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Research Paper

High-resolution patterns of palaeoenvironmental changes during the Little Ice Age and the Medieval Climate Anomaly in the northwestern Iberian Peninsula

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ABSTRACT

A high resolution core (9.7 yr cm^{-1}) from the Chao de Veiga Mol raised bog (NW Iberian Peninsula) was analyzed to identify plant macrofossils, estimate peat humification and calculate hydroclimatic indices based on current bog species, with the overall aim of determining the climate conditions associated with evolution of the bog during the Medieval Climate Anomaly and the Little Ice Age. These proxies, together with historical and climate data, proved to be good indicators of the changes in bog surface wetness.

Analysis: of the core led to identification of 9 different periods: two corresponding to the so-called Medieval Climate Anomaly (930 to 1345 AD, 1075–665 calibrated years before present [cal. yr BP]); four corresponding to the Little Ice Age (1345 to 1905 AD; 665–105 cal yr BP); and three corresponding to the last century (1905 to 2000 AD). The findings revealed a generally dry climate that lasted until the 14th century, followed by a transition to a long period with a more humid, but characteristically very variable climate, which ended at the beginning of the 20th century and was followed by a rapid transition to more humid conditions and finally, a change to drier conditions.

The Medieval Climate Anomaly was indicated by the abundance of dry-adapted mosses (*Leucobryum glaucum*, *Hypnum cupressiforme*) and characterized by warm dry conditions and high levels of peat humification, with alternating wet phases. The LIA period was dated by a large abundance of *Sphagnum* species (an indicator of wetness) and a gradual increase in the humification index. However, four different climate phases were differentiated in this period.

High-resolution reconstruction of the evolution of the CVM bog and the multiproxy approach have together enabled a more detailed identification of climatic variations in this area, which are generally consistent with the global models, as well as better definition of the elusive climatic oscillations in the last millennium and confirmation of the importance of local modulation of global models.

The study provides new information and a detailed chronology of climatic events that will help to refine local modulation of the climate evolution model in the still quite unexplored region of the NW Iberian Peninsula, a key area for understanding the paleoclimatic dynamics in SW Europe.

1. Introduction

Peat-based palaeoclimate proxies have been used to reconstruct Holocene patterns of hydroclimatic variability in many parts of the world (e.g. Payne and Blackford, 2008; Loisel and Garneau, 2010; Castro et al., 2015). Most multi-proxy peatland palaeoclimate studies are based on the

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following assumptions: (i) plant macrofossils and the degree of peat humification can be used to reconstruct records of change in bog water table positions, and (ii) bog surface wetness (BSW) is primarily controlled by the prevailing balance between precipitation and evapotranspiration, as ombrotrophic mires receive their water and nutrition from meteoric sources (Amesbury et al., 2011). Both of the above-mentioned proxies have been used to study the major climate changes in the early and middle Holocene.

Climate changes during the last millennium have been identified by historical documents (classic literature, administrative and ecclesiastical records) and marine, lake and river sedimentological proxies. Due to the scarcity of natural archives with sufficient resolution, the chronology of the main climate episodes in southwestern Europe during the last millennium, is not well delimited. This particularly applies to the Medieval Climate Anomaly (MCA), which occurred between the 11th and 13th centuries (e.g. Lamb, 1965), and the Little Ice Age (LIA) which occurred between 1350 and 1850 AD (Jones and Bradley, 1992). Nonetheless, available data suggest a high level of regional variability in the Iberian Peninsula (Lebreiro et al., 2006; Moreno et al., 2012; Abrantes et al., 2017; Oliva et al., 2017). The LIA is usually considered a cold climate period subsequent to the high temperatures in the MCA. This model was created considering the northern European glaciers and is consistent with global patterns; however, the model remains to be validated for southern Europe and for more local scales.

The Iberian Peninsula can be considered a hotspot in terms of regional modulation of global climate models (Giorgia and Lionello, 2008). The peninsula has a unique planetary position situated almost between two continents, at the southwest end of the Eurasian continent and very close to the African continent, and between the Atlantic Ocean and the Mediterranean Sea (Martín and Olcina, 2001). Under these conditions, wind flows from the west and southwest, and the climate is modified by the influence of the Gulf Stream. The influence of the Mediterranean Sea in the east increases the climate gradient. The proximity to the African continent modifies climate patterns, especially because of the injection of continental tropical air masses. In other words, there is a highly dynamic balance between diverse and opposing influences, i.e. oceanic and continental, and temperate and subtropical influences. In addition, the extreme compactness of the territory, together with the high mean elevation (650–700 m a.s.l.) and several peripheral mountain alignments, endows the Iberian territory with unique climate characteristics and dynamics. All of this occurs within a context of general atmospheric circulation defined in the north by the dominant winds from the west and southwest, and in the south by subtropical anticyclones, both with seasonal migrations.

A recent review of Oliva et al. (2017) analysing a large number of palaeoclimate Iberian records, has enabled construction of a robust and coherent general framework for climate evolution in the Iberian Peninsula during the last millennium.

There is now a need to validate, adjust and strengthen this model according to local modulations, to which such a dynamic and heterogeneous climatic territory may be prone.

The model must be improved in two ways: (i) by considering the geographical distribution of the data, as although a large number of records are available for the Pyrenees and Cantabrian range, they are much scarcer in the northwest and southwest of the Iberian Peninsula; and (ii) by locating and studying natural archives whose diagenesis and rates of evolution enable improvement of the sensitivity, resolution and stability of the model for periods as short as the last millennium, and in particular the LIA.

The present study aims to examine climate evolution in the study area during the last millennium, by using a high resolution record and a multi-proxy approach and paying particular attention to the LIA. The study will attempt to provide new information that will help to refine local modulation of the regional models established in the Iberian Peninsula, as an area of special relevance in the context of the northern hemisphere.

2. Study site

The Chao de Veiga Mol (CVM) raised bog (43°32′34.4″N, 7°30′13.41″W; Pontevedra-Pombal et al., 2019) is located in the Xistral Mountains (NW Iberian Peninsula) at an elevation of 700 m a.s.l. and 15 km south of the coast of the Bay of Biscay, occupying a palaeo-glacial cirque (Fig. 1). It consists of a central raised bog of 2.1 ha, surrounded by fens (3.9 ha). The lithology is dominated by two-mica granite. The mean annual temperature is 7.0 °C and the mean annual rainwater precipitation is 1700 mm (Pontevedra-Pombal et al., 2014). The rainfall gradient is close to 100 mm per 100 m altitude. These values define a cool and very humid environment. The seasonality of precipitation is the lowest in the Iberian Peninsula.

The bog includes different microhabitats, which are mainly determined by the microtopography and the water table level and which shelter heath and grass plant communities.

The CVM bog be characterised as follows: (i) it has the highest known resolution rates of Iberian peatlands (a mean value of 1.26 mm/yr or 7.9 yr/cm in the first 1000 years; Pontevedra-Pombal et al., 2017); (ii) it is highly sensitive to climate changes because it lies close to the coast, with no barriers to mitigate the impact of the storms; (iii) it is located in the north-west of the Iberian Peninsula, an area of particular value in the context of the local modulation of global change (Gutiérrez and Pons, 2006); and (4) it has an age-depth model of high resolution (Pontevedra-Pombal et al., 2019).

3. Material and methods

3.1. Present plant cover and hydrological preferences of the plant species

Floristic inventories were carried out throughout 2013 (in February, April, August and November), in 33 plots (1 m^2). The plots were selected according to physical and chemical properties such as the groundwater table, temperature (°C), pH value, oxygen concentration (ppm) and redox potential (mV). The values of these properties were used to cluster the plots from drier to wetter areas, as follows: (i) dry hummock, (ii) wet hummock, (iii) lawns, (iv) damp lawns, and (v) waterlogged pools. In the field, we described the floral composition and took photographs for analysis of floral cover.

We selected those species covering more than 10% in any plot to carry out the statistical analysis. Analysis of their hydroclimatic preferences of the selected species was performed on the basis of previous and our own data (Dupont, 1986; Rodwell, 1998; Castro et al., 2015; Romero Pedreira, 2015). The relationships between species were examined by discriminant analysis (DFA) implemented in IBM SPSS Statistics 20 software. The DFA anabled us to create groups of species that grow in similar environments.

To create the Hydroclimatic Index, we used the DFA-derived groups together with knowledge of the ecohydrobiological behaviour of these species. The values of the index vary from 1 to “n”, where 1 is associated with species growing in waterlogged conditions and “n” with species growing in dry conditions.

The historical hydrological changes in the bog were assessed on the basis of the present ecological analysis, historical climate data (Font Tullot, 1988; Fernández-Cortizo, 2005; Losada, 2008), publications on the climate of Galicia (Carballeira et al., 1983) and data from weather stations in the area surrounding the bog (www.meteogalicia.es).

3.2. Peat samples

A peat monolith of depth 845 cm was obtained, from the center of the raised area. The top 100 cm was extracted with a Wardenaar corer, and the fresh monolith was sliced into 1 cm sections in the field. The deeper samples were obtained with a Byelorussian corer and sliced into 2 cm sections. The top 135 cm was analyzed. Four sub-samples were prepared per sample. One was frozen at −10 °C, the second was stored at 4 °C, the third was lyophilized and the fourth was dried at 105 °C. The latter two

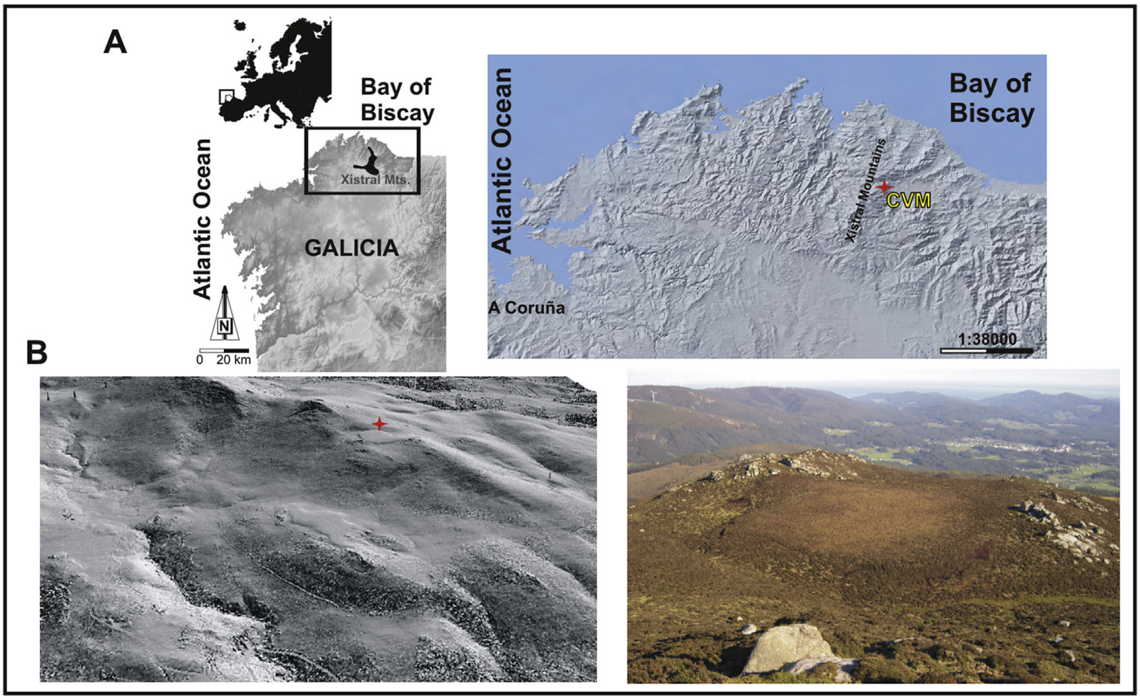

Fig. 1. (A) Location of the study area. (B) General view of the CVM raised bog.

types of sample were finely milled in an agate mortar, homogenized and stored in a cool dark place.

3.3. Extraction and analysis of plant macrofossils

Sub-samples of 5 cm^3 of fresh peat were extracted by a standard procedure (Mauquoy et al., 2010). Sieved residues were suspended in Petri dishes with a thin layer of distilled water and analyzed to determine the relative abundance of species remains, by the quadrat and leaf count technique (Mauquoy et al., 2010). *Sphagnum* leaves ($n > 100$) were analyzed by microscopy ($\times$ 40–400 magnification). Plant remains were identified to the lowest possible taxonomic level by comparison with a reference collection (of herbarium specimens and microscopic slides of different parts of the vegetative apparatus and reproductive structures of the species constituting the current vegetation of this and other Iberian and European bogs). Keys and descriptions reported in various papers were also used (Grosse-Brauckmann and Streitz, 1992; Wójcicki et al., 2006; Mauquoy and van Geel, 2007; Cappers and Neef, 2012; Souto et al., 2017). Bryophytes were identified by consulting the *Flora Briofítica Ibérica* (Casas et al., 2006; Guerra and Ros, 2006). The stratigraphic diagrams were generated with C2 software (Juggins, 2011).

3.4. Hydroclimatic indices

The macrofossil hydroclimatic indices were generated using two variations of the method proposed by Dupont (1986):

(i) The Dupont Hydroclimatic Index (DHI) (Dupont, 1986), which includes weighted values for dicotyledonous remains (Daley and Barber, 2012).
(ii) A new Hydroclimatic Index adapted to CVM (HI-CVM), for which the current species of CVM were separated into 5 groups resulting from the discriminant analysis of their hydrological preferences. Each species group was given a hydrological value of between 1 and 5, representing conditions ranging from wet to dry.

The following equation was used to calculate both indices (DHI and HI-CVM) (Daley and Barber, 2012):

$$\text{DHI and HI} - \text{CVM} = \frac{\sum_{i=0}^{n} x_i w_i}{\sum_{i=0}^{n} x_i}$$

where:

x = species abundance (%)
w = species hydrological value (see Table 2)
i = a given sample level in the core

3.5. Humification analysis

The subsamples were dried at 30 °C for 1 week before being ground in a mill. An aliquot (0.01 g) of this material was treated by alkaline extraction (with 8% NaOH), and the extract was filtered to remove suspended solids. A 50 mL aliquot of the filtrate was then diluted with 50 mL of distilled water (Blackford and Chambers, 1993). Four hours after the initial mixing, the percentage of light transmission at 540 nm was measured in a Jenway 6305 spectrophotometer. The raw data were normalized and detrended (Blundell and Barber, 2005). The results were expressed as the percentage light transmission (T_{av}). Low percentages of light transmission denote well-humified peat, and high percentages denote poorly humified peat (Blackford and Chambers, 1993). The extractions were performed in triplicate, and the spectrophotometric measurements were repeated three times for every sample.

To correct for dilution of the mineral content of the peat samples, we calculated the corrected transmittance (T_c), following the method of Payne and Blackford (2008). To modulate the short frequency fluctuations and highlight the trends over longer periods, the 3-point moving average of T_c values were calculated (T_{mov}) (Castro et al., 2015).

The method proposed by Chambers et al. (2011) was used in order to remove the effect of peat evolution with increasing age and the different dynamics in the acrotelm and catotelm. The humification index (HuI) is the residual time series, obtained by fitting a Structural Time Series model. According to Harvey and Shephard (1993), we defined the original time series as being composed by a time-varying trend and an irregular component. To establish the standard state-space representation of our time series, we used the Kalman Filter to subtract the time-varying trend component from the series. Finally, we obtained the residual term as the difference between the real time series and the estimated trend component for each time interval. Low HuI values indicate high levels of humification.

3.6. Peat core dating

Twenty-two peat samples, devoid of woody debris and with the rootlets removed, were sent to the Ångström Laboratory, Div. of Ion Physics, ^{14}C-Lab (Uppsala University, Sweden) and to the Center for Applied Isotope Studies (University of Georgia, USA) for radiocarbon AMS dating. The calibration ^{14}C dates are reported elsewhere (Pontevedra Pombal et al., 2019). Ages are expressed as calibrated years before present (cal. yr BP), and they were adjusted to the year of sampling (2007) by adding the difference between 2007 and 1950 to all estimated ages.

To improve the resolution of the age model established in the peatland for the last 1000 years, radionuclide data were used together with radiocarbon data. The first thirty surface samples of CVM core were used to determine fallout ^{137}Cs, ^{210}Pb, ^{214}Pb and ^{241}Am activity concentrations. The concentrations were determined at the Consolidated Radioisotope Facility (CoRiF) at Plymouth University (UK) following the methodology described in detail by Appleby (2002). The Constant Rate of Supply (CRS) model was then applied in order to build the ^{210}Pb age-model (Pontevedra-Pombal et al., 2019).

Bacon age-modelling software (Blaauw and Christen, 2011) was used to construct an age-depth model based on all ^{210}Pb and ^{14}C dates. Details of the CVM age/depth model are reported elsewhere Pontevedra-Pombal et al. (2019) (Fig. 2).

4. Results

4.1. Ecological preferences of the plant species

For the statistical analysis, we selected the 17 species that each provided more than 10% of the cover in any plot. Analysis of the data by DFA revealed significant differences (Wilks Lambda test, $p < 0.01$) in the distribution of the cover (Fig. 3). Discriminant function 1 explained 66% of the variance and function 2 explained 20.4% of the variance.

Comparison of the DFA results with the existing hydrobiological data generated 5 groups (Table 1). Together these groups represent a hydroclimatic index for the CVM flora (Fig. 3).

These findings are consistent with those obtained in a previous study (Castro et al., 2015) of the ecological profiles of the mire species in the NW Iberian Peninsula.

4.2. Macrofossil analysis

Most of the plant macrofossils identified are also important components of the present flora in the CVM bog. The distribution of the flora along the core is shown in Fig. 4.

We identified nine bryophytes, five of which belong to the genus *Sphagnum*. The most abundant of these are from the Section Acutifolia (*S. capillifolium/S. rubellum*); *S. papillosum* and *S. tenellum* are less frequent; and *S. cuspidatum* is rare or occasional. Other bryophytes include the mosses *Leucobryum glaucum*, *Hypnum cupressiforme* and *Racomitrium lanuginosum* and the liverwort *Odontochisma sphagni*.

Within vascular plants, we identified *Molinia caerulea* (rhizomes, leaves and caryopses), *Eriophorum angustifolium* (rhizomes, leaves and achenes), *Carex durieui* (rhizomes, leaves and achenes), *Juncus bulbosus* (seeds), *Drosera rotundifolia* (seeds), *D. intermedia* (seeds), *Erica mackaiana* (wood, shoots, flowers, seeds and leaves), *Calluna vulgaris* (seeds and shoots) and *Betula pubescens* (samaras). Three vascular plant species (*E. mackaiana, M. caerulea* and *C. durieui*) and *Sphagnum* Sect. *Acutifolia* (*S. capillifolium/S. rubellum*) were always present throughout the bog profile, although the abundance varied widely (Fig. 4).

On the basis of macrofossil taxa composition, we differentiated 9 zones throughout the CVM profile (Fig. 4):

In the first (deepest) zone (CVM-a, 135–119 cm deep), the relatively high abundance of *L. glaucum* was remarkable as this species was absent in the rest of the core. Likewise, at the beginning of this period we

A)

material	Depth (cm)	Age ^{14}C (B.P.)	Error ^{14}C age (BP)	Age ranges (cal. yr BP)	Lab. Code
peat	14.5	modern			
peat	26.5	60	20	33-253	UGAMS-8991
peat	51.5	270	20	285-426	UGAMS-8992
peat	101,5	790	25	675-738	UGAMS-8993
peat	151	1220	25	1064-1241	UGAMS-8994
peat	201	1640	25	1418-1610	UGAMS-8995
peat	251	2100	25	1999-2137	UGAMS-8996
peat	301	2850	25	2878-3039	UGAMS-8997
peat	425	3890	25	4248-4413	UGAMS-8998
peat	513	4520	35	5048-5307	UGAMS-25538
peat	527	4870	25	5587-5647	UGAMS-25539
peat	551	5200	25	5916-5991	UGAMS-9236
peat	601	5640	30	6321-6490	UGAMS-9002
peat	637	6160	30	6972-7162	UGAMS-9003
peat	651	6320	30	7172-7308	UGAMS-9004
peat	683	6980	30	7721-7927	UGAMS-9005
peat	701	7010	30	7786-7935	UGAMS-9006
peat	749	7740	30	8444-8589	UGAMS-9007
peat	805	8040	30	8778-9021	UGAMS-9008
peat	833	8550	30	9493-9547	UGAMS-9009
peat	846.25	8640	55	9522-9742	UGAMS-9010

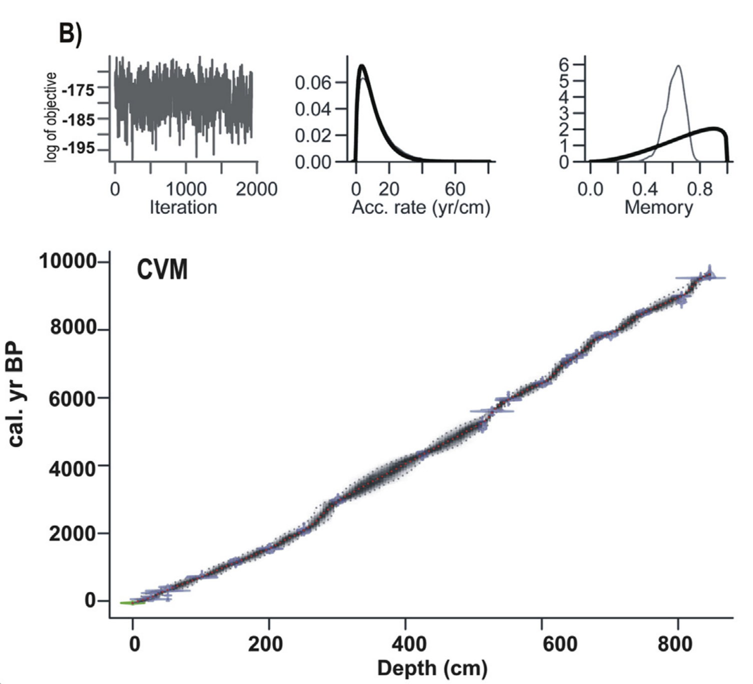

Fig. 2. Age-depth model based on ^{14}C and ^{210}Pb results and produced with BACON software. (A) ^{14}C data; (B) calibrated ^{14}C (blue) and ^{210}Pb (green) dates, and the age-depth model where grey-scales indicate all possible age-depth models, and dotted lines indicate the mean and 95% confidence ranges (from Pontevedra-Pombal et al., 2019).

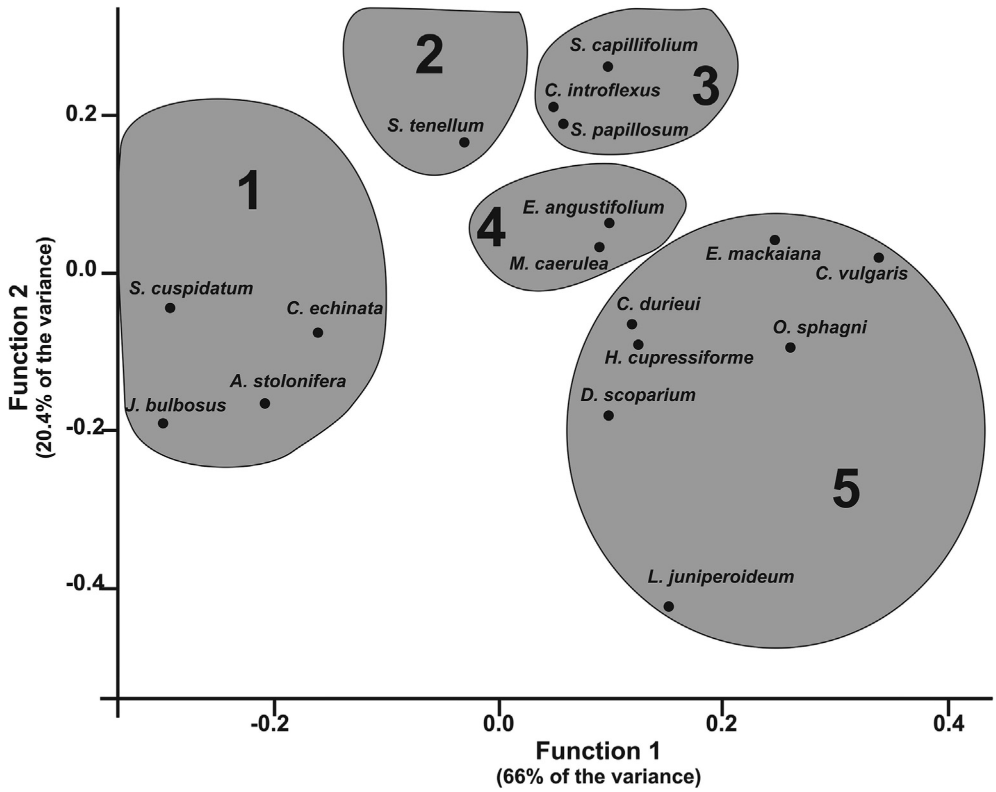

Fig. 3. Plot of discriminant scores (DFA) for Function 1 versus Function 2, discriminating the five species clusters related to bog hydrology. Function 1 explains 66% of the variance (waterlogged–dry habitats) and Function 2 explains 20.4% of the variance (tolerance to water table fluctuations).

Table 1
Hydroecological groups of plant species currently present in the CVM, based on ecological preferences. The hydrological values for the species used to calculate the Hydroclimatic Index are shown.

Hydroecological group	Species	Hydrological value
Species of waterlogged habitats	*S. cuspidatum, J. bulbosus, C. echinata, A. stolonifera*	1
Species adapted to fluctuating water table levels but with preference for damp habitats	*S. tenellum*	2
Species growing close to the pools	*S. papillosum, S. capillifolium, C. introflexus*	3
Species of wet lawns	*E. angustifolium, M. caerulea*	4
Species of the dry heaths	*C. duriaeui, E. mackaiana, C. vulgaris, O. sphagni, D. scoparium, L. glaucum, H. cupressiforme.*	5

Table 2
Species weightings (w) used in reconstruction of the Dupont Hydroclimatic index (DHI) and the CVM Hydroclimatic Index (HI-CVM).

Taxon	DHI weighting	HI-CVM weighting
Calluna vulgaris	8	5
Carex duriaei	[a]	5
Dicranun scoparium	[a]	5
Eriophorum angustifolium,	2	4
Erica mackaiana/tetralix,	8	5
Hypnum_cupressiforme	[a]	5
Juncus bulbosus	[a]	1
Leucobryum_glaucum	[a]	5
Molinea caerulea	[a]	4
Monocot leaves and stem undifferentiated	7	[b]
Monocot node/root undifferentiated	7	[b]
Monocot roots, undifferentiated	7	[b]
Odontochisma sphagni	8	5
Racomitrium lanuginosum	6	5
Sphagnum papillosum	3	3
Sphagnum Sect. *Acutifolia*	6	3
Sphagnum Sect. *Cuspidata*	1	1
Sphagnum tenellum	2	2
UOM	8	[b]
Wood	8	[b]

[a] New index derived for these species in the present study.
[b] According to our analysis these species do not have any hydrological indicator value. UOM: unidentified organic matter.

observed the largest number of *E. angustifolium* macrofossils for the whole profile, although this species disappeared in the second half of this zone and then reappeared in the following years.

The first half of the second zone (CVM-b, 119–91 cm deep) was characterized by a high abundance of *M. caerulea* and *C. duriaeui*. The presence of *D. rotundifolia* seeds was also noteworthy in this period.

In the following four zones (CVM-c,d,e,f, 93–31 cm deep), there was a significant increase in the presence of *Sphagnum* species and *J. bulbosus*.

In CVM-c (90.5–66.5 cm deep), *D. rotundifolia* seeds were also abundant and then disappeared in the remaining layers.

In the following zone (CVM-d, 67–55 cm deep), there was a decrease in the presence of *S. tenellum* and *Sphagnum* Sect. *Acutifolia* (*S. capillifolium/S. rubellum*) and an increase in *S. papillosum*.

In CVM-e (55–46 cm deep), there was a general decrease in the abundance of *Sphagnum* macrofossils and an increase in *J. bulbosus*, as well as *Drosera intermedia* seeds, which were only recorded in this zone.

J. bulbosus, *S. tenellum* and *S. papillosum* were most abundant in CVM-LIA-f (47–31 cm deep), in addition to *S. cuspidatum* and *B. pubescens*, which were only recorded in this zone.

In the upper 31 cm layer, *Sphagnum* macrofossils were absent or

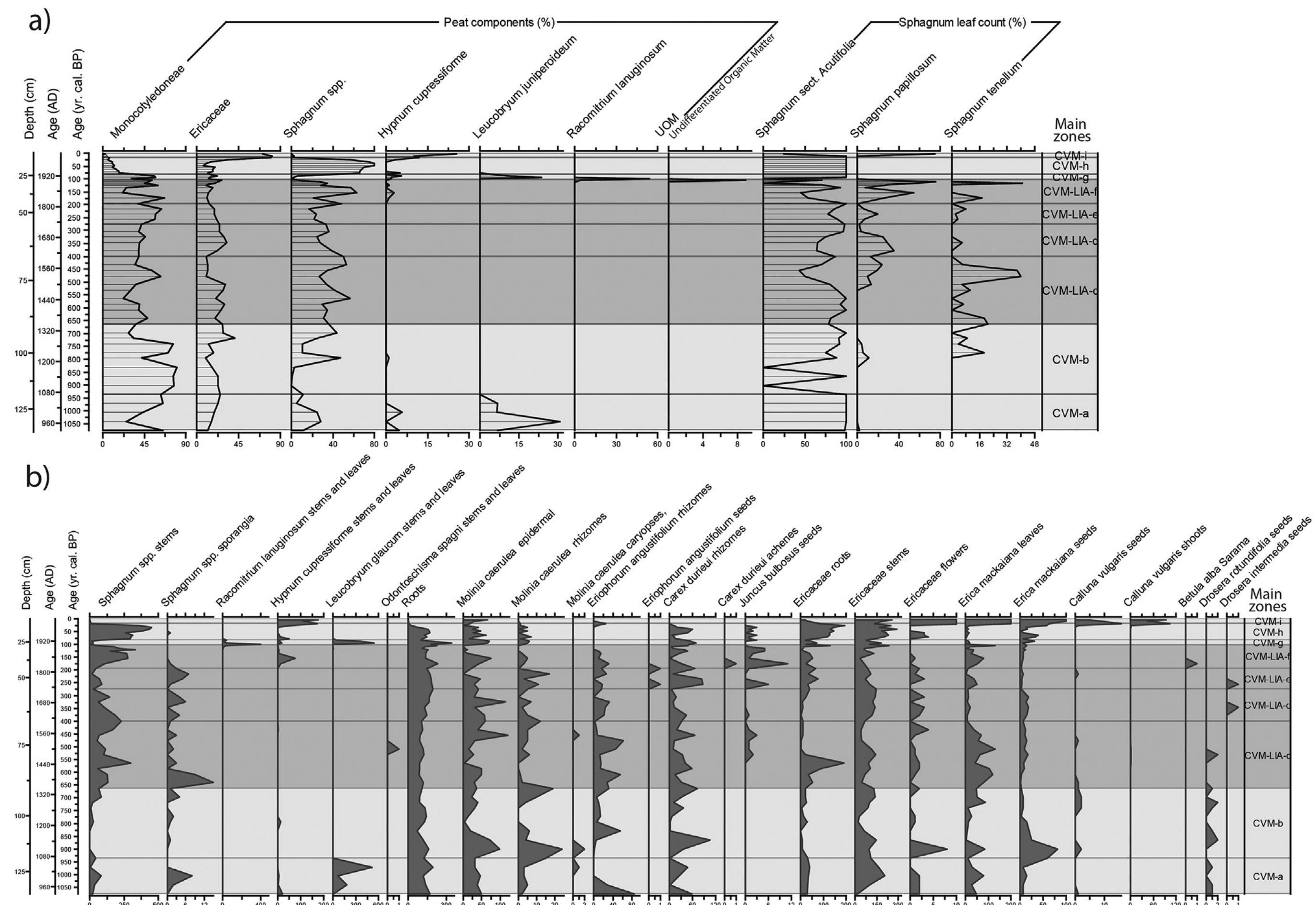

Fig. 4. CVM plant macrofossil diagram: (a) main plant groups and *Sphagnum* species (expressed as a percentage); (b) vascular plant species and mosses (expressed as total numbers).

scarce, except for *Sphagnum* Sect. *Acutifolia*. In CVM-g (31–23 cm deep), *R. lanuginosum* and *L. glaucum* were very abundant.

These two species disappeared in the following zone (CVM-h, 23–5 cm deep), in which the only recorded mosses were *Sphagnum* Sect. *Acutifolia* and *H. cupressiforme*.

In the top layer (5–0 cm deep) of the core, most of the plant remains corresponded to *E. mackaiana*, *C. vulgaris* and *H. cupressiforme*.

4.3. Hydroclimatic index (HI)

Most of the species weightings for the hydroclimatic indices derived from the ecological preferences of the present flora in CVM (section 3.1) are new, and only those obtained for *S. tenellum*, *S. papillosum* and *Sphagnum* Sect. *Cuspidata* (Table 2) are consistent with those reported by Dupont (1986). The main differences between our weightings and those of Dupont (1986) are related to macrofossils not identified to species level (monocots, UOM, wood), as they may correspond to groups of species with different hydrological preferences. We therefore consider that these unidentified macrofossils do not have any value as hydrological markers, contrary to the suggestion of Dupont (1986).

Fig. 5 shows the results of the use of both hydroclimatic indexes, DHI and HI-CVM. The positive values represent an increase in bog surface wetness (BSW), while negative values indicate dry conditions. Although both indices generally show similar trends ($r = 0.716$; $p < 0.0001$), there are also some discrepancies due to the different criteria used to calculate the indices, as already mentioned.

In our analysis, wet conditions were mainly associated with the presence of *J. bulbosus*, *D. rotundifolia* and *S. tenellum,* and dry conditions were associated with the presence of *H. cupressiforme* and *C. vulgaris*. Different species combinations caused variations throughout the core.

4.4. Humification index

The results of the peat humification analyses are presented in Fig. 6 as the moving average (T_{mov}) of raw data of the percentage of light transmission (T_{av}) corrected for the inorganic ash content (T_c). Detrending raw humification values are necessary to correct for diagenetic effects on the climate proxy signal (Blundell and Barber, 2005). Peat age was highly significantly and negatively correlated with T_{av} and T_{mov} ($r = -0.710$ to -0.760; $p < 0.0001$).

In the CVM core, two zones with different dynamics were observed; the acrotelm (upper 50 cm), in which autogenic decay occurs rapidly, and the catotelm (50–135 cm), in which peat decay is stabilized. The transition zone between the acrotelm and catotelm was clearly established from the change in soil density and the inorganic ash and carbon content (Pontevedra-Pombal et al., 2019). For each zone, we calculated a different linear regression and used the detrended humification index (HuI) (Fig. 6). A series of significant shifts from relatively high HuI (related to wet events) to low HuI (related with dry events) were recorded. Levels with high HuI at 9–21 cm, 35–45 cm, 62–93 cm and 127–135 cm and relatively low HuI levels at 23–33 cm, 47–59 cm, 95–100 cm and 107–127 cm were recorded.

5. Discussion

Hydroclimatic indices and the humification index, considered proxies for climate data, showed a high level of consistency and coherence,

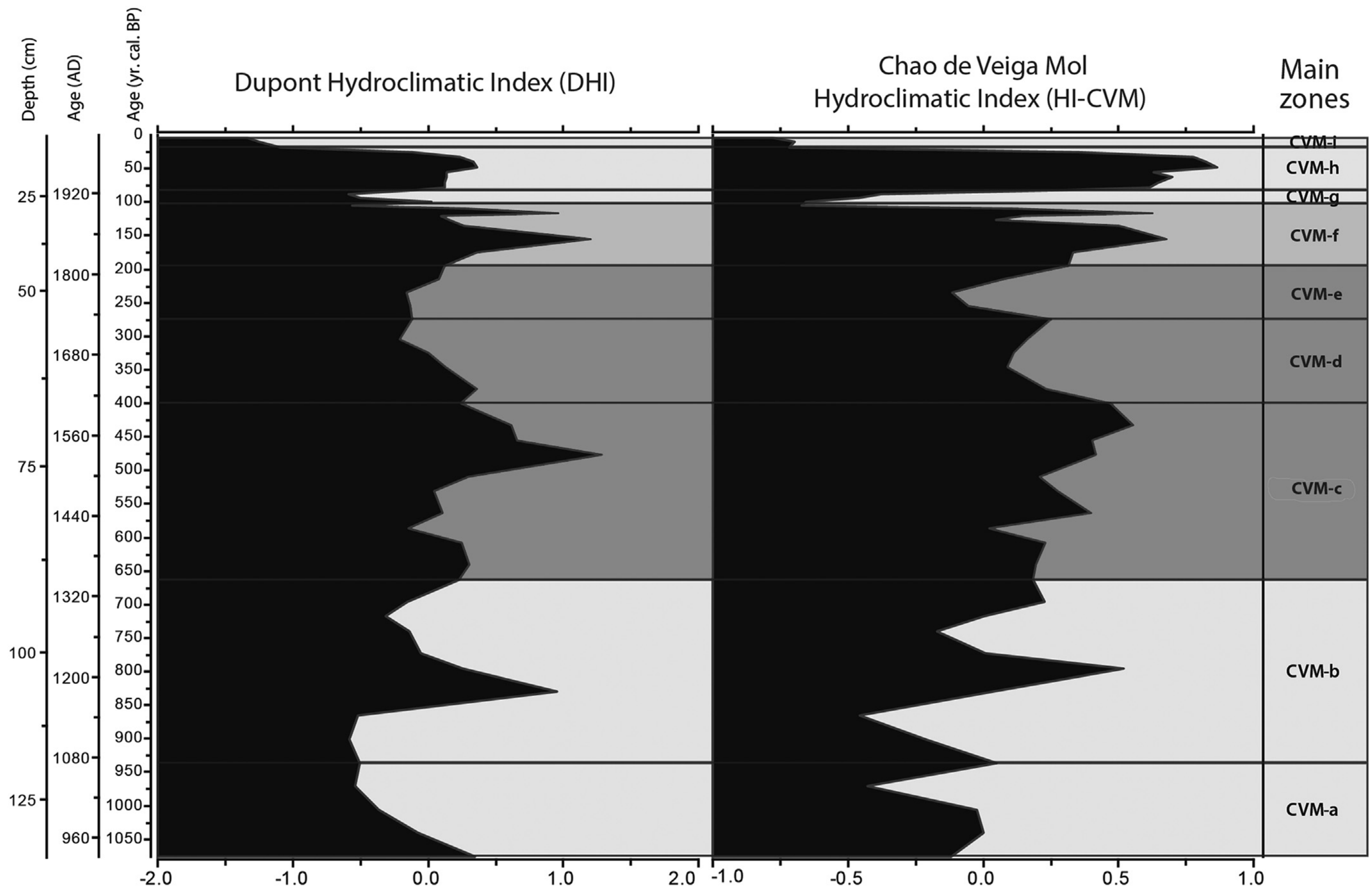

Fig. 5. Hydroclimatic indexes for CVM: Dupont Hydroclimatic Index (DHI) and Chao de Veiga Mol Hydroclimatic Index (HI-CVM). Main phases: dark grey = wet phase, light grey = dry phase.

although some discrepancies were also observed, mainly in the 20th century AD. The causes of these differences can be attributed to weighting of the wetness values attributed to some species with wide hydroecological distributions. The humification index (HuI) was significantly and positively correlated with the DHI hydroclimatic index ($r = 0.649$; $p < 0.0001$), but much more significantly with the HI-CVM hydroclimatic index ($r = 0.803$; $p < 0.0001$).

The temporal differences in the composition of peat-associated species throughout the bog profile are very similar to the spatial variation in current plant cover composition, in relation to hydrological gradients. The hydrological preferences of *Sphagnum* species are currently consistent with those outlined by Clymo (1963): thus, *S. cuspidatum* is the dominant species in permanent waterlogged habitats; *S. tenellum* mainly grows in seasonally waterlogged areas; *S. papillosum* grows around pools and hollows; and *Sphagnum* Sect. *Acutifolia* (*S. capillofolium*, *S. rubellum*) prefers less wet habitats, such as small hummocks.

It has been suggested that the presence of *R. lanuginosum* and *H. cupressiforme* is a good indicator of changes in the climate towards drier conditions (Ellis and Tallis, 2003). In the CVM, a significant increase in the abundance of these two species was detected in the last century.

On the basis of the analysis of the aforementioned proxies, and of climate data from historical sources and from weather stations from the surroundings of CVM, we performed a reconstruction of the hydrological conditions of this bog during the last 1000 years of its development (Figs. 7 and 8).

The periods identified in the Chao de Veiga Mol bog (Fig. 7) are generally consistent with regional patterns (Luterbacher et al., 2005): drier climate up to the 14th century; a rapid transition to more humid climates during a highly variable period that lasted until the mid–late 19th century, and a rapid transition to a less humid climate during the last century.

5.1. Medieval Climate Anomaly in the CVM (930–1345 AD, 1075–665 cal yr BP; zones: CVM-a,b)

The Medieval Climate Anomaly (MCA) refers to a period of climate history during which temperatures in Europe and neighbouring regions of the North Atlantic are believed to have been comparable to, or even to have exceeded, those of the late 20th century. This period is conventionally believed to have occurred between approximately 900 and 1300 AD (Easterbrook, 2016).

The reconstructions, of greater or lesser resolution, of the climatic evolution during the MCA in the Iberian Peninsula have shown that there is no univocal answer. Clear regional variations are observed in the data, which are mainly marine and lake records (Moreno et al., 2012). In the northwest, warm and humid conditions dominated, while in the rest of the Iberian Peninsula, warm and dry or even arid conditions dominated. Moreno et al. (2012) mainly attributed these conditions to a stable positive phase of the North Atlantic Oscillation (NAO), while Alvarez et al. (2005) proposed that these climatic conditions (ca. 252–1368 AD) in the northwest are due to a negative phase of the NAO. However, a recent model that reconstructs the evolution of the NAO in the last millennium, proposes, that there has not been a persistent positive NAO phase during the whole MCA (Ortega et al., 2015).

The following periods were defined for this epoch in the CVM core:

CVM-a (930–1070 AD, 1075–935 cal yr BP) was defined as a dry period because of the abundance of *L. glaucum* (at present is significantly correlated with dry habitats), the high hydroclimatic indices and the high level of peat humification. This is consistent with a previous

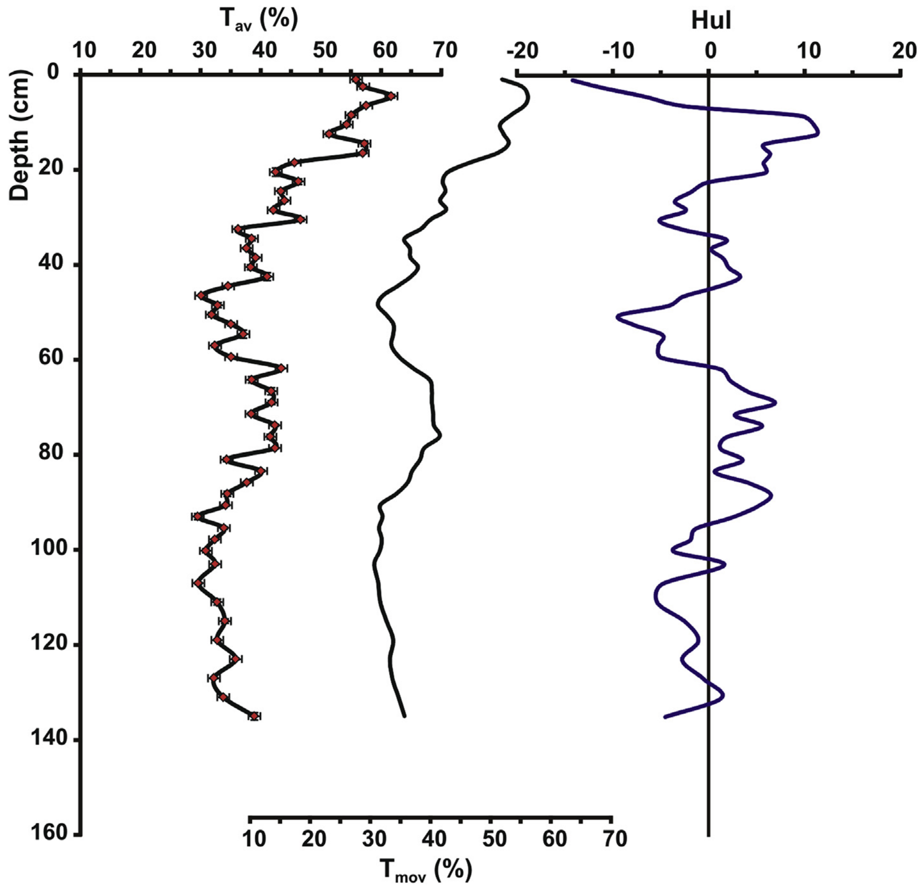

Fig. 6. Peat humification profile for the CVM core: (T_{av}) average light Transmission; (T_{mov}) percentage of light transmission corrected for the inorganic ash content and using a 3-point moving average; (HuI) detrended function for humification data.

consideration as a dry and relatively warm period on the basis of historical climate data (Losada, 2008). The conditions of this climatic phase are similar to those observed in the rest of the Iberian Peninsula (Moreno et al., 2012).

The ocean temperature in western Europe during this period (Fig. 8) was higher than average (Eiríksson et al., 2006), there was an increase in the surface temperature of the snowy mantle of Greenland (Kobashi et al., 2011) and also a significant increase in the summer temperature in Europe (Luterbacher et al., 2016).

CVM-b (1070–1345 AD, 935–665 cal yr BP). At the local or supra-local level, this period has been characterized by a warm humid climate (700–1300 AD; Alberola Romá, 2014). According to our findings, the climate in this period was not uniform, but had alternating wet and dry phases, with the dry phases predominating. The proxies analyzed indicate the existence of these intermediate phases of changeable climate, as shown by the variations in the abundance of the most representative species of this period, i.e. *M. caerulea*, *C. duriaeui*, *E. angustifolium* and *D. rotundifolia*, as well as in the values of the hydroclimatic index and peat humification levels.

So far, analysis of palaeoenvironmental records in the Iberian Peninsula established a single phase of wet and warm conditions in the northwest versus the hot and dry conditions of the rest of the Iberian Peninsula (Moreno et al., 2012). The characteristics of CVM enable us to identify two warm phases during MCA, one dry and one wet stage. The latter may represent a phase considered by Muñoz Sobrino et al., (2014) to have transitional characteristics associated with an increase in storminess, caused by the strengthening of the teleconnection pattern of the Eastern Atlantic (EA).

Our findings are consistent with documentary sources (Losada, 2008) showing that the 12th and 13th centuries were generally warm and rainy in the NW Iberian Peninsula, with some dry years such as 1172, 1220 and 1300 AD. Other studies on the Iberian Peninsula have also reported higher temperatures (Martinez-Cortizas et al., 1999) and wet-warm conditions, with some dry episodes (Benito et al., 2008) during medieval times. Similarly (Fig. 8), the summer temperature increased in Europe (Luterbacher et al., 2016) as did the ocean temperature in western Europe (Eiríksson et al., 2006).

The CVM record is consistent with global reconstructions (Mann et al., 1999; Briffa, 2000) documenting warmer conditions between the 12th and 14th centuries, probably related to an increase in solar irradiance (Fig. 8) (Bard et al., 2000; Crowley, 2000), persistent La Niña-like tropical Pacific conditions, a warm phase of the Atlantic Multidecadal Oscillation, and a more frequent positive phase of the North Atlantic Oscillation (Seager et al., 2007).

5.2. Little Ice Age in CVM (1345–1905 AD, 665–105 cal yr BP; zones: CVM-c,d,e,f)

Although the LIA was mainly cold, the rainfall patterns and temperature vary throughout the period. The onset of the LIA in the CVM sequence is marked around ca. 1345 AD by a high abundance of *Sphagnum* wetness indicator species (*S. tenellum* and *S. papillosum*) and a gradual increase in HuI. This initial date is consistent with a phenomenon of substantial winter cooling, with increased snow cover and the extent and duration of frozen water bodies in the winter months, described for the whole of Europe (Pfister et al., 1996). The end is dated to 1905 AD when these species disappeared and were replaced by other mosses that indicate drier conditions (*R. lanuginosum* and *H. cupressiforme*).

There is some controversy regarding the onset of the LIA. The most recent (Oliva et al., 2017) dated the commencement of the LIA at ca. 1300

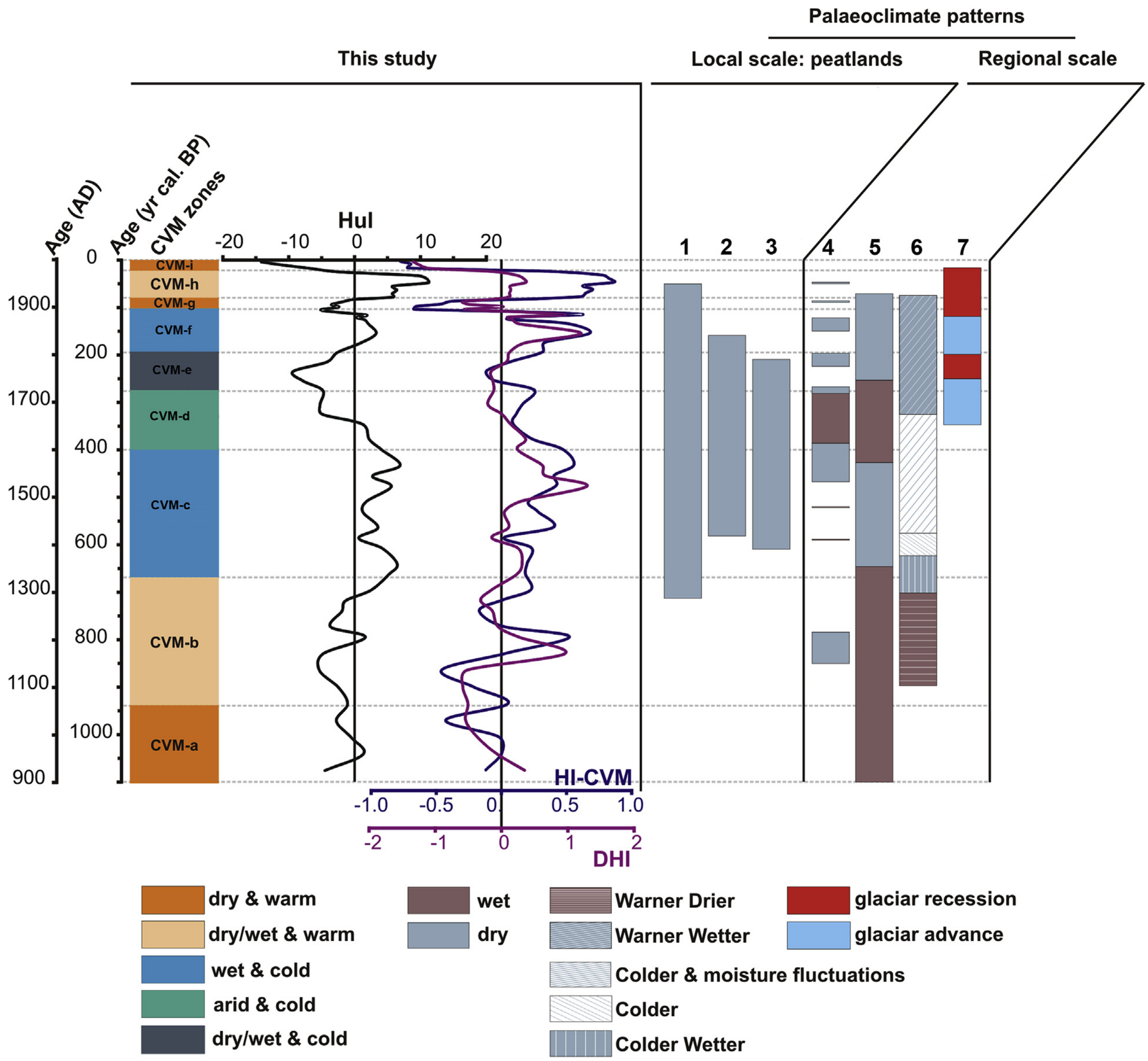

Fig. 7. Relationship between temperature and humidity data and other local and regional climate periods identified "CVM data" are a summary of the records of plant macrofossil analysis, humification index and hydroclimatic index in Chao de Veiga Mol bog. "Local climate patterns" indicate studies conducted in other bogs of the Xistral mountains (NW Iberian Peninsula) with other different proxies (1–Castro et al., 2015; 2–Schellekens et al., 2011; 3–Martínez-Cortizas et al., 1999). "Regional climate patterns" indicate paleoenvironmental studies carried out in the Iberian Peninsula with different records and different proxies (4–Benito et al., 2003; 5–Riera et al., 2002; 6–Morellón et al., 2008; 7– González-Trueba et al., 2008).

AD. However, previous studies (Font Tullot, 1988; Alberola Romá, 2014) do not consider that the LIA lasted into the 14th and 15th centuries in the Iberian Peninsula as the cold signal is low. However, the same studies report a decrease in temperature and an increase in rainfall. Font Tullot (1988) described the 15th century as one of the periods with most rainfall and least drought in the history of Spain. Other reconstructions of the LIA in the NW Iberian also suggest a much later onset and a more limited extension, focused on the 16th and 17th centuries (Muñoz et al., 2007). However, this reconstruction may be inaccurate, as it is based exclusively on the interpretation of a single proxy (pollen) in an archive without sufficient resolution for this period, and for a climate event over which intense anthropogenic pressure on forests is superimposed (Pontevedra-Pombal et al., 2012). In other studies, Lebreiro et al. (2006) and Abrantes et al. (2017), detected a cold period between 1300 and 1850 AD, with the coldest phase centred at 1400 AD, in the western Iberian Peninsula.

By contrast, other geochemical signals that are less affected by anthropogenic deforestation processes (Martínez-Cortizas et al., 1999), although with low resolution, also detected the early onset of LIA (1345 AD) and a late end (1903 AD), similar to that established by the proxies analyzed in the CVM. Moreover, Schellekens et al. (2011) and Castro et al. (2015) observed a long wet period in the same area and coinciding with the LIA.

In this study, the resolution of the CVM core was sufficiently high to show climate events not previously described. We differentiated several phases in CVM-LIA.

5.2.1. *Increase in wetness and first wet maximum of the LIA (zone CVM-c)*

According to macrofossil, hydroclimatic indices and peat humification data, the CVM-LIA-c (1345–1610 AD, 665–400 cal yr BP) was a wet period with some relatively dry episodes. Although the most abundant species were *E. mackaiana* and *Sphagnum* Sect. *Acutifolia*, the presence of wetness indicator species (*S. tenellum, Juncus bulbosus* and *S. papillosum*), good indicators of bog surface wetness, led to positive values in the hydroclimatic indices. The evolution of the HI is consistent with that of HuI.

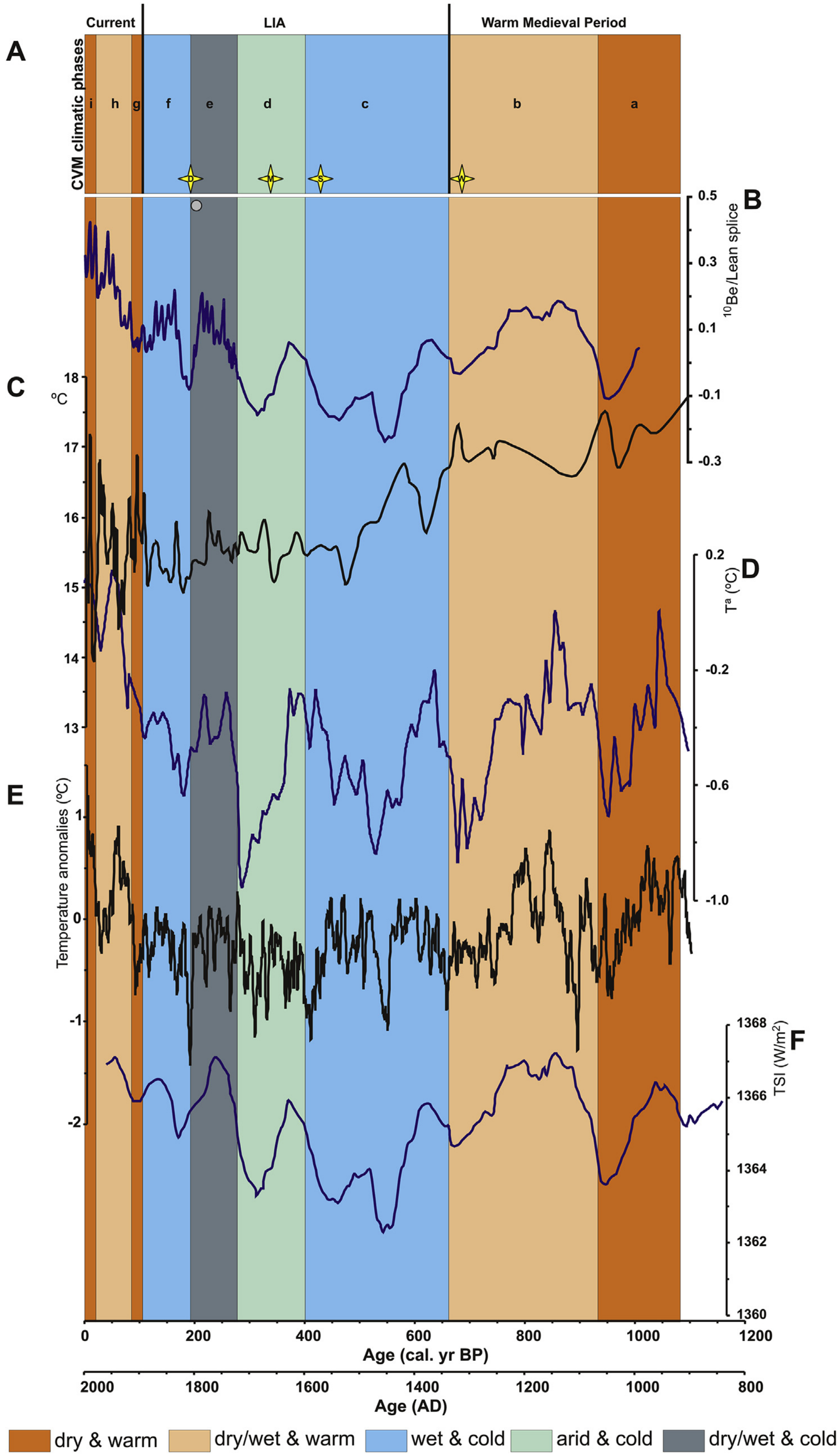

Fig. 8. (A) Climatic phases established from the study of macrofossils and humification in Chao de Veiga Mol bog for the last millennium. (B) Reconstruction of solar variability based on ^{10}Be measurements in the Northern Hemisphere (after Crowley, 2000). (C) Sea surface temperature reconstruction for the North Atlantic area of western Europe (after Eiríksson et al., 2006). (D) Reconstruction of variability of Greenland snow surface temperature (after Kobashi et al., 2011). (E) European summer temperature anomalies (after Luterbacher et al., 2016). (F) Total solar irradiance (TSI) variations (after Bard et al., 2000). Stars: Solar minimum events (Usoskin et al., 2007) where "D star": Dalton Minimum (1790–1820 AD), "M star": Maunder Minimum (1645–1715 AD), "S star": Spörer Minimum (1450–1550 AD) and "W star": Wolf minimum (1280–1350 AD). Circle: 'Maldá' Anomaly event (Barriendos and Llasat, 2003). The data used in Fig. 8B, C, D, E and F were obtained from the Paleo Data Search repository (https://www.ncdc.noaa.gov/paleo-search/).

The beginning of this phase is consistent with observations made by Oliva et al. (2017), i.e. moderate cooling and extreme rainfall events that triggered major flooding of rivers on the Mediterranean and Atlantic sides of the peninsula, particularly in the latter side. Losada (2008) described the climate in NW Iberian Peninsula in the 14th century as changeable, with dry years and years with flooding. Historical (Losada, 2008) and dendrochronological (Saz, 2003) data both showed that rainfall was generally more frequent than drought in the 15th century.

Periods of moderate rainfall predominated in the first half of the period, while torrential rain and droughts were more frequent in the second half. Likewise, Saz (2003) observed an increase in rainfall in winter and spring in the 16th century, especially between 1499 and 1535 AD, but also noted differences in the amount and seasonality of rainfall, between several sites in northwestern Spain, during the 15th and 16th centuries. Thus, the general agreement between the present data and the reference data demonstrates the validity of the proxies analyzed here for reconstructing bog surface wetness; the few discrepancies can be explained by climate particularities in the CVM area.

According to Ortiz et al. (2010), dry and humid periods are not necessarily related to changes in temperature; bog surface wetness differs depending on the amount of precipitation and evaporation, affecting the local vegetation biome. Given that none of the proxies that we studied reliably indicates the temperature changes during this subperiod, we consulted bibliographical sources to complete the information on the CVM-LIA-c climate characteristics. On a global scale, the lower temperatures in the LIA after the 14th century (Mann et al., 1999; Moberg et al., 2005) coincided with colder North Atlantic (Bond et al., 2001) and Mediterranean Sea Surface Temperatures (SSTs, Taricco et al., 2008) and a phase of mountain glacier advance (Wanner et al., 2008). In the Iberian Peninsula, this period is characterized by generalized low temperatures (Martinez-Cortizas et al., 1999), and the geochemical and sedimentological records on the NW Iberian Continental Shelf (Martins et al., 2012) identify an increase in precipitation during the LIA that has been related to the behaviour of the NAO.

The occurrence of low summer temperatures, and thus, low evapotranspiration, probably generated moister conditions in the Mediterranean Basin (Luterbacher et al., 2005). The cold humid phase recorded in the Iberian Estanya Lake (Riera et al., 2004) between the late 14th century and the beginning of the 15th century (1360–1550 AD) coincides with a first relative maximum of mountain glacier advance (Denton and Broecker, 2008) and more humid conditions (Trachsel et al., 2008) in Central Europe. Water levels in other Iberian lakes, such as Lake La Cruz (Julià et al., 1998) and the Salada Chipriana beach-lake in the Ebro Valley, were also high during this period.

The maximum abundances of *J. bulbosus*, *S. tenellum* and *S. papillosum* (1480–1530 AD) coincide with the Spörer minimum in solar irradiance, which produced global cooling (Camenisch et al., 2016). Thus, the causes of the abundance of wetness indicator species may be due either to increased rainfall or to a decrease in temperatures (especially in summer), which would reduce evapotranspiration, or probably a combination of both circumstances.

Oliva et al. (2017) reported a gradual cooling of the climate during the final decades of this period (as indicated by many records), associated with the increasing occurrence of cold spells and snowstorms and enhanced storminess. Historical sources show evidence of frequent severe flooding in northeast Iberia between 1590 and 1620 AD (Llasat et al., 2005; Barriendos and Rodrigo, 2006), together with high levels of precipitation in southern Spain (Rodrigo et al., 1998).

A sudden decrease in the total solar irradiance (TSI) was detected during this period (1345–1610 AD) (Bard et al., 2000; Crowley, 2000) on a global scale (Fig. 8), and a constant decrease in the oceanic temperature occurred from the Iberian margin northeastwards via Scotland to western Norway and Iceland (Eiríksson et al., 2006).

5.2.2. Decreased and minimum wet phases of LIA (zones CVM-d,e)

In the CVM-LIA-d phase (1610–1735 AD, 400–275 cal yr BP) there was a general decrease in the abundance of plant species, mainly the wetness indicator species. *M. caerulea* is the only species that remained at similar levels of abundance as in the previous phase. Because of this, and the small reduction in the peat humification levels, we consider that this phase was less humid than the previous one.

During this period, a systematic decrease in several climate indicators was detected at a different spatial scale (Fig. 8), indicating a clear tendency toward very cold conditions (Bard et al., 2000; Crowley, 2000; Eiríksson et al., 2006; Kobashi et al., 2011; Luterbacher et al., 2016). On a local scale, documentary and palaeoecological records indicate an intense drop in temperature between 1645 and 1715 AD, which has been associated with the prolonged sunspot minimum (Maunder minimum) (Fernádez-Cortizo et al., 2016).

The short phase CVM-LIA-e (1735–1815 AD, 275–195 cal yr BP) differs from the previous phase by an increase in the presence of *J. bulbosus* and *C. durieui*, a decrease in *Sphagnum* sect. *Acutifolia*, *S. papillosum* and *M. caerulea*, and the appearance of *D. intermedia*. There was also an increase in hydroclimatic indices and a decrease in peat humification index. Therefore, we assume that the dryness increased relative to the previous phase, but also with episodes in which droughts alternated with rainfall.

The perception of a less wet bog surface is consistent with Galician historical and dendrochronological climate data. According to Saz (2003) and Losada (2008), the weather was generally colder and with less persistent rainfall in the 16th and 17th centuries than in the 15th century, but also with extreme episodes of droughts and flooding, in addition to some very cold winters and hot summers.

Oliva et al. (2017) reported that written sources reveal cold and very dry conditions in the Iberian Peninsula during the following decades, intensifying during the second half of the 17th century (Domínguez-Castro et al., 2015). Historical documents suggest that a critical period occurred between 1680 and 1700, when severe cold and prolonged droughts caused serious famines in farming communities (Domínguez-Castro et al., 2015).

Fluctuations in humidity and temperature, which have been detected in CVM-LIA-e, are located chronologically (Fig. 8) at a time of slight recovery of the TSI (Bard et al., 2000; Crowley, 2000), although the records do not show a significant increase in temperature (Eiríksson et al., 2006; Kobashi et al., 2011; Luterbacher et al., 2016).

Four colder periods have been identified during the 17th century for the Iberian LIA: 1615–1619 AD, 1636–1640 AD, 1669–1673 AD, 1678–1682 AD (Martinez-Cortizas et al., 1999). The plant macrofossils recorded for these periods (end of the CVM-LIA-d and CVM-LIA-e) are indicative of the adverse weather conditions for the vegetation, not only because of the cold temperatures, but also because of alternanting droughts and floods. According to Font Tullot (1988), precipitation varied markedly in the North of Spain, with alternating pronounced droughts and torrential rains and flooding; thus, during the 17th century, climate conditions frequently prevented crop ripening. Olcina and Martín (1999) indicated that the north–south meridian circulations increased in frequency and resulted in cold and dry winters (a consequence of the persistence of blocking anticyclones) and warm but short summers. Dry and warm episodes were also recorded in dendroclimatological series between 1675 and 1750 AD (Creus and Saz, 1999).

On a global scale, the CVM-LIA-d phase coincides with the Maunder Minimum (1645–1715 AD). Oliva et al. (2017) described this period as a relative climate optimum and that the increased solar radiation following the Maunder Minimum promoted warmer temperatures and relatively stable conditions in Europe until 1760, with a low frequency of extreme events.

5.2.3. Second wet maximum of LIA (zone CVM-f)

The final LIA phase (CVM-LIA-f, 1815–1905 AD, 195–105 cal yr BP) is mainly characterized by the abundance of *Sphagnum* mosses. *S. cuspidatum* was only recorded in this period, which is also when *S. tenellum* and *S. papillosum*, and also *J. bulbosus* were most abundant. The values of the hydroclimatic indexes also increased during this period. The peat humification levels for the first half of this phase are also indicative of wetness, but the increase in these in second half is not consistent with the macrofossil proxy. These discrepancies may be due to the fact that this section corresponds to the acrotelm, in which the humification process is still and early stage.

As in the previous phases of the LIA, our findings for this phase are consistent with historical and dendrochronological climate data (Font Tullot, 1988; Saz, 2003; Losada, 2008).

The first half of the 18th century was marked by cold winters across Europe (Glaser and Riemann, 2009), coinciding with a sharp decline in the index of the NAO (Bradley et al., 2003). Although the weather in the South of Europe during the 18th century was very variable, the climate in the NW Iberian Peninsula was characterized by high rainfall (Fernández Cortizo, 2005). The variability and magnitude of climate anomalies decreased in the NW Iberian Peninsula in the 18th century, indicating a gradual end to the LIA, although in the central third of the 19th century there was a cold crisis that for some authors marks the end of LIA (Saz, 2003).

The decrease in the presence of *S. papillosum* and *J. bulbosus*, around 1800 AD, corresponds to the Maldà anomaly (1760–1800 AD) (Barriendos and Llasat, 2003), characterized by long winters with many episodes of frosts and snow and relatively cold summers, with alternating floods and droughts. This anomaly was intensified after eruptions of the Laki (1783) and Tambora (1818) volcanoes.

Le Roy Ladurie (2007) established the second hyper-LIA at between 1815 and 1860 AD. In the Iberian Peninsula, the first years of this century were marked by a climate and social crises; the spring and autumn were very rainy and the harvests rotted. The very wet conditions were more or less continuous during the final phase of LIA in North West of Iberian Peninsula. Oliva et al. (2017) documented a slight increase in temperature in the period between 1835 and 1850 AD in parallel to enhanced hydrometeorological dynamics, including storms, persistent rain and dramatic flooding. We believe that the drastic reduction in *J. bulbosus*, *S. tenellum* and *S. papillosum* macrofossils until their disappearance at around 1900 AD, can be interpreted as the end of the LIA in the CVM, generally dated around 1850–1860 AD (Le Roy Ladurie, 2007).

The climate conditions recorded during this period coincide with a worsening of the climate (Fig. 8) at regional and global scales (Bard et al., 2000; Crowley, 2000; Eriksson et al., 2006; Kobashi et al., 2011; Luterbacher et al., 2016).

5.3. The recent climate cycle

We differentiated three periods in the 20th century on the basis of the proxies analyzed: 1905–1925 AD (zone CVM-g) 1925–1990 AD (zone CVM-h) and 1990–2000 AD (zone CVM-i).

The first (CVM-g) is considered a dry period because of the abundance of mosses associated with dry conditions (*R. lanuginosum, L. glaucum, H. cuprresiforme*) and the absence of mosses indicating wet conditions (negative values of the hydroclimatic indexes), as well as high peat humification values. In the second period (CVM-h), the presence of *J. bulbosus*, the increase in *Sphagnum* Sect. *Acutifolia* and the absence of *R. lauginosum* and *L. glaucum* are indicative of increased wetness, which is reinforced by low peat humification levels; whereas in the third period (CVM-i), the absence of wetness indicator species, together with the large number of *H. cupressiforme*, *E. mackaiana* and *C. vulgaris* macrofossils (negative values of the hydroclimatic indexes), as well as high peat humification levels, were considered signals of a reduction in bog surface wetness.

Although analysis of Iberian lake and marine records identifies a single drier phase driven by a positive NAO behaviour, among other factors, during the twentieth century (Lebreiro et al., 2006; Martins et al., 2012), these periods are consistent with previously reported data and weather station data. There was a marked contrast before and after in the frequency and intensity of major rain storms that occurred in Spain during the 20th century. In the period 1921–1935 AD, the most important rainstorms occurred in Galicia and in the Cantabrian area, even in summer (Losada, 2008). The period 1891–1920 AD was dry, while 1921–1985 AD was wet, with short, scant episodes of dry conditions (Font Tullot, 1988).

The climate studies conducted by Carballeira et al. (1983) for the period 1945–1974 indicate that in phase CVM-h the weather was temperate and humid, with an average temperature of around 10 °C, rainfall of 1700 mm and ETP around 700 mm.

Climate data from weather stations in the NW Iberian Peninsula indicate low rainfall between 1890 and 1921 AD (Llorente, 1955), which corresponds with our interpretation of the results for CVM-g. Likewise, climate data from weather stations located near CVM confirm that CVM-h was wet, although less so at the end of the period. The decrease in humidity became more pronounced in CVM-i because of a slight increase in the average temperature and ETP, associated with a slight reduction in rainfall.

Our findings are consistent with the recovery of the TSI values (Bard et al., 2000; Crowley, 2000), the ocean temperature in western Europe (Eiríksson et al., 2006), the surface temperature in Greenland (Kobashi et al., 2011) and summer temperature in Europe (Luterbacher et al., 2016).

6. Conclusions

A multiproxy approach was used to reconstruct the hydrological conditions in a peat bog in the NW of the Iberian Peninsula throughout the last millennium. The approach consisted of identification of plant macrofossil presence, calculation of hydroclimatic indices (derived from the ecological preferences of the present flora) and of humification indices and enable construction of a high-resolution continuous age-depth model for the entire Holocene.

Chao de Veiga Mol is a raised bog characterised by the highest known resolution rates of Iberian peatlands (a mean value of 9.7 yr cm^{-1}) and, due to its geomorphological characteristics and geographical location, is highly sensitive to climate changes, in an area of particular value for compression of the local modulation of climate change.

An overall view of the sample core from the bog shows a generally dry climate during the last millennium that lasted until the 14th century, with a transition to a long period with a more humid, but very variable, climate, ending at the beginning of the 20th century, followed by a rapid transition first to more humid conditions and later to drier conditions.

The high resolution of the core enabled us to obtain a detailed chronology of the climatic events. Nine climate phases were differentiated in the period considered: two corresponding to the so-called Medieval Climate Anomaly (930 to 1070 AD); four corresponding to the LIA (1345 to 1905 AD); and three corresponding to the last century (1905 to 2000 AD).

The MCA, believed to have occurred in Europe between c. 900 and 1300 AD and with clear variations at regional level, was found to have occurred in the peat bog from 930 to 1345 AD, but two well-contrasted phases were clearly distinguished: a dry period (900–1070 AD), followed by a period (1070–1345 AD) with alternating wet and dry phases. Until now, a single warm and wet phase has been proposed for the Iberian Atlantic region and a warm and dry phase for the Mediterranean area.

The LIA is generally considered a cold period, but with variations in temperature and in rainfall patterns, the beginning and ending of which are the subject of some controversy. In the CVM sequence, the onset of the LIA is dated to around 1345 AD, and the end is dated to 1905 AD. This early beginning of the LIA could not be established until now at the necessary level of resolution. The resolution of the CVM core was sufficiently high to reveal climate events not previously described: a wet period, with a first wet maximum and some relatively dry episodes that lasted from 1345 to 1610 AD; a less humid phase, with a clear tendency to very cold conditions, from 1610 to 1735 AD, followed by a short phase (1735–1815 AD) with increased dryness relative to the previous period, with alternating drought and rainfall episodes, and, until the end of the LIA, a second wet maximum, from 1815 to 1905 AD.

Finally, we differentiated three periods in the 20th century. The first, between 1905 and 1925, is considered a dry period, followed by an increase in wetness between 1925 and 1990 and then by a reduction in bog surface wetness between 1990 and the end of the century.

The zonation determined by analysis of the core and the different periods defined are generally consistent with existing knowledge of global climate changes, but also mark regional and local climate variations. The above-mentioned climate variations, with generally good agreement between the proxies, are similar to information derived from other studies, at global and local scales.

For the first time in the NW Iberian Peninsula, a continuous record of sufficient resolution of the last thousand years has been established, showing the variability that occurred during this climate period.

The intrinsic and environmental characteristics of CVM bog and a multiproxy approach have made it possible (i) to establish that climatic variations in this area are generally consistent with existing knowledge on a global scale, (ii) to identify climatic oscillations during the last millennium that remained hidden or observed with low resolution, and (iii) to verify the presence of a local modulation of regional and global models.

The research findings provide new information and a detailed chronology of climatic events that will help to refine local modulation of the regional models established in this geographical context, a key area of special relevance for understanding the paleoclimatic dynamics of the northern hemisphere.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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