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Dry and wet periods over the last millennium in central-eastern Spain - a paleolimnological perspective

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ABSTRACT

Dry and wet periods over the last millennium in central-eastern Spain-a paleolimnological perspective

A compilation of sedimentological, chemical and mainly biological proxies from sedimentary records in three lacustrine systems (La Cruz, El Lagunillo del Tejo and El Tobar) in the Iberian Range provides a synthetic view of hydroclimatic variability in central-eastern Spain during the last millennium. A quantitative rainfall reconstruction from varved sediments in Lake La Cruz was used to calibrate the sedimentary inputs of five biological proxies (photosynthetic pigments, diatoms, cladoceran sub-fossils, plant macrofossils and stable isotopes in authigenic carbonates) in the longer sequence of the nearby Lagunillo del Tejo. In spite of the resolution and the distinct responses of the proxies analysed, the three reconstructions are internally coherent and consistent with available North Atlantic Oscillation reconstructions. The Medieval Climate Anomaly (MCA; AD 900-1300) was marked by changes in humidity but it was generally wet, which contrasts with some reconstructions for Iberia and offers interesting information about the spatial heterogeneity of this period in the region. A drier period (AD 1300-1400) occurred at the onset of the Little Ice Age (LIA; AD 1300-1850), which was generally marked by increasing precipitation. The 20th century generally records higher humidity except from the beginning of the century. The recovery of longer and higher resolution lake sediments in this key region offers exceptional scientific opportunities for climate research.

Key words: Hydroclimate reconstruction, lake sediments, climate proxies, North Atlantic Oscillation, last millennium

RESUMEN

Periodos secos y húmedos durante el último milenio en el centro-este de España- una perspectiva paleolimnológica

En este estudio se ofrece una recopilación de indicadores sedimentarios, químicos y especialmente biológicos de testigos sedimentarios de tres sistemas lacustres (La Cruz, El Lagunillo del Tejo y El Tobar) en el Sistema Ibérico, que proporciona una visión sintética de la variabilidad hidroclimática en el centro-este de España durante el último milenio. Se utilizó la reconstrucción cuantitativa de la lluvia a partir de los sedimentos varvados del lago La Cruz para calibrar la señal sedimentaria de cinco indicadores biológicos (pigmentos fotosintéticos, diatomeas, sub-fósiles de cladóceros, macrofósiles de plantas e isótopos estables en carbonatos autigénicos) en una secuencia más larga procedente del Lagunillo del Tejo. A pesar de las distintas resoluciones y respuestas de los indicadores analizados, las tres reconstrucciones muestran concordancia entre ellas y son consistentes con la Oscilación del Atlántico Norte (NAO). La Anomalía Climática Medieval (AD 900-1300) estuvo marcada por cambios en la precipitación pero fue un periodo generalmente húmedo, lo cual contrasta con algunas reconstrucciones en la Península Ibérica y ofrece información interesante sobre la heterogeneidad climática de este periodo en la región. Entre AD 1300 y 1400 se registraron valores bajos aunque la Pequeña Edad del Hielo (AD 1300-1850) estuvo marcada por un progresivo aumento de la precipitación. El siglo XX registró niveles de precipitación mayores, excepto a principios de siglo. Secuencias más largas y con una resolución más alta en esta región ofrecerían excepcionales oportunidades científicas para la investigación climática.

Palabras clave: *Reconstrucción hidroclimática, sedimento lacustre, indicadores climáticos, Oscilación Atlántico Norte, último milenio*

INTRODUCTION

Climate change projections for the Iberian Peninsula (IP) suggest both an increase of temperature (by 1.5 ºC to 3.6 ºC in the 2050s) and also precipitation decreases in most of the territory, which may indicate an increased likelihood of droughts (Iglesias, 2009). According to several studies, these effects have already started in the IP (Vicente-Serrano & Cuadrat-Prats 2006; García-Herrera *et al.*, 2007; González-Hidalgo *et al.*, 2009). Iglesias *et al.* (2007) shows that drought events, defined as a natural episodes that exists when precipitation is significantly below normal recorded levels (UN Secretariat General, 1994), have been more frequent since AD 1970 in Spain. Documented data series on precipitation in the IP are scarce, and those that exist are relatively short. The longest data series, for San Fernando (Cadiz), records precipitation only from AD 1854. Natural archives such as tree rings, ice cores, stalagmites and lake sediments can be used to extend instrumental data back in time and thus, to gain a wider perspective on climatic variables.

Many hydroclimatic reconstructions using lake sediments from IP have been published in the last decade (e.g. Moreno *et al.*, 2008-Lake Taravilla; Morellón *et al.*, 2011-Lake Estanya; Corella *et al.*, 2014-Lake Montcortés; Barreiro-Lostres *et al.*, 2014-Lake La Parra). These studies have mainly focused on sediments from the last millennium, which include key periods for understanding hydroclimatic variability such as the Medieval Climatic Anomaly (MCA; ca. AD 900-1300) and the Little Ice Age (LIA; ca. AD 1300-1850). Some sedimentary sequences also extend beyond this period, and even as far as the onset of the Holocene (e.g. Martín-Puertas *et al.*, 2010; Corella *et al.*, 2011; Morellón *et al.*, 2018; Moreno *et al.*, 2012; Sánchez-López *et al.*, 2016). Unlike most of these studies, which have mainly used sedimentological and geochemical approaches to infer climate variability, Rosa Miracle´s research group at the University of Valencia worked with biological proxies in the Cañada del Hoyo lakes (Cuenca Mountains, Iberian Range) and in L'Albufera, a coastal lagoon in Valencia (eastern Spain). These systems were very well-known to the research group, who had started studying their limnological features at the beginning of the 1980s (Miracle & Vicente,1983; Garcia *et al.*,1984; Serra *et al.*, 1984; Miracle, 1984; Oltra & Miracle, 1984; Vicente & Miracle, 1984). In the mid-2000s, the research line in paleolimnology lead by Rosa Miracle was one of the most active research groups in Spain, as shown by the group´s key publications (i.e. Romero-Viana *et al.*, 2006; 2008; 2009 a, b; 2010; 2011; López-Blanco *et al.*, 2011; 2012a, b; 2013a, b; 2016 a, b; Marco-Barba *et al.*, 2013a, b). Rosa Miracle was an exceptional scientist with a global ecological perspective. She contributed to building the bridge between neo- and paleolimnology, improving lake sediment interpretations and consequently increasing our knowledge of past climatic variability (SIL news, 2017).

Fifteen years after the first paleolimnological studies by Rosa Miracle's research team, we publish a review of three lacustrine sedimentary sequences (La Cruz, El Lagunillo del Tejo and El Tobar). This is our tribute to our mentor and thesis director, who was one of the most important limnologists of recent years. This paper offers a synthetic view of hydroclimate in central-eastern Spain, which will contribute to gaining a wider overview of the hydroclimatic situation in this key area.

LACUSTRINE SYSTEMS AND SEDIMENTARY SEQUENCES

The sinkholes

The three lacustrine systems studied, La Cruz, El Lagunillo del Tejo and El Tobar are dolines located in the southern part of Iberian Ranges at an altitude of ca. 1000 m a.s.l. (Fig. 1). The study area is characterised by a Mediterranean climate with a typical seasonal pattern of very dry, hot summers and cooler, rainier winters (Csa type according to the climatic characterisation of Köppen, Atlas climático de España, 2011) (Fig. 2). The total annual rainfall is 525 ± 123 mm (mean of instrumental data series 1950–2003 from the nearby town of Cuenca). Regional winter precipitation, contributing 50 % of the total amount, is highly correlated with the phase of the North Atlantic Oscillation (NAO) (Rome-

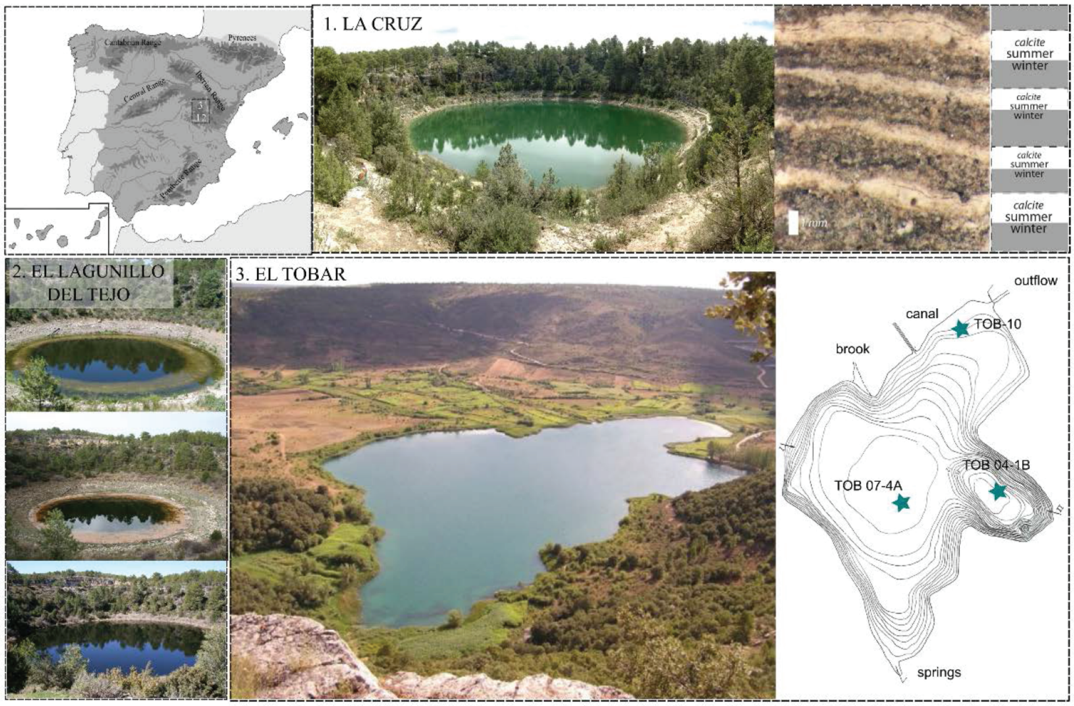

Figure 1. Situation of the lakes in the IP and photographs of each system. Note that photographs from Lagunillo del Tejo show lake level changes in July 2007, March 2008 and April 2010 from top to bottom. In the upper right corner micrography of La Cruz laminated sediment. *Situación de los lagos lagos en la PI y fotografías de cada sistema. Las fotografías del Lagunillo del Tejo muestran los cambios de nivel en julio 2017, marzo 2008 y abril 2010 de arriba a abajo. En la esquina superior derecha micrografía del sedimento laminado en La Cruz.*

ro-Viana *et al.*, 2008; López-Blanco *et al.*, 2016a) (Fig 2). The selected lakes have two common features: 1) a karstic origin and 2) a carbonate (or evaporate) bedrock.

Lake La Cruz and Lagunillo del Tejo are in close proximity. They belong to the karstic complex of Cañada del Hoyo, which is composed of 34 sinkholes and the polje crossed by the Guadazaon river. They were developed in Cretaceous dolostones (Cenomanian-Turonian stages) through dissolution and fracture processes in the Pliocene (Gutiérrez-Elorza & Pena-Monne, 1998). The lateral expansion of the Valdemoro fault and the NW-SE anticlinal folding (Eraso, 1979) may favour water capture with seven sinkholes intercepting the phreatic level (Escudero & Regato, 1992). La Cruz is significantly bigger than the Lagunillo del Tejo (Fig. 1). The first has a circular surface with a mean diameter of 122 m and a maximum depth of 21 m. Water fills the bottom of a sinkhole of greater dimensions (170 m mean diameter with walls standing 16-25 m above the water level). Lake La Cruz is currently meromictic with a permanently anoxic monimolimnion below 18 m. A complete review of La Cruz features has been published recently in Camacho *et al.* (2017). One peculiarity of this lake is the annual summer whiting through a short-term massive $CaCO_3$ precipitation process (Rodrigo *et al.*, 1993; Miracle *et al.*, 2000). The water turns suddenly turbid and just few days after surface becomes clearer, with whiting ending in one or two weeks. Although temperature could control the abrupt precipitation, the high number of picocyanobacterial cells collected by the sediment traps after whiting (Camacho *et al.*, 2003) suggest that biogenic processes might be also involved in the precipitation. Seasonal pulses of calcite crystal precipitation are responsible for varve sediment formation (Fig. 1).

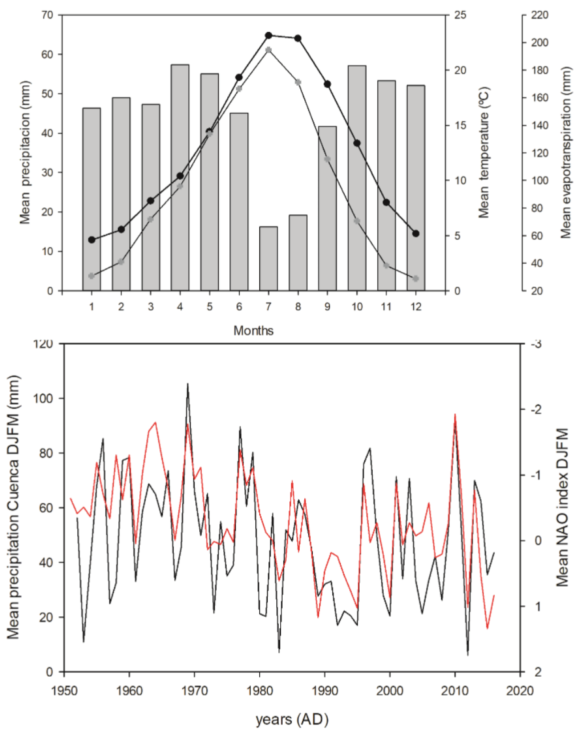

Figure 2. Regional climate conditions. A) Monthly precipitation and mean temperature and B) Correlation between winter rainfall and NAO index (r = -0.66, $p < 0.01$). *Condiciones climáticas regionales. A) Precipitación mensual y temperatura media y B) Correlación entre la precipitación de invierno y el índice NAO (r = -0.66,* p *< 0.01).*

Lagunillo del Tejo is also fed by groundwater and is subjected to marked water-level fluctuations (Vicente & Miracle, 1984; Romero-Viana *et al.*, 2009b). The lake is monomictic, thermally stratified from May to early autumn. An anoxic and deep hypolimnion develops in summer only during high-water level. Conversely, the whole water column remains mixed during periods of low water level (< 5 m) (Vicente & Miracle, 1984). Due to its particular shape, changes in lake level drastically affect the lake diameter (see Fig.1).

From a limnological and morphological point of view, Lake El Tobar is quite different from La Cruz and El Lagunillo. It is also a karstic lake situated northern of the Canada del Hoyo complex, in Jurassic and Cretaceous dolostones, but it is much larger, open and it has two different sub-basins (Fig.1). The holomictic sub-basin is larger, elongated and has a maximum depth of 12.8 m. The meromictic sub-basin is smaller but deeper, circular and has a maximum depth of 19.5 m (Vicente *et al.*, 1993). The lake basin was formed by solution of carbonated rocks and the underlying evaporitic Keuper formations. The latter is evident from the meromictic sinkhole, which has a saline water layer below 12 m that is permanently anoxic (Vicente *et al.*, 1993). The lake is naturally fed mainly by freshwater from subaquatic springs on the Eastern shore and, to a much lesser extent, by a surface water brook. There is also a canal, which was built between AD 1964 and AD 1966 to transfer water from Reservoir La Tosca to Lake El Tobar. El Tobar has functioned as a regulatory water reservoir since this connection (López-Blanco *et al.*, 2011).

The exceptional varved sediment of La Cruz

The most outstanding feature of the La Cruz sediment is an excellently preserved laminated structure in the uppermost 40 cm (Julià *et al.*, 1998) (Fig. 1). This is formed by couplets of alternated white and brownish laminations. The light laminae are composed of calcium carbonate crystals deposited after the summer whiting event each year. The dark laminae consists of organic silts with a minor section of fine mineral clasts (Romero-Viana *et al.*, 2008). Each couplet, called a varve, therefore represents an annual cycle of sedimentation.

A calibration study confirmed the potential use of laminations as a quantitative climate proxy (Romero-Viana *et al.*, 2008). In this study, the rainfall and temperature data series recorded in the region from AD 1950 onwards were compared with lamination thickness. The results have shown that accumulated winter rainfall, from December to March, is the best predictor of calcite lamina thickness. A monitoring study carried out in Lake La Cruz over three consecutive years (AD 1996-1998), considering sediment traps and the water column data available supported this relationship (Miracle *et al.*, 2000; Romero *et al.*, 2006). Although high water temperature and photosynthetic activity (Camacho *et al.*, 2003) are trigger factors of the massive calcite precipitation during summer, the total amount of crystal precipitated in the lake during summer whiting depends on annual dissolved calcium renewal, which in turn is dependent on the aquifer discharge after winter rainfall (Miracle *et al.*, 2000; Romero-Viana *et al.*, 2008).

Given the relationship between rainfall and calcite lamina thickness, Romero-Viana *et al.* (2011) attempted the reconstruction of annual rainfall from December to March over the last centuries. Three sediment cores were used to construct the varve chronology. The sediments were freeze-dried in the laboratory and hardened with epoxy resin. Thin sections were obtained and scanned to obtain high-resolution digital images. The number and thickness of laminae present in each thin section were determined between visually discernible marked horizons using the measurement tools in image analyses software UTHSCSA (ftp://maxrad6.uthscsa.edu). The three sequences were cross-matched according to sedimentological criteria the occurrence of detrital layers and the number of varves between detrital events. After the sequences cross-matching, a total of 423 annual laminations were then identified; confirming the onset of laminated sediments from AD 1579. Annual laminations provide better chronological data than radioisotopic methods, however, lamination chronology has been tested by an independent dating method. The chronological model based on ^{210}Pb activity (Romero-Viana *et al.*, 2009a) matches the varve dating.

To identify the climate signal, each raw calcite laminae thickness series was normalised, resulting in three dimensionless annual index series. The three index series were averaged year by year to produce a master series increasing the climate signal and partially cancelling non-climatic noise. Annual winter (DJFM) rainfall values were inferred using the calibration function described in Romero-Viana *et al.*, (2008) after adding new data corresponding to the series CV-98 (AD 1950-1988). The accuracy of rainfall

Table 1. Compilation of the sediment cores recovered in Lagunillo del Tejo. The table compiles information about the core names, year of recovery and place of collection, recovery methods, analysed proxies in each core and the articles published by the group in this system. *Recopilación de los testigos sedimentarios recuperados en el Lagunillo del Tejo. La tabla muestra información sobre los nombres de los testigos, el año y lugar de muestreo, el método de recuperación, los indicadores analizados y los artículos publicados por el grupo en este sistema.*

Core name	Year	Location	Recovery method	Proxy	References
CN1	2003	Center	Livingston core	Photosynthetic pigments and diatoms	Romero-Viana *et al.* (2009b, 2009c)
CN2	2005	Center	Livingston core	Dating	Romero-Viana *et al.* (2009b, 2009c)
CN3a	2008	Center	Russian peat corer	Cladocerans	Romero-Viana *et al.* (2009a); López-Blanco *et al.* (2012b); López-Blanco *et al.* (2013b)
CN3b	2008	Center	Russian peat corer	Dating	López-Blanco *et al.* (2011, 2012)
CN4	2009	Littoral	UWITEC gravity corer	Macrofossils, charcoals and stable isotopes	López-Blanco *et al.* (2012a,b); López-Blanco *et al.* (2016a)

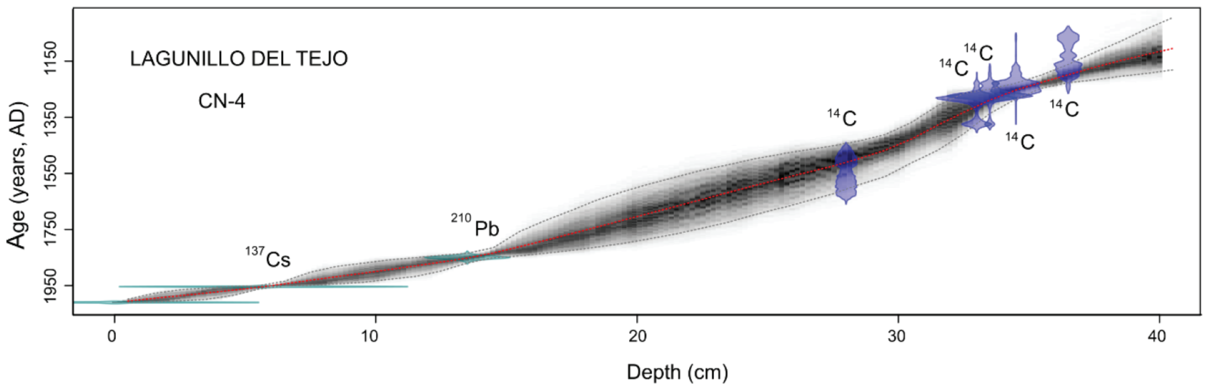

Figure 3. Chronological model in El Lagunillo del Tejo based on weighted spline regression (Blaauw, 2010) of five AMS ^{14}C dates, ^{210}Pb and ^{137}Cs dates. *Modelo cronológico del Lagunillo del Tejo basado en regresión lineal ponderada (Blaauw, 2010) de cinco dataciones de AMS ^{14}C dates y dataciones superficiales de ^{210}Pb and ^{137}Cs.*

reconstruction was verified by comparing the reconstructed values for AD 1859 to AD 1949 with the available instrumental data series from Cuenca and Madrid (Romero-Viana *et al.*, 2011). The positive value of the reduction error (RE) measure and the coefficient of efficiency (CE) confirmed the skill of this reconstruction.

The smallest lake and the longest record: El Lagunillo del Tejo

From 2003 to 2009, five sediment cores were recovered from Lagunillo del Tejo in order to study photosynthetic pigments, diatoms, cladocerans, plant macrofossils, charcoals and stable isotopes. The presence of conspicuous oxidised and reduced layers in the lithology together with a distinctive pattern in physical properties (density, water content, organic matter and carbonates) in all the analysed sediment cores, allowed correlations to be identified. Table 1 shows the complete list of sediment cores, locations, recovery methods, studied proxies and references.

A preliminary chronological model applying the constant initial concentration method (CIC) was established according to the activity of two different radionuclides (^{137}Cs and ^{210}Pb) (Romero-Viana *et al.*, 2009a, b). Afterwards, terrestrial plants and charcoal macroremains from CN-3 and CN-4 cores were then used for accelerator mass spectrometry (AMS). An age-depth model was established on the basis of the ^{210}Pb and ^{137}Cs dates and five AMS dates though an interpolation of the calibrated ages. This chronological model was published in López-Blanco *et al.* (2012) and was remodelled for this paper using the new tools for Bayesian statistical age-models in the Bacon package (Blaauw & Christen, 2011) in R software. This new model includes ^{137}Cs peak, ^{210}Pb model and the five available ^{14}C dates (Fig. 3). The radiocarbon dates were calibrated using the IntCal13 calibration curve (Reimer *et al.*, 2013) and the 95.4 % distribution (2δ probability interval) was taken into account to build the age-depth model. The results were very similar to those obtained in the AD 2012 model but more accurate since the Bayesian approach considered the chronological dates in the stratigraphy to build the model in terms of probability. The chronological uncertainties published by López-Blanco *et al.* (2012a) in the middle of the sequence were partially solved by this approach (Fig. 4). New extrapolations beyond dated samples at the bottom of the core, and taking into account the calibrated ages and the 2δ distribution in the new model, yield an age of AD 1112 for the bottom of the core (40.5 cm). López-Blanco *et al.* (2012a) estimated the age of this core as around AD ca. 1100 with accumulation rates of 0.26 mm/ yr between AD 1100 and AD 1530, 0.44 mm/yr to AD 1850 and 0.87 mm/y in the top layers. This new chronological model completes and confirms the previous age-depth relationship in CN-4. However, there are still uncertainties when running the chronological model in the longest core (CN-3; 72.5 cm) since the latest dating was done at 47.5 cm from this sediment core (López-Blanco *et al.*, 2012a). The extrapolation of dates beyond the last dated level results in a wider range of possible ages for certain depths at the bottom of CN-3 sediment core (from 47.5 to 72.5 cm).

Up to 60 different photosynthetic pigments were identified in the Lagunillo del Tejo sediment core (Romero-Viana *et al.*, 2009b). In addition to chlorophyll derivatives, specific carotenoids such as zeaxanthin, alloxanthin and also bacteriochlorophylls a and d were used as tracers of algal and bacterial populations, respectively. Given the high number of variables, it was necessary to apply a principal component analysis (PCA). PCA of specific pigment depth profiles suggested two different ecological communities that have switched in relative importance during the past centuries in response to lake-level variability; 1) (positive values PC) a planktonic group of algal populations comprising chlorophytes, cryptophytes, cyanobacteria, and phototrophic bacteria populations associated with higher lake level and water column temporal stratification; and 2) (negative values, PC) a littoral community with benthic and epiphytic alga and macrophytes, indicators of lower level.

López-Blanco *et al.* (2013) showed that sediment from the central part of this small lake truly represent the whole cladoceran community, which means that the relative abundance of cladocerans was a good descriptor of the overall community in the lake at one determining point of time. Cladoceran assemblages were composed of one planktonic (*Daphnia longispina* group) and 16 littoral species. The crustacean community was typical from shallow karstic sinkholes in the Serranía de Cuenca. The whole sedimentary sequence was characterized by an alternation of planktonic and littoral cladocerans. Within the littoral cladocerans, there was also an alternation between cladocerans highly associated with macrophytes (i.e. *Graptoleberis testudinaria*) and facultative planktonic cladocerans (i.e. *Chydorus sphaericus*). The planktonic/benthic ratio (P/B ratio) was not a good proxy of lake level changes in this ecosystem due to the shape, littoral configuration and distribution of cladoceran populations according to habitat preferences. López-Blanco *et al.* (2012b) showed that the main factor controlling the cladoceran community in this lake was the configuration of the littoral zone, which depends on the lake water depth. At higher lake levels, the lake had two rings of macrophytes and the sedimentary signal was comprised of a higher relative abundance of phytopilous cladocerans. When water level reduced, the outer ring of macrophytes (*Chara* spp, *Ranunculus* subsg Batrachium, and *Nitella*) dried out together with all the associated cladoceran community. The sedimentary signal in such circumstances was composed of a high relative abundance of *Daphnia longispina* group. This early hypothesis was confirmed by analysing plant macrofossils record in the sediment, as shown in López-Blanco *et al.* (2012a) and López-Blanco *et al.* (2012b).

Although diatom concentration in Lagunillo del Tejo was low, 34 diatom taxa (26 genera) were identified (Romero-Viana *et al.*, 2009c). Diatom assemblages were mainly dominated by peri-epiphytic genera, and characterized by mesotrophic and alkaliphylic taxa. The increase of tycoplanktonic diatoms was associated to lake level drops.

Isotopic ratios of C and O from authigenic carbonates were used in Lagunillo del Tejo to extract important information about the basin hydrology, and to confirm all the inferences about past lake level changes inferred from biological proxies. Analysis of modern water from the lake plot below the Global Meteoric Water Line, indicated that evaporative processes control the lake´s isotopic composition. Sediment samples showed a covariant trend between carbonate $\delta^{18}O$ and $\delta^{13}C$, showing that the precipitation/evaporation ratio largely controlled the isotopic composition of this lake and was used to reconstruct the hydrological past of this system. Higher isotopic ratios were interpreted as arid periods while low isotopic ratios corresponded to wetter periods. Evaporation is higher during arid conditions, and authigenic lake carbonates are enriched in ^{18}O. During wetter periods the situation reverses, and the $\delta^{18}O$ of the lake water reflects the

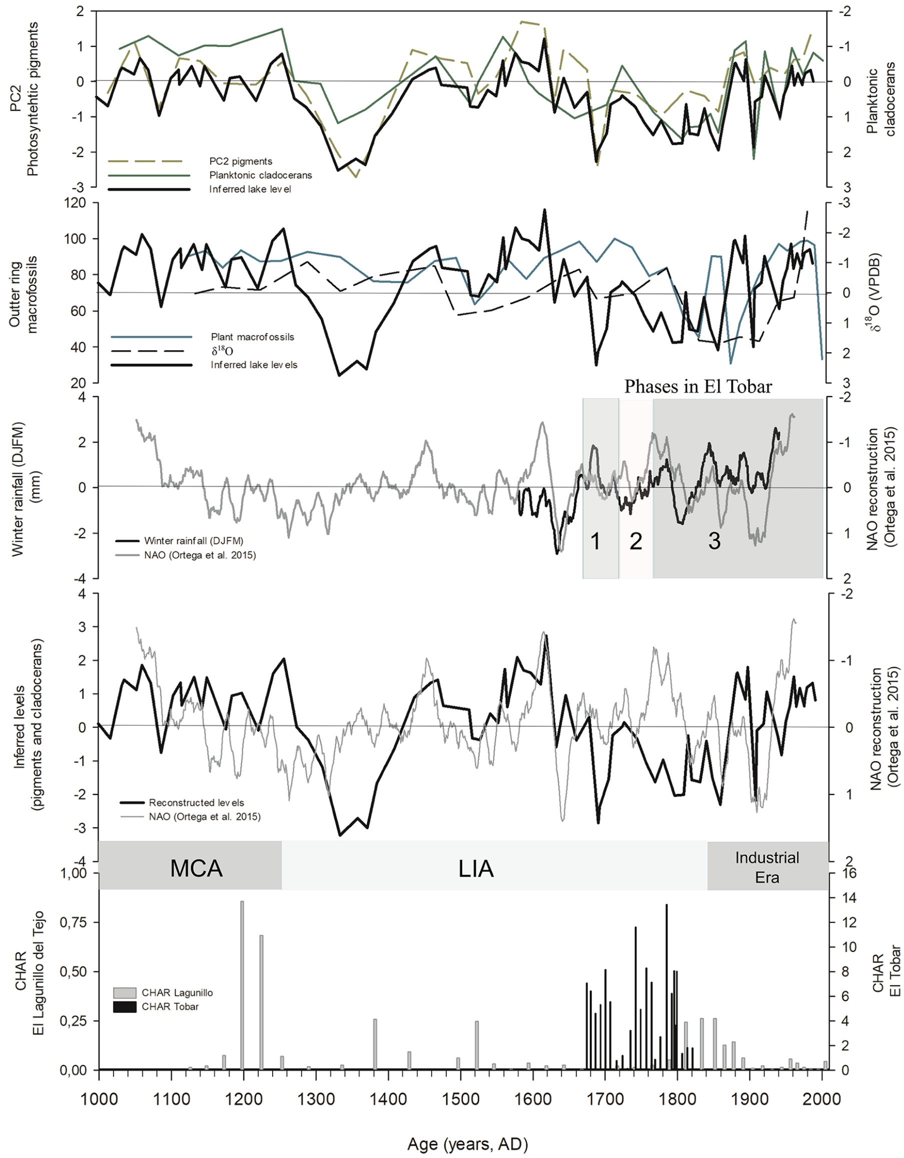

Figure 4. Compilation of the results obtained in the three lakes. From upper to bottom panels. 1) PC2 from photosynthetic pigments, normalized data of planktonic cladocerans (Romero-Viana *et al.*, 2007), and reconstructed levels based on mean values of these variables; 2) Percentages of plant macrofossils from the outer ring (López-Blanco *et al.*, 2012a), normalized date of $\delta^{18}O$ (López-Blanco *et al.*, 2016a) and reconstructed levels based on pigments and cladocerans; 3) Comparison of the Winter Rainfall signal inferred in La Cruz (Romero-Viana *et al.*, 2011) , the NAO reconstruction (Ortega *et al.*, 2015) and phases of transgression and regressions in the shore line of Lake El Tobar (López-Blanco *et al.*, 2016b); 4) Comparison of the inferred lake level in El Lagunillo with the NAO reconstruction (Ortega *et al.*, 2015); 5) Charcoal signal (in charred particles/cm^3.yr) in El Lagunillo and El Tobar. Note that all the normalization was done by using the mean and standard deviation. *Recopilación de los resultados obtenidos en los tres lagos. De arriba abajo: 1) PC2 de pigmentos fotosintéticos, datos normalizados de cladóceros planctónicos (Romero–Viana* et al.*, 2007), y reconstrucción de los niveles basado en valores medios de estas variables; 2) Porcentajes de macrofósiles de plantas del anillo exterior (López –Blanco* et al.*, 2012a), datos normalizados de $\delta^{18}O$ (López-Blanco* et al.*, 2016a) y niveles reconstruidos basados en los pigmentos y cladóceros; 3) Comparación de la señal de lluvia de invierno inferida en La Cruz (Romero-Viana* et al.*, 2011), la reconstrucción de la NAO (Ortega* et al.*, 2015) y las fases de trasgresión y regresión del litoral de El Tobar (López-Blanco* et al.*, 2016b);4) Comparación de los niveles inferidos en El Lagunillo del Tejo con la reconstrucción de la NAO (Ortega* et al.*, 2015); 5) Señal de carbones (en partículas quemadas/cm^3.yr) en El Lagunillo y El Tobar. Todas las normalizaciones han sido hechas utilizando la media y desviación estándar.*

lighter isotopic composition of the recharge (López-Blanco *et al.*, 2016a).

Past changes in the El Tobar shore line

Due to the complex morphological characteristics of Lake El Tobar, sediment cores were recovered from both deeper-meromictic and shallower-holomictic sub-basins to better represent the diverse communities inhabiting the lake (Fig. 1; Table 2).

The radioisotopic activity of ^{210}Pb and ^{137}Cs published in López-Blanco *et al.* (2011) and López-Blanco *et al.* (2016b) shows very different sedimentation rate in the central and littoral parts of lake El Tobar. TOB04-1B and TOB07-4A only covered the previous 60 years while TOB-10 dated back the last 350 years. Therefore, the central core recorded the eutrophication process and species introduction in the lake after canal construction (López-Blanco *et al.*, 2011).

The overlapping sedimentary sequence using the three consecutive littoral cores (TOB10) was characterised by the presence of three sedimentary units and five facies; deeper water facies were located in the uppermost part of the sequence (59-0 cm) while shallower-water facies were in the bottom part of the core (120-60 cm) (Fig. 5). Plant macrofossils from 18 taxa were identified in the same sedimentary sequence. Based on their occurrence and ecological characteristics (aquatic, marsh or terrestrial environment), five different periods of changes in shore line were found. The isotopic signal complemented and supported this information with data about present and past lake hydrology (López-Blanco *et al.*, 2016). Modern surface water samples for hydrogen and oxygen isotope analyses indicated that precipitation was the main factor governing the isotopic composition of lake water. The δ^{13}C profile of bulk carbonates showed lower values (around 5 ‰) at the bottom of the core and less negative

Table 2. Compilation of the sediment cores recovered in El Tobar. The table compiles information about the core names, year and place of collection, the recovery methods, the analysed proxies in each one and the articles published by the group in this system. *Recopilación de los testigos sedimentarios recuperados en el El Tobar. La tabla muestra información sobre los nombres de los testigos, el ano y lugar de muestreo, el método de recuperación, los indicadores analizados y los artículos publicados por el grupo en este sistema.*

Core name	Year	Location	Recovery method	Proxies	References
TOB04-1B	2004	Meromictic sub-basin	Livingston	Chronology Lithology Cladocerans Pigments and diatoms	López- Blanco *et al.* (2011)
TOB07-4A	2007	Holomictic sub-basin	Livingston	Chronology Lithology Cladocerans Pigments and diatoms	López-Blanco *et al.* (2011)
TOB10-1 TOB10-2 TOB10-3 (Composite core TOB10)	2010	Holomictic	Russian peat corer	Plant macrofossils Isotopes Charcoal analysis	López-Blanco *et al.* (2016b)

values in the two upper-thirds of the sediment record (Fig. 5). These changes were also evident in the δ18O profile, with the lowest values at the bottom and highest in the middle. Additionally, several peaks in the δ18O profile were detected in the middle part of the sediment core. The most plausible explanation for the δ18O peaks observed in the El Tobar sequence was a change in drainage characteristics and residence time in littoral environments resulting in varying degrees of evaporative enrichment, with all of these processes occurring during the LIA due to changes in precipitation.

REGIONAL HYDROCLIMATIC SIGNAL

The sediments from La Cruz, El Lagunillo del Tejo and Lake El Tobar provide evidence for climatic changes during the last centuries in the Iberian Range. Unlike La Cruz and El Tobar sequences, the sediment cores from El Lagunillo del Tejo fortunately cover the whole last millennium. Hydroclimatic variability in this lake is recorded as successive lake level changes, which determine: i) the sedimentary inputs of photosynthetic pigments, ii) diatom, cladoceran subfossils and plant macrofossils signal and iii) stable isotope ratios in endogenic carbonates (Table 1, Fig. 4).

The Lagunillo del Tejo sedimentary sequence as a whole shows good agreement between all the indicators for the major arid and humid phases and reinforces the robustness of past lake level reconstruction (Fig. 4). Small differences between the proxies are partially related to the correlation methodology used between sediment cores and to the level of sample resolution. Correlation was

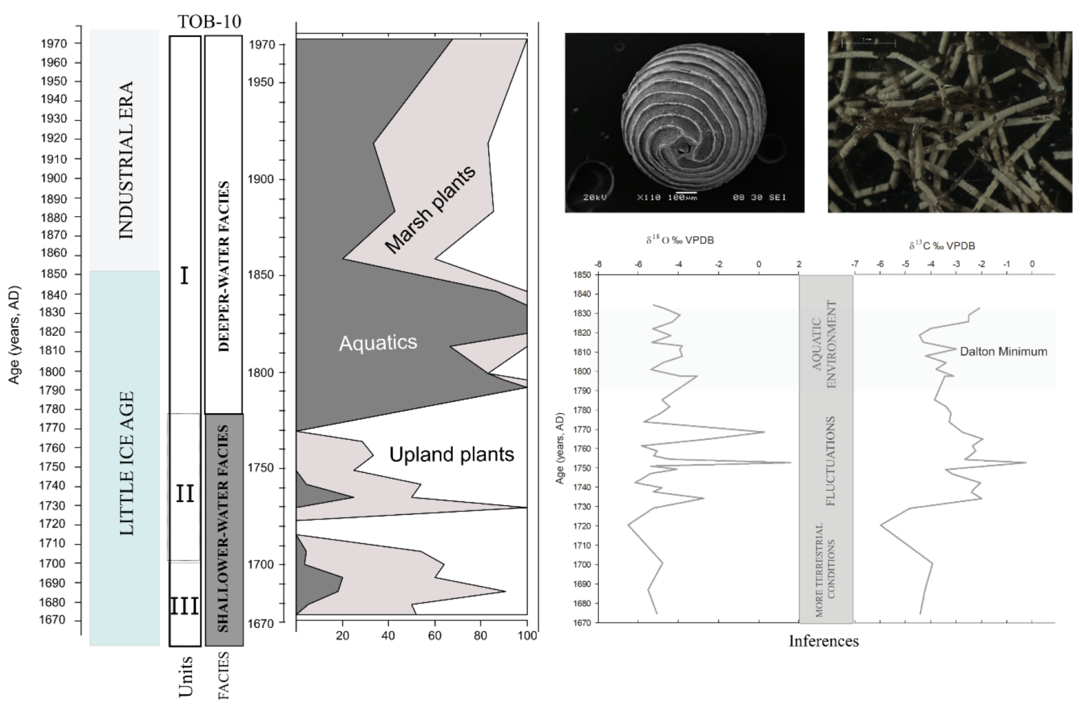

Figure 5. Compilation of the results obtained in littoral cores (TOB10-1, TOB10-2 and TOB10-3) from El Tobar. In the figure, only the composite TOB-10 is represented for sake of simplicity. From left to right: Main climatic periods, sedimentary facies and units, relative abundance of aquatics, marsh and upland plants and δ18O, δ13C signals. Pictures in the upper right part show a gyrogonite and calcifications from *Chara* sp., which were quite abundant during the aquatic phase. *Recopilación de los resultados obtenidos en los testigos litorales (TO10-1, TOB10-2 y TOB10-3) de El Tobar. En la figura, solo se representa la secuencia solapada TOB-10 por simplificación. De izquierda a derecha: periodos climáticos principales, facies y unidades sedimentarias, abundancias relativas de plantas acuáticas, de marjal y terrestres y señales de δ18O, δ13C. Las fotografías en la parte superior derecha muestran un girogonito y las calcificaciones de* Chara *sp., que eran muy abundantes durante la fase acuática.*

based on physical properties such as density or organic matter, and although the profiles fitting was precise, this factor cannot be ruled out as responsible for small differences. The proxy signal for photosynthethic pigments (core CN-1, Table 1) also corresponded to discrete values of about 10, 5 and 3 years due to the different sedimentation rate throughout the sediment core with a temporal resolution of ca. 30 years. The age resolution in the case of cladocerans (CN-3, Table 1) is about 15 years in the upper part of the sequence and 35 years at the bottom, and the resolution of plant macrofossils and isotopes is ca. 10, 25 and 40 years in few samples at the bottom. Other factors, such as the different climatic sensitivities of the proxies, can also explain the discrepancies found in some specific periods.

According to inferred lake levels in El Lagunillo del Tejo, the MCA (ca. AD 900-1300) was a period marked by rainfall oscillations but generally wet. This agrees with records from north and/or western IP, which indicate an increase in humidity during the MCA (references in Moreno *et al.*, 2012). Despite this, many lacustrine records from the Mediterranean IP such as Basa de la Mora, Estanya and Arreo in the northeast and Zoñar in the south seem to indicate drier conditions (Moreno *et al.*, 2012). Notably our results showed a very good agreement with the lake level fluctuations inferred in the nearby Lake La Parra (Barreiro-Lostres *et al.*, 2014) (Fig. 6 confirming relatively wetter conditions during MCA in the Iberian Ranges. Although the onset of the LIA was not equally registered by all our proxies, they all agree with the idea of a progressive increase of level from the onset of the LIA to ca. AD 1550. Relatively humid conditions during the fifteenth and sixteenth centuries were directly related to the onset of the meromixis in La Cruz (Julià *et al.*, 1996) and coincided with the beginning of calcite lamination deposition in AD 1579 (Romero-Viana *et al.*, 2011). In this period, the El Lagunillo del Tejo lake level reconstruction overlaps with the La Cruz signal, which serves as a chronological and quantitative anchor for hydroclimate calibration. After the Maunder Minimum (AD 1645-1715), there may have been an increase in humidity according to the La Cruz record, the plant macrofossils record of El Lagunillo and all the indicators in El Tobar. However, the three sequences also show continuous changes in hydrovariability through the whole seventeenth century, with a dry period ca. AD 1690. Barreiro-Lostres *et al.* (2014) also inferred a highly variable but humid period from the occurrence of sandy layers intercalated within fine-laminated facies in the nearby Lake La Parra. The isotopic signal and sedimentology from El Tobar strongly support the idea of an alternation of humid and drier periods that could have altered the lake recharge during the changing precipitation conditions in the late LIA. Benito *et al.* (2003) described five periods of concentrated floods events in the Tagus drainage basin in: AD1200-1230; AD 1560-1620; AD 1700-1720; AD1740-1810; AD 1860-2000, which agrees well with the transgression and regressions of the shore line described in El Tobar, which is located in Tagus headwaters, but also with the hydrological reconstruction in El Lagunillo for the whole millennium. At a more local scale, inferences from the nearby Taravilla Lake (Moreno *et al.*, 2008), together with unpublished results from Benito about historical floods from the Guadiela River (Fig. 6) also support the increase in level inferred from phase 2 to 3 in El Tobar. Higher sediment delivery (events S2, S3 and S4) (Fig. 6) inferred from a distal core in El Tobar could be the results of synergic effects of humid periods and human impacts during the 19 and 20th centuries (Barreiro-Lostres *et al.*, 2014). In spite of the differences in size, hydrology, limnology and sensibility to rainfall oscillations, the three main phases of lake level changes reconstructed in El Tobar agree with the quantitative signal of rainfall in Lake La Cruz (see Fig. 5), showing both a trend from drier towards more humid conditions over this period. Lower lake levels detected in El Tobar ca. AD 1715 and AD 1772 agreed well with a relatively dry period recorded in La Cruz ca. (1720-1780 AD) (Fig.4). High stand lake conditions recorded in El Tobar during the late LIA- Dalton Minimum ca. AD 1772-1850 are coincident with the two wettest periods in La Cruz (ca. AD 1770-1800 and 1815-1830). Finally, the 20th century appeared as a relatively wet period compared with the hydroclimatic conditions in the previous centuries.

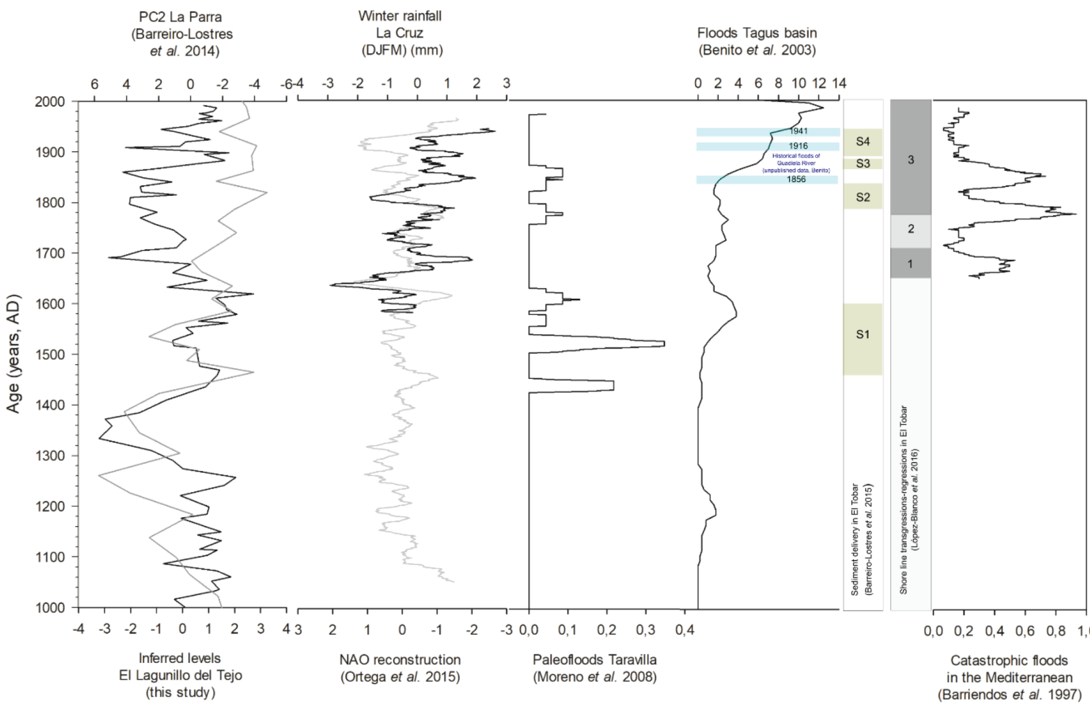

Figure 6. Compilation of inferences in La Cruz, El Lagunillo del Tejo and El Tobar with other paleoclimatic reconstructions at regional scale. From left to right: inferred levels in El Lagunillo (this study) and La Parra (Barreiro-Lostres *et al.*, 2014); the NAO (Ortega *et al.*, 2015) and Winter Rainfall reconstruction in La Cruz; paleofloods frequency in Taravilla Lake (Moreno *et al.*, 2008); floods in the Tagus basin (Benito *et al.*, 2003) and historical floods of Guadiela River (unpublished data, Benito); events of sediment delivery (Barreiro-Lostres *et al.*, 2015) and shore-line transgressions and regressions in El Tobar (López-Blanco *et al.*, 2016); catastrophic floods in the Mediterranean (Barriendos *et al.*, 1997). *Recopilación de las inferencias en La Cruz, El Lagunillo del Tejo and El Tobar con otras reconstrucciones paleoclimaticas a escala regional. De izquierda a derecha: niveles inferidos en el El Lagunillo (este estudio) y La Parra (Barreiro-Lostres* et al.*, 2014); reconstrucción de la NAO (Ortega* et al.*, 2015) y la precipitación de invierno en La Cruz; frecuencia de paleoavenidas en Taravilla (Moreno* et al.*, 2008); avenidas en la cuenca del Tajo (Benito* et al.*, 2003) y avenidas históricas en el río Guadiela (datos no publicados, Benito); eventos de aporte sedimentario (Barreiro-Lostres* et al.*, 2015) y trasgresiones y regresiones de la línea litoral de El Tobar (López-Blanco* et al.*, 2016); avenidas catastróficas en el Mediterráneo (Barriendos* et al.*, 1997).*

The climate signal recorded through calcite annual lamination in Lake La Cruz was analysed in detail in Romero-Viana *et al.* (2011). The presence of 0.12 and 0.25/year periodicities in this regional rainfall reconstruction, which are similar to those observed for NAO index series (Hurrell, 1995), confirmed a strong correlation with this large-scale pattern. The current comparison between calcite varves signal and the NAO index reconstruction from Ortega *et al.* (2015) showed higher correlations over the whole millennium, and a decoupling signal during shorter time periods (Fig. 4), than previous comparisons with three other NAO index reconstructions (Romero-Viana *et al.*, 2009). Ortega *et al.* (2015) have performed a yearly NAO reconstruction for the past millennium, based on an initial selection of 48 annually resolved proxy records distributed around the Atlantic Ocean, and built it through an ensemble of multivariate regressions. Unlike a previous NAO reconstruction by Trouet *et al.* (2009), Ortega *et al.* (2015) showed no persistent positive NAO during the MCA but more frequently positive values during AD 1270-1320. Our regional reconstruction from central-eastern Spain does not support the positive values of the NAO index during the MCA either, and showed a highly qualitative agreement with Ortega *et al.* (2015). Although the chronological model from El Lagunillo in the bottom of the core CN-4 is well constrained by four consecutive AMS ^{14}C dates, this chronology is far from showing annual resolution, and it is possible that the low lake levels recorded in El Lagunillo from ca. AD 1280-1400 could correspond to the NAO signal between ca. AD 1270-1320, where more positive values were recorded (Ortega *et al.*, 2015) (Fig. 4).

Another proxy that supports the existence of specific drier periods that favoured the occurrence of natural fires in the last millennium is the macrocharcoal content. In Lagunillo del Tejo, there was a continuous occurrence throughout the sedimentary sequence (Fig. 4). However, two main peaks were observed in ca. AD 1200-1250 and between AD 1800-1900, and two minor peaks were registered between ca. AD 1390 and AD 1525 (Fig. 4). The first two peaks of charcoal were most probably related to wars between Christians and Muslims, and also to the upsurge in sheep raising ("Mesta") based on transhumance (Lozano-Sahuquillo, 2002). The other two minor peaks were synchronous with dry periods in this reconstruction but also agree well with other local activities that could have generated human-made fires (López-Blanco *et al.*, 2012a). In El Tobar, the charcoal concentration was higher than in El Lagunillo. However, they were concentrated in a specific period of time ca. AD 1675 until AD 1820. This period agrees well with lower lake levels, but also with abundant historical information that relates fires to the collapse of the transhumance in the northern part of la Serrania de Cuenca (Bacaicoa *et al.*, 1993). As López-Blanco *et al.* (2012a) have argued previously, there were obvious socio-economical causes behind the fire history in this highly anthropogenic landscape, however, fires were probably favoured by drier conditions, showing the interplay between climate and human activity in the area.

When comparing our hydroclimate regional signal with other Iberian reconstructions, we found that the MCA is one of the most controversial periods. As mentioned before, arid conditions are inferred during this period in northeastern and southern IP, (e.g. Basa de la Mora, Estanya, Arreo and Zoñar) (see review of Moreno *et al.*, 2012) but sedimentary sequences situated in the western and central Iberia like this study indicated relatively wetter conditions for this key period. Small discrepancies between these inferences may be partially due to the influence of different climatic circulation patterns over a territory as complex as the IP. Recent studies suggest that other modes of variability than the NAO, such as the Eastern Atlantic or the Scandinavian (SCAND) patterns, significantly affect climate in the IP (Jerez & Trigo, 2013). Sánchez-López *et al.* (2016) published a review where they discussed the role of the NAO on humidity patterns in Iberian precipitation, and found homogeneous spatial climate conditions dominating the MCA and LIA in the IP. They discovered N-S and E-W humidity gradients acting during the Roman Period or the Early Middle Ages, however, as a result of the predominant coincidence of the NAO and East Atlantic index (EA) in opposite phases. On the other hand, Hernandez *et al.* (2015) demonstrated that the NAO is responsible for winter precipitation while the EA governs winter and summer temperatures, which agree very well with the hydroclimatic reconstruction in La Cruz and NAO relationship. It is therefore possible that the inclusion of more well-dated and multiproxy sequences in future spatial analysis in the IP will reveal new gradients or patterns in the hydroclimatic variability and its relationship with different modes of variability.

CONCLUSIONS

This study shows that the three karstic lakes described above preserved a valuable hydroclimatic signal in their sediments. The fact that this climatic signal was inferred not only by a single proxy, but by a combination of geochemical and biological indicators in different lacustrine systems, enhances the reliability of the reconstruction, shows the complexity of paleolimnological interpretations and highlights the importance of neolimnological knowledge in understanding the sedimentary inputs. Our results offer interesting and new information about the hydroclimatic conditions during the MCA in central eastern Spain. We have inferred relatively humid and highly variable conditions from ca AD 1000-1300, and this is strongly supported by new findings on NAO variability during the last millennium. Located in a key region under the influence of the NAO, the climatic reconstruction of these small sensitive systems could provide valuable information about this atmospheric circulation mode. Longer and higher resolution sediments in these and other permanent sinkholes in La Serranía de Cuenca could serve to quantitatively calibrate the different proxies, extending and improving this reconstruction back in time and thus, placing current tendencies into a longer-term context.

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