. (2018) found that events exceeding 200 mm/day were associated with negative phases of WEMOI during autumn.

In summary, extraordinary precipitation events on the Spanish Mediterranean coast are primarily linked to situations where cyclonic instability, eastern flows, or a combination of both prevail, with topography playing a significant role in triggering these events. This conclusion is supported by the comprehensive analysis of monthly Rx1day and the catalogue along the Mediterranean coast. However, the present catalogue also reveals that other types of air masses are associated with extreme precipitation events in southwestern regions, as well as in western and northern parts of the country. The variation in the origin of these air masses explains the observed monthly and spatial differences in precipitation events exceeding 100 or 200 mm.

5.3 | Seasonal Patterns

Extraordinary precipitation events in Spain exhibit distinct seasonal patterns, with a tendency to cluster in autumn along the Mediterranean coast, although winter events are also common. During the colder months, these extreme events are often associated with Atlantic cold fronts in northern and western regions, whereas in the southwestern quadrant, they are linked to southern Atlantic advections.

The relief features of the region play a significant role in shaping the distribution of these precipitation events, sometimes channelling them inland. The patterns identified in this study, such as those from the North, West, and Southwest, demonstrate how topographic barriers can constrain the spatial extent of extreme rainfall.

Notably, the findings of this catalogue align with the pioneering research conducted by Font-Tullot (1983) and Elías-Castillo and Ruiz-Beltrán (1979), confirming the accuracy of their early observations. This study extends the reference period and spatial coverage of these earlier studies to 1916–2022, providing a comprehensive collection of maps for each event.

5.4 | Are the Extremes Increasing in Spanish Mainland?

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (IPCC-AR6, 2021) published in 2021 indicates that there is no clear positive trend in extreme precipitation events, except under the most extreme scenario (RCP8.5/SSP5-8.5), which is considered as highly unlikely by some experts (Hausfather and Peters 2020; Hausfather et al. 2022; Pielke Jr. and Ritchie 2021; Burguess et al. 2022) and acknowledged as exaggerated by the IPCC itself (AR6 Table 12.12, Chapter 12, page 1856).

However, despite this lack of a clear trend, there is still high uncertainty surrounding potential changes in seasonal rainfall patterns, even if annual total precipitation remains stable. This is because minor changes in heavy precipitation episodes can significantly alter the distribution of monthly or annual totals due to their high contribution to total rainfall. Such changes could have severe consequences for both natural systems and human societies, impacting water storage, runoff, soil erosion, and slope stability. The recent flood disasters in Libya (summer 2023) and Valencia (fall 2024) illustrate the devastating impact that extreme precipitation can have, highlighting the need for adaptation and increased resilience.

This study found no evidence of an increase in the frequency of extraordinary precipitation events exceeding 100 or 200 mm in the Spanish mainland from 1916 to the present. The observed variations in the frequency of extraordinary events seem to be more related to changes in the observation network rather than to a genuine increase in the frequency of extremes.

The present study is consistent with the literature review presented in Section 2 of this article, from which no generalised trends of extreme events are detected in the Mediterranean basin and western European countries (Gallego et al. 2006, 2011; García et al. 2007; Rodrigo 2010; Merino et al. 2016; Serrano-Notivol et al. 2018). However, some studies have reported positive trends in extreme events in specific areas of coastlines, such as the Mediterranean Sea south of France (Tramblay et al. 2013b; Ribes et al. 2019; Blanchet et al. 2021; Nouaceur et al. 2022; Blanchet and Creutin 2022), the eastern and southern coastland of the Iberian Peninsula (Romero et al. 1999; Goodess and Jones 2002; Acero et al. 2011; Fernández-Montes et al. 2012; Miró et al. 2018, 2022), and Morocco (Khomsi et al. 2015;

Ouatiki et al. 2019; Hadria et al. 2019). These findings suggest that future detailed spatial analyses are necessary to understand the relationship between the warming of the Mediterranean Sea and extraordinary precipitation in this area.

6 | Conclusions

This study offers a comprehensive examination of extraordinary precipitation in the Spanish mainland, drawing on a new catalogue of monthly Rx1day records. It highlights the significant spatial and temporal variability of such events and underscores the influence of geographical features and weather patterns on extreme rainfall distribution. The catalogue, spanning from 1916 to 2022, provides valuable insights into the frequency, intensity, and distribution of high rainfall events, contributing to a better understanding of their historical context and patterns, and offers an exhaustive cartography of each event. Key findings from the study include:

- Extraordinary precipitation events, though rare, occur with a frequency worth noting across the Spanish mainland. From 1916 to 2022, a total of 4814 days recorded rainfall exceeding 100 mm in at least one observatory (12.4% of days), and rainfall over 200 mm has been recorded in 530 days (1.4% of time).
- Mediterranean regions, particularly along the eastern coast and southern regions, experience higher frequencies of extreme rainfall compared to other areas. In contrast, Atlantic influences are more significant in the northern and western parts of the Iberian Peninsula.
- No temporal trend is detected in the frequency of extraordinary events in the Spanish mainland (period 1916–2022).
- The relief plays a crucial role in shaping extraordinary rainfall event patterns. Atlantic advections produce heavy rainfall far inland from the west, while Mediterranean advections tend to be concentrated along the coast due to the barrier effect of mountain ranges.
- A few weather types are associated with most extraordinary precipitation events. For instance, cyclonic conditions and easterly flows are prominent in Mediterranean regions, while west and south-west advections are linked to rainfall in northern and western areas. Seasonal variability shows that autumn (in the Mediterranean coast) and winter months (in northern, western and southwestern regions) are more prone to extreme events, although significant rainfall also occurs in summer and spring.
- The extraordinary precipitation events catalogue, while comprehensive, does not yet cover the archipelagos and might miss events below the established thresholds that could have had significant local impacts.

In conclusion, this study underscores the need for ongoing research to track trends in extreme precipitation and adapt to potential future changes. While no significant increase in extreme rainfall has been observed in Spain over the study period, continued monitoring and analysis are essential for understanding the evolving patterns of extreme weather and mitigating its impacts on both natural systems and human societies.

Author Contributions

José Carlos Gonzalez-Hidalgo: conceptualization, funding acquisition, investigation, writing – original draft, methodology, formal analysis, project administration, supervision. **Santiago Beguería:** data curation, software, formal analysis, methodology, investigation, conceptualization, writing – review and editing. **Dhais Peña-Angulo:** visualization, investigation, data curation, writing – review and editing, software. **Victor Trullenque Blanco:** investigation, validation, data curation, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in DIGITAL CSIC at <http://hdl.handle.net/10261/354840>.

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