THE CASE OF "MALDÁ" ANOMALY IN THE WESTERN MEDITERRANEAN BASIN (AD 1760-1800): AN EXAMPLE OF A STRONG CLIMATIC VARIABILITY

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Abstract. The study of climatic anomalies on the basis of various types of instrumental information and proxy-data allows unusual events to be identified. The objective of this paper is to introduce and explain a hydrometeorological anomaly that occurred between 1760 and 1800 (Maldá Anomaly), characterised by a sequence of both anomalous droughts and floods, and to compare it with the features of the second part of the 20th century. Firstly, some climatic indices obtained from proxy-data (mainly documentary sources) have been generated. Secondly, instrumental observations made in earlier times, in conjunction with data from the bibliography, have been used in order to relate this period to the different circulation patterns and to analyse the geographical extension of the anomaly. The results confirm the presence of considerable variations in the atmospheric action centres, especially between 1780 and 1795, which in the Western Mediterranean gave rise to a simultaneous increase in the frequency of droughts and heavy rainfalls, either having nothing comparable or sharing similarities with periods in the 19th and 20th centuries.

Key words: Maldá Anomaly, proxy-data, floods, droughts, pressure data, NAOI.

1. Introduction

Uncertainties in the face of natural and man-induced climatic changes that might arise in the course of the 21st century are leading climatic research into different lines of work. In particular, the recent report of the IPCC (IPCC, 2001) shows that "an increase in climate variability and some extreme events is projected as a consequence of the increasing atmospheric concentrations of greenhouse gases and aerosols". The same report nevertheless reveals that "there is a lack of reliable local or regional detail in climate projections for precipitations and for changes in extreme events". In the face of such missing elements, identification of similar patterns which occurred under pre-industrial conditions might help to define "future regional scenarios of global change". The study of extreme episodes which occurred in the past has the advantage that, in addition to providing better knowledge of climatic dynamics, it permits the positing of strategies to mitigate impact and reduce vulnerability. In the particular case of extreme hydrometeorogical events, such as droughts and flooding, such study becomes all the more important in those zones – such as the Mediterranean Basin – for which optimum availability of hydric resources does not even exist under normal natural conditions, in that one of the major "natural hazards" is indeed flooding. In this case, the interest of the information obtained from documentary series in relation to the hydric extremes would justify the carrying out of such research work within an interdisciplinary scientific framework with the final objective of assessing the "water resources" in future scenarios of "global change and management of water resources impacts: characterisation, planning, warning, mitigation".

The objective of this paper is to characterise an anomalous historical period (1760-1800) characterised by a succession of droughts and floods in Catalonia (NE of Iberian Peninsula), known as the "Maldá Anomaly". It is thus a case which is in accordance with the responses which in future scenarios of "global warming the climatic models are projecting: An increase in climate variability and some extreme events". As will be seen in the course of the paper, that anomaly mainly affected the Mediterranean zone of Europe.

The paper starts with a brief introduction to the main characteristics of floods and droughts in the zone under study, so as to assist understanding of the anomaly examined. The proxy-data and instrumental sources used are then presented, together with the criteria and methods used for drawing up various climatic indices. These are used as the basis for presentation of the general climatic context in relation to extreme hydrometeorological episodes in Catalonia, from the 14th century. Chapter 5 goes more deeply into the anomaly identified for the NE of Spain through hydrometeorogical indices (catastrophic droughts and floods) based on historical information and qualitative references from contemporary witnesses. There follows, in chapter 6, a quest for similar patterns in other zones of Europe on the basis of different multi-proxy information. Finally, and before drawing conclusions, the zonality indices introduced in the previous sections are applied to the anomalous period studied in order to obtain an approximation to the atmospheric processes linked with such an anomaly.

2. Main characteristics of floods and droughts in Catalonia

First of all, it is important to know that in the hydrological basins dealt with in this study extraordinary and catastrophic flooding are usually linked with three types of pluviometric episode (Llasat, 1997, 2001):

- Episodes of very short duration (less than 6 hours) but very high intensity (intensity peaks of over 3 mm/min). They mainly take place in summer and the beginning of autumn and give rise to "local flash-floods". These are episodes of the "strongly convective" type.
- Episodes of short duration (less than 72 hours) with moderate pluviometric intensity values, while there may be some peaks of precipitation. They mainly occur in autumn and sporadically in spring. They can give rise to "extensive flash-floods". These are episodes of the "moderately convective" type.
- Episodes of long duration (approximately one week) with weak pluviometric intensity values, while there may be peaks of high intensity. Although not very frequent, they usually occur in winter. These are episodes of the "slightly convective" type.

Floods linked with snowmelt are infrequent and affect only some rivers; in order to maintain the homogeneity of the series, they have not been included in this study.

In relation to periods of drought in past epochs, they may be said to have been linked essentially with climatic conditions, in that the more recent factors of overexploitation of rivers/aquifers and desertification did not exist then. They were usually linked (and this remains today the predominant factor in the zone of study) with nill precipitation values or values below normal over long periods of time.

It should be noted that on some occasions the worst consequence of such drought periods is that the population invades the riverbed, which can increase the number of human victims as a result of a rise of the river. The number of human victims is thus not considered decisive when it comes to differentiating the character of the historical floods.

3. Documentary sources: data and methodology

This paper was drawn up using data obtained from historical documentary sources and instrumental sources from earlier times. This is information which allows a relatively limited period of time to be covered over Europe – some 1000 years and 250 years, respectively. On the other hand, these data do allow work at high spatial and temporal resolutions, for the analysis bears upon information and observation dated day by day.

3.1. DATA

The obtaining of information on floods from historical documentary sources is a line of research work that does not have a long tradition in Spain, despite offering good potential for study. Indeed, systematic work has only been carried out in the Iberian Peninsula since the 1990s, which means that research work can still not be carried out at broader working scales. Furthermore, there is the inherent difficulty of the documentation largely containing only information relating to extreme meteorological episodes, particularly those of a hydric nature. In consequence, the information usable for climatic purposes is restricted to extreme hydric episodes: droughts and floods.

Intense rainfall episodes causing floods in inhabited zones were a relatively infrequent phenomenon, but one which had serious effects on the day-to-day life of any human community. This made floods, along with other climatic risks like droughts, events that generated a volume of information easily detectable and analysable by following the methods inherent to historical climatology.

The basic documentary sources used here were taken from municipal archives (e.g. minutes books or resolution books), ecclesiastical archives (e.g. resolution chapter books) and various duly checked private sources (dietaries, chronicles). For more detailed information, see Barriendos (1994) or documentary references in Martin-Vide & Barriendos (1995) and Barriendos & Martin-Vide (1998a). In summary, the information-gathering work at various research centres involved 112 series of documents, mostly minutes books of councils, with a total of more than 2,130 volumes of manuscript documentation

The data currently available are series of hydric indices drawn up from two basic types of proxy-data information:

a) Information about the frequency and intensity of drought events based on “pro pluvia” rogation ceremonies (Martín-Vide & Barriendos, 1995). Continuous data series are available for seven cities in Catalonia: Girona, Barcelona, Tarragona, Tortosa, Seu d’Urgell, Vic and Cervera (see Figure 1).

b) Information about the frequency and intensity of floods caused by intense precipitation events (Barriendos & Martín-Vide, 1998a). Continuous data series are available for twelve cities in Catalonia: Girona, Calella, Arenys, Mataró, Montcada (Besós river), Barcelona, Prat de Llobregat (Llobregat river), Tarragona, Tortosa, Seu d'Urgell, Balaguer and Lleida (see Figure 1). In selecting points or localities for generating data series, special attention was paid to the possibility of taking in different types of river basins and courses, so that there was one large river course (Ebro, >500 km in length), medium-sized rivers (100-200 km in length), short rivers (<100 km in length) and intermittent water courses along the coastal zone (5-10 km in length).

At a strictly qualitative level, some texts were gathered in which contemporary testimonies revealed the authors' own perception of the climatic conditions.

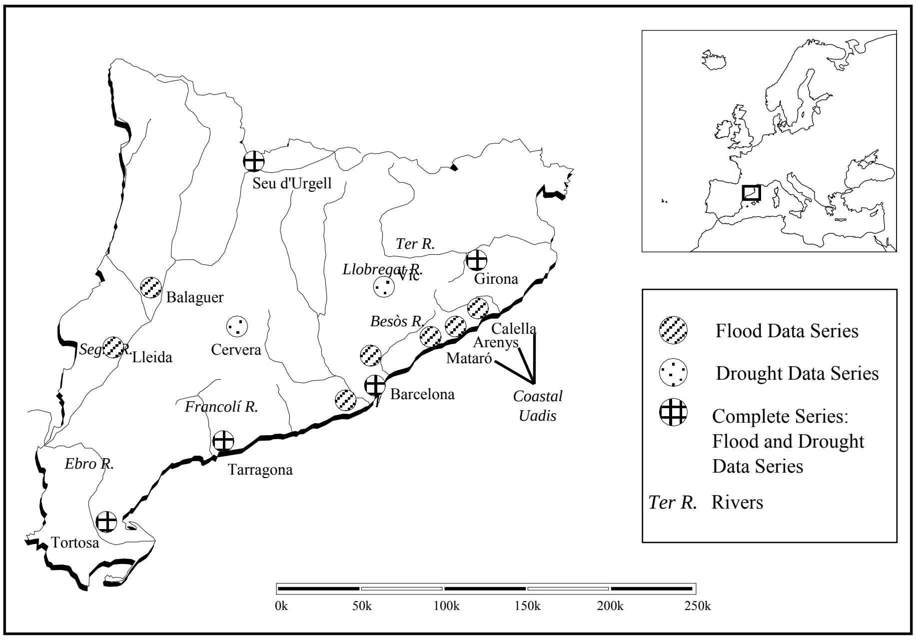

Figure 1. Location of the data series taken from documentary sources

3.2. METHODOLOGY

The basic criteria applied for acceptance of the information obtained from the documentary sources was the continuity and homogeneity of the information, together with the complete reliability of the documents used and exact dating of the episodes (Le Roy, 1967; Alexandre, 1987).

In the case of floods, the available information was objectified by following a criterion based solely on the effects produced by each flooding episode. Experience obtained in Catalonia has permitted three types of high waters to be distinguished, according to their impact, though only floods can be treated objectively:

a) simple high waters: precipitation episodes which give rise to increases in the flow of fluvial courses or freshets, though without leading to them overflow their banks.

Such episodes can cause damage and loss of life 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 damage in the locality. These episodes can cause discomfort and inconvenience to the daily life of the population.

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

In order to process this information, simple indices were 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 to the twelve stations (Figure 1) to the series of annual values composed of 1 (at least one flood recorded) and 0 (no flooding 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:

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

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_{medj} is the annual average of floods in 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:

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

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*.

The process for producing drought indices was rather more complex, since the initial information consisted of “pro pluvia” rogation ceremonies, organised into five levels according to the intensity of the event. An anual index for every location could not be drawn up using the absolute frequency of cases, as had been done for floods. Faced with a hierarchisation of rogations according to the characteristics of the drought recorded, we chose to produce a weighted index in which the ceremonies for the more serious events would have a steadily increasing weight (see Table 1).

Level	Rogations ceremony	Situation	Weight
Level I	Simple prayer	Preventive level	1
Level II	Display of relics	Slight drought	2
Level III	Public processions	Moderate drought	3
Level IV	Immersion of relics in water	Severe drought	4
Level V	Pilgrimage to sanctuaries	Critical drought	5

Table 1. Quantification of rogation ceremonies for generating drought indices (Martín-Vide & Barriendos, 1995)

The drawing up of conventional hydric indices (Pfister 1988, Glaser 1996, etc.), in which hydric excess and deficit are integrated, was not considered in this study. The virtual simultaneousness in time of opposing phenomenon such as droughts and floods was not made clear when the monthly information was used to draw up the corresponding seasonal or annual averages. Thus, entire seasons or complete years were characterised as "normal periods" when in fact they concealed extreme values in one or the other sense. These paradoxical situations nevertheless of themselves contained some kind of climatic information. The frequency with which paradoxes appeared was analysed, as annual and seasonal hydric indices (+2/-2) were available for the seven cities/towns which had flood and rogation ceremony series (Barriendos & Martín-Vide 1998b).

4. Instrumental sources: data and methodology

While the main objective is to develop powerful predictive tools, there is no contradiction involved in devoting research work to characterising in the greatest possible detail the behaviour of climate in the past. The availability of climatic information for broad time spans can help to identify and characterise climatic behaviour which in the recent past has occurred only moderately or indeed not at all (Xoplaki et al., 2001). One of the tools which fulfils these perspectives of predictability and at the same time knowledge of the past is analysis of the relationship between Zonality Indices and extreme events.

Among the indices of general circulation we might stress the North Atlantic Oscillation Index (NAOI) (Hurrell, 1985; García et al., 2000). To the use of the NAOI should be added the many other indices of general circulation which attempt to explain anomalies or behaviour in certain zones which cannot be explained by the variability of the NAOI. Among these we might note indices such as the zonality indices for Central Europe (Jacobeit et al., 2001), or those drawn up for the Mediterranean Basin (Maheras et al., 1994, 1999). Here we have research work in progress and thus still open to the generation of new regional indices and, in particular, of indices based on instrumental data and proxy-data of physical, biological or human provenance. Following this line of open investigation, this paper will be presenting an index whose advantage lies in the availability of instrumental data for the historical period selected.

4.1. DATA

The availability of instrumental meteorological series recorded prior to the existence of official meteorological services (EIP: Early Instrumental Period) is quite limited, and especially so in the Mediterranean basin. The monthly mean pressure data issued by the Climatic Research Unit, University of East Anglia, Norwich (Jones et al., 1999) were used to draw up a zonality index using the oldest series and covering the extreme angles of the European continent as fully as possible. Furthermore, within the context of the European ADVICE and IMPROVE projects, in which the authors of this paper took part, more than 50 pressure series were drawn up at monthly resolution, and some of them at daily resolution (Camuffo and Jones, 2002). These are series whose length and continuity make them an important climatic analysis tool. For the last decades of the 18th century, however, the result proved to be modest indeed: only Barcelona, Milan, Padua, Edinburgh, Trondheim, Stotckholm and Uppsala have a complete pressure series for this period.

In considering a zonality index suitable for the study, Stockholm and Uppsala were ruled out because, while well-situated latitudinally, they are too far away longitudinally. Knowledge of the synoptic situations associated with intense rainfall and droughts in the East of the Iberian Peninsula (Llasat and Puigcerver, 1994) points to a greater influence of instability at latitudes below 50º. In the case of the catastrophic flooding episodes, the circulation is usually southerly, with flow from the SE and European anticyclone. As an object of research, therefore, we chose to work with points situated at lower latitudes. Padua was excluded due to its proximity to Milan, this last already used in this paper. The series for Belgium and Saint Petersburg have no atmospheric pressure records, and Cádiz-San Fernando, despite being well-situated, is very incomplete for the period 1786-1820. In conclusion, the series used in this paper were those for Barcelona, Milan, Edinburgh and Trondheim (Figure 2).

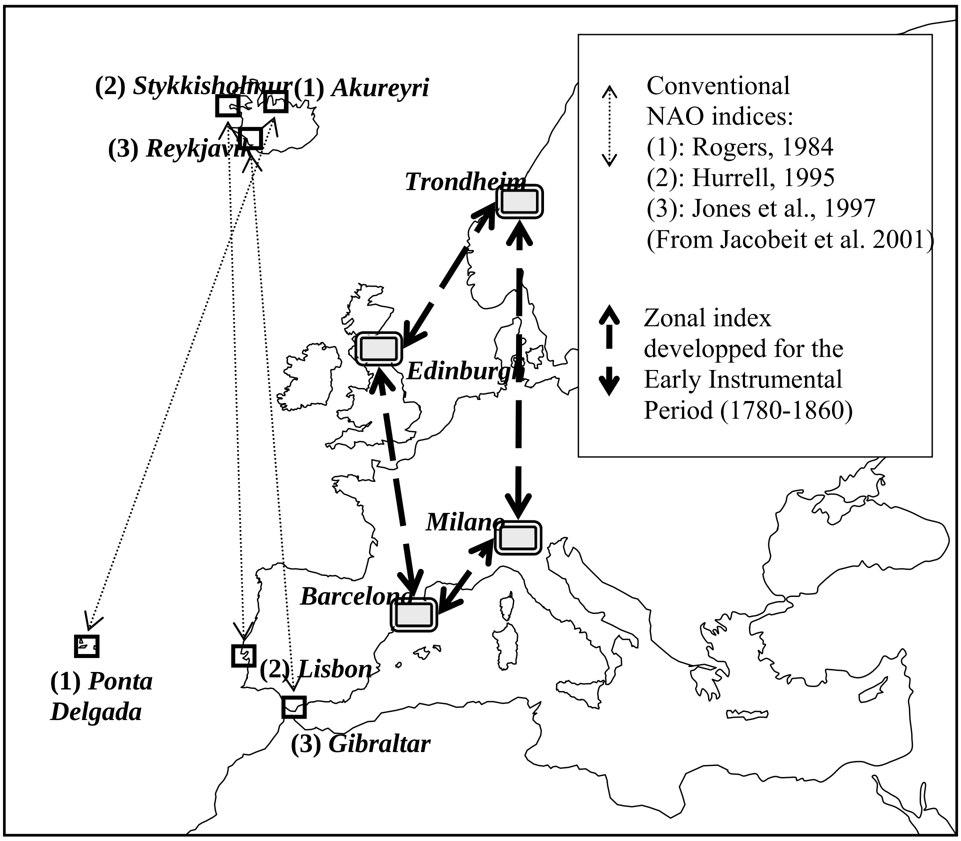

Figure 2. Location of surface-pressure data series used to generate zonality indices

3.3. METHODOLOGY

The instrumental series available do not permit complete analyses to be undertaken in respect of barometric values, so it is only possible to note the characterisable features and their degree of anomaly. On the one hand, only a few series are available for Europe for that period, and on the other hand very few series completely cover the duration of the Maldá Anomaly (1760-1800). In this paper, some zonality indices have been used, thus following the line of research currently arousing greatest interest, related to the general characteristics of the pressure fields in Western Europe and their anomalous behaviour (Jones et al., 1997, Jones et al., 1999, Jacobeit et al., 2001).

The first step in analysis of the barometric data lay in recreating a zonal index using data for Barcelona and Edinburgh. The interest of the exercise lies in analysing the supposedly anomalous period alongside a period of reference from similar points of departure. Secondly, a zonality index was drawn up on the basis of the earliest monthly instrumental observations of surface atmospheric pressure in Western Europe (see Figure 2), under the formula:

$$\frac{(P_{Barcelona} + P_{Milan})}{2} - \frac{(P_{Edinburgh} + P_{Trondheim})}{2} \qquad (3)$$

in which P is the standardised value of the mean seasonal pressures over the period for which the four series show data. This temporal resolution was chosen because a monthly resolution proved to be excessive for analysing a period in which the available proxy-data were only annual.

Regarding temporal cover, these zonality indices are available from spring 1780 up to the last years of 20th century. Although the occasional observatory analysed started the series of observations earlier, it was only from January 1780, when observations were started in Barcelona, that the zonality index was complete. But then, the zonality index permits analysis of barometric behaviour for the second half of the anomaly only, that is, from its peak intensity (c. 1780) through to its end or recovery of the normal values. Results for this period are compared with the evolution of these indices for the period 1950-1990.

Given the importance of the role of the NAOI and of its application in other studies to the Mediterranean basin (Xoplaki et al., 2001; Martín Vide et al., 2000), it was felt appropriate also to make a comparison with the values presented by the NAOI over the period of study. From this objective, we used reconstructions of NAO indices based on proxy-data and instrumental records, generated from the 17th century (Luterbacher et al., 1999), in order to analyse the possible influence of this factor on the anomaly studied.

Moving averages were applied to smooth out the general behaviour of the extreme hydrometeorological episodes in a Mediterranean regime of precipitations. This type of regime is highly irregular in its temporal dynamics, and it is for this reason that it is useful to use moving averages to suppress the responses of limited time scale and to stress in so far as possible the more persistent behaviour. Furthermore, there is some recent bibliography which shows the application of moving averages in similar studies on extreme episodes over long time periods (e.g.: Redmond et al., 2001).

A detailed study that has been carried out on the instrumental series for precipitation of Barcelona, 1850-1991, corroborates, for the common period, the results obtained in this paper (Rodriguez et al., 1999). Indeed, the analysis of anomalies and of the temporal evolution clearly reveals between 1850 and 1869 the presence of maximum pluviometric values which would be encompassed within the oscillation found between 1830 and 1870 following application of the drought and flood indices shown in this paper. Similarly, the spectral analysis does not show any notable period at all in the zone of low frequencies, which corroborates the lack of periodicity found following application of the indices generated from documentary sources.

5. Climatic Framework of the Maldá Anomaly

5.1. GENERAL PATTERNS

Figure 3 shows the evolution of the drought and flood indices generated in Catalonia from documentary sources for the past 500 years, drawn up as obtained in the preceding sections. Three very marked oscillations were recorded, located between the 16th and 17th centuries, at the end of the 18th century and in the middle of the 19th century. There were other oscillations of shorter temporal length and lower intensities than the three just mentioned in the central decades of the 15th century, between the third and fourth decades of the 16th century and during the last decades of the 17th century. This last could coincide chronologically with the climatic episode known as "Late Maunder Minimum", extensively studied for the medium and high latitudes (Frenzel, 1994), although its repercussions in our geographic area are still under investigation and are just now offering their first results.

The most notable aspect is nevertheless the presence of two climatic oscillations lasting some 40 years and characterised by a decrease in the frequency of drought episodes and a simultaneous increase in the presence of floods. These two oscillations arose, approximately, between 1580-1620 and 1830-1870 (Barriendos, 1996-1997). In the interval between these two oscillations no singular or anomalous behaviour is observed, except for a third oscillation which lasted approximately 40 years and was characterised by a simultaneous increase in the frequency of both drought and flood episodes. This third oscillation arose between the years 1760 and 1800 and cannot be linkened to other points of reference. It is this oscillation which constitutes the theme of study of this paper. In commemoration of the person who left a detailed written contemporary account about the climatic conditions experienced over that period, it has been decided to call this oscillation the "Maldá Anomaly".

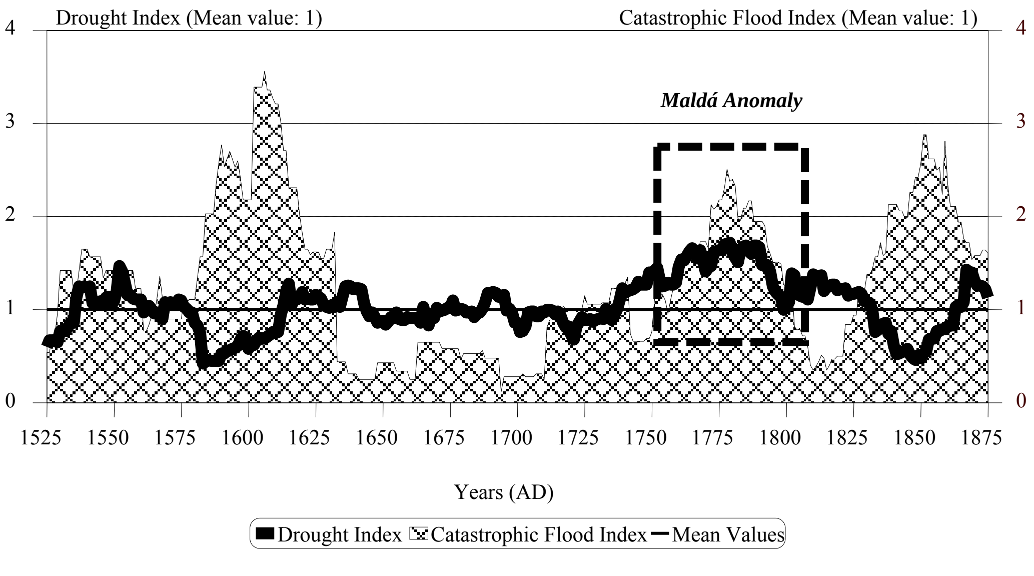

Figure 3. Drought and Flood Indices for Catalonia (NE Spain). 31-year moving averages

4.2. THE MALDÁ ANOMALY IN SPAIN FROM QUALITATIVE RECORDS

Given that some readers may not be familiar with historical climatology, it was deemed appropriate to include some of the main testimonies available for characterisation of the climatically anomalous period studied herein. Similarly, and given that this is an anomaly on which references are scarcely to be found so far in the international biography, the information set out herein should help provide a clearer understanding of the problems it entailed for the population.

The first manifestations were not very clear. The only indications we have refer to the winter of 1764-65 being “severe and strange”:

“Saturday 2 March 1765. Extraordinary session. (Chaired by the Cantor): *...regarding continuation of the changeable weather, the outlook is not very good and the weather is very harsh and cold; and the Session, considering the harshness and strangeness of the season orders that the procession be postponed once again to the 15th of this month, and that the secretary should notify his Eminence the Prelate of this, and the Master of Ceremonies should notify the Provost Secretary and Chief Barrister of the City. Cantor and Minister Mr. Francisco Olazábal.”* (Historical Archive of the Cathedral of Seville, “Chapter Resolution Books”, 1765).

And right in the middle of this climatic anomaly, a doctor from the city of Córdoba (Southern Spain) described anomalous states in thermal and pluviometric conditions between 1783 and 1785. In his case, he used observation of this climatic anomaly to explain outbreaks of epidemic illnesses:

“...from this weather irregularity, extraordinary for Córdoba, came the epidemic of tertian fever which is as strong and recurring now as it was at the beginning” (Capel 1998-99).

But the most illustrative text dates from 1786. It was penned by a Barcelona nobleman, the Barón of Maldá, who left this testimony to the strange behaviour of the climate over those years, following a winter thunderstorm:

“The matter of the thunder was most unexpected as it is an extraordinary phenomenon, for storms normally begin in the middle of April and go on until October. This shows that the climate has undergone a mutation and the weather has changed concerning the seasonal sequence many years ago” (Historical Municipal Archive of Barcelona, Manuscript A-202, Rafael d’Amat i de Cortada, 20th March 1786).

When the anomaly had practically come to an end, there came a paradoxical testimony from the municipal authorities of Girona (100 km NE of Barcelona). In 1803 they made an unusual record of the climatic conditions of the summer of that year, expressing their surprise that they had experienced no similar summer in the last thirty years, for it had been hot and dry (Historical Municipal Archive of Girona, “Resolution Book”, vol. 409, p. 101, 15th August 1803). Of course, one of the features of the Mediterranean climate in Catalonia is precisely that it has hot and dry summers.

Finally, among possible subjective appreciations, one example of severe climatic conditions leading to agricultural and social crisis is obtained from a private diary from Seu d’Urgell, a little town in the Pyrenees mountains (700 m a.s.l.) for the year 1772:

20th April: *Severe frosts damaging harvests. Rogation ceremonies at cold weather level 1 to St. Ot and St. Armengol.*

1st May: *Cold weather damages vineyeards. Rogation ceremonies at cold level 2.*

28th May: *Rogations stopped. Cold weather finished. Celebration of Te Deum Laudamus.*

1st June: *Excessive sunny weather. Grain harvests in danger of getting sunburnt. Unusual rogation “due to excessive sun” (not drought) with Holy Cross in procession to Segre river.*

22th July: *Te Deum Laudamus because of having obtained good rainfall. Grain harvest was poor, partially lost.*

27-29th September: *Strong rainfall produces a catastrophic flood. Rogations pro serenitate against the rainfall were unsuccessful. Fields around the city recorded 80 centimetres of water height.*

(Historical Municipal Archive of Seu d’Urgell, “Llibre de notes comensat en lo any de 1726”, 1 vol.).

4.3. MALDÁ ANOMALY FROM PRECIPITATION INDICES

An initial approximation to this climatic anomaly through the use of instrumental data with a broad spatial-temporal perspective also reveals its special nature. Within the anomaly it is possible to identify meteorological episodes of extreme intensity and severe human impact, such as the intense cold of the winter of 1788-1789. But there is a perception of a climatic anomaly on a broader scale, of which the extreme meteorological episodes taken together are just a manifestation (Kington, 1980, 1988, 1991): "...the 1780s contain a number of outstanding temperature and rainfall extremes, both positive and negative, which must represent some very pronounced regional anomalies in the general circulation" (Kington, 1988, p. 2).

The hydric indices series show a complete oscillation centring on the 1780s. As already noted, the most obvious characteristic of this anomalous climatic oscillation is the simultaneous presence of severe drought (from several months to 2-4 years) and heavy precipitations that caused floods with major damage. While irregular precipitation is commonplace in the Mediterranean climate, at both intraannual and interannual time-scales, what is anomalous in this case is the high frequency with which these situations of drought/flooding took place.

Furthermore, this phenomenon is difficult to identify from the values or estimates of total annual precipitation. The instrumental meteorological records and the hydric indices drawn up from documentary sources both show that the total annual precipitation were not so very different from what could be considered average values. However, a detailed study of these paradoxes allows them to be appreciated at intraannual (seasons of the same year with opposing values) and intraseasonal (months of the same season with opposing values) resolutions. During the 40 years of the Maldá Anomaly there was an increase in the frequency of these annual and seasonal paradoxes (see Tables 2 and 3). Figure 4 shows the temporal concentration of both the anomalous years (seasons of the same year with droughts and floods) and the anomalous seasons (months of the same season with both droughts and floods): the thirty-year periods 1751-1780 and 1781-1810 account for a large proportion of the cases in Catalonia.

Anomalous Years Season with drought and another with flood			Number of Cases. All available period		Number of Cases. During Maldá Period	
Locality	Period	Years	Nr.	Freq.	Nr.	% from total
Barcelona	1521-1896	376	28	11.5	10	**36%**
Girona	1438-1881	444	34	13.1	8	**24%**
Tarragona	1493-1874	382	8	34.3	3	**38%**
Tortosa	1565-1858	294	20	14.7	10	**50%**
Seu d'Urgell	1539-1843	305	4	76.3	1	**25%**
Vic	1568-1900	333	11	30.3	0	**0%**
Cervera	1484-1850	367	4	91.8	2	**50%**

Table 2. Number and frequency of anomalous years in available data series (Barriendos & Martín-Vide, 1998b modified)

Anomalous Seasons (DJF, MAM...) Month with drought and another with flood			Number of Cases. All available period		Malda Period Cases. During Maldá Period	
Locality	Period	Years	Nr.	Freq.	Nr.	% from total
Barcelona	1521-1896	376	5	75.2	3	**60%**
Girona	1438-1881	444	6	74.0	4	**67%**
Tarragona	1493-1874	382	1	<382.0	1	**100%**
Tortosa	1565-1858	294	7	42.0	3	**43%**
Seu d'Urgell	1539-1843	305	3	101.7	2	**67%**
Vic	1568-1900	333	4	83.3	2	**50%**
Cervera	1484-1850	367	0	>367.0	0	--

Table 3. Number and frequency of anomalous seasons in available data series (Barriendos & Martín-Vide, 1998b modified)

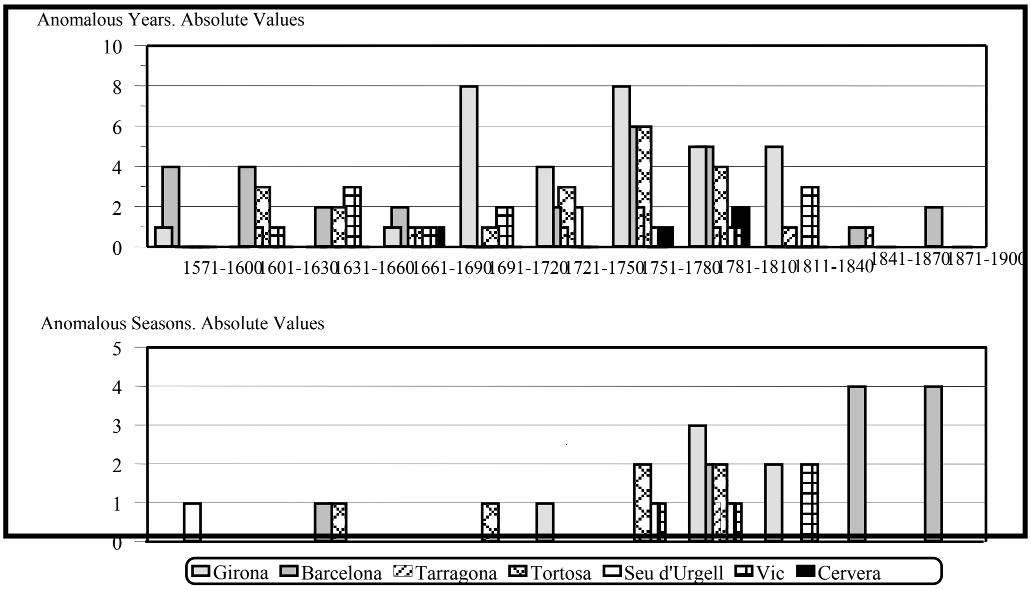

Figure 4. Anomalous years (above) and seasons (below) by thirty-year periods (AD 1571-1600 to 1871-1900)

4.4 THE END OF 18th CENTURY IN EUROPE. MULTI-PROXY INDICATORS

Study of climatic variability has focussed mainly on the study of temperature, given its important role in evaluating *global warming*, and this has provided us with highly creditworthy series and results (Jones et al., 1998). For the study of precipitation, on the other hand, no such complete results are available, due to the complexity of precipitation patterns and their links with various geographic factors.

In Europe, moreover, the geographical diversity gives rise to regional climatic behaviour which obscures and hinders the obtaining of simple overviews (Koslowski & Glaser, 1999). In order to analyse the possible geographical extension of the Maldá Anomaly it was necessary to have recourse to work published by other authors, based on proxy-data, which due to its temperal extension could be considered included in this period. Figure 5 shows the localisation of the proxy-data and instrumental indicators used in this paper in order to find out the zone affected by the Maldá Anomaly.

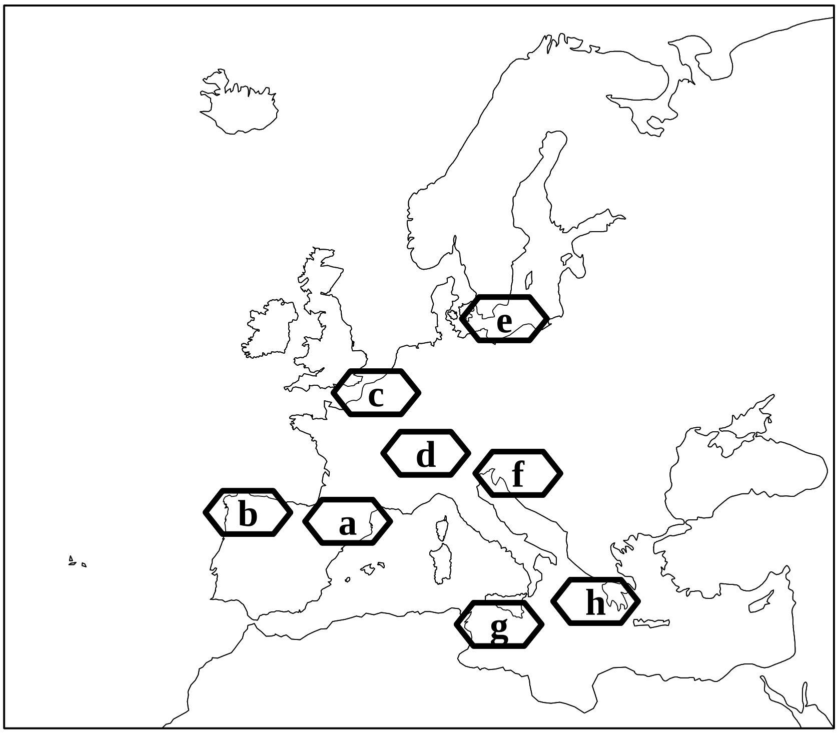

Figure 5. Location of proxy-data indicators for 18th century anomaly period.
a. Documentary Sources. Rainfall indices. Catalonia (NE Spain)
b. Dendroclimatology. Rainfall regime. Galicia (NW Spain)
c. Old instrumental records. Mean annual temperature in Paris and Central England
d. Alpine glacier advances. Alps mountains
e. Baltic Winter Severity. NE Europe
f. Adriatic and Western Mediterranean sea-storms
g. Documentary Sources. Rogation ceremonies by drought in Sicily
h. Balkan famines due to climatic anomalies

The observations likewise show that Atlantic and Central Europe showed different behaviour from that of Southern Europe. For the first there is dendroclimatological information (NW of the Iberian Peninsula), thermal information (central England) and information on glaciar advance (Alpine zone). For the second, there were also the general indices for NE Spain, those from the study “Baltic Winter Severity”, from “Adriatic and Western Mediterranean sea-storms”, from “Rogation ceremonies due to drought in Sicily” and “Balkan famines due to climatic anomalies”. The results are shown below.

<u>Dendroclimatology. Rainfall regime</u>

Dendroclimatology constitutes a good method for study of hydric variability. In this case the spring precipitation series for the period 1757-1992 was available, generated on the basis of “dendro” data for the NW of the Iberian Peninsula (Creus et al., 1995). The period 1760-1899 is found to show records of 50% of “rainy springs and

57% of dry springs", while 19 years had months of May that were anomalously rainy or dry (see Table 4, Figure 6).

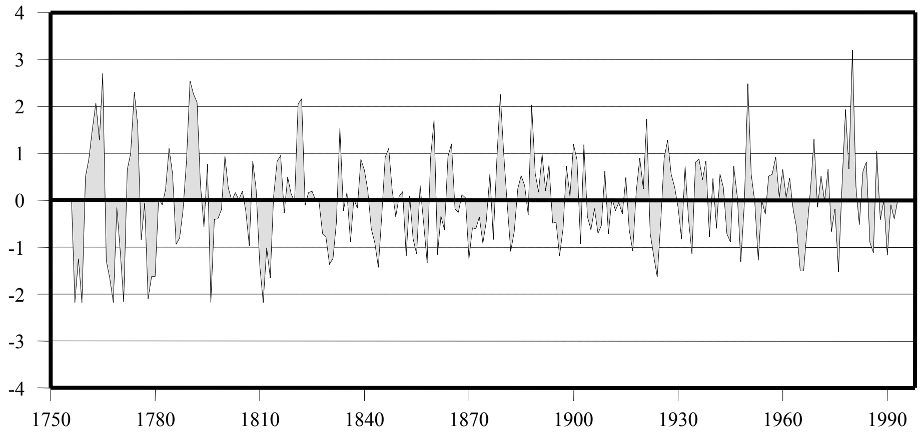

Figure 6. May rainfall in Xinzo de Limia, Galicia (NW Spain) from dendrochronological analysis (data obtained from Creus et al., 1995)

Rainy Years (>+2s)	**1763, 1765, 1774, 1790-92,** 1821-22, 1879, 1888, 1950, 1980
Dry Years (<-2s)	1757, 1759, **1768, 1771, 1778, 1796,** 1811

Table 4. Anomalous rainfall springs from dendroclimatic proxy indicators. Reconstructed May rainfall for Xinzo de Limia (NW Spain) (data obtained from Creus et al., 1995)

Old instrumental records. Mean annual temperature in Paris and Central England

The old instrumental records for the mean annual temperatures of Paris and central England show a moderate cooling during the period 1760-1800. This cooling was nevertheless not as marked as that recorded during the Maunder Minimum (see Figure 7). This coincides with the absence of anomalous years or decades (warm or cold) within the period 1760-1800 with respect to the data for the thousand-year period AD 1000-2000 (Jones et al., 1998).

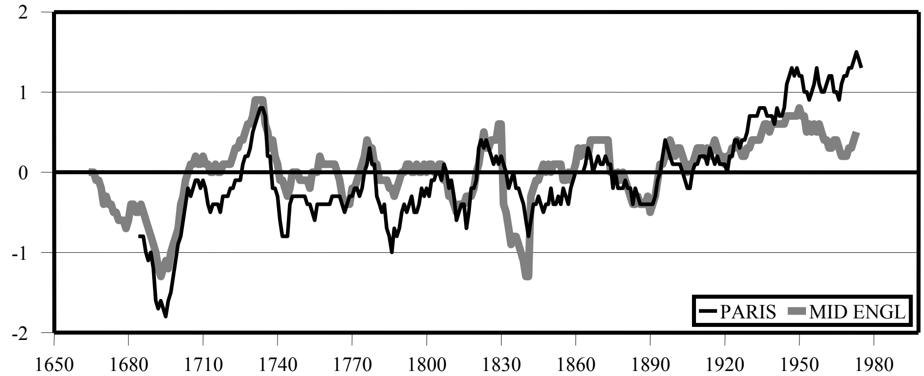

Figure 7. Mean annual temperature from old instrumental records in Paris and Central England

Alpine glacier advances. Alps mountains

Another source of information comes from analysis of the Alpine glacier advances (Bray, 1982). They show important climatic fluctuations over the past centuries. In particular, the period 1760-1800 shows an increase in glacier advances, though not of great magnitude (see Table 5).

a)	1590-1640		**1770-1780**	1820-1850
b)	1580-1620		**1765-1778**	1835-1850
c)	1600		**1770**	1850
d)	1599-1607		**1767-1780 and 1786-1790**	1818-1820 and 1845-1860
e)	1599	1678	**1771**	1845 (1)

a) Unterer Grindelwald (46,30N-8E) (Grove, 1988, p. 179)
b) Grindelwald (46,30N-8E) (Pfister, 1988)
c) Ötztal (46,40N-10,50E) (Grove, 1988, p. 164)
d) General synthesis (Bray, 1982)
e) Vernagt, Ötztal (46,40N-10,50E) (Grove, 1988, p. 155) (1)
(1): Catastrophic floods of Rosen river by breaking of ice dam effect from Vernagt glacier.

Table 5. Chronologies of large glacier advances during the Little Ice Age in the Alps

Baltic Winter Severity

The analysis of the past 500 years shows an increase of the Baltic Winter Severity during the periods 1661-1700 and 1781-1820. The period 1760-1780 recorded the transition from a warm period to a cold period. It involved a change in zonal atmospheric patterns with westerlies to blocking situations, with northeastern winds (Koslowski & Glaser, 1999).

Adriatic and West Mediterranean sea-storms.

An abnormally high frequency of sea-storms with catastrophic effects occurred during the periods 1500-1550 and 1755-1802 (Camuffo et al., 2000). Winds related with these phenomena and impacts are produced by southerly circulation patterns: *sirocco* wind in the Adriatic Sea, *xaloc* wind in Catalonia, both from the Southeast. In addition to sea-storms, this period was characterised also by frequent episodes of intense cold that froze over the Venice Lagoon (Camuffo and Enzi, 1995).

Sicilian rogation ceremonies due to drought.

During the period 1781-1810 low values of drought frequency were observed, similar to Late Maunder Minimum period. But in this case, inhomogeneities by Napoleonic War are described for ecclesiastical activities (Piervitali & Colacino, 2001) (see Figure 8).

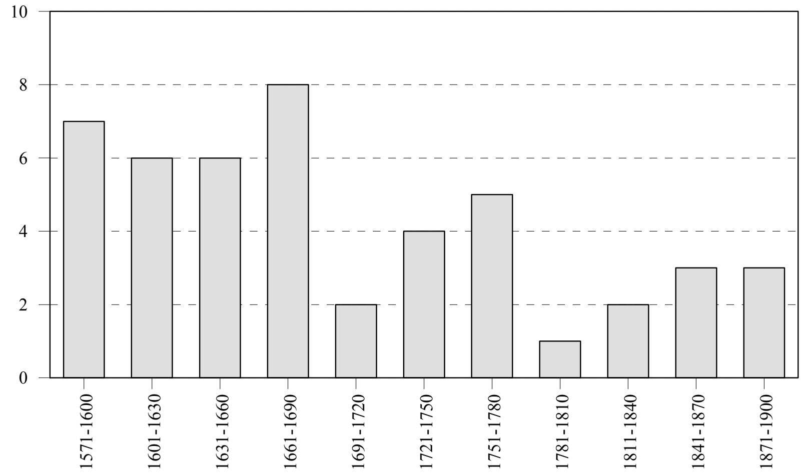

Figure 8. Severe drought events from rogation ceremonies in Erice (Sicily)

<u>Balkan famines due to climatic anomalies</u>

Finally, from a study that selects different periods for climatic analysis in the Balkan region, different general famines due to climatic factors are identified. All of them occurred within the Late Maunder Minimum (1683, 1700) or during the Maldá Anomaly (1775, 1779-1783) (Xoplaki et al., 2001).

It is therefore possible to conclude that the Maldá oscillation mainly affected the whole of southern Europe. This result is hardly surprising if compared with the results obtained on the basis of pluviometric regionalisation carried out for the south of Europe (Llasat and Rodriguez, 1997).

6. Seasonal analysis of zonality and NAO indices

6.1. ZONALITY INDICES

Analysis of the zonal index for Barcelona-Edinburgh shows an atmospheric pressure behaviour or pattern that varied considerably between the different seasons of the year (see Figure 9).

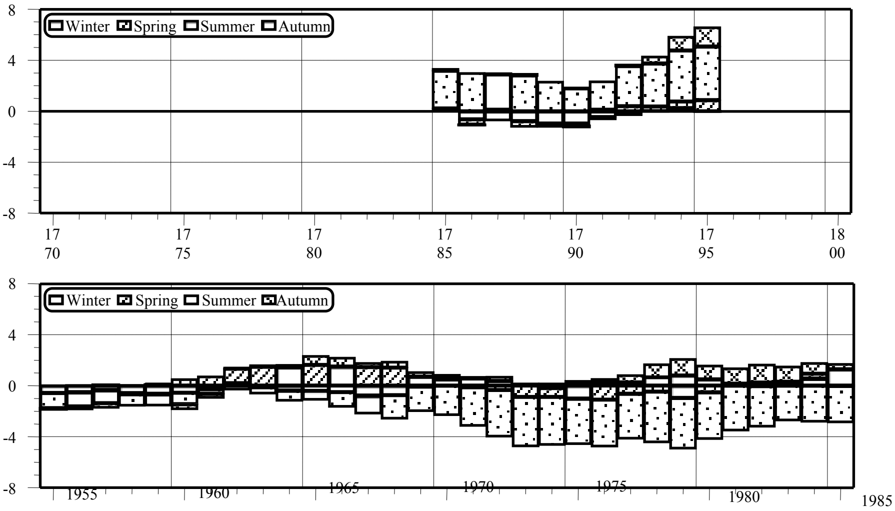

Figure 9. Zonal index for Barcelona-Edinburgh. 11-year moving averages (seasonal values obtained by adding up the monthly indices)

The most characteristic feature is a change of the behaviour patterns of the solsticial seasons (winter and summer). During the Maldá Anomaly the winters showed persistent and intense negative values, especially between 1785 and 1790, when at present they are not very intense and are mostly positive. Summer was the season most altered: the values are anomalously positive and persisted over the entire period under study. At present, this index is also intense and persistent, but with negative values.

Such differing behaviour constitutes an initial indication that during the Maldá Anomaly the climatic conditions over Europe really were unusual and quite different from those obtaining now. The proxy-data indicators showed a climatic situation which can now be confirmed instrumentally.

The results of the seasonal zonality indices (Barcelona/Milan-Edinburgh/Trondheim) do not differ from these initial appreciations (see Figure 10).

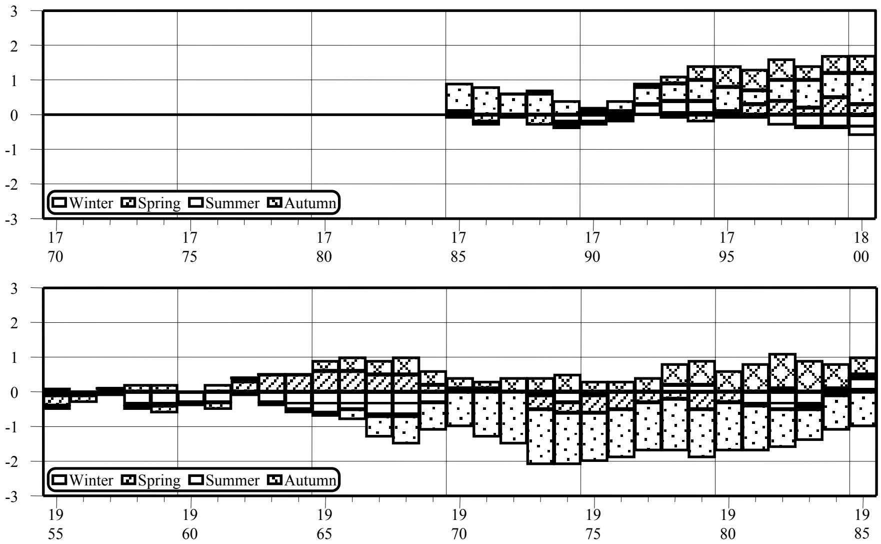

Figure 10. Barcelona/Milan-Edinburgh/Trondheim zonality index. 11-year moving averages

Two different phases are observable during the Maldá Anomaly. There is an initial ten-year period (1785-1795) that coincides with a time of maximum frequency of droughts and floods according to proxy-data indicators, in which only the summer showed particularly pronounced positive-anomaly behaviour. The autumn showed hardly any anomaly at all, when nowadays it has significant positive values. During this sub-episode, neither the spring nor the winter showed any anomaly of note.

From 1795 through to the end of the anomaly, the summer maintained its positive anomalous behaviour, while the other three seasons of the year showed behaviour very similar to that of the 20th century reference period.

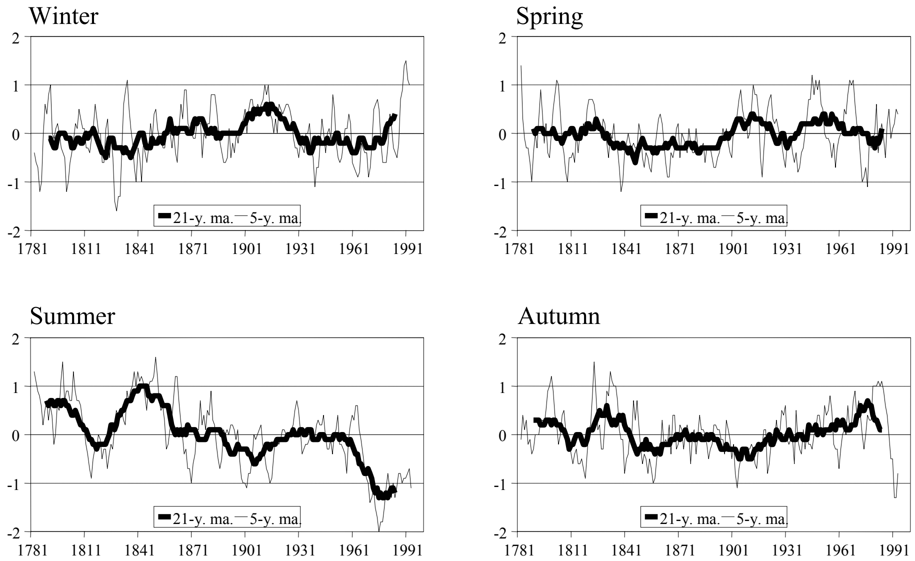

Figure 11. Zonality index Barcelona-Milano vs. Edinburgh-Trondheim. Complete available period

Along general lines, the interannual distribution of the complete series shows (see Figure 11) values with scant oscillation during the 20th century. The period of the Maldá Anomaly and the central ten-year periods of the 19th century, on the other hand, show more marked irregularity. The origin may lie in the specific characteristics of the Little Ice Age, whose effects on climatic variability persisted through to the end of the 19th century. Observation of the last years of the series, the ten-year period of the 1990s, shows, curiously enough, a pattern once again characterised by a strong interannual irregularity in winter and autumn. Another notable aspect is the clear plurisecular summer trend towards an increase in negative anomalies.

6.2. RECONSTRUCTED NAO INDICES

Research work on reconstruction of NAO indices from different types of proxy-data is beginning to yield results with climatic application (Luterbacher et al., 1999). In relation to characterisation of the Maldá Anomaly, these NAO indices present some clearly similar behaviour patterns, since they share to a large extent the instrumental databases underlying them.

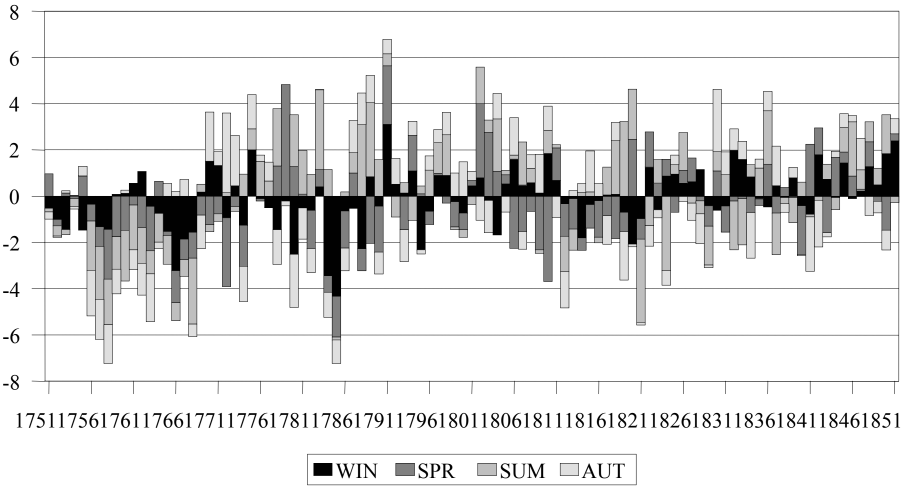

Figure 12. Reconstructed NAO indices. Accumulated seasonal values (from Luterbacher et al., 1999)

From these results, we might well note the significant interannual anomaly detected in the central phase of the Maldá Anomaly. The sum of the monthly values (Figure 12) shows extremely irregular behaviour between 1781 and 1791. More specifically, in less than 5 years there was a shift from an accumulated value of -6σ (1786) to one of +6σ (1791).

Thanks to the length of the series reconstructed, which runs from the Maunder Minimum (AD1675-1715) down to the present day, the behaviour of the Maldá Anomaly can be compared with other phases of the Little Ice Age (14th-19th centuries) and with contemporary climatic variability. For this purpose, we chose to reduce the original monthly NAO index values to an annual mean value. In order to permit identification of the episodes or phases of greatest barometric irregularity, a subtraction was made, taking from each annual value that for the previous year. This reveals the Maldá Anomaly to be a highly irregular period, though one followed by other periods of similar characteristics over the course of the last 350 years (Figure 13). Notable here are two brief phases of minimal oscillation around 1725 and 1925, while the periods of maximum oscillation centre around the middle of the 19th century, the end of the 18th century and, to a lesser extent, the end of the 17th century. The 20th century, on the other hand, scarcely shows any oscillating behaviour of such magnitude. In any case, a certain regularity is discernible in the appearance of regularly distributed negative oscillations, together with an absence of extreme positive values. It can be no coincidence that the periods of maximum interannual oscillation coincide with major increases in the frequency of extreme meteorological episodes as reported in proxy-data records (see Figure 3).

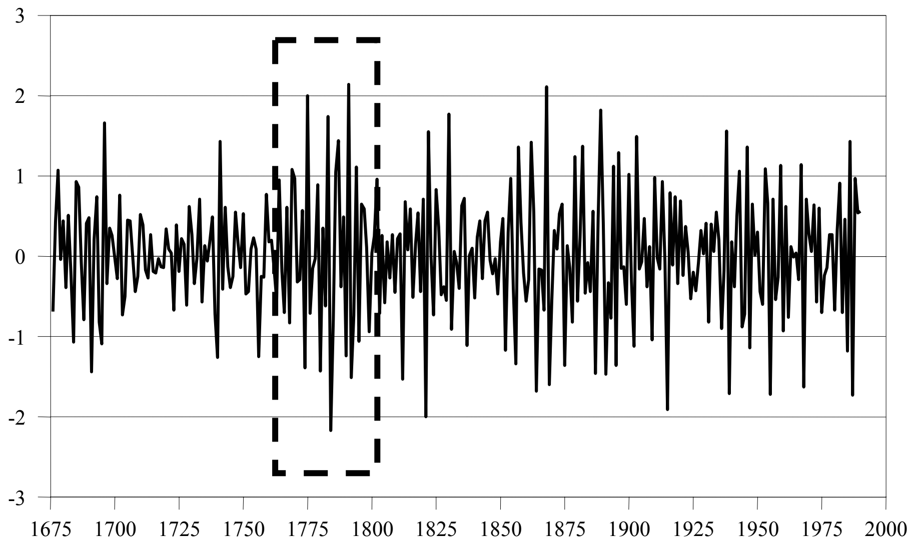

Figure 13. Successive subtractions from the annual average of the NAO index

The Maldá Anomaly shows the largest oscillations, centring precisely around the 1780s, when proxy-data indicators and qualitative accounts alike reveal the point of maximum anomaly of the entire episode.

6. Conclusions

The Maldá anomaly can be defined as a lengthy period of time in which the inherent characteristics of the Mediterranean climate became accentuated and showed a simultaneous frequency in droughts and floods not experienced with such frequency in the last 500 years, at least not in Catalonia. This anomaly affected not only Northeastern Spain, but also other regions of Southern Europe.

Compared with the climatic variability of the 20th century, the Maldá Anomaly constitutes singular climatic behaviour. It is characterised by considerable interannual irregularity, positive and negative episodes succeeding each other within short periods of time and reaching very extreme values. The proxy-data indicators reveal this clearly. The anomaly was even shown in the usual barometric pattern of some seasons of the year, with index values opposed, for example, to values for the second half of the 20th century. That anomaly was particularly marked in the summers, with positive anomalies not experienced during the 20th century. At the meteorological level, the Maldá Anomaly presents the unusual feature of strong and persistent patterns of meridian atmospheric circulation. Anticyclonic blocking both in subtropical latitudes (Mediterranean) and in Scandinavia was intense and persistent.

As only one oscillation of this type has been recorded, this is precisely the question it would be interesting to investigate. It would appear in principle to be merely a situation of predominance of southerly circulations or weakness of zone circulation. Other authors, however, consider that within the 'Little Ice Age' this pattern might have predominated and generated specific types of weather. Perhaps instrumental period research may help, despite the fact that similar behaviour of such lengthy duration is unknown. Another difficulty is that the general conditions of the ‘Little Ice Age’ are no longer present.

Some factors can be ruled out. Volcanic activity is present, although it would be strange that this would of itself have had repercussions over so many years. Variations of the solar constant do not explain such anomalies, as the Maldá oscillation was active at the start of the Dalton minimum (1795-1830). An analysis of the evolution from the 15th century shows that the Maunder minimum (1675-1715) left no record of similar hydrometeorological behaviour. Another possible explanation might be found in some anomaly in the climatic system itself or in the oceanic current system, though we feel that this would be the starting point of future research.

At the methodological level, it was interesting to note that the results of a simple analysis of available instrumental observations confirm the information of a proxy-data nature gathered and gleaned exclusively from historical documentary sources. Finally, the possibility is opened up of making further use of high temporal resolution studies using instrumental and proxy-data sources to permit characterisation of any behaviour which might arise in the near future. Human intervention in the climatic system and its possible effect on natural climatic variability would provide grounds for such a line of work. Indications during the 1990s of growing variability, particularly in the pluviometric regime of the Western Mediterranean, would also counsel undertaking this type of research.

Acknowledgements

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