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The Medieval Climate Anomaly in the Iberian Peninsula reconstructed from marine and lake records

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ABSTRACT

Selected multi-proxy and accurately dated marine and terrestrial records covering the past 2000 years in the Iberian Peninsula (IP) facilitated a comprehensive regional paleoclimate reconstruction for the Medieval Climate Anomaly (MCA: 900–1300 AD). The sequences enabled an integrated approach to land–sea comparisons and, despite local differences and some minor chronological inconsistencies, presented clear evidence that the MCA was a dry period in the Mediterranean IP. It was a period characterized by decreased lake levels, more xerophytic and heliophytic vegetation, a low frequency of floods, major Saharan eolian fluxes, and less fluvial input to marine basins. In contrast, reconstruction based on sequences from the Atlantic Ocean side of the peninsula indicated increased humidity. The data highlight the unique characteristics of the MCA relative to earlier (the Dark Ages, DA: ca 500–900 years AD) and subsequent (the Little Ice Age, LIA: 1300–1850 years AD) colder periods. The reconstruction supports the hypothesis of Trouet et al. (2009), that a persistent positive mode of the North Atlantic Oscillation (NAO) dominated the MCA.

1. Introduction

The combination of proxy records from several paleoclimate archives (including tree rings, lake sediments, marine cores and speleothems) has enabled identification of five climatic periods during the last two millennia. These have been characterized in terms of temperature and precipitation variability (Mann and Jones, 2003), and include: the Roman Warm Period (RWP; 0–500 years AD), the Dark Ages (DA; 500–900 AD), the Medieval Warm Period (MWP; 900–1300 AD), the Little Ice Age (LIA; 1300–1850 AD), and a subsequent period of warming. Thus, the MWP, which is also termed the Medieval Climate Anomaly (MCA) because of its large heterogeneity in space and time, is the most recent pre-industrial warm era in European climatology (Mann et al., 2009). Although the rates of temperature change (approximately 0.25°C/100 years in the MCA *vs.* 2–6°C/100 years at present) and the forcing mechanisms (natural *vs.* anthropogenic) (Solomon et al., 2007) were probably very different during the MCA relative to those under the current conditions of global warming, in both cases the ecosystem and human societies faced new environmental changes. Our understanding of the dynamics and impact of present-day global change will be enhanced from studies of past analogues of periods of abrupt change, and also from comparison

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with previous warmer periods that were characterized by more gradual changes, such as the MCA. To adapt to and mitigate the effects of present-day global warming it is crucial to understand the causes of the MCA and its forcing factors. Better characterization of temperature and precipitation changes that occurred at a large number of sites located in geographically diverse areas is required to corroborate the global character of the MCA and its spatial variability. To date, the MCA has been mainly described by temperature reconstructions that did not provide a worldwide coverage (Jones et al., 2009).

Climate variability during the last millennium has been related to fluctuations in solar irradiance amplified by feedback mechanisms including ozone production or changes in cloud formation (Gray et al., 2010). Thus, in response to greater solar irradiance during the MCA, persistent La Niña-like tropical Pacific Ocean conditions (Mann et al., 2009), a warm phase of the Atlantic Multidecadal Oscillation (AMO), and a more recent positive phase of the North Atlantic Oscillation (NAO) (Trouet et al., 2009) have been reconstructed in attempts to explain the observed worldwide hydroclimate variability during this period (Seager et al., 2007). The NAO signature appears to be particularly evident in climate reconstructions from Scottish stalagmites (wet during the MCA) (Proctor et al., 2002) and from tree rings from Morocco (dry during the MCA) (Esper et al., 2007); in both cases a positive NAO index was likely to have been a major forcing factor, as suggested by Trouet et al. (2009).

Reconstructions of precipitation variability during the MCA are particularly challenging (Seager et al., 2007), and are much rarer than those of temperature. However, the impacts of climate warming on the hydrological cycle are of paramount importance in the Mediterranean region, which is a densely populated area characterized by a permanent water deficit, and is likely to be subject to extreme hydrological events (particularly droughts) in coming decades (Giorgi, 2006). Within the Mediterranean Basin the Iberian Peninsula (IP) (which is located at the southern edge of the storm tracks that are associated with mid-latitude westerly winds and largely controlled by the NAO and the AMO) is a location uniquely placed for exploration of the influence of the long-term NAO index and the Atlantic Ocean dynamics on hydrological variability.

The study of sedimentary records from small lakes, in which considerable fluctuations in lake levels, water chemistry and biological processes controlled by changes in effective moisture have occurred (Last and Smol, 2001), appears to be the best approach to investigating the impact of the MCA on the hydrological cycle in the IP. Other terrestrial records, such as those in speleothems, provide good information on past temperature conditions. Thus, a recent study of three caves in northern Spain indicated that warmer conditions occurred during the MCA (Martín-Chivelet et al., 2011). Marine sediments in the vicinity of the IP also provide evidence of changes in sea surface temperature (SST), river sediment delivery, and wind patterns related to climate changes during the last millennium (Abrantes et al., 2005; Lebreiro et al., 2006). A review of rapid climate change events during the Holocene (Fletcher and Zielhofer, in press) has shown that in several IP records there is clear evidence of contrasting humidity conditions during the MCA and the LIA. Comparison of marine and terrestrial records provides an integrative approach to the reconstruction of climate variability during past centuries.

The purpose of this study was to review recently published and new Iberian paleoenvironmental records for the last two millennia that fulfil the following requisites: (1) the paleoclimate interpretations were based on multi-proxy reconstructions; and (2) the chronology was independent, based on calibrated accelerator mass spectrometry (AMS) ^{14}C dates and ^{137}Cs/^{210}Pb models. Based on available records for the IP (Table 1, Fig. 1) we undertook the first synthesis of the environmental response in the region during the MCA (900–1300 AD), and characterized and integrated the signals recorded from the marine and terrestrial realms.

2. Study sites: current climatic and oceanographic setting

The current climate of the IP is mainly driven by the position of the Azores high pressure system. The weather in summer is usually dry and hot because of the influence of the atmospheric subtropical high pressure belt (Sumner et al., 2001). During winter the subtropical high shifts to the south, enabling mid-latitude storms to enter the region from the Atlantic Ocean, which brings rainfall to the IP. As a consequence of the geographic situation and topographic conditions, the climate of the IP is extremely diverse but can be roughly divided into three main climatic areas (Fig. 1): (i) the inland areas having a moderate continental climate; (ii) the Mediterranean climate region; and (iii) the oceanic (Atlantic Ocean) climate of the north and northwest of the IP. In addition, some of the higher altitude areas (including the Pyrenees, Sierra Nevada and Iberian Range) have a mountainous (alpine) climate. Both geography and climate are critical influences on the distribution of vegetation, and determine the biogeographical features of the Euro-Siberian and Mediterranean regions (Blanco-Castro et al., 1997; Rivas-Martínez, 2007).

At a decadal scale climate variability over western Europe is strongly influenced by the NAO (Trigo et al., 2004; Vicente-Serrano and López-Moreno, 2006). According to recent studies the NAO explains 21%, 28% and 33% of total atmospheric circulation variability in spring, autumn and winter, respectively (Trigo and Palutikof, 2001). A very positive NAO index results from a strong meridional pressure gradient that forces the North Atlantic depression to follow a more northerly route, which produces wetter winters over northern Europe (Scandinavia, Scotland and Iceland) and drier winters over southern Europe and northern Africa (Wanner et al., 2001; Trigo et al., 2002). A very negative NAO index is associated with a southward displacement of the storm tracks, which leads to more rainfall in southern latitudes. This was the case in winter 2010, when the IP (particularly the western and southern areas) received historically unprecedented levels of precipitation (Vicente-Serrano et al., 2011). In contrast to the Atlantic Ocean sources of precipitation, localized precipitation, and particularly that resulting from Mediterranean influences, is unrelated to the NAO but shows a moderate correlation with the ENSO (Rodó et al., 1997). Martín-Vide and López-Bustins (2006) investigated sea level pressure differences between the Gulf of Cadiz and northern Italy, and defined the Western Mediterranean Oscillation index (WeMOi); when this is in a positive phase there is a decrease of precipitation in the eastern IP. These studies all highlight the complexity of the IP climate.

From an oceanographical point of view the IP lies in the recirculation regime linking the Gulf Stream with the North Equatorial current *via* the Portuguese–Canary boundary current, which flows north to south along the western Iberian margin and favours the upwelling of cold and nutrient-rich intermediate waters (Fiúza, 1983). A branch of that current enters the western Mediterranean Sea through the Strait of Gibraltar, and mixes at the surface with the Mediterranean Surface Water (MSW), forming the Modified Atlantic Water (MAW) as the water becomes saltier and denser. The semi-enclosed character of the Mediterranean Sea leads to a complete thermohaline circulation system, involving the entry of the MAW, *in situ* densification by air–sea interaction, and deep outflowing to the Atlantic Ocean through the Alboran Sea (Pinardi and Masetti, 2000). The Western Mediterranean Deep Water (WMDW) is produced in the Gulf of Lion (Fig. 1) by evaporation and