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Circulation weather types associated with extreme flood events in Northwestern Mediterranean

Joan Gilabert[a,b]* and María Carmen Llasat[a]
[a] *GAMA, Department of Applied Physics, University of Barcelona, Spain*
[b] *Institute Cartographic and Geological of Catalonia, Barcelona, Spain*

ABSTRACT: The aim of this work was to identify the circulation weather types associated with flood events that occurred in Catalonia (Northeastern Spain) during the period 1900–2010. To achieve this objective, 261 extraordinary and catastrophic flood and flash flood events that were recorded during this period were characterized and classified based on impact data. A preliminary analysis of maximum precipitation and discharge was conducted in order to have some quantitative hydrometeorological indicators associated with these kinds of events. The objective classification developed by Jenkinson and Collison, which is based on differences in synoptic patterns according to surface pressure, was implemented. Once the weather regimes for each flood event had been established, a statistical and comparative analysis was performed that allowed us to determine which synoptic patterns were more frequently associated with the different flood types, their differences and their similarities. The results show that most synoptic situations were pure cyclonic structures, in both extraordinary and catastrophic events, although they were more frequent in the latter. Catastrophic floods generally had a synoptic origin enhanced by certain mesoscale factors, while extraordinary floods were usually associated with local flash floods that occurred primarily in summer and early autumn, highlighting the undetermined types that were not reflected at a synoptic scale. As the Mediterranean basin is a region where floods cause serious socio-economic impacts, this work will help improve prevention measures and provide information for policymakers, mainly for land-use planning and early warning systems.

KEY WORDS circulation weather types; floods; Catalonia; Mediterranean; precipitation; trend analysis; impacts; cyclones

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1. Introduction

Floods represent a significant risk to people and can have a major economic impact on society. According to the report ‘Flood Risks to People’ (DEFRA, 2006), 12% of deaths caused by natural disasters in the 20th century were due to flooding. Between 1980 and 2000, more than 170 000 flood-related deaths were recorded (Dao and Peduzzi, 2004). The same research suggests that about 196 million people in 90 countries are exposed to flooding each year. In Europe, the countries most frequently affected by this phenomenon are Italy, France and Spain, which are all located in the Mediterranean basin (Llasat *et al.*, 2010). In Spain, more than 2000 people died as a result of floods between 1950 and 2000; 64% of these deaths occurred in Catalonia (Northeastern Spain). In terms of economic impact, more than 60% of the payments made by the Spanish Public Reinsurer Compensation Consortium (Consorcio de Compensación de Seguros, CCS) between 1971 and 2014 were related to floods, according to its database. These facts demonstrate that the impact of flooding is greater than that of any other natural disasters in Spain.

* Correspondence to: J. Gilabert, Department of Applied Physics, Faculty of Physics, University of Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain. E-mail: jgilabert@meteo.ub.edu

Most floods in the Western Mediterranean basin are due to warm, humid air coming in at low levels from the sea, mainly during the autumn (SON) and summer (JJA) seasons. In many cases, the incoming air is associated with the presence of a low-pressure (cyclonic) weather system (Ramis *et al.*, 1994; Fiori *et al.*, 2014; Jansà *et al.*, 2014). Air mass inflow is mostly associated with cyclonic conditions. The complex topography of the region is also an important factor, in addition to synoptic-scale processes. In many cases, this combination acts as a catalyst by triggering any latent instability or favouring the formation of mesoscale structures such as orographic dipoles that create disturbances or intensify the cyclogenesis process.

The aim of synoptic climatology is to determine the relationships between atmospheric patterns and local weather (Yarnal *et al.*, 2001). In order to do so, different techniques are used to characterize weather types. The first approaches were called subjective classifications, the most important of which were developed by Lamb (1972), and in the case of Spain, by Tullot (2000) and Martín-Vide (1991). The problem with these classifications lies in their subjective nature, which prevents their replication, and the fact that they are not usually applied to periods exceeding 10–15 years (Rastilla Álvarez, 2003) increases their internal inconsistency and hinders their duplication. Objective classifications, on the other hand, are based on the application of algorithms that use ratios derived from atmospheric pressure fields and allow objective comparisons to be made. Different methodologies for determining weather types are used, including multivariate techniques, which use principal component analysis (PCA) or cluster analysis; a study by Casas *et al.* (2004) used such techniques to classify extreme rainfall events in the Western Mediterranean basin. Another type of automatic classification is the Jenkinson and Collison (JC) classification (Jenkinson and Collison, 1977), which was adapted from the Lamb catalogue and uses surface pressure data. This classification was first applied to the British Isles but has been adapted to many other regions and is one of the most commonly used classification types (e.g. Jones *et al.*, 1993; Spellman, 2000; Trigo and DaCamara, 2000; Tang *et al.*, 2009; Cortesi *et al.*, 2014; Sarricolea *et al.*, 2014). Although it is not based on multivariate techniques like PCA, the JC classification has the advantage of being a universal and standardized method that allows comparison between different regions. The JC classification is widely used in Mediterranean latitudes and can be used to make comparisons with other similar studies (e.g. Martín-Vide, 2002; Grimalt *et al.*, 2013). The JC method was included in the framework of COST7333 Action (Harmonization and Applications of Weather Type Classifications for European Regions), which involved researchers from 23 countries working to find the most suitable automatic classifications in Europe (Huth *et al.*, 2008).

The classification of the weather types associated with heavy rains has been addressed in a number of projects, such as MEDEX (Jansà *et al.*, 2014) and HyMeX (Llasat *et al.*, 2013; Drobinski *et al.*, 2014). The studied events usually exceed a certain rainfall threshold, and the main components used to synoptically classify the most common weather types are analysed. One such study was carried out by Martinez *et al.* (2008), who identified occasions on which rainfall exceeded 60 mm in 24 h in the Western Mediterranean basin. Other studies have analysed the synoptic situations associated with severe weather in the Iberian Peninsula (IP), including one by Martín-Vide, 2002, who used the JC classification to analyse episodes of heavy rain in the eastern Peninsula.

Only a few studies have analysed the circulation weather types (CWTs) associated with episodes that produce flooding. One such study was carried out by Llasat *et al.* (2005), who classified the surface synoptic situations associated with flood episodes in Catalonia between 1840 and 1870. Another example is the study by Prudhomme and Genevier (2011), which linked floods and weather types from different circulation type catalogues compiled in Action COST733. Yet another noteworthy study is that of Quinn and Wilby (2013), who applied the JC classification in their study about variations in multi-decadal floods.

In an attempt to address this scarcity of studies, the current study focused on the characterization of CWTs on a synoptic scale for all flood events recorded in Catalonia between 1900 and 2010, which caused considerable damage. Characterization was carried out by means of the JC classification. While it is true that mesoscale factors play an important role in explaining the triggering and stationarity of convective systems that give rise to the heavy rainfall associated with flash floods and floods in this region (Rigo and Llasat, 2007; del Moral *et al.*, 2017), the synoptic framework is needed to explain dynamic forcing, synoptic advections and circulation (Ramis *et al.*, 1994; Martinez *et al.*, 2008).

The article begins with a description of the area of study, the data source used and an explanation of the methodology applied. This is followed by characterization of the floods. The results are subdivided into different sections; the first focuses on the characterization of flood events; the second on the synoptic types associated with them; and the third on the seasonal distribution and the final section on trend analysis. The article ends with a discussion section and conclusions regarding the results.

2. Data and area of study

We studied the impact of CWTs on flood events in Catalonia (NE Spain), which is located in the Northwestern Mediterranean basin (Figure 1). The region is characterized by two mountain ranges that are close to the sea and run parallel to the coastline: the Catalan littoral range (average altitude around 500 m a.s.l.) and the Catalan pre-littoral range (average altitude around 1200 m a.s.l.). The Pyrenees are located northeastwards of the study area, on the border with France. They are mainly orientated in an east-to-west direction and have altitudes that exceed 2500 m. As they affect low-level wind circulation by forcing it to rise and release convective instability, this orography plays a key role in flood development. It also affects the pressure fields by generating mesoscale circulations like orographic dipoles, mesoscale lows and/or convergence lines (Jansà *et al.*, 2014).

The flood events selected were taken from the INUNGAMA database ('INUN' is from the word for flood in Spanish, while GAMA is the name of the team that developed this database) (Barnolas and Llasat, 2007; Llasat *et al.*, 2014). The database contains a total of 376 flood events that occurred in Catalonia during the period 1900–2010, and was created based on press reports, technical reports, scientific articles and other databases containing local and historical records. INUNGAMA was constructed within a geographical information system (GIS) with an associated MS Access database. The database includes information such as dates, the counties and municipalities affected by rainfall and flow data and flood impacts. In this work only extraordinary (EXT) and catastrophic (CAT) flood events (***see definition in next section) were considered, giving a total of 261 flood events.

In order to identify the CWT for each day on which one or more floods were recorded, surface pressure data for the period 1900–2010 from the 20th century reanalysis project (20CR) were used. Note that the 20CR reanalysis data are likely to be more accurate from 1979 onwards as it encompasses more detailed ground and satellite observations than data from previous years.

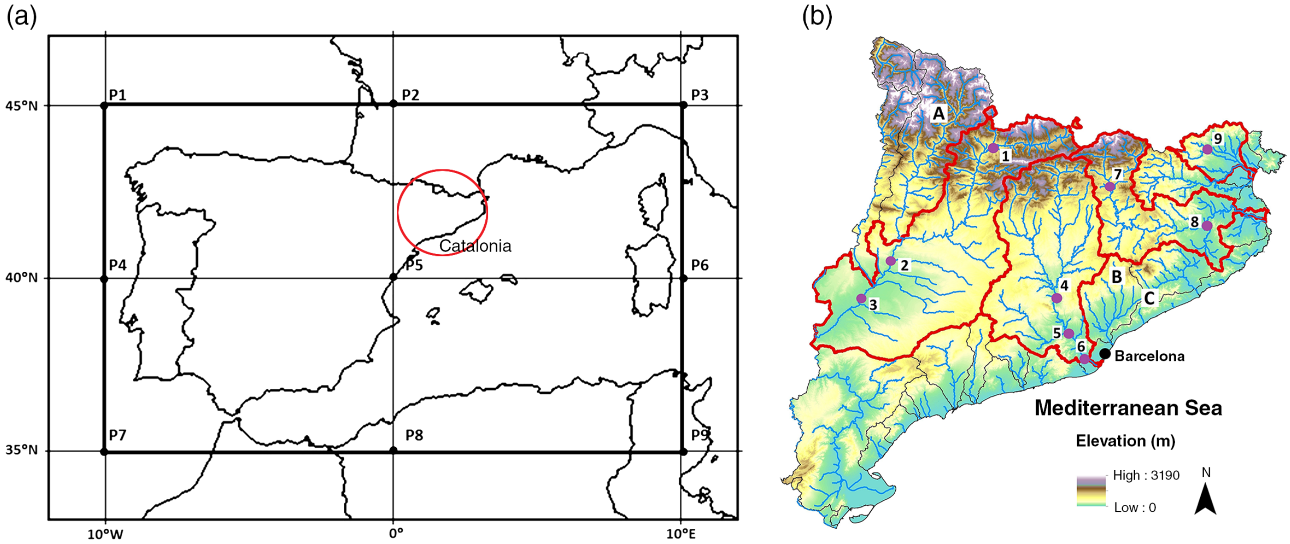

Figure 1. (a) Selected grid showing the area of study, the nine points for the JC and Catalonia (circle); (b) Catalonia: A, Pyrenees, B, pre-littoral range, C, littoral range; numbers 1–9 correspond to the flow gauges showed in Table 2 for the selected catchments (in red). [Colour figure can be viewed at wileyonlinelibrary.com].

The reanalysis model has a spatial resolution of almost 200 km (approximately 2°) on an irregular Gaussian grid in the horizontal (Compo *et al.*, 2011). Pressure data were obtained for the nine points marked on the grid, selected and delimited by the coordinates 10°W–10°E, 45°–35°N (Figure 1(a)). All these information were processed using ArcGIS 10 Software. Within the latitudes of the IP, nine points were sufficient to produce a significant gradient of vorticity and direction and strength of wind.

To perform a simple hydrometeorological characterization of each flood event, rainfall data were obtained from the INUNGAMA database for the period 1981–2010 (Table 1). Flow data series were obtained from Centre of Study and Experimentation of Public Works (CEDEX) and Catalan Water Agency (ACA) (Table 2).

3. Methodology

The flood events were classified based on the following impact levels (Barriendos *et al.*, 2003; Llasat *et al.*, 2016):

- *Ordinary flood events:* flooding that does not cause overflowing of banks, but causes damage if activity is present in or near the river.
- *EXT flood events:* flooding that causes overflowing of banks, which can create problems and inconveniences the daily life of residents, damage to structures located near the river and partial destruction.
- *CAT flood events:* flooding that causes overflowing of banks, which leads to serious damage or destruction of hydraulic installations, infrastructure, paths and roads, buildings, crops, etc.

This kind of classification based on the compilation of historical information of flood events has been used in many European studies (Brázdil *et al.*, 1999; Glaser and Stangl, 2003; Jacobeit *et al.*, 2003) in the Mediterranean region (Pavese *et al.*, 1992; Camuffo and Enzi, 1996; Coeur and Lang, 2000) or in Spain (Barriendos and Martin-Vide, 1998; Benito *et al.*, 2003). This classification is mainly based on socio-economic impacts and not hydrometeorological data. It is usual to consider it as a bottom-up approach.

In order to have some objective characterization of EXT and CAT flood events, the maximum daily precipitation was obtained for each flood event (Table 1). In addition, the return period of all available daily flow data for the rivers highlighted in Figure 1(b) and Table 2 were calculated (Gilabert *et al.*, 2014).

To estimate the return periods, the generalized extreme value (GEV) distribution was employed for extreme events. The cumulative distribution function of the GEV is

$$F(x, \mu, \sigma, \xi) = \exp\left\{-\left[1 + \xi\left(\frac{x-\mu}{\sigma}\right]^{-1/\xi}\right\}$$

where three parameters, ξ, μ and σ represent the shape, location and scale of the distribution function, respectively. The σ and $1 + \xi(x - \mu)/\sigma$ must be greater than zero. The GEV was fitted to the annual maximum discharges with the regional value of the L-coefficient of skewness following the methodology proposed by Mediero *et al.* (2010).

The JC classification is an objective scheme based on daily grid-point mean sea-level pressure data. It is an extension of the Lamb classification from 10 to 27 CWTs, as shown in Table 3. The method was adapted to the IP in accordance with the proposal by Spellman (2000) and moved 5° to the east, as suggested by Garau and Garau (2012) and Grimalt *et al.* (2013) in their studies on the Balearic Islands, to ensure that Catalonia was more central to the study area. A 9-point grid was chosen rather than the

Table 1. Number of floods with maximum precipitation in 24 h (used in Section 4.1) and number of flood events used to JC.

Region	Variable	Year	Flood number	Source data
Catalonia	Precipitation in 24 h	1981–2010	118	INUNGAMA
	Surface pressure	1900–2010	261	20CR

Table 2. Gauges sites and number of floods recorded in each gauge for the available period.

Basin	Gauges	Period	No. of floods	Source data
Segre (Ebro)	Seu d'Urgell	1913–2010	13	CEDEX
	Balaguer	1946–2010	14	CEDEX
	Lleida	1913–1992	9	CEDEX
Llobregat	Castellbell i el Vilar	1912–2010	23	ACA
	Martorell	1912–2006	23	ACA
	Sant Joan Despí	1968–2010	21	ACA
Ter	Ripoll	1915–2010	10	ACA
	Girona	1959–2010	20	ACA
Muga	Boadella	1971–2010	16	ACA
	–	Total	67	–

Table 3. JC weather types [north (N), south (S), east (E) and west (W) are wind direction].

CWT	Types
Cyclonic	*C*
Anti-cyclonic	*A*
Advectives	N, NE, E, SE, S, SW, W, NW
Cyclonic hybrid advectives	CN, CNE, CE, CSE, CS, CSW, CW, CNW
Anti-cyclonic hybrid advectives	AN, ANE, AE, ASE, AS, ASW, AW, ANW
Undetermined	*U*

16-point grid proposed in other studies, as we did not want to cover a larger surface area.

To estimate CWTs using the JC classification, eight input variables derived from surface pressure (P) are required. These variables are the zonal component of geostrophic wind (W) and the meridian component of geostrophic wind (S), calculated as the pressure gradient; wind direction (D); wind speed in m s^{-1} (F); the zonal vorticity component (ZW); the meridian vorticity component (ZS); and the total vorticity (Z). The variables are deduced from the points of surface pressure (Pi) using the following expressions:

$$P = 0.0625\,[(P1 + P3 + P7 + P9) + 2\,(P2 + P4 + P6 + P8) + 4P5]\,,\mathrm{hPa}$$

$$W = 0.25\,[(P7 + 2P8 + P9) - (P1 + 2P2 + P3)]$$

$$S = 0.653\,[0.25\,(P3 + 2P6 + P9) - 0.25\,(P1 + 2P4 + P7)]$$

$$D = \mathrm{arctg}\,(W/S)\,,^{\circ}\ \mathrm{azimuth}$$

$$F = \left(W^2 + S^2\right)^{1/2},\mathrm{m\ \ s^{-1}}$$

$$\mathrm{ZW} = 1.056\,[(P7 + 2P8 + P9) - (P4 + 2P5 + P6)] - 0.951\,[(P4 + 2P5 + P6) - (P1 + 2P2 + P3)]$$

$$\mathrm{ZS} = 1.305\,[0.25\,(P3 + 2P6 + P9) - 0.25\,(P2 + 2P5 + P8) - 0.25\,(P2 + 2P5 + P8) + 0.25\,(P1 + 2P4 + P7)$$

$$Z = \mathrm{ZW} + \mathrm{ZS}$$

where Pi are the grid points.

Based on these expressions and the rules set out below, CWTs associated with each flood event were classified as follows:

1 The flow direction is indicated by D (a wind rose of eight directions is used, and the W and S signs are considered).
2 If $|Z| < F$, an advective or pure directional type exists, defined according to rule 1 (N, NE, E, SE, S, SW, W and NW).
3 If $|Z| > 2F$, a cyclonic type exists (C), if $Z > 0$, or anti-cyclonic (A), if $Z < 0$.
4 If $F < |Z| < 2F$, a hybrid type exists, according to the Z sign (rule 3) and the flow direction (rule 1) (CN, CNE, CE, CSE, CS, CSW, CW, CNW, AN, ANE, AE, ASE, AS, ASW, AW and ANW).
5 If $F < 6$ or 4.8 and $|Z| < 6$ or 4.2, an undetermined type exists (U).

A study conducted by Spellman (2000) in the IP considered U as set out by Jenkinson and Collison (1977), where F and Z are below 6. Our study considered the initial proposal, in addition to the Goodess and Jones (2002) variance, which is recommended for the Peninsula, where F is less than 4.8 and Z is less than 4.2, based on the assumption that vorticity is less vigorous on the IP.

This classification was applied to each flood event using the average daily surface pressure data according to Lorenzo *et al.* (2008) or Post *et al.* (2002) for each of the nine points. When the events lasted more than 1 day, the date with the maximum precipitation was selected.

In addition, the flood events were compared with daily precipitation maps by plotting the online version of the 20CR. It was observed that in some cases (corresponding to situations U and A, pure and hybrid) rainfall data were not reflected in the synoptic analysis. One possible explanation is that these episodes could be associated with flash floods, which are characterized by factors that are mainly reflected in α-mesoscale systems (200–2000 km scale of phenomena) and β-mesoscale systems (20–200 km scale phenomena). Most of these cases were linked to EXT floods, because CAT flood events are characterized as being more extended due to their notable synoptic factors. The U types are analysed in more detail in the results section.

A quantitative assessment was carried out to compare the CWTs associated with these events. A comparative analysis was performed between CWTs of EXT and CAT flood events and their monthly and annual distribution. The final section features a trend analysis of the series of flood events (Glaser and Stangl, 2003; Petrucci *et al.*, 2012) and CWTs (when flood occurs) using the nonparametric Mann–Kendall (MK) test (Kendall, 1975), based on a significance level of 95%. The MK test statistic is calculated as,

$$t = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right)$$

where n is the number of data points, x_i and x_j are the data values in time series i and j ($j > i$), respectively, and $sgn(xj - xi)$ is the sign function as

$$sgn\left(x_j - x_i\right) = \begin{cases} 1 & \text{if} x_j - x_i > 0 \\ 0 & \text{if} x_j - x_i = 0 \\ -1 & \text{if} x_j - x_i < 0 \end{cases}$$

The statistic t is standardized using the expressions for the mean and variance,

$$u\left(t\right) = t / \left[1/18N\left(N-1\right)\left(2N+5\right)\right]^{1/2}$$

Before applying the trend analysis, Pettitt's test (Pettitt, 1979) was used to determine whether the flood series had any inhomogeneity. The statistic used is defined as

$$X_d = 2\sum_{i=1}^{d} r_i - d\left(n+1\right)$$

$$u\left(t\right) \approx \mathcal{N}\ \left(0,1\right)$$

for $d = 1, 2, \ldots, n$ where variation is detected when the value of the year m complies with $X_m = \max_{0 \le d \le n} \left|X_{d.}\right|$

4. Results

4.1. Flood characterization

After taking into account the precipitation data available, 118 flood events were selected for the period 1981–2010. Figure 2(a) shows boxplots of the distribution of precipitation during EXT and CAT events. The precipitation represented in Figure 2(a) to characterize each flood event corresponds to maximum daily rainfall recorded in at any station of the affected region.

There was a clear difference between the amount of precipitation associated with EXT and CAT flood events. The median values of the two categories differed strongly: EXT events were associated with rainfall of ~100 mm, while CAT floods were associated with rainfall events of ~250 mm. The maximum value for EXT events (240 mm) did not exceed the median of CAT events and the minimum of CAT events (140 mm) was higher than the median of EXT events. The minimum of an EXT flood event was 50 mm in 24 h.

Two main flood types can be distinguished in the Mediterranean basin: (1) laminar inundations due to torrential rainfall not bound to rivers or streams and (2) floods typically caused by rivers overflowing; the sudden nature of both directly affects the population. Although both types can be seen in Catalonia, the first is more predominant (being less frequent in central Europe where there are large rivers and usually less intense rainfall). Heavy rainfall normally affects comparably small streams that are not monitored and whose return period cannot be reliably estimated. We calculated the return period for the average daily discharge in the gauges of the most important Catalonian Internal Basins shown in Figure 1(b) and Table 2, for 67 flood events with discharge data, corresponding to a total of 149 flow measurements.

The boxplot diagram corresponding to these return periods (Figure 2(b)) is similar to the one created for precipitation. Median values of return periods were 4 years for EXT and 10 for CAT. Maximum values did not exceed 20 years for EXT or 50 years for CAT. However, it is important to highlight that the majority of damage may occur in ungauged catchments. Therefore, these data only provide an indication of the behaviour of the most important rivers in Catalonia that are usually considered in the analysis of historical floods (i.e. Barriendos *et al.*, 2003; Llasat *et al.*, 2005).

4.2. CWTs identified

When the JC classification was applied to each of the 261 flood events, 22 synoptic types were identified (Table 4). A total of 78.5% of the analysed flood events were EXT and were associated with 20 CWTs, while the CAT events (21.5%) were associated with just nine CWTs, two of which (CW and CSW) only occurred in this category. On the other hand, five CWTs were not involved in any of the episodes analysed: three anti-cyclonic types (ASE, AW and ANW), one cyclonic type (CNW) and one advective type (N). It is also worth noting that episodes associated

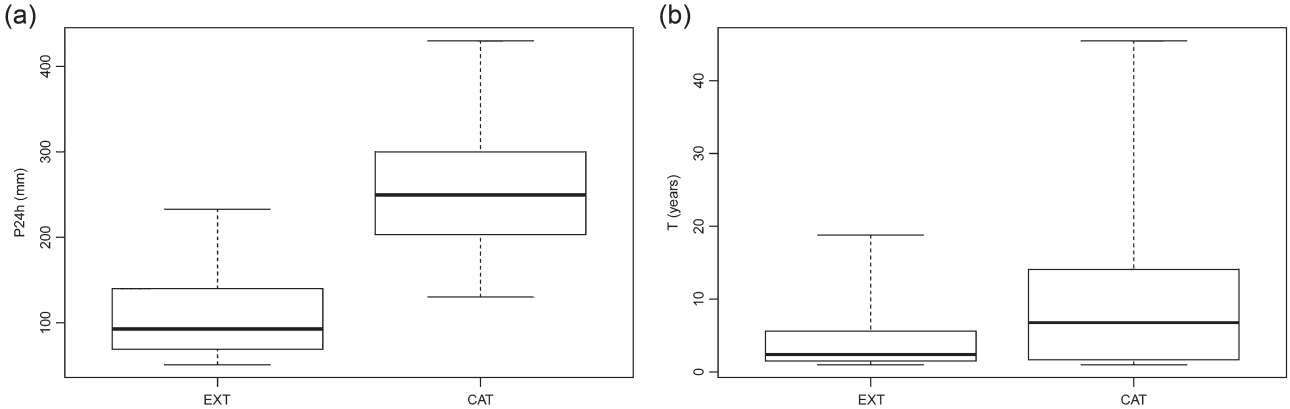

Figure 2. (a) Boxplot of maximum daily precipitation for each flood event by categories; (b) boxplot of return periods corresponding to floods recorded in the different gauges showed in Table 2. [Correction added on 20 October 2017, after first online publication: The x-axis labels were exchanged and have been corrected in this current version.]

with northerly advection were among the least frequent. Advections from the north are not humid due to the flow proceed from the continent.

Note that type C (pure cyclonic), which refers to centred low pressure, was the most frequently repeated type (45.6%), in line with the findings of Garau and Garau (2012) for heavy rainfall in the Balearic Islands.

Thus, the CWT most associated with CAT events was cyclonic (57.1%), followed by advective SE (10.7%). With respect to EXT events, the cyclonic weather type accounted for 42.4%, while the undetermined type accounted for 20%, making it the second most common type.

As shown in Figure 3, if all CWTs are grouped into four general categories (advective, anti-cyclonic, cyclonic and undetermined), it is clear that the most common types were cyclonic (61.3% of all events), followed by advective (16.9%) and undetermined (16.1%).

CAT floods were mainly caused by cyclonic (78.6%) and advective weather systems (19.6%). In contrast, although cyclonic configurations were predominant in EXT floods, undetermined types (20.0%) were more common than advective types (16.1%). Moreover, the EXT floods were the only events attributed to anti-cyclonic patterns, although these only accounted for 6% of the total. This behaviour suggests that these events could be due to diurnal summer convection, which generates highly localized floods (Llasat and Puigcerver, 1997).

It is noteworthy that 85% of the flood events analysed were associated with eight of the 22 CWTs identified (Table 4). Thus, in order to simplify the analysed sample and identify the most representative features, we focus on the types shown in Figure 4, comprising three cyclonic types, four advective types and one undetermined type. The cyclonic type *C* represents 54% of the sample, followed by the undetermined type *U*, at 18%. All advective and hybrid CWTs arrive from the Mediterranean Sea, that is, from the NE, E, SE or S.

Forty-two flood events were classified as *U*; 1 of these occurred in springtime, 2 during the winter, 17 in the summer and 22 during the autumn (mainly in September). Out of these 42 cases, all except one were EXT. The anomalous case was a CAT event that took place on 6 September 1986; it was a fairly isolated flash flood in a torrential stream in central Catalonia that resulted in significant damage to infrastructure, including destruction of a bridge. Out of the other cases, in 88.1% of them the rain lasted less than 24 h. In 92% of the cases flash flood events were produced in the coastal region, usually favoured by the sea breeze and the diurnal cycle. The three events recorded inland were produced by summer thunderstorms as a consequence of the convection triggered by the insolation.

Figure 5 shows a corodiagram of the distribution of the eight predominant CWTs. The figure combines a conceptual map with a cartogram. It maps CWTs and was proposed in a study by Garau and Garau (2012). Each event is located (following the logic marked by the wind direction) and each area is proportional to the frequency of each of the main CWTs. As can be seen, the highlighted surface shows the cyclonic type (*C*) followed by the *U* and CNE configurations. Despite the fact that *U* types are not a CWT they were included in the corodiagram because they are an important type for interpreting the results. They were placed in the middle of the cartogram because *U* types have a slight Mediterranean origin.

When the two categories of flood episode were analysed, it was clear that cyclonic weather (*C*) was predominant in both CAT and EXT flood episodes (Figure 6). The undetermined type appeared only in EXT episodes (except for one case). In contrast, the advective cyclonic southwest type (CSW) appeared only in occasional CAT events, so was not among the eight main types of weather. This type was linked to floods associated with low pressure on the Galician coast (NW IP). One of these situations caused the well-known flood event of 6–8 November 1982, which seriously affected the Pyrenees (Spain, France and Andorra) following rainfall of over 400 mm (up to 610 mm), which led to landslides, widespread damage and more than 40 deaths (Trapero *et al.*, 2013).

Table 4. Number of all CWTs by categories (EXT and CAT) for all flood events. Frequency is expressed in %, in grey there are highlighted the eight principal CWT.

CWT	Flood events	Frequency	EXT	Frequency	CAT	Frequency
A	5	1.9	5	2.4	0	–
AN	1	0.4	1	0.5	0	–
AE	3	1.1	3	1.5	0	–
ANE	3	1.1	3	1.5	0	–
AS	2	0.8	2	1.0	0	–
ASW	1	0.4	1	0.5	0	–
C	119	45.6	87	42.4	32	57.1
CN	3	1.1	3	1.5	0	–
CNE	17	6.5	13	6.3	4	7.1
CE	5	1.9	5	2.4	0	–
CSE	9	3.4	4	1.9	5	8.9
CSW	2	0.8	0	–	2	3.6
CS	4	1.5	4	1.9	0	–
CW	1	0.4	0	–	1	1.8
E	11	4.2	11	5.4	0	–
SW	4	1.5	2	1.0	2	3.6
SE	9	3.4	3	1.5	6	10.7
NW	2	0.8	2	1.0	0	–
NE	9	3.4	9	4.4	0	–
S	6	2.3	3	1.5	3	5.4
W	3	1.1	3	1.5	0	–
U	42	16.1	41	20.0	1	1.8
Total	261	–	205	–	56	–

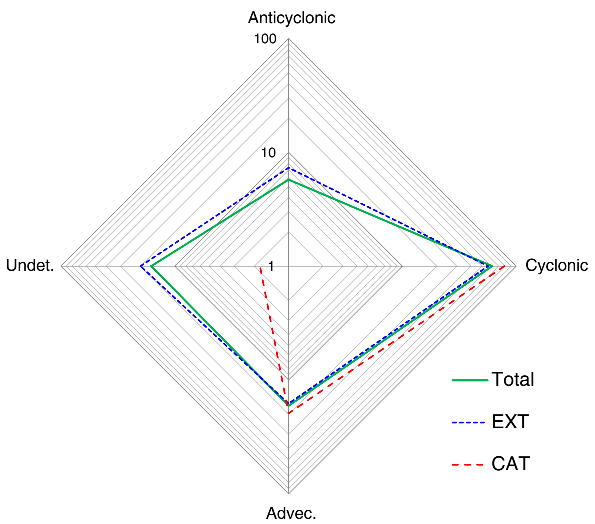

Figure 3. Simplified CWTs (%) of all events by categories (LogN scale). [Colour figure can be viewed at wileyonlinelibrary.com].

EXT floods were linked with a large number of *U* types that were associated with summer and early autumn storms (JJAS; a total of 31 cases), and were characterized by flash floods. They were short-lived and unstructured and did not show in the synoptic scale. They were determined by local factors reflected on the β-mesoscale. CAT floods, on the other hand, were linked with fewer categories, featured more structured pressure schemes, and were usually based on types for which synoptic factors are relevant.

When the changes in the algorithm of the JC classification for the *U* types proposed by Goodess and Jones (2002) and explained in the methodology were applied, only two *U*-type CWTs of flood events showed any variation; these represented just 1% of the total sample. Therefore, most *U* types maintained rates of vorticity and wind speeds below the threshold of 4.8–4.2 and 6 proposed by Jenkinson and Collison (1977). Thus, the known *U* types had especially low rates of vorticity, as already stated. At the synoptic level, these types are defined as barometric swamp.

Advective types came from the Mediterranean Sea. Cyclonic types (*C*), although marked by the presence of low pressure, often also created flows at low levels, providing the necessary moisture from the Mediterranean Sea, as shown in Figure 4. CAT floods often had a dominant SE component (Figure 6) that caused the heavy rains characteristic of autumn due to a corridor of markedly warm air from the south and high levels of humidity.

4.3. Seasonal and monthly distribution

Figure 7 shows the seasonal distribution of *C* and *U* schemes and flood event types for the two categories. It clearly shows a higher frequency of EXT events in summer and autumn, and a higher frequency of CAT cyclonic events in autumn.

At the seasonal level, cyclonic types (*C*) were predominant in spring and winter, although in relative terms they predominated in late summer and autumn (Figure 8). It is important to note that there were more CWTs linked to barometric swamp or undetermined types (*U*) in summer; these can produce intense local rainfall, especially due to diurnal heat. Of note in this season was the presence of events with a NE component, which can provide relatively cool air that favours the rise of the air mass. Eight CWTs were recorded in autumn, which was the only season when floods were associated with SE advection. In contrast, northerly component types disappeared

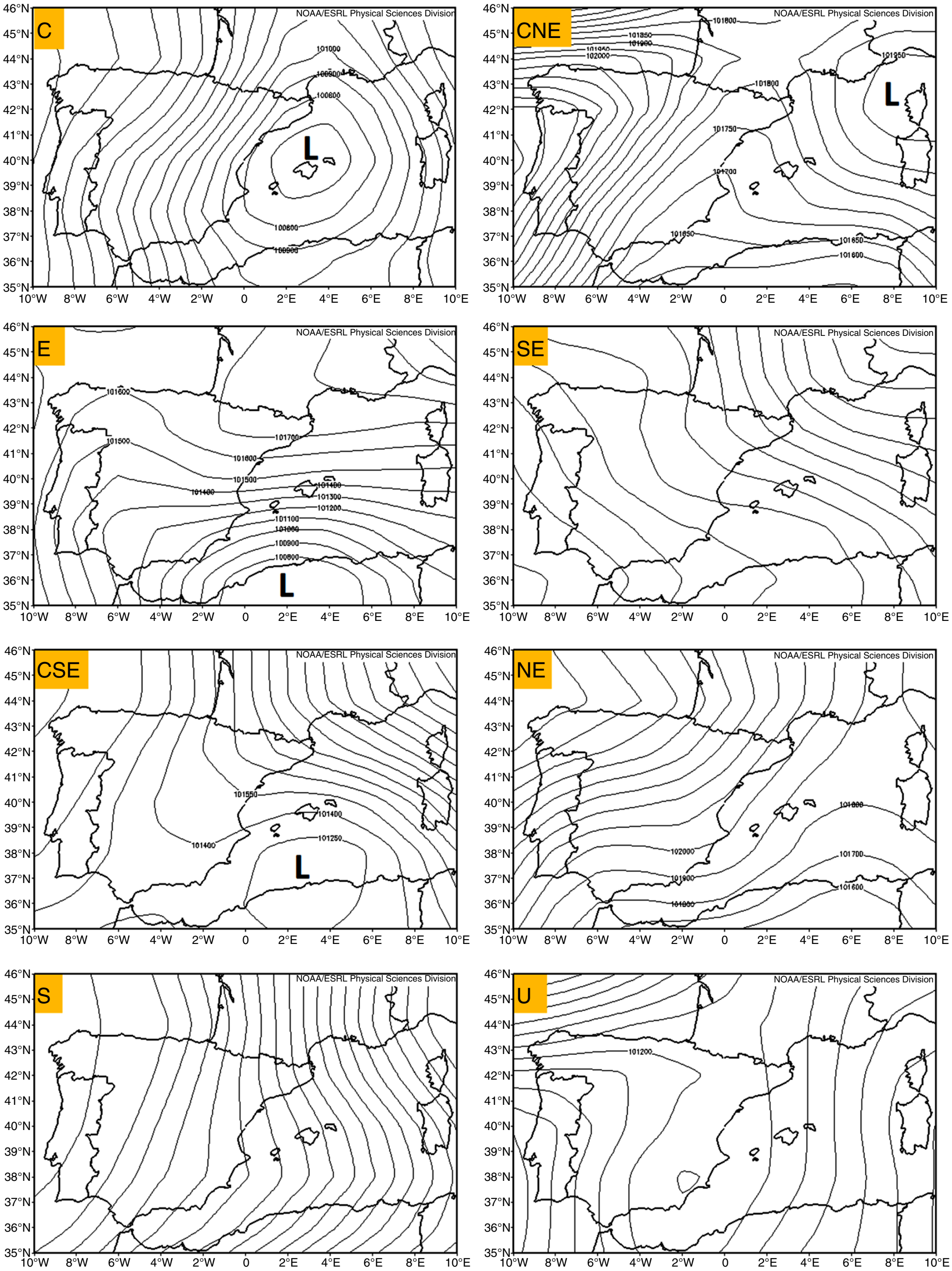

Figure 4. Patterns of sea level pressure corresponding to the eight CWTs built from the flood events recorded in Catalonia from 1900 to 2010. [Colour figure can be viewed at wileyonlinelibrary.com].

in winter, while cyclonic component types increased to about 80%.

4.4. Trend analysis

The trend analysis applying the MK test at 95% significance showed that the total number of flood events increased significantly from 1900 to 2010, due to an increase in EXT events, with 0.4 events decade^{-1} (Figure 9). These results are consistent with those obtained by Barrera-Escoda and Llasat (2015) for some basins in Catalonia since the 14th century. A breakpoint was identified in the series, in 1979, when the Pettitt test was applied. This is probably because the collection of data from the daily press became more systematized and more data were collected after 1981 (Llasat *et al.*, 2014).

When the two periods were analysed separately, a significant positive trend can be seen from 1981 to 2010 for EXT events (1.2 floods decade^{-1}), but not for the total.

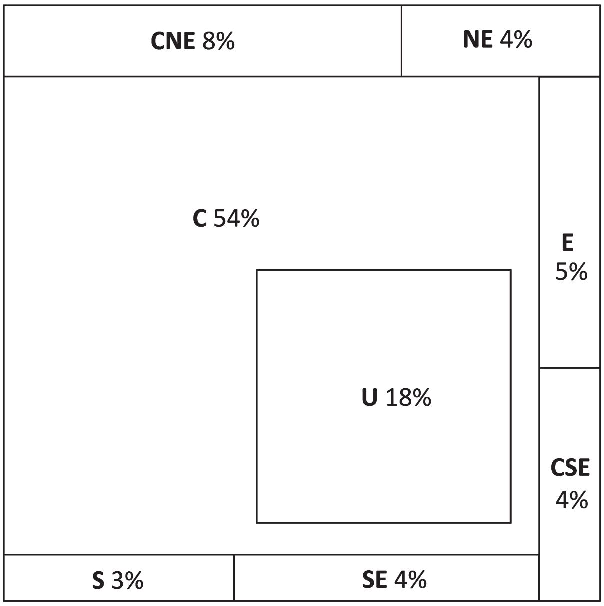

Figure 5. Corodiagram of the eight principal CWTs in NW Mediterranean.

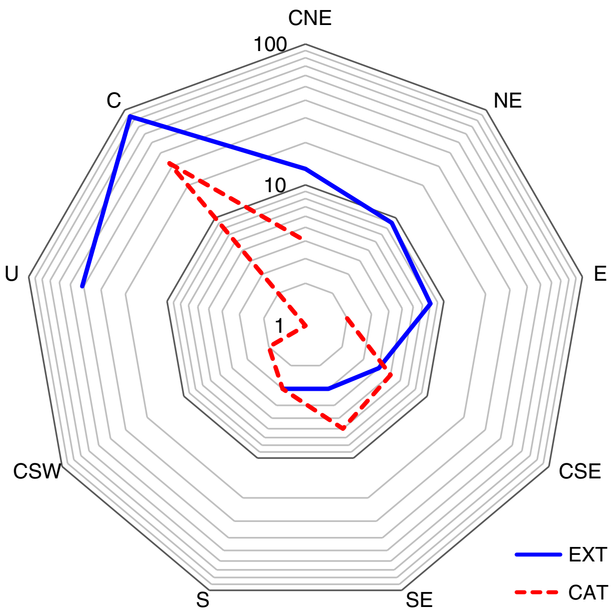

Figure 6. Frequency of the eight principal CWTs plus CSW by categories (LogN scale). [Colour figure can be viewed at wileyonlinelibrary.com].

Furthermore, there was no significant trend in any of the series analysed in the period 1900–1981.

When the trends for each weather type were calculated, a significant and positive trend was observed only on days with pure cyclonic types (*C*) in the period 1981–2010, with a value of 0.7 cyclonic episodes/decade. Therefore, *C* types play a more important role in flooding nowadays, especially in autumn.

Other types were too infrequent to be attributed to any significant trend. If all hybrid CSE or CNE advections and pure advections with an E, NE or SE component were grouped, a non-significant increase was observed.

5. Discussion

The cyclonic type is characterized by the formation of a low-pressure system off the Catalan Mediterranean coast, which leads to advection originating from the Mediterranean Sea towards Catalonia and convergence at low levels (Figure 4). This pattern was also reported by Llasat *et al.* (2005) and was associated with 50% of the flood events that occurred between 1840 and 1870 in Catalonia. In the work of Martinez *et al.* (2008) this configuration was observed in 15% of the situations that produced daily rainfall above 60 mm, but if we add those southern situations favoured by a low in Western Iberia, the percentage increases to 50%. The NE cyclonic situation is characterized by a low-pressure area near Sardinia causing an inflow from the NE direction, and was associated with more than 10% of the cases analysed by Martinez *et al.* (2008) in Catalonia. This situation is common in summer and is associated with short, intense flooding brought on by mesoscale factors. Martinez *et al.* (2008) found that this configuration has the maximum frequency in the Northwest Mediterranean area in summer (40.4%) and that it is the most frequent pattern during summer of the nine synoptic configurations identified. The advective type is defined by air carried in a particular wind direction; the most common cases originate from the Mediterranean region. In many cases, advections from the S, E and SE (called 'llevantades') are created during autumn and the end of summer. However, the NE types are similar to the CNE types. The undetermined weather types can be attributed to barometric swamp, advective or cyclonic situations with very weak vorticity.

According to Llasat *et al.* (2016) the *U* type is likely associated with highly convective events involving unicellular and multicellular convective systems. In these cases, the synoptic situation tends to be weakly defined and, for this reason, they have been classified as *U* type. The subjective analysis of the synoptic configurations associated with these indeterminate types corroborates that the majority of them share a maritime advection. The sea breeze could direct the wet air perpendicularly to the littoral and pre-littoral chains, favouring the triggering of the instability (Millan *et al.*, 2005), with radiative warming amplifying this instability. In most cases a mesoscale low located in the Mediterranean Sea would give rise to the flow (Fiori *et al.*, 2014). It was not necessary to check the synoptic situation from the previous day as all cases corresponded to flash floods.

Our analysis suggests that the undetermined types (*U*) produce flood events initiated by mesoscale factors. As seen previously, EXT floods are often related to flash floods, and the contribution of convective precipitation can exceed 80% (Llasat, 2001). The trends seen in Catalonia suggest an increase in convective precipitation but a decrease in the number of days on which precipitation is recorded (Llasat *et al.*, 2016). This meteorological pattern mainly relates to local EXT or ordinary flooding that causes damage that may be severe at the local level due to its sudden nature, but without synoptic forcing and

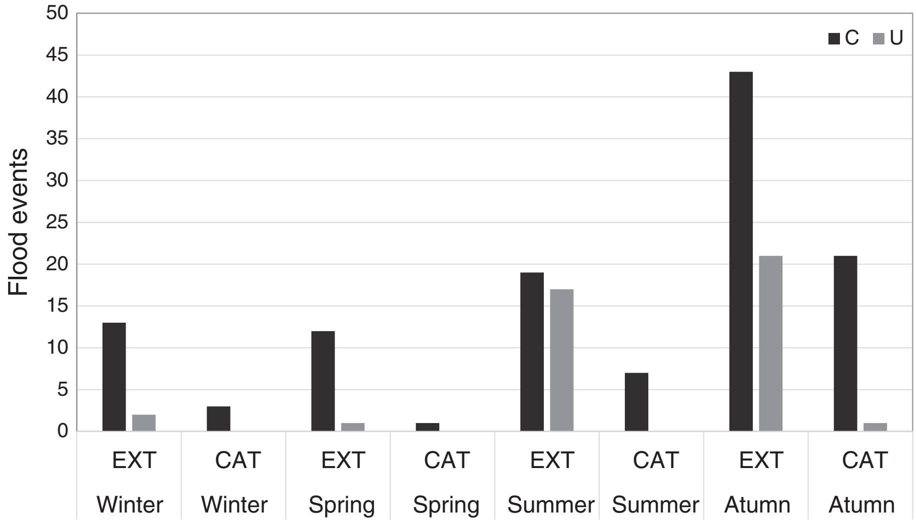

Figure 7. Seasonal distribution of the cyclonic and undetermined CWTs by categories.

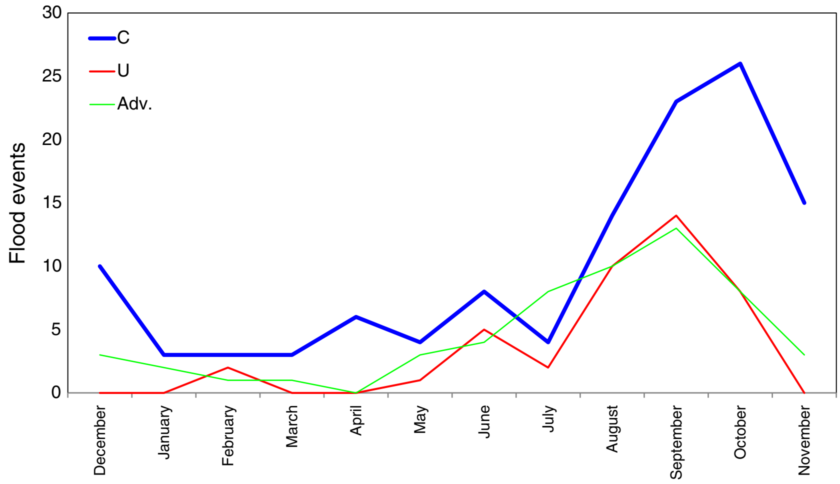

Figure 8. Monthly regimes of main CWTs grouped in advectives plus cyclonic hybrid advectives (Adv.), undetermined (*U*) and cyclonic (*C*) following Table 3. [Colour figure can be viewed at wileyonlinelibrary.com].

advection it does not produce high values of cumulative precipitation or affect a larger area (Llasat *et al.*, 2009).

Cyclonic types were the predominant category in our work. This is consistent with the findings of Jansà *et al.* (2014) and Rigo and Llasat (2007). These studies found, based on an analysis of case studies, that at least 70% of heavy rainfall episodes in the Eastern IP involved low pressure. It can therefore be stated that, in situations of intense precipitation, the most commonly repeated patterns are linked to pure cyclonic CWT, as highlighted in previous studies such as those by Martinez *et al.* (2008) and Cortesi *et al.* (2014) for precipitation and Llasat *et al.* (2005) for floods.

It was also noted that there was only a significant increase in *C* type in autumn. Some studies indicate that overall cyclonic types in the Western Mediterranean basin are declining, especially during winter and spring (Guijarro *et al.*, 2006). Furthermore, other studies have found an increase during the summer months (Ulbrich *et al.*, 2009). Tous *et al.* (2009) showed that moderate cyclones could increase in the Western Mediterranean region in future scenarios.

6. Conclusions

This work analyse 261 EXT and CAT flood events in Catalonia during the period 1900–2010. We have characterized them from impact data to hydrometeorological data (bottom-up approach), examining the differences in precipitation and discharge data between incidences of CAT and EXT flooding. A total of 21.5% of the flood events were classified as 'CAT' due to the damage produced, and the rest were classified as 'EXT'. Analysis of the maximum daily precipitation recorded in each event showed that the median in the EXT cases was around 100 mm in 24 h and in the CAT events the value was around 250 mm. Despite flooding in some rivers, the return period of daily discharge in the main rivers did not exceed 20 years for EXT or 50 years in the case of CAT events.

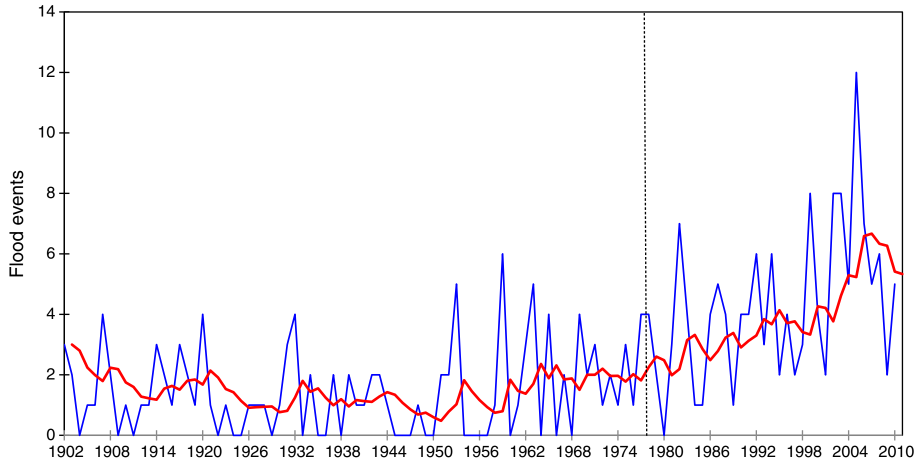

Figure 9. Yearly floods evolution (EXT and CAT), exponential smoothing and break point (dash line). [Colour figure can be viewed at wileyonlinelibrary.com].

The CWT of these events were classified using the JC classification (Jenkinson and Collison, 1977). The 261 cases were grouped into 22 CWTs (out of the 27 set out in the JC classification system). The EXT events were distributed across 20 CWTs. The CAT floods represented 21.5% of the total sample, distributed across nine CWTs, two of which were found only in this category of event.

More than 85% of the events were distributed in only eight CWTs: three cyclonic, four advective and one undetermined. The most frequent CWT was pure cyclonic, which accounted for 54% of the main CWTs, followed by undetermined, which accounted for 18%. In all cases, the surface air mass proceeded from the Mediterranean Sea.

Analysis of the synoptic types for EXT and CAT categories showed that the pure cyclonic types were the most frequent in both categories, especially for CAT floods. EXT floods were linked with more CWTs, and undetermined types and advective types were also important. It should be noted that undetermined types were the most common for EXT events and represented just one case of CAT flooding. Such types without a defined structure correlated with local flash floods, which are sudden floods caused by factors that are explained on smaller scales such as the β-mesoscale system.

CAT events were usually produced by air masses coming from the SE and caused the heaviest precipitation in autumn, due to a corridor of warm, humid southern air. Moreover, EXT events, usually associated with local flash floods, were characterized by a dominant NE origin, late summer rains and less structure (Ramis *et al.*, 1998).

Floods were most common in autumn, followed by summer. In autumn, pure cyclonic types were the most common, with more than 50% of the total. During the summer, cyclonic types accounted for approximately 40% of cases and undetermined and CNE were the most common, along with flash floods.

There was a significant increase in overall flooding and EXT floods (though not in CAT floods) from 1900 to 2010. For the period 1981–2010, a significant positive trend can be observed for EXT floods only. When the series was analysed by weather type, only pure cyclonic types showed a significant increase for the period 1981–2010

In terms of the practical applicability of the results, this work provides a simple but accurate tool with which to characterize weather types associated with flood events, which will be very useful for education and outreach activities. On the other hand, the introduction of objective hydrometeorological indicators to characterize this kind of events will be useful to improve prevention measures. The Spanish legislation considers a risk event as CAT when the return period is 500 years and this same threshold has been selected to delimitate a ‘flood risk area’. However, the present study indicates that events with return periods less than 100 years can result in extensive damage. Although this is only a preliminary result and a more in-depth subregional analysis is required, the study provides some important information for policymakers, mainly for land use planning and early warning systems. In fact, the results have already been taken into account in a report about the implementation of the sustainable development goals in Catalonia (CADS, 2016).

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