Was there a common hydrological pattern in the Iberian Peninsula region during the Medieval Climate Anomaly?

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Climate variability reconstructions for the last millennium from several Iberian lake and marine records shed light on the spatial and temporal hydroclimate and associated climate mechanisms during the Medieval Climate Anomaly.

In order to understand the causes and spatial extent of the Medieval Climate Anomaly (MCA; ca. 900-1350 AD) and the Little Ice Age (LIA; ca. 1350-1850 AD), a better characterization of temperature and precipitation changes in a larger number of sites around the globe is required. Understanding the dynamics of MCA in the climatically-vulnerable Mediterranean region is particularly interesting since it encompasses a comparison between the hydrological response to a generally accepted warm period (the MCA) and to the present global warming. To tackle the question of how the MCA and the present global warming compare, the most pertinent approach is to study highly resolved records that are mostly driven by moisture changes. Sediments from small lakes that experience considerable fluctuations in terms of lake level and chemistry and biological proxies record such information on effective moisture variability. Coastal and marine sediments also provide evidence of changes in sea surface temperature (SST), river sediment delivery, and wind patterns related to climate.

Figure 1: Satellite image of the Iberian Peninsula region with the location of lake records (stars) and marine sites (dots) discussed in the text. Image from: Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC.

The Iberian MCA signal: Marine and terrestrial records

Their relative small size, direct connection to surface aquifers, and rapid response to precipitation make Iberian karstic lakes particularly sensitive to moisture changes. Detailed sedimentological and geochemical analyses, complemented with the study of biological proxies (chironomids, diatoms and pollen), have been performed on long sedimentary records retrieved in 2004 from several Spanish lakes. In Figure 1 we show the location of the lakes where the MCA signal is recorded, together with some marine cores discussed below.

Most of the studied lakes (e.g., Estanya, Taravilla, Zoñar, Arreo and Montcortés) record relatively shallower lake levels and more arid conditions during the MCA. This is indicated by higher chemical concentrations in the water, and the predominance of *sclerophyllous* Mediterranean vegetation, heliophytes and more evergreen trees in the catchment. In Figure 2, the most representative Iberian records are compared with global reconstructions, such as the number of sunspots (Vaquero et al., 2002). The fact that each lake is unique and responds differently to climate variability according to its geological, hydrological, and limnological characteristics makes it necessary to use case-specific proxies and apply local individualized interpretations. The reconstruction of lake level in Lake Estanya in the Pre-Pyrenees, mostly based on sedimentary facies and elemental and isotopic geochemistry (Morellón et al., in press), clearly shows a lake level increase from the end of the MCA to the LIA (Fig. 2). Similarly, the presence of gypsum-rich laminated facies in Arreo Lake (northern Ebro Basin, Fig. 1) suggests generally lower lake levels during the MCA (Corella et al., unpublished), while a thermophilous plant association recorded in the Montcortés Lake sedimentary sequence (Rull et al., in press) points towards warmer climate in the central Pre-Pyrenees. A comparable paleohydrological signal is recorded in Lake Taravilla, located in the Iberian Range. In this lake, coarser grain-size layers with higher siliciclastic content reflect paleoflood events during periods of increased run-off triggered by intense rainfall (Moreno et al., 2008). These layers are more frequent during the LIA and almost absent during the MCA (Fig. 2). Rb/Al ratios and Si concentration, used as proxies for run-off in Lakes Zoñar and Basa de la Mora, further indicate that a drier climate extended across the Iberian Peninsula during the MCA, compared to the following centuries (Martín-Puertas et al., 2010; Pérez et al., unpublished data). Despite local differences and some dating uncertainties, the MCA stands out as a relatively dry period, which was characterized by decreased lake water balance in the eastern and, likely, the southern part of the Iberian Peninsula.

The western Iberian Peninsula lacks high-resolution lake records of the MCA, but marine sediment cores provide some paleohydrological information. Several studies conducted offshore of Lisbon indicate that the MCA was a dry interval as inferred from reduced run-off (Abrantes et al., 2005; Lebreiro et al., 2006). On the Mediterranean side, the percentage of coarse particles in

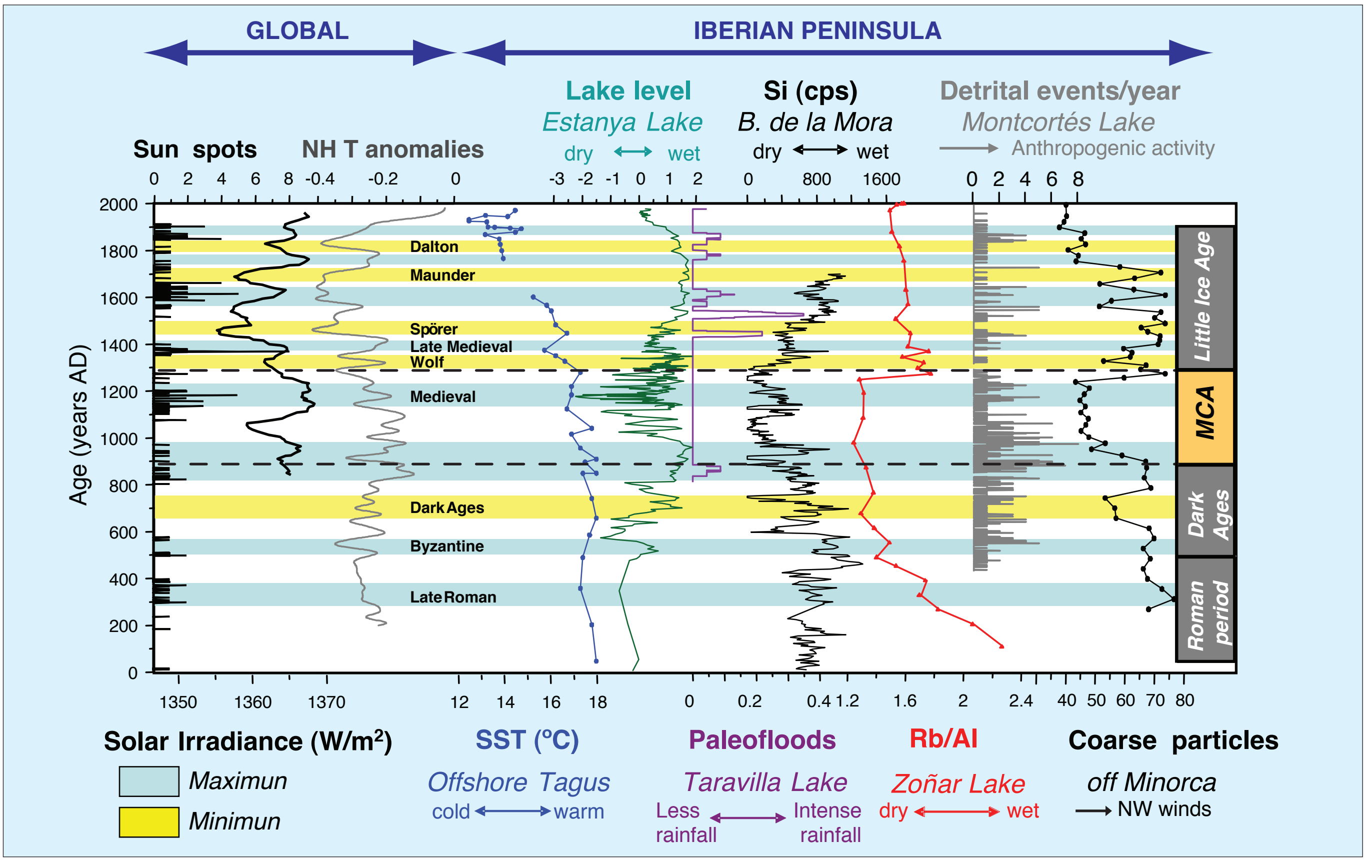

Figure 2: Compilation of global and Iberian climate reconstructions over the last 2000 years. Global records include sun spot numbers (Vaquero et al., 2002), solar irradiance (Bard et al., 2000) and temperature anomalies for the Northern Hemisphere (Jones and Mann, 2004). Iberian Peninsula records are aligned from west to east (see Fig. 1 for location) and include SST from marine cores offshore Tagus River (Rodrigues et al., 2009), lake level of Estanya Lake (Morellón et al., in press), number of floods observed in Taravilla Lake (Moreno et al., 2008), Rb/Al ratio from Zoñar Lake record (Martín-Puertas et al., 2010), number of detrital events per year recorded in Montcortés Lake (Corella et al., in press) and coarse detrital grain fraction from off Minorca (Frigola, unpublished data).

a sediment core from north of Minorca, located in a contourite drift, highlights an episode of weaker deep-water formation after 1300 AD, corresponding to the LIA (Fig. 2). At that location, particle grain-size is directly related to the intensity of deep-water currents that are formed in the nearby Gulf of Lions (Frigola et al., 2007). This result points to weaker westerlies during the MCA, which is consistent with a positive North Atlantic Oscillation (NAO) index at this latitude.

Climatic versus anthropogenic forcings

The areas surrounding some of the studied Iberian lakes were well populated during medieval times. This raises the need to discriminate climatically forced signals from anthropogenic effects on the lake dynamics (Rull et al., in press). For instance, in both Montcortés and Arreo lakes, sedimentation rates increased during the MCA (Fig. 2). However, discerning whether the higher sediment delivery was the result of climatic factors (increase in high-intensity storm events, relatively lower lake levels due to higher temperatures, more intense evaporation and decreased precipitation or more development of littoral environments) or produced by changes in land use practices (deforestation, farming and intensification of cultivation) is not an easy task. Most likely, human impact and climate variability had a joint effect on Iberian lakes during historical times. Fortunately, an integrated multiproxy approach provides some clues to detangle both factors. In Taravilla Lake, peak contents of Cerealia and other "anthropogenic" taxa associated with crops and ruderal plants occur at the base of the sequence when terrigenous paleoflood layers are scarce (Fig. 2). Thus significant removal of vegetation by human attributed fires or deforestation practices cannot be considered the main forcing for the increase in terrigenous layers (Moreno et al., 2008). In the same period, pollen reconstructions from Estanya (Morellón et al., in press), and Montcortés (Rull et al., in press) reflect warmer and drier conditions in a landscape dominated by junipers, Mediterranean elements (evergreen *Quercus*, *Olea*, *Phillyrea*, *Buxus*, *Thymelaea* and *Rosmarinus*), a relatively low presence of mesophylic woody taxa, heliophytes, some cultivated plants and a poorly developed aquatic component.

A global context for the Iberian aridity during the MCA

The Iberian records clearly documenting warmer conditions during the MCA are consistent with global paleoclimate reconstructions (e.g., Mann et al., 2009). Climate variability during the last millennium has been related to solar irradiance fluctuations and tropical volcanic eruptions (e.g., Shindell et al., 2001; Wanner et al., 2008). Recently, a persistent positive mode of the NAO during the MCA has been suggested (Trouet et al., 2009). This would lead to warmer and more arid climate in the western Mediterranean region. The Iberian Peninsula serves as a laboratory to explore the long-term pattern of the NAO index because of its location at the southern edge of the storm tracks associated with mid-latitude westerlies. Thus, a dry climate during the MCA is coherent with a dominant positive phase of the NAO, characterized by lower river discharge offshore Lisbon (Lebreiro et al., 2006; Alt-Epping et al., 2009), lower lake levels in northeast (Morellón et al., in press) and southwest Iberia (Martín-Puertas et al., 2010), fewer flood events in the Tagus River Basin (Benito et al., 2004; Moreno et al., 2008), and less intense westerly winds offshore Minorca Island (Frigola et al., unpublished data). Recent model simulations for temperature and precipitation in the Iberian Peninsula during the last millennium support the role of the NAO in creating a dry anomaly during medieval times (Gómez-Navarro et al., 2010). More analyses in progress and improved chronologies will facilitate a more detailed comparison of records to clarify the internal structure and spatial coherence of the main phases of environmental change during the MCA in the Iberian Peninsula.

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Medieval drought in North America: The role of the Atlantic Multidecadal Oscillation

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The sea surface temperature anomalies associated with the Atlantic Multidecadal Oscillation may have been a major factor contributing to widespread drought in North America during Medieval times.

The role of the Atlantic Multidecadal Oscillation

Medieval times (900-1330 AD; hereafter referred to as MT) in central and western North America were, according to proxy data reconstructions, generally warm, and especially dry (Fig. 1), with numerous decadal or longer "megadroughts" that were the worst of the past 2000 years (Woodhouse and Overpeck, 2000). Considerable attention has been paid to the role of sea surface temperature (SST) anomalies in forcing these prolonged periods of drought, especially that of the La Niña-like condition in the eastern tropical Pacific (e.g., Graham et al., 2007; Seager et al., 2007). Compelling recent evidence suggests that North Atlantic SST, through the Atlantic Multidecadal Oscillation (AMO), may also have a strong effect on persistent summertime drought in North America (Fig. 1b). At present, the AMO expresses a 60-80 year cycle between relatively warm (warm phase) and cool (cold phase) SST (Kerr, 2000; Enfield et al., 2001).

We investigated the role of the AMO in MT drought in North America using modern (present-day) observations, proxy paleo-data, and simulations from multiple climate models (Feng et al., 2010). Considering present-day relationships, for which instrumental observations can be used, the results show that persistent summertime droughts in the U.S. Great Plains and southwest North America are closely related to multidecadal variations of North Atlantic SST (AMO). During the AMO warm (cold) phases, most of North America is dry (wet).

Next, the influence of North Atlantic SST on modern North American drought was examined using simulations made by five global climate models (Feng et al., 2010). When forced by warm North Atlantic SST anomalies, all models captured significant drying over North America despite some regional differences. Specifically, all the models simulate dry summers in the Great Plains and southwestern North America. The response of precipitation to a cold North Atlantic is much weaker, with greater disagreement among the models. Overall, the ensemble of the five models reproduced the statistical relationships between dry/wet fluctuations in North Amer-

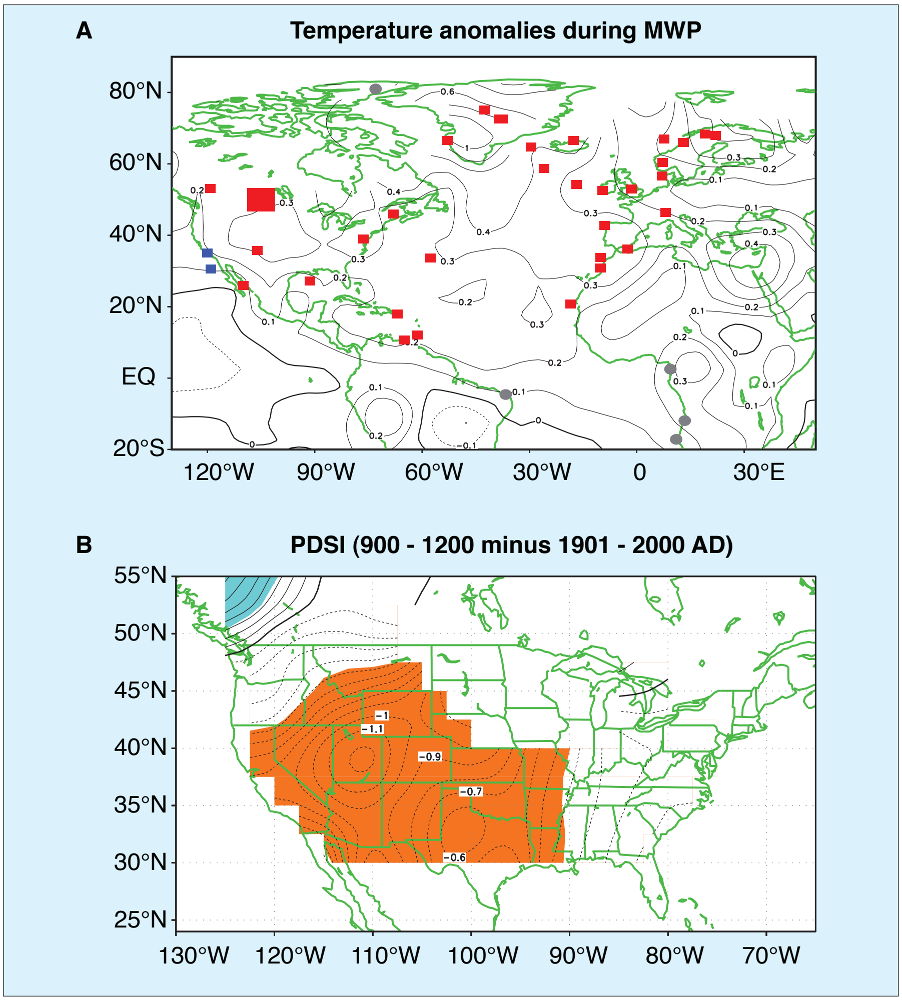

*Figure 1: **A**) Spatial distribution of the proxy data of temperature changes during MT. Blue squares, gray dots and red squares indicate cooling, no changes and warming during Medieval Times, respectively. The contour lines are the observed temperature anomalies associated with AMO warm phases for the period 1901-2006 AD. The contour interval is 0.1°C. Details of the proxy data can be found in Feng et al. (2009). **B**) Difference in tree ring reconstructed Palmer Drought Severity Index (PDSI) for 900-1200 minus 1901-2000 AD. Shadings indicate the differences are significant at 95% confidence level by two-tailed student-test. The figure is adapted from Feng et al. (2010).*