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

Joan A. Lopez-Bustins (1), L. Arbiol-Roca (1), J. Martin-Vide (1), A. Barrera-Escoda (2) and M. Prohom (1,2)

(1) Climatology Group, Department of Geography, University of Barcelona (UB), Barcelona, Spain.
(2) Department of Climatology, Meteorological Service of Catalonia, Barcelona, Spain.

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 precipitation 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 created a catalogue of 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. We confirmed 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 extreme torrential episodes is detected from early to late autumn; this can be related to a statistically significant warming of sea temperature.

Keywords

Mediterranean, sea temperature, teleconnection indices, torrential precipitation, WeMO.

1. Introduction

The Mediterranean seasonal precipitation 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 precipitation 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 precipitation 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 a higher sea surface temperature (SST) than in the Atlantic at the same latitude, especially in summer and autumn (Pastor *et al*., 2015). 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 precipitation events, above all in the Western Mediterranean (Beguería *et al*., 2011; Cortesi *et al*., 2012; Caloiero *et al*., 2019); all this reveals the need for water management in Spain to be based upon precipitation variability rather than on the precipitation mean (Lopez-Bustins, 2018). Heavy precipitation 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 can have serious social and economic consequences, even human casualties, in 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 in southern Spain (Gil-Guirado *et al*., 2019; Naranjo-Fernández *et al*., 2020). Climatological studies on torrential precipitation 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 flows are predicted to increase in Southern Europe during the current century (Alfieri *et al*., 2015), and the frequency of heavy precipitation events is projected to be higher for the 2011-2050 period (Barrera-Escoda *et al.*, 2014).

Previous studies have associated extreme daily precipitation 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 precipitation 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 indices, 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.

Most torrential events in the Mediterranean region present a cyclonic centre at surface level (Jansà *et al*., 1996; Rigo and Llasat, 2003). These cyclonic centres, which are mainly mesoscale lows, can contribute to the structure of low-level flows and therefore to the creation or intensification of a low-level warm and wet current that can feed and sustain convection in favourable environmental conditions (Jansà and Genovés, 2000; Jansà *et al*., 2000). Furthermore, the Mediterranean Sea moistens and warms the low level of the atmosphere. Consequently, the southerly to easterly flow that prevails before and during torrential events in the Western Mediterranean transports the air under conditional instability toward the coasts, where convection is often triggered by an interaction between the flow and the orography. Studies based upon mesoscale modelling, such as the research conducted by Lebeaupin *et al*.

(2006), show that an increase (or a decrease) in SST by several degrees intensifies (or weakens) convection. In addition, the presence of a cut-off low in the upper troposphere might be playing a significant role in the occurrence of heavy precipitation, creating a cyclonic circulation in the lower troposphere, thus enabling Atlantic air to be carried over the Mediterranean Sea. This warm and very wet air in the lower layers impinges on the coastal mountains ranges and the forced ascent is sufficient to trigger potential instability. This meteorological configuration is accounted for the negative phase of the WeMO, which defines a synoptic pattern prone to producing torrential precipitation and floods on the Eastern Iberian coast. Daily precipitation amounts over 200 mm are not unusual in such cases, particularly in eastern Spain, where many catastrophic floods are related to the presence of a cut-off low (Llasat, 2009). Thus, these catastrophic floods in the Northwestern Mediterranean basin are generally of synoptic origin and are defined by the negative phase of the WeMO and enhanced by certain mesoscale factors (Gilabert and Llasat, 2018).

The present study provides an exhaustive inventory of the most intense daily precipitation events in Catalonia (NE Iberia) over the last few decades (1951-2016) in order to provide a better understanding of their temporal distribution. Moreover, we will analyse changes in frequency according to subperiods, since the Western Mediterranean basin constitutes 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 our study involves creating a catalogue of extreme torrential events in Catalonia in order to establish a period of high potential torrentiality in the area analysed at daily resolution. 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. Consequently, the present research attempts to use a more accurate timescale than the monthly one in order to determine the period with the highest accumulation of heavy precipitation episodes 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.

Additionally, we analyse SST in order to establish a sea-atmosphere interaction to explain WeMOi values and changes in the frequency of events. Seawater constitutes an energy store, i.e. recharge areas, which can influence water vapour content and can intensify precipitation episodes (Pastor *et al*., 2018; Iizuka and Nakamura, 2019) by means of a sea-atmosphere moisture exchange. Furthermore, a significant release of latent heat occurs during atmospheric convection over a warm sea like the Mediterranean at the end of summer and the beginning of autumn (Pastor *et al*., 2015).

In section 2, we describe the main orographic and pluviometric features of the study area. The data and 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, WeMOi values and sea temperature trends are analysed and discussed. 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 (northwestern Pyrenees) m.a.s.l. The Coastal and Pre-Coastal ranges, with an altitude ranging from 500 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 precipitation 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 comes 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 (1951-2016) homogenized and provided by the Meteorological Service of Catalonia (SMC, 2017), 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 of autumn precipitation can be observed, followed by spring precipitation, especially in the coastal zone. The driest season on the coast is summer; however, the driest time of year inland is winter. Many areas of the Pyrenees, above all in the east, exhibit their maxima in summer as a result of convective precipitation.

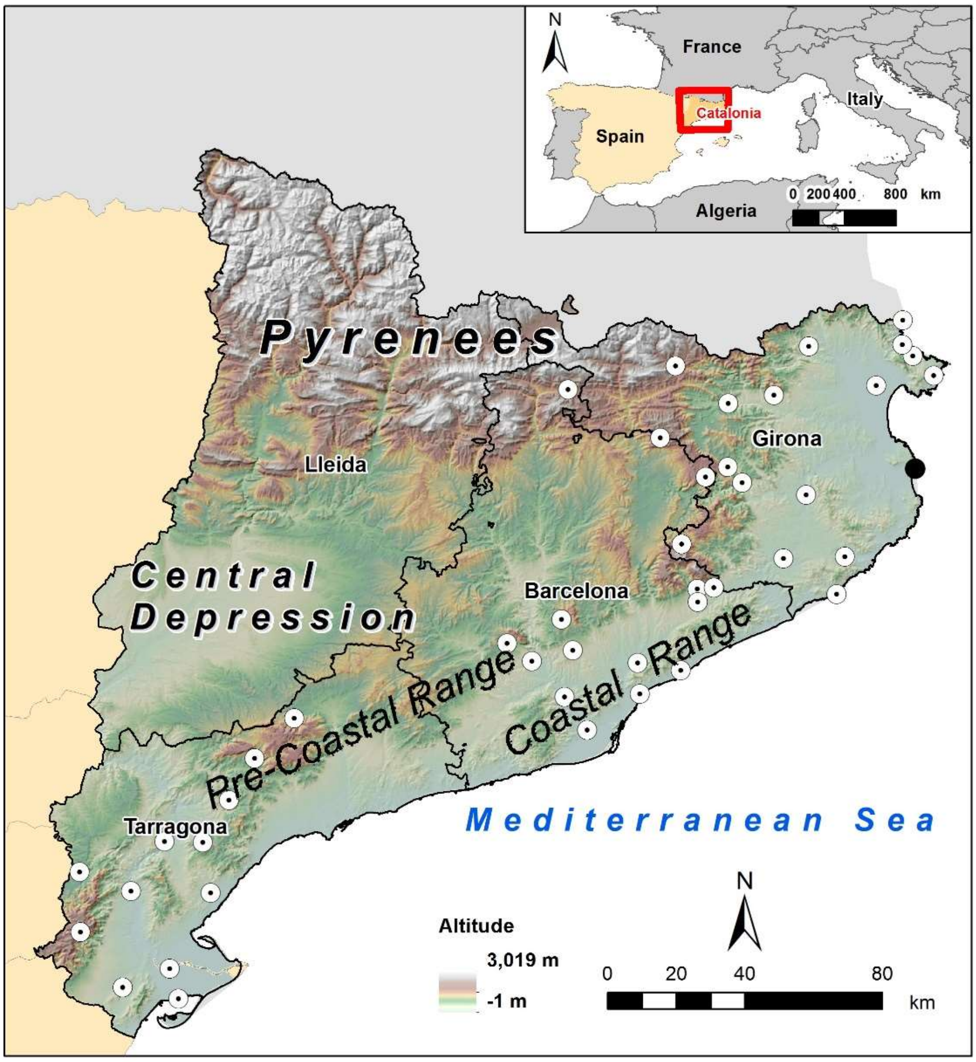

Figure 1. Location of Catalonia (NE Spain) within Europe, altitude and provinces. The white dots indicate the 43 different weather stations that have recorded the highest precipitation amount during an extreme torrential event at least once in Catalonia during the 1951-2016 study period. The black dot indicates the location of the sea temperature series. Base map provided by the Cartographic and Geological Institute of Catalonia.

(a) (b)

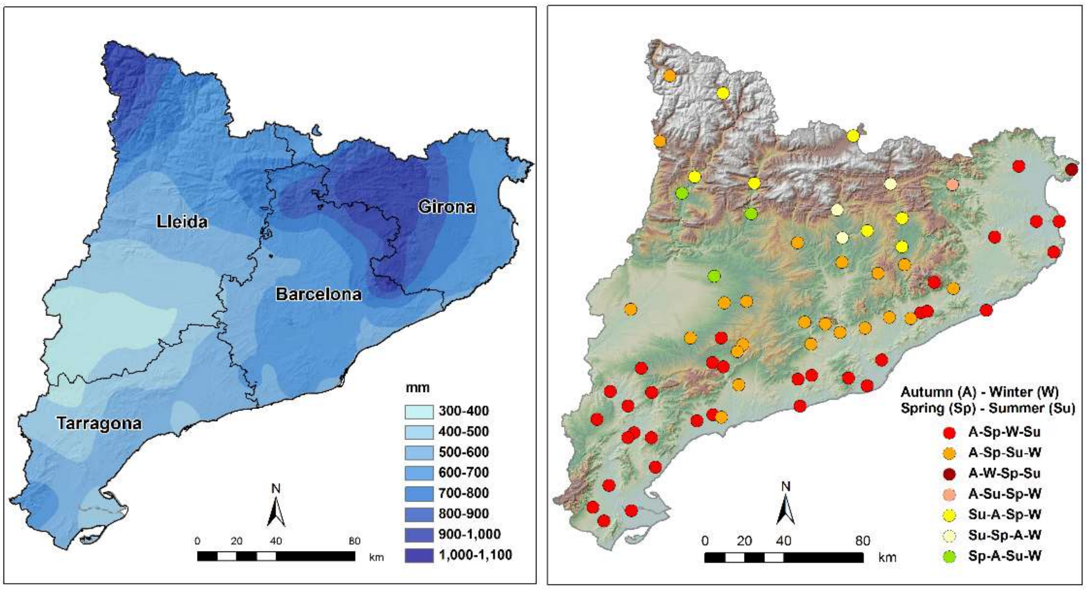

Figure 2. (a) Annual mean precipitation (mm) and (b) seasonal precipitation regimes for 70 weather stations in Catalonia for the 1951-2016 study period. Data source: SMC (2017). Base map provided by the Cartographic and Geological Institute of Catalonia.

3. Data and methods

3.1. Selection of torrential events

Several studies have selected the torrential precipitation 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) (Martin-Vide, 2002; 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. precipitation duration (Jang, 2015), initial soil moisture conditions and hydrological parameters (Norbiato *et al*., 2008; Martina *et al*., 2009). Furthermore, the area affected by episodes of ≥100 mm in 24 h is sometimes local and is therefore not easily associated with advective synoptic patterns (Gilabert and Llasat, 2018).

In order to select the extreme torrential events, we considered all available precipitation data sources in Catalonia (Meteorological Service of Catalonia, Spanish National Meteorological Agency, Catalan Water Agency and Ebro Hydrographic Confederation). Thus, 1,466 weather stations were identified during 1951-2016, of which 986 were manually managed (67.3%) and provided one register per day, at 7 h UTC. Until 1987 the manual weather stations had constituted the only precipitation data source in Catalonia. The remaining 480 weather stations were automatic observatories, reporting hourly or semi-hourly data depending on the network and period. The 1988-2016 period was covered by both manual and automatic 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. We conducted an exhaustive spatial and temporal verification of 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 rectified several episodes recorded by weather stations the day after the pluviometric day, and we eliminated events derived from the accumulation of precipitation for over one day.

The catalogue of extreme torrential events in Catalonia contains 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). A total of 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 precipitation events. This effect has no influence on the results of the present research.

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**

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 precipitation 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). Pressure data for both series were extracted from Martin-Vide and Lopez-Bustins (2006), who performed a statistical treatment of homogenization and the Climatology Group (University of Barcelona) periodically update the data. 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 precipitation over areas that were weakly influenced by the North Atlantic Oscillation (NAO): these areas are the northernmost and easternmost parts of Spain; precipitation over the Cantabrian fringe (northern Spain) is strongly and positively correlated with the WeMOi, and precipitation over the Spain's eastern façade is strongly and negatively correlated with the WeMOi.

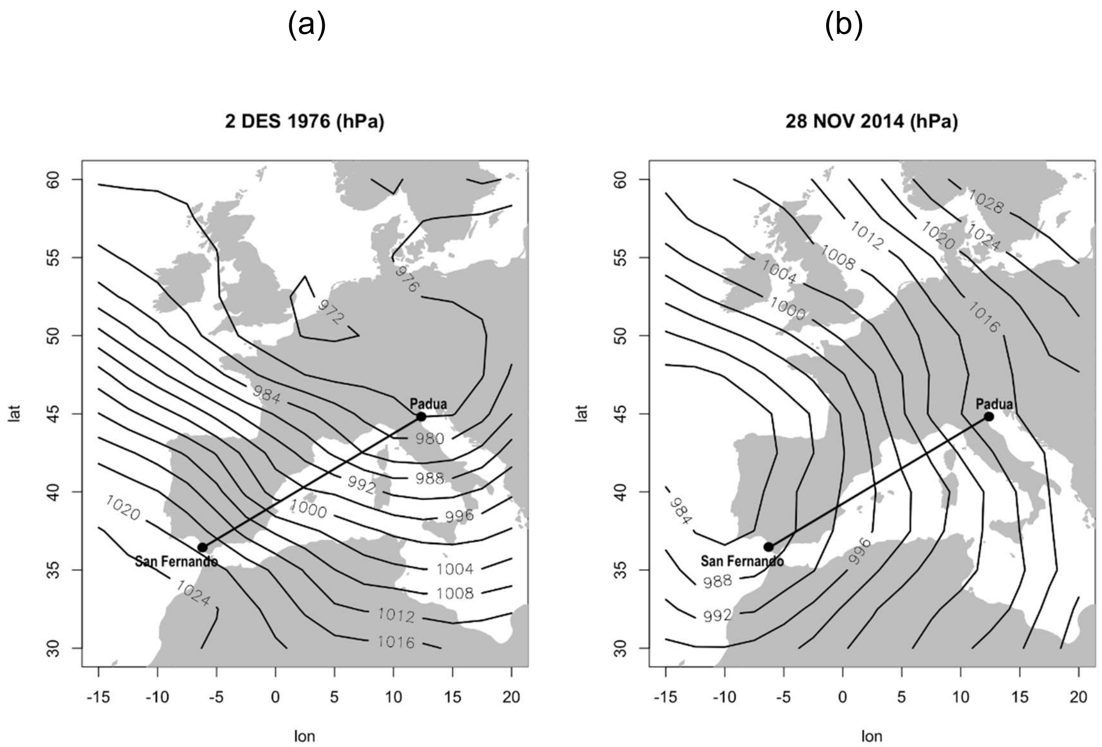

Figure 3. (a) Most extreme positive phase of the Western Mediterranean Oscillation (WeMO) in a daily synoptic situation during the 1951-2016 study period (2nd December 1976). (b) Most extreme negative WeMO phase in a daily synoptic situation during the 1951-2016 study period (28th November 2014). Data 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 standardizing each series of the dipole. It is necessary to use the daily mean and standard deviation of the 1961-1990 reference period of all days of the year (January 1st 1961 – December 31st 1990).

For example, the WeMOi on January 1st 1981

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

where P is pressure, SF, San Fernando, PD, Padua, $\overline{X}$, 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 precipitation 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 negative (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 (5.2%) and negative (3.9%), represent less than 10% of the total number of days for which WeMOi values are available. Daily NAO index (NAOi) values are also used for comparison with WeMOi values and to enhance the role played by the WeMO in torrential precipitation. Following the calculation method based on daily WeMOi values, daily NAOi values are computed by means of surface pressure data from the San Fernando (SW Spain) and Reykjavík (SW Iceland) weather stations; the data for Reykjavík were provided by the ECA dataset (Klein Tank *et al.*, 2002). The NAOi values present the same percentage as that of the negative WeMOi daily values (55.1%) and almost half of the days are around 0. The distribution of the daily values of the NAOi presents more extreme positive and negative values than the WeMOi distribution, 12.4 vs 5.2% and 8.7 vs 3.9%, respectively (Figure 4).

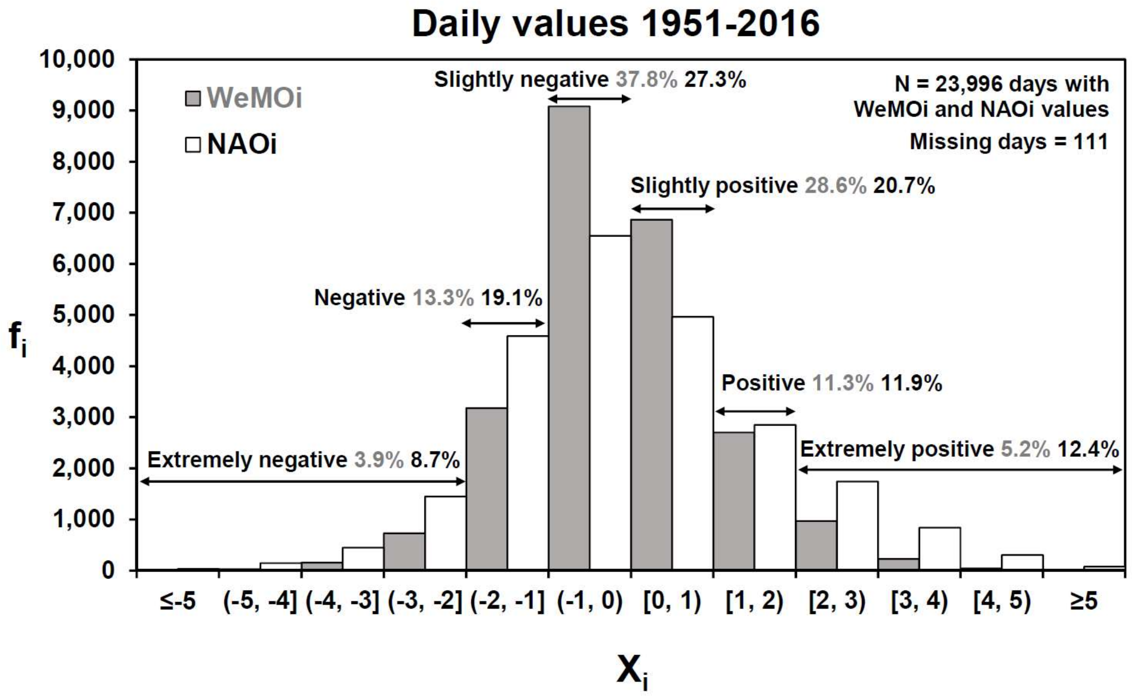

Figure 4. Frequency histogram of all daily WeMO index (WeMOi) values and North Atlantic Oscillation index (NAOi) values during the 1951-2016 study period.

3.3. Construction of calendars

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

Additionally, we analysed these calendars according to subperiods, together with changes in SST and subsurface temperature at several depths (20, 50, and 80 m.b.s.l.) at a site located on the coast of Girona province (Figure 1). These data constitute a reference series of sea temperature observations in Spain; the data on the 1973-2017 period were provided by the Meteorological Service of Catalonia. We calculated monthly temporal trends in sea temperatures using the least-square linear fitting, and we estimated the statistical significance by means of the Mann–Kendall non-parametric test (Sneyers, 1992). The standardized values (Z) of sea temperatures were computed at 10-day resolution, and the Z differences were obtained between two 5-yr subperiods from the beginning and the end of the 1973-2017 period: 1973-1977 and 2013-2017; we showed the Z differences for the months of the wet season (September, October and November) for most of Catalonia (Figure 2b), and also for December in order to detect a potential temporal shift of sea warming rates towards the early winter.

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 precipitation 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 precipitation 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) WeMO 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 (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) WeMO phase. No extreme torrential episodes presenting a positive WeMOi value occurred in Catalonia during the study period. Furthermore, 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. On the other hand, the maximum concentration of extreme torrential events according to NAOi values falls within the interval (-1.00, 0.00), and both negative and positive NAOi values can account for an event. This result demonstrates the fact that daily WeMOi values are more useful than daily NAOi values. This is further evidenced by the fact that only 24% of the total number of events took place during an extreme negative (≤-2.00) NAO phase, whereas this percentage rises to 60% in an extreme negative WeMO phase.

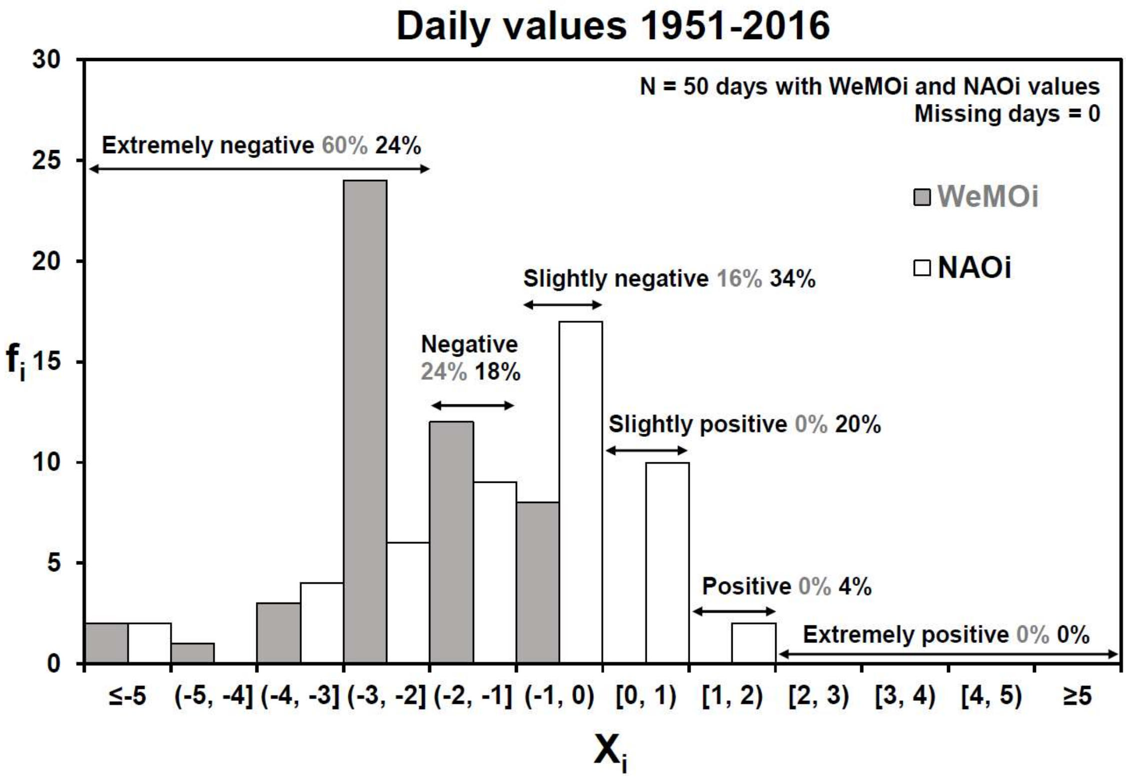

Figure 5. Frequency histogram of the daily WeMOi and NAOi values of the 50 extreme torrential events recorded in Catalonia during the 1951-2016 study period.

Most of the years in the 1951-2016 period present no episodes, or only one (Figure 6); in six years there were 2 or 3 episodes, depending on the year, 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 in September, with another one-day episode occurring in October. The former 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 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 precipitation events, many studies on Iberian precipitation are showing an increase in precipitation 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 precipitation variability over the Western Mediterranean (Hartmann *et al*., 2013, Caloiero *et al*., 2019). On the other hand, non-statistical temporal trend is observed in the annual frequency of the extreme torrential episodes (i.e. ≥200 m in 24 h) in Catalonia during 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.

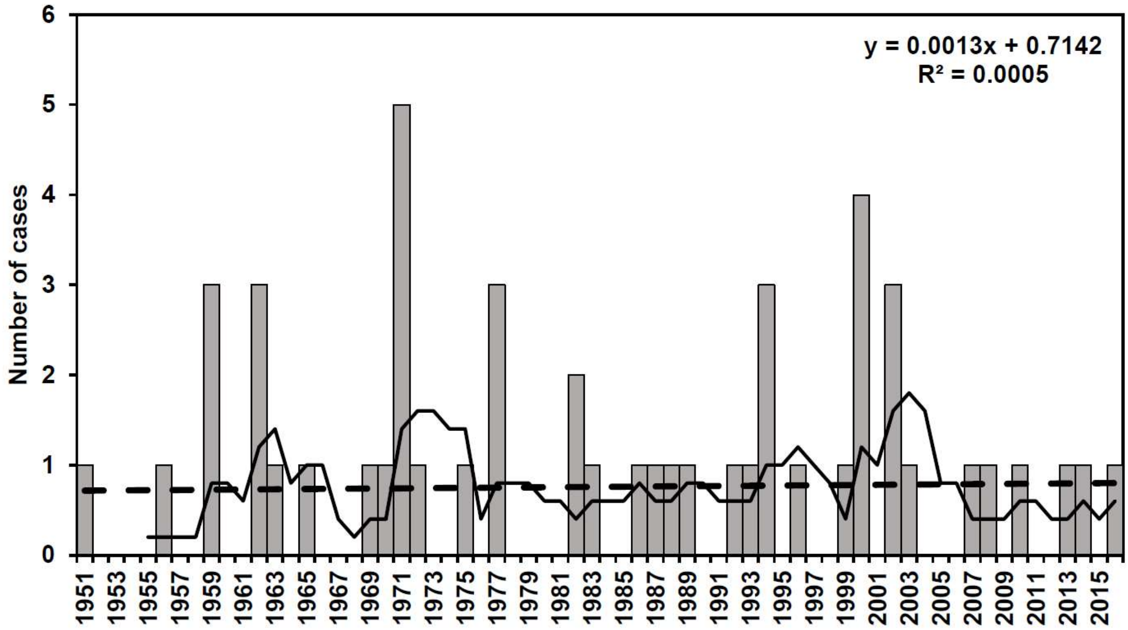

Figure 6. Temporal evolution of the annual frequency of extreme torrential events (≥200 mm in 24 h) throughout the 1951-2016 study period. The figure shows the linear regression (dashed line) and 5-yr running mean (black line).

4.2. Calendars of the daily WeMOi values

The lowest WeMOi values are detected in autumn, especially in October (-0.38) (Figure 7a), usually with humid easterly flows from the Mediterranean Sea. 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). This is coherent with subsurface sea temperature, which reaches its annual maximum in autumn (not shown). 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. Sea temperature decreases after the wet season, and the first months of the year constitute the period when sea waters are the coldest (not shown). Additionally, WeMOi values are very high in January and February, and the precipitation-convection phenomenon can therefore be halted by a strong decrease in SST (Lebeaupin *et al*., 2006). 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 one 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 11th 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 high 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 January 1st to 10th (+0.38); this indicates the total predominance of the positive phase of the teleconnection during these days, according to the 1951-2016 study period (Figure 8a). During this 10-day period, the occurrence of extreme torrential events in eastern Iberia is strongly inhibited by the NW atmospheric circulation over the study area; sea waters are cold and the Genoa low is well represented. The remaining 10-day periods in winter also present a predominance of the western circulation over the Iberian Peninsula. This pattern causes positive pressure differences between the Gulf of Cadiz (at a lower latitude) and the North of Italy (at a higher latitude), which produces positive WeMOi values and inhibits 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 – 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).

This is approximately 60% of the year falling under negative WeMOi values at monthly N= 8 (out of 12) (Figure 7d), fortnightly N = 14 (out of 24) (Figure 7e), and 10-day N = 23 (out of 36) (Figure 7f) timescales. The linear regression between negative WeMOi values and episodes is statistically significant at all timescales, providing an R of -0.73 (Figure 7d), -0.72 (Figure 7e) and -0.72 (Figure 7f). There is a statistically significant increase in the occurrence of events as the WeMOi value decreases. The linear fitting is especially significant at 10-day resolution.

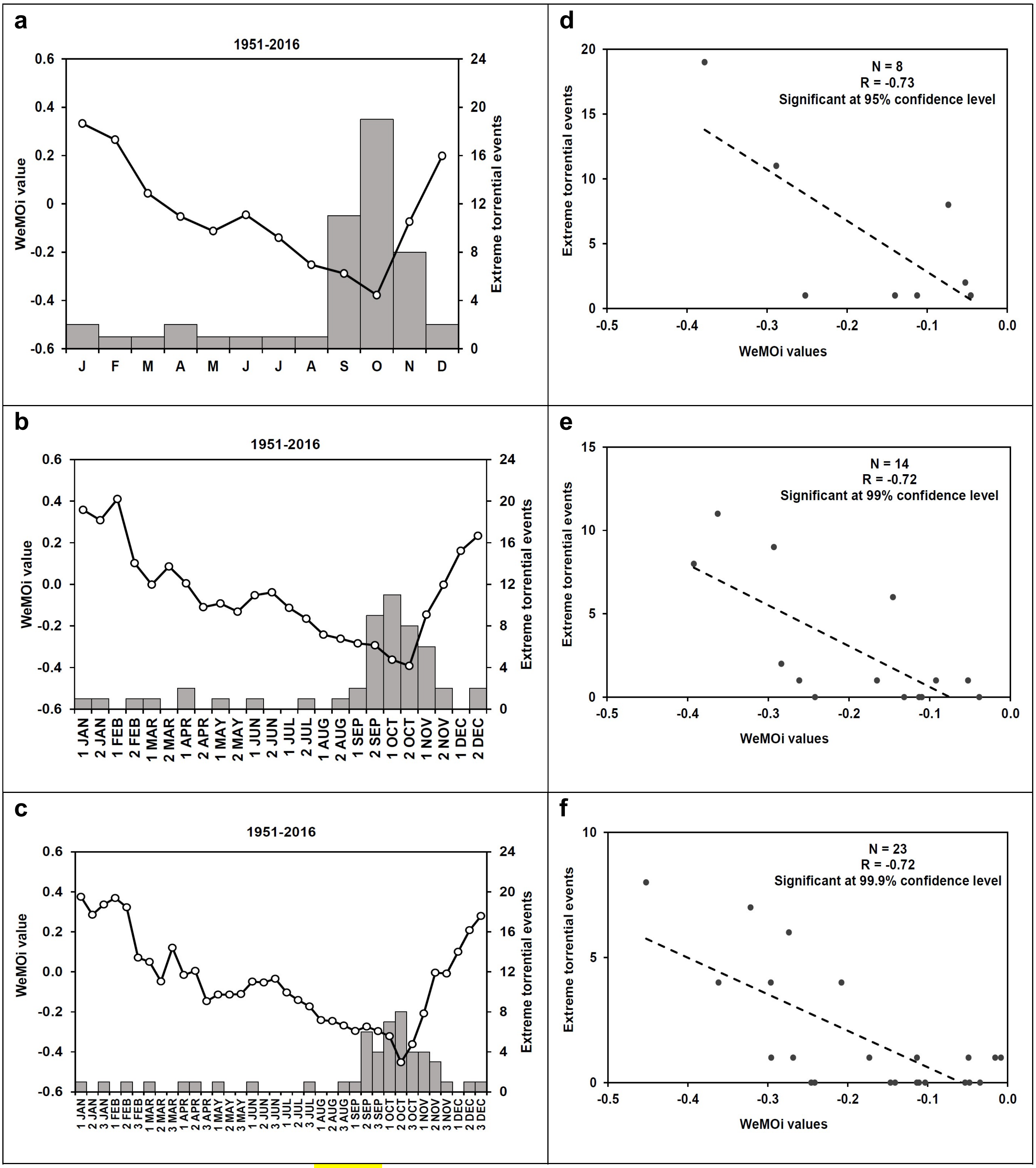

Figure 7. WeMOi calendars (lines) and frequency of extreme torrential episodes (bars) at several timescales: monthly (a), fortnightly (b) and 10-day (c). Scatterplot of the relationship between extreme torrential events and negative WeMOi values at several timescales: monthly (d), fortnightly (e) and 10-day (f); (the linear regression is shown as a dashed line).

(a) (b)

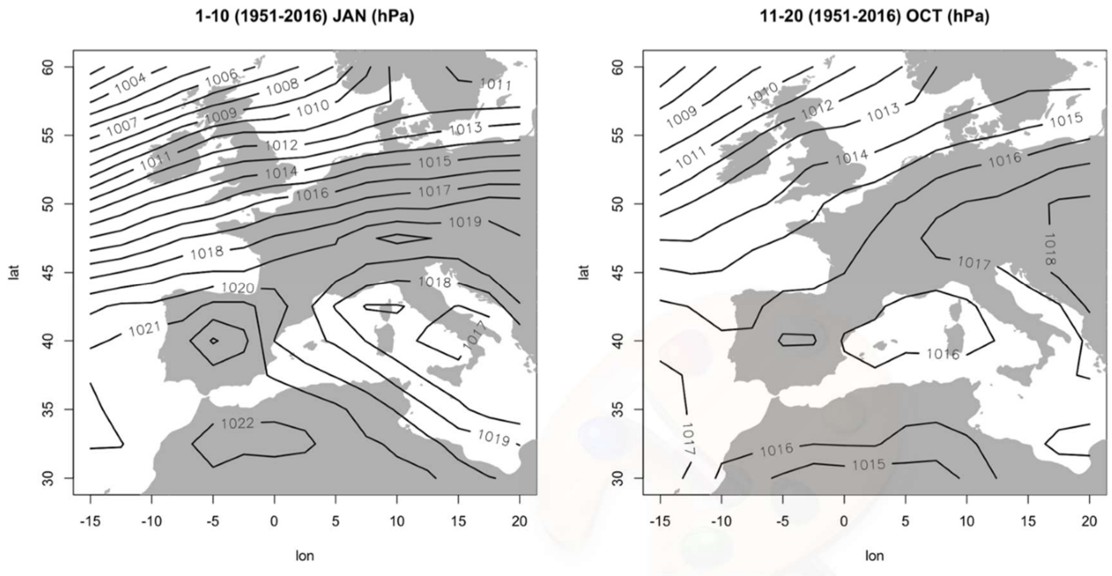

Figure 8. Sea level pressure (SLP) mean of the synoptic window 30ºN-60ºN and 15ºW-20ºE from January 1st to 10th (a) and from October 11th to 20th (b) during the 1951-2016 study period. Data source: NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA.

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*., 2020). This central period of October may be the most prone to torrential events over many regions of the western Mediterranean due to presenting the lowest WeMOi value of the year. On the Iberian Peninsula, the Almanzora river (SE Spain) suffered 2 of the 4 most 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 13th-14th 1957 and October 19th-20th 1982 (Olcina *et al*., 2016; Miró *et al*., 2017).

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 9). On the contrary, 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 October during the first half (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 early winter (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. All these seasonal changes can be related to trends in SST during the last few decades; the highest rate of SST warming is in November (0.42 °C per decade) (Table 2). A general warming of sea temperature has occurred along the year at all levels (SST, 20, 50, and 80 m.b.s.l.), particularly in spring, late autumn and early winter, a fact which might explain these more negative WeMOi values during the second subperiod; the warming of the lowest level of the atmosphere over the Western Mediterranean Sea contributes to the formation of mesoscale lows (Jansà *et al*., 2000). Similar rates of warming at near-surface sea level have been recorded in other locations in the north Mediterranean Sea (Raicich and Colucci, 2019). The highest warming rates have been observed at SST and 20 m.b.s.l., but the statistical significance has been greater at the deepest levels, i.e. 50 and 80 m.b.s.l. (Table 2). Figure 10 shows that changes in WeMOi values between both subperiods are negatively and statistically correlated with sea temperature trends, above all, in the underlying layers, especially at 80 m.b.s.l., where sea temperature displays a low interannual and intra-annual variability and sea heat content hardly varies (Sparnocchia *et al*., 2006).

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, the lowest value is observed in the second fortnight of October during the 1984-2016 period (-0.58). All WeMOi values according to fortnights showed 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 show a decrease over these 10-day periods of the year during the second subperiod. This is in line with the fact that the warming was moderate, or that there was even a certain degree of cooling, during the first 10-day periods of the wet season, i.e. from September 1st to October 20th, in the underlying sea layers (Table 3); and consequently, episodes might not have been favoured during the second subperiod. The highest sea temperature increase at all levels during the wet season is in the third 10-day period of October (Table 3), when the highest increase in extreme torrential episodes is observed (Figure 9). The changes in the frequency of episodes are statistically correlated with sea temperatures at subsurface layers, i.e. 50 and 80 m.b.s.l. (Figure 11). The deepest level (80 m.b.s.l.) shows the strongest warming in late autumn (from October 21st to November 30th), whereas this warming is weak in early autumn (from September 1st to October 20th) (Figure 12).

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 and an increase in precipitation irregularity due to a deeper WeMO negative phase (Lopez-Bustins and Lemus-Canovas, 2020). This seasonal shifting might be caused by a recent increase in sea temperature in the Western Mediterranean basin, particularly in November (Table 2) and late October (Table 3) (Lopez-Bustins, 2007; Estrela *et al.*, 2008; Lopez-Bustins *et al.*, 2016; Arbiol-Roca *et al.*, 2017). Pastor *et al.* (2018) used satellite data to identify an overall increase in SST throughout the Mediterranean basin during the 1982-2016 period, highlighting its role in torrential events in the Western Mediterranean.

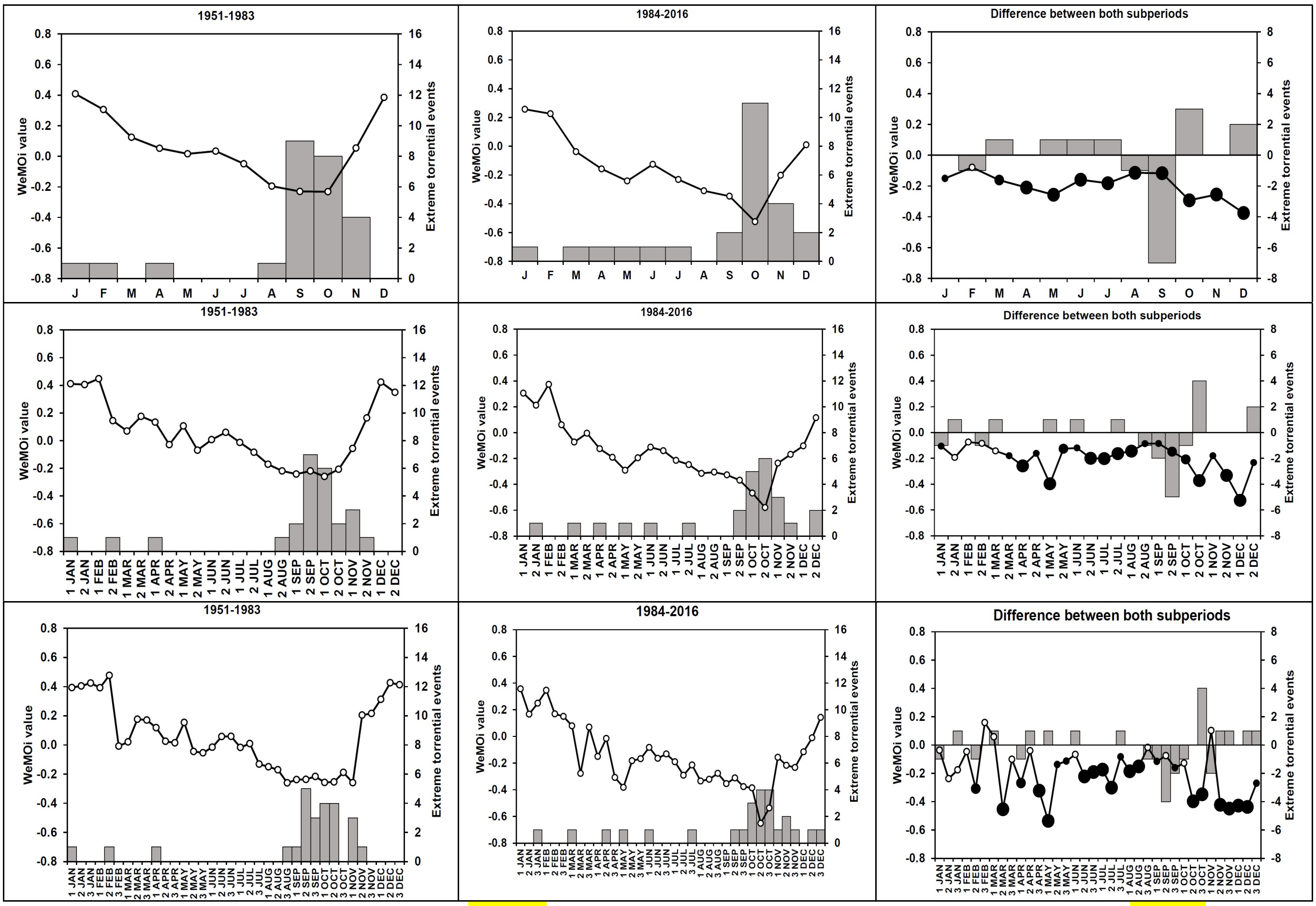

Figure 9. WeMOi calendars (lines) and frequency of extreme torrential episodes (bars) at several timescales: monthly (above), fortnightly (middle) and 10-day (below) for the 1951-1983 (left) and 1984-2016 (central) subperiods. The right-hand column shows the difference in the number of episodes and WeMOi 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).

N = 44 1973-2016	J	F	M	A	M	J	J	A	S	O	N	D	°C 10yr^{-1}	
SST	*	*	*	*	*	*	*				*	*	<0.15	0.30-0.34
-20 m	*	*		*	*	*	*	*	*		*	*	0.15-0.19	0.35-0.39
-50 m	*			*	*	*	*	*	*	*	*	*	0.20-0.24	≥0.40
-80 m	*			*	*	*	*	*		*	*	*	0.25-0.29	

Table 2. Monthly sea temperature trends at surface (SST), 20, 50, and 80 m.b.s.l. during 1973-2016 (*statistically significant trends at the 95% confidence level by means of the Mann-Kendall non-parametric test).

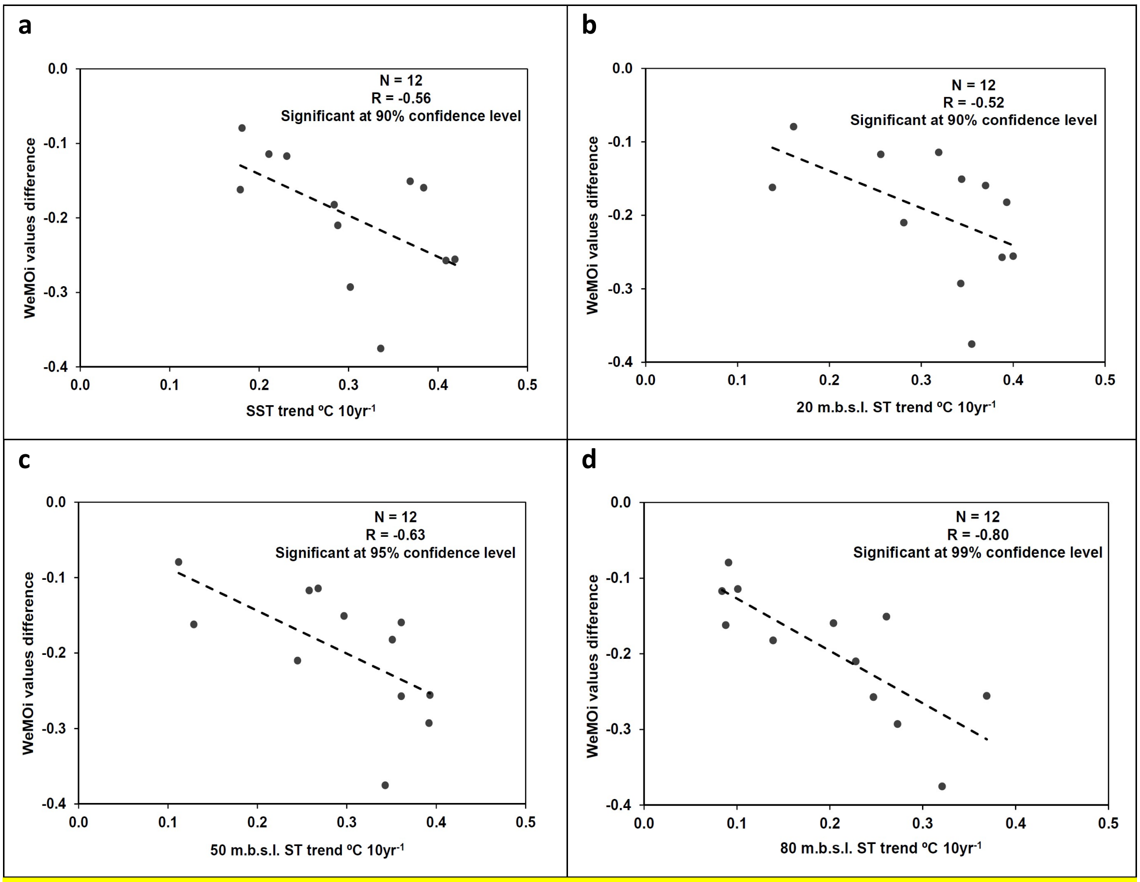

Figure 10. Scatterplot of the monthly relationship between the WeMOi value differences (1984-2016 minus 1951-1983) and sea temperature (ST) trends during the 1973-2016 period at surface (SST) (a), 20 (b), 50 (c), and 80 (d) m.b.s.l. (a dashed line indicates the linear regression).

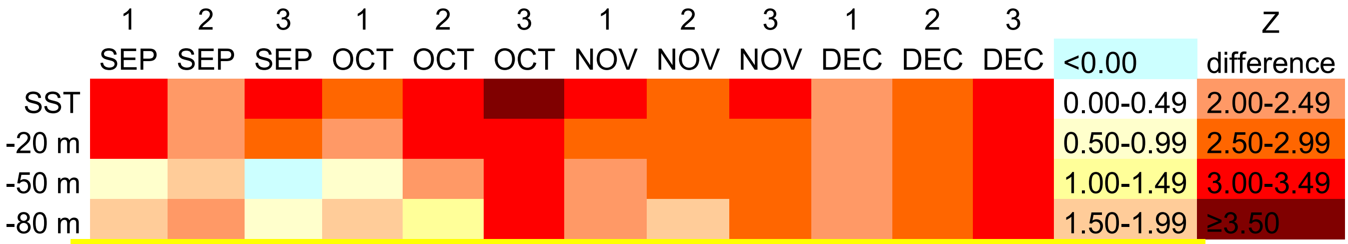

Table 3. 10-day period ST standardized values (Z) differences for two 5-yr subperiods (2013-2017 minus 1973-1977) at surface, 20, 50, and 80 m.b.s.l. during the wet season (from September to November) and December.

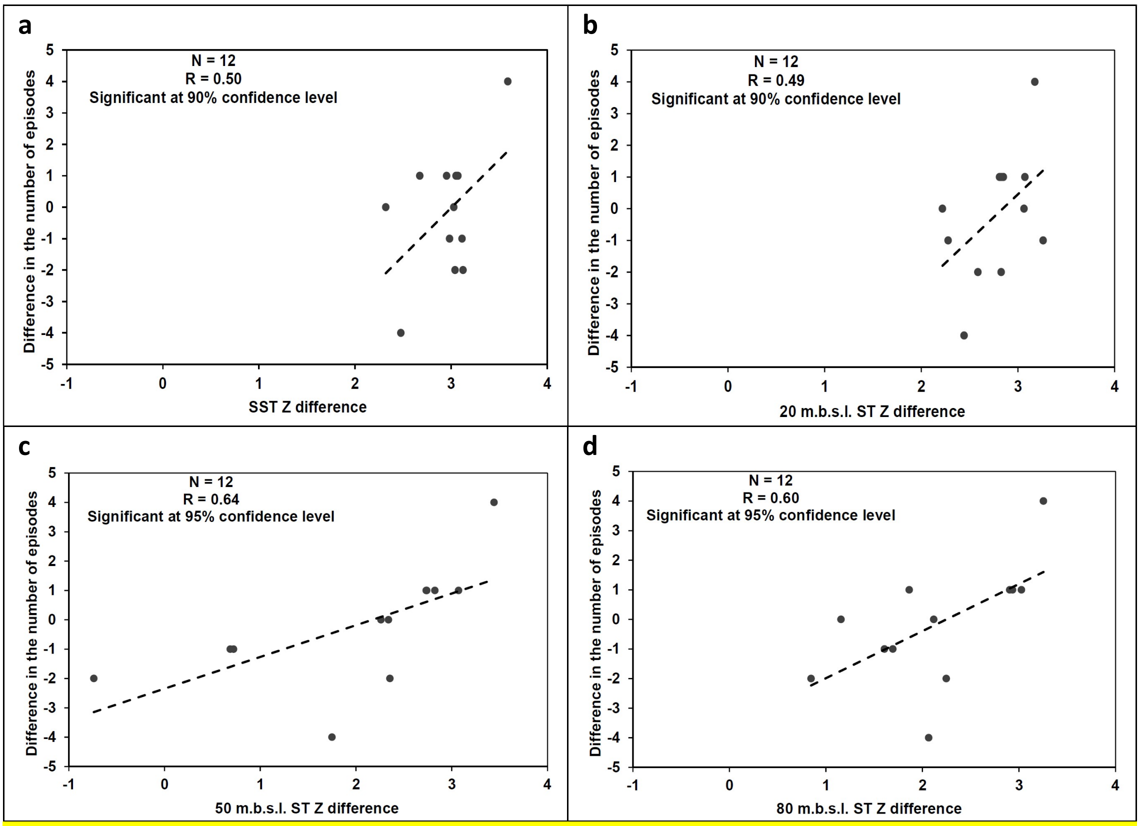

Figure 11. Scatterplot of the 10-day relationship between the differences in the number of episodes (1984-2016 minus 1951-1983) and ST Z differences for two 5-yr subperiods (2013-2017 minus 1973-1977) at surface (a), 20 (b), 50 (c), and 80 (d) m.b.s.l. during the wet season (from September to November) and December (a dashed line indicates the linear regression).

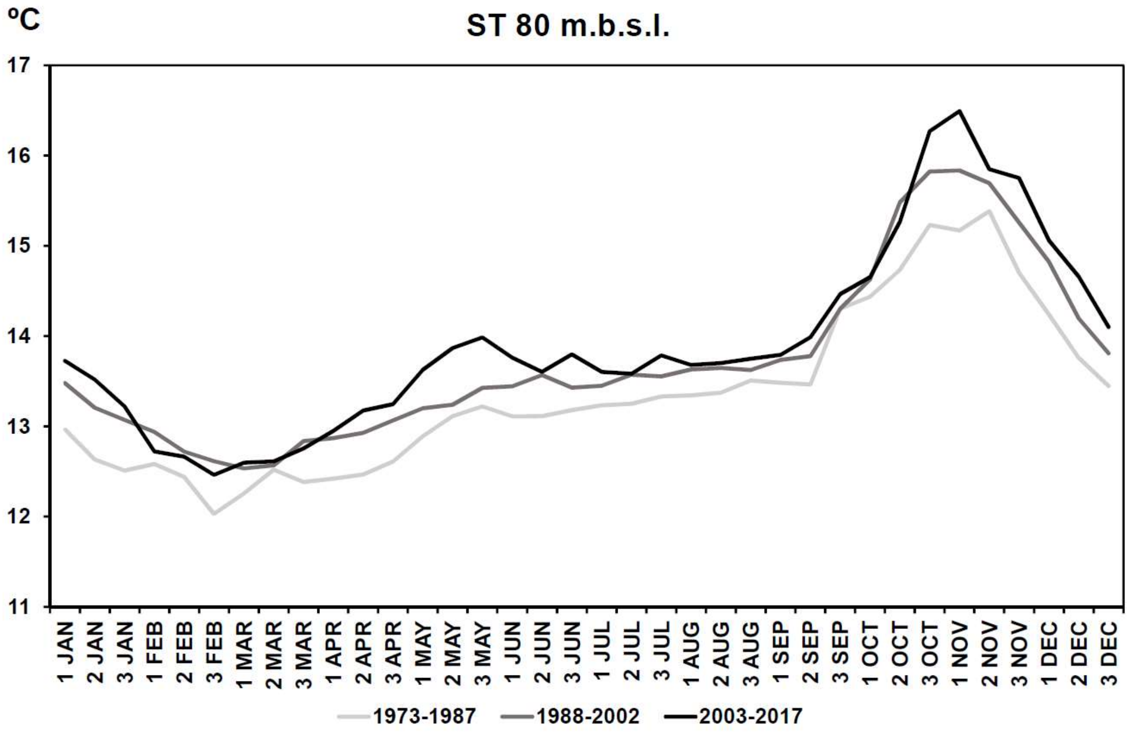

Figure 12. ST 10-day calendar at 80 m.b.s.l. for three 15-yr subperiods: 1973-1987, 1988-2002 and 2003-2017.

5. 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 precipitation over NE Spain. October is the rainiest month in most regions of the Northwestern Mediterranean basin and can account for the lowest value of the year on the WeMOi monthly calendar, together with the warmest sea temperature of the year at subsurface level. 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 Mediterranean. The present study considers the threshold of 200 mm in 24 h for extreme torrential episodes, due to the fact that this precipitation accumulation in one day can cause serious widespread damage over a large area. Having thoroughly reviewed several databases and contrasted these results with the original files and nearby weather stations, we confirmed that Catalonia registered

0.8 cases per year (50 episodes in 66 years) of extreme torrential episodes during the 1951-2016 study period, in accordance with the 7-7 UTC pluviometric day.

The 10-day period from October 11th to 20th exhibits both the greatest 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 this Northwestern Mediterranean area, according to the WeMOi values. The most intense torrential event in Catalonia ever recorded by an official weather station is in Cape Creus (the easternmost part of the Iberian Peninsula) within the 10-day period most susceptible to torrential precipitation (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 and sea temperature conditions of this time of the year inhibit torrential events.

No extreme torrential episodes in Catalonia occurred in a positive WeMO 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. This might have been caused by an overall increase in sea temperature throughout the year, particularly in late autumn. On the other hand, extreme torrential events show no changes in frequency between both subperiods; no temporal trend is observed, either, during the 1951-2016 study period. The most notable change involves the displacement of extreme torrential episodes from early 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. Increases in sea temperatures in the underlying layers during the end of the wet season can provide an understanding of these changes in extreme torrential events and in the WeMOi calendars.

Data availability

The WeMOi data can be downloaded from the Climatology Group (University of Barcelona) website http://www.ub.edu/gc/en/ (last accessed May 23rd 2020).

Author contributions

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

Competing interests

The authors declare that they have no conflict of interest.

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Anonymous Referee #1 "Author's response"

Overview:

This manuscript addresses the occurrence of extreme torrential precipitation episodes in Catalonia (Northeast Spain). These episodes are considered as 24-hour periods with total precipitation amounts over 200 mm, rather than the commonly considered 100 mm threshold. The analysis is carried out from 1951 through 2016 (66 years) and using 70 weather stations covering Catalonia. A total of 50 episodes was identified and their occurrence was subsequently related to a teleconnection pattern index, the Western Mediterranean Oscillation index (WeMOi). These relationships are assessed not only at the monthly timescale but also at two-week and 10-day timescales.

We are very grateful for the reviewer's comments and for the revision of our manuscript. The paper has been revised in accordance with the referee's comments and suggestions, which are addressed below. Our answers appear in bold.

General comments:

The manuscript is clearly presented and the results are generally sounding and in line with previous studies. A satisfactory state-of-the-art is provided, giving credit to the most relevant preceding studies. Nonetheless, I found that the manuscript does not add significant new information to this topic of research. As it is currently, the manuscript is mostly a statistical description of the connections between extremes and WeMOi. From my viewpoint, the study lacks a more detailed analysis of the mechanisms underlying the occurrence of these events in Catalonia. The use of a single teleconnection index is too simplistic and does not bring any added value to both the forecast of these events and to their understanding. More focus should be given to mesoscale processes and dynamical features, also highlighting singularities.

The main contribution of the paper involves an accurate database of extreme torrential episodes. It was a painstaking task to select the appropriate episodes, as well as to review several databases and handwritten cards. Indeed, we consider this to constitute the most reliable extreme torrential database existing for this region.

We agree with the reviewer in that dynamical mechanisms are lacking; we have therefore included new analyses that consider the temporal evolution of sea temperature from one specific high-quality series on the coast covering several decades (1973-2017) (please see tables 2 and 3, and figures 10, 11 and 12). The results show a statistical relationship between changes in the WeMOi and SST trends. Furthermore, we have added a long text explaining the dynamical mechanisms in the introduction on L88-114 and we have included many new references. We have also added three references from 2020.

We agree with the reviewer that it is too simplistic to use only one teleconnection index. We have added NAOi values for figures 4 and 5 in order to demonstrate the better fit of the WeMOi in comparison to the NAOi, and these are commented on in the text on L323-331 and L404-411.

Specific comments:

1. I recommend replacing "rainfall" with "precipitation" throughout the text, as e.g. hailfall may have occurred on some occasions.

We agree with the reviewer. We have replaced it throughout the manuscript.

2. Keywords are too vague. Please revise.

We have changed some of them. The current keywords are Mediterranean, sea temperature, teleconnection indices, torrential precipitation, WeMO.

3. Lines 93-101: The authors state that: "The main aim of the study involves establishing a period of high potential torrentiality in Catalonia at daily resolution" and below that "Therefore, the present research attempts to go beyond the monthly timescale in order to determine the period with the highest accumulation of heavy rainfall according to fortnights 99 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". As previously mentioned, from my point of view this single objective of the study is not enough to justify the publication of the study. A much more detailed analysis should be provided, including an analysis of dynamical precursors, which would be very important for improving weather forecasts and the general understanding of these events.

We have rewritten the main aim of the study on L123-125 to highlight the importance of the creation of the catalogue. Furthermore, new analyses involving SST have been added (Tables 2 and 3, and Figures 10, 11 and 12).

4. Ln 108: the authors mention several times "south of France", but the weather stations located in France only cover a very limited area of southern France. Hence, this terminology is a bit misleading and should be revised. Furthermore, the analysis for the French stations does not bring any significant new information and should be discarded from the study. Further, a different threshold is used (100 mm), as is said in Ln 471, thus not allowing a comparison.

We agree with the reviewer and we have discarded it from the study.

5. Fig. 3: The use of NCEP reanalysis is not the best option. The ERA5 dataset should be used instead. Also, the quality of the panels should be considerably improved.

ERA5 is a better (higher resolution and a more complete global circulation model), updated reanalysis in comparison with the NCEP/NCAR reanalysis, but ERA5 currently only covers the time period from 1979. Therefore, we are unable to redesign figure 3 (a) and figures 8 (a) and 8 (b). Moreover, the definition of spatial resolution is not relevant with regard to shaping the WeMO phase occurring on these days. Nonetheless, we have improved the quality of all figures with NCEP/NCAR reanalysis.

6. Ln 368: five consecutive days? Fig. 6 shows 5 instead of 4. Please clarify.

For clarity, we have modified the sentence as follows "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 in September, with another one-day episode occurring in October" (L417-420).

7. Fig. 7 and subsequent: the means of the bars and lines are not explained in the panels. Please revise.

To clarify it we have modified the sentence in the caption of the figures 7 and 10 as follows "WeMOi calendars (lines) and frequency of the extreme torrential episodes (bars) at several timescales".

8. The 2-order polynomial fitting is not duly explained. What is the purpose of these adjustments? What can be concluded from them?

We have checked why we used the 2nd-order polynomial fitting. We did so following a simple visual inspection, but it makes little physical sense. There is no atmospheric reason for an increase in extreme torrential events with positive WeMOi values. We have therefore calculated the regression line for only the WeMOi negative values, after verifying the statistically significant correlation between episodes and the WeMOi. In Figure 7 (d, e, and f) we have replaced the quadratic fit with the linear fit, and accordingly, we have done the same in the caption of the figure and in the text L497-504. The linear fit is especially significant at 10-day resolution. There is an evident increase in the occurrence of events with a decrease in WeMOi values.

9. Ln 584-586: The authors mention that "Further research on this theme 584 is required and SST temporal trends might provide a better understanding of these changes in extreme torrential events and WeMOi calendars". This type of analysis should not be left to a forthcoming study. This is a good suggestion to improve the manuscript.

We have included new analyses considering the temporal evolution of SST from one specific high-quality station on the coast which covers several decades (1973-2017) (please see Tables 2 and 3, and Figures 10, 11 and 12).

Technical comments:

1. Please replace "furnished" by "provided" or similar throughout the text.

Done.

2. The overall quality and resolution of the figures should be improved.

To this end we have redesigned all the figures.

Anonymous Referee #2 "Author's response"

General Overview:

The authors analyzed the intra-annual variability of the Western Mediterranean Oscillation and occurrence of extreme torrential rainfall in Catalonia (NE Iberia). Despite the target region and topic is of interest to be study due the possible socio-economic impacts of the torrential rainfall, the manuscript in the present form do not add much to the present knowledge. In addition, it has some very important methodological and organizational issues which are listed below:

We wish to thank the reviewer for his/her comments and for reviewing our manuscript. The manuscript has been revised in consonance with the referee's comments and suggestions, which are addressed below. Our answers appear in bold.

1) My main concern is that the manuscript fails to add new knowledge to the literature. In the present form, the manuscript is rather descriptive specially in section 4.2 and 4.3 where there is a statistical description between WeMO and the torrential rain which was previously known. From my point of view, there is the lack of understanding what is the physical mechanism which are behind the extreme torrential rainfall in Catalonia, for example, the atmospheric forcing, the role of SST, or even the soil moisture availability.

We agree with the reviewer regarding the lack of physical mechanisms; consequently, we have included new analyses, considering the temporal evolution of sea temperature from one specific high-quality series on the coast which encompasses several decades (1973-2017) (please see tables 2 and 3, and figures 10, 11 and 12). The results show a statistical relationship between changes in the WeMOi and SST trends. Furthermore, we have added a text explaining the atmospheric mechanisms related to mesoscale convective systems in the Western Mediterranean, which justifies the application of WeMO calendars (L88-114). Moreover, we have added new references to the introduction. We have also added three references from 2020. Furthermore, we have added NAOi values for figures 4 and 5 in order to demonstrate the better fit of the WeMOi in relation to that of the NAOi.

2) Figure 2a) is computed with data from where? The monthly series provided by the Meteorological Service of Catalonia?

Figure 2a is extracted from the 70 precipitation monthly series computed by the SMC (Yearly Bulletin of Climate Indicators, 2017) which have been quality controlled and analysed for homogeneity. The caption of Figure 2 now includes a paragraph explaining the origin of the data. The study period has been changed from 1950-2015 to 1951-2016. The caption now reads "Figure 2. (a) Annual mean precipitation (mm) and (b) seasonal precipitation regimes for 70 weather stations in Catalonia for the 1951-2016 study period. Data source: SMC (2017). Base map provided by the Cartographic and Geological Institute of Catalonia".

3) The authors use a fix threshold to define the extreme torrential episodes which is >200mm in 24h. L168-173. I do not agree with this sentence. Based on my experience I can imagine that precipitation >100mm in a relative larger area will have more impacts than a precipitation >200mm only recorded in one single weather station. Therefore, I encourage the authors to think of a way to define the torrential episodes based not only on the amount of precipitation but also on its spatial extent.

Thank you for your comment, which has brought us to further reflect upon the thresholds defining torrential rainfall in the Mediterranean. We partly agree with your comment, but episodes presenting precipitation ≥100 mm/day in a relatively larger area are not so common in Catalonia, and when they do occur, they do not cause major damage or destruction. For example, Gilabert and Llasat (2018), one of the new references we have included, found that catastrophic flood events (rivers overflowing with major damage or total destruction), associated with extreme torrential precipitation events, are generally of synoptic origin and are enhanced by certain mesoscale factors, a phenomenon that is clearly reflected by the negative phase of the WeMO. We have chosen the threshold of ≥200 mm in one single weather station as a maximum value in order to capture the most important torrential precipitation events, but within these, the area affected by precipitation values ≥100 mm is sizeable. This area usually encompasses a significant part of Catalonia (almost one third). Further information in this respect has been added to the new manuscript on L109-114, L193-201 and L659-661.

Moreover, in the first paragraph of subsection 3.1. 'Selection of the torrential events', we have further distinguished between 'torrential events' (threshold of ≥100 mm/24 h), widely used by Spanish authors, and 'extreme torrential events' (≥200 mm/24 h), already used in several previous studies, particularly in Lopez-Bustins et al (2016), cited in the References and also in Martin-Vide (2002), one of the new references we have included, as well as in others, with good results. It is true that the spatial domain of heavy precipitation conditions the fluvial response and the possibility of flooding, and the combination of precipitation amounts and area affected therefore enables a more complete hydrological analysis than when only precipitation amounts are used. In the future, the authors may intend to explore a hydrological definition of torrential precipitation for the western Mediterranean basin, taking into account both precipitation values and area affected.

4) There is an inconsistent between the period of analyses. On line L126 is mentioned 1950-2015 and on L167 1950-2016.

Many thanks for the observation. Indeed, there is an inconsistency that has been rectified both in the text (L162) and in Figure caption 2. The correct study period is 1951-2016.

5) The authors need to include a better description of the weather stations. How many of them are at a daily scale vs semi-hourly data. Since which year do you have access to automatic weather stations?

There were 986 weather stations at daily timescale (manual) and 480 at hourly or semi-hourly timescale (automatic) throughout Catalonia during the 1951-2016 period. The 1951-1987 period was covered by manual weather stations only. The 1988-2016 period was covered by both manual and automatic weather stations. We specified this information on L205-211.

6) L220-222 The WeMo is computed using SLP from the weather stations mentioned in the text? They are quality controlled?

Yes, it is (L243-247). Yes, they are (we have added new text to specify this L247-250).

7) In Figure 3 and Figure 8 the authors used the outdated NCEP/NCAR reanalysis. Please use ERA5 instead.

ERA5 is a better (higher resolution and a more complete global circulation model), updated reanalysis in comparison with the NCEP/NCAR reanalysis, but ERA5 currently only covers the time period from 1979. Therefore, we are unable to redesign figure 3 (a) and figures 8 (a) and 8 (b). Moreover, the definition of spatial resolution is not relevant with regard to shaping the WeMO phase occurring on these days. Nonetheless, we have improved the quality of all figures with NCEP/NCAR reanalysis.

8) Figure 7 d , e ,f). These results are not mentioned in the text. I would exclude it from the manuscript.

Following the suggestion of the other reviewer, we have checked why we used the 2nd-order polynomial fit. We did so after a simple visual inspection, but it makes little physical sense. There is no atmospheric reason for an increase in extreme torrential events presenting positive WeMOi values. We have therefore calculated the regression line for only the WeMOi negative values, having verified the statistically significant correlation between episodes and the WeMOi. In Figure 7 (d, e, and f) we replaced the quadratic fit with the linear fit, and accordingly, we did the same in the figure caption; the figures are now commented in the text on L497-504. The linear fit is especially significant at a 10-day resolution. There is an evident increase in the occurrence of events with a decrease in WeMOi values.

9) L268 The mean and standard deviation is computed at an annual scale or at a day level?

They are computed at a day level. We have included "daily" on L286.

10) Figure 4. Why this division?

Because we have already used it in previous studies and the results were sound (Martin-Vide and Lopez-Bustins, 2006; Azorin-Molina and Lopez-Bustins, 2008). These references are included in the bibliography and in the manuscript L301-302.

11) Regarding section 3.3, why don't the authors use a moving average instead of artificial 10-day or 15-days intervals?

In the present paper we used moving averages to perform an inter-annual analysis of the frequency of extreme torrential events (Figure 6). The construction of a calendar involved an intra-annual analysis based on climatological means. In this case, in addition to the simple monthly frequency, we preferred to use the half-monthly and the 10-day frequencies. The relative scarcity and temporal randomness of extreme torrential events at daily resolution reveal many "saw teeth", which are of no climatic or statistical significance.

12) L468-470. I don't think that 4 weather stations are representative of southern France. I would delete everything related with these 4 weather stations from the text, including Figure 9.

We agree with the reviewer and we have discarded it from the study.

13) L527-529 I agree with the authors and I think an analysis on this, among physical mechanisms (see comment 1), should be included in the new version of the manuscript.

We have included new analyses considering the temporal evolution of SST from one specific high-quality station on the coast covering several decades (1973-2017) (please see Tables 2 and 3, and Figures 10, 11 and 12).

Therefore, I recommend the major revision of the manuscript