Climate of the Past

A multi-proxy perspective on millennium-long climate variability in the Southern Pyrenees

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Abstract. This paper reviews multi-proxy paleoclimatic reconstructions with robust age-control derived from lacustrine, dendrochronological and geomorphological records and characterizes the main environmental changes that occurred in the Southern Pyrenees during the last millennium. Warmer and relatively arid conditions prevailed during the Medieval Climate Anomaly (MCA, ca. 900–1300 AD), with a significant development of xerophytes and Mediterranean vegetation and limited deciduous tree formations (mesophytes). The Little Ice Age (LIA, 1300–1800 AD) was generally colder and moister, with an expansion of deciduous taxa and cold-adapted montane conifers. Two major phases occurred within this period: (i) a transition MCA–LIA, characterized by fluctuating, moist conditions and relatively cold temperatures (ca. 1300 and 1600 AD); and (ii) a second period, characterized by the coldest and most humid conditions, coinciding with maximum (recent) glacier advances (ca. 1600–1800 AD). Glaciers retreated after the LIA when warmer and more arid conditions dominated, interrupted by a short-living cooling episode during the late 19th to early 20th centuries. Some records suggest a response to solar activity with colder and slightly moister conditions during solar minima. Centennial-scale hydrological fluctuations are in phase with reconstructions of NAO variability, which appears to be one of the main climate mechanisms influencing rainfall variations in the region during the last millennium.

1 Introduction

Climate reconstructions for the last millennium are crucial for our understanding of past natural variability and for assessing the influence of external forcing factors such as solar activity and volcanic eruptions. The perspective of a current

global warming scenario has provoked an increasing interest in studies of climate fluctuations prior to the industrial era (Jansen et al., 2007). Furthermore, long-term palaeoclimatic perspectives offer an excellent basis to improve predictive models (Solomon et al., 2007). Past climate conditions have been reconstructed using various proxies, such as tree rings (Büntgen et al., 2011), lake sediments (Last and Smol, 2001), historical documents (Brázdil et al., 2005, 2010), marine sediments (Abrantes et al., 2005), corals (Goodkin et al., 2008), speleothems (Proctor et al., 2002), and, ideally, a combination thereof (Jones et al., 2009).

In spite of an wide range of associated uncertainties (Frank et al., 2010), most climate reconstructions agree on the existence of two different stages with distinct climatic conditions during the last millennium: a period of relatively high temperatures at ∼900–1300 AD, known as the Medieval Climate Anomaly (MCA); and a phase with relatively cooler temperatures at ∼1300–1800 AD, the so-called Little Ice Age (LIA). Unfavourable climate conditions during the LIA had also a considerable impact in European societies (Fagan, 2000). They likely contributed to the decline of health and economic wealth of medieval societies triggered by the Black Death (Büntgen et al., 2011), for instance, and led to the abandonment of different areas such as Norse settlements in Greenland (Patterson et al., 2010; D'Andrea et al., 2011). Despite the precise chronology, the spatial extent and mechanisms behind these climatic phases still remain a subject of debate (Paasche and Bakke, 2010).

The impact of the LIA on Central European ecosystems and societies has been widely documented (Büntgen et al., 2011; Magny et al., 2011b; Denton and Broecker, 2008). However, environmental responses to the LIA in the Mediterranean region are not yet well understood (Touchan et al., 2011; Esper et al., 2007; Büntgen et al., 2008, 2010b; Luterbacher et al., 2005). Several studies have suggested that the hydrological impact of climate changes will dramatically affect snow-fed watersheds, such as the headwaters of many rivers located in the Pyrenees (Beniston, 2003; García-Ruiz et al., 2011). The Southern Pyrenees constitute the main source of water resources at present, supplying more than 45 % of the annual runoff to the surrounding semi-arid Ebro Basin, a relatively densely populated area of NE Spain (López-Moreno and García-Ruiz, 2004). To understand future climate changes induced by global warming it is necessary to assess the impact of climate change on the hydrological cycle and through examination of climate variability and threshold values during the last millennia.

New information from different palaeoclimatic archives in the Pyrenees during the last millennium has become available during recent years: lacustrine records (Valero-Garcés and Moreno, 2011, and references therein), glacier extension (González Trueba et al., 2008) and dendroclimatic reconstructions (Büntgen et al., 2008). Together they provide a unique opportunity to assess the timing, amplitude, and internal structure of this period, and a re-evaluation of

the environmental changes associated with the LIA phase in the Southern Pyrenees. This paper reviews the available near millennium-long palaeoclimatic evidence from the Pyrenees, including: (i) glacier advances and retreats reconstructed from moraine sediments, (ii) the climatic and landscape changes evidenced by multi-proxy-based lake and shallow-marine sediments reconstructions, and (iii) the rainfall and temperature fluctuations evaluated from tree-ring chronologies. Comparison of these paleoclimate sequences and correlation with regional records across the Mediterranean region and mountain areas of Europe allows a more precise evaluation of the spatial extent and chronology of the main climate and environmental changes that occurred during the last millennium, and permits the testing of possible climate mechanisms for this type of event.

2 Regional setting

The Pyrenees are limited by the Bay of Biscay in the west and Cape Creus to the east (Fig. 1a) and represent a ∼440 km long longitudinal belt from the Atlantic Ocean to the Mediterranean Sea. This geographical location between these two climatic zones; their southern latitude and East–West orientation and its complex topography lead to a high climatic heterogeneity (López-Moreno et al., 2008). Altitudes reach more than 3000 m above sea level (a.s.l.) with a highly contrasting relief (Del Barrio et al., 1990). The highest massifs are located in the central areas of the range and the altitude decreases towards the west and the east, as well as towards the Aquitaine (France) and Ebro Depressions (Spain) (north and south, respectively) (Fig. 1b). Annual precipitation exceeds 600 mm and sometimes even reaches 2000 mm at the highest altitudes. Most of the annual precipitation occurs during the cold season in the Atlantic areas but during spring and autumn in the Mediterranean regions, with relatively dry summers. The annual averaged 0 °C isotherm is located at ∼2700 m a.s.l. (Del Barrio et al., 1990).

This study is restricted to the Southern Pyrenees, which are characterized by a stronger Mediterranean influence and thus, warmer and drier conditions than the northern slopes (Cuadrat et al., 2008), which makes this area more sensitive to hydrological fluctuations. In the highest altitudes (above 1800 m a.s.l.) vegetation is mainly composed of subalpine and alpine pastures (*Carex curvula* and *Festuca scoparia*) with conifers (*Pinus uncinata* and *Juniperus* sp) as the only arboreal component. Small forested areas of *Fagus sylvatica, Fraxinus excelsior, Corylus avellana, Betula pubescens, Acer campestre, Sorbus aucuparia* and *Sorbus aria* and mixed forest with *Pinus sylvestris, Fagus sylvatica* and *Abies alba* can be also found (Peinado Lorca and Rivas-Martínez, 1987). Between 1500 and 1800 m, *Pinus sylvestris* and *Quercus faginea* forests are dominant, while at around 1000 m Mediterranean influence increases and vegetation is composed of *Quercus ilex-rotundifolia* and *Quercus pubescens*,
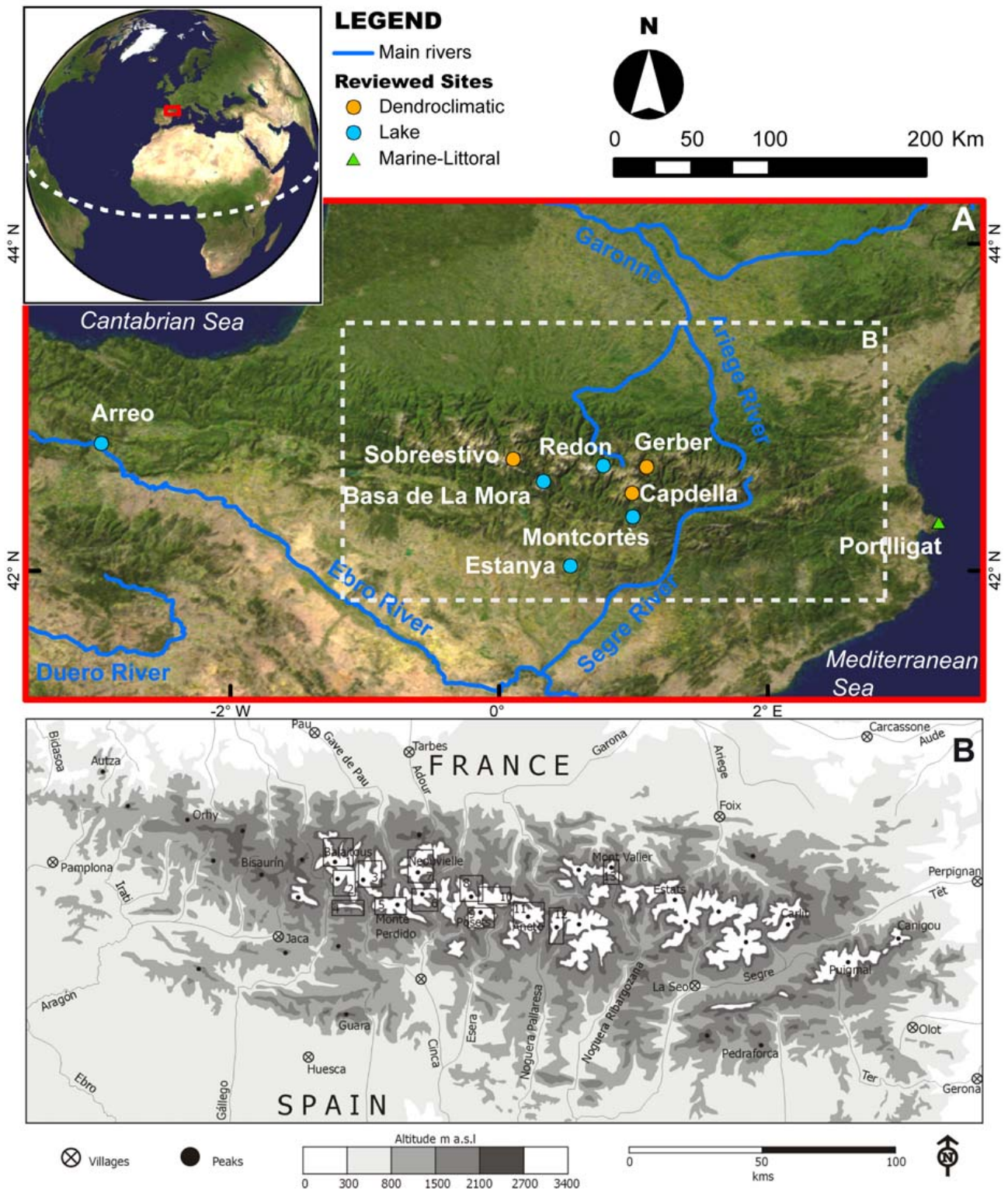
Fig. 1. (A) Location of the different records reviewed in this paper within the Pyrenees, including lacustrine, dendroclimatic and marine-littoral reconstructions (see legend). **(B)** Detailed map of the different massifs with the presence of glaciers during the LIA (modified from González-Trueba et al., 2008).

depending on the annual precipitation. Foothills are mainly covered by Mediterranean pine (*Pinus Sylvestris* and *Pinus Halepensis*) and oak forests (*Quercus ilex-rotundifolia, Q. faginea, Q. pubescens*), with dense shrub land (*Rhamnus, Pistacia, Arbutus, Prunus, Cornus, Buxus,* Genisteae, Cistaceae, etc.). *Corylus avellana* and other phreatophytes such as *Salix, Fraxinus, Populus* or *Ulmus* are only located on riverine soils (Blanco-Castro et al., 1997).

There are two main types of lakes in the Southern Pyrenean domain (Fig. 1a): (i) karstic lakes, located at the Southern foothills of the Pyrenees, in the so-called External Ranges, between 600 and 1000 m a.s.l., in the transition between Atlantic and Mediterranean climate types and vegetation domains (García and Gómez, 2008) and subject to a considerable human influence during the last millennia (Arreo, Estanya, Montcortès); (ii) high-mountain, glacial lakes located in the Axial Pyrenees, above 1800 m a.s.l., characterized by colder and more humid conditions, near to the timberline (e.g. Basa de la Mora, Redon) where human impact is limited. Currently in the Pyrenees there are 21 active glaciers with a total extension of about 495 ha. On the Spanish side there are 29 ice bodies, of which only 10 can be considered as glaciers (260 ha) (González Trueba et al., 2008), and thus, appear the most relevant for this study. Nevertheless, LIA remains such as moraines and proglacial materials do exist in more than 100 deglaciated cirques in the Pyrenean high mountains. These deposits are located in the current glaciated and non-glaciated massifs (Fig. 1b) (Serrano and Martínez de Pisón, 1994; Grove and Gellatly, 1995; Chueca et al., 1998a, b). Although the Pyrenean glaciers experienced an expansion during the LIA, they are currently reduced in thickness and spatially limited to the highest summits, displaying bevelled shapes, burials, and even some disappearance of ice bodies. From 1880 to 1980 AD at least 94 glaciers became extinct, while 17 glaciers have disappeared on the Spanish side since the 1980s.

3 Paleoclimate archives

For this study, we selected paleoclimate sequences from published studies that fulfill the following requirements: (i) reconstructions are based on natural archives, (ii) these records have independent chronologies based either on absolute dating (tree ring or lacustrine varve counting, calibrated radiometric dating) or documentary sources and (iii) climate variability is considered as the main forcing mechanism of environmental changes reconstructed at these sites. Paleoclimatic archives analyzed here comprise: (i) dendroclimatic reconstructions (Fig. 1a), (ii) lake and marine-littoral sequences (Fig. 1a), and (iii) geomorphologic evidence of glacier advances or retreats (Fig. 1b). Reconstructed environmental variables vary from climatic parameters (temperature, precipitation) to evidence of environmental changes directly related to these parameters (changes in vegetation cover, runoff and effective moisture fluctuations reconstructed by lake

level changes and/or salinity fluctuations). We consider this transect of multi-proxy reconstructions of climatic and environmental changes to represent the best strategy to discern between climate and human forcings in landscape changes, as demonstrated in previous research carried out in this area (Moreno et al., 2008; Morellón et al., 2011; Rull et al., 2011).

3.1 Lake and marine-littoral sequences

Unravelling the complex interplay between climate changes and human impact in Pyrenean lakes and littoral marine sequences is complex and requires the use of multiple proxy-data and robust chronologies based on either radiometric techniques (^{137}Cs, ^{210}Pb, ^{14}C) or varve counting or a combination of these two methods. Furthermore, the correlation with historical events detected in most of the sequences provides further chronological support (e.g. onset and/or intensification of farming, introduction of particular cultivars, deforestation events (Rull et al., 2011)). Most of the lacustrine sequences used in this review have been analysed following a multidisciplinary strategy, comprising a variety of proxies: (i) sedimentology (sedimentary facies, microfacies and varve sub-layering), (ii) elemental and isotopic geochemistry, and (iii) biological indicators (pollen, diatoms, chironomids and chrysophytes). Other lake and peatbog records (i.e. Tramacastilla and Bubal (Montserrat-Martí, 1992), Bosc dels Estanyons (Miras et al., 2007), Riu dels Orris fen (Ejarque et al., 2010), Lake Burg (Bal et al., 2011) and Col d'Ech (Rius et al., 2012), among others), have not been considered for this paper because of the lack of a multi-proxy analysis or their exclusive focus on human activities.

3.1.1 Lake Arreo

Lake Arreo (42°46′ N, 2°59′ W, 655 m a.s.l.) is a karstic lake located in the transition between the Westernmost Ebro Basin and the foothills of the Pyrenees (Fig. 1a). The chronology of the sequence is based on the combination of varve counting, ^{137}Cs/^{210}Pb, and ^{14}C dating and spans the last 2600 yr (Corella, 2011). The main paleoindicators analysed include sedimentary facies and microfacies, elemental geochemistry, pollen and diatoms. The sensitivity of some of these proxies has been demonstrated by their successful correlation with instrumental climate data series and limnological monitoring data at shorter timescales (Corella et al., 2011a).

The onset of the LIA in the Arreo sequence (1300 AD) is characterized by a better development and preservation of biogenic varves, decreased content in aragonite and gypsum, and corresponding lower values of strontium (Sr), and the increase in the centric diatom *Cyclotella distinguenda* and arboreal pollen. These proxies are indicative of the development of higher lake levels and associated meromixis, and a forest recovery likely caused by moister conditions (Table 1). Additionally, an increase in *Typha* indicates the flooding of the littoral platform previously emerged during the MCA. The decrease in deciduous *Quercus* since 1870 AD

points towards more arid conditions since the end of the LIA. An arid phase was detected between 1730–1790 AD, characterized by a deposition of clay-rich facies (Fig. 2) and high Sr content in the sediment (Corella, 2011) (Table 1, Fig. 3). Nevertheless, the presence of biogenic varves, and the dominant presence of *Cyclotella distingüenda* and the low Sr values indicates relatively high lake levels during the mid-19th–mid-20th century (Corella, 2011; Corella et al., 2011a). The increase in gypsum and Sr (Fig. 3) in the sediment suggests that lake waters were more concentrated than during the warmer mid-20th century.

3.1.2 Lake Estanya

The Balsas de Estanya karstic system (42°02′ N, 0°32′ E, 670 m a.s.l.) is located at the foothills of the External Ranges, in the central-eastern Pre-Pyrenees (Fig. 1a). The sedimentary sequence has been dated by ^{137}Cs/^{210}Pb and radiocarbon and spans the last 21 ka.

The multi-proxy analysis of sediment cores recovered in the distal areas of the main lake, including sedimentology, elemental and isotopic geochemistry and biological indicators (pollen, diatoms and chironomids) reveals arid conditions during the MCA followed by more positive water balances during the LIA, starting at 1300 AD and lasting to 1850 AD. Consistently, pollen reflects warmer and drier conditions for the MCA, with a landscape dominated by junipers and Mediterranean elements, a relatively low abundance of mesophytes and a poorly developed aquatic component. The increase in water availability during the LIA is characterized by increase of riparian and hygrohydrophytes (*Salix, Ulmus, Tamarix, Potamogeton, Myriophyllum, Nuphar, Lemna*), and a recovery of mesophytes (*Betula, Corylus, Alnus,* deciduous *Quercus, Abies*) (Fig. 2, Table 1). Likewise diatom assemblages suggests low water levels and saline conditions during the MCA (Morellón et al., 2011).

A reconstruction of salinity, based on the results of Principal Component Analyses applied to the high-resolution geochemical dataset (see details in Morellón et al., 2011) identifies large hydrological fluctuations. Other biological proxies (diatoms, chironomids) and sedimentological indicators show a coherent evolution (Table 1, Fig. 3). The LIA in Estanya is characterized by complex internal fluctuations with increased water balance during the solar minima.

3.1.3 Lake Montcortès

Lake Montcortès (42°19′ N, 0°59′ E, 1027 m a.s.l.) is located 50 km north-east of Estanya (Fig. 1a). The composite sequence of Montcortès spans the last 5.3 ka and constitutes the longest varved, annually resolved sequence recovered to date in the Iberian Peninsula (IP) (Corella, 2011; Corella et al., 2011b). The age model is particularly robust because of the combination of varve counting, ^{210}Pb and radiocarbon dating.

The analysis of microfacies and sublayering of laminae revealed colder conditions during the LIA (1300–

1800 AD); (Corella, 2011). During this period, most of the calcite laminae show a fine-coarse sub-layering interpreted as a result of prolonged winter conditions with a delayed warming in spring, which may cause supersaturation leading to rapid nucleation of small calcite crystals. Higher Fe/Mn ratios also suggest more frequent and longer anoxic conditions at the hypolimnion (Corella, 2011), and increased abundance of planktic diatom *Cyclotella cyclopuncta* points to higher lake levels (Scussolini et al., 2011). The lack of diatom valves during the MCA is explained though the synergy of arid conditions and higher anthropogenic pressure on the lake. The presence of the Mediterranean scrub community reflects warmer conditions during the MCA, and its disappearance during the LIA in the 15th century, together with the increase in forest, are interpreted as colder and more humid conditions during the LIA (Rull et al., 2011). Towards the end of the LIA (ca. 1700 to 1900 AD) intermittent abundance of diatoms and occasional predominance of pennate, littoral taxa point to fluctuating lake levels; in more recent times, the presence of oligotrophic species marks the shift to poorer nutrient levels (Fig. 3).

3.1.4 Lake Basa de la Mora

Lake Basa de la Mora (42°32′ N, 0°19′ E, 1914 m a.s.l.) is a shallow, glacial-karstic lake located in the Cotiella Massif, in the Central-Eastern area of the Internal Ranges of the Pyrenees (Fig. 1a).

This radiocarbon-dated sedimentary sequence displays the highest resolution for the Holocene period in the region (117 cm kyr^{-1}). The multi-proxy analyses of sediment cores revealed more arid conditions in medieval times (900–1300 AD), as indicated by: a rise in *Juniperus*, a decrease in mesophytes and aquatic plants and the highest percentages of heliophyte herbs (including *Artemisia*, although this taxum could also indicate the existence of anthropogenic activities in the area) (Table 1, Fig. 2), and a decreased in clastic input, represented by lower silicon (Si) content (Fig. 3). The MCA is also characterized by high organic and carbonate productivity related to a larger development of the palustrine area and, possibly, the lowest lake level of the last 2000 yr. During most of the LIA (1300–1750 AD), an opposite pattern occurs, leading to higher values of elements associated to detrital input due to an increase in runoff (Moreno et al., 2010; Pérez-Sanz, 2009; Pérez-Sanz et al., 2011). Sedimentological and geochemical signatures for the last 200 yr are coherent again with lower lake levels and drier climate conditions.

3.1.5 Lake Redon

Lake Redon (42°38′ N, 0°46′ E) is located at a high altitude (2240 m a.s.l.) in the Maladeta batholith, an area characterized by low human impact (occasional sheep grazing in summer) (Fig. 1a). The age model of the sequence is based on ^{210}Pb dating and 12 radiocarbon dates, covering the entire Holocene (Camarero et al., 1998). Chrysophytes cysts
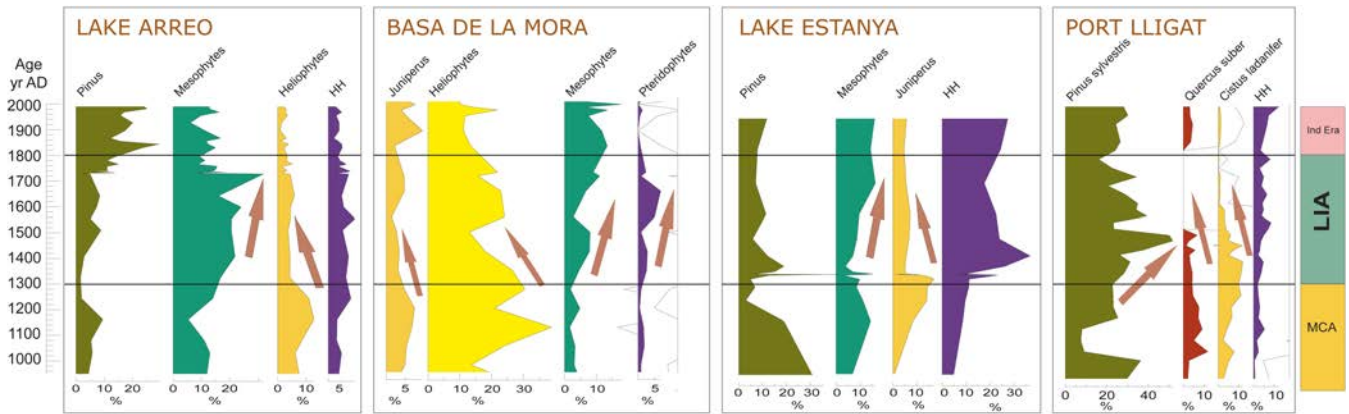
Fig. 2. Selected pollen taxa and group diagrams from lakes Arreo, Basa de la Mora, Estanya and Portlligat and correlation between them. In Arreo sequence Mesophytes curve is composed by deciduous *Quercus, Fagus* and *Corylus*; Heliophytes group by *Artemisia, Chenopodiaceae, Asteraceae*; and Hydro-hygrophytes includes *Cyperaceae* and *Typha*. In Basa de la Mora, Heliophytes group is formed by *Ephedra distachya, E. fragilis, Artemisia, Cichorioideae, Asteroideae, Carduaceae, Chenopodiaceae, Plantago*, and *Heliamthemum*; whereas Mesophytes comprise: deciduous *Quercus, Alnus, Carpinus, Salix, Ulmus, Populus, Fraxinus* and *Juglans*. Estanya groups of Mesophytes and Hydro-hygrophytes are composed by *Betula, Corylus, Alnus, Tilia, Ulmus, Populus, Salix, Fagus*, and deciduous *Quercus*; and Cyperaceae, *Typha, Potamogeton, Myriophyllum, Nuphar* and *Lemna*, respectively. Finally, Portlligat hydro-hygrophytes curve includes: *Cyperaceae, Myriophyllum, Asplenium, Pteridophyta monolete* and *Pteridophyta trilete*.

are used as proxies of winter-spring temperatures (Pla and Catalán, 2005) and diatoms for water alkalinity (Catalan et al., 2009), which eventually can be related to air temperature of the snow-free period (summer and autumn). For both proxies, transfer functions were developed, based on calibration sets of more than one hundred lakes. A recent study has confirmed the relationship between chrysophyte assemblages and winter–spring temperatures, as well as the mechanism behind it (Pla-Rabes and Catalan, 2011).

Interestingly, the two records did not show a parallel behaviour (Fig. 3). A decrease of snow period temperatures (winter–spring) would have started earlier than a similar decrease in snow-free period temperatures (summer–autumn). While summer temperature was still high during 11th and 12th centuries, winter temperatures decreased sharply. According to the Redon record, summer cooling occurred abruptly by 1200 AD and reached the lowest temperature values by 1700 AD. The snow period temperatures improved progressively from the 12th century but showed cold phases in the 14th, 18th and early 20th centuries.

3.1.6 Portlligat Bay

Portlligat Bay (42°17′ N; 3°17′ E, 0 m a.s.l.) is a shallow (maximum depth, 7.1 m) and small inlet located in the NE Mediterranean coast of the IP, connected to the sea (Fig. 1a). Pollen associations (López-Sáez et al., 2009) (Fig. 2) indicate relatively dry conditions and high temperatures during the MCA, following the drop of *Pinus sylvestris* formations and the development of Mediterranean taxa such as Cistaceae and *Quercus suber*. The sequence shows a different pattern of forest evolution during the LIA with higher percentages of

Pinus sylvestris and lower Mediterranean formations. These could be related to colder temperatures. Concentration of fungal ascospores Type 18 has been used for the reconstruction of humidity (Van Geel, 1978) and fluctuating but more humid conditions were reconstructed from 1250 AD to the early 1800s (Table 1). Maximum humidity was reached from 1450 to 1550 AD, whereas the most arid conditions took place during the 19th and 20th centuries and additionally, during the MCA (1000–1150 AD) (López-Sáez et al., 2009) (Fig. 2).

3.2 Dendroclimatological reconstructions

3.2.1 Gerber-Sobreestivo (GER-SOB) chronology

Two timberline sites (GER and SOB) of similar ecological and climatic conditions were selected for this reconstruction (see Büntgen et al., 2008 for details). Samples include living and dry-dead pine trees (*Pinus uncinata* Mill.) of all age-classes. The Gerber site (GER) (42°38′ N, 1°60′ E, 2200–2350 m a.s.l.) is located within the central-eastern part of the Pyrenees, whereas the Sobreestivo (SOB) site (42°41′ N, 0°06′ E, 2300–2400 m a.s.l.), is located 70 km west of the GER site (Fig. 1a). Temperature records from the Pic du Midi de Bigorre mountain observatory (43°04′ N, 0°09′ E, 2862 m a.s.l.) were used for proxy calibration trials. Methodological details can be found in Büntgen et al. (2008). This annually resolved record of June–September temperature variations spans the 1260–2005 AD period, and thus constitutes the longest annually-resolved warm season temperature record for the Pyrenees.
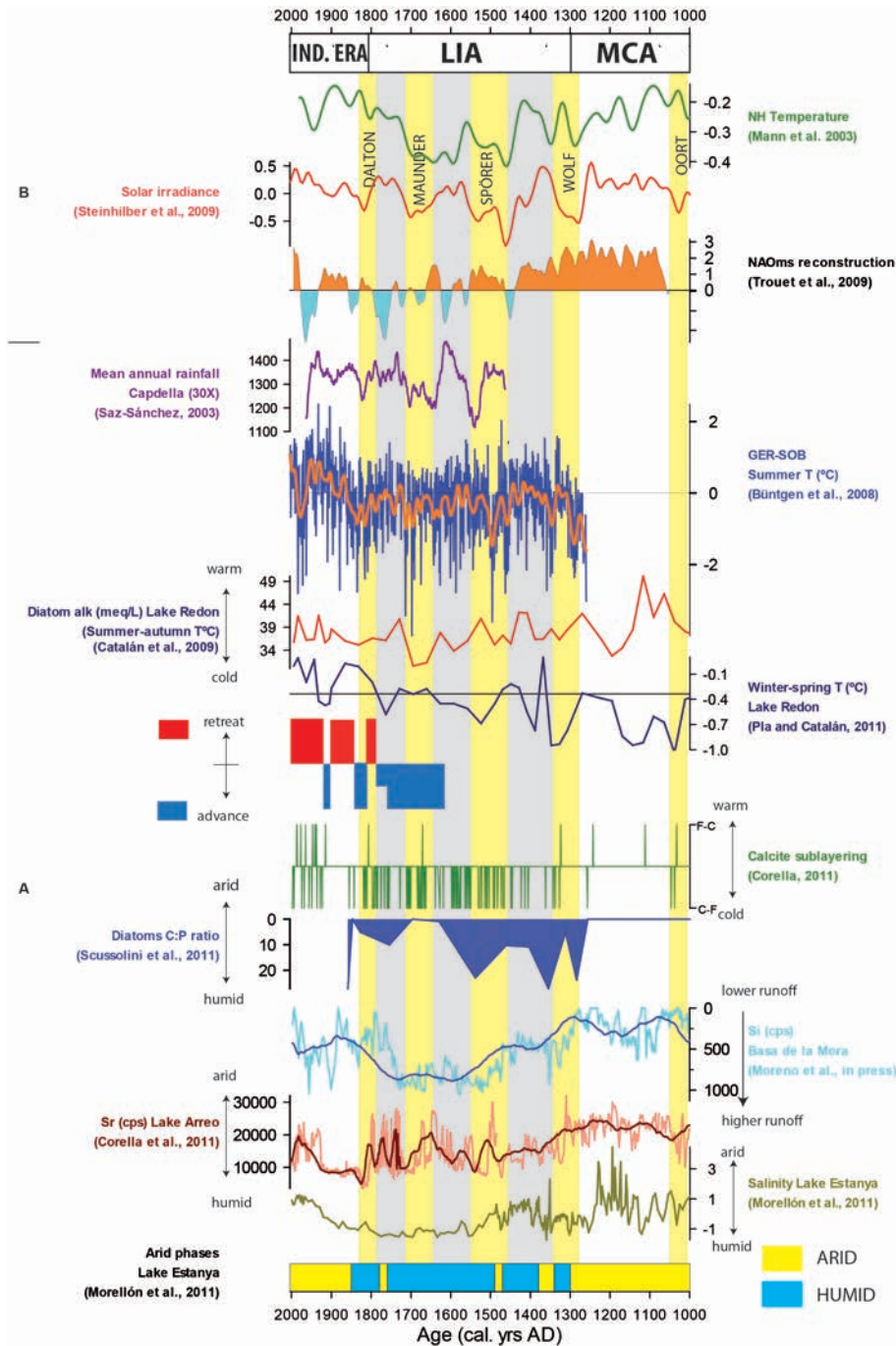
Fig. 3. (A) Selected records from the Southern Pyrenees reviewed in this paper, from top to bottom: Capdella tree-ring based mean annual rainfall (30× moving average) (Saz Sánchez, 2003), GER-SOB summer temperature tree-ring based reconstruction (original data and 20× moving average) (Büntgen et al., 2008), diatom alkalinity-based summer–autumn temperature and chrysophyte-based winter–spring temperatures reconstruction in Lake Redon (Pla and Catalán, 2005; Catalan et al., 2009), phases of advance and retreat of the Pyrenean glaciers (González Trueba et al., 2008), calcite sublayering (Fine–Coarse (F–C) or Coarse–Fine (C–F)) (Corella, 2011) and diatom C:P ratio (Scussolini et al., 2011) in Lake Montcortès, Si (cps) content in Lake Basa de la Mora (original data and 30× moving average) (Moreno et al., 2012), Sr (cps) content in Lake Arreo sequence (original data and 30× moving average) (Corella, 2011) and XRF-based salinity reconstruction and humid/arid phases in Lake Estanya (Morellón et al., 2011). **(B)** Supplementary regional and global records, from top to bottom: NH temperature reconstruction (Mann and Jones, 2003), solar irradiance (Steinhilber et al., 2009), and NAOms reconstruction (Trouet et al., 2009). Vertical yellow bars represent the chronology of the grand sunspot minima and temporal divisions Medieval Climate Anomaly (MCA), Little Ice Age (LIA) and Industrial Era (IND. ERA) are also indicated at the uppermost part of the figure.

Table 1. Lacustrine and marine-littoral sequences from the Southern Pyrenees reviewed in this paper, including climate/hydrology and vegetation conditions recorded for the different chronological stages defined in this paper: Late MCA (1000–1300 AD), LIA (1300–1800 AD) and Post-LIA (after 1800 AD).

Site and location	Type	Environmental conditions					
		Late MCA (1000–1300 AD)		LIA (1300–1800 AD)		Post-LIA (after 1800 AD)	
		Hydrology/ Climate	Vegetation	Hydrology/ climate	Vegetation	Hydrology/ climate	Vegetation
Arreo 42°46′ N 2°59′ W 655 m a.s.l.	Lake	Low lake levels, high salinity, Holomictic conditions	Fall in mesophytes, mainly deciduous *Quercus* and development of ruderals, meadows and pastures.	High lake levels, Lower salinity, Meromictic conditions	Deciduous forest recovery (mainly *Quercus* sp. and *Fagus*). Decrease in human activities (meadows and pastures).	Low lake levels, higher salinity, Holomictic conditions	Deforestation of oak and beech forest and development of *Pinus* formations (including recent *Pinus radiata* cultivation)
Estanya 42°02′ N 0°32′ E 670 m a.s.l.	Lake	Low lake levels, High salinity, variable runoff	Increase of *Juniperus* and Mediterranean taxa. Reduced proportions and variety of aquatic plants.	Higher lake levels, lower salinity, variable runoff	Development of Mesophytes, peak of *Pinus nigra* type, and increase of aquatic taxa.	High lake levels, higher salinity, Reduced runoff	Recovery of open mixed Mediterranean/deciduous formations with Pine. Maximum expansion of cultivated areas
Montcortès 42°19′ N 0°59′ E 1027 m a.s.l.	Lake	Warm conditions, reduced anoxia, higher runoff	Establishment of Mediterranean shrubland with increase in evergreen Quercus and decrease of pines. Development of cultivated taxa.	Cold conditions, Higher anoxia, lower runoff	Increase in AP formations, specially conifers and deciduous taxa. Decrease in shrubland and heliophytes.	Warm conditions, lower anoxia, higher runoff.	Expansion of conifer formations and anthropogenic influenced areas (mainly pastures with ruderals).
Basa de la mora 42°32′ N 0°19′ E 1904 m a.s.l.	Lake	High carbonate precipitation, decreased runoff	Development of *Juniperus* and heliophytes and decrease in all deciduous taxa.	Lower carbonate precipitation, higher clastic input	Fall in *Juniperus* and heliophytes and increase in Mesophytes and Pteridophytes.	High carbonate precipitation, decreased runoff	Recovery of mixed conifer (*Pinus* and *Juniperus*) / deciduous taxa formations.
Redon 42°38′ N 0°46′ E 2240 m a.s.l.	Lake	Higher summer– autumn temperatures Lower winter–spring conditions	–	Lower summer– autumn temperatures Relatively low winter–spring temperatures	–	Relatively high summer–autumn temperatures High winter–spring temperatures	–
Portlligat 42°17′ N 3°17′ E 0 m a.s.l.	Shallow marine	–	Increase in *Quercus suber*, deciduous *Quercus* forests and Mediterranean shurblands (*Cistus ladanifer*)	–	Expansion of *Pinus sylvestrys* and reduction in *Quercus suber* and Mediterranean shrublands	–	Recovery of *Quercus suber* and deciduous *Quercus* forests in mixed formations with conifers

Relatively high summer temperatures were reconstructed during most of the 1300–1500 AD period and the 20th century, separated by a rather prolonged cooling from around 1500 to 1850 AD, within the LIA (Fig. 3). The six warmest decades occurred during the 20th century and the following four warmest during the period 1360–1440 AD (Büntgen et al., 2008).

3.2.2 Capdella record

Five chronologies from several sites in the Southern Pyrenees were used for this reconstruction: Aigües Tortes and Larra,

obtained from *Pinus uncinata R.* samples, and Pinobajo, Trapa and Ibonciecho, from *Pinus sylvestris* (Saz Sánchez, 2003). Standard techniques were applied for the sampling, construction of chronologies and reconstruction of climatic variables (Fritts, 1990). Among 20 and 25 samples were extracted from living trees to construct each chronology. Tree-rings widths were measured with a resolution of 0.01 mm using an ANIOL measuring table (Aniol, 1983). Absolute dating of tree rings was checked by program COFECHA (Holmes, 1986). ARSTAN was used to standardize ring-width measures in order to eliminate low frequency non climatic signal and to combine standardized indices into

site chronologies (Cook and Kairiukstis, 1990). Rainfall records from Capdella weather station (42°28′ N, 0°59′ E, 1407 m a.s.l.) were used for proxy calibration. Finally, using PRECON (Fritts and Shashkin, 1995) chronologies and climatic data were calibrated in order to obtain a response function. Methodological details can be found in Saz Sánchez (2003) and Chueca Cía et al. (2005) (Fig. 3). The reconstructed precipitation shows relatively higher values than in recent times for the last 500 yr, with several marked decade – long humid periods around 1500, 1600, 1700 AD and the early 20th century; with relative rainfall minima centred at ca. 1800 AD, 1900 AD and an abrupt decreasing trend during the late 20th century.

3.3 Evidence of glacier fluctuations

Extensive research carried out by González-Trueba et al. (2008) demonstrated that glaciers occurred in more than 20 different massifs of the Pyrenees during the LIA, with a wide range of mean equilibrium line altitudes (ELAs) above and between 2650 m a.s.l. in the oceanic-influenced massifs (Balaitous and Infierno massifs among others) and 2900 m a.s.l. in the continental massifs (Maladeta and Posets massifs among others). Thirteen massifs with glaciers were considered relevant for this study (Fig. 1b). The most common aspect was the development of cirque glaciers with reduced or absent tongues. This study is based on geomorphologic and morphostratigraphical surveys and historical archives and demonstrates the rapid response of these ice bodies to climatic variations.

The historical maximum extent of glaciers in the Pyrenees took place between 1600 and 1750 AD, followed by a retreat during the next 50 yr, alternating with minor readvances responsible for the development of numerous small moraines (Fig. 3). A secondary advance, characterized by a rapid, short-lived growth of ice bodies occurred during the 19th century, lasting until the 1920s. The temperatures estimated from the lowering of the ELAs are 0.7–0.9 °C colder than present-day conditions in this area. A generalized phase of glaciers retreat occurred since the 1870s, with minor readvances during the last decades of the 19th century and the 1920s. Since then, glaciers underwent a continuous retreat, becoming ice patches in most of the cirques affected by LIA glaciations, with minor expansions in 1945 and 1964 AD in the French slopes. Since the 1970s–1980s, a drastic retreat started, continuing till the present (Fig. 3) (González Trueba et al., 2008).

4 Millennium-long environmental changes in the Southern Pyrenees

4.1 Evaluation of the reviewed records

Selected records from the Southern Pyrenees, including lacustrine and marine-littoral sequences, dendroclimatological records, and reconstructions of glacier fluctuations, provide evidence of a broadly consistent pattern of climatic fluctuations during the last millennium. Nevertheless, before comparing these records, the differences in chronological resolution and climate sensitivities of each type of sequence and proxies must be evaluated (North et al., 2006).

Tree rings provide annually resolved records and are sensitive to high-frequency climate fluctuations (Briffa, 2000). The two sequences reviewed in this paper respond to both temperature fluctuations (GER-SOB) and rainfall variability (Capdella). These two high-resolution sequences start at ca. 1260 and 1460 cal yr BP, respectively, which limits their record to intra-LIA (1300–1800 AD) variability and the transition between the LIA and recent warming (after 1800 AD). In contrast, lake sequences comprise the whole studied time interval and allow comparison with previous MCA, but they generally have radiocarbon-based chronologies characterized by a lower resolution, and able to capture only lower frequency variability (multi-decadal to centennial). Karstic lakes reviewed in this paper are particularly sensitive to changes in the hydrological balance (precipitation *minus* evaporation) reflected by different inorganic and biological proxies, as outlined in the previous section. Only lakes Arreo and Montcortès have varved (i.e. annual) chronologies able to record higher-frequency fluctuations. Changes in sublayering in Montcortès calcite laminae reflect relative changes in water temperature (colder or warmer stages). Accordingly, higher density of Fine–Coarse (F–C) sublayering through this record are interpreted as periods of predominantly colder conditions.

Lake Redon also provides information about thermal conditions not only as relative changes (summer–autumn) but also as a semi-quantitative estimation (winter–spring), inferred from biological proxies. The chronological control is robust, obtained by combining different radiometric techniques (^{137}Cs, ^{210}Pb, ^{14}C), but because of the comparatively lower sedimentation rate of this sequence the chronological resolution is relatively low and variable. In spite of these limitations, visual comparison of reconstructed summer–autumn temperatures reflects a relatively good match with the main trends in summer temperatures recorded in GER-SOB (Fig. 3). The relative maximum winter–spring temperatures reconstructions also coincide with and major episodes of glacier retreat (1750–1900 and after the 1920s). Only the early 19th century glacier advance was not coincident with a winter temperature drop in Redon.

Glaciers in Mediterranean mountains are characterized by a high sensitivity to climate variability (Hughes, 2010), but the relatively short time span of the Pyrenean records (from ca. 1600 AD to the present) and their relatively lower chronological resolution are major shortcomings when comparing to other records. As expected, reconstructed fluctuations show a broadly consistent pattern with temperature and hydrological changes inferred from other records and major advances are coincident with more positive water balances and colder conditions.

Pollen records from lake sequences are subject to the same chronological uncertainties derived from radiocarbon dating. Despite the impact of anthropogenic activities, previous research on these sequences has demonstrated the reliability of pollen as a proxy of climate fluctuations (Moreno et al., 2008, 2010; Morellón et al., 2011; Pérez Sanz et al., 2011). The proportion between xerophytic and Mediterranean components and mesophytes, whose development is favoured under drier and more humid conditions, respectively, reflects changes in the regional hydrological conditions at a centennial timescale (Fig. 2). The coincidence of changes in the terrestrial vegetation components, aquatic taxa and other non-palynological proxies provides further support for this hypothesis. The geographical location of each of these pollen sequences determines differences in local vegetation, with an increasing content of Mediterranean elements towards the east and the south. These differences have also been taken into account for the selection of taxa indicative of dry conditions in each case: herbaceous heliophyte taxa (westernmost lake Arreo), heliophytes and junipers (Central Pyrenees: Basa de la Mora and Estanya) or other Mediterranean taxa such as *Cistus* (easternmost Portlligat site) (Figs. 1a and 2).

Comparison among these sequences and correlation with other regional and global records enable us to investigate the timing, intensity and chronology of the main environmental changes occurring prior, during and after the LIA and their relationship with climatic forcing mechanisms (Fig. 3). The overall good agreement of a wide range of records with different locations and altitudes, likely subjected to variable human activity, suggests that they respond to common climatic forcings.

4.2 The last phases of the MCA

In agreement with the rest of the IP (Moreno et al., 2012, 2011), generally arid conditions have been reconstructed for the last phases of the MCA (1000–1200 AD) in the Pyrenees. Lower lake levels and higher salinity occurred in lakes Arreo, Estanya, and Montcortès. Relatively low clastic input, reflecting decreased runoff caused by less precipitation also occurred in Basa de La Mora. Pollen associations in these sites and Portlligat Bay (Fig. 2) also indicate dry conditions with the development of the xerophytic and Mediterranean component (*Juniperus* and heliophyte herbs increase, evergreen *Quercus* increased while deciduous *Quercus* decreased), a decrease in mesophytes and the aquatic component. Despite spatial differences and the human influence on these watersheds, drier conditions can be interpreted for the MCA (Moreno et al., 2012).

Only two records provide indirect information about thermal conditions during this period. An increase in the calcite laminae thickness in Lake Montcortès indicates generally warmer conditions compared with the subsequent LIA-associated cooling. The discrepancy in lake Redon re-

constructions with the occurrence of higher but variable summer–autumn temperatures in Redon (Catalan et al., 2009) (Fig. 3) and the lowest winter temperatures (Pla and Catalán, 2005) would be explained as a reflection of the strong seasonality during this period.

4.3 The LIA

Higher lake levels and hence, moister conditions started ca. 1300 AD in lakes Arreo, Estanya and Montcortès. An increase in sediment delivery and runoff also occurred at this time in Basa de la Mora (Fig. 3). Pollen associations from Basa and Estanya sequences show a general decline of xerophytes and Mediterranean taxa (*Juniperus*, evergreen *Quercus*), some expansion of deciduous trees (mesophytes) and a rise of the aquatic content (*Potamogeton* increase). Arreo and Montcortès vegetation composition show similar patterns of changes. The Portlligat Bay sequence also suggests the start of a humid period, even though mediated by higher human – induced fires and an increase of cattle raising, resulting in a change to mesotrophic conditions (López-Sáez et al., 2009) (Table 1, Fig. 2).

The increase in stream flow activity in the alluvial systems of the Central Ebro Basin, whose headwaters are located in the Pyrenees, also indicate increased water availability during this period (Sancho et al., 2007; Constante et al., 2011). An increased number of flood events was also recorded in the nearby Ebro watershed after 1300 AD (Benito et al., 1996). The occurrence of predominantly humid conditions during the LIA has been widely detected elsewhere in the IP (Moreno et al., 2012): (i) higher lake levels were reconstructed in the north (e.g. La Cruz Lake, Iberian Range (Julià et al., 1998)) and in the south of Spain (Martín-Puertas et al., 2008, 2010), (ii) increased continental runoff reconstructed from marine sequences (e.g. Nieto-Moreno et al., 2011), (iii) increased Westerlies in the W Mediterranean (Moreno et al., 2012), (iv) increased storm activity in the nearby French Mediterranean Coast (Dezileau et al., 2011) and (v) more frequent floods in the Tagus headwaters (Moreno et al., 2008; Benito et al., 2003). Accordingly, increased water availability has been reconstructed in other areas of the W Mediterranean, such as Morocco (Détriché et al., 2009; Esper et al., 2007) and in the Alps (Magny et al., 2008, 2010).

The onset of the fine-to-coarse sublayering in the calcite laminae of Lake Montcortès, interpreted as a dominance of lower temperatures, occurred after ca. 1350 AD (Corella, 2011), coinciding with colder conditions in Lake Redon, both in winter and summer temperatures (Pla and Catalán, 2005; Catalan et al., 2009). Other evidence of widespread colder conditions in the region come from the neighbouring regions of Landes and Aquitaine (SW France) were loess deposits occurred from 0.8 to 0.2 ka BP (Bertran et al., 2011). The lack of temperature data from GER-SOB dendroclimatic reconstruction prior to 1300 AD makes it difficult to attribute an exact date to the onset of cold conditions associated with

the LIA. In fact, Büntgen et al. (2008) reconstructed the four warmest decades of pre-industrial times during the period 1360–1440 AD, which indicates the predominance of relatively mild thermal conditions during the first part of the LIA. However, a drop in temperatures occurred during the mid to late 15th century, consistent with a decrease in winter temperatures in Redon.

Other indirect evidence of temperature changes also indicate that the coldest conditions of the LIA in NE Iberian Peninsula did not take place until the 16th–19th centuries. As an example, the Ebro River (Fig. 1a), fed by many tributaries from the Southern Pyrenees, froze near its mouth in the town of Tortosa (Tarragona), 17 times since ca. 1400 AD (Puente, 2007). According to historical reports (Benito et al., 1996), the maximum frequency of frost episodes and intensity occurred between the 16th and 18th centuries. Historical reports also document colder conditions in the IP between the 16th and 19th centuries (Font-Tullot, 1986), with minimum temperatures during the 17th century. Accordingly, maximum (recent) glacier advances in the Southern Pyrenees took place from 1600 to 1750 AD, leading to a slower development during the late 18th and early 19th century. The chronology of this phase coincides with reconstructions for the European Alps (Schaefer et al., 2009). However, Calderone Glacier in Gran Sasso Massif (Italy), one of the southernmost glaciers in Mediterranean Europe, experienced a minor advance in the period 1313–1373 AD, prior to a maximum advance later on during the LIA, coinciding with higher lake levels in lakes Acessa and Fucino centered around 500 cal yr BP (Giraudi et al., 2011). In spite of the occurrence of cold and humid conditions along the LIA, glacier advances required a combination of high winter precipitation and low summer temperatures (Paasche and Bakke, 2010). According to this dataset, these two conditions were probably not fulfilled during the early phases of the LIA in the Pyrenees, between 1300 and 1600 AD. Coldest summer temperatures, accompanied by relatively cold winter conditions in Redon occurred from 1500 to 1700 AD. Consistently, the most humid conditions, indicated by minimum salinity and maximum lake levels and/or clastic input, were not reached until the period 1500–1600 AD (Fig. 3) and maximum precipitation in Capdella was recorded by tree rings ca. 1600 AD (Saz Sánchez, 2003) (Fig. 3). Flood records also show an increase in the number of events in Ebro Basin and in the Eastern Pyrenean rivers after 1600 AD (Benito et al., 1996).

In summary, we can broadly identify two major phases of environmental change that occurred during the LIA in the Southern Pyrenees: (i) a transitional phase MCA–LIA, characterized by fluctuating, moist conditions and relatively cold temperatures, between ca. 1300 and 1600 AD; and (ii) a second period, extending from ca. 1600 to 1800 AD, characterized by lower temperatures and higher water availability, leading to maximum glacier advances. In spite of the predominance of cold and humid conditions along the LIA, a lower amplitude hydrological and thermal internal variability was recorded in most of the sites (Fig. 3), as discussed below.

4.4 LIA to recent warming transition

An aridification trend started synchronously in lakes Arreo, Estanya, Montcortès and Basa de la Mora after ca. 1800 AD. Higher water concentration and/or more frequent oxic conditions in these settings indicate lower lake levels and decreased water balance. Pollen records show a new increase of human pressure and no aridity trends can be clearly extracted. Nevertheless, humidity reconstruction based on non-pollen palynomorphs in Portlligat indicates an abrupt decrease starting ca. 1750 AD, coinciding with an abrupt reduction of *Castanea* and *Vitis* culture while cereal cultivation is completely interrupted; the percentage of several arboreal elements (*Fagus, Abies, Corylus, Quercus suber* type) are also reduced or even disappear.

Decreased water availability has been also recorded in lakes in the North of the IP (e.g. Taravilla (Moreno et al., 2008), Lake Enol (López-Merino et al., 2012) and S Spain, (e.g. Doñana (Sousa and García-Murillo, 2003); Lake Zoñar (Martín-Puertas et al., 2008)). Marine cores around the IP also documented reduced river input associated with lower runoff (e.g. Nieto-Moreno et al., 2011). A similar hydrological response was detected in other areas of the W Mediterranean, like the French Jura (Magny et al., 2008) or Morocco (Détriché et al., 2009). However, Capdella tree ring sequence display a more complex variability, characterized by relative rainfall minima centred at ca. 1800 AD, 1900 AD and an abrupt decreasing trend during the late 20th century (Fig. 3).

Temperatures started to rise at the same time, between 1800 and 1850 AD, according to GER-SOB record, reaching their maximum values during the 20th century. Dendroclimatological reconstructions carried out in Morocco also show an increase in aridity after the mid-20th century (Esper et al., 2007). A change in calcite sublayering also occurred in Montcortès at this time pointing in the same direction (Fig. 3). Consistently with this general trend glaciers started to retreat continuously after 1850 AD (Fig. 3). Glacier readvances in the Pyrenees occurred between the last decades of the late 19th century and the 1920s (González Trueba et al., 2008) and have also been documented in other Mediterranean areas, like the Apennines (Giraudi, 2005), the Balkans (Hughes, 2010), Sierra Nevada (Gómez Ortiz et al., 2002, 2009), or the Cantabrian Mountains (González-Trueba, 2006, 2007; Serrano et al., 2011). Interestingly, this episode correlates with lower winter temperatures at Lake Redon (Pla and Catalán, 2005), a relative maximum in precipitation recorded in Capdella and a relative temperature minima in the GER-SOB records (Fig. 3) and globally with a decrease in NAO values during the early 20th century (Trouet et al., 2009). The onset of more arid conditions reconstructed for lake sediments in

Arreo occurred right afterwards, since 1870 AD. Finally, a further decrease in temperatures occurred in the mid-20th century, as documented by GER-SOB and Redon records. Minor glacier stabilisation phases described by González-Trueba et al. (2008) might also be related to this short-lived climate deterioration phase, in the frame of a generalized warming trend.

5   Regional context and paleoclimatic implications of the LIA in the Pyrenees

Temperature fluctuations in the Southern Pyrenees display a similar pattern compared to other reconstructions from Central Europe (Büntgen et al., 2010a), the Mediterranean Basin (Camuffo et al., 2010) and with other Northern Hemisphere palaeoclimate records at centennial timescales (e.g. Jones et al., 1998; Mann and Bradley, 1999), showing consistency with changes in solar activity (Steinhilber et al., 2009; Bard et al., 2000; Vaquero et al., 2002), global temperature fluctuations (Mann et al., 2008) and NAO index (Trouet et al., 2009). Comparison of climate records and volcanic activity (Gao et al., 2008) does not show a clear pattern in the Southern Pyrenees. On the one hand, some climate records show the expected cooling after volcanic eruptions, for example after the eruption of Tambora in 1815 AD. On the other hand, the largest eruption in the past 1500 yr (about 2.5 times larger stratospheric sulphate injection than Tambora) of an unknown volcano in the 1258 AD does not show up in any of the analysed climate records. Both low solar activity and volcanic eruptions lead to surface cooling compared with solar activity and no volcanic eruptions. In the past 1000 yr these eruptions coincided with times of low solar activity as, e.g. during the LIA and only a few of them occurred during the MCA, when solar activity was relatively high. Thus, reconstructed colder conditions are interpreted as a result of low solar activity partly influenced by volcanic eruptions.

5.1   The footprint of solar activity

In spite of the limited chronological resolution of most of the records, derived from radiocarbon dating, several oscillations in the hydrological and thermal dynamics of the reviewed sequences during the LIA suggest that colder temperatures and at least, more positive water balances and/or increased runoff dominated during periods of diminished solar activity, the so-called grand solar minima.

Contrasting patterns have been recorded for the Oort Minimum (1010–1050 AD): although lower winter and summer temperatures were recorded in Lake Redon and relatively more humid conditions were reconstructed in Arreo, variable conditions occur in the rest of the lakes (Estanya, Montcortès and Basa de la Mora). However, during the Wolf Minimum (1282–1342 AD) all lakes experienced more humid conditions, evidenced by increased lake levels, lower water concentration and/or increased sediment delivery. Al-

though Portlligat Bay has recorded more humid conditions in the Eastern Pyrenees during the LIA, in contrast to drier environments during the MCA, no significant hydrological response occurs for this solar minimum. In agreement with the expected pattern, an abrupt decrease in temperature was recorded in tree-ring based reconstructions of GER-SOB and higher altitude (colder) conditions occurred in Lake Redon (Fig. 3).

Colder conditions also occurred in the Pyrenees during the Spörer Minimum (1460–1550 AD), as indicated by lower temperatures in GER-SOB dendroclimatic reconstruction, calcite sublayering in Montcortès and lower winter temperature in Redon. Interestingly, within this phase, lasting for almost 100 yr (1460–1550 AD), generally recorded as a relatively humid period, all the lacustrine sequences reviewed in this paper show a short lived reversed pattern (more negative water balance) centred around 1500 AD. Higher mean annual rainfall was also recorded in Capdella tree-ring sequence, with an abrupt decrease in precipitation at the end of this phase. During the Maunder Minimum (1645–1715 AD), reduced summer temperatures were recorded both in GER-SOB and Redon, coinciding with a major phase of glacier advances. Most of the lake sequences clearly evidence higher effective moisture and/or increased runoff. However, the easternmost records of the region reviewed in this paper (Montcortès, Portlligat) show a less clear response, probably due to particular, local conditions. Mean annual rainfall reconstructed from Capdella also shows a relative maximum, less evident than the one corresponding to the Spörer Minimum (Fig. 3). In contrast, a clear temperature drop becomes evident in GER-SOB towards the end of the Dalton Minimum (1790–1830 AD), coinciding with a series of volcanic eruptions at the beginning of the 19th century, and contemporaneous to a short phase of glacier advances, also recorded in the Pyrenees. The short duration of the Dalton Minimum event (ca. 40 yr) and the low resolution of the age models might be responsible for contrasting responses reconstructed from the lake sequences.

Although most of the reviewed sequences display colder and more humid conditions during the grand solar minima, the intensity of the environmental response is highly variable. The influence of volcanic eruptions, other regional and local climate mechanisms and/or human influence might be responsible for this. Additionally, the variable chronological resolution of these records in some cases (e.g. lacustrine sequences, glacier fluctuations) limits a more precise correlation with this high-frequency climate variability. This environmental response disagrees with proposed patterns for the Western Mediterranean (Fletcher and Zielhofer, in press), but it is consistent with results obtained in Central European lakes (e.g. Magny et al., 2008, 2011a), likely indicating a high influence of local conditions and other as yet undetermined climate mechanisms.

5.2 Hydrological variability and the potential influence of the NAO

Centennial-scale hydrological fluctuations in the Southern Pyrenees appear to be in phase with the NAO reconstruction (Trouet et al., 2009) for the last millennium. In agreement with most of the IP (Moreno et al., 2011), arid conditions prevailed during the MCA, when reconstructed NAO values were predominantly positive (Trouet et al., 2009), as a result of a positive radiative forcing (Shindell et al., 1999) (Fig. 3). During the instrumental period, there is clear evidence of interannual precipitation variations in the W Mediterranean area, with the highest positive rainfall anomaly located over N Iberia at the mean time as high pressure is dominant in N Europe (Cullen and deMenocal, 2000). Negative rainfall anomalies during the MCA and vice-versa during the LIA for the W Mediterranean region have been also reproduced by gridded high-resolution precipitation reconstructions (Pauling et al., 2006) and ECHO-G model simulations (Liu et al., 2009). Widespread proxy evidences for this centennial-scale pattern also exist (Graham et al., 2011). In spite of the complex spatial heterogeneity and the influence of other climate variability patterns, the NAO strongly affects the precipitation events in most parts of the IP (Trigo et al., 2004). Furthermore, correlation maps between NAO and winter precipitation over the IP for the period 1950–1990 reproduced by models display particularly high negative values for the Southern Pyrenees within the IP (Gómez-Navarro et al., 2011).

Accordingly, hydrological patterns reconstructed from the reviewed lake sequences agree on centennial timescales, reproducing this transition from arid conditions during the MCA into higher humidity during the LIA (Fig. 3). However, lake records show an increase in water levels starting at ca. 1300 AD, whereas, although NAO values show a decreasing trend after the MCA, most negative values are not reached until 1600 AD. Increased water availability recorded in lakes during the period 1300–1600 AD might have been amplified by increased aquifer recharge, resulting from reduced evaporation and thus, more positive water balance driven by lower temperatures during the LIA (e.g. Cacho et al., 2010, and references therein). Glacier maximum development in both northern and southern slopes coincides with this coldest and most humid period of the LIA in the Southern Pyrenees (1600–1800 AD) and displays a similar pattern compared to other Mediterranean mountains, like the Apennines (Giraudi, 2005) and the Balkans (Hughes, 2010). At lower timescales, some of the relative maxima in precipitation recorded in the Capdella tree-ring rainfall reconstruction during the last ca. 600 yr correlate with negative reconstructed NAO-values.

Main phases of environmental change during the last millennium are synchronous at a regional scale with most of the Iberian Peninsula (Moreno et al., 2011) and also can be recognized across the Western Mediterranean area (Fletcher and Zielhofer, 2012). Exceptions to this pattern occur in the northwestern Atlantic shore of the IP (Ría de Muros, (Lebreiro et al., 2006; Galop et al., 2011) and Ría de Vigo (Kanner et al., 2012)) and also in South (Martín-Puertas et al., 2011), revealing an intra-regional complex variability in the hydrological conditions within the IP (Moreno et al., 2012). An antiphase behaviour in the hydrological signal, with wet MCA and dry LIA, has also been recorded in some eastern Mediterranean lakes (Roberts et al., 2011). This Mediterranean see-saw pattern might be related to the higher influence of the NAO in westernmost areas, like the Southern Pyrenees. Thus, the NAO appears to be one of the main climatic mechanisms influencing rainfall variability in the Southern Pyrenees at a centennial timescale during the last millennium. Further research will clarify a more precise timing a spatial variability of the reconstructed climate changes in the context of the IP.

6 Conclusions

Paleoclimatic records from the Southern Pyrenees, including lacustrine and marine-littoral sequences, tree rings, and records of glacier fluctuations, evidence a broadly consistent pattern at centennial to multi-decadal timescales for hydrological and thermal fluctuations during the last millennium, likely due to a common climate forcing.

Warmer and arid conditions prevailed during the MCA (up to 1300 AD) and colder and humid conditions, evidenced by higher lake levels, increased runoff and a change in dominant vegetation during the LIA (1300–1800 AD). Although the LIA is characterized by a complex internal structure, two major phases of environmental change can be identified in all the records within this period: (i) a transitional phase MCA–LIA, characterized by fluctuating, moist conditions and relatively cold temperatures (ca. 1300 and 1600 AD); and (ii) a second period, characterized by lower temperatures, higher runoff and more positive water balances, coinciding with maximum (recent) glacier advances in the second half of the LIA (ca. 1600–1800 AD)

A synchronous increase in temperature and aridity, coinciding with glacier retreat is found in all the records after 1800 AD, coinciding with the end of the LIA. A short-living return towards colder conditions and glacier stabilisation occurred during the late 19th–early 20th century, leading to warmer and more arid conditions afterwards.

Climatic oscillations reconstructed for the last millennium are consistent with other reconstructions from the Western Mediterranean area and glacier fluctuations are also in phase with other Western European (i.e. Alps) and Mediterranean mountains (e.g. Apennines and Balkans). A broadly consistent response to phases of low solar activity has also been found, generally characterized by colder and more humid conditions, unlike in other areas of the IP, and a clear pattern regarding the climatic response on volcanic eruptions

was not found. Hydrological changes in the Southern Pyrenees correlate with reconstructed NAO variability, which appears to be one of the main climate mechanisms influencing centennial-scale variations in precipitation totals during the last millennium.

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