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Intra-annual variability of the Western Mediterranean Oscillation (WeMO) and occurrence of extreme torrential rainfall in Catalonia (NE Iberia)

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Abstract

In previous studies the Western Mediterranean Oscillation index (WeMOi) at daily resolution has proven to constitute an effective tool for analysing the occurrence of episodes of torrential rainfall over eastern Spain. The Western Mediterranean region is therefore a very sensitive area, since climate change can enhance these weather extremes. In the present study we selected the extreme torrential episodes (≥200 mm in 24 hours) that took place in Catalonia (NE Iberia) during the 1951-2016 study period (66 years). We computed daily WeMOi values and constructed WeMOi calendars. Our principal results reveal the occurrence of 50 episodes (0.8 cases per year), mainly concentrated in the autumn months. We inferred a threshold of WeMOi ≤-2 to define an extreme negative WeMO phase at daily resolution. Most of the 50 episodes (60%) in the study area occurred on days presenting an extreme negative WeMOi value. Specifically, the most negative WeMOi values are detected in autumn, during the second 10-day period of October (11th-20th), coinciding with the highest frequency of extreme torrential events. On comparing the subperiods, we observed a statistically significant decrease in WeMOi values in all months, particularly in late October, and in November and December. No changes in the frequency of these extreme torrential episodes were observed between both subperiods; in contrast, a displacement of the episodes is detected from early to late autumn.

Keywords

Catalonia, climate variability, torrential rainfall, WeMO.

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1. Introduction

The Mediterranean seasonal rainfall regime is characterised by rainy winters and dry summers, linked to the westerly atmospheric circulation in winter and to the subtropical anticyclone belt in summer. Nevertheless, in some regions of the Mediterranean basin, the seasonal rainfall regime differs from the typically Mediterranean one; for example, most of eastern Iberia (Spain) displays a seasonal precipitation maximum in autumn, and a secondary one in spring (De Luis *et al*., 2010; González-Hidalgo *et al.*, 2011). This bimodal rainfall pattern is recorded in few regions of the world. It only occurs over approximately 7% of the global land surface, and is commonly associated with locations within the tropics (Knoben *et al.*, 2019). This bimodal behaviour in eastern Spain is mainly due to the physical geographic complexity of the Iberian Peninsula, which comprises several mountain ranges, all of which present different slope orientations. Furthermore, the Mediterranean Sea is practically cut off from other water bodies, which favours higher surface sea temperatures (SST) than in the Atlantic at the same latitude in summer and autumn. This contributes to the development of high vertical gradients of air temperature in some months over the Mediterranean basin (Estrela *et al*., 2008; Pérez-Zanón *et al*., 2018). These physical geographical factors give rise to a high concentration of daily precipitation in the Mediterranean basin, i.e. torrential rainfall events, above all, in the Western Mediterranean (Beguería *et al.*, 2011; Cortesi *et al*., 2012); all this reveals the need for water management in Spain to be based upon rainfall variability rather than on the rainfall mean (Lopez-Bustins, 2018). Heavy rainfall in the Western Mediterranean is mainly centred in eastern Spain, the south of France and the region of Liguria (NW Italy) (Peñarrocha *et al*., 2002). These torrential events can cause dangerous floods and have an important social and economic impact on the Mediterranean regions, e.g. in eastern Spain (Olcina *et al*., 2016; Kreibich *et al*., 2017; Nakamura and Llasat, 2017; Martin-Vide and Llasat, 2018) and particularly in southern Spain (Gil-Guirado *et al*., 2019). Climatological studies on torrential rainfall frequency and intensity are therefore relevant with regard to improving emergency plans and mitigating flood damage. Extreme precipitation is expected to increase with global warming as a result of a greater atmospheric water content (Papalexiou and Montanari, 2019); for instance, extreme peak river

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flows are predicted to increase in Southern Europe during the current century (Alfieri *et al*., 2015), and the frequency of heavy rainfall events is projected to be higher for the 2011-2050 period (Barrera-Escoda *et al*., 2014).

Previous studies have associated extreme daily rainfall events in Spain with synoptic patterns (Martin-Vide *et al*., 2008; Peña *et al*., 2015); these studies have addressed several different tropospheric levels (Romero *et al*., 1999; Merino *et al*., 2016; Pérez-Zanón *et al*., 2018). Furthermore, many studies have also statistically correlated several teleconnection indices (El Niño Southern Oscillation, North Atlantic Oscillation, Arctic Oscillation, Mediterranean Oscillation, Western Mediterranean Oscillation, etc.) with rainfall series for the Iberian Peninsula at different timescales (Rodó *et al*., 1997; Rodríguez-Puebla *et al*., 2001; Trigo *et al*., 2004; Lopez-Bustins *et al*., 2008; González-Hidalgo *et al*., 2009; Ríos-Cornejo *et al*., 2015a; Merino *et al*., 2016). Among these, the Western Mediterranean Oscillation (WeMO) was found to be the index most statistically and significantly correlated with annual, monthly and daily precipitation on the littoral fringe of eastern Spain (Martin-Vide and Lopez-Bustins, 2006; González-Hidalgo *et al*., 2009). The daily timescale of the WeMO index (WeMOi) could constitute a potential tool for analysing the frequency of torrential events in some regions of the Western Mediterranean basin.

The present study provides an exhaustive inventory of the heaviest rainfall events in Catalonia (NE Iberia) over the last few decades (1951-2016) in order to furnish a better understanding of their temporal distribution. Moreover, we will analyse changes in frequency according to subperiods, since the Western Mediterranean basin is a global warming hotspot, where a decrease in mean annual precipitation is expected for the following decades, particularly in summer, together with a potential rise in storm-related precipitation and drought duration (Christensen *et al*., 2013; Barrera-Escoda *et al*., 2014; Cramer *et al*., 2018; Greve *et al*., 2018). The main aim of the study involves establishing a period of high potential torrentiality in Catalonia at daily resolution, considering the catalogue of extreme torrential events in the area analysed. Most studies delimit the wet season of a region within one or several months (Kottek *et al*., 2006), and do not employ a smaller timescale than the monthly one. Therefore, the present research attempts to go beyond the monthly timescale in order to determine the period with the

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highest accumulation of heavy rainfall according to fortnights and 10-day periods. The intra-annual variability of the daily WeMOi values may help to establish the period with the highest propensity for torrential events in Catalonia.

In section 2, we describe the main orographic and pluviometric features of the study area. The methods followed to calculate daily WeMOi values and construct the WeMOi calendar are explained in section 3. In section 4, the results of the intra-annual variability of torrential episodes and WeMOi values are analysed and discussed; additionally, we have demonstrated the usefulness of the WeMOi calendar for pinpointing the time of year presenting the heaviest rainfall events in another region of the Western Mediterranean, the south of France. Finally, in section 4 we derive the conclusions.

2. Study area

Catalonia covers an area of 32,100 km^2 in northeast Spain; it is physically separated from France by the Pyrenees (Figure 1). Altitude ranges from 0 (littoral) to 3,100 m (northwestern Pyrenees) a.s.l. The Coastal and Pre-Coastal ranges, with an altitude ranging from 500 m.a.s.l. to 1,700 m.a.s.l., present a SW-NE orientation. On the western border, the Central Depression is approximately 200-300 m.a.s.l., constituting the driest part of the study area (350 mm annual-mean precipitation) (Figure 2a). The wettest part of Catalonia is located in the Pyrenees, with an annual-mean rainfall over 1,200 mm. In general terms, southern Lleida and Barcelona, as well as almost the entire province of Tarragona, make up the dry part of Catalonia (<700 mm). The rainy part of Catalonia (≥700 mm) comprises the province of Girona and the northern halves of the provinces of Lleida and Barcelona.

Catalonia's complex orography, as well as the fact that it falls under the influence of the Atlantic Ocean and the Mediterranean Sea, endow it with a highly heterogeneous spatial distribution of seasonal precipitation regimes throughout the study area. Using 70 monthly precipitation series (1950-2015) provided by the Meteorological Service of Catalonia (SMC, 2016), we ascertained that, of the total of 24 possible permutations between winter, spring, summer and autumn as dominant and subdominant precipitation seasons, 7 of these are detected in Catalonia (Figure 2b) (Martin-Vide and Raso-Nadal, 2008). A clear predominance

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of autumn rainfall can be observed, followed by spring precipitation, especially in the coastal zone. The driest season on the coast is summer; however, inland the driest time of year is winter. Many areas of the Pyrenees, above all, in the east, exhibit their maxima in summer as a result of convective rainfall.

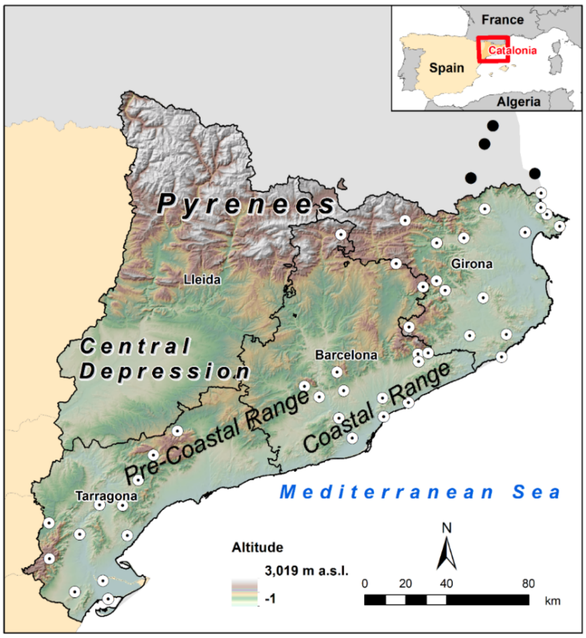

Figure 1. Location of Catalonia (NE Spain) within Europe, altitude and 4 provinces. The white dots indicate the 43 different weather stations that have recorded the highest rainfall amount during an extreme torrential event at least once in Catalonia. The black dots show the four weather stations located in the south of France. The base map was provided by Cartographic and Geological Institute of Catalonia.

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(a) (b)

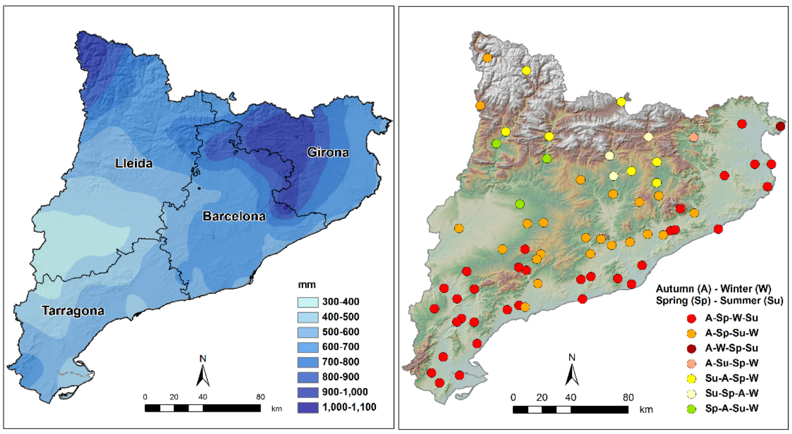

Figure 2. (a) Average annual precipitation (mm) in Catalonia for the 1950-2015 period. (b) Seasonal precipitation regimes for 70 weather stations during the 1950-2015 period. The base map was provided by Cartographic and Geological Institute of Catalonia.

3. Data and Methods

3.1. Selection of torrential events

Several studies have selected the torrential rainfall events in Spain based on the threshold of 100 mm in 24 h (Pérez-Cueva, 1994; Martin-Vide and Llasat, 2000; Armengot, 2002; Riesco and Alcover, 2003; Martin-Vide *et al*., 2008). Herein we chose the extreme torrential episodes (≥200 mm in 24 h) (Lopez-Bustins *et al*., 2016) that took place over Catalonia during the 1951-2016 study period (66 years). We consider the threshold of 200 mm in 24 h to present a natural risk in most cases, with significant consequences. Episodes involving ≥100 mm in 24 h are more frequent, but sometimes have no direct impact, or quite a negligible effect, because other factors are the main drivers of floods, e.g. rainfall duration (Jang, 2015), initial soil moisture conditions and hydrological parameters (Norbiato *et al*., 2008; Martina *et al*., 2009).

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In order to select the extreme torrential events, we considered all available rainfall data sources in Catalonia (Meteorological Service of Catalonia, Spanish National Meteorological Agency, Catalan Water Agency and Ebro Hydrographic Confederation). Data sources were furnished both by automatic (semi-hourly data) and manual (one register per day) weather stations. We considered the pluviometric day as 7-7 UTC in both types of observatories in order to ensure a homogeneous criterion when selecting episodes along the whole study period and analysing any temporal changes in their frequency. Manual weather stations, which record the pluviometric day as 7-7 UTC, were the only precipitation data source in Catalonia until the end of the 1980s. Therefore, we adjusted the episodes provided by the automatic stations to the pluviometric day 7-7 UTC. An exhaustive spatial and temporal check was performed among the extreme torrential episodes identified. We tested the reliability of the events considering the daily precipitation recorded in neighbouring stations and examining the original handwritten observation cards. Furthermore, we fixed some episodes registered the day after the pluviometric day from manual weather stations, and we eliminated events derived from rainfall accumulation of over one day. The additional pluviometric data used in section 4.4. were provided by Météo-France.

The catalogue of extreme torrential events in Catalonia addresses the following columns: date, maximum precipitation in 24 h, location, province and daily WeMOi value. Several observatories in Catalonia can occasionally register ≥ 200 mm in 24 h on one same date, but only the highest amount was taken into account. Finally, we obtained 50 extreme torrential events for consideration in the present study (Table 1). 32 out of the 50 episodes (64%) have a decimal place of 0, and 10 out of the 50 episodes (20%) present a decimal place of 5. Most of these episodes were registered by manual weather stations prior to the 1990s. This is known as the rounding effect (Wergen *et al.*, 2012): a weather observer rounds off the daily precipitation accumulation value during heavy rainfall events. This effect has no influence on the results of the present research.

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Date	Max RR (mm)	Location	Province	WeMOi value
13 October 1986	**430.0**	**Cadaqués**	**Girona**	**-2.22**
11 April 2002	**367.5**	**Darnius**	**Girona**	**-3.85**
20 September 1971	308.0	Esparreguera	Barcelona	-1.75
20 September 1972	307.0	Sant Carles de la Ràpita	Tarragona	-1.58
09 October 1994	**293.0**	**Cornudella de Montsant**	**Tarragona**	**-2.88**
03 October 1987	291.0	Castelló d'Empúries	Girona	-1.96
22 September 1971	**285.0**	**Cadaqués**	**Girona**	**-2.19**
19 October 1977	**276.0**	**Cadaqués**	**Girona**	**-2.80**
21 September 1971	**275.0**	**Santa Maria de Palautordera**	**Barcelona**	**-2.21**
18 October 1977	**271.8**	**Camprodon**	**Girona**	**-2.21**
21 October 2000	**270.0**	**Falset**	**Tarragona**	**-2.26**
07 November 1982	**266.0**	**la Pobla de Lillet**	**Barcelona**	**-5.56**
12 October 2016	257.0	Vilassar de Mar	Barcelona	-1.86
05 March 2013	**253.5**	**Darnius**	**Girona**	**-5.32**
29 November 2014	**253.5**	**Parc Natural dels Ports**	**Tarragona**	**-4.54**
16 February 1982	**251.2**	**Amer**	**Girona**	**-2.41**
25 September 1962	250.0	Martorelles	Barcelona	-1.52
04 November 1962	**248.5**	**SantLlorenç del Munt**	**Barcelona**	**-2.79**
02 September 1959	*246.5*	*Cadaqués*	*Girona*	*-0.84*
10 October 1994	**245.0**	**Beuda**	**Girona**	**-2.33**
22 October 2000	**240.0**	**Tivissa**	**Tarragona**	**-2.50**
12 November 1999	**233.5**	**Castellfollit de la Roca**	**Girona**	**-3.00**
06 January 1977	**233.0**	**Girona**	**Girona**	**-2.22**
20 December 2007	**230.2**	**Parc Natural dels Ports**	**Tarragona**	**-3.54**
06 October 1959	230.1	Tossa de Mar	Girona	-1.36
03 October 1951	230.0	Cornellà de Llobregat	Barcelona	-1.02
20 September 1959	230.0	Gualba de Dalt	Barcelona	-1.49
11 October 1970	230.0	Riudabella	Tarragona	-1.61
23 October 2000	**229.0**	**Horta de Sant Joan**	**Tarragona**	**-2.41**
26 September 1992	**226.4**	**Amposta**	**Tarragona**	**-2.22**
04 April 1969	**226.0**	**Rupit**	**Barcelona**	**-2.21**
12 November 1988	**225.0**	**Corbera de Llobregat**	**Barcelona**	**-2.76**
11 October 1962	223.0	Sils	Girona	-1.20
20 November 1956	*221.0*	*Cornellà de Llobregat*	*Barcelona*	*-0.45*
06 November 1983	**220.0**	**Terrassa**	**Barcelona**	**-2.34**
19 October 1994	**220.0**	**el Port de Llançà**	**Girona**	**-2.36**
31 July 2002	*218.2*	*Badalona*	*Barcelona*	*-0.13*
13 September 1963	217.5	l'Ametlla de Mar	Tarragona	-1.14
19 September 1971	*217.0*	*Xerta*	*Tarragona*	*-0.97*
17 September 2010	*216.8*	*l'Ametlla de Mar*	*Tarragona*	*-0.60*
17 October 2003	**213.0**	**Vidrà**	**Girona**	**-2.48**
09 June 2000	*210.0*	*el Bruc*	*Barcelona*	*-0.23*
31 August 1975	*208.5*	*Santa Agnès de Solius*	*Girona*	*-0.15*
29 January 1996	**206.5**	**Fogars de Montclús**	**Barcelona**	**-2.37**
09 October 1971	*204.0*	*Miravet*	*Tarragona*	*-0.86*
26 December 2008	**202.5**	**Darnius**	**Girona**	**-2.84**
07 May 2002	**200.8**	**Godall**	**Tarragona**	**-2.47**
07 October 1965	**200.0**	**les Planes d'Hostoles**	**Girona**	**-2.12**
27 October 1989	200.0	el Port de la Selva	Girona	-1.90
01 November 1993	**200.0**	**Portbou**	**Girona**	**-2.57**

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Table 1. Catalogue of extreme torrential events (≥200 mm in 24 h, 7-7 UTC) in Catalonia (NE Iberia) during the 1951-2016 period. Max RR is the highest rainfall accumulation of the episode. The events are classified according to the extreme negative Western Mediterranean Oscillation (WeMO) phase (bold), the negative WeMO phase and the slight negative WeMO phase (italics).

3.2. Daily WeMOi values

The WeMOi is a regional teleconnection index defined within the Western Mediterranean basin (Martin-Vide and Lopez-Bustins, 2006) and already used in a wider range of studies (Azorin-Molina and Lopez-Bustins, 2008; Vicente-Serrano *et al*., 2009; Caloiero *et al*., 2011; El Kenawy *et al*., 2012; Coll *et al*., 2014; Ríos-Cornejo *et al*., 2015b; Lana *et al*., 2017; Jghab *et al*., 2019). WeMOi values are computed by means of surface pressure data from the San Fernando (SW Spain) and Padua (NE Italy) weather stations (Figure 3); the synoptic window 30º-60ºN - 15ºW-20ºE is found to best represent WeMO phases (Arbiol-Roca *et al*., 2018). The positive phase of the WeMO corresponds to the anticyclone over the Azores encompassing the southwest quadrant of the Iberian Peninsula and low pressures in the Gulf of Genoa (Figure 3a); its negative phase coincides with an anticyclone located over Central or Eastern Europe and a low-pressure centre, often cut off from the northern latitudes, within the framework of the Iberian southwest (Figure 3b). Martin-Vide and Lopez-Bustins (2006) found that the WeMOi was significantly and statistically correlated with rainfall over areas that were weakly influenced by the North Atlantic Oscillation (NAO): in the northernmost and easternmost parts of Spain; precipitation over the Cantabrian fringe (northern Spain) was strongly and positively correlated with the WeMOi, and precipitation over the Spain's eastern façade was strongly and negatively correlated with the WeMOi.

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(a) (b)

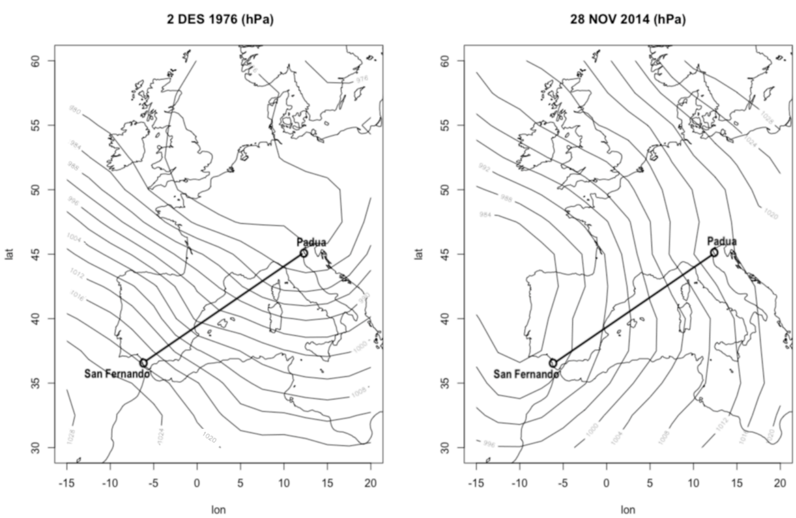

Figure 3. (a) Most extreme positive phase of the Western Mediterranean Oscillation (WeMO) in a daily synoptic situation during the 1951-2016 period (2nd December 1976). (b) Most extreme negative WeMO phase in a daily synoptic situation during the 1951-2016 period (28th November 2014). Data source: NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA.

Application of the daily WeMOi is a methodological contribution by Martin-Vide and Lopez-Bustins (2006). It converts the low-frequency feature of the teleconnection patterns into a high-frequency mode. It is suitable for application both to the regional scale of the WeMO teleconnection pattern and the lesser variability of atmospheric pressure at Mediterranean latitudes. Patterns have rarely been used at daily resolution (Baldwin and Dunkerton, 2001; Beniston and Jungo, 2002; Azorin-Molina and Lopez-Bustins, 2008; Liu *et al.*, 2018). The method selected consists of previously standardising each series of the dipole. It is necessary to use the mean and standard deviation of the 1961-1990 reference period of all days of the year (from 1st January 1961 to 31st December 1990).

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For example, the WeMOi on January 1st 1981

$$\text{Z WeMOi 1st Jan 1981} = \frac{\text{P 1st Jan 1981 SF} - \overline{\text{X}}\ \text{1961\_1990 SF}}{\text{S 1961\_1990 SF}} - \frac{\text{P 1st Jan 1981 PD} - \overline{\text{X}}\ \text{1961\_1990 PD}}{\text{S 1961\_1990 PD}},$$

where P is pressure, SF, San Fernando, PD, Padua, $\overline{\text{X}}$, mean, and S, standard deviation.

This calculation method, which considers all days of the year in the reference period, enables all Mediterranean flows (negative WeMO phase) to be detected, even if they are very weak. Otherwise, these moderate Mediterranean winds would not be detected in autumn, since the WeMOi means are clearly negative during this season. Likewise, the weak Mediterranean flows would be overestimated in winter due to the high WeMOi mean during the coldest months. According to previous studies (Martin-Vide and Lopez-Bustins, 2006; Azorin-Molina and Lopez-Bustins, 2008), in the histogram of daily WeMOi frequencies, WeMOi values between -1.00 and 1.00 are considered to constitute a neutral WeMO phase, values ranging from 1.00 to 1.99 are considered as a positive WeMO phase, those between -1.99 and -1.00 as a negative WeMO phase, values ≥2.00 are deemed to represent an extreme positive WeMO phase and those ≤-2.00 to indicate an extreme negative WeMO phase. The most positive WeMOi value (+5.99) of the 1951-2016 study period refers to December 2nd 1976 (Figure 3a), when an intense rainfall episode was recorded in the Basque Country (northern Spain) according to ECA & Dataset (Klein Tank *et al*., 2002; Cornes *et al.*, 2018). The most negative WeMOi value (-5.97) during the 1951-2016 period corresponds to November 28th 2014 (Figure 3b), when 253.5 mm was registered in the *Parc Natural dels Ports* (Tarragona) during the following day (Table 1). Lana *et al*. (2016) studied the statistical complexity and predictability of the WeMOi and demonstrated the Gaussian distribution of this index. Most daily WeMOi values are positive (55%) and two thirds of the 23,996 days displaying WeMOi values correspond to a neutral WeMO phase (Figure 4). The positive (negative) WeMO phase was detected in 16.5% (17.2%) of the total days presenting a WeMOi value. The extreme WeMOi values, both positive

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(5.2%) and negative (3.9%), represent less than 10% of the total number of days for which WeMOi values are available.

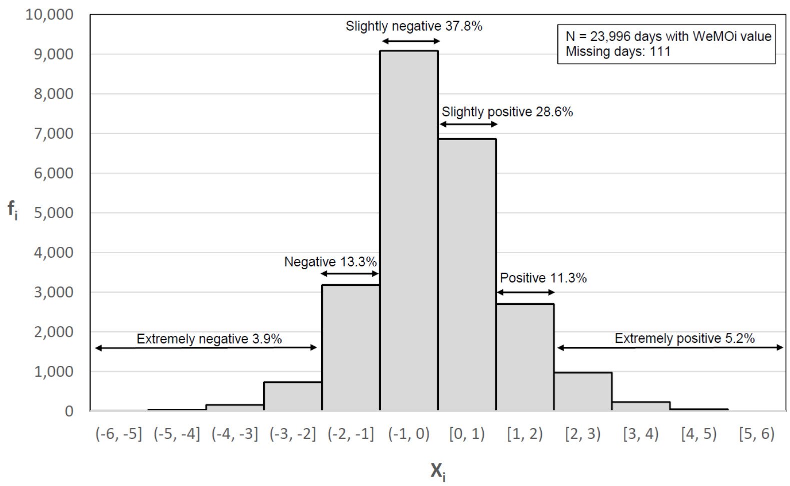

Figure 4. Frequency histogram of all daily WeMO index (WeMOi) values during the 1951-2016 study period.

3.3. Construction of calendars

Constructing calendars is a common procedure in climatological studies (Soler and Martin-Vide, 2002; Azorin-Molina and Lopez-Bustins, 2008; Meseguer-Ruiz *et al.*, 2018). They enable the intra-annual variability of the climate variable to be visualised. We computed daily WeMOi values for the 1951-2016 (66 years) study period, constructing two WeMOi calendars based upon the mean values obtained for each month, a 15-day period (i.e. a fortnight) and a 10-day period; the latter period corresponds approximately to the baroclinic prediction period (Holton, 2004). The first climate calendar will show the annual cycle of the WeMOi values according to months (12 values), the second will display a more detailed intra-annual oscillation with 24 values and, finally, the 36 WeMOi values derived from the 10-day calendar will enable the slightest intra-annual variations in the WeMOi to be detected. We will add to these calendars all the extreme torrential events in order to observe correspondences between WeMOi values and heavy rainfall events along the year. In order to detect any changes in the calendars throughout the study period, we consider two subperiods for the construction of two

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additional calendars: 1951-1983 (33 years) and 1984-2016 (33 years). The mean WeMOi values according to subperiods were statistically tested to detect significant differences. This statistical significance is computed by means of a Normal distribution test according to several levels of confidence: 95.0% (z=1.960), 99.0% (z=2.576) and 99.9% (z=3.291).

4. Results and discussion

4.1. Frequency and temporal evolution of the extreme torrential events

During the 1951-2016 period, 50 episodes presenting ≥200 mm in 24 h were detected (0.8 cases per year) in Catalonia (Table 1); these were mainly concentrated in the Eastern Pyrenees (Girona) and southern Catalonia (Tarragona) (Figure 1). In the province of Lleida no maximum values for precipitation episodes have been recorded, because this province is less influenced by easterly flows as a result of its continental features. Other parts of Iberia register a higher frequency of extreme torrential events, e.g. in the Valencia Region, eastern Spain, there were 2 cases per year during the 1971-2000 period (Riesco and Alcover, 2003). The highest frequency of torrential events (≥100 mm in 24 h) over the Iberian Peninsula also corresponds to the Valencia Region, where more than one case per year can be recorded by one same observatory (Pérez-Cueva, 1994) and approximately 11 cases per year by all the stations in the Valencia Region (Riesco and Alcover, 2003). Catalonia exhibits a lower frequency of these torrential events (i.e. ≥100 mm in 24 h), 5-6 cases per year for the whole region (Martin-Vide and Llasat, 2000; Lopez-Bustins *et al*., 2016). The highest rainfall amount during 7-7 UTC ever recorded in Catalonia is 430 mm. This occurred in Cadaqués (Cape Creus, in the easternmost part of the Iberian Peninsula) on October 13th 1986. It was an extraordinary episode which also affected the region of Pyrénées-Orientales (S France) (Vigneau, 1987), albeit with a lower amount of rainfall than that produced by other extreme torrential events of over 800 mm in Liguria Region (NW Italy), Valencia Region (E Spain) and this region of Pyrénées-Orientales (Peñarrocha *et al*., 2002).

Most of the episodes in Catalonia (60%) (30 events) took place in an extreme negative (≤-2.00) WeMOi phase (Figure 5), whereas less than 4% of the total number of days with WeMOi data showed a value equal to or lower than -2.00

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(Figure 4). Moreover, 24% (12 events) of the episodes occurred in a negative (-2.00, -1.00] WeMO phase. The remaining 8 events (16%) took place in a slightly negative (-1.00, 0.00) WeMOi phase. No extreme torrential episodes presenting a positive WeMOi value occurred in Catalonia during the study period. In addition, Martin-Vide and Lopez-Bustins (2006) found no positive daily WeMOi values for torrential episodes (≥100 m in 24 h) in Tortosa (south Catalonia) during the 1951-2000 period.

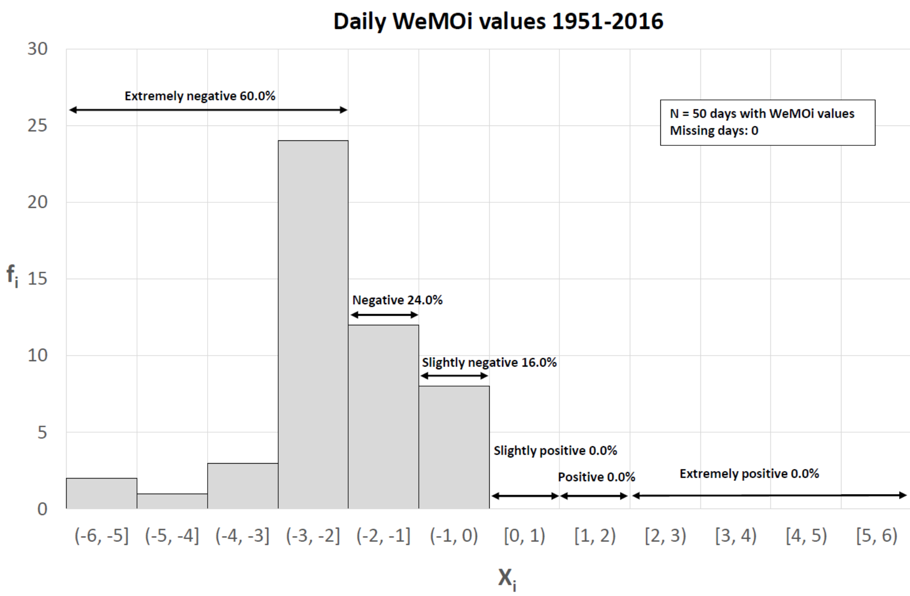

Figure 5. Frequency histogram of the daily WeMOi values of the 50 extreme torrential events recorded in Catalonia from 1951 to 2016.

No statistical temporal trend is observed in the annual frequency of the 50 extreme torrential episodes during the 1951-2016 period (Figure 6). Most of the years in the study period present no episodes, or only one; in six years there were 2 or 3 episodes, and in just two years (1971 and 2000) we detected over 3 episodes in one year. The greatest accumulation of cases can be observed in 1971, when a long-lasting torrential episode exceeded the threshold of 200 mm in 24 h during four consecutive days. This is one of the most noteworthy episodes recorded in Catalonia (Llasat, 1990; Martin-Vide and Llasat, 2000) in the last few decades. It started on September 19th in southern Catalonia and ended on September 22nd in the northeast of the study area (Llasat *et al.*, 2007). During

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the last decade, there has been no more than one episode in one single year. However, for torrential events (≥100 mm in 24 h) in Catalonia, Lopez-Bustins *et al*. (2016) detected a 45% increase in cases between the 1950-1981 and 1982-2013 subperiods. In accordance with this rise in torrential rainfall events, many studies on Iberian precipitation are showing an increase in rainfall of Mediterranean origin in eastern Spain (Miró *et al*., 2009; Lopez-Bustins *et al*., 2008; De Luis *et al*., 2010); this contributes to an increase in rainfall variability over the Western Mediterranean (Hartmann *et al*., 2013). On the other hand, extreme torrential rainfall (i.e. ≥200 m in 24 h) in Catalonia does not show any statistical increase along the study period (Figure 6). This is in line with Llasat *et al*. (2016), who found non-statistical temporal trends in extreme daily precipitation in Catalonia.

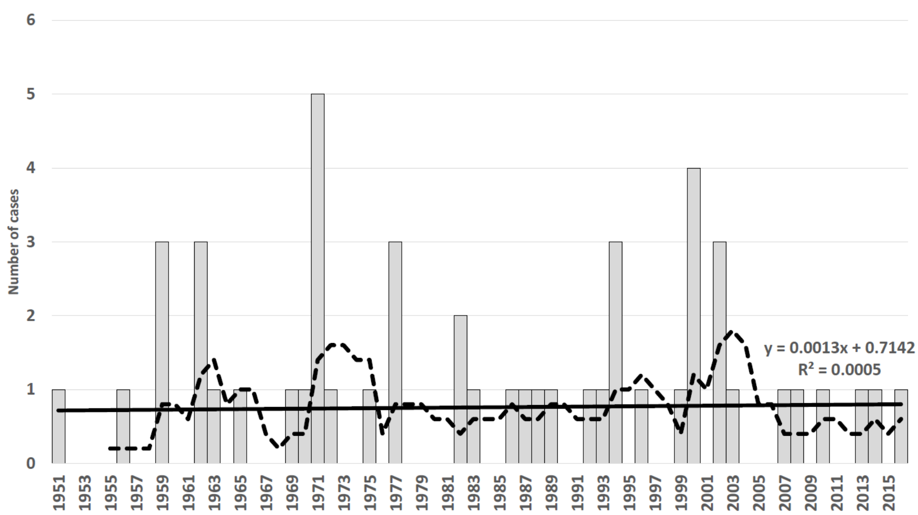

Figure 6. Temporal evolution of the annual frequency of extreme torrential events (≥200 mm in 24 h) throughout the 1951-2016 period. The figure shows the linear regression (black line) and 5-year running mean (dashed line).

4.2. Calendars of the daily WeMOi values

The lowest WeMOi values are detected in autumn, especially in October (-0.38) (Figure 7a), when the humid easterly flows from the Mediterranean Sea are usually expected. This explains why autumn and October are the wettest season and month, respectively, on most of Spain's eastern façade (De Luis *et al*., 2010). The greatest accumulation of extreme torrential events in Catalonia is in October, with 19 events (38% of all cases). September also shows a remarkable accumulation of events (11 cases), displaying the second lowest WeMOi monthly value (-0.29). Positive WeMOi values are observed from December to March, with very few events occurring. Although negative WeMOi values are detected from April to November, very few episodes are registered in late spring and summer; the predominance of atmospheric stability during the warm season reduces the chances of extreme torrential events occurring over the study area. At the fortnightly timescale, we detected the minimum WeMOi value (-0.39) during the second half of October (Figure 7b). The greatest accumulation of episodes, however, is in the first half of October. The lowest WeMOi values are found from September 16th to October 31st. This short period of the year (46 days) accumulates over a half of the total amount of extreme torrential events (28 cases, 56%). The most positive WeMOi values are detected in the winter months, particularly from January 1st to February 15th, and only 2 episodes are registered.

At the 10-day timescale, we observed the WeMOi minimum value (-0.45) from October 11^{th} to 20th (Figure 7c). This 10-day period also presents the largest accumulation of extreme torrential events in Catalonia (8 cases; 16% of the total number of cases). At least 4 cases are registered in each 10-day period from September 11th to November 10th. This period of the year (61 days) accumulates two thirds (33 cases, 66%) of all extreme torrential events. WeMOi values are lower than -0.20 from August 1st to November 10th, fitting well with the period of highest frequency of extreme torrential events in Catalonia. From August 1st to September 10th, only 2 cases are registered due to the above-mentioned atmospheric conditions in summer. From September 11th to November 10th, favourable conditions can arise for the occurrence of extreme torrential events in Catalonia: a higher SST in the Western Mediterranean Sea and the early cut-off of subpolar lows travelling to Mediterranean latitudes (Estrela *et al*., 2008; Lopez-Bustins, *et al*., 2016; Pérez-Zanón *et al*., 2018). The positive WeMOi values are observed from December to March and each 10-day period presents either no episode or only a single one. The most positive WeMOi value is observed from

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January 1st to 10th (+0.38); this indicates the total predominance of the positive phase of the teleconnection during these days, according to the study period (1951-2016) (Figure 8a). During this 10-day period, the occurrence of extreme torrential events in eastern Iberia is highly inhibited by the NW atmospheric circulation over the study area, and the Genoa low is well represented. The remaining 10-day periods in winter also present a predominance of the western circulation over the Iberia Peninsula. This pattern causes positive pressure differences between the Gulf of Cadiz (at lower latitude) and the North of Italy (at higher latitude), which means positive WeMOi values and the inhibition of precipitation in eastern Iberia because of its location in the lee of the westerlies. On the other hand, the mean sea level pressure (SLP) map from October 11th to 20th shows a predominance of the negative WeMO phase, with humid easterly flows over Iberia, low pressure usually located in the Western Mediterranean basin, and a blocking anticyclone over Central and Eastern Europe (Figure 8b).

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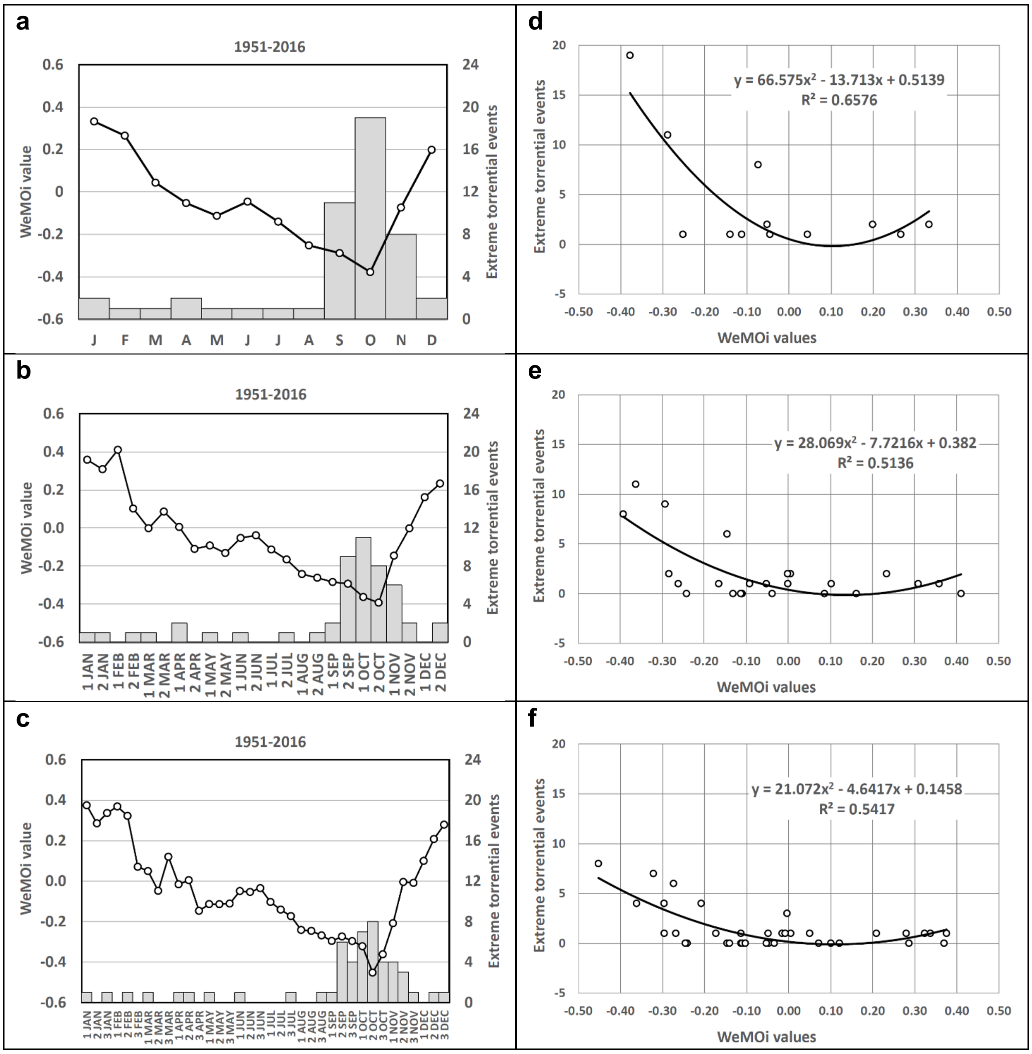

Figure 7. WeMOi calendars and frequency of the extreme torrential episodes at several timescales: monthly (a), fortnightly (b) and 10-day (c). Scatter plot of the quadratic function of the relationship between extreme torrential events and WeMOi values at several timescales: monthly (d), fortnightly (e) and 10-day (f).

The fitness of the second-order polynomial is statistically significant at all timescales, obtaining an R^2 of 0.66 (Figure 7d), 0.51 (Figure 7e) and 0.54 (Figure 7f), respectively. Fitness is especially significant at monthly resolution. There is an increase in the occurrence of events as the WeMOi value decreases.

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(a) (b)

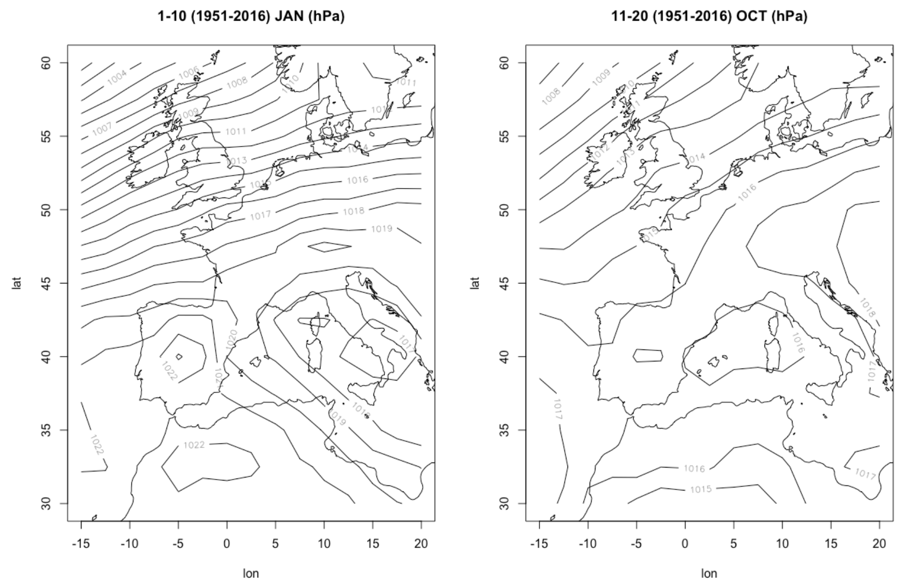

Figure 8. Sea level pressure (SLP) mean of the synoptic window 30ºN-60ºN and 15ºW-20ºE from January 1st to 10th (a) and from October 11th to 20th (b) during the 1951-2016 study period. Data source: NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA.

The WeMO teleconnection pattern can exert its influence upon precipitation variability in other regions of Southern Europe (Caloiero *et al*., 2011; Milosevic *et al*., 2016; Mathbout *et al*., 2019). This occurs in the south of France, where four weather stations located in the southernmost region of continental France, Pyrénées-Orientales, are analysed for the 1951-2016 study period (Figure 1). They recorded 62 torrential events (i.e. ≥100 mm in 24 h) during these 66 years, almost one case per year provided by these four weather stations. Figure 9 shows a remarkable column of episodes on the calendar, which corresponds to the period from October 11th to 20th; 8 cases are accumulated in the south of France in this 10-day period, i.e. 13% of all cases. This central period of October is confirmed to be the most prone to torrential events over many regions of the western Mediterranean due to presenting the lowest WeMOi values of the year. On the Iberian Peninsula, the Almanzora river (SE Spain) suffered 2 of the 4 most

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catastrophic floods in the last 450 years within this central interval in October (Sánchez-García *et al*., 2019). Moreover, the deadliest torrential episodes in the Valencia Region (E Spain) occurred on October 13-14th 1957 and October 19-20th 1982 (Olcina *et al*., 2016; Miró *et al*., 2017).

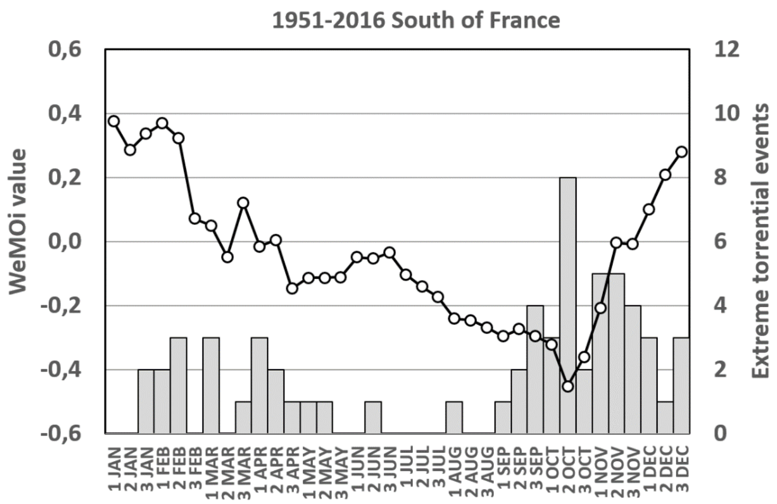

Figure 9. The WeMOi calendar and frequency of torrential episodes in the south of France at the 10-day scale during the 1951-2016 period.

4.3. Subperiods and differences in the calendars

In relation to the calendars, and according to subperiods, we observed an overall decrease in WeMOi values throughout the year (Figure 10). On the other hand, no change was observed in the frequency of episodes between both subperiods; exactly 25 extreme torrential events occurred in each subperiod. At the monthly timescale, the extreme torrential period takes place in September and the first half of October (1951-1983). For the second half (1984-2016), the maximum accumulation of cases shifts from September-October to October-November, with the highest concentration of cases in October, whilst new cases occur during the very late autumn (December). All WeMOi values are statistically and significantly lower during the second subperiod than during the first one in all months, especially from October to December. In the summer months, the decrease in WeMOi values is moderate, albeit statistically significant due to the low variability of the WeMOi values during the warm months.

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At the fortnightly timescale, a shifting of maximum torrentiality is observed from September 16th-October 15th to October 1st–October 31st. The lowest WeMOi value of the calendar from 1951 to 1983 was in the first fortnight of October (-0.26); however, this value is observed in the second fortnight of October during the 1984-2016 period (-0.58). All WeMOi values according to fortnights displayed a statistical and significant decrease during the second period, except from January 16th to March 15th. The sharpest decline in WeMOi values is in the first fortnight of May, the second fortnight of October, the second fortnight of November and the first fortnight of December. The lowest WeMOi value during the second subperiod is detected in the second fortnight of October, when the greatest increase in extreme torrential events is observed.

At the 10-day timescale the lowest WeMOi values remain relatively constant from the end of August to the beginning of November during the first subperiod, which corresponds well with the occurrence of extreme torrential events. During the second subperiod, the lowest WeMOi values are found from October 11th to 31st, with an accumulation of 8 cases (32% of the total number of cases of the second subperiod). A continuous and statistically significant decrease in WeMOi values (at the 99.9% confidence level) is observed from October 16th to December 20th during the second subperiod, except for the first 10-day period of November. The increase in torrential events is especially concentrated from October 21st to 31st. From August 21st to October 10th there is an overall decline in extreme torrential events, which might be associated with the fact that the WeMOi values hardly decrease over these 10-day periods of the year during the second subperiod.

In general terms, no more cases of extreme torrential events are observed during the 1984-2016 period in comparison with the 1951-1983 period. Nonetheless, a greater accumulation of cases can be observed during late autumn and a lesser accumulation in early autumn during the second subperiod, in comparison with the first one. A sharp and continuous drop in WeMOi values is observed at the very end of autumn, which might indicate a shift in the seasonality of the extreme torrential period from September-October to October-November. This seasonal displacement might be caused by a recent increase in SST in the Western Mediterranean basin, particularly in November (Lopez-Bustins, 2007; Estrela *et al*., 2008; Lopez-Bustins *et al*., 2016; Arbiol-Roca *et al*., 2017).

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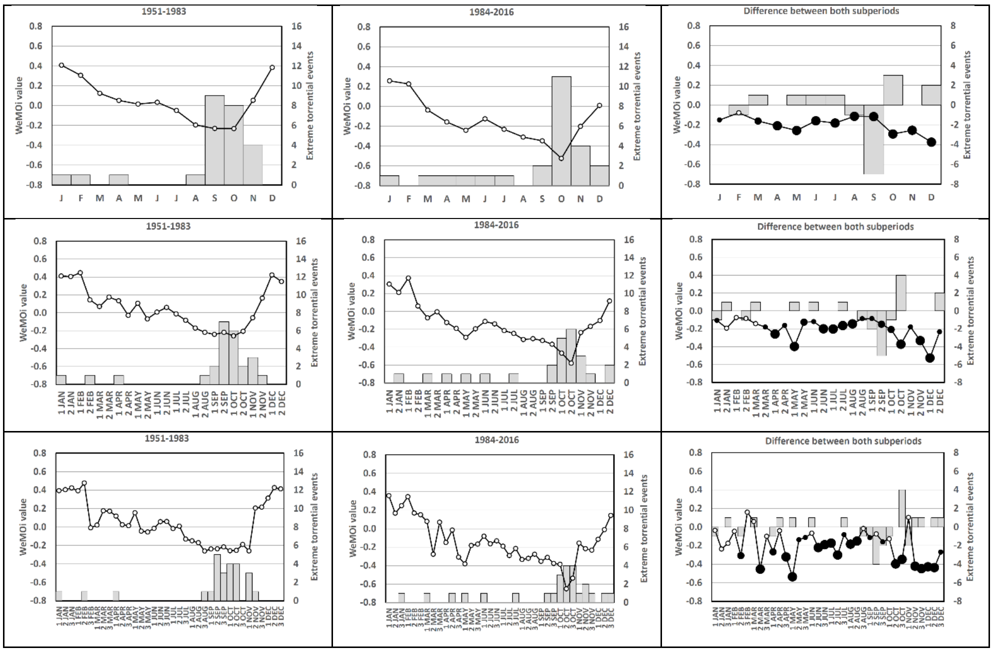

Figure 10. WeMOi calendars and frequency of the extreme torrential episodes in Catalonia at several timescales: monthly (above), fortnightly (middle) and 10-day (below) for the 1951-1983 (left) and 1984-2016 (central) subperiods. The right-hand column shows the difference in the number of episodes and WeMOi values between both subperiods (for WeMOi values: white dots indicate not statistically significant differences, and small-, medium- and large-sized black dots show statistically significant differences at the 95.0%, 99.0% and 99.9% confidence levels, respectively.

4. Conclusions

The present research confirms the usefulness of the WeMOi at daily resolution as an effective tool for analysing the occurrence of episodes of torrential rainfall over eastern Spain and the south of France. October is the rainiest month in most regions of the Northwestern Mediterranean basin and can account for the lowest values of the year on the WeMOi monthly calendar. Moreover, most torrential episodes take place during a very short period in the middle of this month.

Catalonia is located in the Northwestern Mediterranean basin and its extreme precipitation is highly dependent upon the atmospheric circulation over the

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Mediterranean. The present study considers the threshold of 200 mm in 24 h for extreme torrential episodes, due to the fact that this rainfall accumulation in one day can cause serious widespread damage. Following thorough review of several databases, and contrasting these results with the original files and nearby weather stations, we confirmed that Catalonia registered 0.8 cases per year of extreme torrential episodes during the 1951-2016 period in accordance with the 7-7 UTC pluviometric day.

The 10-day period from October 11th to 20th exhibits both the highest accumulation of extreme torrential episodes in Catalonia and the lowest intra-annual WeMOi value. This 10-day period has been demonstrated to be the most prone to torrential events in the Northwestern Mediterranean area according to the WeMOi values; and this is also confirmed by the accumulation of episodes in the same 10-day period in the south of France. The most torrential event in Catalonia ever recorded by an official weather station is in Cape Creus (the easternmost part of the Iberian Peninsula) within the period most susceptible to torrential rainfall (October 13th 1986) with a total amount of 430 mm. The most positive WeMO phase of the year usually takes place in January, especially from January 1st to 10th, when the synoptic conditions of this time of the year inhibit torrential events.

No extreme torrential episodes in Catalonia occurred in a positive WeMOi phase. Additionally, 60% of the cases occurred in an extreme negative WeMO phase, i.e. a WeMOi value equal to or lower than -2.00. In the present study this threshold is considered to constitute the onset of a rainstorm favoured by a strong Mediterranean flow. The lower WeMOi value is related to an increase in extreme torrential events at all timescales.

On comparing both study subperiods (1951-1983 and 1984-2016), an overall statistically significant decrease is detected in most WeMOi values of the year, especially at the end of October and some periods in November and December. On the other hand, extreme torrential events show no changes in frequency between both subperiods; no temporal trend is observed, either, over the 1951-2016 study period. The most notable change involves the displacement of extreme torrential episodes from early autumn to late autumn; this is in accordance with the lower WeMOi values detected in the last three months of the year during the second subperiod. Further research on this theme is required and SST temporal trends might provide a better understanding of these changes in extreme torrential events and WeMOi calendars.

Data availability

WeMOi data can be downloaded from the Climatology Group website http://www.ub.edu/gc/en/

Author contributions

JALB carried out the analysis and wrote the paper. LAR updated WeMOi data and plotted pressure maps. JMV discussed results. ABE elaborated the inventory of the episodes and discussed results. MPD discussed results.

Competing interests

The authors declare that they have no conflict of interest.

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References

Alfieri, L., Burek, P., Feyen, L., Forzieri, G.: Global warming increases the frequency of river floods in Europe. Hydrology and Earth System Sciences 19, 2247-2260. DOI: 10.5194/hess-19-2247-2015, 2015.

Arbiol-Roca, L., Lopez-Bustins, J.A., Martin-Vide, J.: The role of the WeMOi in the occurrence of torrential rainfall in Catalonia (NE Iberia). Abstracts book: 6th International Conference on Meteorology and Climatology of the Mediterranean (MetMed). Zagreb (Croatia): ACAM, 2017.

https://doi.org/10.5194/nhess-2019-374
Preprint. Discussion started: 10 December 2019

Arbiol-Roca, L., Lopez-Bustins, J.A., Esteban-Vea, P., Martin-Vide, J.: Cálculo del índice de la Oscilación del Mediterráneo Occidental con técnicas de análisis multivariante. In: Montávez-Gómez, J.P., Gómez-Navarro, J.J., López-Romero, J.M., Palacios-Peña, L., Turco, M., Jerez-Rodríguez, S., Lorente, R., Jiménez-Guerrero, P. (eds.), El Clima: Aire, Agua, Tierra y Fuego, pp. 761-771. Cartagena (Spain): Asociación Española de Climatología (AEC), 2018.

Armengot, R.: Las lluvias intensas en la Comunidad Valenciana. 263 pp. Madrid (Spain): Ministerio de Medio Ambiente, Dirección General del Instituto Nacional de Meteorología, 2002.

Azorin-Molina, C., Lopez-Bustins, J.A.: An automated sea breeze selection based on regional sea-level pressure difference: WeMOi. International Journal of Climatology 28, 1681-1692. DOI: 10.1002/joc.1663, 2008.

Baldwin, M.P., Dunkerton T.J.: Stratospheric harbingers of anomalous weather regimes. Science 294, 581-584. DOI: 10.1126/science.1063315, 2001.

Barrera-Escoda, A., Gonçalves, M., Guerreiro, D., Cunillera. J., Baldasano, J.M.: Projections of temperature and precipitation extremes in the North Western Mediterranean Basin by dynamical downscaling of climate scenarios at high resolution (1971-2050). Climate Change 122, 567-582. DOI: 10.1007/s10584-013-1027-6, 2014.

Beguería, S., Angulo-Martínez, M., Vicente-Serrano, S.M., López-Moreno, J.I., Kenawy, A.: Assessing trends in extreme precipitation events intensity and magnitude using non-stationary peaks-over-threshold analysis: a case study in northeast Spain from 1930 to 2006. International Journal of Climatology 31, 2102-2114. DOI:10.1002/joc.2218, 2011.

Beniston, M., Jungo, P.: Shifts in the distributions of pressure, temperature and moisture in the Alpine region in response to the behaviour of the North Atlantic Oscillation. Theoretical and Applied Climatology 71, 29-42. DOI: 10.1007/s704-002-8206-7, 2002.

Caloiero, T., Coscarelli, R., Ferrari, E., Mancini, M.: Precipitation change in Southern Italy linked to global scale oscillation indexes. Natural Hazards and

https://doi.org/10.5194/nhess-2019-374
Preprint. Discussion started: 10 December 2019

Earth System Sciences 11, 1683-1694. DOI: 10.5194/nhess-11-1683-2011, 2011.

Christensen, J.H., K. Krishna Kumar, E. Aldrian, S.-I. An, I.F.A. Cavalcanti, M. de Castro, W. Dong, P. Goswami, A. Hall, J.K. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D.B. Stephenson, S.-P. Xie and T. Zhou, T.: Climate Phenomena and their Relevance for Future Regional Climate Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. DOI: 10.1017/CBO9781107415324.028, 2013.

Coll, M., Carreras, M., Ciércoles, C., Cornax, M.J., Gorelli, G., Morote, E., Sáez, R.: Assessing fishing and marine biodiversity changes using fishers' perceptions: the Spanish Mediterranean and Gulf of Cadiz case study. PLoS ONE 9(1): e85670. DOI: 10.1371/journal.pone.0085670, 2014.

Cornes, R., van der Schrier, G., van den Besselaar, E.J.M., Jones, P.D.: An Ensemble Version of the E-OBS Temperature and Precipitation Datasets. Journal of Geophysical Research: Atmospheres 123, 9391-9409. DOI: 10.1029/2017JD028200, 2018.

Cortesi, N., Gonzalez-Hidalgo, J.C., Brunetti, M., Martin-Vide, J.: Daily precipitation concentration across Europe 1971-2010. Natural Hazards and Earth System Sciences 12, 2799-2810. DOI: 10.5194/nhess-12-2799-2012, 2012.

Cramer, W., Guiot, J., Fader, M., Garrabou, J., Gattuso, J.P., Iglesias, A., Lange, M.A., Lionello, P., Llasat, M.C., Paz, S., Peñuelas, J., Snoussi, M., Toreti, A., Tsimplis, M.N., Xoplaki, E.: Climate change and interconnected risks to sustainable development in the Mediterranean. Nature Climate Change 8, 972–980. DOI: 10.1038/s41558-018-0299-2, 2018.

De Luis, M., Brunetti, M., Gonzalez-Hidalgo, J.C., Longares, L.A., Martin-Vide, J.: Changes in seasonal precipitation in the Iberian Peninsula during 1946-2005.

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

Global and Planetary Change 74, 27-33. DOI: 10.1038/s41558-018-0299-2, 2010.

El Kenawy, A., López-Moreno, J.I., Vicente-Serrano, S.M.: Trend and variability of surface air temperature in northeastern Spain (1920-2006): Linkage to atmospheric circulation. Atmospheric Research 106, 159-180. DOI: 10.1016/j.atmosres.2011.12.006, 2012.

Estrela, M.J., Pastor, F., Miró, J., Valiente, J.A.: Precipitaciones torrenciales en la Comunidad Valenciana: La temperatura superficial del agua del mar y áreas de recarga. Primeros resultados. In: M.J. Estrela Navarro (ed.), Riesgos climáticos y cambio global en el mediterráneo español ¿hacia un clima de extremos?, pp. 121-140. Valencia (Spain): Colección Interciencias, 2008.

Gil-Guirado, S., Pérez-Morales, A., Lopez-Martinez, F.: Natural Hazards and Earth System Sciences 19, 1955-1971. DOI: 10.5194/nhess-19-1955-2019, 2019.

González-Hidalgo, J.C., Lopez-Bustins, J.A., Stepanek, P. Martin-Vide, J., De Luis, M.: Monthly precipitation trends on the Mediterranean fringe of the Iberian Peninsula during the second-half of the twentieth century (1951-2000). International Journal of Climatology 29, 415-1429. DOI: 10.1002/joc.1780, 2009.

González-Hidalgo, J. C., Brunetti, M., de Luis, M.: A new tool for monthly precipitation analysis in Spain: MOPREDAS database (monthly precipitation trends December 1945–November 2005). International Journal of Climatology 31, 715-731. DOI: 10.1002/joc.2115, 2011.

Greve, P., Gudmundsson, L., Seneviratne, S.I.: Regional scaling of annual mean precipitation and water availability with global temperature change. Earth System Dynamics Discussion 9, 227-240. DOI: 10.3929/ethz-b-000251688, 2018.

Holton, J.R.: An Introduction to Dynamic Meteorology. Elsevier Academic Press, International Geophysics Series, volume 88, 4th edition, 535 pp, 2004.

Hartmann, D.L., Klein Tank, A.M.G., Rusticucci, M., Alexander, L.V., Brönnimann, S., Charabi, Y., Dentener, F.J., Dlugokencky, E.J., Easterling, D.R., Kaplan, A., Soden, B.J., Thorne, P.W., Wild, M., Zhai, P.M.: Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis.

Natural Hazards and Earth System Sciences
Discussions

Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. DOI: 10.1017/CBO9781107415324.008, 2013.

Jang, J.H.: An advanced method to apply multiple rainfall thresholds for urban flood warnings. Water 7, 6056-6078. DOI: 10.3390/w7116056, 2015.

Jghab, A., Vargas-Yañez, M., Reul, A., Garcia-Martínez, M.C., Hidalgo, M., Moya, F., Bernal, M., Ben Omar, M., Benchoucha, S., Lamtai, A.: The influence of environmental factors and hydrodynamics on sardine (Sardina pilchardus, Walbaum 1792) abundance in the southern Alboran Sea. Journal of Marine Systems 191, 51-63. DOI: 10.1016/j.jmarsys.2018.12.002, 2019.

Klein Tank, A.M.G., Wijngaard, J.B., Können, G.P., Böhm, R., Demarée, G., Gocheva, A., Mileta, M., Pashiardis, S., Hejkrlik, L., Kern-Hansen, C., Heino, R., Bessemoulin, P., Müller-Westermeier, G., Tzanakou, M., Szalai, S., Pálsdóttir, T., Fitzgerald, D., Rubin, S., Capaldo, M., Maugeri, M., Leitass, A., Bukatis, A., Aberfeld, R., van Engelen, A.F.V., Forland, E., Mietus, M., Coelho, F., Mares, C., Razuvaev, V., Nieplova, E., Cegnar, T., López, J.A., Dahlström, B., Moberg, A., Kirchhofer, W., Ceylan, A., Pachaliuk, O., Alexander, L.V., Petrovic, P.: Daily dataset of 20th-century surface air temperature and precipitation series for the European climate assessment. International Journal of Climatology 22, 1441-1453. DOI: 10.1002/joc.773, 2002.

Knoben, W.J.M., Woods, R.A., Freer, J.E.: Global bimodal precipitation seasonality: A systematic overview. International Journal of Climatology 39, 558-567. DOI: 10.1002/joc.5786, 2019.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F.: World Map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift 15, 259-263. DOI: 10.1127/0941-2948/2006/0130, 2006.

Kreibich, H., Di Baldassarre, G., Vorogushyn, S., Aerts, J.C.J.H., Apel, H., Aronica, G.T., Arnbjerg-Nielsen, K., Bouwer, L.M., Bubeck, P., Caloiero, T., Chinh, D.T., Cortès, M. Gain, A.K., Giampá, V., Kuhlicke, C., Kundzewicz, Z.W., Llasat, M.C., Mård, J., Matczak, P., Mazzoleni, M., Molinari, D., Dung, N.V., Petrucci, O., Schröter, K., Slager, K., Thieken, A.H., Ward, P.J., Merz, B.: Adaptation to flood risk: Results of international paired flood event studies. Earth's Future 5, 953-965. DOI: 10.1002/2017EF000606, 2017.

Lana, X., Burgueño, A., Martínez, M.D., Serra, C.: Complexity and predictability of the monthly Western Mediterranean Oscillation index. International Journal of Climatology 36, 2435-2450. DOI: 10.1002/joc.4503, 2016.

Lana, X., Burgueño, A., Martínez, M.D., Serra, C.: Monthly rain amounts at Fabra Observatory (Barcelona, NE Spain): fractal structure, autoregressive processes and correlation with monthly Western Mediterranean Oscillation index. International Journal of Climatology 37, 1557-1577. DOI: 10.1002/joc.4797, 2017.

Liu, Y.; Li, Z.; Yin, H.: A timely El Niño-Southern Oscillation forecast method based on daily Niño index to ensure food security. Published in: 2018 7th International Conference on Agro-geoinformatics (Agro-geoinformatics) DOI: 10.1109/Agro-Geoinformatics.2018.8476070, 2018.

Llasat, M.C.: Influencia de la orografía y de la inestabilidad convectiva en la distribución espacial de lluvias extremas en Cataluña. Acta Geologica Hispanica 25, 197-208, 1990.

Llasat, M.C., Martín, F., Barrera, A.: From the concept of 'kaltluftropfen' (cold air pool) to the cut-off low. The case of September 1971 in Spain as an example of their role in heavy rainfalls. Meteorology and Atmospheric Physics 96, 43-60. DOI: 10.10077s00703-006-0220-9, 2007.

Llasat, M.C., Marcos, R., Turco, M., Gilabert, J., Llasat-Botija, M.: Trends in flash flood events versus convective precipitation in the Mediterranean region: The case of Catalonia. Journal of Hydrology 541, 24-37. DOI: 10.1016/j.jhydrol.2016.05.040, 2016.

Lopez-Bustins, J.A.: The Western Mediterranean Oscillation and Rainfall in the Catalan Countries. PhD Thesis, Department of Physical Geography and Regional Geographical Analysis, University of Barcelona, 184 pp, 2007.

https://doi.org/10.5194/nhess-2019-374
Preprint. Discussion started: 10 December 2019

Natural Hazards and Earth System Sciences
Discussions

Lopez-Bustins, J.A.: Lluvias fuertes, pero mal repartidas. El caso del clima mediterráneo. Biblio3W Revista Bibliográfica de Geografía y Ciencias Sociales vol. 23, nº 1243, 2018.

Lopez-Bustins, J.A., Martin-Vide, J., Sanchez-Lorenzo, A.: Iberia winter rainfall trends based upon changes in teleconnection and circulation patterns. Global and Planetary Change 63, 171-176. DOI: 10.1016/j.gloplacha.2007.09.002, 2008.

Lopez-Bustins, J.A., Martin-Vide, J., Prohom, M., Cordobilla, M.J.: Variabilidad intraanual de la Oscilación del Mediterráneo Occidental (WeMO) y ocurrencia de episodios torrenciales en Cataluña. In: Olcina, J., Rico, A.M., Moltó, E. (eds.), Clima, sociedad, riesgos y ordenación del territorio, pp. 171-182. Alicante (Spain): Asociación Española de Climatología (AEC), 2016.

Martin-Vide, J., Llasat, M.C.: Las precipitaciones torrenciales en Cataluña. Serie Geográfica 9, 17-26, 2000.

Martin-Vide, J., Lopez-Bustins, J.A.: The Western Mediterranean Oscillation and rainfall in the Iberian Peninsula. International Journal of Climatology 26, 1455-1475. DOI: 10.1002/joc.1388, 2006.

Martin-Vide, J., Raso-Nadal, J.M.: Atles Climàtic de Catalunya, 1961-1990. 32 pp. Barcelona (Spain): Servei Meteorològic de Catalunya, Departament de Medi Ambient i Habitatge, Generalitat de Catalunya, 2008.

Martin-Vide, J., Sanchez-Lorenzo, A., Lopez-Bustins, J.A., Cordobilla, M.J., Garcia-Manuel, A., Raso, J.M.: Torrential rainfall in northeast of the Iberian Peninsula: synoptic patterns and WeMO influece. Advances in Science and Research 2, 99-105. DOI: 10.5194/asr-2-99-2008, 2008.

Martin-Vide, J.P., Llasat, M.C.:The 1962 flash flood in the Rubí stream (Barcelona, Spain). Journal of Hydrology 566, 441-454. DOI: 10.1016/j.jhydrol.2018.09.028, 2018.

Martina, M.L.V., Todini, E., Libralon, A.: Rainfall thresholds for flood warning systems: a Bayesian decision approach. In: Sorooshian S., Hsu KL., Coppola E.,

https://doi.org/10.5194/nhess-2019-374
Preprint. Discussion started: 10 December 2019

Natural Hazards and Earth System Sciences
Open Access
Discussions

Tomassetti B., Verdecchia M., Visconti G. (eds.), Hydrological Modelling and the Water Cycle. Water Science and Technology Library, vol 63, pp. 203-227. Springer, Berlin, Heidelberg (Germany). DOI: 10.1007/978-3-540-77843-1_9, 2009.

Mathbout, S., Lopez-Bustins, J.A., Royé, D., Martin-Vide, J., Benhamrouche, A.: Spatiotemporal variability of daily precipitation concentration and its relationship to teleconnection patterns over the Mediterranean during 1975-2015. International Journal of Climatology DOI: 10.1002/joc.6278, 2019.

Merino, M., Fernández-Vaquero, M., López, L., Fernández-González, S., Hermida, L., Sánchez, J.L., García-Ortega, E., Gascón, E.: Large-scale patterns of daily precipitation extremes on the Iberian Peninsula. International Journal of Climatology 36, 3873-3891. DOI: 10.1002/joc.4601, 2016.

Meseguer-Ruiz, O., Lopez-Bustins, J.A., Arbiol-Roca, L., Martin-Vide, J., Miró, J., Estrela, M.J.: Episodios de precipitación torrencial en el este y sureste ibéricos y su relación con la variabilidad intraanual de la Oscilación del Mediterráneo Occidental (WeMO) entre 1950 y 2016. In: Montávez-Gómez, J.P., Gómez-Navarro, J.J., López-Romero, J.M., Palacios-Peña, L., Turco, M., Jerez-Rodríguez, S., Lorente, R., Jiménez-Guerrero, P. (eds.), El Clima: Aire, Agua, Tierra y Fuego, pp. 53-63. Cartagena (Spain): Asociación Española de Climatología (AEC), 2018.

Milosevic, D.D., Savic, S.M., Pantelic, M., Stankov, U., Ziberna, I., Dolinaj, D., Lescesen, I.: Variability of seasonal and annual precipitation in Slovenia and its correlation with large-scale atmospheric circulation. Open Geosciences 8, 593-605. DOI: 10.1515/geo-2016-0041, 2016.

Miró, J., Estrela, M.J., Pastor, F., Millán, M.: Análisis comparativo de tendencias en la precipitación, por distintos inputs, entre los dominios hidrológicos del Segura y del Júcar (1958-2008). Investigaciones Geográficas 49, 129-157, 2009.

Miró, J.J., Caselles, V., Estrela, M.J.: Multiple imputation of rainfall missing data in the Iberian Mediterranean context. Atmospheric Research 197, 313-330. DOI: 10.1016/j.atmosres.2017.07.016, 2017.

https://doi.org/10.5194/nhess-2019-374
Preprint. Discussion started: 10 December 2019

Nakamura, I., Llasat, M.C.: Policy and systems of flood risk management: a comparative study between Japan and Spain. Natural Hazards 87, 919-943. DOI: 10.1007/s11069-017-2802-x, 2017.

Norbiato, D., Borga, M., Esposti, S.D., Gaume, e., Anquetin, S.: Flash flood warning based on rainfall thresholds and soil moisture conditions: An assessment for gauged and ungauged basins. Journal of Hydrology 362, 274-290. DOI: 10.1016/j.jhydrol.2008.08.023, 2008.

Olcina, J., Sauri, D., Hernández, M., Ribas, A.: Flood policy in Spain: a review for the period 1983-2013. Disaster Prevention and Management 25, 41-58. DOI: 10.1108/DPM-05-2015-0108, 2016.

Papalexiou, S.M., Montanari, A.: Global and regional increase of precipitation extremes under global warming. Water Resources Research 55, 4901-4914. DOI: 10.1029/2018WR024067, 2019.

Peña, J.C., Aran, M., Pérez-Zanón, N., Casas-Castillo, M.C., Rodríguez-Solà, R., Redaño, A.: Análisis de las situaciones sinópticas correspondientes a episodios de lluvia severa en Barcelona. In: Libro de Resúmenes de la XXXV Reunión Bienal de la Real Sociedad Española de Física, pp. 450-451. Gijón (Spain): Real Sociedad Española de Física (RSEF), 2015.

Peñarrocha, D., Estrela, M.J., Millán, M.: Classification of daily rainfall patterns in a Mediterranean area with extreme intensity levels: the Valencia region. International Journal of Climatology 22, 677-695. DOI: 10.1002/joc.747, 2002.

Pérez-Cueva, A.J.: Atlas Climàtic de la Comunitat Valenciana (1961-1990), 205 pp. Valencia (Spain): Generalitat Valenciana, 1994.

Pérez-Zanón, N., Casas-Castillo, M.C., Peña, J.C., Aran, M., Rodríguez-Solà, R., Redaño, A., Solé, G.: Analysis of synoptic patterns in relationship with severe rainfall events in the Ebre Observatory (Catalonia). Acta Geophysica 66, 405-414. DOI: 10.1007/s11600-018-0126-1, 2018.

Riesco, J., Alcover, V.: Predicción de precipitaciones intensas de origen marítimo mediterráneo en la Comunidad Valenciana y la Región de Murcia. 124 pp. Madrid (Spain): Centro de Publicaciones, Secretaría General Técnica, Ministerio de Medio Ambiente, 2003.

https://doi.org/10.5194/nhess-2019-374
Preprint. Discussion started: 10 December 2019

Ríos-Cornejo, D., Penas, A., Álvarez-Esteban, R., del Río, S.: Links between teleconnection patterns and precipitation in Spain. Atmospheric Research 156, 14-28. DOI: 10.1016/j.atmosres.2014.12.012, 2015a.

Ríos-Cornejo, D., Penas, A., Álvarez-Esteban, R., del Río, S.: Links between teleconnection patterns and mean temperature in Spain. Theoretical and Applied Climatology 122, 1-18. DOI: 10.1007/s00704-014-1256-2, 2015b.

Rodó, X., Baert, E., Comin, F.A.: Variations in seasonal rainfall in Southern Europe during the present century: relationships with the North Atlantic Oscillation and the El Niño-Southern Oscillation. Climate Dynamics 13, 275-284, 1997.

Rodríguez-Puebla, C., Encinas, A.H., Sáenz, J.: Winter precipitation over the Iberian Peninsula and its relationship to circulation indices. Hydrology and Earth System Sciences 5, 233-244, 2001.

Romero, R., Sumner, G., Ramis, C., Genovés, A.: A classification of the atmospheric circulation patterns producing significant daily rainfall in the Spanish Mediterranean area. International Journal of Climatology 19, 765-789, 1999.

Sánchez-García, C., Schulte, L., Carvalho, F., Peña, J.C.: A 500-year flood history of the arid environments of southeastern Spain. The case of the Almanzora River. Global and Planetary Change 181, DOI: 10.1016/j.gloplacha.2019.102987, 2019.

SMC-Servei Meteorològic de Catalunya: Butlletí Anual d'Indicadors Climàtics BAIC 2015. Technical report. Meteorological Service of Catalonia, Department of Territory and Sustainability, Government of Catalonia, Barcelona, 85 pp. Available at: http://static-m.meteo.cat/wordpressweb/wp-content/uploads/2016/05/25153646/00_BAIC2015_TOT.pdf. Climate dataseries available at: http://www.meteo.cat/wpweb/climatologia/serveis-i-dades-climatiques/series-climatiques-historiques/, 2016.

Soler, X., Martin-Vide, J.: Los calendarios climáticos. Una propuesta metodológica. In: Guijarro, J.A., Grimalt, M., Laita, M., Alonso, S. (eds.), El Agua y el Clima, pp. 577-586. Mallorca (Spain): Asociación Española de Climatología, 2002.

https://doi.org/10.5194/nhess-2019-374
Preprint. Discussion started: 10 December 2019

Trigo, R.M., Pozo-Vázquez, D., Osborn, T.J., Castro-Díez, Y., Gámiz-Fortis, S., Esteban-Parra, M.J.: North Atlantic Oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. International Journal of Climatology 24, 925-944. DOI: 10.1002/joc.1048, 2004.

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., El Kenawy, A.M., Angulo-Martínez, M.: Daily atmospheric circulation events and extreme precipitation risk in northeast Spain: Role of the North Atlantic Oscillation, the Western Mediterranean Oscillation, and the Mediterranean Oscillation. Journal of Geophysical Research 114, D08106. DOI: 10.1029/2008JD011492, 2009.

Vigneau, J.-P.: 1986 dans les Pyrénées Orientales: deux perturbations méditerranéennes aux effets remarquables. Revue Géographique des Pyrénées et du Sud-Ouest 58, 23-54. DOI:10.3406/rgpso.1987.4969, 1987.

Wergen, D., Volovik, D., Redner, S., Krug, J.: Rounding Effects in Record Statistics. Physical Review Letters 109(16): 164102. DOI: 10.1103/PhysRevLett.109.164102, 2012.