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The Little Ice Age in Iberian mountains

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ABSTRACT

The Little Ice Age (LIA) is known as one of the coldest stages of the Holocene. Most records from the Northern Hemisphere show evidence of significantly colder conditions during the LIA, which in some cases had substantial socio-economic consequences. In this study we investigated the magnitude and timing of climate variability during the LIA in the mountains of the Iberian Peninsula, based on a wide range of natural records (including from glacial, periglacial, and lacustrine/peatland areas; fluvial/alluvial deposits; speleothems; and tree rings), historical documents, and early instrument data. The onset of the LIA commenced in approximately CE 1300, and cold conditions with alternating moisture regimes persisted until approximately CE 1850; the environmental responses ranged from rapid (e.g. tree rings) to delayed (e.g. glaciers). The colder climate of the LIA was accompanied by severe droughts, floods, and cold/heat waves that showed significant spatio-temporal variation across the Iberian mountains. Several phases within the LIA have been detected, including (a) 1300–1480: increasing cooling with moderate climate oscillations; (b) 1480–1570: relatively warmer conditions; (c) 1570–1620: gradual cooling; (d) 1620–1715: coldest climate period of the LIA, particularly during the Maunder Minimum, with temperatures approximately 2 °C below those at present; (e) 1715–1760: warmer temperatures and a low frequency of extreme events; (f) 1760–1800: climate deterioration and more climate extremes (i.e. cold and heat waves, floods and droughts); (g) 1800–1850: highly variable climate conditions alternating with stability (1800–1815), extreme events (1815–1835), and a slight trend of warming associated with intense hydrometeorological events (1835–1850); (h) since 1850: a gradual staggered increase in temperature of approximately 1 °C. Post-LIA warming has led to substantial changes in geo-ecological dynamics, mainly through shrinking of the spatial domain affected by cold climate processes.

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

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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 and 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 and Jones, 1992; Jacoby et al., 1999; Prohom et al., 2003; Hegerl et al., 2011), together with a decline in incident solar radiation on the Earth's surface (Benedict and 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 and Briffa, 2005). The LIA corresponds to Bond event 0 (1200–1800 CE), 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 and 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, among 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 and Martín-Vide, 1998; Rodrigo et al., 1999, 2000; Alcoforado et al., 2000; Barriendos and 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.

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 and 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