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Climatic extremes in Portugal in the 1780s based on documentary and instrumental records

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ABSTRACT: The final stage of the Little Ice Age in Europe was characterised by strong climatic variability. New documentary sources containing information referring to weather and climate are used in this study to reconstruct and to describe climate conditions in Portugal during the 18th century, mainly in the 1780s. Indexation of documentary data concerning hydric and thermal conditions was based on C. Pfister's methodology and early instrumental data (1780s and 1790s) were used to verify the reconstruction. Precipitation and temperature were highly variable throughout the 18th century: an alternation of extremely hot to extremely cold months was found. Very cold years occurred mostly in the first 2 decades of the 18th century, but several other cold winters were also detected. Precipitation information is far more frequent than for temperature, and allowed yearly and seasonal indexations. The highest variability was detected in the 1730s and the 1780s. The early 1780s were very dry: during the winter and spring of 1781 and the spring of 1782 several drought episodes occurred, as confirmed by 'pro-pluvia' rogations. In contrast, heavy precipitation prevailed from 1784 onwards. The year 1786 was the rainiest in Portugal, triggering floods in northwestern and central Portugal. The year of 1788 was extremely wet and rainfall caused floods along the largest rivers: Douro, Mondego and Tagus. A storm that struck Northwestern Iberia between 23 and 24 February 1788 is analysed in detail.

KEY WORDS: Climate variability · Little Ice Age · Extreme events · Storm · Portugal

1. INTRODUCTION

According to the IPCC fifth assessment report (2013) and its 'Special report on managing the risks of extreme events and disasters to advance climate adaptation' (IPCC 2013), southern Europe is a climate change hot spot (see also Giorgi 2006), where the intensity and frequency of climatic extremes are projected to increase over the next decades (Kovats et al. 2014). Knowledge from past climates can help understand climate variability and change by weighting natural versus external climatic forcing, thus improving future projections. Furthermore, the availability of longer climatic series contributes to a greater understanding of anthropogenic forcing, particularly at regional scales (Zorita et al. 2010, Masson-Delmotte et al. 2013), where additional processes may modulate climate responses under external forcing (Gómez-Navarro et al. 2014).

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Previous climate studies of Europe (Alcoforado et al. 2000, Barriendos & Llasat 2003, Diodato 2007, Camuffo et al. 2010, 2013, Luterbacher et al. 2012) have identified a lack of instrumental data in Iberia during the Early Instrumental Period (EIP: 1780–1830; Xoplaki et al. 2001) compared to other European regions (Brázdil et al. 2005, 2010a). Over the last decades there has been a growing interest in historical climatology in Iberia. Natural proxies, namely tree-rings (Dorado-Liñán et al. 2015, Santos et al. 2015), documentary sources (Alcoforado et al. 2000, Taborda et al. 2004, Domínguez-Castro et al. 2008, 2012, Rodrigo et al. 2012, Domínguez-Castro et al. 2014) and early instrumental data (Alcoforado et al. 2012, Domínguez-Castro et al. 2013, Fernández-Fernández et al. 2014) are being used to reconstruct past climate.

The final stage of the Little Ice Age (LIA) period in Europe was characterised by strong climatic variability (Kington 1988, Pfister et al. 1998, Brázdil et al. 2010b), particularly in the western Mediterranean basin between 1760 and 1800 (the 'Maldá anomaly'; Barriendos & Llasat 2003). In Iberia, this hydrometeorological anomaly was characterised by a sequence of either severe droughts or intense precipitation and floods. Additionally, temperature extremes were also identified, such as the severe cold winter of 1788–89 (Taborda et al. 2004). This strong variability was also evident in Portugal, with severe dry years occurring in 1779 and 1781 and a rainy period during 1783–1789 (Taborda et al. 2004). Moreover, the Lakagígar volcanic eruption, which started in June 1783 and lasted until February 1784, also influenced weather and climate worldwide (Highwood & Stevenson 2003, Thordarson & Self 2003, Trigo et al. 2010, Alcoforado et al. 2012).

The vast majority of European countries were already carrying out meteorological observations in the second half of the 18th century (Kington 1988, Brázdil et al. 2005, 2010a). Portugal took part in this progress, with instrumental measurements beginning in the last quarter of the 18th century (Alcoforado et al. 2012). These early meteorological observations allow for a characterisation of climatic variability in Portugal, particularly in the 1780s, which is the decade with the most valuable and reliable instrumental data of the 18th century. In addition to the availability of instrumental records, the finding of relevant documentary sources and the identification of the 1780s as a decade with numerous climatic extremes in Portugal were further important motivations to undertake the present research. There remain important gaps in the understanding of climatic variability in Southwestern Europe during the final stage of LIA. The present study aims to address this knowledge gap, by analysing early meteorological observations and documentary sources. The 3 specific objectives of the present study are:

(1) To use new documentary data from different historical sources with climate-related evidence for the 1700s in Portugal, covering several locations

(2) To carry out a climatic reconstruction and an identification of extremes for the 1780s in Portugal, based on documentary sources and early meteorological records

(3) To analyse and discuss the meteorological conditions and impacts of a particularly violent storm in northwestern Iberia (23–24 February 1788).

2. MATERIALS AND METHODS

2.1. Documentary data

The present study is partly based on new descriptive documentary sources, collected under the framework of the KlimHist project (Alcoforado et al. 2015) . This database assembles hand-written and printed information on weather and climate from 1645 to 1815 in Portugal. It allows for systematic queries of its records, classified according to their level of reliability, type of reported event, date and location. Furthermore, metadata referring to sources (e.g. type of source, archives, collections, library codes) and relevant transcriptions are included. A synthetic presentation of the historical sources (HS) used for the climate reconstruction in Portugal is depicted in in the Appendix, where they are classified using an adapted version of the Brázdil et al. (2010a) classification. The number of available sources increases markedly from the 17th to the 18th century. The documentary sources of the 18th century are briefly described below and a summary of the sources concerning the 1780s is shown in Table 1. The documentary proxy data used consist mainly of individual and institutional sources (Brázdil el al. 2010a).

Individual sources include memoirs, newspapers and voyage books. Memoirs contain descriptions of events directly or indirectly related to weather and climate, (sometimes with comparisons with what would be expected as 'normal' atmospheric conditions); information is found in texts reporting wars, diseases, mortality or revealing agricultural losses, harvests dates or other phenological aspects of crops. After the development and diffusion of handwritten

Table 1. Main documentary and early instrumental sources used for climate reconstruction in mainland Portugal. References in brackets are to historical sources (HS) listed in the Appendix. Orange: documentary sources available; red: annual data; yellow: monthly data; green: daily data; grey: data presumed to exist, but not found

Document type	Title/description (source)	1780	1781	1782	1783	1784	1785	1786	1787	1788	1789	1790
Individual Sources												
Memoirs	Memórias (HS3)										orange	
	Várias notícias de casos (HS18)			orange								
	Lembranças (HS17)				orange	orange	orange	orange	orange	orange	orange	
	Descrição topográfica … (HS35)									orange		
Poem	Mondegueida Poema… (HS37)									orange		
Voyage books	Três Diários de Viagem em Portugal (HS38)									orange	orange	
	Viagem a Portugal (HS44)	orange										
	Viagens a Portugal (HS38)									orange	orange	
Private Correspondence	Letter by João Pereira (HS10)					orange						
Newspapers	Gazeta de Lisboa/ Supl. (HS25–33)	orange	orange	orange	orange	orange	orange	orange	orange	orange	orange	orange
	O Tripeiro (HS20, HS36)									orange	orange	
	O Conimbricense (HS24)									orange		
	Curiosidades de Guimarães (HS21)	orange							orange			
	Almanach de Lisboa (HS40–42)			orange								
Institutional Sources												
Civil	Livro dos Termos (HS4)					orange						
	Actas da Vereação (HS5)		orange			orange		orange				
	Memoria sobre os dannos do Mondego… (HS22)										orange	
	Livro das Cartas de D. José I (HS2)		orange		orange			orange	orange		orange	
Ecclesiastical	Assentos do Cabido (HS7–9)	orange	orange	orange	orange	orange	orange	orange	orange		orange	
	Livro das Procissões (HS1)	orange	orange	orange	orange	orange	orange	orange	orange			
	Cartas do Cabido da Sé (HS6)	orange										
Early meteorological data	J.Veiga (HS14)	red	red	red	red	red	red					
	J. Pretorius (HS12, HS40–43)	grey	yellow	yellow	yellow	yellow	yellow	grey	grey	grey	grey	grey
	J. Velho (HS15–16, HS45–48)			green	green	green	green	green	green			
	H. Schulze (HS13)										yellow	

and printed press in the 17th century in Portugal, several newspapers divulge information on weather and climate, particularly citing extreme events and associated impacts on health and agriculture. The dissemination of quantitative meteorological data in printed newspapers only started in the 19th century, with the publication of the Franzini meteorological observations (Alcoforado et al. 2015). Voyage books of foreigners visiting Portugal provide useful information through their descriptions of meteorological conditions and their comparison with weather and climate in their countries of origin. International interest in Portugal increased after the 1755 Lisbon earthquake, and subsequent writings of philosophers such as Voltaire.

Institutional sources include records maintained by hospitals, bishoprics, municipalities and military authorities. These documents were created to compile a record of activities and notable facts and/or to permit later inquiries or audits. This led to a certain level of organisation of the records and, consequently, these sources offer more reliable and homogenous information compared to individual sources. Ecclesiastical and civil documentary sources provide the most useful proxy data. Numerous minutes of the cathedrals and official letters of prelates contain information on anomalous weather and climate conditions and news on processions and 'pro-pluvia' and 'pro-serenitate' ceremonies (to ask God for rain, or to stop the rain, respectively) (Alcoforado et al. 2000, Barriendos & Llasat 2003, Barriendos & Rodrigo 2006). Regarding civil sources, the minutes of town-halls also give indirect information on weather extremes, since municipalities occasionally had to limit water consumption (e.g. in case of drought events), or had to support public works to reconstruct damaged infrastructure (e.g. due to floods and storms), or needed to react to price rises due to poor harvests caused by adverse meteorological/climatic episodes.

In order to evaluate the quality of the compiled information and the reliability of the descriptions, a cross-comparison of sources was carried out; biographical examinations (e.g. instruction level and scientific skills) of every individual record were useful to estimate the relevance of the descriptions. Furthermore, each report introduced in the database was classified according to its reliability, from Level 1 (low quality) to Level 3 (high quality), in order to select the most accurate and useful proxy data, based on a quality control of all gathered documentary information.'

2.2. Instrumental data

As instrumental data are already described in detail by Taborda et al. (2004) and Alcoforado et al. (2012), only a brief summary is given here (cf. Table 2). The earliest records began in 1770 in Lamego in northern Portugal (Fig. 1) and were carried out by J. B. Veiga. During the 1780s, J. A. Velho, J. C. Pretorius and H. Schulze conducted meteorological observations in the Lisbon region. Velho made 3 daily weather observations in Mafra, 30 km northwest of Lisbon, from 1783 until 1787. Detailed metadata are provided (Table 2). Data from Pretorius' station in Southwestern Lisbon are available from 1781 to 1785 and for 1793 (although others must have existed), whereas data measured by Schulze are only available for 1789. Velho and Pretorius described in detail their instruments and, along with Veiga, were also members of the Lisbon Royal Academy of Sciences. Parts of their data were published by this institution.

2.3. Methods

2.3.1. Documentary data retrieval and classification

The KlimHist database currently contains 3045 entries extracted from 263 different sources. The most reliable qualitative data were transformed into semi-quantitative information, commonly known as climatic indices, expressed at monthly or seasonal scales. Following Taborda et al. (2004, p. 16), it should be stated that the documentary records 'were based on extreme situations with socio-economic impact, the indices are interpreted as a measurement for the behaviour of

Table 2. General description of the instrumental data collected for the 18th century in Portugal (adapted from Taborda et al. 2004). Ticks: available data; crosses: unavailable data; question marks: unknown or not confirmed information. no/adj.: no wind/undetectable

	LAMEGO	MAFRA (Real Colégio de Mafra)	LISBON (Real palácio de Nossa Senhora das Necessidades)	LISBON (Alcântara)
Weather observer	João Borges da Veiga	Joaquim da Assunção Velho	Jacob Chrysostomo Pretorius	Henrique Schulze
Location of observations				
Latitude N	?	38° 57′ 20″	38° 42′ 23″ (?)	?
Longitude W	?	8° 47′ 30	9° 10′17″ (?)	?
Altitude	?	500–600 ft (162–194 m)	45–50 m (?)	6 fathoms (13.2 m) above sea level
Observation period(s)	1770–1784	1783–1787	1777, 1781–1785,1793 1794	1789
Temporal resolution	Annual	3 daily observations	Monthly	Monthly
Observed parameters / Units of Measurement				
Atmospheric pressure	✓ French system	✓ French system	✓ French system	✓ French system
Temperature	✓ °F	✓ °F	✓ °F	✓ °F
Precipitation	✓ French system	✓ French system	✓ French system	✓ French system
Wind direction	✓	✓	✓	✓
Wind velocity	x	✓ 5 grades from 1 (no/adj.) to 5 (very strong stormy wind)	✓ Handspan s^{-1}, foot s^{-1}, inch s^{-1}, fathom s^{-1}	✓ Fathom s^{-1}
Humidity	x	x	✓ 24 level scale	✓ 24 level scale (?)
Cloudiness	✓ 3 grades	✓ Various adjectives	✓ 3 grades	✓ 3 grades
Severe weather events		Snow, thunderstorm, storm, etc.	Thunderstorm, storm, etc.	

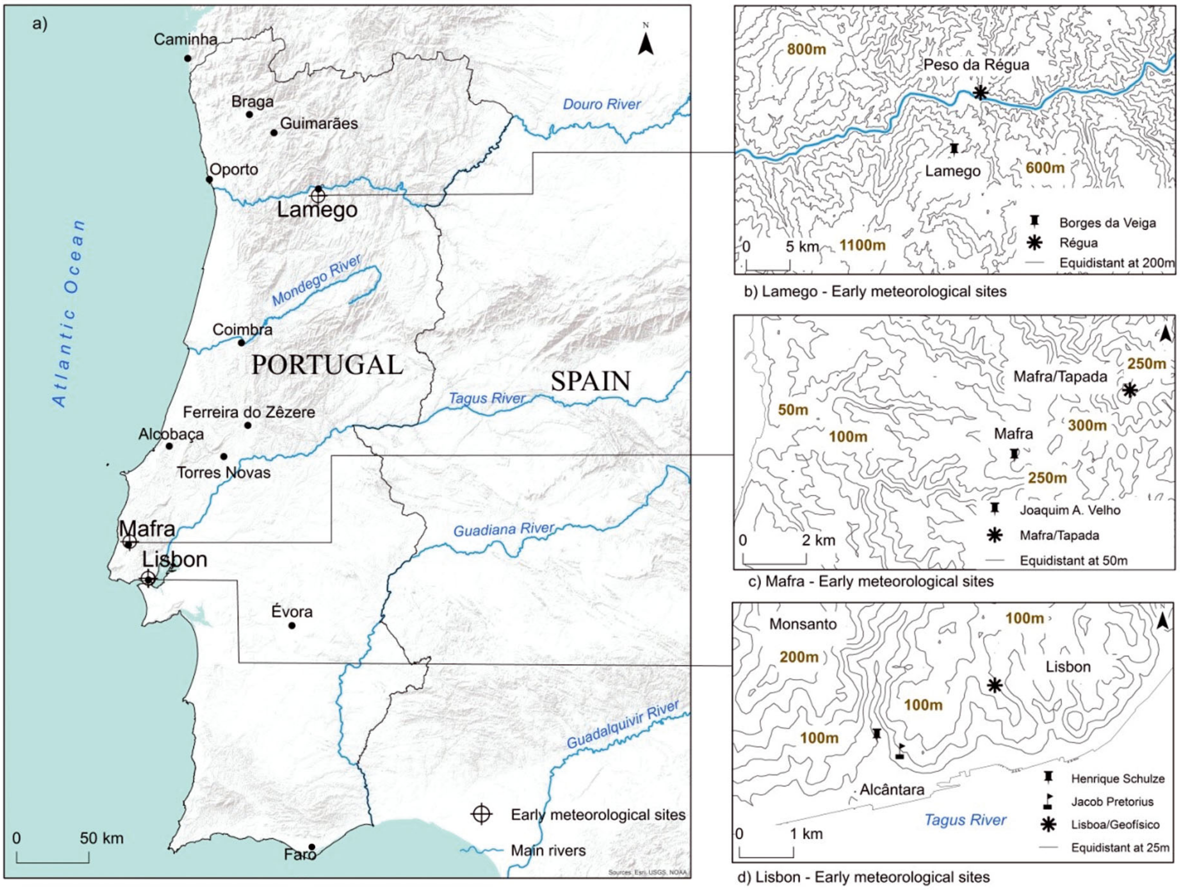

Fig. 1. Location of the meteorological stations in the 1780s (a) in Portugal and at (b) Lamego, (c) Mafra and (d) Lisbon in relation to the hypsometry of the area. (♜, ⚑) Meteorological station in the 1780s, with name of the observer; (✱) location of the nearest modern meteorological station for each site, indicating the period of observations

extreme phenomena (intense and prolonged rainfall or droughts), rather than for the average precipitation'. Therefore, the methodology proposed by Pfister (1992) and also applied by other authors (Alcoforado et al. 2000, Rodrigo & Barriendos 2008) was used to reconstruct hydric conditions in the 1700s. A monthly Precipitation Index (PI) for Portugal was obtained through the quantification of descriptive documentation. The value −1 corresponds to a 'dry' month and +1 to a 'wet' month; 0 values represent either 'normal' (average) months or those with unclear information. As recommended by previous studies (Alcoforado et al. 2000, Rodrigo & Barriendos 2008), summers (June–August) were excluded from the analysis, as summertime precipitation in Portugal is typically very low. Winter is defined as December–February, spring as March–May and autumn as September–November. Seasonal and annual indices were then obtained through algebraic sums of monthly indices. Thus, seasonal indices vary between −3 and +3 and annual indices between −9 and +9. Overlapping short periods between documentary and instrumental data allowed for the verification of the climate reconstruction. The scarcity of documentary evidence for temperature throughout the 1700s, however, does not allow for its indexation. Nevertheless, a reconstruction methodology using the same principles as used for hydric indexation was applied to temperature variability in the 1780s, taking advantage of the higher amount of retrieved documentary evidence for this period.

2.3.2. Early instrumental data

Besides documentary descriptions, the other main source of information used in this research is early instrumental data. Monthly temperature and precipitation series from the 3 available observation sites were used to characterise the 1780s. Given the different locations and measurement conditions of these early observations, their climatic meaningfulness must be carefully interpreted. Hence, the analysis should preferably be based on anomalies (differences to local average values). These anomalies may be expressed in standard deviation units from long-term means (e.g. the 1901–1960 baseline; Brázdil et al. 2005). However, due to the absence of long climatic series, it was only possible to compute these anomalies by comparison with the nearest modern stations (Alcântara/Lisboa, Mafra and Lamego; Fig. 1b–d, respectively). The closest stations with available climatic normals were then chosen as a baseline (Lisboa/Geofísico, Mafra-Tapada and Peso da Régua, Figs. 1b–d, respectively). The 30 yr period 1931–1960 was chosen as a baseline, being the only period with climatic normals available for the 3 selected reference stations. The sensitivity of the precipitation index to the chosen baseline period cannot thereby be tested due to the lack of data. Furthermore, these normals are only for precipitation, since Mafra-Tapada and Peso da Régua are rain gauge stations. These restrictions lead to another method for the estimation of anomalies. They were obtained by dividing monthly, seasonal and annual rainfall totals, recorded in each station during the 1780s, by the corresponding mean amounts (1931–60 normal) of the reference station. Positive anomalies are therefore expressed by non-dimensional values: >1 for wet, 1 for near-average and <1 for dry conditions.

As stated above, the available temperature observations for the 1780s did not permit an estimation of anomalies. The Mafra temperature series (the single location with daily records and restricted to 1783–1787 period; Table 2) was used to evaluate the frequency of cold and hot days, at seasonal scale, by selecting, respectively, days with minimum (maximum) temperature below (above) 6°C (25°C). These limits chosen correspond to temperature thresholds identified by prior regional climatic studies of the Mafra region (Daveau 1985).

3. RESULTS

According to documentary sources, the first 2 decades of the 18th century were particularly cold. 'Between 1720 and 1790, not only did the references to 'cold' diminish, they were also confined to winter and spring' (Taborda et al. 2004, p. 16). Several hot months were detected, related to a positive North Atlantic Oscillation index (NAO index). In additon, very cold winters also took place in 1708–09, 1739–40 and 1788–89; they also occurred in several parts of Europe and were related to negative NAO index. Available information does not yet permit the construction of a detailed graph for temperature during the 18th century (like that shown in Fig. 3d for precipitation).

The 18th century was characterised by a high precipitation variability in Portugal (Fig. 2d), particularly in the first 2 decades, in the 1730s and in the 1780s. Extensive rains persisted from 1706 until 1709, followed by very dry years, particularly from 1712 to 1716. During 1730s, very dry periods (1734, 1737 and 1738, during which pro-pluvia ceremonies took place) alternated with prolonged rainy periods (1732 and 1736, when pro-serenitate ceremonies are registered) (Taborda et al. 2004). However, the highest variability occurred in the 1780s, with very dry years until 1782, followed by heavy and persistent rainy seasons until the end of the 1780s (Fig. 2c). This decade was chosen for a detailed study in this paper due to its high climatic variability, but also because early instrumental sources were available (Alcoforado et al. 2012), permitting validation of information extracted from documentary sources and comparison of precipitation and temperature values with present ones. In Fig. 2a the occurrence of successive hydroclimatic extremes in the 1780s can be observed. During the 18th century, based on documentary evidence, only the decade 1700–1709 exhibits a comparable frequency of positive rainfall anomalies (though with less pronounced extremes). Among the impressive number of extreme climatic events that occurred in Portugal during the 1780s, we have selected the violent storm of 23–24 February 1788 as a case study.

3.1. Temperature variability

Fig. 3 summarises temperature variability in Portugal in the 1780s. According to early instrumental data from Mafra (Fig. 3a), 1784 recorded the lowest mean annual temperature (13.1°C), while 1785 and 1786 were the warmest years, with annual mean air temperature of 14.7 and 14.8°C, respectively. The mean annual air temperature in Mafra for 1783–1787 was 14°C. Negative anomalies in air temperature are common in Iberia during major winter droughts. In fact, based on documentary sources (Fig. 3b) and some meteorological observations carried out by Pretorius in Lisbon (Fig. 3a), the beginning of the decade was marked by cold and dry winters, particularly in 1782 and 1784. On 13 January 1782, Pretorius recorded 0°C in Lisbon. The cold spell lasted several days and was associated with unsettled weather, resulting in a snowfall event on 19 February in Lisbon. The snow

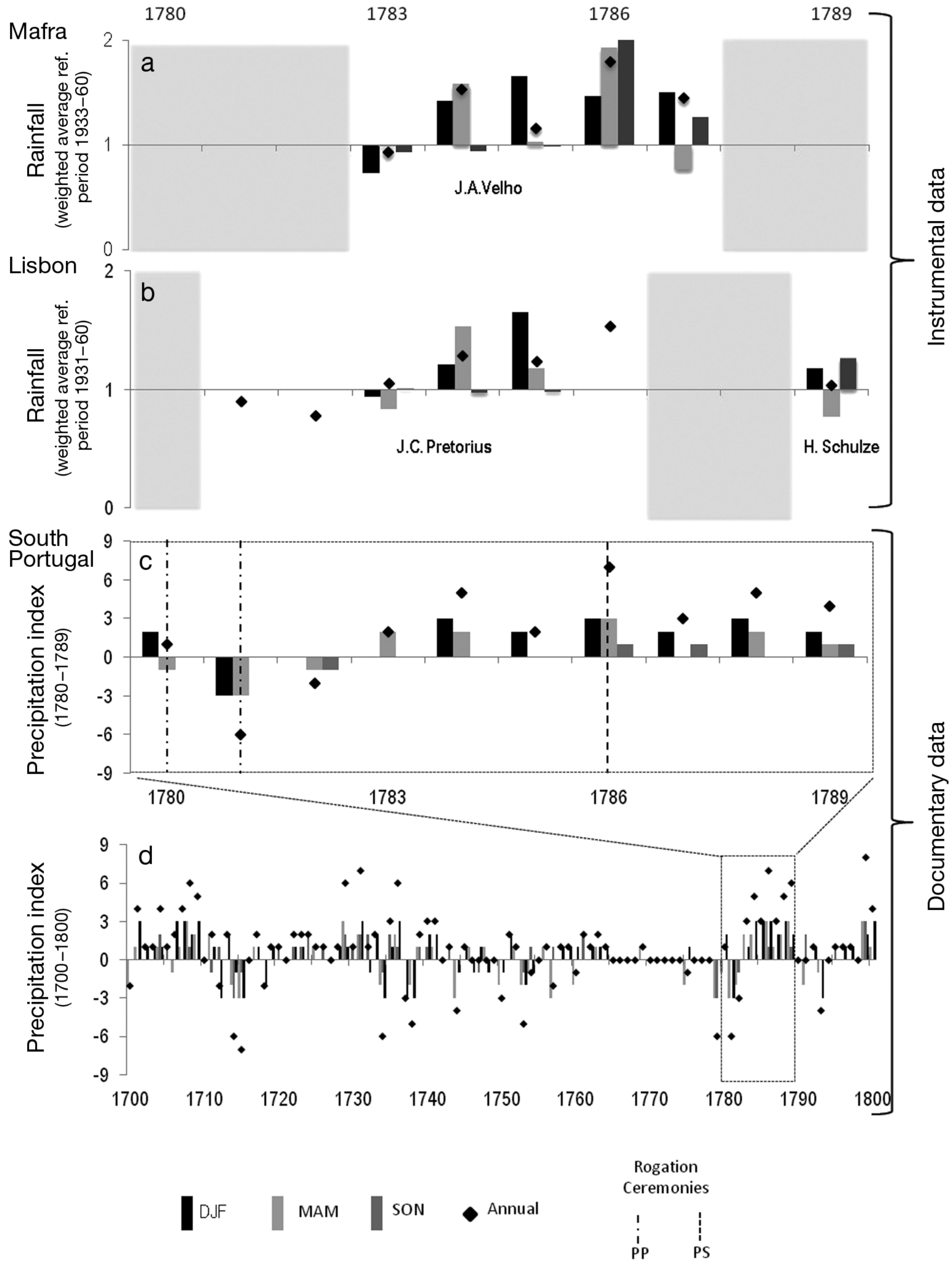

Fig. 2. Seasonal precipitation reconstruction in Portugal in the 1700s — (a,b) instrumental data; (c,d) documentary information. (a,b) Rainfall anomalies (positive if value > 1, negative if value < 1) in (a) Mafra and (b) Lisbon. (c,d) precipitation indices in (c) the 1780s and (d) the 18th century. In all panels, seasonal data are represented by bars and annual data by diamonds. Dot-dash lines and the dashed line in (c) represent pro-pluvia and pro-serenitate rogation ceremonies, respectively. Shadowed areas in (a) and (b) indicate gaps in instrumental data

'*reached a thickness of 11 cm and remained on the ground for 2 days*' (HS27). Negative air temperatures were recorded in December 1784. In addition, Pretorius (HS42) states that '*the coldest weather conditions* (*in Lisbon*) *were felt in the morning of the 4th with −1.1°C and ice was also formed*', whilst daily mean air temperature was 4.4°C in Mafra. This station shows other low daily temperatures (1783–1787), namely 2.2°C on 4 January 1786 and 2.8°C on 4 April 1785.

In Portugal, the coldest winter of the decade occurred in 1789 (strongest negative winter anomaly visible in Fig. 3), with a cold spell in January. The

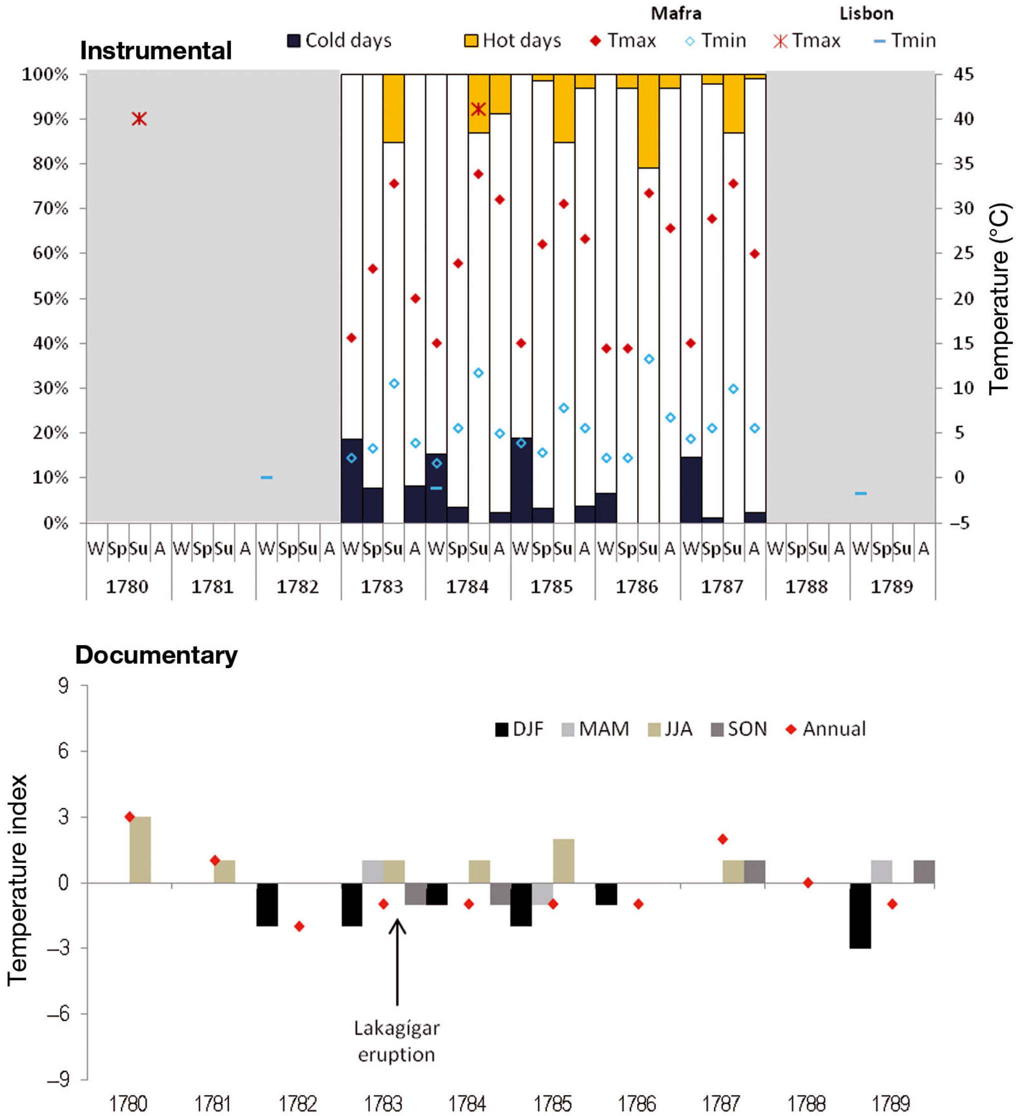

Fig. 3. Seasonal temperature reconstruction in Portugal in the 1780s. (a) Seasonal frequency of cold and hot days and seasonal temperature extremes in Mafra. Shadowed areas indicate gaps in instrumental data. (b) Temperature index based on documentary data. Seasonal values have an all-inclusive range of +3 to −3, and annual values from +9 to −9 (see Section 2.3.1 for further explanation)

mean monthly temperature for January in Lisbon was 9.9°C (HS13), 2.3°C lower than values collected by Pretorius in 1784 and 1785 (HS11, HS12). The 1981–2010 baseline January mean monthly temperature for the Lisbon/Geofísico meteorological station is 11.6°C. The maximum intensity of the cold wave reached −1.7°C in Lisbon on 8 January (HS13), a value that is lower than the extreme minimum air temperature recorded in the Lisbon/Geofísico from 1854 until 2014 (−1.5°C). There are also references to very cold and frosty weather conditions in Coimbra in 1789, with several reported incidences of damage to crops, and strong frosts and snowfall on 8–9 January in Chaves and on 10 January in Oporto (HS33 N°4) (Fig. 1).

Some heat waves were also identified. The August 1784 heat wave was probably one of the most severe of the 18th century in southern Portugal. According to Pretorius, temperatures reached 41.1°C on 13 August. This is only slightly lower than the 41.5°C maximum temperature recorded during the June 1981 heat wave in Lisbon/Geofísico (despite different kinds of metadata). In Mafra, the highest record for this day was 33.9°C (HS16), a lower value owing to its proximity to the Atlantic Ocean. Although lower than the temperature in Lisbon, this record corresponds to the hottest day in the period 1783–1787. Very high air temperatures also characterised the summer of 1780 (the strongest positive anomaly in Fig. 3). The scarcity of daily data does not allow for an accurate assessment of length of the heat wave. Still, it is possible to identify 2 maxima. On 24 June at 12:00 h the air temperature was 37°C and, on the following day, it rose to 40°C. In early July 1784, the air temperature remained high. On 6 July the maximum temperature was 38.1°C, decreasing to 28.9°C 2 d later.

3.2. Precipitation variability

The anomalous number of strong precipitation extremes in the 1780s within the context of rainfall variability in Portugal in the 18th century is clearly suggested by Fig. 2d.

The evolution of the seasonal precipitation index during the 1780s is depicted in Fig. 2b. The index shows prevalent dry conditions until 1782, contrasting with the wetter conditions during the remainder of the decade. In fact, documentary evidence reporting dry conditions during the spring of 1780 was found, with pro-pluvia rogations being held in Oporto and Guimarães and decisions of tax credits (‘quitas’) to farmers in Évora due to the ‘sterility’ of the year. The following winter and spring of 1781, and even the spring of 1782, were also characterized by drought episodes. The rainfall deficits were roughly estimated using the meteorological data of Pretorius (only annual totals). In his published meteorological summaries, Pretorius stated that (HS40) ‘*from the beginning of the year to 23 March, it hardly rained* (...) *motivating our Eminent Prelate to order public rogations in the churches of this capital*’. The year of 1782, particularly in spring, was the last of the decade for which we have found documentary evidence for drought, though it is less abundant.

The year of 1783 exhibits (Fig. 2) a transitional character between the prevalent dryness of the early years of the decade to the very rainy conditions that prevailed thereafter. Data from Mafra and Lisbon reveal no significant anomaly. Nevertheless, there is documentary evidence suggesting that this year, at least during the spring, was wet in Northern Portugal, with the occurrence of a flood event in the Douro River (Oporto) on 9–10 March (HS17).

As shown in Fig. 2, 1784 marked the beginning of a sequence of very rainy years in Portugal, evident both in the interannual variability of the precipitation indices (seasonal to annual scales) and in the available early instrumental information (weighted total amounts). The winter was rainy in Mafra and Lisbon, while spring was even wetter (Fig. 2), triggering floods and inundations in several regions, such as the flood along the Douro River in March that was reported by a contemporary witness (HS17). The documentary evidence also shows that other cities were severely affected by abundant rainfall during the same month, particularly Lisbon and Braga, where pro-serenitate public rogations were held on the 16 and 30 of March 1784, respectively. We have found less documentary information for 1785, though it was a wet year according to Mafra and Lisbon data (particularly the 1784–85 winter).

The year of 1786 may have been the rainiest of this decade in Portugal (Fig. 2). In Mafra, the annual precipitation was 1429.7 mm, whereas the average amount in Mafra-Tapada in the period 1931–60 was of only 797.6 mm. In Lisbon, the total amount was 1082.8 mm, which also represents a strong deviation from the climate-mean amount of the corresponding reference station (707.5 mm). The long-lasting rainfall spells during winter and spring triggered numerous floods across the country, some of them with high-impact consequences in important cities like Braga, Oporto, Coimbra and Lisbon. From 1 January to 31 May, Mafra records show 30 d with precipitation above 10 mm, illustrating the high frequency of heavy rainfall days. Throughout these months, numerous accounts of floods along major Portuguese rivers can be found, except for February 1786. The manuscript of Henckel (HS17) reports 5 floods in the Douro River, with peaks occurring on 14 January, 7 and 18 March, 10 April and 10 May. By 11 May 1786, the excessive rainfall led the authorities of Braga to proclaim 3 days of pro-serenitate rogations. In Central Portugal, the severest flood occurred towards the end of May, when 7 people were drowned by the Mondego River waters (HS30 No. 24). Extensive damage in the farmlands of the lower Mondego valley was mentioned by the same source. Further south, Lisbon was also affected by floods in January and March (with rogation ceremonies held on 24 March) (HS30 Supl. Nº12). The end of the year, particularly November 1786, was again characterised by heavy precipitation.

The following years were also rainy, although a slight decrease in the seasonal and annual amounts is suggested by the available sources (Fig. 2). The documentary evidence referring to 1787 contains 3 descriptions of the impacts of severe thunderstorm episodes, which in some cases triggered flash-floods. Among these events, the thunderstorms of 22 May (that caused severe agricultural damage in Torres Novas, central Portugal) and 21 August (in Barcelos-

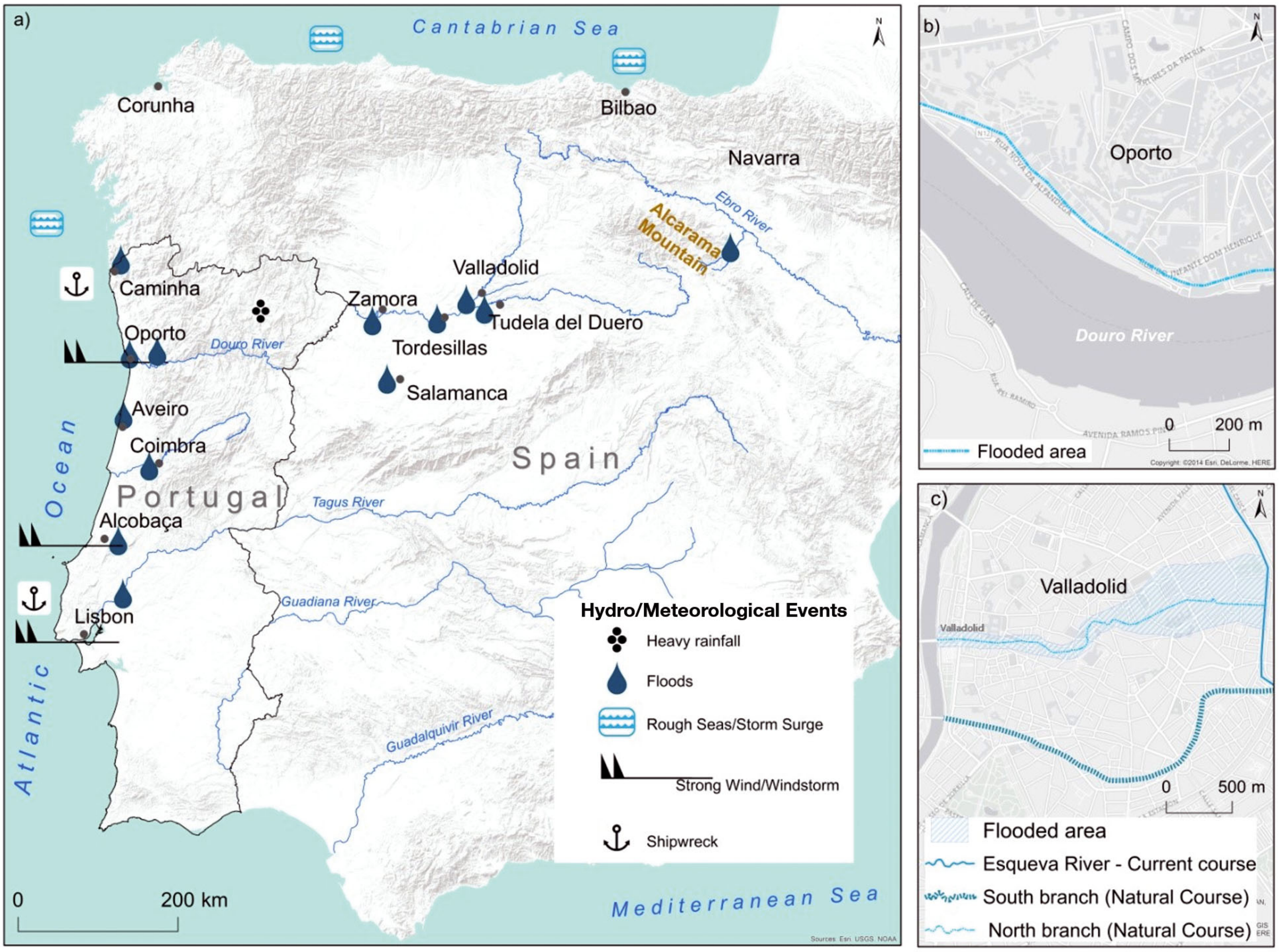

Fig. 4. (a) Principal disaster phenomena across Portugal and Spain triggered by the 23–24 February storm in 1788, and probable limits of flooded areas in (b) Oporto (Portugal; according to HS3) and (c) Valladolid (Spain; according to HS38 and HS39)

Braga, where several people were killed by lightning strikes) stand out as the severest hazards. The year 1788 was again wet and there were floods along the largest rivers: Douro, Mondego and Tagus. The particular relevance of a storm that occurred in February 1788 is detailed in Section 3.3.

The year 1789 was also rainy in Portugal (Fig. 2). According to Schulze's data, the rainiest seasons in Lisbon were winter and autumn (HS13). The available documentary data clearly agree on the effects of abundant rainfall throughout the year, except in summer. Floods and inundations started early in the year and occurred in Lisbon on 9 January (HS33 Supl. Nº2) and in Oporto a few days later, on 13–14 January (HS17). Several cities were affected by floods later on, namely Coimbra (27 January; first week of May) and Ferreira do Zêzere (9 March).

3.3. The February 1788 violent storm

There are significant gaps in information about past extreme meteorological events in Portugal, including those occurring during the 18th century. Even so, the winter-storm 'Barbara' (3–6 December 1739) was a remarkable episode, with disastrous impacts across mainland Portugal (Taborda 2006, Pfister et al. 2010). For a better understanding of storm events and their societal impacts in Portugal during the Enlightenment period, an extreme storm that struck northwestern Iberia between 23 and 24 February 1788 is analysed here in greater detail. This extreme event was selected as a case study because its impacts were very widespread and costly; in fact it may have played a key role in the launching of the national programme of public works during the government of Queen Mary I, as suggested by Martins

(2014). This storm, and the subsequent flooding of downtown Coimbra, inspired a poet (Francisco Malhão) who witnessed the event, to write and publish a long and impressive poem ('Mondegueida', HS37) on the destructive effects of the flood. In spite of the absence of instrumental data to support this case study analysis, there is significant amount of newly found documentary evidence reporting the consequences of this high-impact storm, and this motivated its reconstruction. The following description follows the chronology of these accounts. This enables a hypothetical reconstruction of the storm trajectory and evolution, based on facts and details from sources that are located in time. A summary of the documentary evidence is presented in Table S2 in the Supplement at www.int-res.com/articles/suppl/c066p141_supp.pdf.

From a dynamical viewpoint, this violent storm was presumably linked to an intense extratropical cyclone. Such cyclones typically originate over the North Atlantic and travel towards Europe. According to Pinto et al. (2009), the large-scale conditions triggering their development include anomalously strong baroclinic zones associated with intense jet streams over vast longitudinal sectors. These cyclones generate strong winds and extreme precipitation, being a common feature of mid-latitude winter climates (Fink et al. 2012).

There is evidence suggesting that the arrival of this extratropical cyclone onto the Atlantic margin of Iberia occurred on 19 February 1788, based on accounts mentioning effects consistent with storm surge conditions. On the night of 19 February 3 shipwrecks near Caminha (on the northernmost coast of Portugal) caused an unspecified number of victims. Furthermore, several ships lost their anchorage due to strong winds in the Lisbon harbour (HS32 Supl. Nº13). The following day (20 February 1788) was extremely rainy. From 23 to 24 February the disastrous effects of the intense rainfall and violent winds are described in different locations. The reported impacts reveal a temporal sequence and spatial incidence (Fig. 4) that clearly suggest a westerly travelling system. The storm started by crossing over northwest Portugal, affecting Oporto and lower Douro basin, Alcobaça, Coimbra and the Mondego valley. Shortly afterwards, it moved on to Spain, passing over Salamanca, Zamora, Valladolid (the Douro valley in Castilla-León region), the Cantabrian coast and Navarra. Based on the deduced storm track, the following analysis of the impacts refer to 4 of the most affected areas.

(1) Floods and wind damage in the lower Douro valley (Oporto, Northern Portugal). Between 20 and 22 February, the Oporto area was hit by strong westerly winds. Their force and frequency produced damaging effects, such as uprooted and fallen trees and the destruction of numerous roofs and skylights (HS35). Meanwhile, the intensity of the rainfall during the same 3 d period was responsible for a steady rise in water levels of the Douro River in the Oporto area (HS17, HS35). A newspaper (HS32 Nº11) reported that between 24 and 25 February, in the Oporto area, *'the Douro River rose 31 hand spans* (*6.89 m*) *above its ordinary level',* causing a '*horrible flood*'. These reports are confirmed by the contemporary descriptions by the wine merchant Henckel, who stated that *'we have recorded that in the greater floods, the river rises up to 22 geometric feet* (*6.7 m*), *measured from the point of the last low tide. The river rose to nearly such heights during this last formidable flood, which occurred on the month of February of this year of 1788'* (HS35). According to the same source, the highest level of the flooding in Oporto occurred during the night of 24 to 25 February when the water '*rose above the street* [*alfândega*] *and covered the square* [*terreiro*]'. Henckel also stated that by the afternoon of 25 February, the flood level started to decrease, a steady trend observed over the following days. The impacts of this storm on the Oporto area were '*very large*' (HS35) and the periodical *Gazeta de Lisboa* reported an estimation of total '*costs of more than 2 million cruzados to repair the damages in the city*' (HS32 N°14). A total of 18 streets and over 1000 dwellings were flooded in downtown Oporto (HS35). Four wine warehouses were demolished and a others suffered major damage. Descriptions also report that several Oporto streets (Cais da Ribeira, Rua da Porta Nova, Passeio de Miragaia) were covered with sand (HS35) and 2 people were drowned in the Douro River.

(2) Floods in the Mondego valley (Coimbra) and Alcobaça, Central Portugal. The impacts of the storm were very severe in Coimbra, the largest city of Central Portugal, located on the right bank of the Mondego River. The rainfall was so intense during 23–24 February that it caused a huge flood (HS24, HS32 Supl. No. 11; HS37), the '*largest flood within living memory*' (HS32 Supl. No. 10). Several streets were flooded in the downtown area, where '*the waters rose up to the Church of Santa Cruz*' (HS32 Supl. No. 10; Fig. 5). As a result of this flood, the Coimbra Bridge (built in 1513) was partially destroyed), and several dwellings and mills were also damaged, causing death (also in cattle) by drowning in the Mondego River (HS32, Suppl. 10). Fig. 5 shows a reconstruction of the destruction caused and proba-

Fig. 5. Flood in Mondego valley, Coimbra, 24 February 1788 (reconstruction based on HS5, HS13 and HS37). The blue area shows the probable limits of the flood. The Mondego River covered the Coimbra Bridge, destroying 3 arches (1), flooding the downtown area of the city, where the waters reached the Santa Cruz Church (2) and damaging several buildings (3). This reconstitution is overlaid on an engraving of Pieter van den Berg, titled *Conimbrica, Lusitaniae urbs ad Mundam, aquaeductu Sebastiani regis celebres*, ca. 1720 (available at http://cartotecadigital.icc.cat/), based on Georg Hoefnagel's drawing (1566/67) published by Braun in *Civitates Orbis Terrarum* (Vol. 5, c.1598)

ble flooding limits The exact number of human deaths is not specified in this written source. In Alcobaça, 85 km south of Coimbra, the storm caused flash floods in 2 small catchments (Alcôa and Baça rivers) (HS11, HS32 Supl. No. 10). Alcobaça is a city well known for its Cistercian monastery, built in the 12th and 13th centuries. A fully detailed description of the flooding by an eye witness, Manuel de Figueiredo (HS11), vicar and chronicler, states that floods of the Baça River, on the night of 23–24 February, caused severe erosion of the riverbanks and the destruction of several dwellings. On the same night, the Alcôa River also rose rapidly and inundated the terrains inside the monastery, causing panic to the inhabitants. Although this episode did not cause human casualties, the damage produced by the flooding of the riverine areas of Alcobaça was remarkable. Several dwellings were flooded and walls, bridges and roads were destroyed (HS11).

(3) Flood and wind damage in the Douro valley in the Castilla-León region of northern Spain. Between 24 and 25 February, as the storm moved eastwards, the impacts of rainfall and wind gusts widened to northern Spain. The storm triggered floods in the Douro River in the plateau region of Castilla-León, affecting the areas of Tordesillas and Valladolid (HS19). The town of Tudela del Duero suffered major impacts from flooding on the night of 24 February, with damage to more than 100 dwellings, of which 30 were totally destroyed. The bridge of Boecillo, a village near Tudela del Duero, was also destroyed and the Monastery of El Abrojo suffered severe damage. The most noteworthy impacts of this storm were caused by the floods affecting the city of Valladolid, located at the confluence of the Pisuerga and Esgueva rivers, tributaries of the Douro River. At the time Valladolid was traversed by 2 branches of the Esgueva, the main branch passing through the cen-

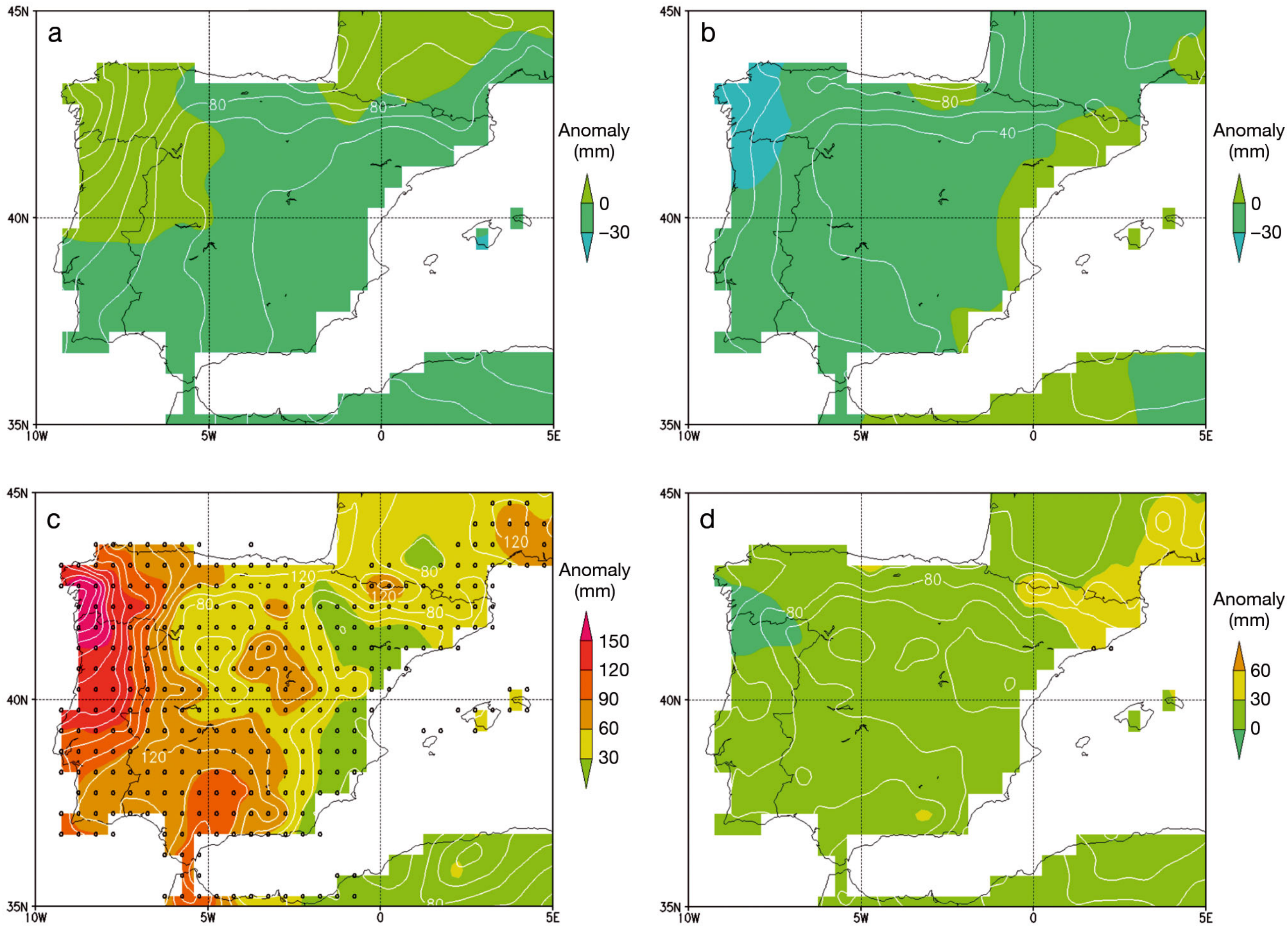

Fig. 6. Monthly precipitation totals (contours in mm, with 20 mm interval) for (a) December 1787, and (b) January, (c) February and (d) March 1788. Corresponding anomalies (colour shading) with respect to their long-term monthly means (baseline of 1773–1803, 31 yr period centred on 1788) are also displayed. Circles indicate gridboxes with statistically significant anomalies at 95% confidence level. Data Source: Casty et al. (2007)

tral area of the city. The floods of 24–25 February flooded the city centre, destroying or damaging more than 150 dwellings. Twelve of the 14 bridges of Valladolid were destroyed (HS34, HS49). The severity of the flood damages was so pronounced that a fully detailed survey (HS34) of the impacts was conducted by the local authorities (Chancillería). An appeal was made to the King to support the reconstruction, the cost of which was estimated at over 470 000 Reales. As a consequence of the storm, 6 days of pro-serenitate rogations were ordered in Valladolid (HS49).

(4) Coastal storms on the Cantabrian coast, northern Spain. The same memoir of Valladolid inundations (HS34) reports contemporary testimonials describing how the sea tides on 23–24 February '*were so high, rapid and impetuous, that the sea reached distant places*' (HS34).

(5) Floods in Navarra, northern Spain. In Sierra de Alcarama, the heavy precipitation on 24 February caused flash floods in 2 river catchments (Añamaza and Alhama rivers), in the upstream sector of the Ebro basin (HS32 Supl. Nº13). Once again the accounts make reference to the severity of the storm, mentioning an '*impetuous wind, a hurricane that came from the west* (...) *and copious rainfall causing a rise of Añamaza and Alhama rivers that had never been seen before, leading to a violent deluge that changed the devastated land*' (HS32 Supl. Nº13).

The geographic extension of the storm's impacts is considered to have been properly assessed by the data presented to this point. Although a search of documentary and instrumental records was carried out for the same dates, by Mariano Barriendos in Barcelona, Bilbao, Madrid, Murcia, Santiago de Compostela, Seville, Toledo and Zamora, and by José Vaquero in Zafra, no additional evidence of impacts was found. Thus, we are confident that the storm only affected northwest and northern Iberia.

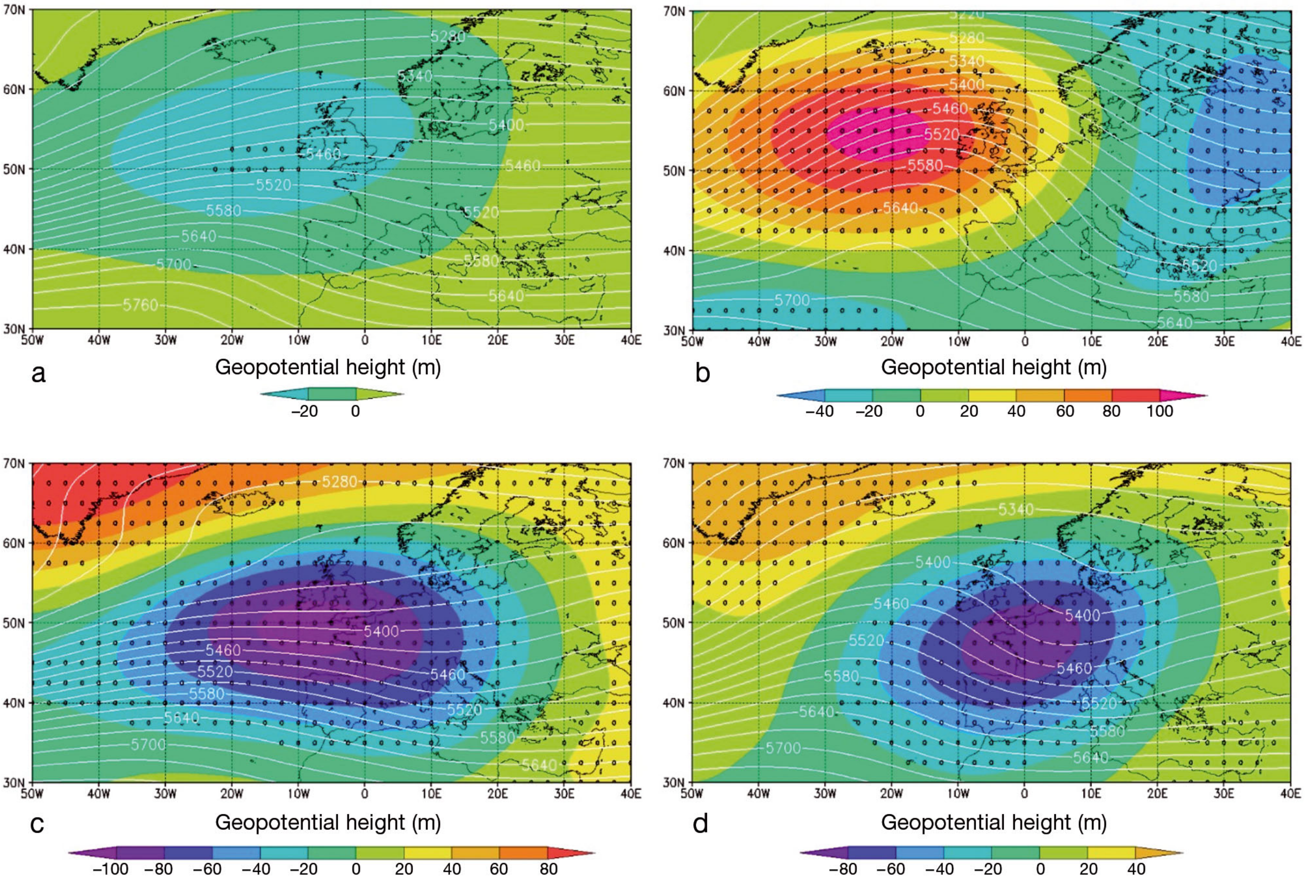

Fig. 7. Monthly mean 500 hPa geopotential height (contours in metres) for (a) December 1787, and (b) January, (c) February and (d) March 1788. Corresponding anomalies (colour shading) with respect to their long-term monthly means (baseline of 1773–1803, 31 yr period centred on 1788) are also displayed. Circles indicate gridboxes with statistically significant anomalies at 95% confidence level. Data Source: Casty et al. (2007)

The consistency between the above-described documentary sources and the information regarding large-scale atmospheric flow obtained from an independent dataset of atmospheric variables is now analysed. In order to identify anomalies in the large-scale atmospheric flow during the 1787–88 winter, the patterns of monthly precipitation totals and mean 500 hPa geopotential height are analysed for the December–March period. These variables were extracted from reconstructions by Casty et al. (2007). The gridded precipitation and geopotential fields are defined over a North Atlantic/European sector (80–30° N, 50° W–40° E) on 0.5° × 0.5° and 2.5° × 2.5° grids, respectively. For precipitation, only the Iberian Peninsula is represented. Monthly anomalies in the 2 previous fields were also computed with respect to their corresponding long-term monthly means over a 31 yr baseline period centred on 1788 (1773–1803). The statistical significance of the anomalies was also assessed by the Student's *t*-test at 5% significance level.

The large-scale fields generally support the documentary sources, hinting at very high precipitation values in February 1788, particularly over northwestern Iberia where the storm first impacted the peninsula (Fig. 6) with local maxima >340 mm in Galicia, northwestern Spain. The precipitation anomalies are >120 mm over a large area extending from central Portugal to Galicia. However, anomalously high precipitation totals are depicted over the entire Iberian Peninsula, which are also statistically significant at 95% confidence level. Furthermore, the monthly 500 hPa geopotential height values clearly reflect the key role played by large-scale patterns over the eastern North Atlantic on precipitation in western Iberia. The anomalously weak anticyclonic ridge located westwards of Iberia in February 1788 was accompanied by a largely zonal flow (Fig. 7; note the statistically significant negative anomalies over western Europe, with a core anomaly <100 geopotential metres). These conditions clearly suggest the presence of very strong cyclonic systems over western

Europe that are favourable to the occurrence of precipitation in Portugal, associated with the passage of frontal systems.

For the other months, however, there are no statistically significant anomalies in precipitation (Fig. 6), which reinforces the exceptionality of the conditions in February 1788. Despite the much less pronounced features, similar conditions as those in February 1788 can be observed in December 1787 (Fig. 7). Conversely, in January 1788, a very strong ridge can be seen over the North Atlantic, consistent with the relatively low precipitation values. Lastly, in March 1788, there is still a very strong mean trough in the 500 hPa geopotential height, though eastwardly displaced with respect to the mean trough in the previous month. In fact, this result suggests a westerly-moving trough, which is also in line with the findings from the documentary sources. As the prevailing wind over Portugal gradually changed from southwest to northwest, the rain-generating conditions progressively weakened, also explaining the decreasing precipitation anomalies.

4. DISCUSSION AND CONCLUSIONS

The results show a remarkably high frequency and strength of climatic extremes in the 1780s in Portugal. This is in agreement with Kington's statement: '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; also cited in Barriendos & Llasat 2003). According to the chronological sequence of extremes, considering thermal and hydrometeorological events separately, the main outcomes of the present study are:

(1) Detection of severely cold seasons in 1782 (winter), 1784 (winter and spring) and 1789 (winter). The occurrence of snowfall is extremely rare in Lisbon (on average 0.0 d yr^{-1} in the 1961–1990 climatic normal), but 1 event was documented in February 1782. The winter of 1784 was also very cold in Portugal and it was widely reported across Europe: in England (where according to Kington 1980 the Thames River froze in February), Belgium (Demarée 2006) and central Europe (Brázdil et al. 2010b, Glaser et al. 2010). This cold anomaly might have been driven by the Lakagígar volcanic eruption. This eruption (occurring from June 1783 until February 1784) was one of the largest over the last 500 yr (Bradley & Jones 1995, Trigo et al. 2010). Foggy and hazy days in the 1783 summer and lower than average air temperatures in 1784 were its main consequences in Portugal (Taborda et al. 2004, Alcoforado et al. 2012). The 1789 winter was also characterised by an intense cold wave in Portugal (maximum on 8 January), according to the available instrumental and documentary information. Over most of Europe the 1788/89 winter was also exceptionally cold, with strong and persistent frosts, snowfall in unusual areas and frozen rivers (Le Roy Ladurie 1983, Barriendos 1997, Xoplaki et al. 2001). According to Barriendos (1997), 2 severe cold episodes were observed in Iberia (26–31 December 1788 and 5–8 January 1789).

(2) Identification of the predominantly dry period of 1779–1782. During this period, 2 particularly severe droughts were detected in Portugal, namely in the spring of 1780 and in the winter and spring of 1781. Due to its Mediterranean-like climate, droughts in Portugal are mostly related to rainfall deficits during the cold semester (October–March). Its dynamical causes are commonly linked to strong and persistent mid-latitude anticyclonic ridges over the eastern North Atlantic (e.g. Santos et al. 2009). The 1780 and 1781 droughts were indeed a manifestation of large-scale precipitation anomalies. They were also identified in Extremadura (Fernández-Fernández et al. 2014), Andalusia (Rodrigo et al. 2012) and central Spain (Domínguez-Castro et al. 2012). The latter includes specific references to pro-pluvia rogation ceremonies, celebrated in the winter, spring and autumn of 1781 in Seville, Murcia, Zaragoza and Tortosa.

(3) Details of the remarkable rainy period 1783–1789. Taborda et al. (2004) and Alcoforado et al. (2012) previously highlighted this very rainy period in southern Portugal. The present study demonstrates that wet conditions also prevailed over northern Portugal. For 7 consecutive years the estimated precipitation index (PI) was strongly positive, values that are corroborated by the available instrumental data. At the annual scale, the highest magnitude of these anomalies occurred in 1783/84, 1785/86 (+7/9) and 1787/88 (+5/9). There is also a good agreement between the detected precipitation extremes and results reported by recent studies in Spain. In Andalusia (a region contiguous with Southern Portugal), Rodrigo et al. (2012) identifies positive precipitation anomalies in 1784 and 1786, referring to the occurrence of pro-serenitate ceremonies in Seville in both years. Barriendos & Rodrigo (2006, their Fig. 5) also state that a total of 7 floods in Seville (Guadalquivir River) occurred during the 1780s. Five of them occurred in winter and the remaining 2 in spring, though they do not specify the years of those extreme events. Among

the mentioned rainfall (positive) anomalies, the 1783/84 hydrological year featured exceptionally severe climatic conditions, with catastrophic and widespread impacts throughout Europe. Brázdil et al. (2010b) state that the 1783/84 winter was characterized by low temperatures, heavy and persistent frosts, icebound watercourses and high rates of snow accumulation across extensive regions northwards of the Alps. These conditions were followed by the most hazardous floods recorded over the past millennium in western-central Europe (Glaser & Stangl 2004, Demarée 2006, Brázdil et al. 2010b). Most of these floods were triggered by fast snowmelt and ice breaking-up on frozen rivers (Brázdil& Llasat 2003, Demarée 2006), thus being driven by different mechanisms from those occurring in 1784 over western Iberia. According to several recent studies (Andrade et al. 2011, Fragoso et al. 2012), positive anomalies of winter precipitation in Portugal tend to be generated by anomalously high frequencies of synoptic disturbances over the eastern North Atlantic, which are also related to the NAO and East Atlantic patterns (Gomes 2011, Trigo 2011).

(4) Details of the violent storm of February 1788. The present study provided a more detailed analysis of a severe Atlantic storm that crossed the northwestern sector of Iberia, producing devastating floods in the Douro River basin. This extreme event illustrates the rainy conditions over 1783–1789, but is also evocative of the high impacts of floods and correlated vulnerabilities in the affected riverside urban centres, particularly Valladolid (Spain) and Oporto (Portugal).

The present study suggests that strong climatic variability was experienced in Portugal during the 1780s. Furthermore, it also shows that the exceptional atmospheric conditions during this decade over Portugal are in clear agreement with the results found by different authors over Spain, as well as over other European regions. These results are also of relevance for assessing the exceptionality of current or future climate extremes in Portugal, as they provide a comparative measure of the magnitude of a given extreme. Future research will focus on the search for additional documentary sources in other parts of the country, improving the current KlimHist database and providing further insight into the mechanisms underlying climate variability in Portugal.

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HS14 Veiga JS (1784) Observações Meteorológicas feitas em Lamego desde o Anno de 1770, athe o de 1784. Série Azul, Manuscrito 990, 17 fls. De texto nums. a lápis, incluindo o rosto + 3fls. Em branco inums.; 2° [340 × 223 mm]
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HS31 Castrioto FA (1787) Gazeta de Lisboa, No. 52. Regia Officina Typografica, Lisboa
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