The Little Ice Age in Iberian mountains

M. Oliva[1]; J. Ruiz-Fernández[2]; M. Barriendos[3]; G. Benito[4]; J.M. Cuadrat[5]; F. Domínguez-Castro[6]; J.M. García-Ruiz[6]; S. Giralt[7]; A. Gómez-Ortiz[1]; A. Hernández[8]; O. López-Costas[9]; J.I. López-Moreno[6]; J.A. López-Sáez[10]; A. Martínez-Cortizas[11]; A. Moreno[6]; M. Prohom[12]; M.A. Saz[5]; E. Serrano[13]; E. Tejedor[5]; R. Trigo[8]; B. Valero-Garcés[6]; S.M. Vicente-Serrano[6]

(1) Department of Geography, University of Barcelona, Spain
(2) Department of Geography, University of Oviedo, Spain
(3) Department of Modern History, University of Barcelona, Spain
(4) Museo Nacional de Ciencias Naturales (MNCN-CSIC), Madrid, Spain
(5) Department of Geography and Spatial Planning, University of Zaragoza
(6) Instituto Pirenaico de Ecología (IPE-CSIC), Campus de Aula Dei, Zaragoza, Spain
(7) Institute of Earth Sciences, Jaume Almera (ICTJA-CSIC), Barcelona, Spain
(8) Instituto Dom Luiz (IDL), Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal
(9) Group Earth System Science, Universidade de Santiago de Compostela, Spain; Laboratory of Physical & Forensic Anthropology, Universidad de Granada, Spain
(10) Institute of History – CSIC, Spain
(11) Group Earth System Science, Universidade de Santiago de Compostela, Spain
(12) Meteorological Service of Catalonia, Spain
(13) Department of Geography, University of Valladolid, Spain

*** Corresponding author**
Marc Oliva, oliva_marc@yahoo.com
Department of Geography
Faculty of Geography and History, University of Barcelona
c/ Montalegre 6, 08001 - Barcelona, Spain
Tel: +34 616104266

1 Introduction

The term Little Ice Age (LIA) was first used by Matthes (1940) to describe an epoch of moderate glaciation that occurred during the last 4000 years, and to highlight evidence of greater glacier oscillations over the last few centuries. Since then, the LIA has been associated with a period of colder climate conditions that prevailed between the Medieval Climate Anomaly (MCA) and the onset of the trend of warming initiated during the second half of the 19th century (Mann et al., 2009; Díaz et al., 2011). Because of the availability of accurate data from a large number and variety of sources, the LIA and associated environmental conditions have been extensively used as the reference for Holocene cold stages (Grove, 2004). One of the widest environmental implications of this colder climate period is strikingly illustrated by the Alpine glaciers, which expanded down valleys and threatened villages in the highest valleys during medieval times (Holzhauser et al., 2005). Glaciers in most of the highest mountain ranges worldwide reached their greatest volumes over the last 10,000 years (Bradley & Jones, 1992).

The physical processes controlling climate cooling during the LIA, also referred to as miniglaciation, have been associated with two distinct external forcing mechanisms (volcanic and solar) that were probably amplified by the coupling of various processes and related feedback that characterizes the internal climate system (Hegerl et al., 2011). The main causes have been identified as increased volcanic activity (Lamb, 1970; Porter, 1986; Bradley & Jones, 1992; Jacoby et al., 1999; Prohom et al., 2003; Hegerl et al. 2006), together with a decline in incident solar radiation on the Earth's surface (Benedict & Maisch, 1989; Lean et al., 1995; Stuiver et al., 1997; Beer et al., 2000; Luterbacher et al., 2001; Shindell et al., 2001; Bradley, 2003; Solanski et al., 2004; Usoskin et al., 2004; Dorado-Liñán et al., 2016) and a slowdown of North Atlantic thermohaline circulation (Broecker, 2000). A series of large volcanic events that took place during the LIA seems to have triggered the summer cooling that characterized this period, which was enhanced by sea ice/ocean positive feedback (Miller et al., 2012). The cool summers resulted in an increase in the extent of sea ice in the Arctic, with the cold subsequently expanding to mid-latitude environments (Wanner et al., 2011).

However, there remains no consensus about the timing of onset and termination of the LIA, or its geographical impact. In most studies the LIA is reported to have spanned the period from the 14th to the 19th centuries, although different time periods have been proposed, depending on the concepts "LIA climate" vs. "LIA glacierization" (Matthews & Briffa, 2005). The LIA corresponds to Bond event 0 (1200–1800 AD), and constitutes the coldest multi-decadal to multi-century Holocene period since the 8.2 ka BP event (Wanner et al., 2011), or during the last 12 ka BP (Bradley et al., 2003; Palacios et al., 2017). Colder climate conditions particularly affected the Northern Hemisphere, although cooling in many other places worldwide has also been extensively documented (Jones & Mann, 2004; Mann et al., 2009). The coldest mean annual air temperatures during the LIA in Europe were recorded during the Maunder Minimum. This is the period from 1645 to 1715, when the level of solar activity was very low (Eddy, 1976), and resulted in temperatures being approximately 0.6–1°C lower than at present (Bradley et al., 2003; Pauling et al., 2003; Luterbacher et al., 2004, 2006, 2016; Zorita et al., 2004; Mann et al., 2009; Díaz et al., 2011). Although temperatures were generally lower than at present, the LIA was characterized by alternating warmer and colder periods, and enhanced spatial and temporal variability in precipitation (Lamb, 1977; Rodrigo et al., 1999; Alcoforado, et al., 2000; Wanner et al., 2004, 2011; Pauling et al., 2006). The extreme climate events that occurred during the LIA had substantial detrimental socio-economic effects, amongst which were dramatic consequences including the abandonment of Greenland's Norse colonies and mountain villages in the Alps (Fagan, 2002).

Several studies over the last two decades have attempted to reconstruct the climate conditions prevailing in the Iberian Peninsula during the centuries of the LIA, which is the coldest period in this area since at least the Mid–Late Holocene (Martínez-Cortizas et al., 1999). Historical, natural records and climate models have provided diverse evidence of lower temperatures accompanied by an intensification in the magnitude and frequency of climate variability and extreme events, including droughts, floods, avalanches, and cold and heat waves (e.g. Barriendos, 1997; Barriendos & Martín Vide, 1998; Rodrigo et al., 1999, 2000; Alcoforado et al., 2000; Barriendos & Llasat, 2003; Benito et al., 2008; Martín-Chivelet et al., 2011; Oliva et al., 2011; Gómez-Navarro et al., 2011, 2012; Morellón et al., 2012; González et al., 2013; Alberola, 2014; Fragoso et al., 2015; Sánchez-López et al., 2016; Tejedor et al., 2017).

The main aim of this study was to review and update knowledge of the chronology and environmental implications of the LIA in Iberian mountains and surrounding lands, using a multi-proxy perspective. To this end we present useful information that will help provide answers to the following key questions:
When was the onset and the end of the climate effects of the LIA in the Iberian Peninsula?
What was the spatio-temporal pattern, timing, and magnitude of LIA climate oscillations?
What were the physical mechanisms that drove climate variability during the LIA?
What were the environmental consequences of these climate oscillations on the various land systems?
What were the socio-economic impacts of the climate extremes that occurred during the LIA?
What geo-ecological changes occurred during and following the LIA in Iberian mountain ranges?

2 Regional setting

The Iberian Peninsula (latitude: 43°47′N to 36°01′N; longitude: 9°30′W to 3°19′E) constitutes the southwest tip of the Eurasian continent. It encompasses an area of 582,925 km^2 in a boundary zone affected by differing influences: maritime (Atlantic/Mediterranean), climatic (subtropical high pressure belt/mid-latitude westerly's), and in terms of biomes (Europe/Africa). The interactions among these influences explains the wide spectrum of landscapes that occur in Iberia.

Figure 1

The central part of the peninsula and coastal regions comprise gentle terrain separated by several mountain ranges exceeding 2000 m a.s.l. aligned in an east–west direction, including the Pyrenees, the Cantabrian Mountains, the northwest ranges, the Central Range, the Iberian Range, and the Betic Range (Fig. 1). Two Iberian massifs, the Sierra Nevada in the Betic Range (Mulhacén, 3478 m) and the Maladeta massif in the Pyrenees (Aneto, 3404 m), are the highest peaks in western Europe outside the Alps.

The climate of the Iberian Peninsula is affected by both tropical and mid-latitude systems, through the direct influence of continental and maritime air masses having distinct origins (Barry & Chorley 1998). The climate is highly seasonal, and controlled to a large extent by westerly winds that dominate the winter circulation, and by the Azores anticyclone, which prevails in summer (Paredes et al., 2006). Most of the precipitation occurs between October and May, when low pressure mid-latitude cyclones follow a prevailing zonal trajectory (Trigo et al., 2004). These synoptic patterns, together with the rough terrain, determine the presence of multiple microclimatic regimes across the peninsula, and within the individual mountain ranges (de Luis et al., 2010; Cortesi et al., 2014; Peña-Angulo et al., 2016). Annual precipitation generally decreases from north to south and from west to east, whereas mean air temperatures follow an opposite pattern, increasing towards the south and the east. The 0 °C isotherm increases in elevation southwards from approximately 2400–2500 m at the Cantabrian Mountains (Muñoz, 1982) to 3400 m in the Sierra Nevada (Oliva et al., 2016b), and is around 2950 m in the Pyrenees (Chueca et al., 2005).

The landscape in Iberian mountain ranges is a consequence of both Pleistocene glaciations and post-glacial environmental dynamics driven by periglacial, slope, and fluvial processes, and shallow and deep-seated landslides (Oliva et al., 2016a). Small glaciers still occur in the Pyrenees, but are increasingly receding and thinning (López-Moreno et al., 2016). These glaciers expanded significantly during the LIA, but are now in strong disequilibrium with current climate conditions (González-Trueba et al., 2008). Consequently, the environmental dynamics from the tree line to the highest peaks in Iberian ranges is mostly driven by periglacial activity through a wide range of processes that result in various landforms and deposits (Oliva et al., 2016a). The periglacial zone is divided into two sub-belts based on the intensity of cryogenic processes and vegetation cover. The upper sub-belt of the periglacial area has little vegetation cover, which enhances the effectiveness of processes related to the presence of ground ice, whereas the lower sub-belt has extensive grasslands, and has been substantially modified by historical practices associated with fire management (Lasanta et al., 2006; García-Ruiz et al., 2016a). Together with climate oscillations, human activity during recent centuries has altered the vertical structure of the geo-ecological dynamics in some Iberian massifs (e.g. Camarero et al., 2015). Below the periglacial belt the forests generally extend across the slopes and valley bottoms. The surface range and altitude of these elevation belts depends on the climate regime, and strongly influences the geo-ecological, geomorphic, hydrological, and edaphic processes prevailing in these environments, and in surrounding areas.

3 Methods

We conducted a comprehensive review of scientific literature concerning the climatic and environmental conditions during the LIA in the mountains of the Iberian Peninsula. The reviewed reports included those based on natural records (glacial, periglacial, lacustrine/peatlands, fluvial/alluvial, speleothems, and tree rings) as well as historical records and early instrumental data (Table 1). This is complemented with the results of recent experiments using paleoclimatic simulations by means of climate models.

Table 1

Because of the lack of consensus regarding the chronology of the LIA, broadly considered to span the period from the 14th to the 19th centuries (Matthews & Briffa, 2005), the chronology and accuracy of each studied proxy in this research depended on the nature of the record. Some records encompassed the last thousand years, enabling the LIA conditions to be framed within the MCA and post-LIA warming, while others only included some of the coldest centuries of the LIA up to the present (i.e. those based on tree rings).

The timing of the LIA internal climatic phases was defined based on the available scientific literature on the European continent with a focus on the Iberian Peninsula. Following these time windows, we examined the prevailing temperature and precipitation conditions suggested by each proxy in each mountain range to infer the main climatic phases within the LIA. For this purpose, we implemented a meta-analysis including all the available information proxy-sources in the different Iberian mountains (Table 2). This approach, although informative is not free of uncertainties since our review clearly shows that some periods with certain prevailing climate conditions (e.g. dry stages) could be affected by extreme short-term events of opposite sign (e.g. floods).

Table 2

The available data are summarized in a table for each proxy, including the environmental setting in each region (altitude, aspect), the type of evidence, the stages within the LIA, and the associated climate conditions. All dates provided in the paper are based on the AD calendar.

Two sets of instrument series were used to characterize climate conditions during the last decades of the LIA in Iberia, and to provide a reference for temperatures and precipitation. The first series concerned yearly temperature at four sites (Cádiz, Gibraltar, Barcelona, and Madrid) providing the longest and most complete temporal coverages, albeit with different starting years. These series were quality controlled and homogenized following the method described by Prohom et al. (2012, 2016). The second group of series consists of twelve homogenized yearly rainfall series, covering a short period commencing in 1859, and grouped into three different climate regions (Cantabrian Mountains, Pyrenees and Sierra Nevada) in order to identify possible geographic patterns. The data for this second series were extracted from Almarza et al. (1996), and updated to 2010 based on data from the Spanish Meteorological Agency.

4 Geomorphological, sedimentological, and historical evidence

Studies of the impact of LIA climate variability in the Iberian mountains have ranged from the top of the highest mountains to the surrounding lowlands, and involved a wide range of perspectives described below.

4.1 Glaciers

Only the highest elevation environments in the Pyrenees, Cantabrian Mountains, and Sierra Nevada had glaciers during the LIA.

Up to 111 cirques across 15 massifs in the Central Pyrenees show geomorphic evidence of the presence of glaciers during the LIA (González-Trueba et al., 2008). The reconstructed LIA Equilibrium Line Altitudes (ELAs) fluctuated between 2620 and 2945 m, depending on the massif and aspect. According to González-Trueba et al. (2008), glaciers in the Pyrenees advanced and retreated significantly during several phases of the LIA (Table 3), and Serrano (1996, 1998) and López-Moreno (2000) found up to four distinct stages during the LIA in the Tendeñera massif (Gállego Valley). The cold and wet conditions that prevailed during the Maunder Minimum were associated with the maximum extent of LIA glaciers during the last decades of the 17th century (García-Ruiz et al., 2014a). Amongst these, the reported maximum reconstructed surface area is that for the Aneto glacier (236 ha) (González-Trueba et al., 2005). The fluctuating cold and moisture regimes led to minor re-advances between 1750 and 1800, followed by a significant expansion until

1830, during the cold pulse promoted by the low solar activity related to the Dalton Minimum (García-Ruiz et al., 2014a). The gradual increase in temperature during the second half of the 19th century resulted in significant glacier retreat, with rates of receding similar to those recorded during the last decades of the 20th century and in the early 21st century (Chueca et al., 2008). Despite a short period involving minor re-advances and general equilibrium between 1890 and 1920, glacier retreat accelerated again during the 1930s, and after a phase of stabilization and minor glacier advances during the 1970s (Marti et al., 2015), it has further increased since the 1980s in response to strong disequilibrium between the glaciers and current regional climate conditions (Chueca et al., 2007; López-Moreno et al., 2016). In 1850 the estimated glacier surface area in the Pyrenees was 2060 ha, but it had declined to 321 ha by 2008 (René, 2013) and to just 244.6 ha in 2016 (Rico et al., *in review*). In the case of the north-facing slope of the Monte Perdido Massif (Marboré Cirque), glaciers covered 239 ha at the end of the LIA, 62.1 ha in 1999, and 49.2 ha in 2010 (Fig. 2a) (Chueca & Julián, 2010), whereas the Maladeta glacier occupied 152.3 ha in the period 1820–1830, but only 54.5 ha in 2000 (Chueca et al., 2005). More than 100 glaciers disappeared from the Pyrenees in the period 1850–2005, and currently only 19 of the LIA glaciers are still mobile (Rico et al., 2017). The patterns of deglaciation in the Pyrenees have been tightly related to the topographic context for each glacier, with exposure to solar radiation being a key factor explaining the rate of shrinkage of each ice body (López-Moreno et al., 2006). Most of the LIA glaciers are now ice patches or semi-permanent snow fields, in some cases favored by topography and increased accumulation from avalanching snow (Hughes, 2018). Sedimentological evidence of glacier advances is in the form of moraine systems (frontal or latero-frontal) in several massifs, and single polygenic moraines in others, where the glacier aggregated sediments in the inner ridge of the external moraines. Glacier erosion features within formerly glaciated environments are also observable, including polished bedrock and glacial striae.

Table 3

In the Cantabrian Mountains, glaciers only developed in the Picos de Europa, namely in the Central and Western massifs. Six small glaciers were present during the LIA within the highest northern cirques (Miotke, 1968; Castañón & Frochoso, 1994, 1995; González-Suárez & Alonso, 1994, 1996; Serrano et al. 2002; González-Trueba, 2005, 2006, 2007a, 2007b; González-Trueba et al., 2008; Serrano et al., 2012, 2013). Several historical documents confirm the presence of these glaciers, which reached their greatest extent during the mid 19th century (González-Trueba et al., 2008). They formed in areas protected from direct solar radiation by the vertical cirque walls, and were snow-fed by avalanches and wind action (Fig. 2b). In all cases, they generated single frontal moraines at elevations from 2200 to 2320 m. The ELA in the Western Massif was situated between 2242 and 2381 m (average 2252 m), and at 2341 m for the Central Massif (González-Trueba, 2005; González-Trueba et al., 2008). The total glaciated area in the Picos de Europa during the LIA was 25.5 ha, including 15.5 ha in the Central Massif and 10 ha in the Western Massif. The progressive temperature increase recorded since the second half of the 19th century has resulted in four of the six glaciers present during the LIA today constituting ice patches (exposed or buried), and two reduced to (semi-)permanent snow fields (González-Trueba, 2005, 2006, 2007a, 2007b; González-Trueba et al., 2008; Serrano et al. 2011; Ruiz-Fernández et al., 2016, 2017). Therefore, post-LIA warming promoted deglaciation of the Picos de Europa, and the entire Cantabrian Mountains.

In the Sierra Nevada, two glaciers formed during the LIA on the northern face of the highest peaks of the massif (Mulhacén and Veleta). Lacustrine records from La Mosca Lake show evidence of the development of a glacier within the Mulhacén cirque between 1440 and 1710, after which it started to shrink and then melted completely. Historical sources confirm that no glacier or permanent snow fields were present in the Mulhacén cirque during the last decades of the 19th century (Oliva & Gómez-Ortiz, 2012). The Veleta cirque persisted as the southernmost glacier in Europe until the mid 20th century (Gómez-Ortiz et al., 2006, 2009). At this time García-Sainz (1947) described it as presenting the "same stratigraphic superimposition of layers of snow and bluish ice as can be observed in the glaciers of the Pyrenees" (Fig. 2c). The explanation for the longer persistence of glacial ice in the Veleta glacier compared with the Mulhacén cirque is related to topographical conditions: the Mulhacén cirque is located at an average elevation of 2950 m and has a north-northwest aspect, while the Veleta cirque is at 3100 m and exposed to the north. Consequently, from 1710 until the mid 20th century the ELA in the Sierra Nevada must have been at approximately 3000 m, and this determined the occurrence of a glacier in the Veleta cirque but snow fields in the Mulhacén cirque (Oliva & Gómez-Ortiz, 2012). These glaciers left a well-defined moraine in the Veleta cirque floor and a sequence of small moraine ridges in the Mulhacén cirque, where the cirque bottom forms a gentle slope. These LIA glaciated environments show geomorphic evidence of the occurrence of permafrost conditions, and buried ice bodies under the debris cover, which are undergoing a rapid process of degradation (Gómez-Ortiz et al., 2014). Consequently, as in Picos de Europa, post-LIA warming resulted in the complete deglaciation of the Sierra Nevada.

Figure 2

4.2 Periglacial records and ice caves

The cold climate conditions that prevailed during the LIA generated widespread reactivation of periglacial processes in the highest parts of Iberian mountain ranges, as suggested by evidence in a wide range of landforms and deposits (Oliva et al., 2016a). The periglacial belt occupied a greater extent and expanded to lower elevations than during previous warm Holocene phases (e.g. the MCA) and under present conditions. In some cases, including in the Sierra Nevada, the difference in elevation of active periglacial landforms (e.g. solifluction lobes) between the coldest stages of the LIA and the present is approximately 400–500 m (2500 m vs. 2900–3000 m) (Oliva & Gómez-Ortiz, 2012). This difference is substantially larger than the elevational increase because of warmer temperatures, which is approximately 150 m in the highest Iberian massifs (Oliva et al., 2016a).

Figure 3

In the Pyrenees, the location of the permafrost was significantly different than today; it potentially occurred at 2440 m and was probable at 2560 m, in both cases 140 m higher than at present. Because the Pyrenean LIA glaciers were very small, the corresponding cryonival belts occupied relatively wide areas in the high mountains. Many permafrost-related landforms (rock glaciers and protalus lobes) that are inactive today in the highest areas of the main massifs developed or reactivated during this cold phase (Fig. 3a). Other periglacial landforms related to seasonal frost conditions, which are now inactive or show very weak dynamics, developed during the LIA under more intense frost shattering, nivation, solifluction, or cryoturbation processes than currently occur.

Periglacial activity in the Pyrenees during the LIA involved the reactivation of some rock glaciers and intensification of cryogenic processes in areas located above 2200 m. Serrano et al. (1999) reported the presence of 13 rock glaciers in the Pyrenees having origins prior to the LIA (probably the Late Pleistocene or the Holocene), five on the northern side and eight on the southern side. These are all located under summits higher than 2950 m, located in extremely marginal positions within the range in north- and northeast-facing glacial cirques. Based on the current displacement values for the rock glaciers and the denudation rates in the cirque headwalls, Serrano et al. (1999) estimated that they developed 4000–5000 years ago. In the case of the Argualas rock glacier, a minimum age of 3400 years is necessary to explain its size (Serrano et al., 2006), whereas the evolution of the Posets rock glacier was clearly very complex, as deduced from its inner structure (Serrano et al., 2010). It was probably a Holocene-derived rock glacier that was invaded by advance of the ice of the Posets glacier during the LIA, and was later buried by a 2 m debris layer when the glacier retreated. At the same time, the LIA advance of the La Paúl glacier eroded the La Paúl rock glacier, modifying its morphology and incorporating glacier rock debris into the frontal moraine complex (Serrano et al., 2002; Lugon et al., 2004).

Limestone, sandstone, and granite scarps show the presence of large talus screes, the development of which was directly related to frost shattering and the consequent rock falls, and to snow avalanches and debris flows (Serrano, 1998; García-Ruiz & Martí-Bono, 2001; García-Ruiz et al., 2011). They were particularly active and widespread during the LIA. Other periglacial processes were also active during the LIA above 2500 m. For instance, patterned ground processes, indicating the occurrence of marked contrasts in ground temperature, led to the development of the magnificent polygons in the Marboré Cirque, which occur in small flat areas having poorly drained sandy soils (Barrère, 1952; Nicolás, 1981; García-Ruiz & Martí-Bono, 2001). On moderately steep areas the polygons were replaced by parallel or isolated stripes (García-Ruiz et al., 2014b). Patterned and mostly inactive grounds are also relatively common in the central–eastern Pyrenees (Gómez-Ortiz, 1987). Many of the cryoturbation-derived landforms are currently inactive, and some of the most outstanding polygons have disappeared in the last few decades, although they represented the geomorphic effect of a recent colder period.

Table 4

In the Cantabrian Mountains, intense nival dynamics prevailed in the highest areas of the main massifs (Picos de Europa, Ubiña, Fuentes Carrionas). This involved the formation or reactivation of protalus ramparts and nivation hollows (Fig. 3b), enhanced activity of debris flows, and other rapid mass movements on slopes as a result of snow melt (González-Trueba, 2007a; Pellitero, 2012). In limestone massifs including Picos de Europa and Ubiña, colder conditions also favored extensive development of nival karst (Castañón & Frochoso, 1994; González-Trueba, 2007a; González-Trueba & Serrano, 2010; Ruiz-Fernández et al., 2014). Solifluction landforms and patterned ground features are widely distributed in the upper parts of these massifs (Table 4). Several of these features are no longer active (or have very limited activity; Fig. 3c) but have clear morphological characteristics. This suggests that they must have formed during a recent cold period, probably the LIA (González-Trueba, 2007a; Pellitero, 2012; Ruiz-Fernández et al., 2016). A similar situation applies to talus screes, which are still active in the highest areas but are inactive to weakly active (and partially covered by vegetation) immediately below, suggesting these are landforms derived from the LIA.

Snow fields in the Sierra Nevada during the LIA were more extensive during the summer than occurs today (Gómez-Ortiz & Plana-Castellví, 2006; Gómez-Ortiz et al., 2009, 2012; Oliva & Gómez-Ortiz, 2012). Two phases of intense solifluction activity above 2500 m during the LIA have been shown to have occurred between 1550 and 1800 in this mountain range (Oliva et al., 2011; Fig. 3d). Patterned ground features from the LIA have been preserved in the flat summit plateaus of the Sierra Nevada, although they are currently inactive (Table 4). A small active rock glacier within the Veleta cirque developed following deglaciation of the Veleta glacier, as a consequence of intense paraglacial dynamics (Gómez-Ortiz et al., 2014).

Several features in the northwest mountains of Iberia, including active screes, protalus ramparts, and solifluction landforms (including lobes and ploughing boulders), have been attributed to the LIA (Pérez-Alberti et al., 1998; Valcárcel, 1998; Carrera & Valcárcel, 2010). Fernández-Cortizo (1996) reported an increase in the extent of snow cover during the LIA in this mountain range. In the Central and Iberian ranges the prevailing process during this cold stage was frost shattering, which reactivated screes and caused the formation of nivation hollows (Pedraza & López, 1980; Peña et al., 2000; Palacios et al., 2003).

Ice caves in some of the highest Iberian massifs have recently been investigated. Several ice caves in the Pyrenees are known to include ice formed during the LIA (Serrano et al., 2017). These caves are located in the massifs of Monte Perdido (Casteret, Sarrios-1, Sarrios-6), Tendeñera (Soaso), Cotiella (A294), and Collarada (SO-01) (Sancho et al., 2016). Perennial LIA ice resulted from the freezing of snowmelt water that infiltrated through the epikarst in the caves (Bartolomé et al., 2015c; Leunda et al., 2015). Based on preliminary radiocarbon dates (Sancho et al., 2016), the congelation ice in the Sarrios-1 cave formed at the beginning of the 18th century, the ice in Soaso cave accumulated between 950 and 1750, and in the SO-01 cave (Collarada massif) the accumulation of ice occurred between 750 and 1650. Therefore, although there are other caves having ice that formed during the mid Holocene in the Pyrenees, much of the ice in these caves accumulated during the last millennium, and mainly during the colder stages of the LIA (Table 4).

More than 130 ice caves have been inventoried in the Cantabrian Mountains (Serrano et al., 2017), but only some caves are being monitored in the Picos de Europa, namely the Altáiz, Verónica, and Peña Castil caves (Gómez-Lende et al., 2011, 2014, 2016; Berenguer-Sempere et al., 2014; Gómez-Lende, 2015). In all cases ice formation in the caves has been related to the inflow of snow from outside. Radiocarbon dating carried out in the Altáiz and Verónica caves showed that most of the ice formed between the beginning of the 14th century and the middle of the 17th century (Gómez-Lende, 2015). However, the dated samples were not collected from the bottom of the ice bodies, so it is possible that, at least in the case of the Verónica cave, the basal ice may have accumulated since the end of the MCA (Gómez-Lende, 2015).

4.3 Lake and peat sedimentary records

Lakes and wetlands are relatively common in the Iberian Peninsula, and although they are mostly located in mountain areas they can occur in almost any environment. Most lakes in high elevation regions are related to glacial processes. However, in carbonate-dominated areas, particularly in the Iberian Range, karstic lakes (including sinkholes and travertine-dammed water bodies) are common (Barreiro-Lostres et al., 2015), and ephemeral saline lakes also occur in the main river watersheds. Past climate and environmental changes over recent centuries have been reconstructed based on biological (pollen, diatoms, chironomids) and geological (sedimentary facies, isotopes, and organic and inorganic geochemistry) indicators in sediments from such environments. In contrast, peatlands in the Iberian Peninsula are mostly located in mountainous areas. Most published peat records, including those representing the LIA, are from northwest Spain, the Cantabrian Mountains, the Pyrenees, and the Central Range. Only two studies on peatlands from southern Spain (the Sierra Nevada) have been reported. Most studies have been based on pollen records, although some have also provided information based on non-pollen palynomorphs or diatoms. Other studies have considered geochemistry, peat molecular chemistry, charcoal, humification, physico-chemical properties, magnetic susceptibility, plant macrofossils, and peat accumulation records (Table 5). Recent regional syntheses of Holocene environmental and climate change in the Central Range

(López-Sáez et al., 2014) and the western Pyrenees (Hernández-Beloqui et al., 2015) have included a large number of peatland records.

We integrated various reconstructions based on both lacustrine and peatland archives. Detailed reviews concerning the Pyrenees (Morellón et al., 2012), and more general reviews including most of the sedimentary records studied in the Iberian Peninsula (Sánchez-López et al., 2016), suggest that relatively humid and cold conditions dominated in the mountains during the LIA. However, because of its complex orography and geography, local climate conditions have been reconstructed for various parts of the Iberian Peninsula (Valero-Garcés & Moreno, 2011) (Table 5). The diverse sensitivity to varied forcing (temperature, humidity, seasonality), the specific characteristics of the proxies used in each study, and the differences in the depositional and paleohydrological behavior of the lacustrine and peatlands basins used to record climate change, probably explain some of the variability among the regional reconstructions (Hernández et al., 2015). Variability in the robustness of the age models could also explain differences in the dating and interpretation of the internal structure of the LIA. Below we discuss results of the main studies concerning vegetation dynamics, temperature reconstructions, and paleohydrological variability during the LIA.

Pollen and non-pollen palynomorph records

Although pollen studies are extensively used for paleoenvironmental reconstruction, there are major limitations to their use in investigations of climate change during historical times. Human activities including agriculture, animal husbandry, and human-induced fires, have been major factors in landscape organization and vegetation changes since medieval times, frequently overshadowing other environmental and climate processes. Evidence of the interrelationship between climate and human activities in shaping mountain landscapes has been found in all studies of peat and lakes in the Cantabrian Mountains (López-Merino et al., 2010; Hernández-Beloqui et al., 2015), the Pyrenees (Bal et al., 2011; Rull et al., 2011; Hernández-Beloqui et al., 2015), the Central Range (López-Merino et al., 2009; Abel-Schaad & López-Sáez, 2013; López-Sáez et al., 2014; Silva-Sánchez et al., 2016), and the Sierra Nevada (Jiménez-Moreno & Anderson, 2012; Ramos-Román et al., 2016). Despite their limitations, a number of studies of pollen records have clearly documented changes in vegetation dynamics related to temperature and humidity variability during the LIA. In the Pre-Pyrenees, Rull et al. (2011) showed that forest recovery that started in approximately 1500 coincided with wetter climates (Montcortés Lake), and Riera et al. (2004, 2006) suggested generally more humid conditions and a dry episode prevailed between 1600 and 1750 at Estanya Lake. Pérez-Sanz et al. (2013) also identified a wetter climate in Basa de la Mora during the LIA, based on forest expansion. An extensive review (López-Sáez et al., 2014) of pollen records from the Central Range identified cooler conditions at high elevations, based on a slight increase in *Betula* and *Pinus sylvestris* abundance. Wetter conditions after the mid 16th century have been reported for El Payo (Silva-Sánchez et al., 2016), Redondo (López-Sáez et al., 2016b), Puerto del Pico (López-Sáez et al., 2016a), and Peña Negra mires (Abel-Schaad & López-Sáez, 2013), although in some cases these conditions were interspersed with severe droughts. Several pollen records spanning the LIA are available for southern Spain. Palynological, non-pollen palynomorphs, charcoal, and magnetic susceptibility analyses in the Borreguiles de la Caldera mire (Sierra Nevada) have indicated a number of rapid, centennial-scale oscillations since 1300, with more humid conditions centered around 1300, 1410, 1550–1620 and 1810 alternating with arid events (Ramos-Román et al., 2016).

Paleohydrological and humidity indicators

Peat geochemistry, composition, and humification studies have also provided detailed reconstructions of past humidity changes. Peat records from the Pena da Cadela and Borralleiras da Cal Grande, northwest Spain, indicate the occurrence of wetter phases at the beginning (1330–1460) and end (1810–1860) of the LIA (Mighall et al., 2006). Wetter conditions during the LIA have also been indicated at more western and lower elevation mountains (the O Bocelo range; Silva-Sánchez et al., 2014). Relatively wet conditions associated with insolation minima (the Spörer, Maunder, and Dalton minima) have also been documented at Penido Vello (Martínez-Cortizas et al., 2007; Castro et al., 2015). Peat molecular chemistry studies performed on Penido Vello bog also support a predominantly wet LIA climate, particularly between 1430 and 1865 (Schellekens et al., 2011, 2012, 2015). Two studies based on peat organic chemistry, at Roñanzas (Ortiz et al., 2010) and Huelga de Bayas (López-Días et al., 2010) in the Cantabrian Mountains, indicate the occurrence of humid phases during the periods 1200–1650 and approximately 1460, respectively.

Most lake records provide quantitative estimates of past hydrological changes, based on analysis of sedimentary facies and from geochemistry indicators (i.e. organic, inorganic, isotopic). The timing of the LIA in the Pyrenees, and its internal variability, have been interpreted by Morellón et al. (2012). All records show more humid conditions during the LIA compared with previous periods, but the timing and intensity of the humidity changes show clear regional differences. The Pyrenean lake records suggest that the main hydrological changes associated with the LIA occurred between 1300 and approximately 1850. Studies of the Arreo (Corella et al., 2013), Basa de la Mora (Pérez-Sanz et al., 2013), and Estanya (Morellón et al., 2011) lakes indicate generally humid conditions during the LIA. The Arreo Lake record shows a decrease in salinity (Corella et al., 2013), while the Basa de la Mora Lake record (Pérez-Sanz et al., 2013) indicates an increase in terrigenous sediment delivery to the lake, which was interpreted as the result of greater storminess. A suite of proxies measured in Estanya Lake sediments suggest a higher lake level, particularly during the mid to late 19th century (Morellón et al., 2011). In the Lake Moncortés record (last 2700 years) the onset of the LIA is characterized by the largest increase in warm season (late spring–summer) heavy rainfall between 1372 and 1452, suggesting an anomalous frequency of arrival of high elevation cold air towards southern latitudes during summer (Corella et al., 2016). Taking into account the diverse resolutions of the age models, the consistency between periods of higher lake levels and lower solar activity suggest a climatic control of lake paleohydrology at centennial scales.

The Sanabria Lake record (Jambrina-Enríquez et al., 2014) showed dominant colder and more humid conditions from 1300 to approximately 1520 (as inferred by organic rich silts having high biogenic silica content) and warmer climate from approximately 1520 to 1850, as suggested by the deposition of more siliciclastic material.

The Central Range has a large number of high elevation lakes, but only the Cimera (Sánchez-López et al., 2016) and Peñalara (Sánchez-López, 2016) lakes have been studied in detail. The chemical composition of these lakes suggests an increase in the duration of ice cover, which led to extreme run-off episodes associated with rain-on-snow events (Sánchez-López et al., 2015, 2016). In both cases the reconstructed LIA climate conditions were cold and humid. In the Iberian Range an increase of extreme events is also recorded in Taravilla Lake (Moreno et al., 2008). Overall, periods of increased flooding appear to correspond to periods of higher solar activity. Higher lake levels have also been reconstructed for several karstic lakes in Cañada del Hoyo (Cuenca) during the LIA, including La Cruz, El Tejo and La Parra Lakes and at El Tobar (Barreiro-Lostres et al., 2015).

Table 5

In the Sierra Nevada, lacustrine sequences from Laguna de Río Seco (Jiménez-Espejo et al., 2014) and La Mosca (Oliva & Gómez-Ortiz, 2012) indicate more humid conditions after approximately 1300–1440 till the end of the LIA. High elevation records show a progressive decrease in colder conditions around the first decades of the 18th century, with a shift from glacial to periglacial conditions in the highest northern cirques (Oliva & Gómez-Ortiz, 2012). However, the hydrological impact of the LIA in the lowlands in central and southern Iberia is unclear. In Zoñar Lake, relatively arid conditions continued till 1550 and the main increase in lake level occurred in the 16th century (Martín-Puertas et al., 2010). In contrast, in Las Tablas de Daimiel National Park a wet phase occurred in the period 1400–1700, and a colder but drier period occurred in 1700–1850 (Domínguez-Castro et al., 2008).

Increased soil erosion during the LIA has been documented in many lakes and peatlands throughout the entire Iberian Peninsula. This has been ascribed to both climate deterioration and human impact (Rull et al., 2011; Barreiro-Lostres et al., 2015; Sánchez-López et al. 2016; Silva-Sánchez et al., 2016). Nevertheless, it is difficult to separate the imprint of climate conditions from that of the increasing impact of human landscape transformations (including changes in land use and deforestation).

Temperature indicators

A decrease in peat (and carbon) accumulation during the LIA in a central–western Iberian peatlands (López-Sáez et al., 2014, 2016a, 2016b) has been interpreted as a response to generally cooler conditions. Changes in productivity in some lakes have also been related to temperature changes (Pla & Catalan, 2005; Morellón et al., 2008). However, quantitative temperature estimates are scarce. The analysis of geochemical proxies in Penido Vello bog has provided a quantitative approximation of temperature variations during the LIA (Martínez-Cortizas et al., 1999). On average, temperatures may have been 1.7°C lower than the average for the period 1960–1990. The record shows rapid cooling since the start of the Spörer Minimum, which intensified during the Maunder Minimum (with the lowest estimated temperature being 2°C lower than the recent average). A later increase in the temperature and another slight cooling probably coincided with the Dalton Minimum

The only available temperature reconstructions from lake sequences have been carried out using a transfer function based on the occurrence of chrysophyte cysts and elevation/temperature in Lake Redon (Pla & Catalan, 2015). Compared with the Holocene, the LIA had a more continental climate, with warmer summers and extremely cold winters (Pla & Catalan, 2005, 2011). Particularly cold winters occurred during the MCA (from 1090 to 1179), during the LIA onset (1350) and from the late 15th to early 16th centuries. Winter temperatures would have been approximately 0.5°C lower during the LIA (1500–1900) than during the 20th century.

In summary, the large variety of proxies (biotic and abiotic) analyzed in peat and lacustrine sediment cores support the conclusion that the climate during the LIA was wetter and colder than during the MCA and at present (Morellón et al., 2012; Sánchez-López et al., 2016). Some studies based on more sensitive proxies and improved age models have identified alternating wetter and drier phases, and suggest a correlation with insolation. Despite the few peat- and lake-based temperature reconstructions, it can be argued that the LIA was a cold phase in the Iberian Peninsula, although the reconstructed temperature range is quite large (0.5–2°C during the coldest phases, compared with the average temperature during recent times). Increased storminess may also have been responsible for enhanced soil erosion in mountainous areas, but this remains difficult to disentangle from the dominant effect of human landscape transformations.

4.4 Fluvial and alluvial archives

In mountain areas the preservation of alluvial deposits has been limited because of the scarcity of alluvial sinks, and the frequent reworking of sediments by flooding. Therefore, understanding of fluvial activity and hydrological variability during the LIA has been interpreted from alluvial records in intra-mountain basins (bedrock and alluvial channels) and lowland alluvial plains. Five types of fluvial archive have been studied in the Iberian Peninsula: (i) overbank floodplain deposits (Wolf et al., 2013a, 2013b); (ii) flood basin environments (Sancho et al., 2008); (iii) river channel gravels (Schulte, 2002); (iv) mountain torrent deposits (debris flows and boulder berms) (Rico et al., 2001); and (v) slack water flood sediments (Benito et al., 2008; 2015a, 2015b). Alluvial valley floor cut-and-fill sequences, where river channel (iii), floodplain (i), and flood basin (ii) deposits are most commonly preserved (Table 6), tend to record changing discharge–sediment load relationships over longer periods (decades to centuries). In contrast, bedrock systems, where slack water (v) and boulder berm (iv) deposits are most commonly found (Table 6), can resolve individual flood events, sometimes on annual to decadal scales (Benito et al., 2008, 2015).

A widespread phase of alluvial aggradation at the onset of the LIA (1300–1400) has been identified (Fig. 4a), including records preserved in southeast Spain (Rambla Torrealvilla: Baartman et al., 2011; Aguas River: Schulte et al., 2002; Rambla de Librilla/Murta: Calmel-Avila, 2002), northeast Spain (arroyos Bisbal and Lluc: Schulte, 2003; Bardenas: Sancho et al., 2008; the Huerva Valley: Peña-Monné et al., 2004; Guadalope Valley: Fuller et al., 1998), and southern Spain (Guadalete River: Wolf et al., 2013a; Tagus-Jarama rivers: Uribelarrea et al., 2003; Wolf et al., 2013b). The alluvial aggradation has evolved into an alluvial terrace that is at 2–3 m above the thalweg, and is commonly composed of laminated silts (including in some cases humic material), sand, and pebble deposits associated with high flows (Sancho et al., 2008; Schulte et al., 2008). The main controls on terrace aggradation probably involved a combination of: (a) high sediment availability from land use changes associated with deforestation and modification of agricultural practices during the Christian Reconquest (Schulte et al., 2002), which overlapped with a period of famine and a series of poor harvests; and (b) a series of droughts and flood episodes resulting in poor harvests, centered in the 14th century (known as the “bad years” in the Kingdom of Aragon). Following the aridity crisis of the late Middle Ages (1290–1487), sediment delivery from Mediterranean river catchments to coastal areas led to progradation of current Iberian deltaic systems. These included the Ebro delta, which underwent a major construction phase between 1500 and 1650 (Guillén & Palanques, 1995; Xing et al., 2014), and in the Llobregat delta (Gámez et al., 2005) and the Vélez River (Málaga; Hoffmann, 1988) between 1450 and 1800. The rate of estuary filling on the southern coast of Spain was up to 1.8 m/yr during the 16th, 17th, and 18th centuries, particularly the latter (Lario et al., 1995; Dabrio et al., 1999). Fluvial aggradation is also recorded on floodplains and flood basins of Mediterranean rivers (Fig. 4). This phase of delta progradation and alluviation was attributed to anthropogenic activity (deforestation, agriculture, and mining), although it is likely that sediment connectivity from source areas to deltas was favored during episodes of flooding.

Table 6

Recent fluvial research has focused on extending flood chronologies through time and space as an indicator of change in atmospheric circulation patterns (Benito et al., 2015a). For Iberian Atlantic rivers, paleoflood records indicate a period of increased flooding associated with unusually wet winters between 1000 and 1200 (Benito et al., 2003b). A later dry period, between 1200 and 1400, is evidenced by colluvial deposits intercalated with the paleoflood sequences (e.g. Guadalentín River: Benito et al., 2010; Duero River: Machado et al., 2016). Regional radiocarbon-dated flood chronology has indicated several peaks in flood activity from 1400 to 1800 in Atlantic and Mediterranean Iberian rivers (Fig. 4b). However, caution is required in interpreting these results because of the relatively poor chronological resolution possible from radiocarbon dating based on the last 300 years (Benito et al., 2008).

The prevailing cooler climate conditions during the LIA suggest an increased influence of cold polar continental air masses associated with northeast flow during winter and early spring. The hydrological response of the main rivers to this frequent circulation pattern would have resulted in decreasing average discharges (dry cold winters) and greater flood irregularity, and a smaller number of large floods compared with previous flood episodes recorded during the MCA (900–1200).

Figure 4

4.5 Speleothems

Speleothems are among the best continental paleoclimate archives because of their greater dating accuracy, and the potential to reconstruct past climate conditions through isotope and elemental composition analysis (Fairchild & Baker, 2012). However, as speleothem growth is sensitive to climate conditions, their grow can be interrupted or cease during cold and/or dry periods (Genty et al., 2010). This, coupled with the fact that speleothem studies in the Iberian Peninsula have only recently occurred, explains the relative lack of speleothem paleoclimate reconstructions for Iberia that concern part or all of the LIA period (Table 7).

Table 7

Based on analysis of several speleothems from six caves located on the northern coast of Spain, Stoll et al. (2013) reported that significant speleothem growth had occurred during the LIA, although this interpretation was not generalized for all speleothems investigated. Following the rationale and interpretation used for other older climate periods, the formation of stalagmites during the LIA was probably related to humid conditions. However, this conclusion must be treated with caution as it is based on a small number of samples obtained from caves having clear anthropogenic influences. Similarly, for northwest Spain Railsback et al. (2011) reported short intervals of stalagmite growth separated by hiatuses during the Holocene, with one period of stasis coinciding with the LIA. The formation of speleothems during the LIA in these two studies suggests that there was sufficient humidity to maintain dripwater flow, at least in low elevation caves.

For the majority of speleothems, particularly those at mid latitudes, it is difficult to distinguish the effects of temperature from hydrological changes based only analysis of calcite isotopes ($\delta^{18}O$ and $\delta^{13}C$); trace element analyses can provide complementary information about humidity (Borsato et al., 2007). The $\delta^{18}O$ values for the Cantabrian Mountains reported by Domínguez-Villar et al. (2008) and Smith et al. (2016) were more negative, implying a wetter period during the LIA. On the other hand, at specific high elevation sites including the Alps the calcite $\delta^{18}O$ has been shown to have been controlled mainly by temperature through seasonal effects (Boch et al., 2011). In recent studies of Pyrenean caves the relationship with temperature appears to be stronger than that with the precipitation amount, based on comparison of instrument records with results of recent analyses of stalagmites. This has also proved to be true for the cold Younger Dryas period (Bartolomé et al., 2015b) and for the last 500 years in Seso Cave (Bartolomé et al., 2015a). Based on this interpretation, the onset of the LIA was characterized by cold conditions and a subsequent trend of warming. Similarly, based on analysis of carbon isotopes ($\delta^{13}C$) and Mg/Ca records from the same stalagmites, the LIA onset was more humid than the second part of the period, after 1600 AD.

Based on a present-day monitoring survey, Martín-Chivelet et al. (2011) combined three speleothem $\delta^{13}C$ records from northern Spain and interpreted the findings as being the result of temperature changes. The record clearly marks the LIA as a cold period having temperature minima occurring in the periods 1350–1450, 1600–1650, and 1800–1850.

In summary, it can be concluded that despite the small number of speleothem records available, it is evident that the LIA in northern Iberian Peninsula was clearly a cold period having two hydrological phases: a humid period from 1300–1600 and a subsequent period of transition to drier (and possibly warmer) conditions.

4.6 Dendroclimatology

Among various paleoclimate proxies, tree ring records constitute an excellent means for examining relatively recent environmental changes (Fritts, 1991), including the LIA, as they provide high resolution temperature and precipitation estimates for recent centuries (Table 8). The first dendrochronological database for the Iberian Peninsula was developed during the late 1980s and early 1990s, and was based on analysis of 1500 trees, particularly *Pinus nigra, P. sylvestris, P. uncinata*, and *Quercus* sp. Using these data, several temperature and precipitation reconstructions were developed for the Iberian Peninsula (e.g. Génova-Fuster et al., 1993). Most studies indicate the occurrence of a sustained period having high climatic variability during the first half of the 17th century. For instance, Génova (2012) identified a great number of extreme years in the Sierra Guadarrama, including the occurrence of severe droughts between 1600 and 1675, and detected a short period that was extremely unfavorable for tree growth during the first half of the 17th century. This was particularly the case for the period 1600–1602, which was attributed to the eruption of the Huaynaputina volcano (Peru); for the second half of the century and most of the 18th century there was no indication of a decrease in tree growth. Génova-Fuster et al. (1993) recorded similarly high climate variability for the Central Range and the western sector of the Iberian Range, with a greater occurrence of extreme years between 1700 and 1740. Climate variability was also evident at the beginning of the 19th century in the Central Range (Fernández-Cancio et al., 1996). In a review of dendroclimatic results in Spain related to precipitation since 1050 and to temperature since 1170, Manrique & Fernández-Cancio (2000) noted a high concentration of years having anomalous precipitation levels (above and below the mean values) between 1400 and 1550, with the coldest temperatures occurring in approximately 1500. Variability in both precipitation and temperature was also significant during the 15th and 16th centuries in the Ebro Valley, followed by a gradual decline until the 20th century. The lowest temperatures coincided with the 16th century (Creus-Novau et al., 1996; Saz-Sánchez & Creus-Novau, 2008).

For northern Spain, Saz (2003) developed several temperature reconstructions for the period since the 14th century. A decrease in temperature was detected in Galicia and the Cantabrian coast between 1540 and 1590, followed by an increase until 1630, then a long decline in temperature until 1790. During the 19th century the temperature increased until 1820 and then declined until 1855. These changes coincide with the main stages of the LIA, including the likely beginning and end dates. The Maunder Minimum resulted in a temperature decline of 0.25–1.2°C in winter and 0.25–0.5°C in spring (Table 8). In Galicia, northwestern Spain, the coldest five-year periods occurred during the 16th century, with mean temperatures 2°C below the 1971–2000 average over some short periods (Saz-Sánchez et al., 2004). Saz-Sánchez & Creus-Novau (2001) also noted that the 16th century stood out in a reconstruction of climate for the central–eastern Pyrenees since the 14th century (using the Capdella weather station as reference), and found that this was followed by a high level of variability during the 17th and 18th centuries. Büntgen et al. (2008) reconstructed summer temperatures for two timberline sites in the Central Pyrenees, and identified the occurrence of warming periods during the 14th century and the first half of the 15th century, and during the 20th century; these were separated by a long cooling period between 1450 and 1850. Six of the 10 warmest decades since the 14th century occurred in the 20th century, and the remaining four occurred during the period 1360–1440. The coldest summers corresponded to the end of the 15th century, between 1600–1700 and approximately 1820. Esper et al. (2015) found similar temporal patterns in the Pyrenees using isotopic analysis of the June-August temperature signal. Dorado-Liñán et al. (2014) reconstructed 800 years of summer temperature in southwest Spain and suggested that the LIA spanned a slightly longer time (1500–1930) than in other summer temperature reconstructions from the Alps and Pyrenees.

Table 8

Tejedor et al. (2017) recently updated the chronologies for the Iberian Range, and developed a maximum temperature reconstruction for 1602–2012. The 17th and 18th centuries were identified as the coldest period, with 73% and 80% of the years having temperatures below the long-term mean, respectively. In contrast, the 19th and the 20th centuries were the warmest, with 66% and 78% of the years exceeding the mean, respectively; this provides evidence of transition to the post-LIA climate. The main climate anomalies associated with major episodes are clearly inferred from dendroclimatological reconstructions, as is shown in Figure 5. For instance, the Maunder Minimum coincided with a cold period from 1645 to 1706, and the Dalton Minimum (1796–1830) is correlated with a cold stage spanning the years from 1810 to 1838. Four warm periods (1626–1637, 1800–1809, 1845–1859, and 1986–2012) coincided with periods of increased solar activity. Based on annual values, the correlation between the reconstruction and solar activity was 0.34 ($p < 0.0001$), and increased to $r = 0.49$ if an 11-year low pass running mean filter was applied to both series. In addition, similar cold and warm phases were observed when these data were compared with reconstructions for the Pyrenees (Büntgen et al., 2008; Dorado-Liñán et al., 2012) and Cazorla (Dorado-Liñán et al., 2014).

Figure 5

Based on the drought reconstruction for the Iberian Range reported by Tejedor et al. (2016), during the 18th century there was a high frequency of occurrence of extreme dry events and a low recurrence of extreme wet years. The 19th century showed fewer years having extreme events, and 38% of all extreme events occurred in the 20th century. Using an 11-year running mean, five dry periods during the LIA were identified (in order of severity: 1798–1809, 1744–1755, 1871–1882, 1701–1712, and 1771–1782), while three wet phases were detected (1756–1766, 1883–1894, and 1810–1821). The most severe droughts occurred in 1725, 1726, 1741, 1803, and 1879. Some of these years (1803, 1879) were also reported by Génova (2012) as being years of severe drought in central and northeastern Spain. In contrast, most of the extremely wet events occurred in the 20th century, while during the LIA phase only 1788 appears to have been an extremely wet year. Recently, Andreu et al. (2017), using stable isotopes, have showed in the Cantabrian range extreme dry periods around 1700 and 1750 but general humid conditions during the first half of the ninetieth century.

Although there is overlap in some extreme dry and wet years reported for the LIA compared with other drought reconstructions across Europe (1725, 1726, 1797: Akkemik et al., 2005; 1803, 1808: Esper et al., 2007; 1725: Levanic et al., 2013), what is remarkable is the consistency of the frequency of extreme events. The 18th century was characterized by a high frequency of extreme precipitation events; this decreased significantly during the 19th century, which could be related to the end of the LIA (Bradley & Jones, 1992). In northeast Spain, compared with the 16th and 17th centuries, the end of the LIA did not appear to be related to a temperature increase, but rather to a decrease in the interannual variability (Saz, 2003) and frequency of extreme drought events (Manrique & Fernández, 2000). Nevertheless, the frequency of extreme events increased again during the 20th century, particularly after 1930.

4.7 Historical sources

A large variety of documentary sources are available to enable reconstruction of the climate variability for the Iberian Peninsula, particularly between the 14th and 19th centuries (Barriendos, 1999). However, the volume of data and the time required to consult the relevant documents and extract information have limited the number of studies focusing on historical climatology. The documentary sources commonly record climatic or meteorological events that altered daily activities, particularly agriculture (e.g. Fernández-Fernández et al., 2015). In Mediterranean areas, these events were mainly caused by anomalies in the precipitation regime; few references concern the temperature regime (González et al., 2013; Alberola, 2014).

Analysis of temperature information has been reported in some studies (Table 9). Although the focus of these is temporally and spatially dispersed, they indicate that temperatures recorded between 1550 and 1850 were lower than current temperatures. These anomalies have been quantified at approximately –1°C during the period 1564–1599, with a minimum of –1.8°C during the period 1564–1575 in the Central Range (Bullón, 2008). Rodrigo et al. (2012) quantified the temperature anomaly at –0.4°C during 1701–1850 in Andalusia. Other studies have not quantified the anomalies, but reports indicate the occurrence of cold periods in southwest Iberia in the 1690s, 1787–1790, 1805–1808, 1818–1821, 1825–1827, and 1832–1837, and mild periods during 1777–1779, 1795–1800, and 1823–1825 (Alcoforado et al., 2002; Fernández-Fernández et al., 2017).

Table 9

Droughts are one of the main climate hazards affecting crops in Iberia. The reconstruction of droughts has been carried out through the study of rogation ceremonies, which are a good proxy for agricultural droughts (Martín-Vide & Barriendos, 1995; Domínguez-Castro & García-Herrera, 2016). Most of the LIA droughts showed strong temporal and spatial variability. Domínguez-Castro et al. (2010, 2012a) studied droughts throughout the entire peninsula for the period 1650–1850. They showed that in the first half of the 16th century the droughts were localized in comparison with droughts from 1650 to 1750, which affected greater areas, and the entire peninsula in 1664 and 1680. During the period 1750–1850 the driest intervals were 1750–1754 and 1779–1783, and the most extensive drought was in 1817, and was probably partially driven by the Tambora eruption in 1815; this caused anomalous climate conditions over Europe in the following two winters (Trigo et al., 2009a). At regional scales, in northeast Iberia drought events of moderate severity occurred almost continuously, with the exception of two wet periods in 1570–1610 and 1830–1870, and a shorter stage between 1795 and 1811 (Martín-Vide & Barriendos, 1995) (Fig. 6a). In the Ebro valley (Zaragoza) intense drought periods occurred in 1725–1775, 1765–1800, and 1814–1825, whereas in central Iberia (Toledo) drought periods were recorded in 1600–1675 and 1711–1775 (Domínguez-Castro et al., 2008).

Figure 6

Floods are also commonly recorded in the documentary sources, mainly when infrastructure damage occurred. High temporal and spatial variability in the frequency of floods during the LIA in Iberia is evident. Barriendos & Rodrigo (2006) analyzed 17 Iberian river basins and noted a major increase in flood frequency during the second half of 16th century and at the end of 18th century. At the regional scale, in northeast Iberia three periods of increased frequency of severe floods were recorded, in 1580–1620, 1760–1800, and 1830–1915 (Barriendos & Martín-Vide, 1998) (Fig. 6b). In the Tagus basin high flood frequencies were recorded in 1160–1210, 1540–1640, 1730–1760, and 1780–1810 (Benito et al., 2003a). In the southeast, high frequencies of large floods were recorded in 1440–1490, 1520–1570, 1600–1740, 1770–1800, and 1820–1840 (Machado et al., 2011).

These extreme hydrological flood and drought events have been used to build precipitation indexes and for reconstructions for various locations in Iberia for the last 500 years. Two dry periods (1501–1589 and 1650–1775) and two wet periods (1590–1649 and 1776–1937) have been identified in Andalusia (Rodrigo et al., 2000). Rodrigo et al. (2012) reported positive seasonal rainfall anomalies (with respect to the reference period 1960–1990) of 43 mm, 35 mm, and 32 mm during winter, spring, and autumn, respectively, during the period 1701–1850.

In the Mediterranean area similar precipitation patterns causing wet periods have been found for Barcelona (winter and spring), Murcia (spring), and Seville (spring) for the second half of the 18th and mid-19th centuries, and dry periods during the first half of the 16th century and from the mid-17th century to the mid-18th century (Rodrigo & Barriendos, 2008). Central Iberia (Zamora and Toledo) were similar in having maximum rainfall around the 1660s and the first decades of the 19th century, and minimum rainfall levels in the first decades of the 17th century and around 1750 (Rodrigo & Barriendos, 2008). In the Central Range, Bullón (2011) identified intense precipitation during 1585–1599. Fernández-Fernández et al. (2015) developed a precipitation index for Extremadura (Zafra), covering the period 1750–1840. This was based on weekly weather observations, and included reports describing extreme events. Their study identified two wet periods (1782–1789 and 1799–1807) and two dry periods (1796–1799 and 1816–1819).

Domínguez-Castro et al. (2015) studied short periods in Portugal based on daily weather observations in Lisbon, and concluded that the period 1631–1632 was wetter than at present. In central–north Portugal the driest years occurred in the early 1780s, and the greatest precipitation was recorded from 1784 onwards (Fragoso et al., 2015). In southern Portugal two intense droughts occurred, in 1694 and 1714–1716.

In summary, the documentary sources provide a large amount of information at high temporal and spatial resolution about the LIA climate and extreme climate events. In general terms the findings suggest that the conditions were colder and wetter, but many spatial and temporal differences are evident for this period, which must be considered within the framework of the non-stationary influence of the North Atlantic Oscillation (NAO) controlling changing precipitation patterns in western Europe (Vicente-Serrano & López-Moreno, 2008).

4.8 Instrumental series

A dense dataset of early instrument observations is available for the European continent, with climate series that commence in the 17th to 18th centuries. During the last three decades several initiatives aimed at detecting, digitizing, and recovering data from historical archives have commenced (Luterbacher et al., 1999; Camuffo & Jones, 2002; Brázdil et al., 2010; http://www.era-clim.eu). The results have been used to reconstruct gridded fields for temperature, precipitation, and pressure over Europe (Casty et al., 2007), and in many cases have been combined with a wide range of proxy data (Luterbacher et al., 2004; Pauling et al., 2006). Unfortunately, Iberia remains poorly represented in early instrument series (prior to 1850). The absence of official initiatives dedicated to developing an efficient network of weather stations (the first Spanish network commenced in 1858), and the historical context (including major wars in which many document archives were destroyed) explain the scarce and fragmented meteorological data available. Care must be taken in interpreting metadata, as many factors may have affected the homogeneity of the series (including the types and exposure of instruments, observers, and instrument relocations). As artifact-driven shifts often have the same magnitude as the climate signal, quality control and homogeneity testing is strongly recommended. However, as noted above almost no long-term series are available for comparison purposes concerning the period prior to 1850. While air temperature is a meteorological variable commonly available for the LIA period, rainfall data are less common, and only series for Gibraltar, Barcelona and Madrid provide data from the late 18th century.

To date, the oldest and most continuous series are for: Gibraltar from 1777 (Wheeler, 2006, 2007, 2011; Wheeler & Bell, 2012); Barcelona from 1780 (Rodríguez et al., 2001; Prohom et al., 2012, 2016); and Cádiz from 1786 (Wheeler, 1995; Barriendos et al., 2002; Gallego et al., 2007; Rodrigo, 2012). Recently, 16 new early series have been recovered for Madrid (1784–1850) and Valencia (1803–1850) (Domínguez-Castro et al., 2014). Portuguese series are also available, but they are quite short and sparse (Alcoforado et al., 2000, 2012; Domínguez-Castro et al., 2012b; Fragoso et al., 2015). More abundant data are more available since 1850, and a new adjusted dataset composed of the 22 longest and most reliable Spanish daily temperature records covering the period 1850–2003 has been provided (Brunet et al., 2007).

Mean annual temperature for four Iberian sites covering the period 1780–2010 was computed for the present study (Fig. 7). The mean annual temperature during the 1780–1940 period was clearly below the mean for the 1961–1990 reference period. During the 19th century there was a widespread cold period covering approximately 1800–1850, with general negative anomalies less than –1°C, and an even colder period from 1810 to 1820. A secondary minimum occurred in approximately the 1880 decade, and a less clear one in the vicinity of 1910–1920. In contrast, the period 1860–1880 had temperatures similar to the mean, and warmer temperatures around 1900. The sharp temperature decrease during the 1810 decade was associated with two major external forcing factors: the solar Dalton Minimum and a period of frequent volcanic activity, including the large volcanic eruptions that occurred in 1809 (of unknown origin) and 1815 (Tambora volcano: Trigo et al., 2009a).

Figure 7

The temporal coverage of data concerning precipitation is poorer. In addition, precipitation has a high spatial and temporal variability that is especially high in mountainous areas and under Mediterranean climates. Therefore, only an overview of the general rainfall conditions can be undertaken for the transition of the LIA to the present. As no early instrument series are available for sites located in mountain areas, 12 yearly homogenized rainfall series from surrounding cities have been grouped for the areas of the Cantabrian Mountains, the Pyrenees and the Sierra Nevada. To aid interpretation, the data were converted to percentages with respect to the 1961–1990 reference period, with 100% indicating a year having a total rainfall amount equal to the 1961–1990 mean (Fig. 8). For the Cantabrian Mountains and the Pyrenees areas, the 1885–1920 period included slightly negative anomalies, with values approximately 80% of the yearly mean precipitation. In contrast, and for the southernmost sector, wet years were more common during the 1870–1885 period. The Sierra Nevada area had higher internal variability compared with the other two areas, as a consequence of being more associated to a Mediterranean climate. Although no complete rainfall series are available for the period prior to 1850, the Barcelona series (starting date 1786) suggests there was a significant decrease in precipitation during the years 1810–1840 (Prohom et al., 2016).

Figure 8

4.9. Climate models

Using external forcing data, models have reconstructed surface temperatures at global and hemispheric spatial scales with reasonable resemblance with proxy reconstructions (e.g., Ahmed et al., 2013; Neukom et al., 2014; Luterbacher et al., 2016). The use of climate models for the validation of reconstructions show some limitations since given the internal variability of the models it is not expected a perfect match with climate reconstruction, mostly at the annual and sub-annual scales (Cane et al., 2006; Zorita et al., 2007). Although simulations are physically consistent they are not a real representation of the past climate variability since unknown initial states of the oceans, insufficient resolution to capture important processes, such as convective rainfall, and simplifications of the basic climate system (Franke et al., 2011). Nevertheless, climate models have demonstrated that external forcing, such as the concentrations of stratospheric volcanic aerosols and changes in total solar irradiance, have affected European temperature variability throughout the past five centuries (Zorita et al., 2010; Hegerl et al., 2011).

There are different simulations for the climate of the last millennium in Europe (Zorita et al., 2004; González-Rouco et al., 2003; Luterbacher et al., 2016; Ljungqvist et al., 2016). These simulations are run at very coarse horizontal spatial resolutions (2.5 – 3.5º) to allow detailed assessment of climate processes in the mountains of the Iberian Peninsula (Harrison et al., 2016), but downscaling approaches provide model simulations in the Iberian Peninsula at the sufficient spatial resolution to identify climate variability in the mountain areas over the past millennium (Gómez-Navarro et al., 2011, 2012). Models in general support climate reconstructions of temperatures by dendrochronological reconstructions in different Iberian mountains (e.g. Dorado-Liñán et al., 2012, 2015) but also recent comparison with robust dendrochronologies in Portugal and the Pyrenees have showed little agreement with climate model simulations (Santos et al., 2015; Büntgen et al., 2017). In any case, paleoclimatic modelling is physically consistent and it allows exploring the physical mechanisms that explain precipitation and temperature variability during the LIA, and determining the role of external forcing and climate internal variability.

Gómez-Navarro et al. (2011) used the mesoscale model MM5, driven by the global model ECHO-G to downscale GCM simulations to 30 km of spatial resolution over the Iberian Peninsula for the last millennium (1001-1990). They used greenhouse gases concentrations, total solar irradiance and the global mean radiative forcing of stratospheric volcanic aerosols as external forcing. The model identified some important cold periods like the Spörer Minimum (around 1450), the Maunder Minimum (around 1700) and the Dalton Minimum (around 1810), coinciding, in general, with a reduction of total solar irradiance and increased volcanic activity. The models also showed that some minima can be identified in all seasons, such as the Spörer Minimum, whereas others, like the

Maunder Minimum, can hardly be identified in winter, suggesting that the physical mechanisms under different cold periods could be very different. Gómez-Navarro et al. (2012) analysed in detail the role of the internal variability of the climate system and the external forcing over the past millennium using two different simulations, characterized by different initial conditions, of the same MM5 model. The model showed high agreement in the evolution of temperatures between both simulations, suggesting that external forcing seems to be the main driver of the temperature variability during the LIA in the Iberian Peninsula. Dorado-Liñán et al. (2012, 2014) used different GCMs to identify drivers of temperature variability in the Pyrenees and Cazorla (Southeast of the Iberian Peninsula) and showed that solar irradiance, but especially volcanism, had the main role to explain decadal to multidecadal summer temperature variability during the LIA. They showed that the combination of low solar irradiance and high volcanic activity coincided with cold phases identified with dendrochronological reconstructions in both regions, and suggested that volcanism could have had the main impact on the temperature variability during the LIA, being responsible of strong punctual decreases of temperatures and could even have cancelled the effect of the warming induced by maximum solar irradiance during the 16 and 17th centuries. For the Pyrenees, Büntgen et al. (2017) also showed general abrupt cooling of summer temperatures responding to the preindustrial eruptions.

Although models considering external forcing may reproduce well some cold phases during the LIA, simulations also show strong uncertainty at the interannual scale. Thus, model simulations show large discrepancies in comparison to dendrochronological reconstructions, such as the duration and magnitude of warming or cooling events of particular climatic episodes (Büntgen et al., 2017). A likely reason for such differences is that at higher frequencies, i.e. decadal time scales, the agreement between model simulations and reconstructions is lower, because the climate variability at these time scales is mostly internal and not driven by the external forcing (Zorita et al., 2007; Gómez-Navarro et al., 2012). Thus, Gómez-Navarro et al. (2011) showed exceptions in the agreement between temperature variability by the MM5 model and the forcing conditions (e.g. around 1620, in which a cold phase was also recorded) and a similar pattern was found by Gómez-Navarro et al. (2015) to reproduce in Europe a warm period during the first decades of the 18th century. Therefore, the characteristic internal variability of the model can be an important source of uncertainty in the climate simulations. Thus, the different studies in the Iberian Peninsula have clearly showed that the amplitudes of the temperature variations are considerably larger in the model simulations than in the reconstructions (Dorado-Liñán, 2012, 2014; Gómez-Navarro et al., 2012; Santos et al., 2015), which is common in this kind of studies (von Storch et al., 2004). In any case, Gómez-Navarro et al. (2015) showed how simulated climate is physically consistent independently of the little agreement in the evolution of temperature reconstructions and simulations.

Internal variability of models seems to be even more critical for precipitation. Simulations of precipitation showed a general mismatch between modelled and reconstructed precipitation for the Iberian Peninsula, suggesting that part of the variation in precipitation is probably caused internally and not related to external forcing but physical mechanisms and different atmospheric circulation processes (Gómez-Navarro et al., 2011, 2012; Santos et al., 2015) as occurs in the present-day climate (e.g., Trigo et al., 2000; Cortesi et al., 2014; Vicente-Serrano et al., 2016). Thus, volcanic forcing could only affect precipitation variability at decadal or longer time-scales via connection with the Atlantic multidecadal variability (Wang et al., 2017), as suggested in the Pyrenees by Büntgen et al. (2017). In any case, the model outputs clearly suggest a strong link between different atmospheric circulation mechanisms (mainly the NAO) and the precipitation variability during the LIA (Gómez-Navarro et al., 2012). Thus, the Maunder and Dalton minima would be characterized by a positive precipitation anomaly linked to the strong minimum in the NAO index (Gómez-Navarro et al., 2012).

Since NAO variability is mainly driven by the internal variability of the climate system (Rodwell et al., 1999; Hurrell et al., 2001), variability of precipitation in the Iberian Peninsula during the LIA is probably driven by these internal variability processes more than by external forcing. Recently, Gagen et al. (2016) have suggested that precipitation and cloud cover in Europe, linked to oscillations in the position of the summer storm track, are independent of external forcing at decadal timescales during the last millennium and equivalent to the atmospheric mechanisms under the current climate scenario.

Gómez-Navarro et al. (2012) showed variable precipitation response between two independent precipitation simulations in the Iberian Peninsula, and stressed the difficulty of identifying an impact of the external forcing on the identified dry and wet periods, suggesting an important role of local circulation and the interaction with the orography. Thus, the spatial pattern of the NAO influence on precipitation variability in the Iberian Peninsula identified in the models is another sign of robustness of the internal variability hypothesis. Gómez-Navarro et al. (2012) showed strong spatial differences in the role of NAO on the precipitation across the Iberian Peninsula in the model simulations, and equivalent to those observed during the second half of the 20t century (Rodríguez-Puebla et al., 1998; Martín-Vide & Fernández, 2001; Trigo et al., 2004). In addition, they showed a noticeable negative correlation between temperature and precipitation in the main mountain chains of the Iberian Peninsula, which is also identified by Gagen et al. (2016) in climate simulations over Europe over the last millennium. This would suggest that cold periods would affect condensation level in mountains and favor precipitation, providing coherent physical mechanisms of the connection between cold and humid periods recorded during the LIA. Moreover, the connection would be robust in simulations since it is independent of the strong internal variability of precipitation that climate models provide.

5 Environmental implications

5.1 Geo-ecological dynamics

A decrease of approximately 1°C in the average temperature during the LIA would have caused geo-ecological changes, particularly in the high mountains of the Iberian Peninsula. It is noteworthy that such a temperature decline represents a climatic altitudinal decrease of approximately 150 m, which would have affected the location of the tree line and the distribution of plant species, particularly those located in the subalpine and alpine belts, where a number of endemic species occur (Pauli et al., 2012). Recent studies in high European mountains have demonstrated that climate warming through the 20th century has resulted in a spatial contraction of alpine environments, including the Pyrenees, and the consequent decline of more cold-adapted species (Gottfried et al., 2012; Winkler et al., 2016), following a process contrasting with that which probably occurred during the LIA.

There are very few reports of landscape changes during the LIA in the Iberian mountains. Some indirect information is available on the effects of temperature decline and sudden climatic changes, including the construction of *neveras* (snow huts), where people stored the snow that fell in winter for use in summer. The LIA period was associated with widespread enhanced construction of *neveras*, even at very low elevations (Capel, 1970). Near the Spanish east coast, some *neveras* have been found below 600 m (Giménez-Font, 2014-2015), at elevations where it would now be impossible to store snow or ice. Use of *neveras* ceased in the second half of the 19th century. Since then, snow cover has shown a continuous negative trend (López-Moreno, 2005), and this has directly affected river regimes and dam operations during the 20th century (López-Moreno & García-Ruiz, 2004; López-Moreno et al., 2008).

It is difficult to distinguish the role of LIA cooling from that of land use changes. Not surprisingly, the cultivated area in mountains enlarged after the 16th century, and its maximum extent occurred in the middle of the 19th century (Lasanta, 1989), coinciding with the population maximum. Remarkably therefore, human factors (i.e. population growth) may have had greater influence than climate and its geo-ecological effects. For instance, the supply of large volumes of sediment from the hillslopes to the fluvial channels, which caused channel widening and braiding, may have been the consequence of more erosion linked to natural extreme events, or to human induced erosion caused by the enlargement of cultivated area on steep slopes, sometimes under shifting agriculture systems (see, for instance the example of the Ijuez River basin in the Upper Aragón Valley, central Pyrenees: Sanjuán et al., 2016).

It is likely that fields located at the highest agronomical limit (e.g. at 1500–1650 m in the central Pyrenees) were not cultivated during the coldest stages of the LIA, because it was impossible for rye to mature under the prevailing conditions of cold temperatures, snowfall, frost, and some alternating extremely dry years. These fields, termed *panares* (Fig. 9a), were located on deep soils of morainic origin, and produced rye in a 13-month cycle. They were re-cultivated from the end of the 19th century, but finally abandoned in the second half of the 20th century because of generalized farmland abandonment in mountain areas following depopulation (Lasanta, 1989). In studies of the characteristics of sediments from lacustrine sequences from the central Pyrenees, Pérez-Sanz et al. (2013) and González-Sampériz et al. (2017) noted that many high mountain areas were affected by temporary abandonment of human activities during the second part of the LIA, because of the unfavorable weather conditions. In mid-mountain areas (e.g. the Pre-Pyrenees), forest recovery has been recorded to have occurred in approximately 1500, coinciding with a wetter climate, although a decline in recovery occurred after the 17th century, coinciding with the expansion of cultivated fields (Rull et al., 2011). In the Neila Sierra (Iberian Range, northern Iberian Peninsula) a retreat of the forest has been deduced from analysis of lacustrine sediments; this was correlated with the LIA and subsequent increasing anthropogenic influence (Vegas, 2007).

Figure 9

Ecotones in mountain areas are the best places to study the effect of climatic change on plant (particularly forest) spatial distribution. The ecotone between the subalpine forests and alpine grasslands typifies temperate mountain ranges, and represents a dramatic transition zone that has complex consequences for runoff generation, geomorphic processes, snow accumulation, snowmelt, and soil formation. The rapid transition between the tree line and the upper extreme of the *krummholz* (Troll, 1973; Ives & Hansen-Bristow, 1983) reflects a zone where conditions became progressively colder, including short summers having temperatures too low to enable tree seedling development and growth, and winters that are extremely cold, snowy, and windy, which causes the dwarfing and warping of shrubs and trees. Snow redistribution by wind enhances the role of topography on the sinuous form of the *krummholz* limits.

However, it is particularly difficult to establish the natural tree line limits in the Iberian Peninsula ranges. The upper forest limit has commonly been artificially lowered to enlarge the area occupied by subalpine grasslands. In the case of the Urbión Sierra (Iberian Range, northeastern Iberian Peninsula) this commenced in Neolithic times, and continued during the Chalcolithic, the Bronze and Iron Ages, and the Middle Ages, based on ^{14}C dates obtained for charcoal fragments from the soil (García-Ruiz et al., 2016a). Two ash layers were also found in a core from Tramacastilla Lake (central Pyrenees). The first (dated at 3500 ^{14}C cal yr BP) suggests the occurrence of a short period of fires during the Bronze Age, after which there was rapid forest recovery, and the second represents generalized deforestation that occurred during the Middle Ages, followed by intense erosion processes and rapid sedimentation in the lake (Montserrat, 1992). The consequence of deforestation of the subalpine belt was the triggering of many shallow landslides (García-Ruiz et al., 2010), the elevational lowering of the area affected by solifluction (Höllermann, 1985), the development of badlands on some shale outcrops, and the presence of large parallel rills on rectilinear slopes (García-Ruiz & Puigdefábregas, 1982). The subalpine belt remained largely deforested after the Middle Ages because of the presence of large sheep flocks in summer, which made it difficult for the forest to re-establish (Ameztegui & Coll, 2015). Thus, fires and grazing were responsible for the location of an artificial tree line below 1600–1700 m.

What were the consequences of the LIA for the evolution of the ecotone forest/subalpine grasslands? It is widely accepted that the temperature decline during the LIA had no major effect on the position of the artificial tree line, as it was usually more than 500 m below the natural upper forest limit. Consequently, a theoretical decline of approximately 150 m in the upper forest limit would be unlikely to have had any significant effect on the tree line position. The contemporary uplift (in the second half of the 20th century) of the treeline is not a direct consequence of the upward trend in temperature because of global warming, as suggested by several authors, but because of land use changes, particularly the decreasing livestock pressure on some steep slopes of the subalpine grasslands (e.g. García-Ruiz et al., 2015, 2016b; Ameztegui et al., 2016). The uplift of the tree line has been estimated to be 50 m since 1956 on the south face of the Urbión Sierra (García de Celis et al., 2008) and the eastern Pyrenees (Ameztegui et al., 2016), and approximately 70 m in the central–western Pyrenees (unpublished data). Other authors consider that the recent evolution of the upper forest areas has been characterized more by increased tree density than by an upshift of the tree line (Camarero & Gutiérrez, 2004, 2007; Ameztegui et al., 2016).

Nevertheless, some evidence of changes during the LIA has been found in the few places where the natural tree line and timberline have been preserved. A dendroclimatic study in the headwater of the Escuaín Valley (Ordesa and Monte Perdido National Park, central Pyrenees) demonstrated that major changes occurred during the LIA in a small *P. uncinata* forest patch located at approximately 2300 m. Figure 9b shows the presence of several dead trees and numerous young trees approximately 10–12 years old. Many of the old trees recruited in the first half of the 18th century, coinciding with a relatively warm period, or in earlier warm periods. The pine deaths correspond to the cold transition period between the mid-17th and the early 18th centuries, and particularly from 1820 to 1860, when the temperature dropped rapidly at the end of the LIA (Camarero et al., 2015). A close relationship was found between the number of dead pines at the tree line and the coldest periods. Intense pine regeneration in the tree line confirms the rapid response of alpine tree lines to climate warming in the last 30 years. In semi-natural tree line places of the eastern Pyrenees, a moderate upward shift of 19.7 m was reported by Ameztegui et al. (2016), suggesting a time lag of more than 50 years in relation to temperature changes Matías (2012).

Thus, some changes in mountain landscapes of Iberia can be identified during the LIA, although many of them can be confused with changes caused by demographic growth in rural areas and the expansion of agricultural lands and grazing. In spite of that, the construction of *neveras*, the abandonment of the fields located at the highest altitudes, neighboring the subalpine belt, and the decline of the timberline in the few areas where the natural upper forest limit occurred, confirm that small changes in temperature and precipitation can affect human activities and the spatial organization of altitudinal belts in mountain areas. The end of the LIA represented the abandonment of *neveras* and the altitudinal recovery of the tree line, in the few sites where it could be considered "natural". Other landscape changes in the montane and subalpine belts that occurred coinciding with the LIA could be related to land use changes rather than to climate changes.

5.2 Social dimensions of climate impacts during the LIA

Extreme climate and meteorological events can have serious impacts on populations, affecting material goods, human lives, and natural environments (Meehl et al., 2000). These events range widely in type, magnitude, and frequency. The most common extreme climate phenomena having major social and natural impacts in the Iberian Peninsula are droughts, floods, and cold and heat waves (e.g. Barriendos & Llasat, 2003; Domínguez-Castro et al., 2008). The LIA was associated with an unusually high frequency of severe climate impacts on society (Pfister & Brázdil, 1999). The social dimensions of these and the corresponding mitigating measures were related to the social context where they occurred (Luterbacher & Pfister, 2015). During the LIA, the populations exposed to these climate impacts and its negative effects on daily life had technological, economic, and human resources that were significantly different from those currently available. Thus, it is difficult to assess and evaluate in any detailed way the ability of the population to respond, because of the uniqueness of each case. Nonetheless, this ability can be considered in terms of the capacity for adaptation to short- or long-term events, and in terms of distinctions between rural and urban settings.

Short-term events in the Iberian Peninsula are mainly floods and cold or heat waves; these showed relatively similar frequencies of occurrence (with the exception of the heat waves) during the LIA, in contrast to the present day situation. In rural contexts, and particularly in high mountain regions, the adverse climate conditions were managed relatively well. Self-protection responses and solidarity were the best resources during exposure to climate hazards (Blocker et al., 1991). Moreover, the return to normality was easier because of access to abundant natural resources (e.g. water, wood, food) and the lower population pressure than in other regions. On the other hand, in urban environments extreme climate impacts prevented the population from working, and they had limited resources available. The urban population had lost contact with the natural environment, and consequently did not have the experience or ability in obtaining contingency resources.

Floods in the Iberian Peninsula are mainly the consequence of heavy rainfall events during autumn, and to a lesser extent rain-on-snow events during spring, which cause rapid thawing in high mountain regions (Sánchez-López et al., 2015; Pino et al., 2016). Both are short-term episodes of limited extent, but their impacts affect many human activities and types of infrastructure. Climate oscillations involving flood events were very common during the LIA (e.g. Benito et al., 2008; Moreno et al., 2008; Morellón et al., 2011). Some of these produced extraordinary flows and involved multiple fluvial systems, but were not recorded during the instrument period. Among these are a flood event that occurred during November 1617 on the Mediterranean side of the peninsula (Thorndycraft et al., 2006), and another in January 1626 on the Atlantic side (Barriendos & Rodrigo, 2006). The effects on the society were direct and indirect. The former involved damage to dwellings and infrastructures, and the loss of human lives, whereas the latter included economic impacts associated with reconstruction, in particular the loss of water-powered mills. These mills played a key role at local scales, because of their use in grinding cereals to make bread. The subsequent shortages of bread affected the health of poorer social classes, making them more susceptible to infectious diseases. In addition, the loss of roads and bridges during extreme floods increased the price of freight transport. Nevertheless, despite the negative social effects of the floods, a positive outcome was the supply of sediments and nutrients essential for crop production.

Cold waves followed by heavy snowfalls were very frequent and particularly severe during the LIA (Rodrigo et al., 1998). Intense snowfall in mountain areas often triggered catastrophic avalanches, such as occurred in the Asturian Massif during the last decades of the LIA (García-Hernández et al., 2017a, 2017b). However, the main impacts of cold episodes were related to human health and difficulties in sourcing fuel in urban areas. During extended events the impacts on livelihoods were often as a consequence of effects on transport by canals, rivers, and roads. In the long-term the greatest impact was damage to crops. The associated losses affected the seasonal harvest, but also caused death of livestock and affected Mediterranean woody crops (e.g. vineyards, olive and fruit trees), which are very slow to recover and return to production. Flat areas supporting Mediterranean crops were highly vulnerable to cold waves, and those that occurred during the Dalton solar minimum were particularly extreme (González-Trueba et al., 2008; García-Ruiz et al., 2014b). There are several reports of prayer ceremonies being performed in response to the extremely low temperatures that occurred in that period (i.e. Municipal Archive of La Seu d'Urgell, "Llibre de Consells", 1826, fol. 13r.).

With their occurrence on the rise as a consequence of global warming (e.g. Barriopedro et al., 2011), heat waves are now considered to be a serious climate hazard in Iberia, with associated fires affecting large areas (Trigo et al., 2016) and significantly increasing associated loss of life (García-Herrera et al., 2005; Trigo et al., 2009b). However, there are few references to heat wave events during the LIA, suggesting that they were very unusual and had little impact on society. Some sources document inconvenience caused to some activities as a consequence of the heat (Fragoso et al., 2015), but in general heat effects were more associated with droughts. The impacts of these on crops through increased evapotranspiration produced a number of community responses, but these mainly involved religious services conducted to mitigate the effects of the droughts and to bring rain (*pro pluvia* rogations), rather than to end the heat wave.

In terms of long-term drought events, the situation was slightly different during the LIA (Domínguez-Castro et al., 2008). The agrarian setting was one of direct dependency on the crops, and in lowlands the limited access to irrigation systems during severe droughts became critical. In contrast, in high mountain areas water availability was better, enabling mitigation strategies to be developed. In urban settings there was even greater potential to develop mitigation strategies. Despite the high population density, the available technological and economic capabilities enabled the population to overcome long periods of drought. Some of the mitigation strategies included the substitution of water mills by wind mills, the deepening of wells and mines, and/or maximizing the maintenance of the piped water networks. Droughts have the most widespread and prolonged impacts on the Iberian Peninsula (e.g. Trigo & DaCamara, 2000; Vicente-Serrano et al., 2006). They had devastating effects during the LIA, negatively impacting food production, which was mainly based on cereals, and affecting large areas used for agriculture (Domínguez-Castro et al., 2012a). Furthermore, the decrease in river flow rates caused a severe hydraulic energy deficit, and reduced the flour supply to densely populated areas. Droughts are unique climate hazards that can trigger complete crises in subsistence economies. A one-year drought may be manageable, but two years of rainfall shortfall can result in conflicts and loss of populations in the most vulnerable social systems; sources have documented such processes, showing that two failed crop harvests at a local scale have led to market crises and eventual starvation. Opportunities for adaptation were very limited, and only available in specific regions; only areas of plain near large waterways, or mountain regions could respond to droughts using irrigation systems. However, these water resources were only effective if there was a large investment in construction of these systems, implying the need for major collective financial effort.

In contrast to other areas including Greenland, where rapid cooling during the LIA also affected the bone isotope composition of local populations from the 15th to the 17th centuries (Fricke et al., 1995), no similar linkages are evident in Iberia. There is evidence of diet changes in individuals from a coastal necropolis in northwestern Spain (12–17th centuries) that suggests modifications in food production during climate anomalies. López-Costas (2012) found that the isotope composition indicated an increase in the consumption of marine resources and C_4 plants (millet, and maize later), and that this coincided with periods of climate deterioration. This has been interpreted as a possible strategy to adapt to productivity decline, following a similar pattern to that detected in a nearby site during the Roman climate anomaly (López-Costas & Müldner, 2016). The short life cycles of millet and maize may have provided an advantage during harsh periods, when longer-growing crops were inhibited, and freed up areas for winter grazing (López-Costas et al., 2015). A similar isotope shift was observed in a 14–15th century population from Valencia (Mundee, 2010); although this was interpreted in terms of cultural and religious issues, the climate hypothesis cannot be dismissed.

In many areas the LIA coincided with a period of travel and migration. Whether the increase in contacts as a result of population movements or climate deterioration were responsible for the expansion of diseases and dietary change is difficult to ascertain (Coltrain, 2009). It is well known that during this period many pandemics affected Europe. For example, the Black Death and cholera decimated human populations at the beginning and end of the LIA, respectively. There are also other proxies to be explored in relation to the LIA, including human longevity and stature. A study of 1200 skeletons from different periods in Iberia showed a trend of increasing longevity that does not appear to have been affected by the occurrence of colder periods (Turbón et al., 1995). Stature has been suggested as a suitable proxy for climatic perturbations (Ahlstrom, 2011), though no particular trends have been found in this respect in the few necropolis sites that cover the period of the LIA (López-Costas, 2012).

6. Timing and climate conditions

The LIA was the last stage of a sequence of six cold events recorded worldwide during the Holocene (Wanner et al., 2011). Its occurrence few centuries ago provides high resolution data from a wide range of well-preserved climate and environmental sources (natural and historical) enabling characterization of one of the coldest events since the Younger Dryas (Bradley et al., 2003). However, because of the various spatio-temporal patterns of climate variability that coexisted during the LIA, there is no clear agreement on the timing of the onset and end of the LIA in the northern Hemisphere or the Iberian Peninsula.

Over recent decades the majority of studies in western Europe suggest that this climate shift commenced between the late 13th and the early 15th centuries. An example of this broad timing for the onset of the LIA is found in recent climate reconstructions; while some studies indicate it began in 1250 (e.g. Luterbacher et al., 2006, 2016), other recent records suggest a delay until as late as 1580 (e.g. Schneider et al., 2015). These differences may be attributable to the different proxies used, and the lag response between climate/geomorphic processes and ecosystem dynamics. At high elevations in the Canadian Arctic and Iceland there is evidence that cold summers and ice growth began abruptly between 1275 and 1300, triggered by volcanic activity and sustained by sea ice/ocean feedbacks (Miller et al., 2012). In Iberia, the longest proxy records (i.e. lacustrine, peatlands and speleotherms) examined in this study suggest that the cooling began in approximately 1300 (Fig. 10), as also suggested by marine records from the nearby Alboran Sea (Nieto-Moreno et al., 2013) and continental lacustrine sediments from the Central Range (Sánchez-López et al., 2016). Although some Arabian texts have highlighted the presence of snow and ice on summits of the Sierra Nevada during summer in the late MCA (Oliva & Gómez-Ortiz, 2012), historical sources indicate a shift to cooling at the end of 13th century in northeast Iberia (vineyards abandoned in high mountain areas in the Urgell bishopric and Andorra). This trend paralleled enhanced climate variability during early decades of the 14th century (detected through catastrophic flood frequency based on data from the PREDIFLOOD Project Database). This increase in extreme climate events is also evident in other Iberian records, including an increase in floods recorded in the western Iberian Peninsula in approximately 1300 (Benito et al., 2015a, 2015b).

Figure 10

Therefore, the establishment of LIA climate conditions followed a staggered pattern from northern to southern latitudes, and at higher elevations, where it is occurred earlier than in the lowlands. The gradual transition from the MCA to the LIA has been suggested to have been driven by a shift from a persistent positive mode of the NAO to a prevailing negative mode (Trouet et al., 2009). Nevertheless, attribution to changes to the internal variability of the climate, driven by atmospheric circulation mechanisms, shows some uncertainties since the natural variability cannot be well reproduced by the climate models (as discussed above). In addition, atmospheric circulation mechanisms show strong seasonality at the European level, making really difficult the attribution of general periods to a single circulation pattern that only affects a particular season (like the case of the NAO). Moreover, climate reconstructions of atmospheric circulation variability show strong uncertainties and different reconstructions of the dominant circulation patterns in the North Atlantic sector can show strong differences (Ortega et al., 2015).

In any case, assuming changes in the NAO as hypothesis of the climate variability during the LIA seems reasonable since the NAO has been considered in the framework of its interplay with the negative phase of the East Atlantic (EA) pattern (Sánchez-López et al., 2016). In Iberia, the positive NAO and EA modes that prevailed during the MCA led to a dry and warm climate regime that led to low lake levels, more xerophytic vegetation, a low frequency of floods, major Saharan aeolian fluxes, and less fluvial input to marine basins (Moreno et al., 2012; Sánchez-López et al. 2016). The changing climate patterns caused significant cooling during the LIA, the magnitude of which has been redefined for some regions based on new tree ring studies, which indicate warmer temperatures during the MCA (Esper et al., 2012). During the LIA, more persistent periods of negative NAO phases triggered frequent and large flood events. Nevertheless, the increasing variability of this index implies that there were also periods characterized by positive NAO phases, which favored prolonged and severe droughts in Iberia.

The various natural records considered in this study show evidence of differences in the timing, magnitude, and type of responses by terrestrial and aquatic ecosystems to the highly variable climate conditions that prevailed during the LIA in the Iberian Peninsula. Some records show relatively rapid environmental changes to atmospheric oscillations (e.g. mass balances of small Iberian glaciers), while others show a more delayed response (e.g. periglacial processes). This is related to the response time for certain land systems; for example, periglacial mass movements will only respond following land system changes including vegetation density, release of clastic material, and sediment mobilization (Oliva et al., 2011). Furthermore, some records infer environmental dynamics involving other land systems, and therefore constitute complementary sources of paleoenvironmental information. For example, the lacustrine sediment sequences of La Mosca Lake, in the Sierra Nevada, have provided evidence of different phases of glacial and periglacial activity in this massif during the LIA (Oliva & Gómez-Ortiz, 2012).

Therefore, our review underlines how the proxies reflect differently the changes occurring at the onset and the end of the LIA. This is related to the fact that each proxie relies in diferent environmental processess that exhibit contrasted times of response to climatic conditions: i.e. glaciers react slowly compared to tree growth or sediment characteristics, and the increase in flood frequency and magnitude does not necessarily coincide with the onset of colder conditions. The environmental and climate processes during the LIA showed complex interactions and they were activated at distinct temporal and spatial scales. Consequently, each proxy recorded the response of particular processes to changes at the onset and end of the LIA that could not be synchronous. The timing of the LIA phases and the internal structure are not also time and space transgressive, but also proxy (and process) dependent. In spite of this, most records indicate that colder conditions occurred from 1300 to 1850 in the Iberian Peninsula, with several climate stages (discussed below) that triggered differing environmental responses in mountain ecosystems and in the surrounding lowlands (Fig. 11).

Figure 11

From 1300 to 1480

This stage encompasses the first decades of increasing climate variability following the MCA, and overlaps with the economic and demographic crisis of the late Middle Ages in Europe, which was characterized by grain shortage and famine, Black Death, and demographic collapse. Temperatures started declining during the 14th century across Europe (Luterbacher et al, 2006) and Iberian records show evidence of moderate cooling (Fig. 11). Extreme rainfall events that triggered major floods occurred in rivers on the Mediterranean and Atlantic Ocean sides of the peninsula, particularly in the latter. Historical sources also record a concentration of torrential rain episodes that triggered devastating floods in two periods including approximately 1310–1330 and 1360–1390 (Llasat et al., 2005; Barriendos & Rodrigo, 2006, PREDIFLOOD Project Database). The moderate cooling persisted during the first decades of the 15th century, and intensified during the middle of that century during the Early Spörer Minimum (1431–1440), when a succession of extremely cold and persistent winters triggered profound socio-economic consequences in central Europe (Miller et al., 2012; Camenisch et al., 2016). A peak of flood activity occurred in western Iberia during that time, probably associated with negative NAO modes. These climate patterns must have also involved increased moisture conditions in the Sierra Nevada, which together with low temperatures flavored the development of a glacier inside the Mulhacén cirque by approximately 1440 (Oliva & Gómez-Ortiz, 2012).

From 1480 to 1570

The Spörer Minimum (approximately 1460–1550; Eddy, 1976) produced very cold conditions that brought severe famines across Europe (Camenisch et al., 2016), although the impact of this solar minimum is not clearly evident in the Iberian Peninsula (Fig. 11). Flood activity decreased in major rivers on the Atlantic Ocean side of the peninsula, except in the Guadalquivir basin (Benito et al., 1996), where there was associated alluvial reactivation in the Guadalete River (Wolf et al., 2013a). In contrast, flood frequency increased in rivers on the Mediterranean side of the peninsula, in the Guadaletín-Segura, Júcar, and Turia basins.

From 1570 to 1620

The late 16th and early 17th centuries included decades in which the coldest summer temperatures during the LIA in central Europe were recorded, whereas the peak of cold reached southern Europe in the late 17th century (Luterbacher et al., 2016). The year 1601 has been described as the coldest year of the millennium (Jones et al., 1998). The combination of cold and high moisture conditions favored the maximum expansion of some glaciers in the European Alps around 1600, including the Lower Grindelwald glacier (Holzhauser & Zumbühl, 1996). In Iberia, gradual cooling of the climate is evident in many records, associated with the increasing occurrence of cold spells and snowstorms, and enhanced storminess. Glaciers expanded in the highest Iberian ranges, and periglacial processes reactivated at lower elevations during this stage (Oliva et al., 2016a). Though alluvial records show moderate flood activity, historical sources show evidence of frequent and severe floods in northeast Iberia between 1590 and 1620 (Barriendos & Martín-Vide, 1998; Llasat et al., 2005; Barriendos & Rodrigo, 2006), together with high levels of precipitation in southern Spain (Rodrigo et al., 1999). Documentary and sediment (paleoflood) records indicate that the 1617 flood was the most extreme event in northeast Iberia in approximately the last 700 years (Thorndycraft et al., 2006). The atmospheric pattern triggering this intense rainfall event, which lasted for an unusually long period (from the 2nd to the 6th November) was probably associated with a predominantly negative NAO phase and blocking anticyclonic conditions to the east of Iberia, coinciding with high altitude cold air over western Europe (Sousa et al., 2016).

From 1620 to 1715

These decades include the coldest climate conditions of the LIA in southern Europe (Luterbacher et al., 2016), particularly during the Maunder Minimum (Shindell et al., 2001), with 1691–1700 being the coldest decade of the millennium (Jones et al., 1998). A wide range of natural and historical sources provide evidence of the socio-economic impacts that the cooling brought to early modern European societies (Fagan, 2002). As shown in dendroclimatic records, this phase also encompassed some short stages having significantly warmer conditions that almost reached post-LIA values, particularly at the beginning (i.e. by 1630). Written sources reveal cold and very dry conditions in Iberia during the following decades, intensifying during the second half of the century (Domínguez-Castro et al., 2010). Historical documents suggest a critical period occurred between 1680 and 1700, when severe cold and prolonged droughts caused serious famines in farming communities (Barriendos, 1997; Domínguez-Castro et al., 2010). These sources also indicate a moderate occurrence of other extreme events including floods and storms at the end of the 17th century, although sediment records suggest intense and frequent flooding in eastern Iberia. Marine and peat records from northwest Iberia also suggest that the coldest climate conditions during the LIA occurred around 1700 (Martínez-Cortizas et al., 1999; Desprat et al., 2003).

From 1715 to 1760

Increased solar radiation following the Maunder Minimum promoted warmer temperatures and relatively stable conditions in Europe until 1760, with a low frequency of extreme events. Therefore, this period can be considered to be a relative climate optimum, which led to an acceleration of population growth across Europe, from 120 to 187 million inhabitants (Bennassar et al., 1980); Barcelona, for instance, tripled in population (Vidal, 1984). These warmer conditions also promoted glacier retreat in the western and central European Alps during the first half of the 18th century until the 1760s (Nussbaumber et al., 2012). In the Sierra Nevada warmer conditions led to disappearance of the glacier that had been present in the Mulhacén cirque at the beginning of this period (Oliva & Gómez-Ortiz, 2012).

From 1760 to 1800

A clear deterioration in the climate occurred across Europe during this period, led by a rapid series of NAO negative/positive changes (Barriendos & Llasat, 2003) that brought a succession of episodes of alternating cold and heat, and floods and droughts, which had impacts on agricultural productivity throughout Europe (Fagan, 2002). Anomalous climate conditions were so persistent that various instances of social unrest and subsistence crises resulted. The deterioration in social conditions also favored the spread of epidemics including malaria (1783–1786), which infected approximately 1 million people including some 100,000 in Iberia (Giménez, 2008). Volcanic eruptions cooled the climate for short periods. These included the Laki eruption of 1783–84, which led to colder temperatures in the Northern Hemisphere until 1785, and had severe socio-economic consequences (Highwood & Stevenson, 2003). Early instrument records for Iberia show evidence of these remarkable temperature and precipitation oscillations (Alcoforado et al., 2012; Prohom et al., 2016). Floods were frequent in Mediterranean rivers, giving rise to alluvial aggradation on floodplains (Guadalete, Torrealvilla) and infilled valleys (e.g. Bardenas; Fig. 4).

From 1800 to 1850

A relatively stable stage, which occurred between 1800 and 1815, ended in the late Dalton Minimum (1790–1820), when low solar forcing and large volcanic eruptions disrupted the stability of climate conditions in Iberia. The most significant event occurred following the Tambora eruption of 1815, which led to global cooling of approximately 0.5°C (Fischer et al., 2007; Auchmann et al., 2012), and summer temperatures that were 2–3°C colder in Iberia (Trigo et al., 2009a). Large tropical volcanic eruptions favored a shift to a positive NAO index, which determined the European climate over the following 1–2 years (Shindell et al., 2004), and produced extreme events (major floods, prolonged droughts, cold summers) between 1815 and 1835. Between 1835 and 1850 there was a slight increase in temperatures in parallel to enhanced hydrometeorological dynamics, including storms, persistent rain, and dramatic floods. The increased moisture favored glacier expansion in the Pyrenees during the first decades of the 19th century, as probably also occurred in the Cantabrian Mountains and the Sierra Nevada. In the western and central European Alps a major glacial advance occurred in approximately 1820 and a minor advance occurred in 1850 (Zumbühl et al., 2009; Nussbaumer et al., 2012). Instrument records from Iberia show evidence of these rapidly changing climate conditions during these decades (Fig. 7).

Since 1850

The second half of the 19th century has been widely referred to in the scientific literature as the end of the LIA, although some recent reconstructions bring it back to 1700 (Luterbacher et al., 2016). Based on the available data (retreating glaciers, increased organic deposition in lakes, low flood activity, dendroclimatic evidence) it seems reasonable to estimate that in Iberia the LIA had ended by 1850. Between 1850 and 1870 there is a temperature increase of almost 1°C, as shown in the evolution of the longest available temperature series in Spain (Fig. 7). By 1860 there were attempts to establish vine plantations in Andorra. Although these failed, the fact of efforts to establish vines in the central Pyrenees suggests that the climate conditions were significantly warmer than during previous decades, and that a less extreme climate prevailed in mountain environments (Martzluff & Mas, 1992). Together with reduced precipitation, warmer conditions led to glacier retreat in all the glaciated mountain environments (Table 3). Temperatures remained almost stable during the following decade, and dropped further by approximately 1°C between 1880 and 1890. During this period the large Krakatoa eruption of 1883 altered global climate, favoring a widespread reduction in temperatures at mid and high elevations (Bradley, 1988). In approximately 1890 this last cold phase of the 19th century, enhanced by volcanic activity, concluded with a sharp temperature increase, and by 1900 the temperatures had reached values similar to those recorded by 1870.

The warming began in approximately 1850, and together with periods of reduced precipitation (Fig. 8) there was gradual shrinking of the small LIA glaciers. This led to their complete disappearance from the Cantabrian Mountains and the Sierra Nevada during the first half of the 20th century, and for those still present in the Pyrenees an 80% reduction in volume relative to the LIA (Table 3). An increase in elevation of cold climate geomorphological processes was also observed for nival and periglacial dynamics, which shifted to the highest lands (Oliva et al., 2011). Geo-ecological processes responded to the warming with a spatial shrinking of alpine environments (García-Ruiz et al., 2015), a decrease in cold adapted species (Gottfried et al., 2012; Winkler et al., 2016), and an uplift of the tree line, triggered by reduced livestock pressure in the subalpine grasslands (e.g. García-Ruiz et al., 2015, 2016b; Ameztegui et al., 2016).

The magnitude of cooling during the LIA varied among regions, and was highly dependent on the reference period. Based on glacier records, Lampre (1994) reported an increase in the mean annual air temperature of 0.5–0.8°C since the end of the LIA. Serrano (1996), Chueca et al. (1998), López-Moreno (2000) and González-Trueba et al. (2008) reported increases of 0.76ºC, 0.9–0.95ºC, 0.85–1ºC and 0.9 ºC, respectively, although these values could be underestimates because of lags in the response of glaciers to climatic change. The temperature increase in the Picos de Europa has been estimated to have been 1°C (González-Trueba, 2006, 2007). From peat records in northwest ranges, Martínez-Cortizas et al. (1999) estimated that the coldest LIA mean temperatures were approximately 1.7°C below 1960–1990 values. The distribution of periglacial landforms and long-term snow patches suggests a temperature increase of 0.93°C has occurred in the Sierra Nevada since the first decades of the 19th century (Oliva & Gómez-Ortiz, 2012). The recent climate trends in Iberia reveal an overall increase in solar radiation and surface air temperature (approximately 0.3°C decade^{-1}, particularly during summer), and a decline in relative humidity (Vicente-Serrano et al., 2017).

7. Conclusions

The review demonstrates a large impact of the LIA climate variability on mountain ecosystems and surface processes in the Iberian Peninsula, with distinct changes in environmental dynamics at the LIA onset (ca 1300 AD) and end (ca 1850 AD). Although reconstructed conditions were generally cooler, a complex internal structure shows large variability in humidity and extreme events. The impact of the LIA climate on mountain ecosystems is still evident in many Iberian mountain ranges, with environmental dynamics in some cases reacting to post-LIA warming.

A multi-proxy analysis of natural and historical records for Iberian mountains provided evidence of the intensity of cooling and the timing of the LIA across Iberia. The reported spatio-temporal consequences for natural systems diverge, depending on the characteristics of the natural records, with rapid responses evident in some cases (e.g. tree rings) and delayed responses in others (e.g. glaciers). In general, natural archives, historical sources and climate models point to centuries of enhanced climate variability involving the occurrence of events including severe droughts, floods, and cold/heat waves; this occurred under persistently colder conditions than occur at present.

The records suggest that the onset of the LIA resulted from a shift from the warmer climate conditions that prevailed during the MCA, associated to external forcing (mostly volcanic eruptions and solar irradiance reductions) that affected internal climate variability dominated by negative phases of the NAO and AE that brought more unstable air masses to Iberia. This climate pattern commenced around approximately 1300 and lasted until approximately 1850, with various phases mostly driven by variations in solar and volcanic activity, and by sea ice/ocean feedbacks. These factors determined the dominant atmospheric circulation patterns over western Europe, and thus over the Iberian Peninsula. The phases include:

1300–1480: moderate cooling and increasing climate variability;
1480–1570: relatively warmer conditions with low frequency of extreme events;
1570–1620: gradual cooling with increasing occurrence of cold spells, snowstorms, and enhanced storminess;
1620–1715: the coldest climate conditions of the LIA, particularly during the Maunder Minimum, and severe cold and prolonged droughts between 1680 and 1700;
1715–1760: warmer temperatures and relatively stable conditions, with low frequency of extreme events;
1760–1800: climate deterioration with cold and heat waves, floods, and droughts;
1800–1850: highly variable climate conditions alternating with stable conditions (1800–1815), extreme events (1815–1835), and a slight trend of warming with intense hydrometeorological events (1835–1850);
and since 1850: progressive and staggered temperature increase, with the occurrence of short cold phases and extreme events.

In general, the temperatures during the coldest stages in the late 17th and early 18th centuries were on average of approximately 1°C lower than those in 1850, and approximately 2°C lower than present-day values. Significantly lower values occurred during years following major volcanic events. For example, 1816 is known as the year without summer, and it followed the Tambora eruption in April 1815. Therefore, since the end of the LIA the increase in mean annual temperature has been estimated to have been 1°C, as suggested by both natural records and instrument data.

Environmental responses to this cooling included expansion of glaciers, downslope migration of the periglacial belt, low lake productivity, increased sediment runoff, and periods having increased flood activity. In many mountain environments, the cooling also brought an increase of natural hazards (e.g. catastrophic avalanches), geo-ecological (e.g. tree lines) and land use (e.g. agriculture practices) changes. Subsequently, with the temperature increase that commenced in 1850 and population growth in mountain areas, some of the agricultural lands abandoned during the coldest phases of the LIA were re-cultivated.

Post-LIA warming associated with changing precipitation patterns has impacted the mountain ecosystems in a wide variety of ways, including the gradual shrinking of glaciers, reduced periglacial activity and movement of periglacial activity to higher elevations, up-slope migration of certain plant species, enhanced soil development, and changes to the tree line level, which has been helped by the abandonment of the subalpine grasslands belt. It is expected that the forecasted climate scenarios for the coming decades, with temperatures projected to increase by more than 2°C by the end of the 21st century (IPCC, 2013), will reinforce recent environmental dynamics, and that the spatial extent of cold climate processes will shrink in Iberian mountains.

Acknowledgements

MO is supported by the Ramón y Cajal Program of the Spanish Ministry of Economy and Competitiveness (RYC-2015-17597). OLC is funded by Plan Galego I2C mod. A and Juan de la Cierva Incorporación (IJCI-2015-26864). This study was supported by the research projects CRIOINDI (CGL2015-68144-R), ESPAS (CGL2015-65569-R), DESIRÈ (HAR2013-43701-P), (CGL2014-58127-C3-1-R) and CLIMED (CGL2015-69985R) of the Spanish Ministry of Economy and Competitiveness (MINECO/FEDER) and IMDROFLOOD financed by the Water Works 2014 co-funded call of the European Commission.

References

Abel-Schaad, D., López-Sáez, J.A., 2013. Vegetation changes in relation to fire history and human activities at the Peña Negra mire (Bejar Range, Iberian Central Mountains System, Spain) during the last 4000 years. Vegetation History and Archaeobotany, 22, 199–214.

Aguilar, E., Auer, I., Brunet, M., Peterson, T.C., Wieringa, J., 2003. Guidelines on climate metadata and homogenization. World Meteorological Organization, Geneva, 51 pp.

Ahlstrom, T., 2011. Life-history theory, past human populations and climatic perturbations. International Journal of Osteoarchaeology 21 (4), 407–419.

Ahmed, M., Anchukaitis, K.J., Asrat, A., Borgaonkar, H.P., Braida, M., Buckley, B.M., Büntgen, U., Chase, B.M., Christie, D.A., Cook, E.R., Curran, M.A.J., Diaz, H.F., Esper, J., Fan, Z.-X., Gaire, N.P., Ge, Q., Gergis, J., González-Rouco, J.F., Goosse, H., Grab, S.W., Graham, N., Graham, R., Grosjean, M., Hanhijärvi, S.T., Kaufman, D.S., Kiefer, T., Kimura, K., Korhola, A.A., Krusic, P.J., Lara, A., Lézine, A.-M., Ljungqvist, F.C., Lorrey, A.M., Luterbacher, J., Masson-Delmotte, V., McCarroll, D., McConnell, J.R., McKay, N.P., Morales, M.S., Moy, A.D., Mulvaney, R., Mundo, I.A., Nakatsuka, T., Nash, D.J., Neukom, R., Nicholson, S.E., Oerter, H., Palmer, J.G., Phipps, S.J., Prieto, M.R., Rivera, A., Sano, M., Severi, M., Shanahan, T.M., Shao, X., Shi, F., Sigl, M., Smerdon, J.E., Solomina, O.N., Steig, E.J., Stenni, B., Thamban, M., Trouet, V., Turney, C.S.M., Umer, M., van Ommen, T., Verschuren, D., Viau, A.E., Villalba, R., Vinther, B.M., Von Gunten, L., Wagner, S., Wahl, E.R., Wanner, H., Werner, J.P., White, J.W.C., Yasue, K., Zorita, E. 2013. Continental-scale temperature variability during the past two millennia. Nature Geoscience, 6 (5), 339–346.

Alberola, A., 2014. Los cambios Climáticos. La Pequeña Edad del Hielo en España. Cátedra, Madrid.

Alcoforado, M.J., Nunes, M.F., García, J.C., Taborda, J.P., 2000. Temperature and precipitation reconstruction in Southern Portugal during the late Mauder Minimum (AD 1675-1715). The Holocene, 10 (3), 333–340.

Alcoforado, M.J., Vaquero, J.M., Trigo, R.M., Taborda, J.P., 2012. Early Portuguese meteorological measurements (18th century). Climate of the Past, 8, 353–371.

Almarza, C., López-Díaz, J.A., Flores, C., 1996. Homogeneidad y variabilidad de los registros históricos de precipitación de España. Instituto Nacional de Meteorología, Ministerio de Medio Ambiente, Madrid, 318 pp.

Alonso, V., González-Suárez, J.J., 1998. Presencia de hielo glaciar en los Picos de Europa (Cordillera Cantábrica). El helero del Jou Negro. Cuaternario y Geomorfología, 12, 35–44.

Ameztegui, A., Coll, L., 2015. Herbivory and seedling establishment in Pyrenean forests: Influence of micro- and meso-habitat factors on browsing pressure. Forest Ecology and Management, 342, 103–111.

Ameztegui, A., Coll, L., Brotons, L., Ninot, J.M., 2016. Land-use legacies rather than climate change are driving the recent upward shift of the mountain tree line in the Pyrenees. Global Ecology and Biogeography, 25 (3), 263–273.

Andreu-Hayles, L., Ummenhofer, C.C., Barriendos, M., Schleser, G.H., Helle, G., Leuenberger, M., Gutiérrez, E., Cook, E.R., 2016. 400 Years of summer hydroclimate from stable isotopes in Iberian trees. Climate Dynamics, doi: 10.1007/s00382-016-3332-z.

Auchmann, R., Brönnimann, S., Breda, L., Bühler, M., Spadin, R., Stickler, A., 2012. Extreme climate, not extreme weather: the summer of 1816 in Geneva, Switzerland. Climate of the Past, 8, 325–335.

Baartman, J.E.M., Veldkamp, A., Schoorl, J.M., Wallinga, J., Cammeraat, L.H., 2011. Unravelling late Pleistocene and Holocene landscape dynamics: The upper Guadalentin basin, SE Spain. Geomorphology, 125, 172–185.

Bal, M.C, Pèlachs, A., Pérez-Obiol, R., 2011. Fire history and human activities during the last 3300 cal yr BP in Spain's Central Pyrenees: The case of the Estany de Burg. Palaeogeography, Palaeoclimatology, Palaeoecology, 300 (1-4), 179–190.

Barrera, A., Llasat, M.C., Barriendos, M., 2006. Estimation of extreme flash flood evolution in Barcelona County from 1351 to 2005. Natural Hazards and Earth System Science, 6, 505–518.

Barreiro-Lostres, F., Brown, E., Moreno, A., Morellón, M., Abbott, M., Hillman, A., Giralt, S., Valero-Garcés, B.L., 2015. Sediment delivery and lake dynamics in a Mediterranean mountain watershed: Human-climate interactions during the last millennium (El Tobar Lake record, Iberian Range, Spain). Science of the Total Environment, 533, 506–519.

Barrère, P., 1952. Évolution mécanique et nivation sur les versants calcaires de la haute montagne pyrénéenne. Pirineos, 24, 201–213.

Barriendos, M., 1997. Climatic variations in the Iberian Peninsula during the late Maunder Minimum (AD 1675-1715): an analysis of data from rogation ceremonies. The Holocene, 7 (1), 105–111.

Barriendos, M., 1999. La climatología histórica en el marco geográfico de la antigua Monarquía Hispana. Scripta Nova, 3, 32–54.

Barriendos, M., Llasat, M.C., 2003. The case of the Maldá' anomaly in the Western Mediterranean basin (AD 1760–1800): an example of a strong climatic variability. Climatic Change, 61, 191–216.

Barriendos, M., Martín-Vide, J., 1998. Secular climatic oscillations as indicated by catastrophic floods in the Spanish Mediterranean coastal area (14th-19th centuries). Climatic Change, 38, 473–491.

Barriendos, M., Rodrigo, F.S., 2006. Study on historical flood events of Spanish rivers using documentary data. Hydrological Sciences Journal, 51 (5), 765–783.

Barriendos, M., Martín-Vide, J., Peña, J.C., Rodríguez, R., 2002. Daily meteorological observations in Cádiz-San Fernando. Analysis of the documentary sources and the instrumental data content (1786–1996). Climatic Change, 53, 151–170.

Barrio, G., Creus, J., Puigdefábregas, J., 1990. Thermal seasonality on the high mountain belts of the Pyrenees. Mountain Research and Development, 130, 29–31.

Barriopedro, D., Fischer, E.M., Luterbacher, J., Trigo, R.M., García-Herrera, R., 2011. The hot summer of 2011: redrawing the temperature record map of Europe. Science, 332, 220-224.

Bartolomé, M., Moreno, A., Sancho, C., Cacho, I., Stoll, H., Edwards, L.R., Cheng, H., Mas, J., Fuertes, X., 2015a. Reconstrucción paleoclimática de los últimos 500 años a partir de espeleotemas (Cueva de Seso, Pirineo Central), in: Galve, J.P., Azañón, J.M., Pérez-Peña, J.V., Ruano, P. (Eds.), Una visión global del Cuaternario El hombre como condicionante de procesos geológicos. Asociación Española para el Estudio del Cuaternario. Granada (Spain), 86–89.

Bartolomé, M., Moreno, A., Sancho, C., Stoll, H.M., Cacho, I., Spötl, C., Belmonte, Á., Edwards, R.L., Cheng, H., Hellstrom, J.C., 2015b. Hydrological change in Southern Europe responding to increasing North Atlantic overturning during Greenland Stadial 1. Proceedings of the National Academy of Sciences, 112, 6568–6572.

Bartolomé, M., Sancho, C., Osácar, M.C., Moreno, A., Leunda, M., Spötl, C., Luetscher, M., López-Martínez, J., Belmonte, A. 2015c. Characteristics of cryogenic carbonates in a Pyrenean ice cave (northern Spain). Geogaceta, 58, 107–110.

Beer, J., Mende. W., Stellmacher, R., 2000. The role of the sun in climate forcing. Quaternary Science Reviews, 19, 403–415.

Belmonte-Ribas, A., Sancho, A., Moreno, A., López-Martínez, J., Bartolomé, M., 2014. Present-day environmental dynamics in ice cave A294, Central Pyrenees, Spain. Geografia Fisica e Dinamica Quaternaria, 37, 131–140.

Benedict, J.B., Maisch, M., 1989. The Little Ice Age, Jean M. Grove. Methuen, London and New York, 498 pp.

Benito, G., Machado, M.J., Pérez-González, A., 1996. Climate change and flood sensitivity in Spain. Geological Society of London, Special Publication, 115, 85–98.

Benito, G., Díez-Herrero, A., Fernández de Vilalta, M., 2003a. Magnitude and frequency of flooding in the Tagus Basin (Central Spain) over the last millennium. Climatic Change, 58, 171–192.

Benito, G., Sopeña, A., Sánchez-Moya, Y., Machado, M.J., Pérez-González, A., 2003b. Palaeoflood record of the Tagus River (Central Spain) during the Late Pleistocene and Holocene. Quaternary Science Reviews, 22, 1737–1756.

Benito, G., Thorndycraft, V.R., Rico, M., Sánchez-Moya, Y., Sopeña A., 2008. Palaeoflood and floodplain records from Spain: Evidence for long-term climate variability and environmental changes. Geomorphology, 101, 68–77.

Benito, G., Rico, M., Sánchez-Moya, Y., Sopeña, A., Thorndycraft, V.R., Barriendos, M., 2010. The impact of late Holocene climatic variability and land use change on the flood hydrology of the Guadalentín River, southeast Spain. Global and Planetary Change, 70, 53–63.

Benito, G., Macklin, M.G., Panin, A., Rossato, S., Fontana, A., Jones, A.F., Machado, M.J., Matlakhova, E., Mozzi, P., Zielhofer, C., 2015a. Recurring flood distribution patterns related to short-term Holocene climatic variability. Nature Scientific Reports, 5, 16398.

Benito, G., Macklin, M.G., Zielhofer, C., Jones A., Machado, M.J., 2015b. Holocene flooding and climate change in the Mediterranean. Catena, 130, 13–33.

Bennassar, M.B., Jacquart, J., Lebrun, F., Denis, M., Blayau, N., 1980. Historia Moderna, Akal, Madrid, 1068 pp.

Berenguer-Sempere, F., Gómez-Lende, F., Serrano, E., Sanjosé-Blasco, J.J., 2014. Orthothermographies and 3D modeling as potential tools in ice caves studies: the Peña Castil Ice Cave (Picos de Europa, Northern Spain). International Journal of Speleology, 43 (1), 35–43.

Bide, J.B., 1893. Deuxième excursion dans la Sierra Nevada. Annuaire du Club Alpin Français, 20, 276–305.

Blocker, T.J., Rochford, E.B., Sherkat, D.F., 1991. Political responses to natural hazards: Social movement participation following a flood disaster. International Journal of Mass Emergencies and Disasters, 9 (3), 367–382.

Boch, R., Cheng, H., Spötl, C., Edwards, R.L., Wang, X., Häuselmann, P., 2011. NALPS: a precisely dated European climate record 120–60 ka. Climate of the Past, 7, 1247–1259.

Borsato, A., Frisia, S., Fairchild, I.J., Somogyi, A., Susini, J., 2007. Trace element distribution in annual stalagmite laminae mapped by micrometer-resolution X-ray fluorescence: Implications for incorporation of environmentally significant species. Geochimica et Cosmochimica Acta, 71, 1494–1512.

Bradley, R.S. 1988. The explosive volcanic eruption signal in Northern Hemisphere temperature records. Climatic Change, 12, 221–243.

Bradley, R.S., 2003. Climate forcing during the Holocene. PAGES, 11, 2–3.

Bradley, R.S., Jones, P.D., 1992. Climate since 1500 A.D. Routeledge, London, 679 pp.

Bradley, R.S., Hughes, M., Díaz, H., 2003. Climate in Medieval Time. Science, 302, 404–405.

Brázdil, R., Pfister, C., Wanner, H., Storch, H. Von, Luterbacher, J., 2005. Historical climatology in Europe - The State of the Art. Climatic Change, 70, 363–430.

Brázdil, R., Demarée, G.R., Deutsch, M., Garnier, E., Kiss, A., Luterbacher, J., Macdonald, N., Rohr, C., Dobrovolný, P., Kolár, P., Chromá, K., 2010. European floods during the winter 1783/1784: scenarios of an extreme event during the 'Little Ice Age'. Theoretical and Applied Climatology, 100, 163–189.

Briet, L., 1902. Le glacé de Mont-Perdú. Revue Club Alpine Francaise, secc. SudOuest, nº1500, 183–186.

Broecker, W.S., 2000. Was a change in thermohaline circulation responsible for the Little Ice Age? Proceedings of the National Academy of Sciences of the United States of America, 97 (4), 1339–1342.

Brunet, M., Jones, P.D., Sigró, J., Saladié, O., Aguilar, E., Moberg, A., Della-Marta, P.M., Lister, D., Walther, A., López, D., 2007. Temporal and spatial temperature variability and change over Spain during 1850–2005, Journal of Geophysical Research, 112, D12117

Bullón, T., 2008. Winter temperatures in the second half of the sixteenth century in the central area of the Iberian Peninsula, Climate of the Past, 4, 357–367.

Bullón, T., 2011. Relationships between precipitation and floods in the fluvial basins of Central Spain based on documentary sources from the end of the 16th century. Natural Hazards and Earth System Sciences, 11, 2215–2225.

Büntgen, U., Frank, D., Grudd, H., Esper, J., 2008. Long-term summer temperature variations in the Pyrenees. Climate Dyna.ics, 31 (6), 615–631.

Büntgen, U., Krusic, P.J., Verstege, A., Sangüesa-Barreda, G., Wagner, S., Camarero, J.J., Ljungqvist, F.C., Zorita, E., Oppenheimer, C., Konter, O., Tegel, W., Gärtner, H., Cherubini, P., Reinig, F., Esper, A.J., 2017. New tree-ring evidence from the Pyrenees reveals western Mediterranean climate variability since medieval times. Journal of Climate, 30 (14), 5295–5318.

Calmel-Avila, M., 2002, The Librilla "rambla", an example of morphogenetic crisis in the Holocene (Murcia, Spain). Quaternary International, 93–94, 101–108.

Camarero, J.J., Gutiérrez, E., 2004. Pace and pattern of recent treeline dynamics: response of ecotones to climatic variability in the Spanish Pyrenees. Climatic Change, 63, 181–200.

Camarero, J.J., Gutiérrez, E., 2007. Response of *Pinus uncinata* recruitment to climate warming and changes in grazing pressure in an isolated population of the Iberian System (NE Spain). Arctic, Antarctic and Alpine Research 39, 210–217.

Camarero, J.J., García-Ruiz, J.M., Sangüesa-Barreda, G., Galván, J.D., Alla, A.Q., Sanjuán, Y., Beguería, S., Gutiérrez, E., 2015. Recent and intense dynamics in a formerly static Pyrenean treeline. Arctic, Antarctic, and Alpine Research 47 (4), 773–783.

Camenisch, C., Keller, K.M., Salvisberg, M., Amann, B., Bauch, M., Blumer, S., Brázdil, R., Brönnimann, S., Büntgen, U., Campbell, B.M.S., Fernández-Donado, L., Fleitmann, D., Glaser, R., González-Rouco, F., Grosjean, M., Hoffmann, R.C., Huhtamaa, H., Joos, F., Kiss, A., Kotyza, O., Lehner, F., Luterbacher, J., Maughan, N., Neukom, R., Novy, T., Pribyl, K., Raible, C.C., Riemann, D., Schuh, M., Slavin, P., Werner, J.P., Wetter, O., 2016. The 1430s: a cold period of extraordinary internal climate variability during the early Spörer Minimum with social and economic impacts in north-western and central Europe. Climate of the Past, 12, 2107–2126.

Camuffo, D., Jones, P., 2002. Improved understanding of past climatic variability from early daily European instrumental sources. Climatic Change, 53, 1–4.

Cane, M.A., Braconnot, P., Clement, A., Gildor, H., Joussaume, S., Kageyama, M., Khodri, M., Paillard, D., Tett, S., Zorita, E., 2006. Progress in paleoclimate modeling. Journal of Climate, 19 (20), 5031–5057.

Capel, H., 1970. Una actividad desaparecida de las montañas mediterráneas: el comercio de la nieve. Revista de Geografía, 4 (1), 8–41.

Carrera, P., Valcárcel, M., 2010. La acción geomorfológica del manto nivoso estacional en la Sierra de Ancares: vertiente nororiental del Pico Cuiña (León). Cuadernos de Investigación Geográfica, 36, 85–98.

Castañón, J.C., Frochoso, M., 1994. El periglaciarismo de la Cordillera Cantábrica, in: Gómez-Ortiz, A., Simón, M., Salvador, F. (Eds.), Periglaciarismo en la Península Ibérica, Canarias y Baleares. Monografías de la Sociedad Española de Geomorfología, 7. Servicio de Publicaciones de la Universidad de Granada, Granada, 75–91.

Castro, D., Souto, M., García-Rodeja, E., Pontevedra-Pombal, X., Fraga, M.I., 2015. Cliamte change records between the mid- and late-Holocene in a peat bog from Serra do Xistral (SW Europe) using plant macrofossils and peat humification analyses. Palaeogeography Palaeoclimatology Palaeoecology, 420, 82–95.

Casty, C., Raible, C.C., Stocker, T.F., Luterbacher, J., Wanner, H., 2007. A European pattern climatology 1766-2000. Climate Dynamics, 29 (7), 791–805.

Chueca, J., Julián, A., 2010. Dinámica de los glaciares del Pirineo aragonés: Resultados de la campaña glaciológica del año 2011. Boletín Glaciológico Aragonés, 11, 9–183.

Chueca, J., Julián, A., Saz-Sánchez, M.Á., Creus, J., López-Moreno, J.I., 2005. Responses to climatic changes since the 'Little Ice Age' on Maladeta Glacier (Central Pyrenees). Geomorphology, 68, 167–182.

Chueca, J., Julián, A., López-Moreno, J.I., 2007. Recent evolution (1981–2005) of the Maladeta glaciers, Pyrenees, Spain: extent and volume losses and their relation with climatic and topographic factors. Journal of Glaciology, 53, 547–557.

Chueca, J., Julián, A., López-Moreno, J.I., 2008. The retreat of the Pyrenean Glaciers (Spain) from the Little Ice Age: data consistency and spatial differences, Terra Glacialis, 137–148.

Clark, R., 1981. Cold climate features of the Cordillera Cantábrica, Northern Spain. Biuletyn Peryglacjalny, 24, 5–18.

Coltrain J.B. 2009. Sealing, whaling and caribou revisited: additional insights from the skeletal isotope chemistry of eastern Arctic foragers. Journal of Archaeological Science, 36 (3), 764–775.

Copons, R., Bordonau, J., 1994. La Pequeña Edad de Hielo en el Macizo de la Maladeta (Alta cuenca del Ésera, Pirineos Centrales), in: Martí-Bono, C. and García-Ruiz, J.M. (Eds.), El glaciarismo surpirenaico: nuevas aportaciones. Geoforma Ediciones, Zaragoza, 111–124.

Corella, J.P., Stefanova, V., El Anjoumi, A., Rico, E., Giralt, S., Moreno, A., Plata-Montero, A., Valero-Garcés, B.L. 2013. A 2,500-year multi-proxy reconstruction of climate change and human activities in northern Spain: the Lake Arreo record. Palaeogeography, Palaeoclimatology, Palaeoecology, 386, 555–568.

Corella, J.P., Valero-Garcés, B.L., Vicente-Serrano, S.M., Brauer, A., Benito, G., 2016. Three millennia of heavy rainfalls in Western Mediterranean: frequency, seasonality and atmospheric drivers. Scientific Reports, 6, 38206.

Cortesi, N., González-Hidalgo, J.C., Trigo, R.M., Ramos, A.M., 2014. Weather Types and spatial variability of precipitation in the Iberian Peninsula. International Journal of Climatology, 34, 2661–2677.

Creus-Novau, J., Fernández-Cancio, A., Manrique-Menéndez, E., 1996. Evolución de la temperatura y precipitación anuales desde el año 1400 en el sector central de la Depresión del Ebro. Lucas Mallada, 8, 9–27.

Dabrio, C.J., Zazo, C., Lario, J., Goy, J.L., Sierro, F.J., Borja, F., González, J.A., Flores, J.A., 1999. Sequence stratigraphy of Holocene incised-valley fills and coastal evolution in the Gulf of Cádiz (southern Spain). Geologie en Minjbouw, 77, 263–281.

de Luis, M., Brunetti, M., Gonzalez-Hidalgo, J.C., Longares, L.A., Martin-Vide, J., 2010. Changes in seasonal precipitation in the Iberian Peninsula during 1946-2005. Global and Planetary Change, 74 (1), 27–33.

Desprat, S., Goñi, M.F., Loutre, M.F., 2003. Revealing climatic variability of the last three millennia in northwestern Iberia using pollen influx data. Earth and Planetary Science Letters, 213, 63–78.

Díaz, H.E., Trigo, R., Hughes, M.K., Mann, M.E., Xoplaki, E., Barriopedro, D., 2011. Spatial and temporal characteristics of climate in medieval times revisited. Bulletin of the American Meteorological Society, 92 (11), 1487–1500.

Domínguez-Castro, F., Santisteban, J.I., Mediavilla, R., Dean, W.E., López-Pamo, E., Gil-García, M.J, Ruiz-Zapata, M.B., 2006. Environmental and geochemical record of human-induced changes in C storage during the last millennium in a temperate wetland (Las Tablas de Daimiel National Park, central Spain). Tellus, Series B Chemical and Physical Meteorology, 58, 573–585.

Domínguez-Castro, F., Santisteban, J.I., Barriendos, M., Mediavilla, R., 2008. Seasonal reconstruction of drought episodes for central Spain from rogation ceremonies recorded at Toledo Cathedral from 1506 to 1900: a methodological approach. Global and Planetary Changes, 63, 230–242.

Domínguez-Castro, F., García-Herrera, R., Ribera, P., Barriendos, M., 2010. A shift in the spatial pattern of Iberian droughts during the 17th century, Climate of the Past, 6, 553–563.

Domínguez-Castro, F., Ribera, P., García-Herrera, R., Vaquero, J.M., Barriendos, M., Cuadrat, J.M., Moreno, J.M., 2012a. Assessing extreme droughts in the Iberian Peninsula during 1750-1850 from rogation ceremonies, Climate of the Past, 8, 705–722.

Domínguez-Castro, F., Trigo, R.M., Vaquero, J.M., 2012b. The first meteorological measurements in the Iberian Peninsula: evaluating the storm of November 1724. Climatic Change, 118 (2), 443–455.

Domínguez-Castro, F., Vaquero J.M., Rodrigo F.S., Farrona A.M.M., Gallego, M.C., García-Herrera, R., Barriendos, M., Sánchez-Lorenzo, A., 2014. Early Spanish meteorological records (1780–1850). International Journal of Climatology, 34, 593–603.

Domínguez-Castro, F., García Herrera, R., Vaquero J.M., 2015. An early weather diary from Iberia (Lisbon, 1631-1632). Weather, 70 (1), 20–24.

Domínguez-Villar, D., Wang, X., Cheng, H., Martín-Chivelet, J., Edwards, R.L., 2008. A high-resolution late Holocene speleothem record from Kaite Cave, northern Spain: d18O variability and possible causes. Quaternary International, 187, 40–51.

Dorado-Liñán, I., Büntgen, U., González-Rouco, F., Zorita, E., Montávez, J.P., Gómez-Navarro, J.J., Brunet, M., Heinrich, I., Helle, G., Gutiérrez, E., 2012. Estimating 750 years of temperature variations and uncertainties in the Pyrenees by tree-ring reconstructions and climate simulations. Climate of the Past, 8 (3), 919–933.

Dorado-Liñán, I., Zorita, E., González-Rouco, J.F., Heinrich, I., Campello, F., Muntán, E., Andreu-Hayles, L., Gutiérrez, E., 2014. Eight-hundred years of summer temperature variations in the southeast of the Iberian Peninsula reconstructed from tree rings. Climate Dynamics, 44 (1-2), 75–93.

Dorado-Liñán, I., Sánchez-Lorenzo, A., Gutiérrez-Merino, E., Planells, O., Heinrich, I., Helle, G., Zorita, E., 2016. Changes in surface solar radiation in Northeastern Spain over the past six centuries recorded by tree-ring δ13C. Climate Dynamics, 47 (3-4), 937–950.

Eddy, J.A., 1976. The Maunder Minimum. Science, 192, 1189–1202.

Esper, J., Frank, D.C., Büntgen, U., Verstege, A., Luterbacher, J., Xoplaki, E., 2007. Long-term drought severity variations in Morocco. Geophysical Research Letters, 34, doi: 10.1029/2007GL030844.

Esper, J., Frank, D.C., Timonen, M., Zorita, E., Wilson, R.J.S., Luterbacher, J., Holzkämper, S., Fischer, N., Wagner, S., Nievergelt, D., Verstege, A., Büntgen, U., 2012. Orbital forcing of tree-ring data. Nature Climate Change, 2 (12), 862–866.

Esper, J., Großjean, J., Camarero, J.J., García-Cervigón, A.I., Olano, J.M., González-Rouco, J.F., Domínguez-Castro, F., Büntgen, U., 2015. Atlantic and Mediterranean synoptic drivers of central Spanish juniper growth. Theoretical and Applied Climatology, 121 (3), 571–579.

Fagan, B., 2002. The Little Ice Age: How Climate Made History 1300-1850. Basic Books, New York.

Fairchild, I.J., Baker, A., 2012. Speleothem Science: From Process to Past Environments. John Wiley & Sons.

Fernandes, M., Oliva, M., Palma, P., Ruiz-Fernández, J., Lopes, L., 2017. Glacial stages and post-glacial environmental evolution in the Upper Garonne valley, Central Pyrenees. Science of the Total Environment, 584–585, 1282–1299.

Fernández-Cancio, A., Génova, M., Gutiérrez, E., 1996. Dendroclimatological investigation covering the last 300 years in central Spain, in: Dean, J.S., Meko, D.M., Swetnam, T.W. (Eds.), Tree rings, environment and humanity, 181–190.

Fernández-Cortizo, C., 1996. Neveras y cosecha de nieve en Galicia (Siglos XVI-XVIII). Obradoiro de Historia Moderna, 5, 41–66.

Fernández-Fernández, M.I., Gallego, M.C., Domínguez-Castro, F., Trigo, R.M., García, J.A., Vaquero, J.M., Moreno González, J.M., Castillo Durán, J., 2014. The climate in Zafra from 1750 to 1840: history and description of weather observations. Climatic Change, 126, 107–118.

Fernández-Fernández, M.I., Gallego, M.C., Domínguez-Castro, F., Trigo, R.M., García, J.M., Vaquero, J.M., 2015. The climate in Zafra from 1750 to 1840: precipitation. Climatic Change, 129, 267–280.

Fernández-Fernández, M.I., Gallego, M.C., Domínguez-Castro, F., Trigo, R.M., Vaquero, J.M. 2017. The climate in Zafra from 1750 to 1840: temperature indexes from documentary sources. Climatic Change, do: 10.1007/s10584-017-1910-7.

Fischer, E.M., Luterbacher, J., Zorita, E., Tett, S.F.B., Casty, C., Wanner, H., 2007. European climate response to tropical volcanic eruptions over the last half millennium. Geophysical Research Letters, 34 (5), L05707, 03.2007, 1–6.

Fragoso, M., Marques, D., Santos J.A., Alcoforado, M.J., Amorim, I., García, J.C., Silva, L., Nunes, M.F., 2015. Climatic extremes in Portugal in the 1780s based on documentary and instrumental records. Climate Research, 66, 141–159.

Franke, J., González-Rouco, J.F., Frank, D., Graham, N.E., 2011. 200 years of European temperature variability: Insights from and tests of the proxy surrogate reconstruction analog method. Climate Dynamics, 37 (1), 133–150.

Fricke, H.C., O'Neil, J.R., Lynnerup N., 1995. Oxygen isotope composition of human tooth enamel from medieval Greenland: Linking climate and society. Geology, 23, 869–872.

Frochoso, M., Castañón, J.C., 1995. Comments on 'Glaciers in Picos de Europa, Cordillera Cantábrica, northwest Spain' by González Suárez and Alonso. Journal of Glaciology, 41, 430–432.

Fuller, I.C., Macklin, M.G., Passmore, D.G., Brewer, P.A., Lewin, J., Wintle, A.G., 1996. Geochronologies and environmental records of Quaternary fluvial sequences in the Guadalope basin, northeast Spain, based on luminescence dating, in: Branson, J., Brown, A.G. and Gregory, K.J. (Eds.), Global Continental Changes: the context of Palaeohydrology, Geological Society of London, Special Publication nº 115, London, 99–120.

Gagen, M.H., Zorita, E., Mccarroll, D., Zahn, M., Young, G.H.F., Robertson, I., 2016. North Atlantic summer storm tracks over Europe dominated by internal variability over the past millennium. Nature Geoscience, 9 (8), 630–635.

Gallego, D., Garcia-Herrera, R., Calvo, N., Ribera, P., 2007. A new meteorological record for Cádiz (Spain) 1806-1852: Implications for climatic reconstructions. Journal of Geophysical Research Atmospheres, 112 (12), D12108.

Gàmez D., Simó, J.A., Vazquez-Suñé, E., Salvany, J.M., Carrera, J., 2005. Variación de las tasas de sedimentación en el complejo detrítico superior del Delta del Llobregat (Barcelona): su relación con causas eustáticas, climáticas y antrópicas. Geogaceta, 38, 175–178.

Garcés-Pastor, P. Cañellas, N., Clavaguera, A., Calero, M.A., Vegas, T., 2016. Vegetation shifts, human impact and peat bog development in Bassa Nera pond (Central Pyrenees) during the last millennium. The Holocene, doi: 10.1177/0959683616670221.

García de Celis, A., Arroyo-Pérez, P., Gandía-Fernández, A. 2008. Cambios recientes del límite superior del bosque en Urbión: gestión forestal, ganadería y clima. Zubía, 20, 97–118.

García-Hernández, C., Ruiz-Fernández, J., Sánchez-Posada, C., Pereira, P., Oliva, M., Vieira, G., 2017a. Reforestation and land use change as drivers for a decrease of avalanche damage in mid-latitude mountains (Asturian Massif, NW Spain). Global Planetary Change.

García-Hernández, C., Ruiz-Fernández, J., Oliva, M., Gallinar, D., 2017b. El episodio de movimientos en masa asociado a la nevada de 1888, en el Macizo Asturiano. Boletín de la Asociación de Geógrafos Españoles.

García-Herrera, R., Díaz, J., Trigo, R.M., Hernández, E., 2005. Extreme summer temperatures in Iberia: health impacts and associated synoptic conditions. Annales Geophysicae, 23, 239–251.

García-Ruiz, J.M., Puigdefábregas, J., 1982. Formas de erosion en el flysch eoceno surpirenaico. Cuadernos de Investigación Geográfica 8, 83–126.

García-Ruiz, J.M., Martí-Bono, C., 2001. Mapa geomorfológico del Parque Nacional de Ordesa y Monte Perdido. Organismo Autónomo de Parques Nacionales, Ministerio de Medio Ambiente, Madrid, 106 pp.

García-Ruiz, J.M., Alvera, B., del Barrio, G., Puigdefábregas, J., 1988. Geomorphic processes above the timberline in the Spanish Pyrenees. Mountain Research and Development, 10 (3), 201–214.

García-Ruiz, J.M., Beguería, S., Alatorre, L.C., Puigdefábregas, J. 2010. Land cover changes and shallow landsliding in the flysch sector of the Spanish Pyrenees. Geomorphology, 124, 250–259.

García-Ruiz, J.M., Peña-Monne, J.L., Martí-Bono, C., Gómez-Villar, A., Constante, A., Espinalt, M., 2011. El relieve del Alto Aragón Occidental. Cartografía y síntesis geomorfológica. Publicaciones del Consejo de Protección de la Naturaleza de Aragón, Zaragoza, 91 pp.

García-Ruiz, J.M., Palacios, D., Andrés, N., Valero-Garcés, B.L., López-Moreno, J.I., Sanjuan, Y., 2014a. Holocene and 'Little Ice Age' glacial activity in the Marboré Cirque, Monte Perdido Massif, Central Spanish Pyrenees. The Holocene, 24 (11), 1439–1452.

García-Ruiz, J.M., Valero-Garcés, B.L., Beguería, S., López-Moreno, J.I., Martí-Bono, C., Serrano-Muela, P., Sanjuan, Y., 2014b. The Ordesa and Monte Perdido National Park, in: Gutiérrez F., Gutiérrez, M. (Eds.), Landscapes and landforms of Spain, Springer, Dordrecht, 165–172.

García-Ruiz, J.M., López-Moreno, J.I., Lasanta, T., Vicente-Serrano, S., González-Sampériz, P., Valero-Garcés, B.L., Sanjuán, Y., Beguería, S., Nadal-Romero, E., Lana-Renault, N., Gómez-Villar, A., 2015. Los efectos geoecológicos del Cambio Global en el Pirineo Central español: una revision a distintas escalas espaciales y temporales. Pirineos, 170, e012. doi: 10.3989/Pirineos.2015.170005.

García-Ruiz, J.M., Sanjuán, Y., Gil-Romera, G., González-Sampériz, P., Beguería, S., Arnáez, J., Coba-Pérez, P., Gómez-Villar, A., Álvarez-Martínez, J., Lana-Renault, N., Pérez-Cardiel, E., López de Calle, C., 2016a. Mid and late Holocene forest fires and deforestation in the subalpine belt of the Iberian range, northern Spain. Journal of Mountain Science, 13 (10), 1760–1772.

García-Ruiz, J.M., Sanjuán, Y., Arnáez, J., Beguería, S., Gómez-Villar, A., Álvarez-Martínez, J., Lana-Renault, N., Coba-Pérez, P., 2016b. La evolución del piso subalpino en la Sierra de Urbión (Sistema Ibérico, norte de España): un modelo de impacto geoecológico de actividades humanas en el valle de Ormazal. Pirineos, e022, doi: 10.3989/Pirineos.2016.171006.

García-Sainz, L., 1947. El clima de la España cuaternaria y los factores de su formación. Secretariado de Publicaciones de la Universidad de Valencia, Valencia (Spain).

Génova, M., 2012. Extreme pointer years in tree-ring records of Central Spain as evidence of climatic events and the eruption of the Huaynaputina Volcano (Peru, 1600 AD). Climate of the Past, 8, 751–764.

Génova-Fuster, M.M., Fernández-Cancio, A., Creus-Novau, J., 1993. Diez series medias de anillos de crecimiento en los sistemas Carpetano e Ibérico. Investigación Agraria. Sistemas y Recursos Forestales, 2, 151–172.

Genty, D., Combourieu-Nebout, N., Peyron, O., Blamart, D., Wainer, K., Mansuri, F., Ghaleb, B., Isabello, L., Dormoy, I., von Grafenstein, U., Bonelli, S., Landais, A., Brauer, A., 2010. Isotopic characterization of rapid climatic events during OIS3 and OIS4 in Villars Cave stalagmites (SW-France) and correlation with Atlantic and Mediterranean pollen records. Quaternary Science Reviews, 29, 2799–2820.

Giménez-Font, P., 2008. La epidemia de malaria de 1783-1786: notas sobre la influencia de anomalías climáticas y cambios de usos del suelo en la salud humana. Investigaciones Geográficas, 46, 141–157.

Giménez-Font, P., 2014-2015. El último pozo de nieve de la Sierra de Aitana. Mètode, 84, 11-15.

Gómez-Lende, M., 2015. Las cuevas heladas en Picos de Europa: clima, morfologías y dinámicas. PhD thesis, University of Valladolid.

Gómez-Lende, M., Serrano, E., Berenguer, F., 2011. Cuevas heladas en Picos de Europa. Primeros estudios en Verónica, Altáiz y Peña Castil. Karaitza, 19, 56–61.

Gómez-Lende, M., Berenguer, F., Serrrano, E., 2014. Morphology, ice types and termal regime in a high mountain ice cave. First studies applying terrestrial laser scanner in the Peña Castil Ice Cave (Picos de Europa, Northern Spain). Geografia Fisica e Dinamica Quaternaria, 37, 141–150.

Gómez-Lende, M., Serrano, E., Bordehore, L.J., Sandoval, S., 2016. The role of GPR techniques in determining ice cave properties: Peña Castil ice cave, Picos de Europa. Earth Surface Processes and Landforms, 41 (15), 2177–2190.

Gómez-Navarro, J.J., Montávez, J.P., Jerez, S., Jiḿenez-Guerrero, P., Lorente-Plazas, R., González-Rouco, J.F., Zorita, E., 2011. A regional climate simulation over the Iberian Peninsula for the last millennium. Climate of the Past, 7 (2), 451–472.

Gómez-Navarro, J.J., Montávez, J.P., Jiménez-Guerrero, P., Jerez, S., Lorente-Plazas, R., González-Rouco, J.F., Zorita, E., 2012. Internal and external variability in regional simulations of the Iberian Peninsula climate over the last millennium. Climate of the Past, 8 (1), 25–36.

Gómez-Navarro, J.J., Bothe, O., Wagner, S., Zorita, E., Werner, J.P., Luterbacher, J., Raible, C.C., Montávez, J.P., 2015. A regional climate palaeosimulation for Europe in the period 1500-1990 - Part 2: Shortcomings and strengths of models and reconstructions. Climate of the Past, 11 (8), 1077–1095.

Gómez-Ortiz, A., 1987. Contribució geomorfològica a l'estudi dels espais supraforestals pirinencs. Gènesi, organització i dinàmica dels modelats glacials i periglacials de la Cerdanya i l'Alt Urgell. Institut Cartogràfic de Catalunya, Barcelona, 161 pp.

Gómez-Ortiz, A., Plana-Castellví, J.A., 2006. La Pequeña Edad del Hielo en Sierra Nevada a partir de los escritos de la época (siglos XVIII y XIX) y relaciones con el progreso de la geografía física y geomorfología española. Boletín de la Asociación de Geógrafos Españoles, 42, 71–98.

Gómez-Ortiz, A., Palacios, D., Schulte, L., Salvador-Franch, F., Plana-Castellví, J.A., 2006. Evidences from Historical Documents of Landscape Evolution after Little Ice Age of a Mediterranean High Mountain Area, Sierra Nevada, Spain (Eighteenth to Twentieth Centuries). Geografiska Annaler. Series A, Physical Geography, 91 (4), 279–289.

Gómez-Ortiz, A., Palacios, D., Schulte, L., Salvador-Franch, F., Plana, J.A., 2009. Evidences from historical documents of landscape evolution after Little Ice Age of a Mediterranean high mountain area, Sierra Nevada, Spain (eighteenth to twentieth centuries). Geografiska Annaler, Series A, Physical Geography, 91, 279–289.

Gómez-Ortiz, A., Oliva, M., Salvador-Franch, F., Salvà-Catarineu, M., Palacios, D., Sanjosé, J.J., Tanarro, L., Galindo-Zaldívar, J., Sanz de Galdeano, C., 2014. Degradation of buried ice and permafrost in the Veleta cirque (Sierra Nevada, Spain) from 2006-2013. Solid Earth, 5, 979–993.

González, J.A., Fidalgo, C., Prieto-Jiménez, I., 2013. La "Pequeña Edad del Hielo" en la Península Ibérica: Estado de la cuestión, in: Martínez-Millán, J., Camarero, C., M., M. (Eds.): La Corte de los Borbones: Crisis del Modelo Cortesano. Editorial Polifemo, Madrid, 237–282.

González-García, M., 2014. La alta montaña periglaciar en el Pirineo Central español. Procesos, formas y condiciones ambientales. PhD thesis. University of Málaga.

González-Rouco, J., Zorita, E., Cubasch, U., von Storch, H., Fisher-Bruns, I., Valero, F., 2003. Simulating the climate since 1000 AD with the AOGCM ECHO-G, in: Wilson A (Ed.), Solar variability as an input to the Earth's environment, International Solar Cycle Studies (ISCS) Symposium. Noordwijk: ESA Publications Division, Tatranská Lomnica (Slovak Republic), 329–338.

González-Sampériz, P., Aranbarri, J., Pérez-Sanz, A., Gil-Romera, G., Moreno, A., Leunda, M., Sevilla-Callejo, M., Corella, J.P., Morellón, M., Oliva, B., Valero-Garcés, B., 2017. Environmental and climate change in the southern central Pyrenees since the Last Glacial Maximum: A view from the lake records. Catena, 149, 668–688.

González-Suárez, J.J., Alonso, V., 1994. Glaciers in Picos de Europa, Cordillera Cantábrica, northwest Spain. Journal of Glaciology, 40 (134), 198–199.

González-Suárez, J.J., Alonso, V., 1996. Reply to the comments of Frochoso and Castañón on «Glaciers in Picos de Europa, Cordillera Cantábrica, northwest Spain». Journal of Glaciology, 42 (141), 386–389.

González-Trueba, J.J., 2005. La Pequeña Edad del Hielo en los Picos de Europa (Cordillera Cantábrica, NO de España). Análisis morfológico y reconstrucción del avance glaciar histórico. Cuaternario y Geomorfología, 19 (3-4), 79–94.

González-Trueba, J.J., 2006. Topoclimatical factors and very small glaciers in Atlantic mountain of SW Europe: Little Ice Age glacial advance in Picos de Europa (NW Spain). Zeitschrift fuer Gletscherkunde und Glazialgeologie, 39, 115–125.

González-Trueba, J.J., 2007a. Geomorfología del Macizo Central del Parque Nacional de Picos de Europa. OAPN, Ministerio de Medio Ambiente, Madrid.

González-Trueba, J.J., 2007b. La Pequeña Edad del Hielo en los Picos de Europa. Servicio de Publicaciones de la Universidad de Cantabria – Fundación Marcelino Botín, Santander, 186 pp.

González-Trueba, J.J., Serrano, E., 2010. La nieve en los Picos de Europa. Cuadernos de Investigación Geográfica, 36 (2), 61–84.

González-Trueba, J.J., Martín-Moreno, R., Serrano, E., 2005. El glaciarismo de la Pequeña Edad del Hielo en las Montañas Ibéricas. Síntesis y estado actual de conocimiento. Cuatenario y Geomorfología, 21 (1–2), 57–86.

González-Trueba, J.J., Martín-Moreno, R., Martínez de Pisón, E., Serrano, E., 2008. Little Ice Age glaciation and current glaciers in the Iberian Pennsula. The Holocene, 18 (4), 551–568.

Gottfried, M., Pauli, H., Futschik, A., Akhalkatsi, M., Barancok, P., Benito-Alonso, J.L., Coldea, G., Dick, J., Erschbamer, B., Fernández-Calzado, M.R., Kazakis, G., Krajci, J., Larsson, P., Mallaun, M., Michelsen, O., Moiseev, D., Moiseev, P., Molau, U., Merzouki, A., Nagy, L., Nakhutsrishvili, G., Pedersen, B., Pelino, G., Puscas, M., Rossi, G., Stanisci, A., Theurillat, J.P., Tomaselli, M., Villar, L., Vittoz, P., Vogiatzakis, I., Grabherr, G., 2012. Continent-wide response of mountain vegetation to climate change. Nature Climate Change, 2, 111–115.

Grove, J.M., 2004. Little Ice Ages: Ancient and Modern. Routledge, London (2 volumes).

Grove, J.M., Gellatly, A.F., 1995. Little Ice Age fluctuations in the Pyrenees. Zeitschrift fuer Gletscherkunde und Glazialgeologie, 31, 199–206.

Guillen, J., Palanques, A., 1997. A historical perspective of the morphological evolution in the lower Ebro River. Environmental Geololgy, 30 (3–4), 174–80.

Harrison, S.P., Bartlein, P.J., Prentice, I.C, 2016. What have we learnt from palaeoclimate simulations? Journal of Quaternary Science, 31 (4), 363–385.

Hegerl, G., Luterbacher, J., González-Rouco, F., Tett, S.F.B., Crowley, T., Xoplaki, E, 2011. Influence of human and natural forcing on European seasonal temperatures. Nature Geoscience, 4 (2), 99–103.

Hernández, A., Trigo, R.M., Pla-Rabes, S., Valero-Garcés, B.L., Jerez, S., Rico-Herrero, M., Vega, J.C., Jambrina-Enríquez, M., Giralt, S., 2015. Sensitivity of two Iberian lakes to North Atlantic atmospheric circulation modes. Climate Dynamics, 45, 3403–3417.

Hernández-Beloqui, B., Iriarte-Chiapuso, M.J., Echazarreta-Gallego, A., Ayerdi, M., 2015. The late Holocene in the western Pyrenees: a critical review of the current situation of palaepalynological research. Quaternary International, 364, 78–85.

Highwood, E.J., Stevenson, D.S., 2003. Atmospheric impact of the 1783–1784 Laki Eruption: Part II Climatic effect of sulphate aerosol. Atmospheric Chemistry and Physics Discussions, 3 (2), 1599–1629.

Hoffmann, P., 1988. Holozänstratigraphie und Küstenlimienver - lagerung an der Andalusischen Mittelmeer-küste, Berichte aus dem Fachbereich Geowissenschaften der Univ. Bremen, Bremen, 177 pp.

Höllermann, P., 1985. The periglacial belt at mid-latitude mountains from a geoecological point of view. Erdkunde 39, 259–270.

Holzhauser, H., Magny, M., Zumbühl, H.J., 2005. Glacier and lake-level variations in west-central Europe over the last 3500 years. The Holocene, 15, 789–801.

Hughes, P.D., 2018. Little Ice Age glaciers and climate in the Mediterranean mountains: a new analysis. Cuadernos de Investigación Geográfica 44 (1). Doi: 10.18172/cig.3362

Hurrell, J.W., Kushnir, Y., Visbeck, M., 2001. The North Atlantic oscillation. Science, 291 (5504), 603–605.

Instituto Nacional de Estadística (INE). Anuario estadístico de España. Gobierno de España.

IPCC Climate Change 2013, 2013. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 1535 pp.

Ives, J.D., Hansen-Bristow, K.J., 1983. Stability and instability of natural and modified upper timberline landscapes in the Colorado Rocky Mountains, USA. Mountain Research and Development, 3 (2), 149–155.

Jacoby G.C., Workman, K.W., D'Arrigo, R.D., 1999. Laki eruption of 1783, tree rings and disaster for northwest Alaska Inuit. Quaternary Science Reviews, 18, 1365–1371.

Jambrina-Enríquez M., Rico, M., Moreno, A., Leira, M., Bernárdez, P., Prego, R., Recio, C., Valero-Garcés B.L., 2014. Timing of deglaciation and postglacial environmental dynamics in NW Iberia: The Sanabria Lake record. Quaternary Science Reviews, 94, 136–158.

Jiménez-Espejo, F.J., García-Alíx, A., Jiménez-Moreno, G., Rodrigo-Gámiz, M., Anderson, R.S., Rodríguez-Tovar, F.J., Martínez-Ruiz, F., Giralt, S., Delgado-Huertas, A., Pardo-Igúzquiza, E., 2014. Saharan aeolian input and effective humidity variations over western Europe during the Holocene from a high altitude record. Chemical Geology, 374-375, 1–12.

Jiménez-Moreno, G., Scott Anderson, R., 2012. Holocene vegetation and climate change recorded in alpine bog sediments from Borreguiles de la Virgen, Sierra Nevada, southern Spain. Quaternary Research, 77, 44–53.

Jones, P.D., Briffa, K.R., Barnett, T.P., Tett, S.F.B., 1998. High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with general circulation model control-run temperatures. The Holocene, 8, 455–471.

Jones, P.D., Mann M.E., 2004. Climate over past millennia. Reviews of Geophysics, 42, RG2002, doi: 10.1029/2003RG000143.

Julián, A., Chueca, J., 1998. Le Petit Âge Glaciaire dans les Pyrénées Centrales Meridionales: estimation des paléotempératures á partir d'inférences géomorphologiques Sud-Ouest Europeen, 3, 79–88.

Lamb, H.H., 1970. Volcanic dust in the atmosphere, with a chronology and assessment of its meteorological significance. Philosophical Transactions of the Royal Society of London, A266, 425–533.

Lamb, H.H., 1977. Climate, present, past and future. vol. 2: Climatic History and the Future, Methuen, London, 835 pp.

Lario, J., Zazo, C., Dabrio, C.J., Somoza, L., Goy, J.L., Bardají, T., Silva P.G., 1995. Record of recent Holocene sediment input on spit bars and deltas of south Spain. Journal of Coastal Research, 17, 241–245.

Lasanta, T., 1989. Evolución reciente de la agricultura de montaña: el Pirineo aragonés. Geoforma Ediciones, Logroño, 220 pp.

Lasanta, T., Beguería, S., García-Ruiz, J.M., 2006. Geomorphic and hydrological effects of traditional shifting agriculture in a Mediterranean mountain, Central Spanish Pyrenees. Mountain Research and Development, 26 (2), 146–152.

Lean, J., Beer, J., Bradley, R., 1995. Reconstruction of solar irradiance since 1610. Implications for climate change. Geophysical Research Letters, 22 (23), 3195–3198.

Leunda, M., Bartolomé, M., Sancho, C., Moreno, A., Oliva-Urcia, B., González-Samperiz, P., Gil-Romera, G., Gomollón, A., 2015. La cueva helada de Casteret (PNOMP, Huesca): primeras aportaciones del registro de hielo, in: Galve, J.P., Azañón, J.M., Pérez Peña, J.V., Ruano, P. (Eds.): Una visión global del Cuaternario. El hombre como condicionante de procesos geológicos. XIV Reunión Nacional de Cuaternario, AEQUA, Granada, 78–81.

Ljungqvist, F.C., Krusic, P.J., Sundqvist, H.S., Zorita, E., Brattström, G., Frank, D., 2016. Northern Hemisphere hydroclimate variability over the past twelve centuries. Nature, 532 (7597), 94–98.

Llasat, M.C., Barriendos, M., Barrera, A., Rigo, T., 2005. Floods in Catalonia (NE Spain) since the 14th Century. Climatological and meteorological aspects from historical documentary sources and old instrumental records. Journal of Hydrology, 313 (1–2), 32–47.

López-Costas, O., 2012. Antropología de los restos óseos humanos de Galicia: estudio de la población romano y medieval gallega. PhD thesis, University of Granada.

López-Costas, O., Müldner G., Martínez-Cortizas A., 2015. Diet and lifestyle in Bronze Age Northwest Spain: the collective burial of Cova do Santo. Journal of Archaeological Science, 55, 209–218.

López-Costas, O., Müldner, G., 2016. Fringes of the empire: Diet and cultural change at the Roman to post-Roman transition in NW Iberia. American Journal of Physical Anthropology, 161, 141–154.

López-Días, V., Borrego, T., Gutiérrez-Blanco, C., Arboleya, M., López-Sáez, J.A., López-Merino, L. (2010). Biomarkers in a peat deposit in Northern Spain (Huelga de Bayas, Asturias) as proxy for climate variation. Journal of Chromatography, 1217 (21), 3538–3546.

López-Merino, L., López-Sáez, J.A., Alba-Sánchez, F., Pérez-Díaz, S., Carrión, J.S., 2009. 2000 years of pastoralism and fire shaping high-altitude vegetation of Sierra de Gredos in central Spain. Review of Palaeobotany and Palynology, 158, 42–51.

López-Merino, L., Martínez-Cortizas, A., López-Sáez, J.A., 2010. Early agriculture and palaeoenvironmental history in the north of the Iberian Peninsula: a multi-proxy analysis of the Monte Areo mire (Asturias, Spain). Journal of Archaeological Science, 37, 1978–1988.

López-Moreno, J.I., 2000. Los glaciares del alto valle del Gállego (Pirineo Central) desde la Pequeña Edad del Hielo. Implicaciones en la evolución de la temperatura. Geoforma Ediciones, Logroño, 77 pp.

López-Moreno, J.I., 2005. Recent variations of snowpack depth in the Central Spanish Pyrenees. Arctic, Antarctic and Alpine Research, 37 (2), 253–260.

López-Moreno, J.I., García-Ruiz, J.M., 2004. Influence of snow accumulation and snowmelt on streamflow in the Central Spanish Pyrenees. Hydrological Sciences Journal, 49 (5), 787–802.

López-Moreno, J.I., Nogués-Bravo, D., Chueca, J., Julián, J., 2006. Change of topographic control on the extent of cirque glaciers since the Little Ice Age. Geophysical Research Letters, 33, L24505, doi: 10.1029/2006GL028204.

López-Moreno, J.I., García-Ruiz, J.M., Beniston, M., 2008. Environmental Change and water management in the Pyrenees. Facts and future perspectives for Mediterranean mountains. Global and Planetary Change, 66 (3-4), 300–312.

López-Moreno, J.I., Revuelto, J., Rico, I., Chueca-Cía, J., Julián, A., Serreta, A., Serrano, E., Vicente-Serrano, S.M., Azorín-Molina, C., Alonso-González, E., García-Ruiz, J.M., 2016. Thinning of the Monte Perdido Glacier in the Spanish Pyrenees since 1981. The Cryosphere, 10 (2), 681–694.

López-Sáez, J.A., Abel-Schaad, D., Pérez-Díaz, S., Blanco-González, A., Alba-Sánchez, F., Dorado, M., Ruiz-Zapata, B., Gil-García, M.J., Gómez-González, C., Franco-Múgica, F., 2014. Vegetation history, cliamte and human impact in the Spanish Central System over the last 9000 years. Quaternary International, 353, 98–122.

López-Sáez, J.A., Alba, F., Robles, S., Pérez, S., Abel, D., Sabariego, S., Glais, A., 2016a. Exploring seven hundred years of transhumance, climate dynamic, fire and human activity through a historical mountain pass in central Spain. Journal of Mountain Science, 13, 1139–1153.

López-Sáez, J.A., Abel, D., Robles, S., Pérez, S., Alba, F., Nieto, D., 2016b. Landscape dynamics and human impact on high-mountain woodlands in the western Spanish Central System during the last three millennia. Journal of Archaeological Science: Reports, 9, 203–218.

Lugon, R., Delaloye, R., Serrano, E., Reynard, E., Lambiel, C., González-Trueba, J.J., 2004. Permafrost and Little Ice Age glaciers relationships: a case of study in the Posets Massif, Central Pyrenees, Spain. Permafrost and Periglacial Processes, 15, 207–220.

Luterbacher, J., Pfister, C., 2015. The year without a summer. Nature Geoscience, 8, 246–248.

Luterbacher, J., Schmutz, C., Gyalistras, D., Xoplaki, E., 1999. Reconstruction of monthly NAO and EU indices back to AD 1675. Geophysical Research Letters, 26 (17), 2745–2748.

Luterbacher, J., Rickli, R., Xoplaki, E., Tinguely, C., Beck, C., Pfister, C., Wanner, H., 2001. The Late Maunder Minimum (1675-1715) - A key period for studying decadal scale climatic change in Europe. Climatic Change, 49 (4), 441–462.

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., Wanner, H., 2004. European seasonal and annual temperature variability, trends and extremes since 1500. Science, 303, 1499–1503.

Luterbacher, J., Xoplaki, E., Casty, C., Wanner, H., Pauling, A., Küttel, M., Rutishauser, T., Brönnimann, S., Fischer, E., Fleitmann, D., González-Rouco, F.J., García-Herrera, R., Barriendos, M., Rodrigo, F., González-Hidalgo, J.C., Saz, M.A., Gimeno, L., Ribera, P., Brunet, M., Paeth, H., Rimbu, N., Felis, T., Jacobeit, J., Dünkeloh, A., Zorita, E., Guiot, J., Türkes, M., Alcoforado, M.J., Trigo, R., Wheeler, D., Tett, S., Mann, M.E., Touchan, R., Shindell, D.T., Silenzi, S., Montagna, P., Camuffo, D., Mariotti, A., Nanni, T., Brunetti, M., Maugeri, M., Zerefos, C.S., De Zolt, S., Lionello, P., Nunes, M.F., Rath, V., Beltrami, H., Garnier, E., Ladurie, E.L.R, 2006. Mediterranean climate variability over the last centuries: a review, in: Lionello, P., Malanotte-Rizzoli, P., Boscolo, R. (Eds.): The Mediterranean Climate: an overview of the main characteristics and issues. Elsevier, Amsterdam, pp. 27–148.

Luterbacher, J., Werner, J.P., Smerdon, J.E., Fernández-Donado, L., González-Rouco, J., Barriopedro, D., Ljungqvist, F., Büntgen, U., Zorita, E., Wagner, S., Esper, J., McCarroll, D., Toreti, A., Frank, D., Jungclaus, J., Barriendos, M., Bertolin, C., Bothe, O., Brázdil, R., Dario, C., Dobrovolný, P., Gagen, M., García-Bustamante, E., Ge, Q., Gómez-Navarro, J., Guiot, J., Hao, Z., Hegerl, G., Holmgren, K., Klimenko, V., Martín-Chivelet, J., Pfister, C., Roberts, N., Schindler, A., Schurer, A., Solomina, O., von Gunten, L., Wahl, E., Wanner, H., Wetter, O., Xoplaki, E., Yuan, N., Zanchettin, D., Zhang, H., Zerefos, C., 2016. European summer temperatures since Roman times. Environmental Research Letters, 11, 024001, doi: 10.1088/1748-9326/11/2/024001.

Machado, M.J., Benito, G., Barriendos, M., Rodrigo, F.S., 2011. 500 Years of rainfall variability and extreme hydrological events in southeastern Spain drylands. Journal of Arid Environments, 75, 1244–1253.

Machado, M.J., Medialdea, A., Barriendos, M., Benito, G., 2016. Hidroclimatología de las inundaciones históricas y paleocrecidas del río Duero en su tramo medio e internacional, in: Durán Valsero, J.J., Montes Santiago, M., Robador, A., Salazar A. (Eds.): Comprendiendo el relieve: del pasado al futuro. Publicaciones el Instituto Geológico y Minero de España. Geología y Geofísica, 5, 349–356.

Mann, M.E., Bradley, R.S., Hughes, M.K., 1998. Global-scale temperature patterns and climate forcing over the past six centuries. Nature, 392, 779–785.

Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., Ni, F., 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. Science, 326, 1256–1260.

Marti, R., Gascoin, S., Houet, T., Ribière, O., Laffly, D., Condom, T., Monnier, S., Schmutz, M., Camerlynck, C., Tihay, J.P., Soubeyroux, J.M., René, P., 2015. Evolution of Ossoue Glacier (French Pyrenees) since the end of the Little Ice Age. The Cryosphere, 9, 1773–1795.

Martín-Chivelet, J., Muñoz-García, M.B., Edwards, R.L., Turrero, M.J., Ortega, A.I., 2011. Land surface temperature changes in Northern Iberia since 4000 yr BP, based on δ13C of speleothems. Global and Planetary Change, 77 (1–2), 1–12.

Martín-Puertas, C., Valero-Garcés, B.L., Mata, M.P., Moreno, A., Giralt, S., Martínez-Ruiz, F., Jiménez-Espejo, F., 2011. Geochemical processes in a Mediterranean Lake: a high-resolution study of the last 4000 years in Zoñar Lake (southern Spain). Journal of Paleolimnology, 46, 405–421.

Martín-Vide, J., Barriendos, M. 1995. The use of rogation ceremony records in climatic reconstruction: a case study from Catalonia (Spain). Climatic Change, 30, 201–221.

Martín-Vide, J., Fernández, D., 2001. El índice NAO y la precipitación mensual en la España peninsular. Investigaciones Geográficas, 26, 41–58.

Martínez de Pisón, E., Arenillas, M., 1988. Los glaciares actuales del Pirineo español. La nieve en el Pirineo Español. MOPU, Madrid, 29–98.

Martínez-Cortizas, A., Pontevedra-Pombal, X., García-Rodeja, E., Novoa-Múñoz, J.C., Shotyk, W. 1999. Mercury in a Spanish peat bog: archive of climate change and atmospheric metal deposition. Science, 284, 939–942.

Martínez-Cortizas, A., Biester, H., Mighall, T., Bindler, R., 2007. Climate-driven enrichment of pollutants in peatlands. Biogeosciences, 4, 905–911.

Martzluff, M., Mas, S., 1992. Premses i vinyes d'Andorra, Institut d'Estudis Andorrans. Centre de Perpinyà, Perpinyà, 72 pp.

Matías, L., 2012. Cambios en los límites de distribución de especies arbóreas como consecuencia de las variaciones climáticas. Ecosistemas, 21 (3), 91–96.

Matthes, F.E., 1940. Report of the committee on glaciers. Transactions of the American Geophysical Union, 1, 396–406.

Matthews, J.A., Briffa, K.R., 2005. The ‘Little ice age’: Re-evaluation of an evolving concept. Geografiska Annaler Series A, Physical Geography, 87, 17–36.

Saint Saud, 1914. Picos de Europa Massif Occidental. Schema au 50.000e, dressé et desiné par L. Maury. Imprenta del Instituto Cartográphic de Paris.

Meehl, G.A., Karl, T., Easterling, D.R., Changnon, S., Pielke, R.J., Changnon, D., Evans, J., Groisman, P.Y., Knutson, T.R., Kunkel, K.E., Mearns, L.O., Parmesan, C., Pulwarty, R., Root, T., Sylves, R.T., Whetton, P., Zwiers, F., 2000. An introduction to trends in extreme weather and climate events: observations, socio-economic impacts, terrestrial ecological impacts, and model projections. Bulletin of the American Meteorological Society, 81 (3), 413–416.

Mighall, T.M., Martínez-Cortizas, A., Biester, H., Turner, S.E., 2006. Proxy climate and vegetaion changes during the last five nmillenia in NW Iberia: pollen and non-pollen palynomorph data from two ombrotrophic peat bogs in the North Western Iberian Peninsula. Review of Palaeobotany and Palynology, 141, 203–223.

Miller, G., Geirsdóttir, A., Zhong, Y., Larsen, D.J., Otto-Bliesner, B.L., Holland, M.M., Bailey, D.A., Refsnider, K.A., Lehman, S.J., Southon, J.R., Anderson, C., Bjornsson, H., Thordarson, T., 2012. Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. Geophysical Research Letters, 39, L02708.

Miotke, F.D., 1968. Karstmorphologische Studien in der glazialüberformten Höhenstufe der Picos de Europa, Nordspanien. Jahrbuch der Geographischen Gesellschaft zu Hannover. Heft 4, Selbesverlag der Geographischen Gesellschaft Hannover.

Montserrat, J., 1992. Evolución glaciar y postglaciar del clima y la vegetación en la vertiente sur del Pirineo: Estudio palinológico. Instituto Pirenaico de Ecología, Zaragoza, 147 pp.

Morellón, M., Valero-Garcés, B., González-Sampériz, P., Vegas-Vilarrúbia, T., Rubio, E., Rieradevall, M., Delgado-Huertas, A., Mata, P., Romero, Ó., Engstrom, D., López-Vicente, M., Navas, A., Soto, J., 2011. Climate changes and human activities recorded in the sediments of Lake Estanya (NE Spain) during the Medieval Warm Period and Little Ice Age. Journal of Paleolimnology, 46, 423–452.

Morellón, M., Pérez-Sanz, A., Corella, J.P., Büntgen, U., Catalan, J., González-Sampériz, P., González-Trueba, J.J., López-Sáez, J.A., Moreno, A., Pla-Rabes, S., Saz-Sánchez, M.A., Scussolinni, P., Serrano, E., Steinhilber, F., Stefanova, V., Vegas-Villarrubia, T., Valero-Garcés, B., 2012. A multi-proxy perspective on millennium-long climate variability in the Southern Pyrenees. Climate of the Past, 8, 683–700.

Moreno, A., Valero-Garcés, B.L., González-Samperiz, P., Rico, M., 2008. Flood response to rainfall variability during the last 2000 years inferred from the Taravilla Lake record (Central Iberian Range, Spain). Journal of Paleolimnology, 40, 943–961.

Moreno, A., Pérez, A., Frigola, J., Nieto-Moreno, V., Rodrigo-Gámiz, M., González-Sampériz, P., Morellón, M., Martín-Puertas, C., Corella, J.P., Belmonte, A., Cacho, I, Canals, M., Jiménez-Espejo, F., Martínez-Ruiz, F., Vegas, T., Valero-Garcés, B.L., 2012. The Medieval Climate Anomaly in the Iberian Peninsula reconstructed from a compilation of marine and lake records. Quaternary Science Reviews, 43, 16–32.

Mundee, M. 2010. Exploring diet and society in Medieval Spain: New approaches using stable isotope analysis. Doctoral thesis. PhD thesis, Durham University.

Muñoz, J., 1982. Geografía Física. El relieve, el clima y las aguas, in: Quirós, F. (Ed.): Geografía de Asturias, Ayalga Ediciones, Salinas, vol. 1, 1–271.

Neukom, R., Gergis, J., Karoly, D.J., Wanner, H., Curran, M., Elbert, J., González-Rouco, F., Linsley, B.K., Moy, A.D., Mundo, I., Raible, C.C., Steig, E.J., Van Ommen, T., Vance, T., Villalba, R., Zinke, J., Frank, D., 2014. Inter-hemispheric temperature variability over the past millennium. Nature Climate Change, 4 (5), 362–367.

Nicolás, P., 1981. Morfología del circo de Tucarroya. Cuadernos de Investigación Geográfica, 6 (1-2), 51–80.

Nieto-Moreno, V., Martínez-Ruiz, F., Giralt, S., Gallego-Torres, D., García-Orellana, J., Masqué, P., Ortega, M., 2013. Climate imprints during the 'Medieval Climate Anomaly' and the 'Little Ice Age' in marine records from the Alboran Sea basin. The Holocene, 23 (9), 1227–1237.

Nussbaumer, S.U., Zumbühl, H.J., Steiner, D., 2007. Fluctuations of the Mer de Glace (Mont Blanc area, France) AD 1500–2050: an interdisciplinary approach using new historical data and neural network simulations. Zeitschrift fuer Gletscherkunde und Glazialgeologie, 40 (2005/2006), 1–183.

Oliva, M., Gómez-Ortiz, A., 2012. Late Holocene environmental dynamics and climate variability in a Mediterranean high mountain environment (Sierra Nevada, Spain) inferred from lake sediments and historical sources. The Holocene, 22 (8), 915–927.

Oliva, M., Schulte, L., Gómez-Ortiz, A., 2011. The role of aridification in constraining the elevation range of Holocene solifluction processes and associated landforms in the periglacial belt of the Sierra Nevada (Southern Spain). Earth Surface Processes and Landforms, 36, 1279–1291.

Oliva, M., Gómez-Ortiz, A., Palacios, D., Salvador-Franch, F., Salvà-Catarineu, M., 2014. Environmental evolution in Sierra Nevada (South Spain) since the Last Glaciation based on multi-proxy records. Quaternary International, 353, 195–209.

Oliva, M., Serrano, E., Gómez-Ortiz, A., González-Amuchastegui, M.J., Nieuwendam, A., Palacios, D., Pellitero-Ondicol, R., Pérez-Alberti, A., Ruiz-Fernández, J., Valcárcel, M., Vieira, G., Antoniades, D., 2016a. Spatial and temporal variability of periglaciation of the Iberian Peninsula. Quaternary Science Reviews, 137, 176–199.

Oliva, M., Gómez-Ortiz, A., Salvador-Franch, F., Salvà-Catarineu, M., Ramos, M., Palacios, D., Tanarro, L., Pereira, P., Ruiz-Fernández, J., 2016b. Inexistence of permafrost at the top of Veleta peak (Sierra Nevada, Spain). Science of the Total Environment, 550, 484–494.

Ortiz, J.E., Gallego, J.L.R, Torres, T., Díaz-Bautista, A., Sierra, C., 2010. Palaeoenvironmental reconstruction of northern Spain during the last 8000 cal yr BP based on the biomarker content of the Roñanzas peat bog (Asturias). Organic Geochemistry, 41, 454–466.

Palacios, D., Andrés, N., Luengo, E., 2003. Distribution and effectiveness of nivation in Mediterranean mountains: Peñalara (Spain). Geomorphology, 54, 157–178.

Palacios, D., García-Ruiz, J.M., Andrés, N., Schimmelpfennig, I., Campos, N., Léanni, L., ASTER Team, 2017. Deglaciation in the central Pyrenees during the Pleistocene-Holocene transition: timing and geomorphological significance. Quaternary Science Reviews, 162: 111–127.

Paredes D., Trigo, R.M., García-Herrera R., Trigo, I.F., 2006. Understanding precipitation changes in Iberia in early spring: weather typing and storm-tracking approaches. Journal of Hydrometeorology, 7, 101–113.

Pauli, H., Gottfried, M., Dullinger, S., Abdaladze, O., Akhalkatsi, M., Benito-Alonso, J.L., Coldea, G., Dick, J., Erschbamer, B., Fernández-Calzado, R., Ghosn, D., Holten, J.I., Kanka, R., Kazakis, G., Kollár, J., Larsson, P., Moiseev, P., Moiseev, D., Molau, U., Molero-Mesa, J., Nagy, L., Pelino, G., Puscas, M., Rossi, G., Stanisci, A., Syverhuset, A.O., Theurillat, J.P., Tomaselli, M., Unterluggauer, P., Villar, L., Vittoz, P., Grabherr, G. 2012. Recent plant diversity changes on Europe's mountain summits. Science, 336, 353–355.

Pauling, A., Luterbacher, J., Wanner, H., 2003. Evaluation of proxies for European and Horth Atlantic temperature field reconstructions. Geophysical Research Letters, 30 (2–1), 2–4.

Pauling, A., Luterbacher, J., Casty, C., Wanner, H., 2006. Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. Climate Dynamics, 26 (4), 387–405.

Pedraza, J., López, J., 1980. Gredos: geología y glaciarismo. Obra Social de la Caja de Ahorros de Avila, Avila. 31 pp.

Pellitero, R., 2012. Geomorfología, paleoambiente cuaternario y geodiversidad en el Macizo de Fuentes Carrionas-Montaña Palentina. PhD thesis. University of Valladolid.

Peña-Angulo, D., Trigo, R.M., Cortesi, N., González-Hidalgo, J.C., 2016. The influence of Weather Types on the monthly average maximum and minimum temperature in the Iberian Peninsula. Atmospheric Research, 178-179, 217–230.

Peña, J.L., Lozano, M.V., Sánchez-Fabre, M., Jiménez-Martínez, A., Longares, L.A., Chueca, J., Julián, A., 2000. Las acumulaciones de clima frío de la Sierra de Albarracín en el contexto de la Cordillera Ibérica Oriental, in: Peña, J.L., Sánchez-Fabre, M., Lozano, M.V. (Eds.): Procesos y formas periglaciares en la montaña mediterránea. Instituto de Estudios Turolenses, Teruel, 127–147.

Peña, J.L., Julián, A., Chueca, J., Echeverría, M.T., Ángeles, G., 2004. Etapas de evolución holocena en el valle del río Huerva: Geomorfología y Geoarqueología, in: Peña, J.L. (Eds.): Geografía Física de Aragón. Aspectos generales y temáticos. University of Zaragoza – Institución Fernando el Católico, Zaragoza, 289–302.

Pérez-Alberti, A., Valcárcel, M., Martínez-Cortizas, A., Blanco, R., 1998. Evidencias de procesos periglaciares actuales en el noroeste de la Península Ibérica, in: Gómez-Ortiz, A., Salvador-Franch, F., Schulte, L., García Navarro, A. (Eds.): Procesos biofísicos actuales en medios fríos. Universidad de Barcelona, Barcelona, 245–261.

Pérez-Sanz, A., González-Sampériz, P., Moreno, A., Valero-Garcés, B., Gil-Romera, G., Rieradevall, M., Tarrats, P., Lasheras-Álvarez, L., Morellón, M., Belmonte, A., Sancho, C., Sevilla-Callejo, M., Navas, A., 2013. Holocene climate variability, vegetation dynamics and fire regime in the central Pyrenees: the Basa de la Mora sequence (NE Spain). Quaternary Science Reviews, 73, 149–169.

Pfister, C., Brázdil, R., 1999. Climatic variability in sixteenth-century Europe and its social dimension: a synthesis. Climatic Change, 43 (1), 5–53.

Pino, D., Ruiz-Bellet, J.L., Balasch, J.C., Romero-Len, L., Tuset, J., Barriendos, M., Mazon, J., Castelltort, X., 2016. Meteorological and hydrological analysis of major floods in NE Iberian Peninsula. Journal of hydrology, 541, 63–89.

Pla, S., Catalan, J., 2005. Chrysophyte cysts from lake sediments reveal the submillennial winter/spring climate variability in the northwestern Mediterranean region throughout the Holocene. Climate Dynamics, 24, 263–278.

Pla-Rabes, S., Catalan, J., 2011. Deciphering chrysophyte responses to climate seasonality. Journal of Paleolimnology, 46, 139–150.

Porter, S.C., 1986. Pattern and forcing of northern hemisphere glacier variations during the last millenium. Quaternary Research, 26, 27–48.

Prohom, M., Esteban, P., Martín-Vide, J., Jones, P.D., 2003. Surface atmospheric circulation over Europe following major tropical volcanic eruptions, 1780-1995. Volcanism and the Earth´s Atmosphere. Geophysical Monograph 139, American Geophysical Union, 273–281.

Prohom, M., Barriendos, M., Aguilar, E., Ripoll, R., 2012. Recuperación y análisis de la serie de temperatura diaria de Barcelona, 1780-2011, in: Rodríguez-Puebla, C.; Ceballos A.; González, N.; Morán, E. & Hernández A. (Eds.): Cambio Climático. Extremos e Impactos. Publicaciones de la Asociación Española de Climatología (AEC), serie A (8), 207–217.

Prohom, M., Barriendos, M., Sánchez-Lorenzo, A., 2016. Reconstruction and homogenization of the longest instrumental precipitation series in the Iberian Peninsula (Barcelona, 1786–2014). International Journal of Climatology, 36 (8), 3072–3087.

Railsback, L.B., Liang, F., Vidal-Romaní, J.R., Grandal-d'Anglade, A., Vaqueiro-Rodríguez, M., Santos-Fidalgo, L., Fernández-Mosquera, D., Cheng, H., Edwards, R.L., 2011. Petrographic and isotopic evidence for Holocene long-term climate change and shorter-term environmental shifts from a stalagmite from the Serra do Courel of northwestern Spain, and implications for climatic history across Europe and the Mediterranean. Palaeogeography, Palaeoclimatology, Palaeoecology, 305, 172–184.

Ramos-Román, M.J., Jiménez-Moreno, G., Anderson, R.S., García-Alix, A., Toney, J.L., Jiménez-Espejo, F.J., Carrión, J.S., 2016. Centennial-scale vegetation and North Atlantic Oscillation changes during the Late Holocene in the southern Iberia. Quaternary Science Reviews, 143, 84–95.

Rao, M.P., Cook, B.I., Cook, E.R., D'Arrigo, R.D., Krusic, P.J., Anchukaitis, K.J., LeGrande, A.N., Buckley, B.M., Davi, N.K., Leland, C., Griffin, K.L., 2017. European and Mediterranean hydroclimate responses to tropical volcanic forcing over the last millennium. Geophysical Research Letters, 44 (10), 5104–5112.

René, P., 2013. Le réchauffement climatique en images. Ed. Cairn. Pau, France, 167 pp.

Renssen, H., Goosse, H., Fichefet, T., 2007. Simulation of Holocene cooling events in a coupled climate model. Quaternary Science Reviews, 26, 2019–2029.

Rico, M., Benito, G., Barnolas, A., 2001. Combined palaeoflood and rainfall-runoff assessment of mountain floods (Spanish Pyrenees). Journal of Hydrology, 245, 1–4, 59–72.

Rico, I., Izaguirre, E., Serrano, E., López-Moreno, J.I., 2016. Current glacier area in the Pyrenees: an updated assessment 2016. Pirineos, 172, e029, doi: 10.3989/Pirineos.2017.172004.

Riera, S., Wansard, G., Julià, R., 2004. 2000-year environmental history of a karstic lake in the Mediterranean Pre-Pyrenees: the Estanya lakes (Spain). Catena, 55 (3), 293–324.

Riera, S., López-Sáez, J.A., Julià, R., 2006. Lake responses to historical land use changes in northern Spain: The contribution of non-pollen palynomorphs in a multiproxy study. Review of Palaeobotany and Palynology, 141, 127–137.

Rodrigo, F.S., 2012. Completing the early instrumental weather record from Cádiz (Southern Spain): new data from 1799 to 1803. Climatic Change, 111, 697–704.

Rodrigo, F.S., Barriendos, M. 2008. Reconstruction of seasonal and annual rainfall variability in the Iberian Peninsula (16th-20th Centuries) from documentary data. Global and Planetary Changes, 63, 243–257.

Rodrigo, F.S., Esteban Parra, M.J., Castro Diez, Y., 1995. Reconstruction of Total Annual Rainfall in Andalusia (Southern Spain) During the 16th and 17th Centuries from Documentary Sources. Theoretical and Applied Climatology, 52, 207–218.

Rodrigo, F.S., Esteban-Parra, M.J., Castro-Diez, Y., 1998. On the use of the Jesuit order private correspondence records in climate reconstructions: A case study from Castille (Spain) for 1634–1648 AD. Climatic Change, 40 (3-4), 625–645.

Rodrigo, F.S., Esteban-Parra, M.J., Pozo-Vázquez, D., Castro-Diíaz, Y., 1999. A 500-year precipitation record in southern Spain. International Journal of Climatology, 19, 1233–1253.

Rodrigo, F.S., Esteban-Parra, M.J., Pozo-Vázquez, D., Castro-Díez, Y., 2000. Rainfall variability in southern Spain on decadal to centennial time scales. International Journal of Climatology, 20, 721–732.

Rodrigo, F.S., Gómez-Navarro, J.J., Montávez Gómez, J.P., 2012. Climate variability in Andalusia (southern Spain) during the period 1701–1850 based on documentary sources: evaluation and comparison with climate model simulations. Climate of the Past, 8, 117–133

Rodríguez, R., Barriendos, M., Jones, P.D., Martín-Vide, J., Peña, J.C., 2001. Long pressure series for Barcelona (Spain). Daily reconstruction and monthly homogenization. International Journal of Climatology, 21 (13), 1693–1704.

Rodríguez-Puebla, C., Encinas, A.H., Nieto, S., Garmendia, J., 1998. Spatial and temporal patterns of annual precipitation variability over the Iberian Peninsula. International Journal of Climatology, 18, 299–316.

Rodwell, M.J., Rowell, D.P., Folland, C.K., 1999. Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. Nature, 398 (6725), 320–323.

Ruiz-Fernández, J., Poblete, M.A., García, C., 2014. Características morfoclimáticas y procesos y formas periglaciares actuales en el Macizo Occidental de los Picos de Europa (Cordillera Cantábrica), in: Gómez-Ortiz, A., Salvador, F., Oliva, M., Salvà, M. (Eds.): Avances, métodos y técnicas en el estudio del periglaciarismo. University of Barcelona, Barcelona, 91–103.

Ruiz-Fernández, J., Oliva, M., Cruces, A., Lopes, V., Freitas, M.C., Andrade, C., García-Hernández, C., López-Sáez, J.A., Geraldes, M., 2016. Environmental evolution in the Picos de Europa (Cantabrian Mountains, SW Europe) since the Last Glaciation. Quaternary Science Reviews, 138, 87–104.

Ruiz-Fernández, J., Oliva, M., Hrbáček, F., Vieira, G., García-Hernández, C., 2017. Soil temperatures in an Atlantic high mountain environment: The Forcadona buried ice patch (Picos de Europa, NW Spain). Catena, 149 (2), 637–647.

Rull, V., González-Sampériz, P., Corella, J.P., Morellón, M., Giralt, S., 2011. Vegetation changes in the southern Pyrenean flank during the last millennium in relation to climate and human activities: the Montcortès lacustrine record. Journal of Paleolimnology 46, 387–404.

Sánchez-López, G., Hernández, A., Pla-Rabes, S., Toro, M., Granados, I., Sigró, J., Trigo, R.M., Rubio-Inglés, M.J., Camarero, L., Valero-Garcés, B., Giralt, S., 2015. The effects of the NAO on the ice phenology of Spanish alpine lakes. Climate Change, 130, 101–113.

Sánchez-López, G., Hernández, A., Pla-Rabes, S., Trigo, R.M., Toro, M., Granados, I., Sáez, A., Masqué, P., Pueyo, J.J., Rubio-Inglés, M.J., Giralt, S., 2016. Climate reconstruction for the last two millennia in central Iberia: The role of East Atlantic (EA), North Atlantic Oscillation (NAO) and their interplay over the Iberian Peninsula. Quaternary Science Reviews, 149, 135–150.

Sancho, C., Peña, J.L., Muñoz, A., Benito, G., McDonald, E., Rhodes, E.J., Longares, L.A., 2008. Holocene ne alluvial morphopedosedimentary record and environmental changes in the Bardenas Reales Natural Park (NE Spain). Catena, 73, 225–238.

Sancho, C., Belmonte, A., López-Martínez, J., Moreno, A., Bartolomé, M., Calle, M., Santolaria, P., 2012. Potencial paleoclimático de la cueva helada A294 (Macizo de Cotiella, Pirineos, Huesca). Geogaceta, 52, 101–104.

Sancho, C., Bartolomé, M., Moreno, A., Belmonte, A., Leunda, M., Oliva-Urcia, B., López-Martínez, J., Delgado-Huertas, A., 2016. Las cuevas heladas del Pirineo como sensores paleoambientales: estado de la cuestión. Geo-Temas, 16 (1), 311–314.

Sanjuán, Y., Gómez-Villar, A., Nadal-Romero, E., Álvarez-Martínez, J., Arnáez, J., Serrano-Muela, M.P., Rubiales, J.M., González-Sampériz, P., García-Ruiz, J.M., 2016. Linking land cover changes in the sub-alpine and montane belts to changes in a torrential river. Land Degradation & Development, 27, 179–189.

Santos, J.A., Carneiro, M.F., Alcoforado, M.J., Leal, S., Luz, A.L., Camuffo, D., Zorita, E., 2015. Calibration and multi-source consistency analysis of reconstructed precipitation series in Portugal since the early 17th century. The Holocene, 25 (4), 663–676.

Saz, M.A., 2003. Temperaturas y precipitaciones en la mitad norte de España desde el siglo XV. Estudio dendroclimático. Publicaciones del Consejo de Protección de la Naturaleza de Aragón, Zaragoza, 293 pp.

Saz-Sánchez, M.A., 2007. Evolución de las temperaturas medias de la estación cálida (abril-septiembre) en la mitad norte de España durante la Pequeña Edad del Hielo (siglos XVI al XIX). Geographicalia, 52, 143–163.

Saz-Sánchez, M.A., Creus-Novau, J., 2001. El clima del pirineo centro-oriental desde el siglo XV: Estudio dendroclimático del observatorio de Capella. Boletín Glaciológico Aragonés 2, 37–79.

Saz-Sánchez, M.A., Creus-Novau, J., 2008. El cambio climático en La Rioja: evolución reciente de la temperatura media anual en Haro en el contexto de los últimos 600 años. Zubía Monográfico 20, 37–60.

Saz-Sánchez, M.A., Creus-Novau, J., Cuadrat-Prats, J.M., 2004. La Pequeña Edad del Hielo en Galicia: reconstrucción de las temperaturas de Labacolla entre los siglos XVI y XIX. Xeográfica 4, 141–161.

Schellekens, J., Buurman, P., Fraga, I., Martínez-Cortizas, A., 2011. Holocene vegetation and hydrologic changes inferred from molecular vegetation markers in peat, Penido Vello (Galicia, Spain). Palaeogeography, Palaeocliamtology, Palaeoecology, 299, 56–69.

Schellekens, J., Buurman, P., Kuyper, T.W., Abbott, G.D., Pontevedra-Pombal, X., Martínez-Cortizas, A., 2015. Influence of source vegetation and redox conditions on lignin-based decomposition proxies in graminoid-dominated ombrotrophic peat (Penido Vello, NW Spain). Geoderma, 237-238, 270–282.

Schneider, L., Smerdon, J.E., Büntgen, U., Wilson, R.J.S., Myglan, V.S., Kirdyanov, A.V., Esper J., 2015. Revising midlatitude summer temperatures back to A.D. 600 based on a wood density network. Geophysical Research Letters, 42 (11), 4556–4562.

Schulte, L., 2002. Climatic and human influence on river systems and glacier fluctuations in southeast Spain since the Last Glacial Maximum. Quaternary International, 93–94, 85–100.

Schulte, L., 2003. River-response and terrace aggradation in the Mediterranean Iberian Peninsula during historical times, in: Thorndycraft, V.R., Benito, G., Barriendos, M., Llasat, M.C. (Eds.): Palaeofloods, Historical Data & Climate Variability. Consejo Superior de Investigaciones Científicas, Centro de Ciencias Medioambientales, Madrid, 67–72.

Schulte, L., Julià, R., Burjachs, F., Hilgers, A., 2008. Middle Pleistocene to Holocene geochronology of the River Aguas terrace sequence (Iberian Peninsula): Fluvial response to Mediterranean environmental change. Geomorphology, 98, 13–33.

Serrano, E., 1996. Líneas de equilibrio glaciar, glaciares rocosos y paleoambiente postglaciar en la alta montaña pirenaica (Macizo de Panticosa, Pirineo Aragonés), in: Pérez-Alberti, A., Martini, P., Chesworth, W., Martínez-Cortizas A. (Eds.): Dinámica y Evolución de Medios Cuaternarios. Universidad de Santiago de Compostela, Santiago de Compostela, 157–170.

Serrano, E., 1998. Geomorfología del Alto Gállego (Pirineo aragonés). Institución Fernando El Católico, Zaragoza, 501 pp.

Serrano, E., Agudo, C., Martínez de Pisón, E., 1999. Rock glaciers in the Pyrenees. Permafrost and Periglacial Processes, 10, 101–106.

Serrano, E., Agudo, C., González-Trueba, J.J., 2002. La deglaciación de la alta montaña. Morfología, evolución y fases morfogenéticas glaciares en el macizo del Posets (Pirineo Aragonés). Cuaternario y Geomorfología, 16 (1–4), 111–126.

Serrano, E., Sanjosé, J.J., Agudo, C., 2006. Rock glacier dynamics in a marginal periglacial high mountain environment: Flow, movement (1991-2000) and structure of the Argualas rock glacier, the Pyrenees. Geomorphology, 74, 285–296.

Serrano, E., Sanjosé, J.J., González-Trueba, J.J., 2010. Rock glacier dynamics in marginal periglacial environments. Earth Surface Processes and Landforms, 35 (11), 1302–1314.

Serrano, E., González-Trueba, J.J., Sanjosé, J.J., 2011. Dinámica, evolución y estructura de los glaciares rocosos de los Pirineos. Cuadernos de Investigación Geográfica, 37 (2), 145–170.

Serrano, E., González-Trueba, J.J., González-García, M., 2012. Mountain glaciation and paleoclimate reconstruction in the Picos de Europa (Iberian Peninsula, SW Europe). Quaternary Research, 78, 303–314.

Serrano, E., González-Trueba, J.J., Pellitero, R., González-García, M., Gómez, M., 2013. Quaternary glacial evolution in the Cantabrian Mountains (Northern Spain). Geomorphology, 196, 65–82.

Serrano, E., Gómez-Lende, M., Belmonte, A., Sancho, C., Sánchez-Benítez, J., Bartolomé, M., Leunda, M., Moreno, A., Hivert, B., 2017. Ice Caves in Spain, in: Perşoiu, A., Lauritzen S.E., (Eds.): Ice caves. Elsevier, Oxford.

Shindell, D.T., Schmidt, G.A., Mann, M.E., Rind, D. Waple, A., 2001. Solar forcing of regional climate change during the Maunder Minimum. Science, 294, 2149–2152.

Shindell, D.T., Schmidt, G.A., Mann, M.E., Faluvegi, G., 2004. Dynamic winter climate response to large tropical volcanic eruptions since 1600. Journal of Geophysical Research, 109, D05104, doi: 10.1029/2003JD004151.

Silva, P.G., Calmel-Avila, M., Bardají, T., Goy, J.L., Zazo, C., 2008. Transition from alluvial to fluvial systems in the Guadalentín Depression (SE Spain) during the Holocene: Lorca Fan versus Guadalentín River. Geomorphology, 100, 144–153.

Silva-Sánchez, N., Martínez-Cortizas, A., López-Merino, L., 2014. Linking forest cover, soil erosion and mire hydrology to late-Holocene human activity and climate in NW Spain. The Holocene, 24, 714–725.

Silva-Sánchez, N., Martínez-Cortizas, A., Abel, D., López-Sáez, J.A., Mighall, T.M., 2016. Influence of climate change and human activities in the organic and inorganic composition of peat during the Little Ice Age (El Payo mire, Gata range, W Spain). The Holocene, 26, 1290–1303.

Smith, A.C., Wynn, P.M., Barker, P.A., Leng, M.J., Noble, S.R., Tych, W., 2016. North Atlantic forcing of moisture delivery to Europe throughout the Holocene. Scientific Reports, 6, 24745.

Solanski, S.K, Usoskin I.G., Kromer, B., Schüssler, M., Beer, J., 2004. Unusual activity of the Sun during recent decades compared to the previous 11.000 anys. Nature, 431, 1084–1087.

Sousa, P., Trigo, R.M., Barriopedro, D., Soares, P.M.M., Ramos, A.M., Liberato, M.L.R., 2017. Responses of European precipitation distributions and regime to different blocking locations. Climate Dynamics, 48, 1141–1160.

Stoll, H.M., Moreno, A., Mendez-Vicente, A., González-Lemos, S., Jiménez-Sánchez, M., Domínguez-Cuesta, M.J., Edwards, R.L., Cheng, H., Wang, X., 2013. Paleoclimate and growth rates of speleothems in the northwestern Iberian Peninsula over the last two glacial cycles. Quaternary Research, 80, 284–290.

Stuiver, M., Braziunas, T.F., Grootes, P.M., Zielinski, G.A. 1997. Is there evidence for solar forcing of climate in the GISP2 oxygen isotope record? Quaternary Research, 48 (3), 259–266.

Tejedor, E., de Luis, M., Cuadrat, J.M., Esper, J., Saz, M.A. 2016. Tree-ring-based drought reconstruction in the Iberian Range (east of Spain) since 1694. International Journal of Biometeorology, 60 (3), 361–372.

Tejedor, E., Saz, M.A., Cuadrat, J.M., Esper, J., de Luis, M., 2017. Temperature variability of the Iberian Range since 1602 inferred from tree-ring records. Climate of the Past, 13, 93–105.

Thorndycraft, V., Benito, G., 2006. The Holocene fluvial chronology of Spain: evidence from a newly compiled radiocarbon database. Quaternary Science Reviews, 25, 223–234.

Thorndycraft, V.R, Barriendos, M., Benito, G., Rico, M., Casas, A., 2006. The catastrophic floods of AD 1617 in Catalonia (northeast Spain) and their climatic control. Hydrological Sciences Journal, 51 (5), 899–912.

Trigo, R.M., DaCamara, C.C., 2000. Circulation weather types and their impact on the precipitation regime in Portugal. International Journal of Climatology, 20, 1559–1581.

Trigo, R.M., Osborn, T.J., Corte-Real, J.M., 2002. The North Atlantic Oscillation influence on Europe: Climate impacts and associated physical mechanisms. Climate Research, 20 (1), 9–17.

Trigo, R.M., Pozo-Vázquez, D., Osborn, T.J., Castro-Diez, Y., Gámis-Fortis S., Esteban-Parra, M.J., 2004. North Atlantic Oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. International Journal of Climatology, 24, 925–944.

Trigo, R.M., Vaquero, J.M., Alcoforado, M.J., Barriendos, M., Taborda, J., García-Herrera, R., Luterbacher, J., 2009a. Iberia in 1816, the year without a summer. International Journal of Climatology, 29, 99–115.

Trigo, R.M., Ramos, A., Nogueira, P., Santos, F.D., García-Herrera, R., Gouveia, C., Santo, F.E., 2009b. The impact of the 2003 heatwave in Portugal: diagnostics and modelling of excessive mortality. Environmental Science & Policy, 12, 844–854

Trigo R.M., Sousa, P., Pereira, M., Rasilla, D., Gouveia, C.M., 2016. Modeling wildfire activity in Iberia with different Atmospheric Circulation Weather Types. International Journal of Climatology, 36, 2761–2778.

Troll, C. 1973. The upper timberlines in different climatic zones. Arctic, Antarctic and Alpine Research, 5 (3), 5–18.

Trouet, V.R., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., Frank, D.C., 2009. Persistent positive North Atlantic oscillation mode dominated the medieval climate anomaly. Science, 324, 78–80.

Turbón, D., Botella, M.C., Campillo, D., Hernández, M., Jiménez-Brobeil, S.A., Pérez-Pérez, A., Pons, J., Souich, Ph. Du, Trancho G. 1995. Efectos de la presión ambiental sobre poblaciones humanas, in: Botella, M.C., Jiménez-Brobeil, S.A, Ruiz, L. Souich, Ph. (Eds.): Nuevas perspectivas en Antropología. Sociedad Española de Antropología Biológica y Diputación Provincial de Granada, Granada, 1029–1031.

Uribelarrea, D., Pérez-González, A., Benito, G., 2003. Channel changes in the Jarama and Tagus rivers (central Spain) over the past 500 years. Quaternary Science Reviews, 22, 2209–2221.

Usoskin, I.G., Mursula, K., Solanski, S., Schüssler, M., Alanko, K., 2004. Reconstruction of solar activity for the last millennium using 10Be data. Astronomy & Astrophysics, 413, 745–751.

Valcárcel, M., 1998. Evolución geomorfológica y dinámica de vertientes en el NE de Galicia. Importancia de los procesos de origen frío en un sector de las montañas lucenses. PhD thesis, University of Santiago de Compostela.

Valero-Garcés, B., Moreno, A., 2011. Iberian lacustrine sediment records: responses to past and recent global changes in the Mediterranean region. Journal of Paleolimnology, 46, 319–325.

Vegas, J., 2007. Caracterización de eventos climáticos del Pleistoceno Superior-Holoceno mediante el estudio sedimentológico de la Laguna Grande (Sierra Neila, NO Sistema Ibérico). Revista de la Sociedad Geológica de España, 20 (1–2), 53–70.

Vicente-Serrano, S.M., 2006. Differences in spatial patterns of drought on different time scales: an analysis of the Iberian Peninsula. Water Resources Management, 20 (1), 37–60.

Vicente-Serrano, S.M., Cuadrat, J.M., 2007. North Atlantic oscillation control of droughts in north-east Spain: evaluation since 1600 A.D. Climatic Change, 85, 357–379.

Vicente-Serrano S.M., López-Moreno, J.I., 2008. The nonstationary influence of the North Atlantic Oscillation on European precipitation. Journal of Geophysical Research-Atmosphere, 113, D20120, doi: 10.1029/2008JD010382.

Vicente-Serrano, S.M., García-Herrera, R., Barriopedro, D., Azorín-Molina, C., López-Moreno, J.I., Martín-Hernández, N., Tomás-Burguera, M., Gimeno, L., Nieto, R., 2016. The Westerly index as complementary indicator of the North Atlantic Oscillation in explaining drought variability across Europe. Climate Dynamics, 47, 845–863.

Vicente-Serrano, S.M., Rodríguez-Camino, E., Domínguez-Castro, F., El Kenawy, A., Azorín-Molina, C., 2017. An updated review on recent trends in observational surface atmospheric variables and their extremes over Spain. Cuadernos de Investigación Geográfica, 43 (1), doi: 10.18172/cig.3134.

Vidal, T., 1984. El poblament, in: Carreras, J. (Ed.): Gran Geografia Comarcal de Catalunya, Enciclopèdia Catalana, Barcelona, vol. 17, 266–311.

Von Storch, H., Zorita, E., Jones, J.M., Dimitriev, Y., González-Rouco, F., Tett, S.F.B., 2004. Recontructing past climate from noisy data. Science, 306 (5696), 679–682.

Wang, J., Yang, B., Ljungqvist, F.C., Luterbacher, J., Osborn, T.J., Briffa, K.R., Zorita, E. Internal and external forcing of multidecadal Atlantic climate variability over the past 1,200 years. (2017) Nature Geoscience, 10 (7), 512-517.

Wanner, H., Beck, C., Brádzil, R., Casty. C., Deutsch, M., Glaser, R., Jacobeit, J., Luterbacher, J., Pfister, C., Pohl, S., Sturm, K., Werner, P.C., Xoplaki, E., 2004. Dynamic and socio-economic aspects of historical floods in central Europe. Erdkunde, 58, 1–16.

Wanner, H., Solomina, O., Grosjean, M., Ritz, S.P., Jetel, M., 2011. Structure and origin of Holocene cold events. Quaternary Science Reviews, 30 (21–22), 3109–3123.

Wheeler, D., 1995. Early instrumental weather data from Cádiz: a study of late eighteenth and early nineteenth century records. International Journal of Climatology, 15, 801–810.

Wheeler, D., 2006. The Gibraltar climatic record: part 1 – the history of weather observations. Weather, 61, 36–39.

Wheeler, D., 2007. The Gibraltar climatic record: part 2 – precipitation. Weather, 62, 99–104.

Wheeler, D., 2011. The Gibraltar climatic record: part 3 – temperature. Weather, 66, 259–265.

Wheeler, D., Bell, A., 2012. The Gibraltar climatic record – Part 4. The earliest records. Weather, 67 (9), 240–245.

Winkler, M., Lamprecht, A., Steinbauer, K., Hülber, K., Theurillat, J.P., Breiner, F., Choler, P., Ertl, S., Gutiérrez Girón, A., Rossi, G., Vittoz, P., Akhalkatsi, M., Bay, C., Benito, J.L., Bergström, T., Carranza, M.L., Corcket, E., Dick, J., Erschbamer, B., Calzado, R.F., Fosaa, A.M., Gavilán, R.G., Ghosn, D., Gigauri, K., Huber, D., Kanka, R., Kazakis, G., Klipp, M., Kollar, J., Kudernatsch, T., Larsson, P., Mallaun, M., Michelsen, O., Moiseev, P., Moiseev, D., Molau, U., Molero-Mesa, J., Morra di Cella, U., Nagy, L., Petey, M., Pușcaș, M., Rixen, C., Stanisci, A., Suen, M., Syverhuset, A.O., Tomaselli, M., Unterluggauer, P., Ursu, T., Villar, L., Gottfried, M., Pauli, H., 2016. The rich sides of mountain summits – a pan-European view on aspect preferences of alpine plants. Journal of Biogeography, 43 (11), 2261–2273.

Wolf, D., Seim, A., Díaz del Olmo, F., Faust, D., 2013a. Late Quaternary fluvial dynamics of the Jarama River in central Spain. Quaternary International, 302, 20–41.

Wolf, D., Seim, A., Faust, D., 2013b. Fluvial system response to external forcing and human impact- Late Pleistocene and Holocene fluvial dynamics of the lower Guadalete River in western Andalucía (Spain). Boreas, 43 (2), 422–449.

Xing, F., Kettner, A.J., Ashton, A., Giosan, L., Ibáñez, C., Kaplan, J.O., 2014. Fluvial response to climate variations and anthropogenic perturbations for the Ebro River, Spain in the last 4000 years. Science of the Total Environment, 473–474, 20–31.

Zorita, E., Von Storch, H., González-Rouco, F.J., Cubach, U., Luterbacher, J., Legutke, S., Fisher-Bruns, I., Schlese, U., 2004. Climate evolution in the last five centuries simulated by an atmospheric-ocean model: global temperatures, the North Atlantic Oscillation and the late Maunder Minimum. Metorologische Zeitschrift, 13 (4), 271–289.

Zorita, E., Moberg, A., Leijonhufvud, L., Wilson, R., Brázdil, R., Dobrovolný, P., Luterbacher, J., Böhm, R., Pfister, C., Riemann, D., Glaser, R., Söderberg, J., González-Rouco, F. European temperature records of the past five centuries based on documentary/instrumental information compared to climate simulations. (2010) Climatic Change, 101 (1), pp. 143-168.

Zumbühl, H.J., Steiner, D., Nussbaumer, S.U., 2008. 19th century glacier representations and fluctuations in the central and western European Alps: An interdisciplinary approach. Global and Planetary Change, 60 (1–2), 42–57.

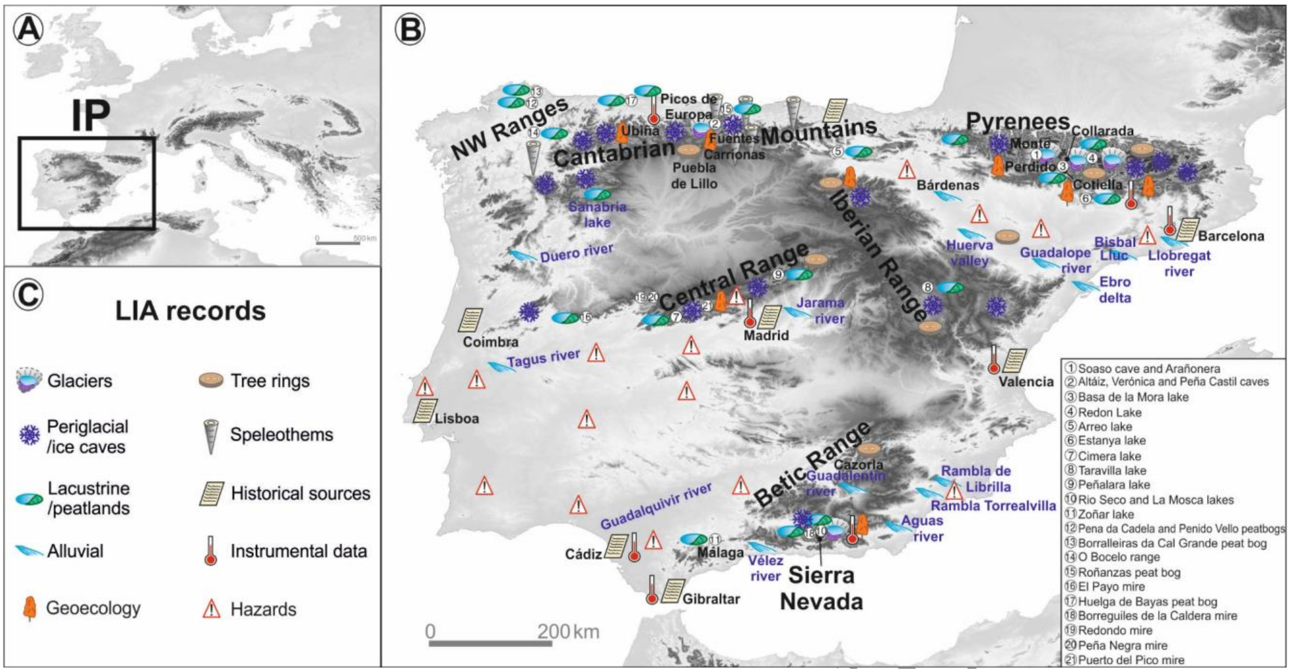

Figure 1. Location of the Iberian Peninsula within Europe (a), and the sites mentioned in the text (b), including those relevant to natural, historical, and instrument records for the LIA.

Figure 2. Comparison of glaciated environments during the LIA and present-day conditions in various cirques: (a) Monte Perdido glacier, the Pyrenees; (b) Cemba Vieya glacier, Western Massif of Picos de Europa; (c) Veleta glacier, the Sierra Nevada.

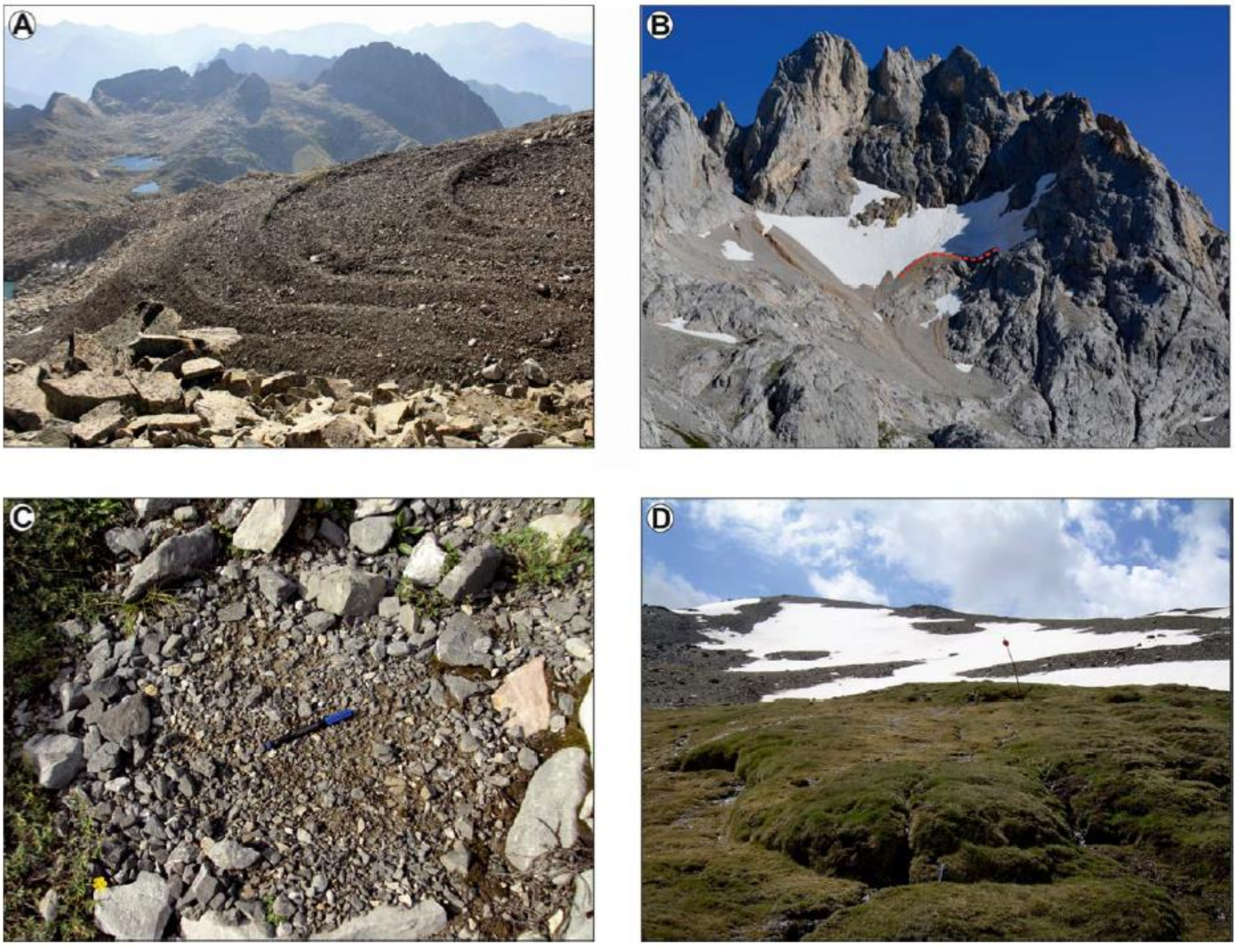

Figure 3. Examples of periglacial features formed during the LIA: (a) Posets rock glacier, located at 3040 m on the northeast face of Posets peak (3369 m, central Pyrenees); (b) LIA protalus rampart at 2380 m on the northern face of Los Campanarios peak (Picos de Europa, Cantabrian Mountains); (c) weakly active sorted circle in the Ubiña Massif (2000 m, Cantabrian Mountains); and (d) currently inactive solifluction lobe in the Sierra Nevada (2900 m, Betic Range).

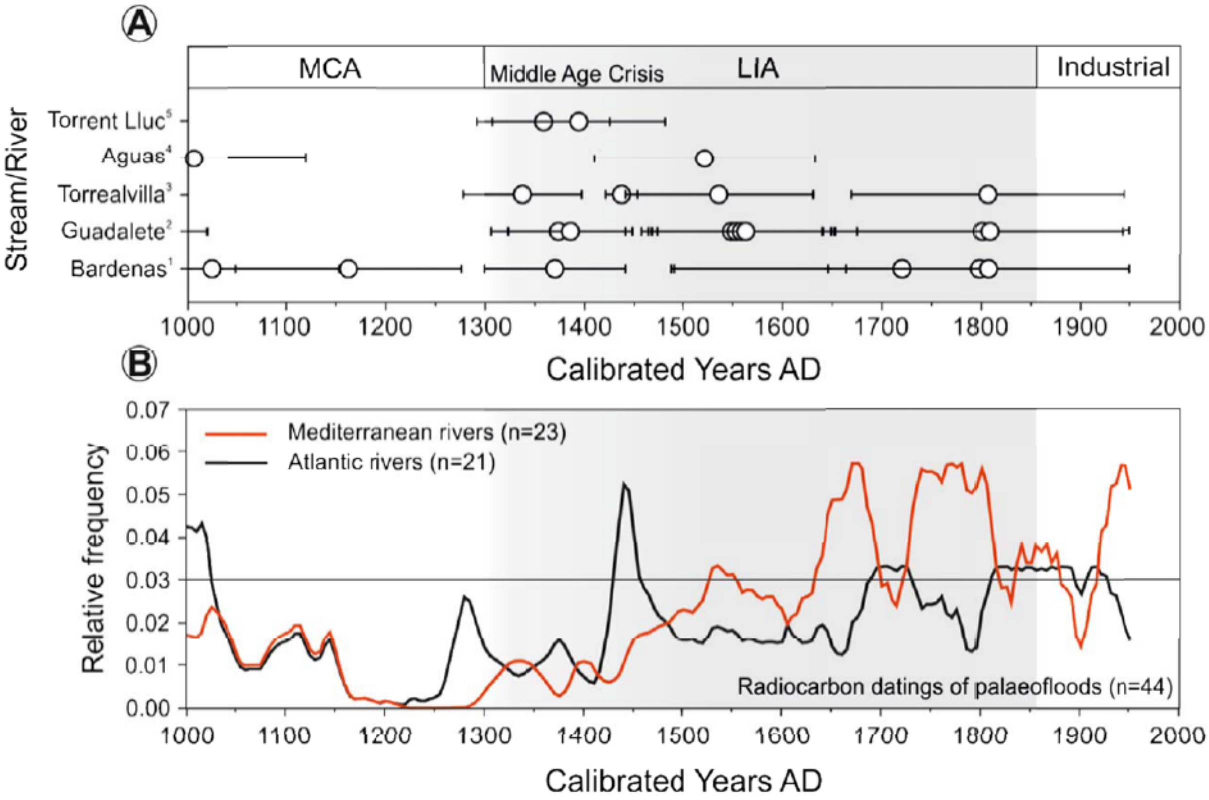

Figure 4. (a) Radiocarbon dates for fluvial terraces and alluvial deposits in selected Iberian rivers over the last millennium. Data source: Torrent Lluc (Schulte, 2003); Aguas River (Schulte et al., 2002), Torrealvilla stream (Baartman et al., 2011); Guadalete River (Wolf et al., 2013a); Bardenas (several streams, Sancho et al., 2008). (b) Cumulative probability density function (CPDF) obtained from the analysis of radiocarbon dates collected from units representing paleofloods and extreme fluvial events in rivers on the Mediterranean and Atlantic Ocean sides of the Iberian Peninsula (data from Benito et al., 2015a, 2015b).

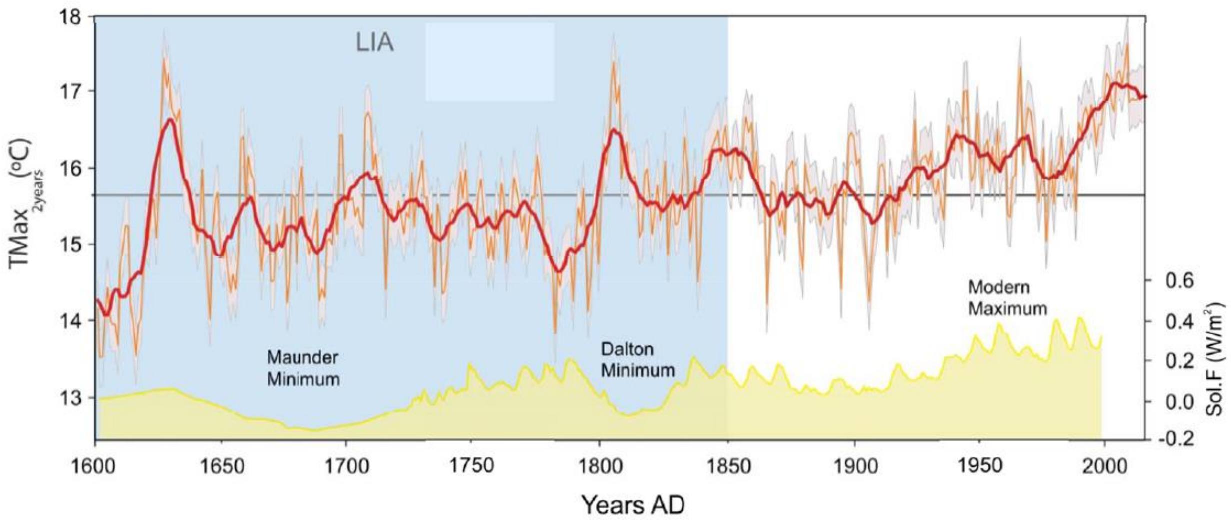

Figure 5. Maximum temperature reconstruction since AD 1602 for the Iberian Range. The blue shading indicates the LIA segment included in the reconstruction, the bold red curve is an 11-year running mean, the grey shading indicates the mean square error based on the calibration period correlation, and the yellow shading at the bottom shows solar forcing (figure adapted from Tejedor et al., 2017).

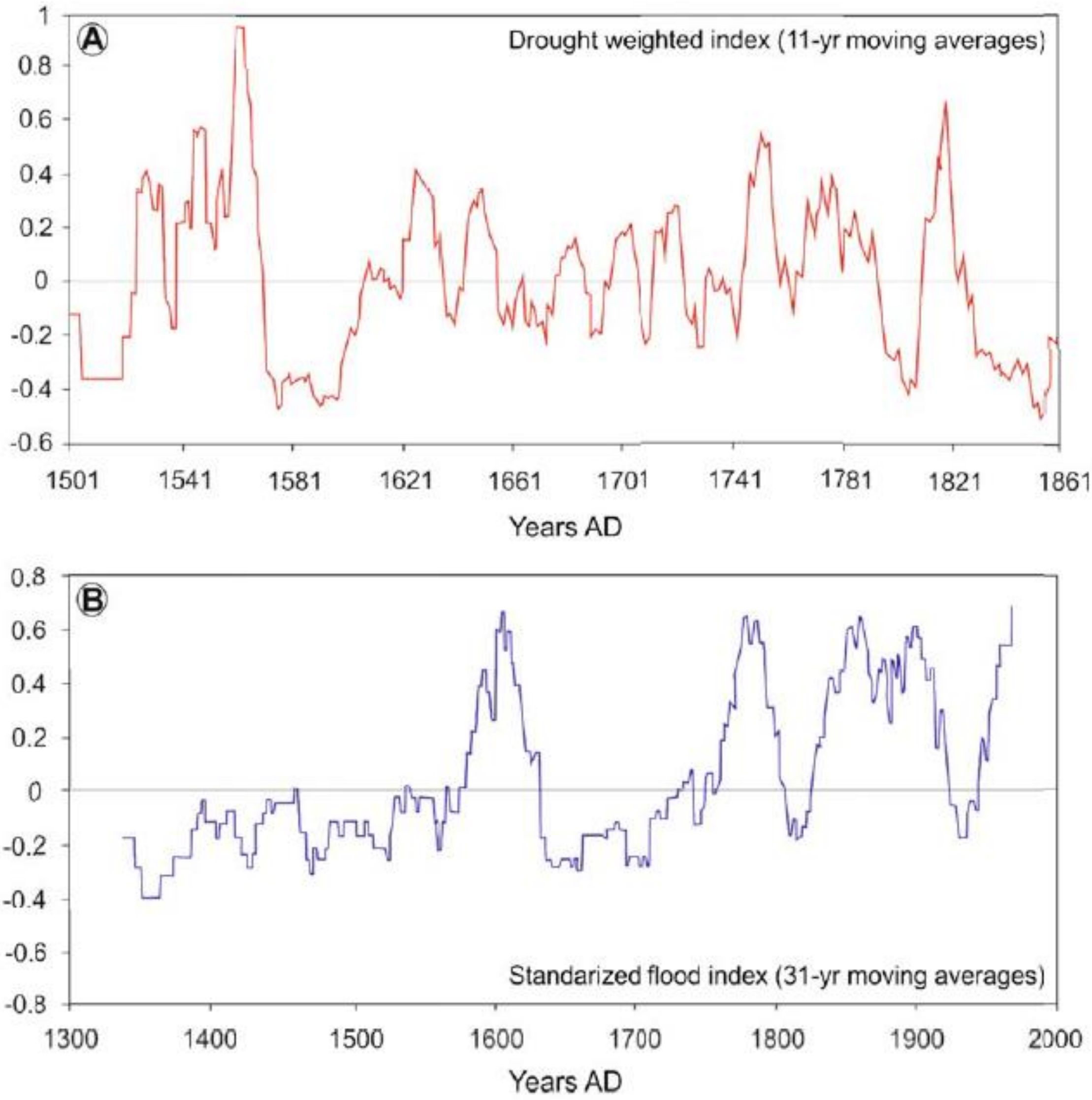

Figure 6. (a) Weighted index for drought rogation ceremonies for selected coastal cities in northeast Iberia. Standardized values smoothed using 11-year moving averages (source: author data modified from Martín-Vide & Barriendos, 1995). (b) Catastrophic flood frequencies for selected cities in northeast Iberia. Standardized values smoothed using 31-year moving averages (source: author data modified from Martín-Vide & Barriendos, 1998).

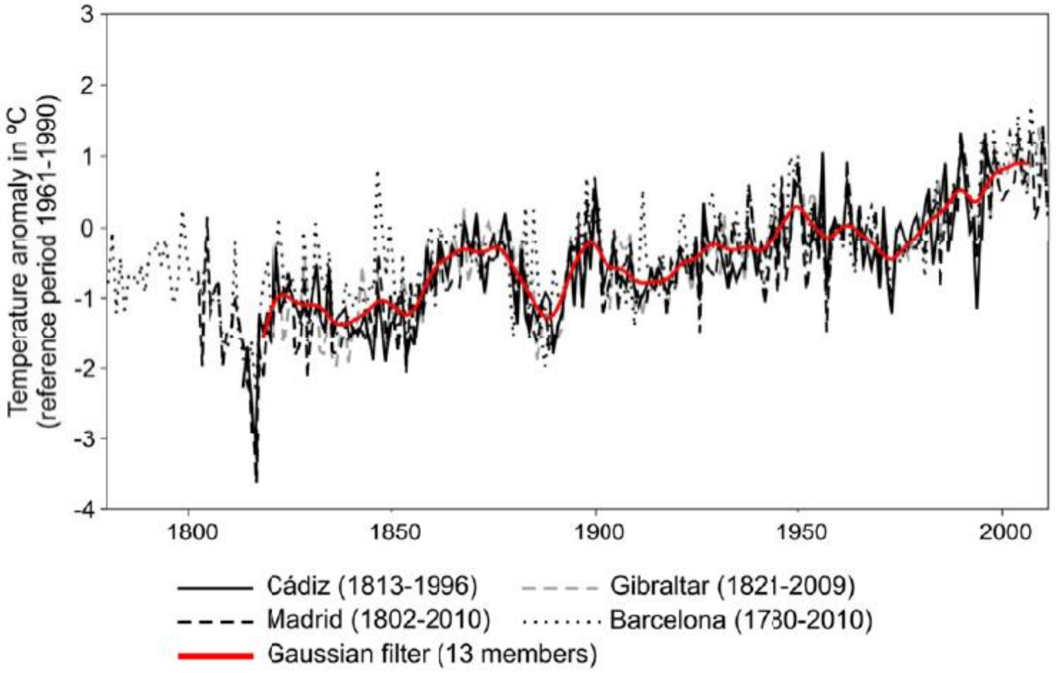

Figure 7. Mean annual temperature for Cádiz, Gibraltar, Madrid, and Barcelona during the period 1780–2010. The values are expressed as departures from the control period 1961–1990. The red line is a 13-period Gaussian filter obtained when at least three series were available.

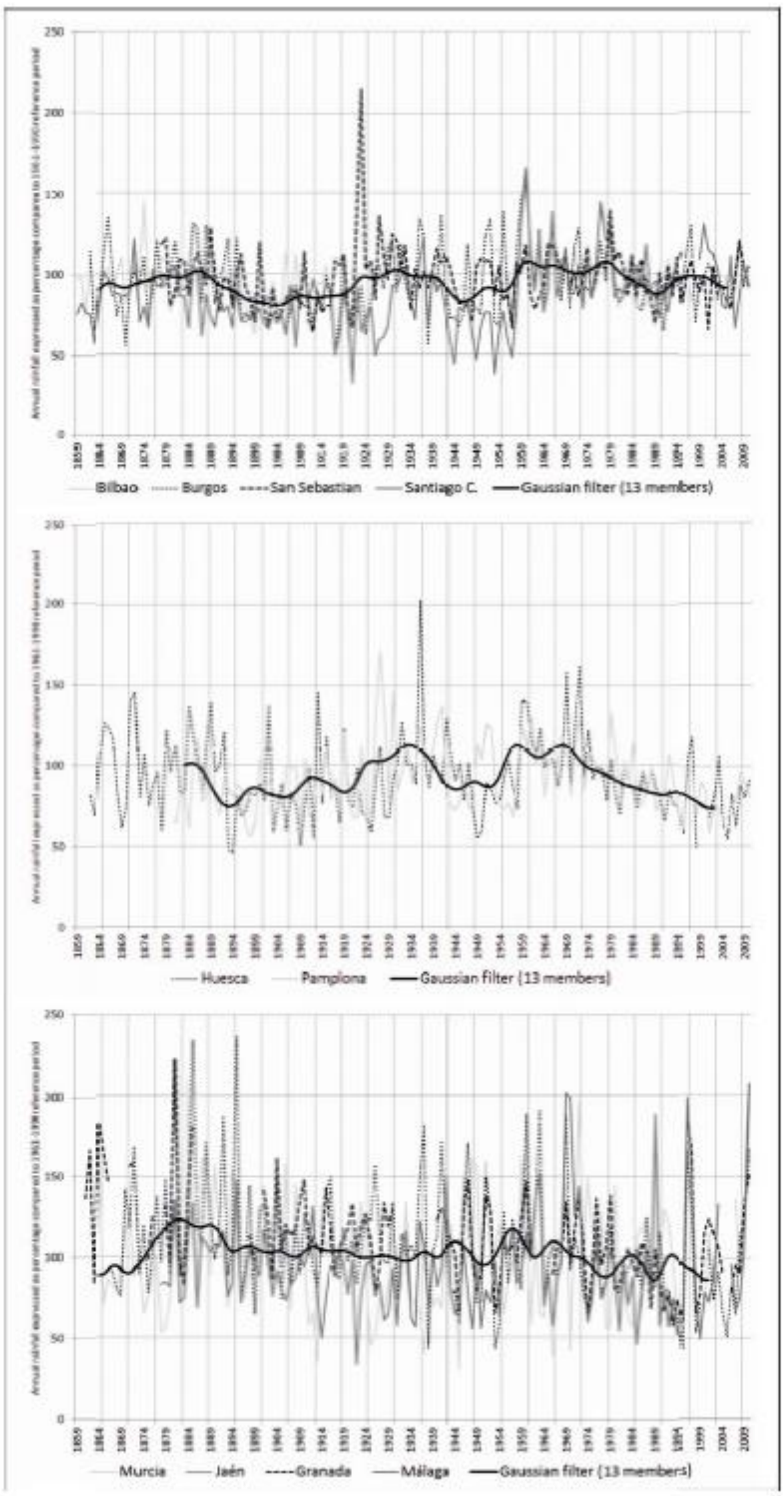

Figure 8. Mean annual rainfall for a set of series derived from near the Cantabrian Mountains (top), the Pyrenees (middle), and the Sierra Nevada (bottom). The series cover the common period 1859–2010, and the values are expressed as percentages with respect to the control period 1961–1990. The thick solid line is a 13-period Gaussian filter obtained when at least two series were available.

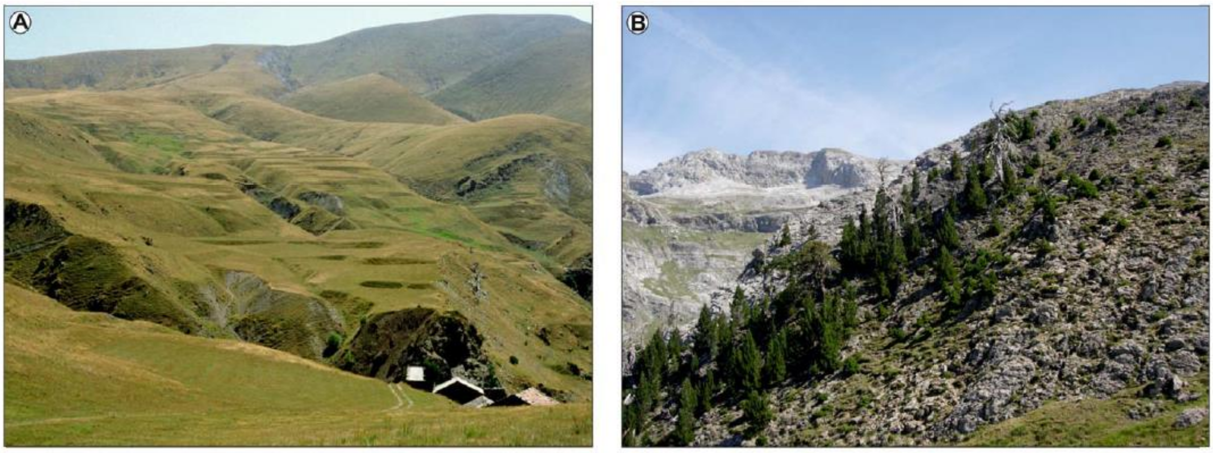

Figure 9. (a) Fields in the Castanesa Valley, central Pyrenees, at approximately 1650 m. These fields are located in the ecotone between the montane belt and the subalpine belt. They were cultivated with rye on a 13-month cycle, and were probably abandoned during the coldest periods of the LIA. (b) Natural upper forest limit in the headwater of the Escuaín Valley. Young *Pinus uncinata* trees are occupying increasingly high positions because of global warming, whereas some dead trees are evidence of a lowering of the natural tree line during the 18th and 19th centuries.

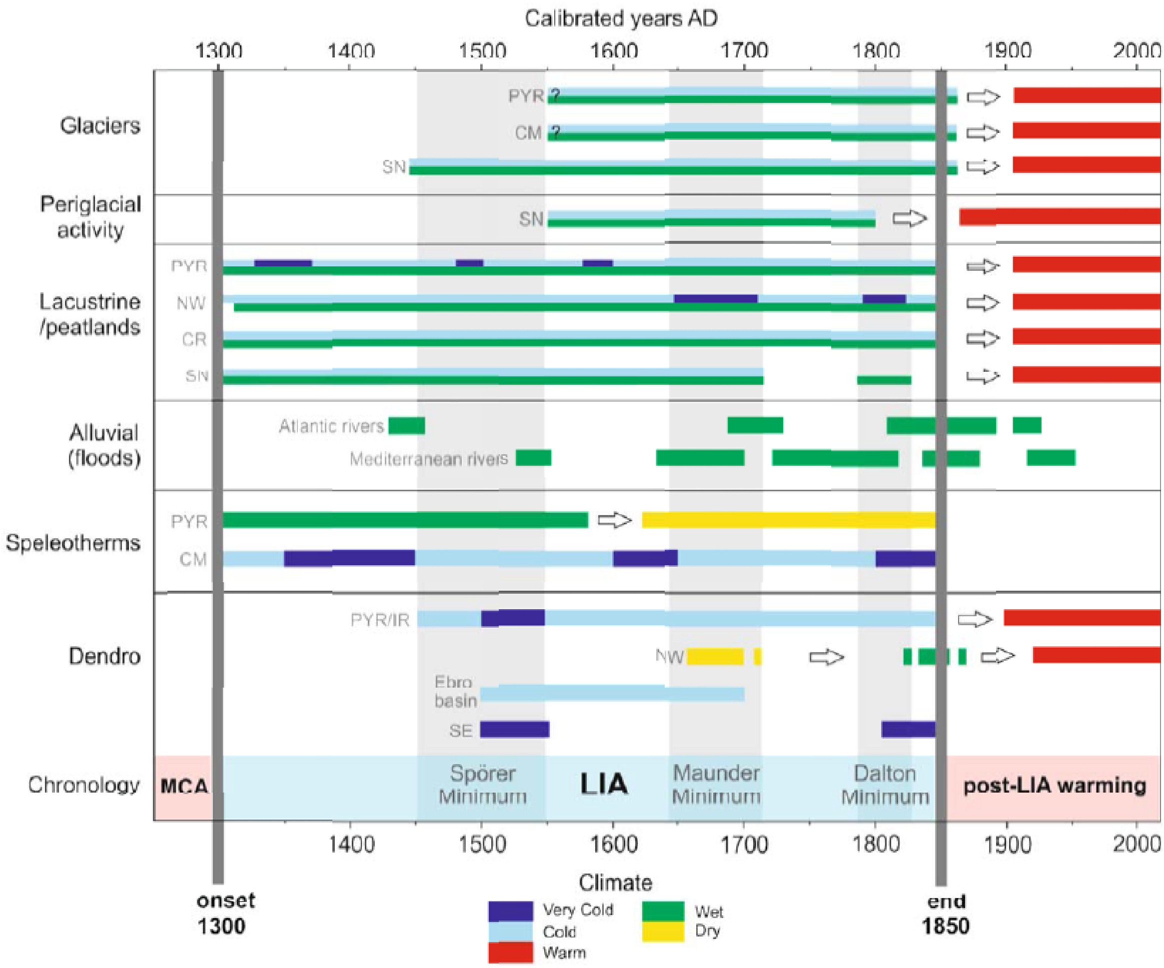

Figure 10. Onset and end of the LIA, based on natural records from the main Iberian mountain ranges (PYR: Pyrenees; CM: Cantabrian Mountains; CR: Central Range; IR: Iberian Range; SN: Sierra Nevada).

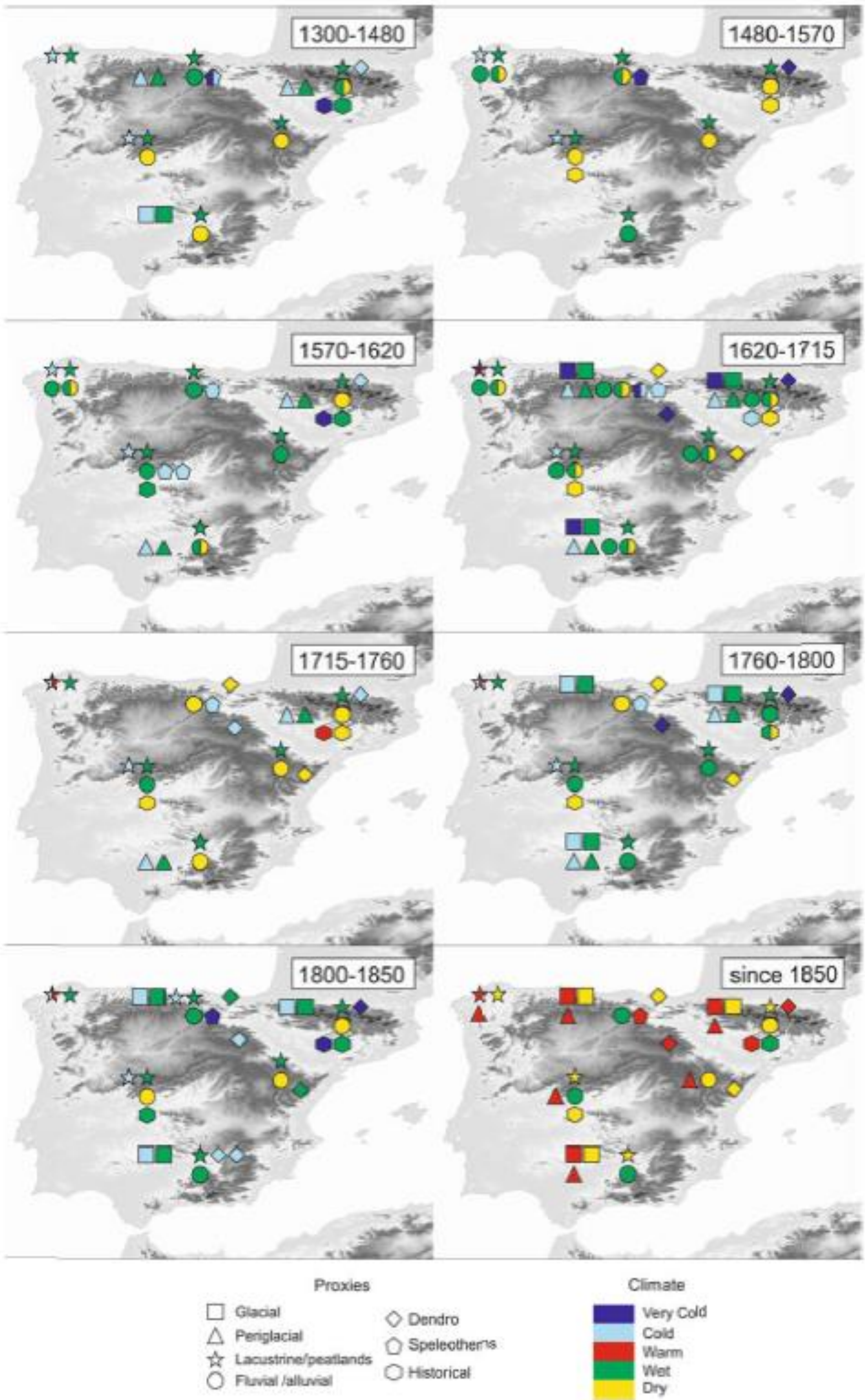

Figure 11. Summary of climate conditions for the various stages of the LIA in the Iberian Peninsula, inferred from each of the studied proxies (symbols represent wide areas, not specific places).

Table 1. Summary of the proxies examined, the nature of the evidence, and the time frame for each proxy for the last millennium.

Proxy	Evidence	Time frame (AD)
Glacial	Sedimentological records (i.e. moraines), historical documents	Discontinuous, from 1440 onwards
Periglacial	Slope deposits, inactive landforms, ice caves	Discontinuous, with few ^{14}C dates
Lake and peat records	Biological and geochemical variations, sedimentation changes	1000–2015
Fluvial and alluvial records	Various types of deposit, sedimentation changes	1000–2000
Speleothems	Geochemical variations, sedimentation changes	1200–2015
Tree rings	Tree-ring widths, stable carbon isotopes	1500–2000
Historical sources	Documents generated by local public administrations and ecclesiastical authorities, private documents	1000–2015
Instrument data	Direct climate measurements from various cities across Iberia	1780–2015

Table 2. Number of proxies indicating prevailing cold temperatures (above) and wet conditions (below) for each period. In brackets the total number of proxies with information for that period and study area.

	Pyrenees	Cantabrian Mountains	NW Ranges	Central Range	Iberian Range	Sierra Nevada	Total
1300-1480	2 (2)	2 (2)	1 (1)	1 (1)	-	1 (1)	7 (7)
1480-1570	1 (1)	1 (1)	1 (1)	1 (1)	-	-	4 (4)
1570-1620	3 (3)	1 (1)	2 (2)	1 (1)	-	1 (1)	8 (8)
1620-1715	4 (4)	3 (3)	0 (1)	1 (1)	1 (1)	2 (2)	11 (12)
1715-1760	2 (3)	1 (1)	0 (1)	1 (1)	1 (1)	2 (2)	7 (9)
1760-1800	3 (4)	2 (2)	0 (1)	1 (1)	1 (1)	2 (2)	9 (11)
1800-1850	2 (3)	2 (2)	0 (1)	1 (1)	1 (1)	2 (2)	8 (10)
Since 1850	0 (5)	0 (3)	0 (2)	0 (2)	0 (2)	0 (2)	0 (16)

	Pyrenees	Cantabrian	NW Ranges	Central Range	Iberian Range	Sierra Nevada	Total
1300-1480	4 (4)	2 (2)	1 (1)	1 (2)	1 (2)	2 (3)	11 (14)
1480-1570	2 (3)	0 (1)	1 (1)	1 (2)	1 (2)	2 (3)	7 (12)
1570-1620	3 (4)	1 (1)	1 (1)	2 (2)	2 (2)	3 (4)	12 (14)
1620-1715	5 (5)	3 (4)	-	1 (2)	2 (3)	4 (4)	15 (18)
1715-1760	2 (3)	0 (2)	-	2 (2)	1 (2)	2 (4)	7 (13)
1760-1800	4 (4)	1 (3)	-	2 (2)	2 (2)	4 (4)	13 (15)
1800-1850	2 (3)	3 (3)	-	1 (2)	1 (2)	4 (4)	11 (14)
Since 1850	0 (3)	1 (3)	-	1 (2)	0 (3)	1 (3)	3 (14)

Table 3. Summary of geomorphological evidence of glacier activity in Iberian mountains during the LIA.

Region	Areas	Evidence	Chronological framework	Climate conditions
Pyrenees	Highest cirques in the Central Pyrenees	Development and/or expansion of glaciers in the highest northern and southern cirques (ELA ≥ 2600–2950 m). The glaciers stayed within the cirques or nearby as small alpine glaciers, with the formation of moraines (frontal and latero-frontal). Presence of glacial erosion features (polished bedrock and glacial striae).	Maximum glacial expansion in the last decades of the 17th century. Minor re-advances 1750 and 1800. Glacier advance 1805–1830. Glacier retreat 1850–1870. Minor re-advances and equilibrium 1890–1920. Glacier retreat during the 1930s. Drastic retreat since the end of 1980s.	Glacier advance was driven by colder conditions and/or greater snowfall. Glacier retreat was favored by warmer temperatures. Long-term temperature increase since the second half of the 19th century.
Cantabrian Mountains	Highest northern cirques in the Picos de Europa	Development of small glaciers in the highest northern cirques of the Western and Central Massifs of the Picos de Europa. ELA, northern face: 2250 m (Western Massif)/2340 m (Central Massif). Formation of frontal moraines. Presence of glacier erosion features (polished bedrock and glacier striae).	Presence of six glaciers that gradually retreated during the second half of the 19th century, and had completely disappeared by the first third of the 20th century.	Glacier advance was driven by colder conditions and/or greater snowfall. Long-term temperature increase since the second half of the 19th century.
Sierra Nevada	Highest northern cirques of the western part of the massif	Development of small glaciers in the highest northern cirques at the foot of the Veleta and Mulhacén peaks (ELA ≥ 2900–3000 m). Formation of frontal moraines.	Presence of two glaciers from mid 15th century that gradually retreated during the second half of the 19th century and had completely disappeared by 1947 (the Mulhacén glacial disappeared by 1710).	Glacier advance was driven by colder conditions and/or greater snowfall. Long-term temperature increase since the second half of the 19th century.

Table 4. Summary of geomorphological evidence from periglacial activity and ice caves in Iberian mountains during the LIA.

Region	Areas	Evidence	Chronological framework	Climate conditions
Pyrenees	Environments above approximately 2000 m	Reactivation of rock glaciers and protalus lobes above 2000 m. Widespread permafrost conditions above 2500 m. Development of patterned ground features and solifluction landforms. Intense cryoturbation and nivation processes. Ice accumulation in ice caves from several massifs.	 Between 950 and 1750 (and earlier in several cases).	Colder conditions with oscillating moisture regimes.
Cantabrian Mountains	Highest lands of the highest massifs	Intense nival dynamics with formation and/or reactivation of protalus ramparts and nivation hollows. Triggering of debris flows and other rapid mass movements. Intense development of nival karst in Picos de Europa and Ubiña massifs. Development of patterned ground features and solifluction landforms. Ice accumulation in ice caves from the Central Massif of the Picos de Europa.	 Between 950 and 1750 (and earlier in several cases).	Colder conditions with oscillating moisture regimes.
Northwest Ranges	Highest lands of the highest massifs	Active screes, formation of protalus ramparts and solifluction landforms. Increase in snow cover.		Colder conditions with oscillating moisture regimes.
Central Range Iberian Range	Highest lands of the highest massifs	Frost shattering reactivating the screes. Formation of nivation hollows.		Colder conditions with oscillating moisture regimes.
Sierra Nevada	Environments above 2500 m	More extensive snow fields. Development of patterned ground features in the flat summit plateaus and solifluction landforms, and debris flows on slopes in glacial cirques/valleys.	Two phases with more intense solifluction activity between 1550 and 1800.	Colder conditions with oscillating moisture regimes.

Table 5. Summary of peat and lacustrine records in Iberian mountains during the LIA.

Region	Areas	Evidence	Chronological framework	Environmental conditions
Central Pyrenees	Estany de Burg, Bassa Nera, Bassa de la Mora, Redon, Estanya	Pollen, charcoal, geochemistry, mineralogy, fossil remains, sedimentary facies, organic matter.	Radiocarbon dating and age-depth modeling.	Proposed chronology for the LIA: 1542–1840. General humid conditions; heavy rainfall (1372–1452); dry episode (1606–1750); LIA onset warm; warmer summers and colder winters. Other: no evidence of landscape change at Estany de Burg; climate oscillations are not reflected by the mature forest; a shift from farming to livestock raising during the LIA at Bassa Nera.
Western Pyrenees	Atlantic zone, Arreo	Pollen, sedimentary facies, mineralogy, geochemistry, fossil remains, charcoal, organic matter.	Radiocarbon dating and age–depth modeling.	General humid conditions. Other: anthropic pressure increases, diversification of farming activities, forest decline (in pulses).
Cantabrian Mountains	Monte Areo, Roñanzas, Huelga de Bayas	Pollen, non-pollen palynomorph, physico-chemical properties, geochemistry, peat organic chemistry.	Radiocarbon dating and age–depth modeling.	Humid period by 1260–1650; wetter conditions in approximately 1460. Other: interference by human activities and the evolution of the peat deposits.
Northwest Iberia	Cruz do Bocelo, Borralleiras da Cal Grande, Pena da Cadela, Penido Vello, Sanabria	Pollen, non-pollen palynomorphs, geochemistry, sedimentary facies, peat organic chemistry, physico-chemical properties, peat humification, organic matter, fossil remains.	Radiocarbon dating and age–depth modeling.	Prevailing wet conditions; wetter at the beginning and end of the LIA; wetter during solar minima; cooling since the Spörer, with lowest temperature in the Maunder and a slight cooling coinciding with the Dalton minima in insolation. Other: increased soil erosion, forest decline.
Central Range Iberian Range	Ayllón Range, Guadarrama Range, Gredos Range, Francia Range, Béjar Range, Gata Range Taravilla, Cañada del Hoyo, El Tobar	Pollen, physico-chemical properties, sedimentary facies, organic matter, geochemistry, mineralogy, fossil remains.	Radiocarbon dating and age–depth modeling.	Generally cooler and wetter conditions are inferred from a slight altitudinal rise of *Betula* at high elevation settings. High abundance of dry and wet phase indicators suggest extreme events. Other: vegetation changes mostly related to human land-use and human induced landscape transformations (agricultural expansion and increasing impact of livestock); increased soil erosion.
Southern Iberia	Borreguiles de la Caldera y de la Virgen (Sierra Nevada), Zoñar, Tablas de Daimiel	Pollen, non-pollen palynomorphs, charcoal, physico-chemical properties, fossil remains, geochemistry, organic matter, mineralogy.	Radiocarbon dating and age–depth modeling.	Rapid centennial-scale oscillations between 1300 and present. Enhanced humid conditions centered in approximately 1300, 1410, 1550–1620, and 1810. Alternating with arid events. Some discrepancies among lowlands records.

Table 6. Summary of fluvial records for Iberian mountain rivers during the LIA.

Region	Areas	Evidence	Chronological framework	Climate conditions
Iberian Peninsula	Atlantic rivers	Slackwater flood deposits	Increasing flooding recorded in slackwater flood deposits during the last millennium at 850–1150 and 1450–1650 cal AD.	A period of increased flooding in Iberian Atlantic rivers between 1000 and 1200 cal AD is also apparent in written documentary records (Benito et al., 2003b), and was associated with unusual wet winters in negative phases of the NAO index. In Iberian Mediterranean catchments, documentary sources indicate highest flood severity during 1580–1620 and 1840–1870.
Northeast Spain	Bisbal, Torrent del Lluc and Gralhera catchments	Alluvial deposition	Colluvial and alluvial aggradation phase after 1365 ± 50 cal AD.	Sedimentation of fluvial deposits started at the onset of the LIA, probably enhanced by deforestation.
Ebro Basin	Arroyo Caldero, Arroyo Bodegas, Arroyo Grande, Arroyo Salinero, Val de la Morea	Infill sequence	Generalized sedimentation in 900–1450 cal AD as a response to arid conditions and human activities during the MCA. Later fluvial incision and aggradation surface (MU4) composed of centimetric sequences of flood sediments dated at 1500–1940 cal AD.	MU4 morpho-sedimentary unit associated with an increase in flood activity during the Maunder Minimum, associated with high hydroclimatic variance during the LIA.
Southeast Spain	Vera Basin: Rambla Ancha, Aguas and Antas River	Fluvial terrace	Historical terrace deposition during the early Middle Ages (terrace +2 m) dated at 1550 cal AD, correlated with either LIA climatic fluctuations or the Christian Reconquest.	Aggradations interpreted as mainly climate-induced, although over the last 500 years human activities in the landscape, related to land-use changes (e.g. Christian Reconquest and expulsion of the Muslims), may have influenced the river dynamics.
Southeast Spain	Librilla/la Murta, Guadalentin	Alluvial deposits	2–3 m above thalweg historic terrace, associated with aggradation episode roughly coinciding with the earliest signals of the LIA, and demographic fluctuations during the Christian Reconquest (dates 1305–1374 cal AD; 1291–1471 cal AD).	This terrace was built after the deep incision of iron deposits and Roman antiquity deposits, between the Medieval and the contemporary period. Less extensive than Middle Holocene fans, showing termination of large accumulation processes in Mediterranean arid climate environments.
Southeast Spain	Ramblas Torrealvilla, Estrecho, Guadalentín and Vélez rivers	Alluvial infill terrace	Historical terrace level deposition occurred in approximately 350, 1250, and 1550 cal AD.	Asynchrony of erosion episodes between the Guadalentín and Rambla Torrealvilla rivers and the absence of younger terraces in the Velez River, interpreted as minor role of external drivers (climate) in river dynamics.
Southwest Spain	Guadalete River	Active sedimentation	Significant floodplain aggradation occurred in historical times starting in 1050 and 1550 cal AD.	The high sedimentation rate at 1550 cal AD points to climate anomalies during the LIA. Anthropogenic signal not clearly distinguishable from that of climate.

Table 7. Summary of speleothem records from Iberian caves during the LIA.

Region	Areas	Evidence	Chronological framework	Climate conditions
Pyrenees	Seso Cave	Speleothem growth, stable isotopes, trace elements	Chronology is well-constrained for the four stalagmites, especially for two that have continued to grow to the present. Records were later combined to produce a stacked profile based on the good overlap of records.	Correlation with instrument data enabled interpretation of $\delta^{18}O$ oscillations in terms of temperature changes. Colder temperatures characterized the onset of the LIA, with cold events during solar irradiance minima. $\delta^{13}C$ and Mg/Ca stacked records show good agreement, and were interpreted as hydrological changes. The LIA onset (approximately 1300–1650) was more humid than the previous period. Water availability decreased afterwards.
Cantabrian lowlands	El Pindal, La Vallina, and Cueva Fría caves	Speleothem growth	Record from El Pindal cave is well-dated but the other two samples (Guillermina and Patricia) based on ^{14}C and U-Th were combined because of the problems associated with detrital particles (associated with flood layers).	The growth of speleothems during the LIA in the three caves was interpreted as the result of a period of more humid conditions than in previous millennia.
	Matienzo, Cueva de Asiul	Speleothem growth, $\delta^{18}O$ records	Combined and de-trended record based on two well-dated speleothems ($\delta^{18}O$ record).	Precipitation amount was the primary factor controlling the high frequency $\delta^{18}O$ oscillations, and was related to variation in the NAO parameter. Thus, the LIA (at least from 1550 to 1650 cal AD) was related to a negative phase of the NAO, and characterized as a wet period.
Cantabrian Mountains	Cueva del Cobre, Kaite Cave, Cueva Mayor	Speleothem growth, $\delta^{13}C$ records	Chronology was well constrained for the three stalagmites, and the records were later combined to produce a stacked profile based on the good overlap of the $\delta^{13}C$ records.	Variation in $\delta^{13}C$ was interpreted as paleotemperature through its relationship to vegetation growth. During the LIA, lower values indicated a colder period (from 1200 to 1850 cal AD) with extremes occurring in 1350–1450, 1600–1650, and 1800–1850 cal AD.
	Kaite Cave	Speleothem growth, $\delta^{18}O$ record	Chronology was well-constrained for the studied stalagmite throughout the Holocene. No changes in growth rate during the LIA were detected relative to the previous interval.	Precipitation amount was the primary factor controlling the high frequency $\delta^{18}O$ oscillations, together with changes in the source of moisture. During the LIA the $\delta^{18}O$ tended to lower values (wetter period) with marked oscillations, but this is not discussed in the text.
Galicia inland	Cova de Arcoia	Speleothem growth, stable isotopes	U-Th dates were not available for the LIA interval. A hiatus was defined within the LIA period (1300–1500) based on petrography, but not dated absolutely.	Stable isotope data ($\delta^{18}O$ and $\delta^{13}C$) were available but not interpreted at this time scale.

Table 8. Summary of dendroclimatic records for the Iberian Peninsula during the LIA.

Region	Areas	Evidence	Chronological framework	Climate conditions
Northeast Spain	Pyrenees, Northern Iberian Range	Tree-ring width, maximum latewood density, stable carbon isotopes, temperature and precipitation signals	Cold period during 1645–1706 (Maunder solar minimum). Cold period during 1810–1838 (Dalton solar minimum). Warm period during the mid-20th and 21st centuries (modern solar maximum).	LIA was characterized by a cold phase having lower annual and summer temperatures relative to the long-term mean, consistent with the solar minima.
Northwest Spain	La Puebla de Lillo	Stable isotopes, precipitation signal	Frequent dry summers from 1665 to 1700. Greater occurrence of dry years during the late Maunder solar minimum. High degree of persistence of pluvial episodes during the mid-19th century. Lack of droughts, and more frequent and severe catastrophic floods.	A greater recurrence of extreme dry summers was evident until the 19th century, when there appeared to be a shift to more frequent and severe catastrophic floods and an absence of droughts. Drivers affecting the northwest precipitation patterns were related to NAO oscillations.
Ebro Basin	Pallaruelo	Tree-ring width, precipitation and temperature signals	High inter-annual climate variability during the Maunder and Dalton solar minima. Decrease in the occurrence of extreme events during the 19th century.	Cold phases during the 16th and 17th centuries. Multi-decadal fluctuations in precipitation and a high degree of recurrence of extreme events during the LIA.
Central Spain	Southern Iberian Range, Sierra de Guadarrama	Tree-ring width, precipitation and temperature signals	High level of recurrence of extreme magnitude dry events during the 18th century. 19th century, low recurrence of extreme events. 20th and 21st centuries, high recurrence and magnitude of extreme dry and wet events.	High inter-annual variability of dry and extreme events during the 18th century, but low variability in the 19th century. The magnitude and recurrence of the extreme dry and wet events in the 20th and 21st centuries was remarkable.
Southeast Spain	Cazorla	Tree-ring width, temperature signal	Coldest period during 1500–1550, coinciding with the second half of the Spörer solar minimum. Cold period during 1800–1860 (Dalton solar minimum).	The LIA spanned a longer period (1500–1930) than found in other European summer temperature reconstructions for the Alps and the Pyrenees. The 20th century did not show unprecedented warmth over the last 800 years.

Table 9. Summary of documented records for the Iberian Peninsula during the LIA.

Region	**Areas**	**Evidence**	**Chronological framework**	**Climate conditions**
Spain	Rogations: Bilbao, Santo Domingo, Calahorra, Girona, Vic, Barcelona, Cervera, Tarragona, Tortosa, Zaragoza, Teruel, Zamora, Toledo, Zafra, Seville, Murcia. Floods: Ter, Besos, Llobregat, Francolí, Ebro, Turia, Jucar, Segura, southern basins, Tajo, Guadalquivir, Segre, northern basins, Duero	Chronologies of droughts (rogation ceremonies) and floods	1500–1850	During 1600–1650 droughts were characterized by their local character; from 1650–1750 droughts affected broader regions and in some cases the entire peninsula. During the period 1750–1850 the more severe droughts periods occurred in 1750–1754 and 1779–1782. Times of high flood occurrence: the middle and late 16th century, the end of the 18th century, and the second half of the 19th century. Times of low occurrence: the middle decades of the 15th century, the early 16th century, 1680–1730, and the early 19th century.
Portugal	Lisbon, Evora, Coimbra, Braga, Evora, Porto, Lamego, Mafra	Chronologies of extreme events (drought/floods) (cold/warm)	1675–1800	1631–1632: rainier than present. 1690s: the coldest decade with severe droughts in 1694 and 1714–1716. The highest variability was detected in the 1730s and the 1780s. The early 1780s were very dry. Heavy precipitation prevailed from 1784–1790.
Northeast Spain	Girona, Barcelona, Tarragona, Tortosa, La Seu d' Urgell, Vic, Cervera, Valencia, Balearic Island	Chronologies of extreme events (drought/floods)	1438–2000	Drought events of moderate severity occurred almost continuously, with the exception of two wet periods (1570–1610 and 1830–1870) and a shorter wet stage between 1795 and 1811. The most severe and extensive drought events took place in 1547–1550, 1561–1567, 1752–1755, and 1819–1821. Three periods of increased frequency of severe floods occurred in 1580–1620, 1760–1800, and 1830–1915.
Northern Spain	Bilbao	Chronologies of extreme events (drought/floods)	1571–2000	Dry periods: 1650–1750, the 19th century, and the last decades of the 20th century.
Ebro valley	Zaragoza	Chronologies of droughts (rogation ceremonies)	1600–2000	Extreme drought periods: 1725–1755, 1765–1800, and 1814–125.
Central Spain	Madrid, Salamanca Valladolid, Zamora, Central Range, Toledo, Aranjuez, Talavera	Chronologies of extreme events (drought/floods) (cold/warm)	1100–2000	Temperature anomalies: 1564–1587(-1.2ºC), 1564–1575 (−1.8°C). Negative temperature anomalies were higher in 1634–1648 than in 1971–1985 (except summer). Precipitation: regular precipitation 1554–1575, with low-intensity floods; low precipitation levels 1576–1584, and few floods; intense precipitation 1585–1599, with large floods interspersed with long-lasting droughts. Intense drought periods: 1600–1675, 1711–1775. High flood frequencies: 1160–1210 (3%), 1540–1640 (11%; peak at 1590–1610), 1730–1760 (5%), 1780–1810 (4%), 1870–1900 (19%), 1930–1950 (17%), and 1960–1980 (12%). The largest floods took place during the periods 1168–1211, 1658–1706, 1870–1900, and 1930–1950.

Andalusia	Seville, Guadalquivir basin, Granada, Sierra Nevada, Málaga	Chronologies of extreme events (drought/floods) (cold/warm)	1500–2000	Wet periods: 1590–1649, 1776–1937. Dry periods: 1501–1589, 1650–1775. Winter temperature (1781–1850): 10.6 ± 0.1°C (11.0°C for 1960–1990). Rainfall (1701–1850): winter 267 ± 18 mm (224 mm for 1960–1990), spring 164 ± 1 (129 mm for 1960–1990), autumn 194 ± 16 mm (162 mm for 1960–1990).
Southeast Spain	Murcia	Chronologies of extreme events (drought/floods)	1400–2000	Dry periods: 1500–1550, 1650–1750, last decades of the 20th century. In autumn, a clear trend of decrease was observed, only interrupted during the second half of the 19th century and beginning of the 20th century. Drought conditions during autumn in approximately 1697 and 1759–1813. A long water deficit was recorded in Murcia between 1815 and 1830. High flood frequencies: 1440–1490, 1520–1570, 1600–1740, 1770–1800, 1820–1840, and 1870–1900.
Southwest Spain	Zafra	Weekly weather observations	1750–1840	Cold periods: 1787–1790, 1805–1808, 1818–1821, 1825–1827, 1832–1837. Warm periods: 1777–1779, 1795–1800, 1823–1825. Wet periods: 1782–1789, 1799–1807. Dry periods: 1796–1799, 1816–1819.