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Floods in Catalonia (NE Spain) since the 14th century. Climatological and meteorological aspects from historical documentary sources and old instrumental records

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Abstract

This paper shows a first approximation towards an interdisciplinary treatment of flood events from an historical, climatic and meteorological point of view. Starting from historical document sources, early instrumental data (basically, rainfall and surface pressure) and the most recent meteorological information, the paper analyses the temporal evolution of floods in NE Spain since the 14th century. Results show than the highest number of floods have been recorded in the Ter river, with 121 flood events (1322–2000 AD), followed by the Llobregat river with 112 cases at its mouth (1315–2000 AD). Any trend has been observed for the catastrophic floods. On the contrary, extraordinary floods show a little positive trend, probably related with the human occupation of the flood prone areas. Besides this, the paper shows an initial approximation of current meteorological master-patterns to the flooding episodes recorded between 1840 and 1870, a period characterised by a higher frequency of flooding. The newness is the reconstruction of those daily charts by using early instrumental data from 11 meteorological or astronomic observatories, some of them collected by the authors in the framework of the SPHERE project. For that purpose, the conceptual models obtained on the basis of the in-depth analysis of recent flooding episodes are compared with the synoptic pattern at the surface of those flood episodes registered in historical times. Following the proposed interdisciplinary approach, the paper bases itself on the documentary collections forming the subject-matter of this study, as well as the older and latest instrumental records.

Keywords: Catalonia; Climatic analysis; Floods; Historical data; Synoptic analysis

1. Introduction

Floods have achieved the distinction of being the natural hazard that year-in year-out produces the most damage in the northwest Mediterranean countries. In August 1996, a flash flood which affected a campsite in the Spanish Pyrenees led to 87 deaths, although the most catastrophic episode recorded in the last 50 years in Spain was the flash flood which occurred in September 1962 in Catalonia, with more than 815 deaths in less than 3 h. In the south of France, the floods recorded on 22 September 1992 produced

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41 casualties in the Ouveze basin. The same event produced catastrophic floods in NW Italy. Between 1950 and 1999, there were a total of over 2200 deaths in Spain (of which 1400 were in Catalonia) and material damage amounting to over €301,000,000 a year (Dolz, 1993; Berga, 1995). As happens in most developed countries affected by this phenomenon, trends for the future point to a reduced number of victims but an increase in material damage.

However, floods are a complex hydrometeorological hazard. Both hydrology and meteorology play a major role. Heavy rains, long rainy periods or snowmelt are necessary but not sufficient to cause them. Other conditions such as previous precipitation, terrain and surface run-off characteristics are also important. The natural phenomenon also interacts with human activities: land uses and their evolution, civil and hydraulic infrastructures can have very variable effects on the natural pattern of response of floods.

This paper is an example towards interdisciplinary treatment focused on a long-scale temporal analysis. Starting from historical document sources and recent instrumental information, the temporal evolution of floods in NE Spain was evaluated in order to improve knowledge of climatic behaviour patterns in the western Mediterranean and meteorological situations involved in flood episodes. For that purpose, the aim was to find out if the conceptual models obtained on the basis of the in-depth analysis of recent flooding episodes (Jansà, 1997; Llasat and Puigcerver, 1994; Llasat et al., 2000; Llasat, 2001; Ramis et al., 1994) are in accordance with the flood episodes registered in historical times. Here, the interest is focused on a period prior to the existence of official meteorological services (approximately 1780–1880), within the 'Little Ice Age' climatic episode, when it now seems proven that there was a considerable irregularity of pluviometric regimens not registered during the instrumental period of the 20th century (Barriendos and Llasat, 2003).

2. Main environmental characteristics producing floods on the area studied

Catalonia is located in the NE corner of the Iberian Peninsula. Its coastline runs in a NE–SW direction and its main orographic features are a littoral mountain range with some peaks exceeding 500 m, a pre-littoral mountain range (1000–2000 m) and the Pyrenees (1500–3100 m), which run roughly W to E along the northern border of Spain (Fig. 1).

The study focused on three of Catalonia's major rivers: the River Segre (22,579 km^2, tributary of the River Ebro), the River Llobregat (4948 km^2) and the River Ter (3010 km^2) (Table 1, Fig. 1). These basins have human settlements with stable populations since Roman Empire and availability of documentary series from the Low Middle Ages. The behaviour of these rivers is dependent upon the torrential rainfall episodes inherent to the Mediterranean region.

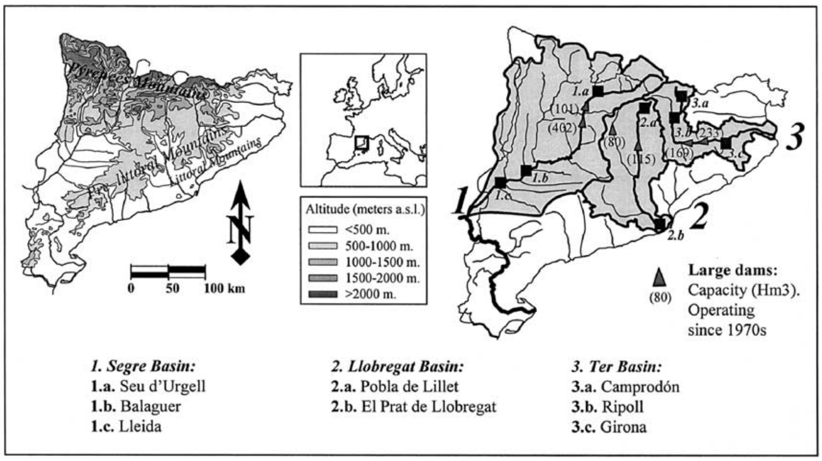

Fig. 1. Location map of Catalonia.

Table 1
Main features of the rivers analysed in the paper. Today average flow (Q) and today maximum instantaneous flow (Qci)

Basin	Location	Surface (km^2)	Q (m^3/s)	Qci measured (m^3/s) (date of event)	Years with data
Segre	Seu d'Urgell	1233	13.5		55
	Balaguer	7796	45.7		30
	Lleida	11,389	84.9	4500 (22nd October 1907)	23
	Total	12,879	185.0		
Llobregat	Pobla de Lillet	–	1.32		15
	Martorell	4561	20.77	3080 (20th September 1971)	75
	Total	4948	17.7		
Ter	Ripoll	738	9.8		64
	Girona[a]	1802	13.95	2350 (18th October 1940)	30
	Total	3010	20.0		

[a] Measured 18 km upstream of Girona: Pasteral dam.

According to research developed into the SPHERE project, flooding could be associated with three types of pluviometric episode:

1. Episodes of very short duration (less than 6 h) but very high rainfall intensity. The local amount of rainfall is nevertheless not usually very high. They appear during summer and the beginning of autumn and produce 'local flash-floods' in short littoral water courses with a torrential regime and non-permanent flows (5–50 km^2), but also in the upper part of the largest rivers that birth in the Pyrenees, where they have a great slope.
2. Episodes of short duration (between 6 and 72 h) with heavy rain sustained for several hours with large amounts of total precipitation (200–500 mm). They mainly occur in autumn and sporadically in spring. They can give rise to 'extensive flash-floods' in all kind of rivers.
3. Episodes of long duration (approximately 1 week) with weak pluviometric intensity values, while there may be peaks of high intensity. Cumulated rainfall can be over 200 mm. Although not very frequent, they usually occur in winter.

It should be noted that the melting of snow around the mountainous heads of the rivers only brings regular and foreseeable rises during the spring, and only occasionally gives rise to overflowing of banks when accompanied by heavy rainfall. The entire period of study contains not a single record of bursting of banks caused exclusively by snowmelt or phenomena other than torrential rainfall.

Although the studied rivers have a usual pluvial snowmelt regime, floods can be associated to the three types of rainfall episodes. The most catastrophic and frequent are those associated to type 2, like the flood events of October 1940 or November 1982, but the events of January 1996 and August 1998 are an example of types 3 and 1, respectively. This feature difficults the analysis of the meteorological pattern associated to historical flood events, because the lapse of time between the maximum rainfall and the flood can last since some minutes until some days. The flood event evolution, some description made by the witness or some rainfall data are revealed of enormous importance for the meteorological explanation.

3. Sources of information and data organisation

3.1. Study intervals

The research work carried out herein is based on information obtained for the period AD 1300–2000. Such information is not homogeneous, however, for which reason it is advisable to distinguish between:

(a) Episodes recorded prior to 1780. Only information from historical archives is available. Proxy data are obtained collecting flooding information from continuous records in municipal and private documentary sources.
(b) Episodes recorded between 1780 and 1950, for which mean daily surface pressure and total rainfall is available for various places in Europe.

(b.1) 1780–1880. Early Instrumental Period. Scattered locations available.
(b.2) 1880–1950. Modern Instrumental Period. Gridded Data Bases available.

(c) Episodes recorded after 1950 and for which pluviometric, hydrological, synoptic and thermodynamic information is available. Information about damage is available from newspapers. It is possible to distinguish between two sub-intervals:
(c.1) 1950–1995. Meteorological data are mainly synoptic and thermodynamic, and raingauge data are from conventional stations.
(c.2) 1996 up to the present. Besides the previous information, radar data, mesoscale data and precipitation and flow data from automatic networks are available.

3.2. Documentary sources

The study of floods from historical documentary sources in Europe experienced the first initiatives in the second half of 19th century, with large data collections like the example of France (Champion, 1864) or Spain (Rico Sinobas, c.1850; Bentabol, 1900). But only recently has attention been paid to it from a modern climatic perspective in various European countries (Brázdil et al., 1999; Pfister, 1999; Glaser and Stangl, 2003; Jacobeit et al., 2003), in the Mediterranean region (Pavese et al., 1992; Camuffo and Enzi, 1996; Lang et al., 1998; Coeur and Lang, 2000) or in Spain (López Gómez, 1983; Font Tullot, 1988; Barriendos and Martín-Vide, 1998; Benito et al., 1996, 2003).

Documentary series from municipal authorities contain most of the available information. The chapter books of resolutions from city councils precise details of the damage caused by the flooding, with the exact date and duration. There are usually some details on the behaviour of the rising water (duration, magnitude, indirect measurements) and further details about the precipitation episode that gave rise to it. The public works files contain cartographic and writing documents about the characteristics and dimensions of the riverbeds, the infrastructure associated with the watercourse (dams, bridges, mills, dykes), and their temporal changes. Private sources

Table 2
List of the historical documents analysed in this research

Data sources	Segre basin			
	Seu d'Urgell	Balaguer	Lleida	Total
Bibliography	1	3	7	11
Documents: City Council Resolution Books	19	16	38	73
Documents: Public Works Files	6	45	80	131
Documents: other manuscript series	3	1	–	4
Total number of volumes	29	65	125	219

Data sources	Llobregat basin		
	Pobla de Lillet	El Prat	Total
Bibliography	3	40	43
Documents: City Council Resolution Books	10	20	30
Documents: Public Works Files	–	–	–
Documents: other manuscript series	–	–	–
Total number of volumes	13	60	73

Data sources	Ter basin			
	Camprodon	Ripoll	Girona	Total
Bibliography	5	22	25	52
Documents: City Council Resolution Books	2	63	409	474
Documents: Public Works Files	–	–	103	103
Documents: Other manuscript series	78	2	8	88
Total number of volumes	85	87	545	717

Table 3
Main data of the flood chronologies

Basin	Location	Available period (AD)	Total no. of floods[a]
Segre	Seu d'Urgell	1453–1987	18
Segre	Balaguer	1617–1982	21
Segre	Lleida	1306–2002	51
Llobregat	Pobla de Lillet	1570–1982	11
Llobregat	El Prat	1315–2002	171
Ter	Camprodon	1617–1992	10
Ter	Ripoll	1577–1987	18
Ter	Girona	1322–2002	177
			>477

[a] Scattered flood events 10–12th centuries not considered.

(memoirs, diaries, chronicles) contain detailed descriptions for scattered floods. Finally, ecclesiastical sources preserve rogation ceremony records for persistent rainfall events ('pro serenitate' rogations). The research work contained herein provides flood chronologies at locations selected of each river studied (Fig. 1). The data collection task usually involves several months' work due to the large quantity of documents that have to be consulted (Table 2). Even so, it is not always possible to reconstruct flood chronologies, which ensure homogeneity and continuousness: the archives and the documents they contain often suffer irreparable loss due to wars, fire and even the very floods themselves. On the other hand, severe inhomogeneities are introduced during the second half of 20th century because of large interventions in any basins (dams, dykes).

This research work on the Segre, Llobregat and Ter rivers has led to the identification of over 400 flooding events and eight systematic chronologies, from the 14th to the 20th centuries (Table 3). This information has been objectified by following a criterion based on the effects produced by each flooding episode and water levels recorded or indirectly referred. Experience obtained in Catalonia (Barriendos and Pomés, 1993; Barriendos et al., 1998) has permitted three types of high waters to be distinguished (Fig. 2):

(a) simple high waters: precipitation episodes which give rise to increases in the flow of fluvial courses,

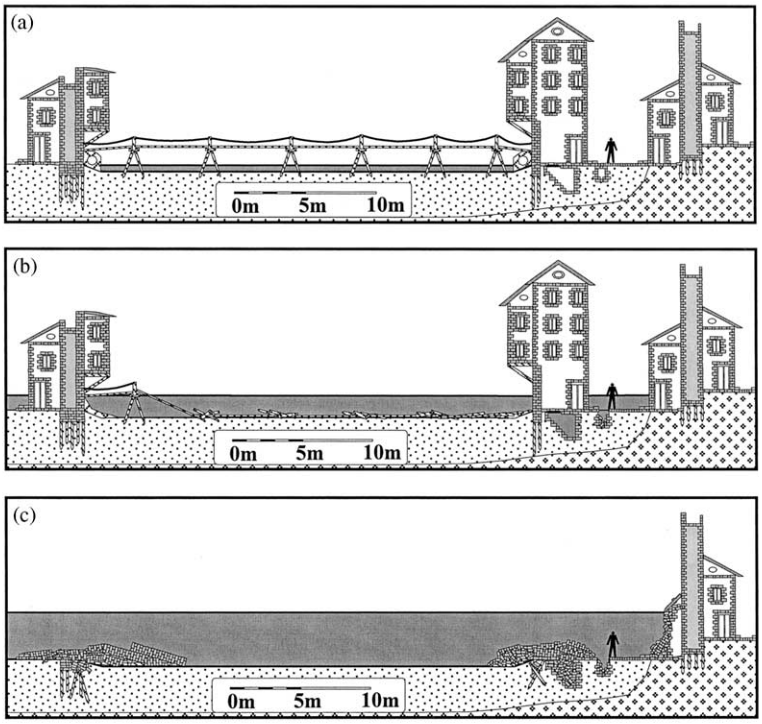

Fig. 2. System for classification of historical floods (non-instrumental data) on the basis of damage and levels recorded: (a) ordinary; (b) extraordinary; (c) catastrophic.

without causing overflow in their banks. Such episodes can cause damages if activities are being carried out in or near the river at the time.

(b) extraordinary floods: precipitation episodes which cause overflowing of banks of an intensity or duration which does not cause serious damage in the locality. Usually, these episodes can cause discomfort and inconvenience to the daily life of the population, but sometimes they can produce some damages in those structures placed near the river.

(c) catastrophic floods: precipitation episodes which cause overflowing of banks leading to serious damage or destruction of infrastructure (bridges, mills, walls, paths), buildings, livestock or crops.

In this classification the number of casualties and injured people has not been considered due to the fact that it is not linearly related with the flood magnitude, because of human behaviour patterns. Besides this, it is not easy to distinguish between the victims produced directly by the flood, by accidents produced during the rainfall event or produced indirectly as a consequence of the destruction of infrastructures or crops.

3.3. Old meteorological instrumental sources

The gathering and treatment of instrumental observations since the 18th century constitutes work somewhere between modern meteorology and conventional historiographical techniques. This kind of research work is still under development and the number of series available is limited (Luterbacher et al., 1999; Jacobeit et al., 2003; Barrera et al., 2003), although in Western Europe there may be about a hundred series with daily instrumental observations, kept in various kinds of historical archives. The potential results are modest for that reason: the irregular distribution of rainfall in the Mediterranean climate can hardly be analysed and atmospheric pressure permits only imprecise synoptic reconstructions.

Recourse was had in this paper to the daily series for pressure, rain, temperature and wind direction obtained and digitised in the framework of ADVICE project (Madrid, Barcelona) and IMPROVE project (Cádiz-San Fernando, Uppsala, Stockholm, Milan, Padova), together with series generated or received into the SPHERE project of which this investigation forms part (Paris, Prague, Reykjavik, Bern-Basel).

3.4. Modern instrumental data organisation

Meteorological data from 1948 are available not only at the surface but also at height (NOAA-NCAR). To this information should be added the specific southern European radiosoundings, which permit thermodynamic analyses to be carried out, as well as providing pluviometric information from the information networks. Since 1996 pluviometric information has been available at 5-min scale together with radar images and mesoscalar analyses. This kind of information has been applied in order to understand the meteorological patterns producing floods in the study area and to synthesize the conceptual models (Llasat et al., 2003).

4. Climatic patterns from non-instrumental data

In order to process the non-instrumental data, simple indices have been generated for each series, taking the annual value thereof and dividing it by the mean. In order to quantify the existence of flooding, consideration was given for each station to the series of yearly values composed of 0 (no flooding recorded), 1 (at least one extraordinary flood recorded) and 2 (at least one catastrophic flood recorded). This permitted the series from different localities and of extraordinary or catastrophic level to be operated in a combined manner. The indices were averaged out in order to provide general indices at regional scale that would allow the most general manifestations of climatic variations to be analysed. The procedure used was as follows (Barriendos et al., 1998): for each station j and year i, a standardised index I_{ij} was obtained, according to the expression:

$$I_{ij} = \frac{R_{ij}}{R_{\mathrm{med}j}} \quad j = 1, 2, \ldots, 12 \; i = 1, 2, \ldots, N \qquad (1)$$

Where N is the number of years comprising the series, R_{ij} is the absolute frequency of flooding in year i and for station j, and $R_{\mathrm{med}j}$ is the annual average of floods at station j. The indices were later averaged in order to obtain general indices at regional scale that permit analysis of the most general manifestations of climatic variations. For this purpose, recourse was had to the following expression:

$$I_i = \sum_{j=1}^{M} \frac{I_{ij}}{M} \quad (2)$$

Where M is the number of stations with data available for the year i. I_i is the value of the regional index for the year i.

Once the numerical series had been obtained, the initial analysis involved yearly normalisation of the whole series of flood events, smoothed afterwards by Gaussian low-pass filters (10 and 30 years). Two widely used distribution-free methods were employed to test trends in flood frequency (*Spearman's rank* and *Man–Kendall rank statistics*). A simple method was also used to compare the results of these methods and to determine their credibility. This third method is the *accumulated slopes*. It is based on calculating the slope of a straight line, firstly fitted to the first two pairs of values of the data series (time and frequency), secondly to the first three pairs of values, and so on until the end of the data series. Every step of this method is plotted. Finally, if data currently do not show any kind of trend, the end of the graph will show a perfect or nearby plane line. The possible existence of any trend in the annual precipitation series in the above basins was also studied in order to explain the nature of potential trends in flood-event frequency.

4.1. Result in the basins analysed

The main chronologies obtained offer continuous series of flooding events from the beginning of the 14th century, with similar distribution between the various kinds of flooding, except for a marked preponderance of catastrophic over extraordinary floods in Lleida (Table 4). The highest number of floods corresponds to the river Ter in Girona, with a figure of 177 for the period 1322–2002. The river Llobregat shows 171 floods at its mouth, for the period 1315–2002, and the river Segre, only 51 floods for the period 1306–2002. If only those floods that have produced considerable damages (extraordinary or catastrophic) were considered, those numbers would be 117, 102 and 39, respectively.

Longer flood chronologies selected for detailed analysis (Table 4) show similar behaviour patterns (Fig. 3), with an absence of positive or negative trends and of regular cycles (Table 5). Besides this, the analysis of the oldest rainfall annual series does not show any important trend, and only shows a slope above 1 mm/year in the Lleida series (Table 6). The clearest lack of homogeneity is seen in the extraordinary flooding, which can be attributed to an increasing influence of human activities.

The catastrophic flooding episodes show oscillations of limited duration (between 20 and 40 years) in which the frequency of the floods increases markedly, though with previous values regained within a few decades. The natural origin of such behaviour is assumed from the fact that they are temporary and that the previous conditions are restored. If there had been human intervention or alteration of the environment the conditions would be different and this reversibility would not occur, but rather a stabilisation on new average frequency values.

On occasion these oscillations are only very slight and are distributed between the singular events of apparently random distribution (i.e. central decades of 16th century or late 17th century). But the oscillations of greatest magnitude have a common presence in different basins, which goes to reinforce their general character or origin. At least three large oscillations in magnitude and extension were at the end of the 16th century, the last decades of the 18th century and the central decades of the 19th century.

The results of the chronologies for Lleida (Segre), El Prat (Llobregat) and Girona (Ter) are practically identical to those obtained from Catalonia's rivers

Table 4
Main chronologies obtained and catastrophic flood event distribution by centuries

Location (basin)	ORD	EXT	CAT	Catastrophic floods distribution						
				14th	15th	16th	17th	18th	19th	20th
Lleida (Segre)	12	14	25	4	4	7	3	3	3	1
El Prat (Llobregat)	69	81	21	0	0	4	10	0	6	1
Girona (Ter)	60	95	22	2	1	6	5	3	3	2

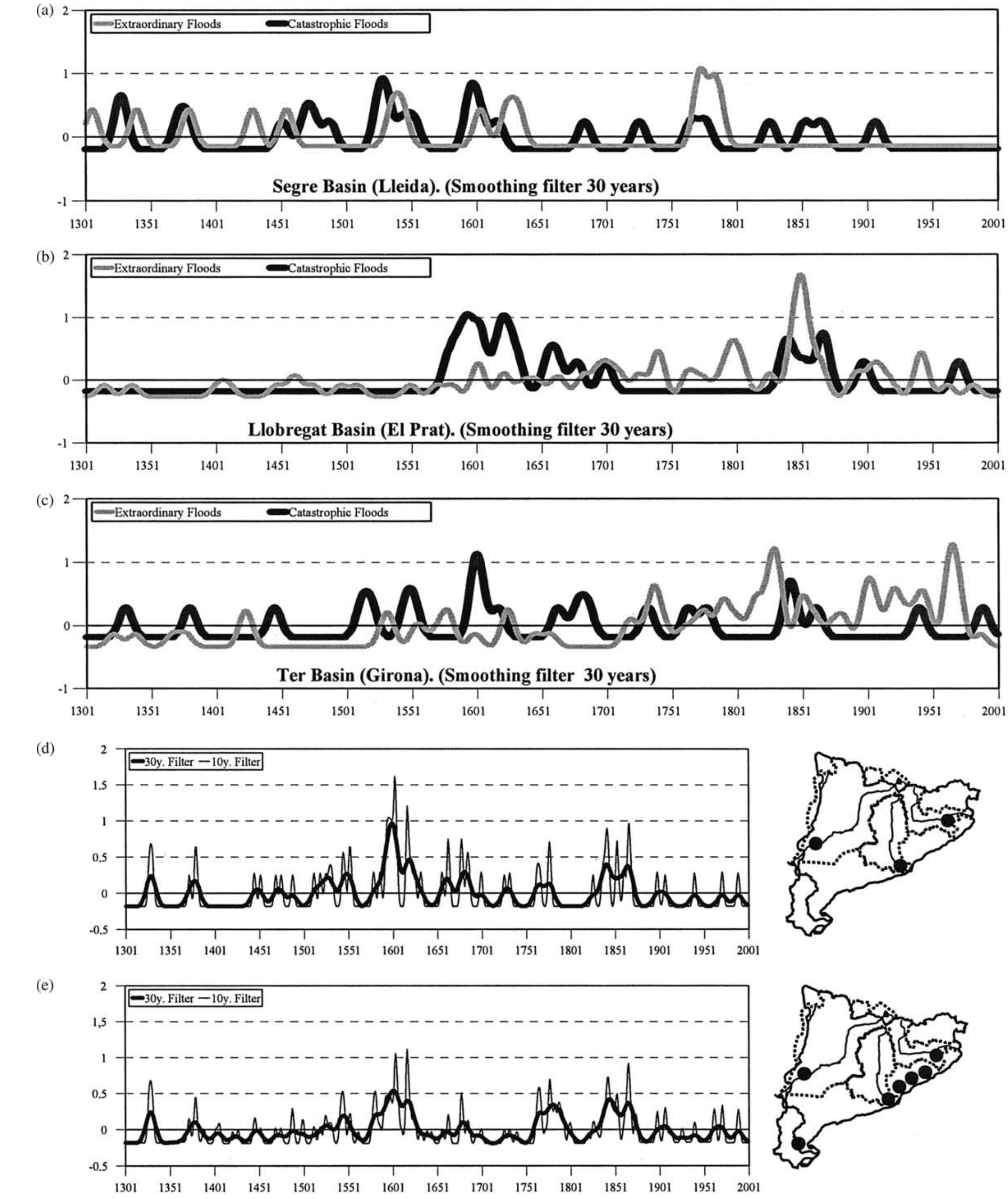

Fig. 3. Evolution of extraordinary and catastrophic flood frequency for the Segre (a), Llobregat (b), and Ter (c) rivers. Evolution of catastrophic flood frequency for the three rivers (d) and for all Catalonia (e). A low-pass smoothing filter of 10 and 30 years has been applied.

Table 5
Results of applying trend tests to flood chronologies

Basin	Flood class	Spearman	Man–Kendall	Accumulate slopes
Ter	Catastrophic	OK	OUT	No trend
Ter	Extraordinary	OK	OUT	Very slight trend
Llobregat	Catastrophic	OK	OUT	Very slight trend
Llobregat	Extraordinary	OK	OUT	Very slight trend
Segre	Catastrophic	OK	OUT	No trend
Segre	Extraordinary	OK	OUT	No trend
Catalonia	Catastrophic	OK	OUT	No trend
Catalonia	Extraordinary	OK	OUT	No trend

considered together and for which differentiation is available between extraordinary and catastrophic events (Fig. 3e). Both series show two very clear climatic oscillations in the periods 1580–1620 and 1830–1870. The result for the three large basins taken together (Fig. 3d) further shows an attenuated reflection of other oscillations detected in Central Europe, such as those of the middle years of the 16th century (Brázdil et al., 1999), and another coinciding with the Late Maunder Minimum (1675–1715). Moreover, the series with greatest representation of the littoral zones (Fig. 3e) shows in more emphasised form the oscillation of the latter years of the 18th century (1760–1800), a peculiar one in that it coincides with a simultaneous increase in the frequency of drought episodes (Barriendos and Llasat, 2003).

4.2. The multisecular climatic context in other basins

The flood chronologies that can be constructed for the western Mediterranean under optimum conditions do not extend further back than the 14th century, except for those in present-day Italy dating from the Roman Empire (Camuffo and Enzi, 1996). Then, only the last climatic episode of 'Little Ice Age' and the beginning of the following episode can be covered (Pfister et al., 1996).

The similarity of each of the basins studied in relation to the simultaneity of climatic oscillations suggests that some outside factor is having a significant effect. In order to examine this relationship more deeply the available flood chronology results for other Spanish and Italian series are compared (Fig. 4). The behaviour of this series of catastrophic floods shows oscillations with duration of some decades. Stronger oscillations have been dated taking the values higher than 0.1 (from values previously standardised and smoothed with 30-year low-pass Gaussian filter) (Fig. 5a).

The similarities in the behaviour of the climatic oscillations are obvious, with the oscillations of 1580–1620, 1760–1800 and 1830–1870 being particularly persistent in many flood chronologies. A simple check, arising only out of a desire to validate the results obtained from documentary sources with another source of information (Fig. 5b), was carried out with the behaviour of different alpine Swiss glaciers (Zumbühl, 1980; Zumbühl and Holzhauser, 1988; Holzhauser and Zumbühl, 1996). The positive-balance pulses or phases of the glacier largely coincide with the increases in frequency of catastrophic flooding. The only differences

Table 6
Results of applying trend tests to annual precipitation series

Series and basins	Temporal period	Spearman	Man–Kendall	Accumulate slopes	Linear regression (mm/year)
Barcelona (Llobregat)	1787–2001	OK	OK	No trend	0.2
Lleida (Segre)	1882–1982	OK	OK	No trend	1.3
IBC[a] areal precipitation (Catalonia)	1898–1997	OK	OK	No trend	0.5

[a] Internal basins of Catalonia (Segre basin and the Catalan parts of the Ebro and Garonne basins are not included). This series has been calculated from various long series for some Catalan basins. It is a reference series that aims to represent the precipitation in the Internal Basins of Catalonia.

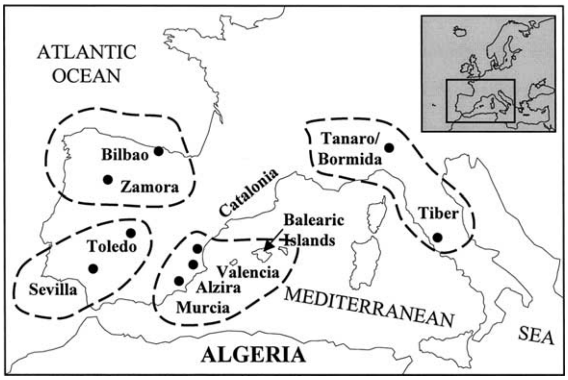

Fig. 4. Localisation of the chronologies prior to this work (from Bentabol, 1900; Font Tullot, 1988; Barriendos and Martín-Vide, 1998; Pavese et al., 1992).

lie in the temporal initial and end rates of these oscillations in the south–east of Spain, i.e. the most distant basins (River Turia in Valencia, River Júcar in Alzira and River Segura in Murcia), with the added difficulty that the pluviometric regime of Murcia has a very unusual dynamic of its own due to its latitudinal location and the complexity relief of the basin.

5. Climatic and meteorological analysis from instrumental data

The newness of this part is the meteorological analysis of the flood events recorded between 1840 and 1870 (an anomalous period identified in chapter 4) in basis to 11 continuous daily pressure series for Europe, besides daily rainfall and wind data in Barcelona. Those data have been mainly recovered by the authors. However, the instrumental data from the 19th century only permit an approximation to the synoptic configurations at the surface. Then, in-depth studies carried out on the basis of all the information available for the second half of the 20th century allow the drawing up of conceptual models associated with torrential rainfall episodes in Catalonia. The aim is therefore to find out if such conceptual models accord with the information available for the 19th century.

The studies carried out on cases of flooding from 1950 (essentially in autumn) allow a broad outline of the synoptic configuration to be sketched (Llasat and Puigcerver, 1992; Llasat, 1997; Jansà, 1997). In Catalonia those conditions generally arise with a synoptic configuration showing predominance of an anticyclone situated in Central Europe or Western Europe. Therefore, over the course of the previous days the entire western Mediterranean region usually registers high pressures. This encourages the entry of a low-level flow from the S or SE over the region, as well as the evaporation and amassing of water vapour over the western Mediterranean. As the Mediterranean is an enclosed sea of no great depth, it is of itself a large source of heat and moisture. Moreover, in many recent episodes it has been observed that the temperature of the sea is even higher than usual. Very often there is an Atlantic depression situated in the western part of the Iberian Peninsula (with an

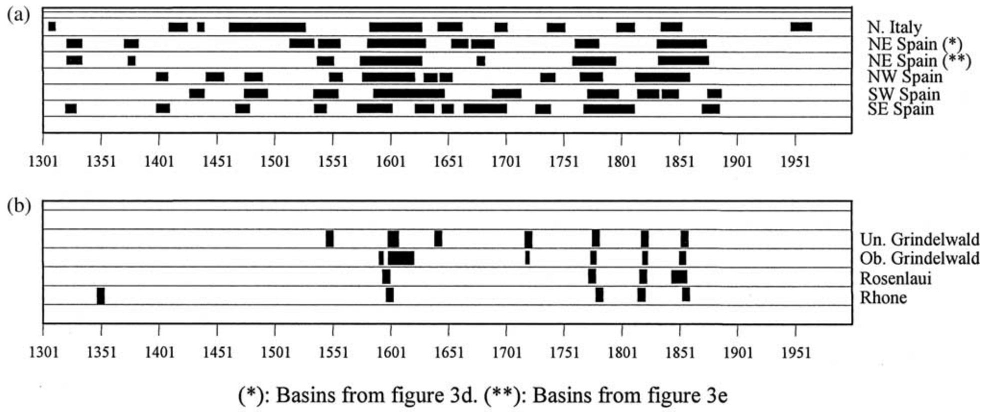

Fig. 5. Comparison between the periods of major flood activity (a) and the advances of different Swiss glaciers (b) (Zumbühl, 1980; Zumbühl and Holzhauser, 1988; Pfister, 1988; Holzhauser and Zumbühl, 1996).

associated front which moves towards the NE of the peninsula) and helps to strengthen this flow.

Mesoscale study of episodes recorded from 1996 (Llasat et al., 2000; Rigo and Llasat, 2003; Ramis et al., 1994; Rigo, 2004) shows that there are frequently depressions on a smaller scale (which will be called Mediterranean), which tend to be located between the Catalan coast and the Balearic Islands. In order to lift the mass of warm, moist air there has to be a forcing mechanism, which can be either meteorological (convergence line, front, dry lines, etc.) or geographical (the coastline or orography themselves, more usually).

The in-depth analysis of the flood event of June 2000, developed into the framework of the SPHERE project, is a clear example of the meteorological situation responsible of a catastrophic flood event. In this case radar data and rainfall data each 5-min has allowed the system tracking. More than 200 mm were recorded in less than 6 h in the Llobregat basin giving place to flash floods in some small tributary streams, where the flow has arrived to be 60 twice the usual flow. Radar and mesoscale data have showed the development of a convergence line as a consequence of the presence of a Mediterranean meso-low and the general out flow inside Catalonia, which has been responsible of triggering the convection. The formation of a train of convective cells and the opposition between the translation movement and the propagation has forced the system to remain stationary, which has been the cause of so much rainfall over the same places (Llasat et al., 2003).

This example and the general conceptual model have been applied to study and to classify the floods that occurred in the basins between 1840 and 1870. During this period 105 floods (from 24 Catalan towns in 10 different Catalan basins) belonging to 62 different meteorological flood events were recorded, resulting an average of three river floods and two meteorological flood events per year. Autumn (49% in September–October) was the season with the highest number of flood events and winter the season with the lowest number.

It should be made clear that two floods are considered to belong to a single meteorological episode if they happen on the same day (since the area of the region studied is sufficiently small to ensure that two distinct episodes do not occur within a single day). Furthermore, when two or more floods are recorded on adjacent days, they will be considered to be a consequence of the same or different meteorological episode(s).

The classification of types of precipitation was based on analysis of synoptic reconstructions of all the flood episodes. In general, we considered the actual days of flooding and the day prior to them, except for those of very short duration (the actual day of the episode only) or very long duration (the 2 days previous to the episode).

5.1. Result in the selected basins for the period 1840–1870

Sixty-two meteorological flood events have been identified using the above criterion for the period 1840–1870. Only three meteorological flood events were left unclassified. Seasonal distribution of flood events shows a prevalence of autumn events (see Figs. 6a and 7a–f). The aim of this analysis is to

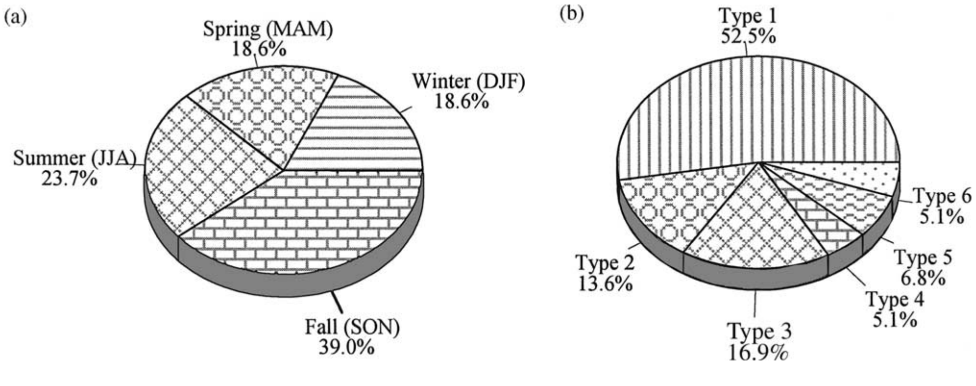

Fig. 6. (a) Seasonal distribution of flood events. (b) Distribution of flood events by weather types.

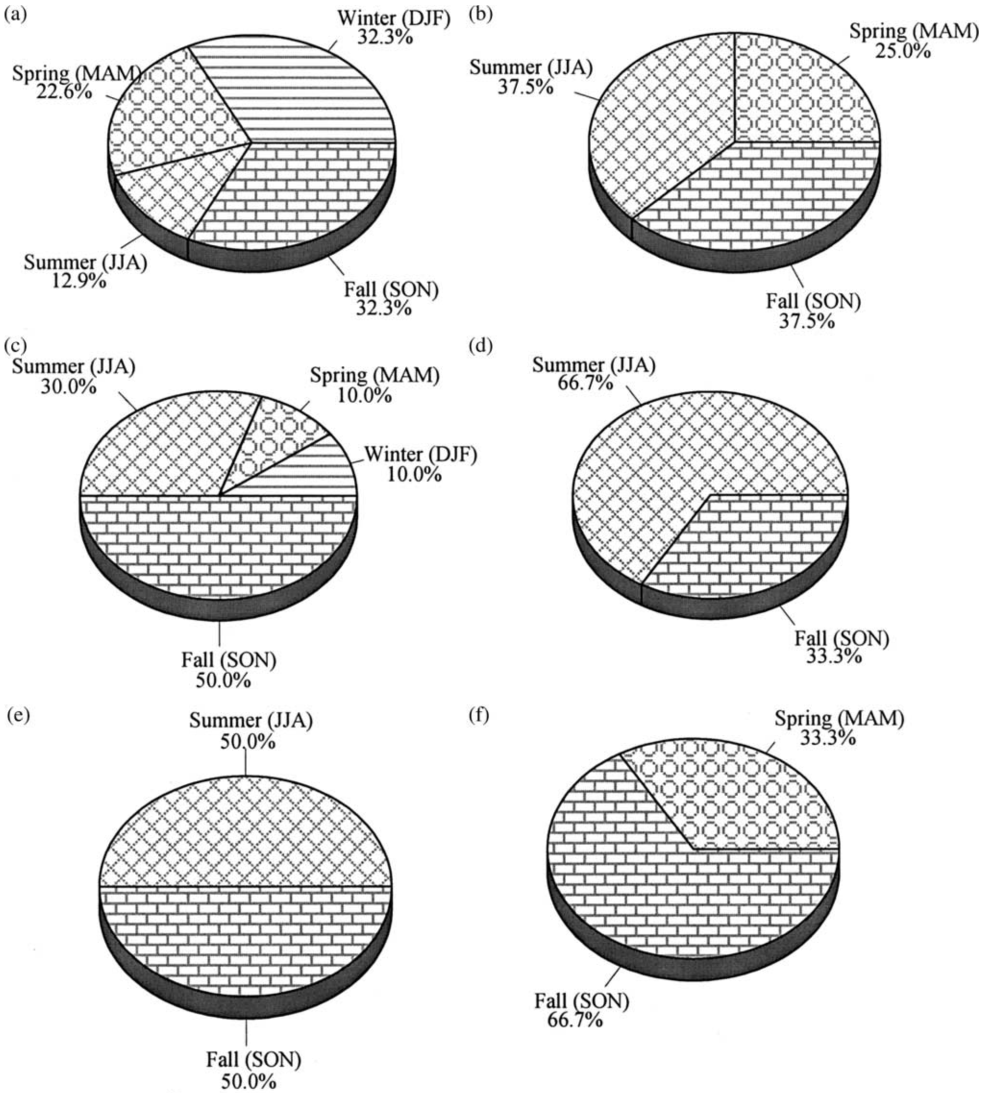

Fig. 7. Seasonal distribution of each type of weather for the period 1840–1870: (a) weather type 1; (b) weather type 2; (c) weather type 3; (d) weather type 4; (e) weather type 5; (f) weather type 6.

compare results obtained for this anomalous period with present weather classifications (Capel Molina, 2000; Martín-Vide and Olcina, 2001) and the typical conceptual model previously presented in this paper. Important changes in the frequency of some weather types could be related with changes in general circulation, that would explain the anomaly of this 1840–1870 period. The six weather types, identified in this paper, have the following characteristics (Fig. 8):

Type 1: *Southern flow (50%)*

(a) Southern winds flow over the Iberian peninsula or central Mediterranean.
(b) High pressures over eastern or north-eastern Europe expanding towards the Mediterranean sea.
(c) Low pressures (subtype A) or relative high pressures (subtype B) over Catalonia.

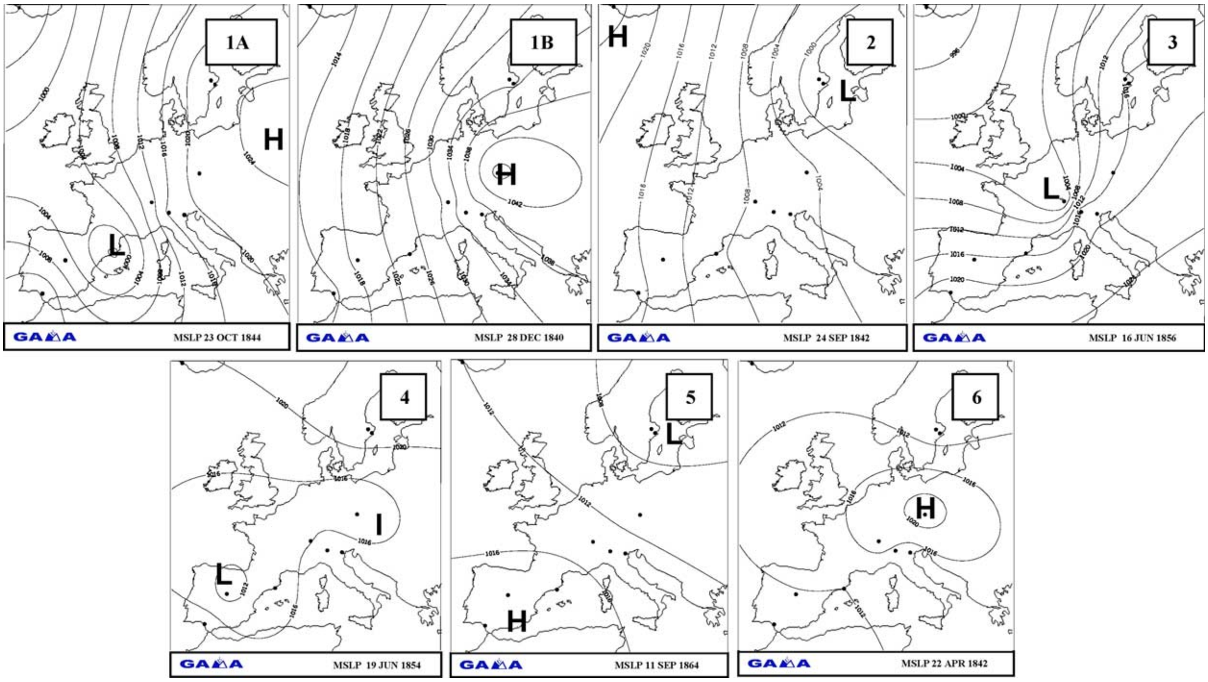

Fig. 8. Surface daily synoptic reconstructions for each weather type.

This type is the most frequent (Fig. 6b), occurring mainly in autumn.

Type 2: *Northern flow (13%)*

(a) Northern winds flow over the Iberian peninsula.
(b) Low pressures over Eastern Europe or Scandinavia.
(c) High pressures over Iceland.

Type 3: *Western zonal circulation (16%)*

(a) Western zonal circulation over Western Europe.
(b) Low pressures over Central Europe and Iceland.
(c) High pressures over Mediterranean sea.
(d) Probable passage of a cold front over Catalonia.

Type 4: *Cyclonic situation (5%)*

(a) Low pressures over Iberian peninsula.
(b) Low pressures over Central Europe.
(c) High pressures over Iceland and Scandinavia.

Type 5: *Anticyclonic situation (6%)*

(a) High pressures over Iberian peninsula.
(b) Low pressures over Central Europe or Scandinavia.
(c) Normal or low pressures over Iceland.

Type 6: *Eastern flow (5%)*

(a) Eastern winds flow over Iberian peninsula.
(b) High pressures over Central Europe.
(c) Normal or high pressures over Iceland.

The flood event of June 2000 was of type 1, which nowadays is also the most dominant. Type 2 is usual in summer, generally associated with the presence of a meso-low near Catalonia. The increase of floods during the period 1840–1870 was due to the increase of events of type 1, related with meridional circulation.

6. Conclusions

Recently, an increasing number of research groups are reconstructing and analyzing flood events from documentary sources. Quality of data series is also increasing thanks to improvement in data sources selection and collection (critical analysis of sources) and data treatment techniques. In this line, the paper provides a climatic application from systematic flood events collection in historical sources and subsequent objective data generation. Besides this, the proposal of some standardised indices allows developing comparative analysis for different regional scenarios over Europe.

Meteorological analysis for flood events identified in documentary sources, when it is possible, is a good tool for comprehension of potential scenarios with strong rainfall variability. This paper shows the application of 11 sea level pressure series from Early Instrumental Period in order to obtain meteorological patterns associated to flood events. Those pressure fields can be compared with the conceptual models associated to heavy rain events obtained from a detailed analysis made in basis to the complete information for 1950–2000. Six weather types have been identified for floods produced between 1840 and 1870. Type 1 produced by southern flow concentrates more than 52% of the cases and it is coherent with the results obtained for the second half of 20th century.

The paper shows flood frequency pattern produced by climatic oscillations with an increase of flood events for the periods 1580–1620, 1760–1800, 1830–1870. This result corroborates preliminary studies obtained from bibliographical approach (local histories). Coincidence in the frequency patterns over different Western Mediterranean area basins demonstrate a singular but common answer to climatic anomalies. Besides this, these periods are coherent with chronologies of maximum advance in several alpine glaciers. Those results point to that distribution of climatic oscillations during the past seven centuries is not regular neither cyclic. On the other hand, only some slight positive trends have been observed for extraordinary floods in the rivers Ter and Llobregat, probably due to human impact on riverbeds.

We may assert that, having analysed responses inherent to the Little Ice Age and due to the low occurrence of frequent flood events or events of exceptional magnitude in the 20th century, the latter did not present an excessively problematic scenario. Having said that, the damage suffered and a perception of increasing vulnerability is something very much alive in public opinion and in economic balance sheets.

Finally, we may note the existence of extreme meteorological episodes with considerable capacity for affecting the territory and whose study for meteorological purposes can be justified by the absence of comparable points of reference in the contemporary instrumental period and by the need to have adaptive strategies in accordance with the context of present-day society.

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