

SECULAR CLIMATIC OSCILLATIONS AS INDICATED BY CATASTROPHIC FLOODS IN THE SPANISH MEDITERRANEAN COASTAL AREA (14TH–19TH CENTURIES)

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Abstract. Historical documentation describing events on the Mediterranean coast of the Iberian Peninsula allows us to reconstruct the record of catastrophic floods. Through this information, it is possible to identify and to date three climatic oscillations within the so-called 'Little Ice Age': 1570–1630, 1760–1800 and 1830–1870, which coincide with advances in some Alps glaciers.

1. Introduction

Historical climatology, using documentary manuscripts as a source of data, offers the possibility of investigating the incidence of various meteorological phenomena. The phenomena most frequently recorded in medieval and modern documents referring to the Mediterranean coastline of the Hispanic Kingdoms were occasions when rivers and 'uadis' burst their banks as a result of especially heavy rainfall.

In the case of Spain, the wealth of documentation contained in historical archives is particularly rich. Unfortunately, up to now, there has been very little research into the subject, and the research that has been carried out has lacked coordination. Compilations such as those of Rico Sinobas (c. 1850), Bentabol (1900), Fontana Tarrats (1971–1977, 1974–1975, 1976a,b, 1977, 1978) and González (1977) were exploited by Font Tullot (1988) in order to produce a first synthesis of the history of climate in Spain. However, he did not attempt to verify the original sources or to specify them. More recently two doctoral theses on the historical climatology of Catalonia (Barriendos, 1994) and of Andalusia (Sánchez Rodrigo, 1994) have been presented to Spanish universities, and a number of papers have appeared in scientific journals and books, including those by Álvarez Vázquez (1986) and Sánchez Rodrigo et al. (1994a,b).

2. Methodology

2.1. SELECTION CRITERIA

The abundance and the variable quality of documentary sources make it necessary to establish some selection criteria in order that the series of data generated be as reliable and credible as possible (Bell and Ogilvie, 1978; Alexandre, 1987).

In this task, we have followed the line taken by Le Roy Ladurie (1967), whereby documentary sources must satisfy four conditions before the information they contain can be used for the study of climatic effects. These four conditions are: that the series must be annual (with the information organised in a temporal sequence which can be easily dated), continuous (without gaps in the documentary records), homogeneous (having a similar content throughout) and quantifiable (containing information which can be processed statistically).

2.2. THE SOURCES AND THEIR CONTENT

The sources used in this paper include both manuscripts and bibliographies (in particular, local or regional histories). The documentation consulted comprises books of municipal agreements, cathedral chapter books, and diaries or books of memoirs. In other words, municipal, ecclesiastical and private sources have all been exploited. Other interesting documentary sources exist but, in the light of the need for careful selection, these sources have been chosen for their homogeneity, reliability and the quantity of information which they contain.

The bibliographic sources used were mostly works of local history based on original documents. Their subject matter tends to be very general, except that entire chapters dedicated to extraordinary meteorological events and memorable floods are commonly included.

The manuscripts used here usually do not make direct references to the intense precipitation causing many floods. The texts normally focus on the consequences of floods, although it is possible to gauge, and even to quantify accurately, their intensity and particular characteristics. The damage caused is described in detail and the institutions involved often provided an estimate of the economic cost of any repairs or rebuilding work necessary. Occasionally, documents contain detailed descriptions of the meteorological phenomena preceding a flood, especially in cases of extreme intensity; these might include information on the direction and strength of the wind, and the intensity and duration of precipitation. Flood data also includes details of the overflowing of rivers and tributaries, and levels reached by the water. It is common to find a brief analysis of the severity of the flood and its characteristics, comparing it with other floods recorded in the documents. Sometimes a meteorological analysis is found containing complementary information about temperature and rainfall based on time-scales varying in each case. Owing to the need to establish an homogeneous series of flood records it has not been possible to extract the maximum benefit from the information in the documents as the criteria

employed are aimed only at analysing the minimum necessary information for each flood. For example, the information concerning the economic losses resulting from the damage caused by every flood has not been used.

In the case of this particular study, the minimum quantity of usable information for each flood consist of their dates and a description of the damage they caused. Both the data given on the flood and the description of the damage caused tend to be highly reliable as the documents were produced by public notaries with municipal or ecclesiastical responsibilities, and who were required to declare publicly the veracity of what was written. The books of memoirs or private diaries were written by professionals and intellectuals possessing an excellent level of education and cultural awareness in relation to the general standards of the epoch. The floods can be classified into two categories:

Extraordinary floods: causing overbank flows of moderate intensity, producing material damage of little importance, such as the flooding of crops and houses or damage to some protective work. In the majority of cases, no damage at all results, simply temporary disruption in the day-to-day activities of the population affected (see Annex I).

Catastrophic floods: overbank flows of a much more intense nature whose effects cause serious damage to agriculture and civil infrastructure, destruction of crops, mills, irrigation channels, bridges, walls and bring about the destruction of houses in centres of population (see Annex I).

2.3. CHARACTERISTICS OF THE SERIES AND METHODS OF ANALYSIS

The geographical range of the series of catastrophic floods which have been reconstructed stretches along the Mediterranean coast of Catalonia, Valencia, Murcia and the Balearic Islands (see Figure 1). The choice of locations includes rivers originating in the Pyrenean and Pre-Pyrenean region of medium-length (200 km), short rivers (50–100 km), rivers originating in the mountainous eastern edge of the high plains of Castile (the Meseta), a river of large flow-volume and length (Ebro, >500 km) and small 'uadis' of intermittent flow (5–10 km).

The period of study stretches from the Late Middle Ages (Fourteenth and Fifteenth centuries) into the present century (see Figure 2). The final list of floods identified for each river is not great in number, as a result of the application of strict objective selection criteria. This makes it easier to appreciate the frequency of serious events. It is easy to find a considerable number of descriptions of intense rainfall but detailed examination reveals that damage was slight or non-existent or that rivers did not even overflow.

Given the simplicity of the data, the statistical treatment applied must be of equal simplicity, at least during the initial stages of research (Alexandre, 1987, p. 45). Above all it is necessary to develop a relatively simple approach aimed at achieving two basic objectives. First, it is necessary to ensure homogeneity between

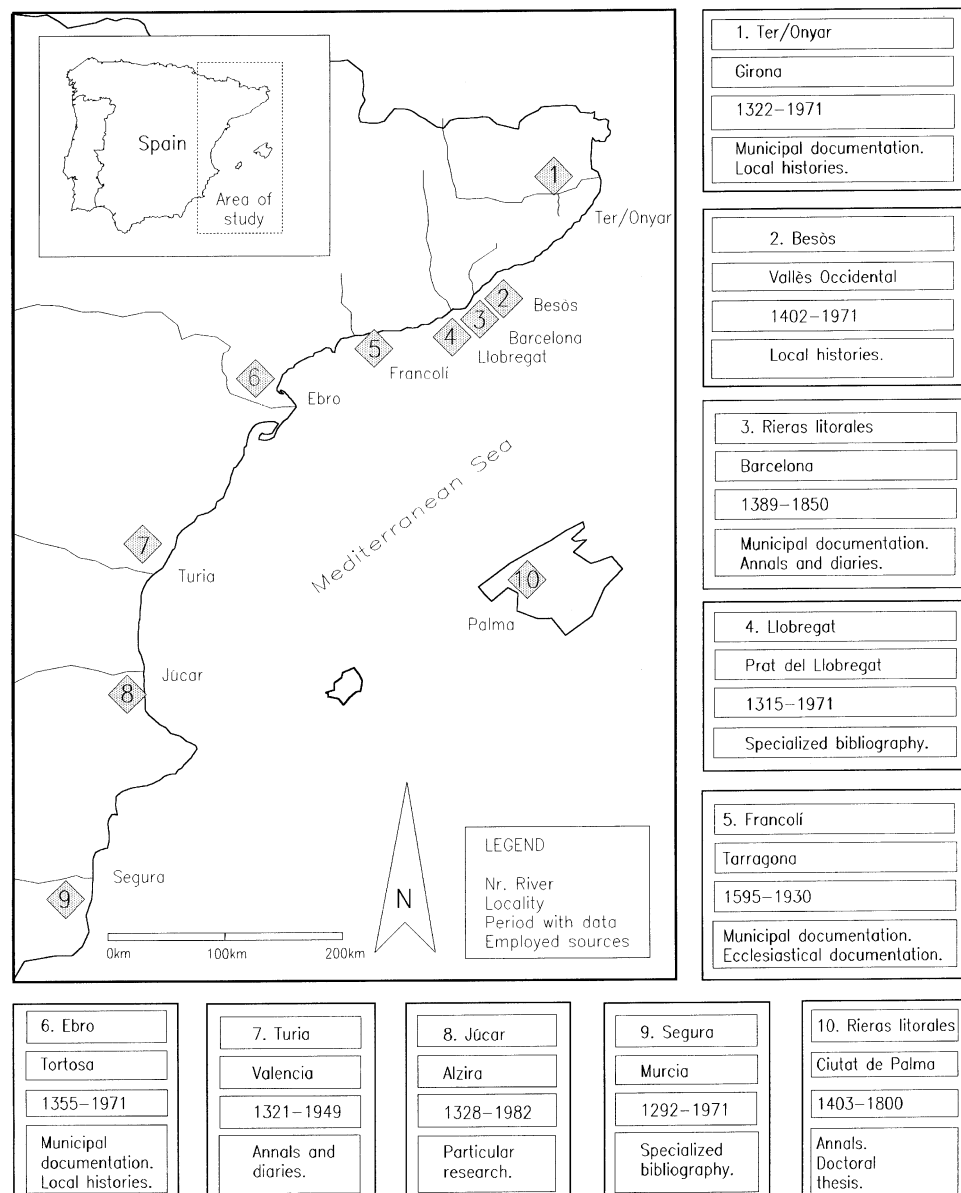


Figure 1. Location and characteristics of floods series.

the series so that they can be compared with each other. To achieve this, the annual number of catastrophic floods is standardised by means of the following formula:

$$y = \frac{x - \bar{x}}{s}$$

Table I
Statistical characteristics of flood series

Rivers or 'uadis'	Number of catastrophic floods	Period (years)	Average ($\bar{x}$)	Standard deviation (s)
Ter/Onyar	14	650	0.02	0.16
Besòs	24	570	0.04	0.21
Barcelona	32	462	0.07	0.25
Llobregat	36	657	0.05	0.24
Francolí	14	336	0.04	0.20
Ebro	14	617	0.02	0.15
Turia	31	629	0.05	0.22
Júcar	17	655	0.03	0.16
Segura	25	680	0.04	0.19
R. Palma	8	398	0.02	0.14

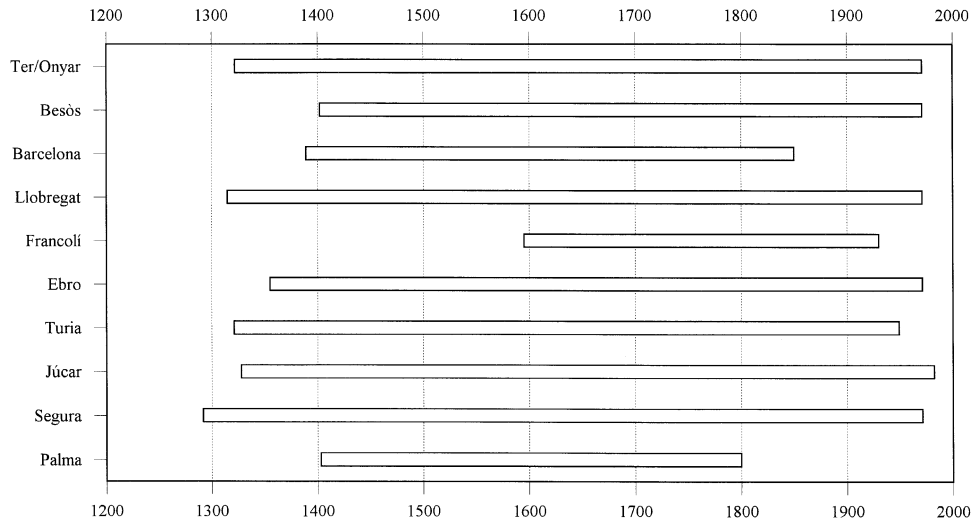


Figure 2. Temporal periods of floods series.

Second, it is necessary to modulate as far as possible the often very great variations in the temporal distribution of floods, and to make an analysis of their frequency over an extended time period. This is accomplished by applying running means of 31 years.

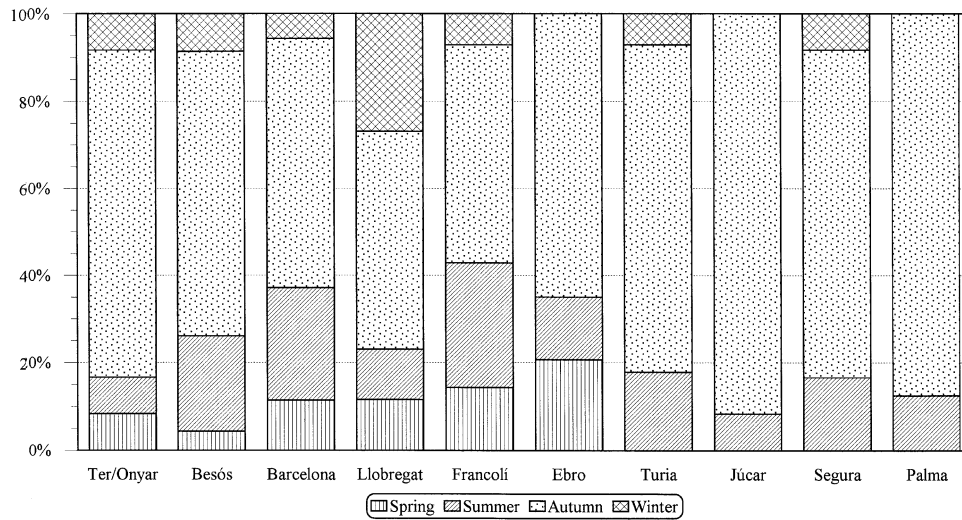


Figure 3. Seasonal regime.

3. Interpretation of the Results

3.1. SEASONAL AND MONTHLY REGIMES

The seasonal regime of catastrophic floods (see Figure 3) reveals a series of interesting features for analysis, leading to the identification and evaluation of several geographical factors. The annual distribution of catastrophic floods barely differs from current established patterns of intense precipitation in the regions studied. Autumn is clearly indicated as the season in which the majority of catastrophic floods are concentrated. This is particularly the case in the southern areas, and demonstrates the influence of the Mediterranean as a propitiating factor in the production of intense precipitation, as the first waves of cold winter air encounter the warm, humid air over the heated sea. Many floods occur in summer, with similar values being recorded at all observation points. These floods are the result of convectional atmospheric activity which affects limited geographical areas but can provoke brief but extremely intense precipitation and lead to catastrophic flooding.

In spring, floods are recorded only in the northern basins, and these are of relatively low frequency. This contrast between northern and southern basins may correspond to the presence in the former of a secondary maximum precipitation occurring in the spring, accompanied by convectional activity before the summer begins, in contrast with the southern basins, where this secondary maximum is barely perceptible. The Ebro basin is peculiar in this aspect, having the highest proportion of spring floods in any series. This results from the spring thaw in the Pyrenees, as water is collected and fed into the Ebro by its numerous left-bank tributaries. This growth in volume can cause serious flooding if it coincides with

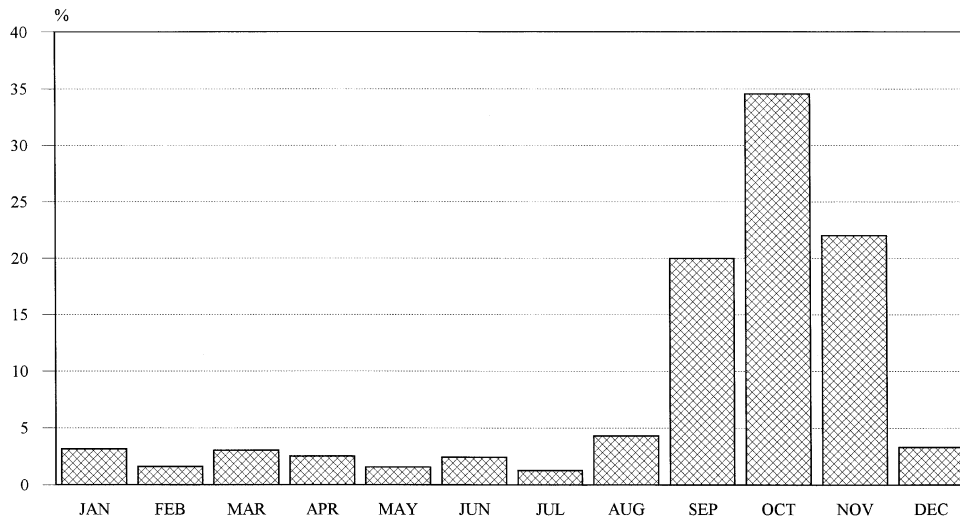


Figure 4. Monthly regime.

periods of intense precipitation. The rainfall, accompanied by warm winds from the Mediterranean (easterly and south-easterly), normally reinforces the effect of a rapid thaw and increases the impact of catastrophic floods. In winter there is a low proportion of floods, mainly concentrated in the southern basins, particularly the Llobregat.

A monthly approach allows a much more detailed analysis to be made (see Figure 4). The monthly distribution clearly shows that autumn is the season of most frequent flooding, with October being the outstanding month, while September and November register slightly lower levels. The remaining months show little activity, with December and March standing out slightly, and August a little more sharply.

3.2. DESCRIPTION OF THE FREQUENCY INDICES OF THE SERIES

The absolute values found display great variation between thirty-year periods (see Figure 5), though it has to be remembered that information is available for all of the time series only for the period 1601–1630/1751–1780. The result which could reasonably be expected if the climate were a random variable would be a regular incidence of floods during each thirty-year period. In fact, the frequency of catastrophic floods exhibits peaks of particular intensity separated by periods of apparent calm, or at least of lower values.

Despite the lack of homogeneity, results warrant further discussion. Clearly, the initial thirty-year periods register a low number of floods because data are available for only a small number of series. On the other hand, recent periods during the twentieth century also register very low values, but this is due to the construction of hydraulic devices which have led, in some areas, to the virtual disappearance of floods as natural phenomena.

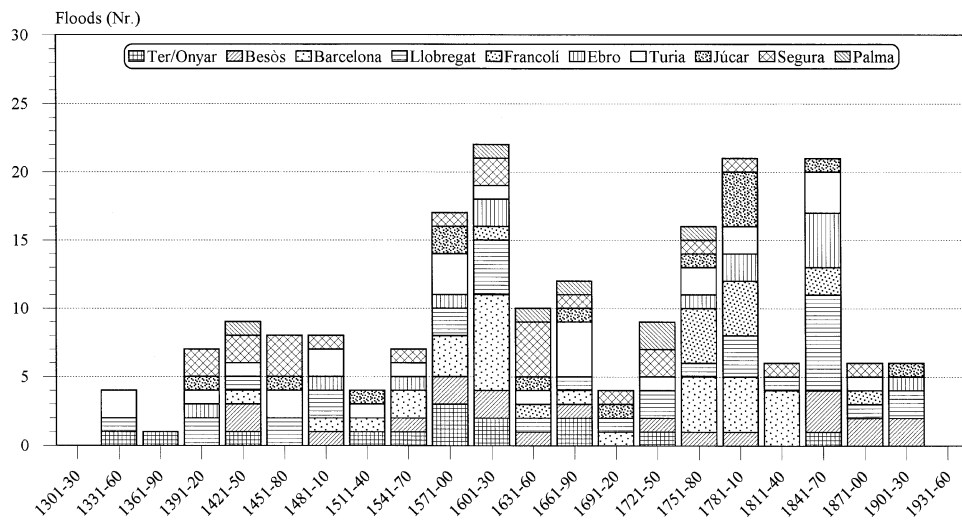


Figure 5. Catastrophic floods. Absolute frequency. 30-year periods. Period with information in all the series: 1601–1780.

A study of the rates of frequency of each series of floods (see Figure 6) confirms the initial impression that they are not homogeneous over time. Of course, each series exhibits rhythms and particular intensities which are a consequence of the respective combination of geographical factors which define each point of observation and each hydrographic basin. Nevertheless the characteristics present in the behaviour of each series, in contrast, show a certain coherence between one another.

Periods of low frequencies (values below 0) are numerous and show a regular distribution across the time period covered by this study. Three prolonged periods can be identified, despite occasional interruptions, in which more than 75% of the series exhibit values lower than 0:

1st. period: The second half of the fourteenth century.

2nd. period: The first two thirds of the sixteenth century.

3rd. period: The last two decades of the nineteenth century and the first half of the twentieth century.

The positive anomalies, which show a dramatic increase in the frequency of catastrophic floods, are more limited in number. There are three periods during which more than 75% of the series exhibit values greater than 0, apart from one isolated occasion (the year 1417):

1st. period: The last two decades of the sixteenth century and the first three of the seventeenth century.

2nd. period: The last quarter of the eighteenth century.

3rd. period: The middle decades of the nineteenth century.

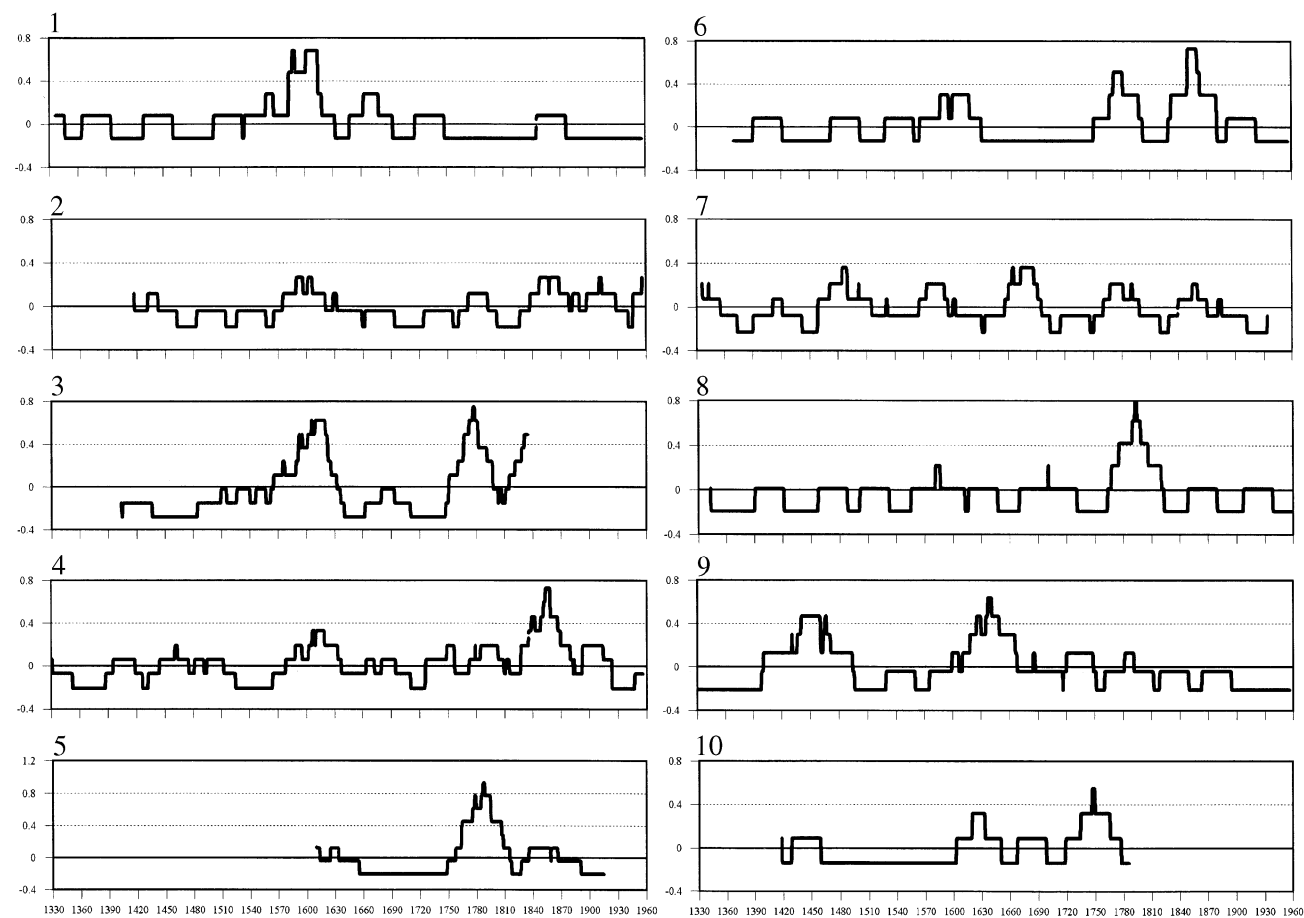


Figure 6. Catastrophic floods frequency. Moving averages of 31 years.

Table II

Temporal behaviour of the series compared to the respective means (only when data are available for $\geq 50\%$ of the series) (see Figure 6)

Negative anomalies	Centuries	Date
100% series < 0	14th	1356–1364
	20th	1939–1946
$\geq 75\%$ series < 0	14th–15th	1347–1390; 1422–1429
	16th	1516–1529; 1533–1555; 1561–1565
	17th–18th	1651–1656; 1696–1718; 1749–1750
	19th	1816–1829; 1880–1883; 1885–1897
	20th	1929–1956
Positive anomalies	Centuries	Date
$\geq 75\%$ series > 0	15th	1417
	16th–17th	1579–1596; 1600–1613; 1617–1632
	18th	1773–1777; 1782–1792
	19th	1846–1870
100% series > 0	16th	1603
	16th	1604

Two exceptional cases exist, the years 1603 and 1604, when 100% of the series had values exceeding 0.

3.3. CLIMATIC OSCILLATIONS IDENTIFIED

If the behaviour of the flood frequency statistics exhibited a random distribution, or was conditioned by environmental factors of multiple origin and effect, the resulting graphical representation of the mean of all the values (see Figure 7) would not offer any conclusions worthy of comment. However, the results permit the identification of three climatic oscillations of similar intensity and duration.

The climatic variations over six centuries indicate three oscillations in which the periods of intense precipitation show a notable increase in frequency. A characterisation of these oscillations cannot be achieved in any great detail owing to the scarcity of documentation, although some significant conclusions can be drawn about their temporal distribution.

Firstly, the closing years of an oscillation in the mid-fourteenth century can be observed. Unfortunately, lack of more complete data sets prevents a detailed analysis of its general characteristics. The first oscillation to be completely identified developed between the years 1570 and 1630 with two maxima (1588–1596 and 1602–1620) lasting a total of 28 years and having a maximum value in the year 1606. The second oscillation came between 1760 and 1800. This had just one maximum between 1772 and 1797, lasted 26 years and reached peak values

Table III
Mean of all series analysed. Dates of positive anomalies (see Figure 7)

Values	Centuries	Periods	Years
> 0.01	14th	1328–1330	3
	16th–17th	1588–1596; 1602–1620	28
	18th	1772–1797	26
	19th	1848–1868	21
> 0.02	16th–17th	1606	1
	18th	1790–1791	2
	19th	1851–1857; 1859–1860	9

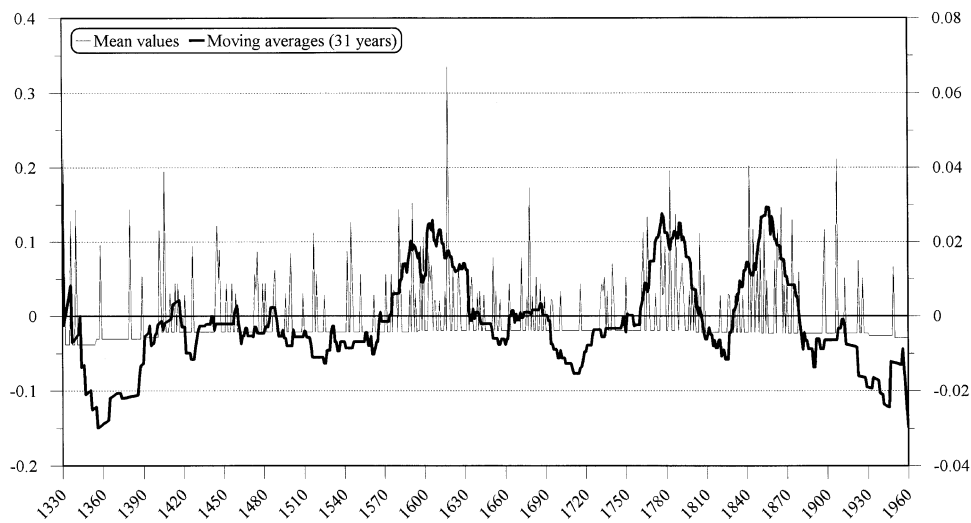


Figure 7. General mean for all series. Base value: 0.

between 1790 and 1791. Finally, the third oscillation developed between the years 1830 and 1870, with a maximum between 1848 and 1868 and two brief periods of extreme values between the years 1851 and 1857 and 1859 and 1860.

3.4. INTEGRATION OF THE RESULTS INTO THE GENERAL CLIMATE DYNAMIC

Assuming flood frequency to be a valid factor in the interpretation of secular climatic oscillations (López Gómez, 1983, p. 27), its analysis appears to illustrate, in the absence of more detailed studies, the existence of a significant pattern producing oscillations characterised by a dramatic increase in incidence. Floods provoked by meteorological phenomena (intense precipitation) are of course common features of the Mediterranean zone. The only way in which the results can be usefully

compared with other geographical zones and studied from other paleoclimatic standpoints is in the noticeable variation in the frequency of this phenomenon.

Whilst maintaining the necessary caution, it can still be stated with some confidence that the grouping of three oscillations forms a part of an already-identified climatic episode which has been described at some length: the Little Ice Age, which can be dated between the first years of the 14th century and the middle of the 19th century (Pfister et al., 1996).

The conclusions which can be drawn from this information are very limited, as a result of both the characteristics of the information considered, and the current state of research in Spain. There exist other elements in the historic documentation of the Iberian Peninsula which may lead to a more detailed and complete interpretation of climatic oscillations in the near future, such as, for example, rogation ceremonies connected with environmental problems, particularly drought, excessive rainfall or very cold spells (Martín-Vide and Barriendos, 1995).

Comparison with the results of other paleoclimatic research in Europe is perhaps premature. The connection between the three oscillations of increased flooding in the sector studied with the three advances in the Grindelwald glaciers during the past four centuries can be noted, however (Pfister, 1988, p. 146, 1992). This circumstance almost certainly means that the variations in general climatic dynamics on a very broad spatial scale may manifest themselves simultaneously in different geographical areas through completely different atmospheric processes, if not perhaps completely independent ones.

In the particular case of floods in the Western Mediterranean area the atmospheric processes which are apparently present with unusual frequency during the identifiable climatic oscillations could be the result of the presence in those latitudes of the jet stream, together with its associated band of depressions, resulting from the latitudinal expansion of the circumpolar vortex. The passage of these depressions, reinforced as they reach the Mediterranean, would produce this intense precipitation. On the other hand, the floods may be attributable to a very noticeable and prolonged form of meridional circulation of the Jet Stream. In Mediterranean latitudes, this is caused by the sharp contrast between cold air masses from the north and warmer and more humid masses already present over the Mediterranean area, with the consequent atmospheric instability.

These two mechanisms currently cause floods in the Western Mediterranean area and were, therefore, probably also the cause of numerous floods throughout history. These hypotheses are put forward at a time when investigation in the Iberian Peninsula is still limited, but the indications are that paleoclimatic conclusions can be drawn by means of extrapolating the identified atmospheric mechanisms through current research. The aspect which remains inexplicable in this particular case is the direct cause of such a noticeable increase in the catastrophic flood frequency over limited periods of time, here defined as climatic oscillations. Complex processes must be involved, on different spatial and temporal scales no doubt involving the participation of different natural elements (atmosphere, solar radiation, marine

currents, etc.). The Mediterranean area is a complex one, where a multitude of environmental factors are constantly interacting together.

4. Conclusions

The Iberian Peninsula possesses an enormous wealth of historical documentation containing interesting paleoenvironmental information which has only recently begun to be employed in paleoclimatic research. The quantity of available information and the absence of transcriptions or editions of this documentation involves a great deal of work. The need to use original manuscripts requires the application of strict methodology and rigid criteria compatible with research carried out by historians. Results of current investigation into catastrophic floods reveal three oscillations within the so-called 'Little Ice Age'. The first (16th–17th centuries) and the third (19th century) may denote the beginning and the end of this climatic episode in the geographical area studied. The second oscillation (18th century) remains dependent for more detailed characterisation on subsequent research into other paleoclimatic elements. The reconstruction of climatic dynamics through historical documentary sources is an area which still offers many possibilities in the Iberian Peninsula, but international collaboration would appear to be both necessary and indispensable if we are to attain an understanding of the processes and factors which govern global climatic dynamics.

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Appendix I

EXTRAORDINARY FLOOD:

Municipal Archive of Girona, Reports of Fire Brigade, vol. 6, March 9th 1872, fol. 5:

Flood of river Onyar. Water level in the city: 1 meter in 'Coles' square, 'Plateria' street and 'Ballesterias' street. 2 meters in 'Pescaderias Viejas' street. 80 centimeters in 'Vino' square. The water did not produce dammages.

CATASTROPHIC FLOOD:

National Library of Catalonia, Ms. 485, August 27th 1389, fol. 293:

'Ano domini m ccc lxxx ix dies xxvii mensis augusti circa horam vespro fuit tot et tanta multitudo et tempestas aquas pluvialis in civitate barchinona et in eio territorio et duravit per tres horas et plo ita qui postravit ad terram murum ditem Civitatis quod erat retro monasterius sancti damiani barchinone et pte dormitori dicti monasteri et per maiori pt ora hospitia q erant in vico dls orbs et in vico den jucglar et in alys diversis locus barchinona et multas vineas destruxit et eraditavit/ Et inplevit regum comdale lapidibus et cementis in tum qp per xii dies stetit qp no potuit intrar aquam moledinos in civitate barchn'.

TRANSLATION:

In the year 1389, on 27 August in the afternoon the city of Barcelona had a storm with heavy rainfall which lasted three hours. The wall of the city collapsed in the 'Saint Damia' monastery. The dormitory of this monastery and the houses of 'Orbs' and 'Jutglar' street collapsed. The rainfall uprooted a lot of vineyards. The Channel of the city filled up with stones and mud. The damage lasted for twelve days. The mills of the city were out of service.

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