Unexpected weak seasonal climate in the western Mediterranean region during MIS 31, a high-insolation forced interglacial

Dulce Oliveiraa, b, c, d, *, Maria Fernanda Sánchez Goñia, b, Filipa Naughtonc, d, J.M. Polanco-Martínez a, b, c, Francisco J. Jimenez-Espejof, Joan O. Grimaltg, Belen Martratg, Antje H.L. Voelkerc, d, Ricardo Trigo b, David HodelliF, Fátima Abrantes c, d, Stéphanie Desprata, b

* Corresponding author. EPHE, PSL Research University, Laboratoire Paléoclimatologie et Paléoenvironnements Marins, UMR 5805 EPOC, F-33615 Pessac, France. E-mail address: dulce.oliveira@ipma.pt (D. Oliveira).

Article history:
Received 8 December 2016
Received in revised form 11 February 2017
Accepted 12 February 2017
Available online 20 February 2017

Keywords:
Marine Isotope Stage (MIS) 31
Super interglacial
Iberian margin
Mediterranean vegetation
Obliquity and precession forcing
Millennial-scale climate variability
Precension harmonics
Land-sea comparison
Pollen analysis

ABSTRACT

Marine Isotope Stage 31 (MIS 31) is an important analogue for ongoing and projected global warming, yet key questions remain about the regional signature of its extreme orbital forcing and intra-interglacial variability. Based on a new direct land-sea comparison in SW Iberian margin IODP Site U1385 we examine the climatic variability between 1100 and 1050 ka including the “super interglacial” MIS 31, a period dominated by the 41-ky obliquity periodicity. Pollen and biomarker analyses at centennial-scale-resolution provide new insights into the regional vegetation, precipitation regime and atmospheric and oceanic temperature variability on orbital and suborbital timescales. Our study reveals that atmospheric and SST warmth during MIS 31 was not exceptional in this region highly sensitive to precession. Unexpectedly, this warm stage stands out as a prolonged interval of a temperate and humid climate regime with reduced seasonality, despite the high insolation (precession minima values) forcing. We find that the dominant forcing on the long-term temperate forest development was obliquity, which may have induced a decrease in summer dryness and associated reduction in seasonal precipitation contrast. Moreover, this study provides the first evidence for persistent atmospheric millennial-scale variability during this interval with multiple forest decline events reflecting repeated cooling and drying episodes in SW Iberia. Our direct land-sea comparison shows that the expression of the suborbital cooling events on SW Iberian ecosystems is modulated by the predominance of high or low-latitude forcing depending on the glacial/interglacial baseline climate states. Severe dryness and air-sea cooling is detected under the larger ice volume during glacial MIS 32 and MIS 30. The extreme episodes, which in their climatic imprint are similar to the Heinrich events, are likely related to northern latitude ice-sheet instability and a disruption of the Atlantic Meridional Overturning Circulation (AMOC). In contrast, forest declines during MIS 31 are associated to neither SST cooling nor high-latitude freshwater forcing. Time-series analysis reveals a dominant cyclicity of about 6 ky in the temperate forest record, which points to a potential link with the fourth harmonic of precession and thus low-latitude insolation forcing.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

The climate transition occurring between the early Pleistocene 41-ky (obliquity-driven) glacial-interglacial cycles and late
Pleistocene 100-ky climate cycles (eccentricity-driven) is known as the Mid Pleistocene Transition (MPT, ~1250–700 ka, Clark et al., 2006), and more recently as the Early Middle Pleistocene Transition (Head and Gibbard, 2015). Within this important and complex transitional interval, but prior to the dominant eccentricity-driven cycles (e.g., Mudelsee and Schulz, 1997), Marine Isotopic Stage 31 (MIS 31; 1081–1062 ka; Lisiecki and Raymo, 2005) stands out for its unusual orbital configuration (high obliquity and eccentricity and minima in precession) leading to some of the highest summer insolation levels of the Pleistocene, with a Northern Hemisphere (NH) maximum at 1070 ka bracketed by two Southern Hemisphere (SH) maxima (Laskar et al., 2004). This strong orbital forcing combined with relatively high CO₂ levels (Honisch et al., 2011; Tripati et al., 2011) contributed to such a remarkable warmth in the high-latitudes that MIS 31 has been described as a “super interglacial” (Pollard and DeConto, 2009; DeConto et al., 2012; Melles et al., 2012; Coletti et al., 2015). Model-predicted ~20 m of eustatic sea-level rise relative to present (Raymo et al., 2008) would be related to major retreats of Greenland, western (WAIS) and eastern Antarctica ice-sheets (EAIS), or some combination of the three (Scherer et al., 2008; Naish et al., 2009; Pollard and DeConto, 2009; DeConto et al., 2012; McKay et al., 2012; Melles et al., 2012; Teitler et al., 2015). However, few recent proxy records provide evidence for MIS 31 warmth across most of the world (Ruddiman et al., 1989; Byrami et al., 2005; Medina-Elizalde and Lea, 2005; McClymont et al., 2008; Weirauch et al., 2008; Herbert et al., 2010; Lawrence et al., 2010; Hillaire-Marcel et al., 2011; Russon et al., 2011; Elderfield et al., 2012; Dyez and Ravelo, 2014; Aubry et al., 2016). However, the magnitude of warmth achieved during MIS 31 varies geographically and the majority of the research has been concentrated in the high-latitudes of the NH and the SH (e.g., Flores and Sierro, 2007; Scherer et al., 2008; Maiorano et al., 2009; Naish et al., 2009; Melles et al., 2012; Villa et al., 2012; Tarasov et al., 2013; Teitler et al., 2015; de Wet et al., 2016). Considerably less information is available from the Mediterranean region, where only three vegetation sequences span MIS 31 (Tenaghi Philippon, NE Greece: Tzedakis et al., 2006; Montalbano Jonico section, southern Italy: Joannin et al., 2008; ODP Site 976, Alboran Sea: Joannin et al., 2011) (Fig. 1). Although these studies show the vegetation response to orbital forcing, they lack the required resolution to provide a detailed assessment of the millennial-scale climatic variability throughout MIS 31. Due to the scarcity and limited time resolution of studies spanning MIS 31, key questions remain concerning the imprint of its extreme orbital forcing and the climate system of the 41-ky world at lower latitudes in both terrestrial and marine ecosystems, and also the magnitude of warming, the duration of the interglacial and the intra-interglacial variability.

Here we present the first high-resolution (centennial-scale) pollen record from IODP Site U1385 covering the early Pleistocene interval, 1100 ka (MIS 32) to 1050 ka (early MIS 30) including MIS 31, that allows the reconstruction of vegetation and atmospheric systems, and also the magnitude of warming, the duration of the interglacial and the intra-interglacial variability.

2. Regional setting
2.1. Core site and hydrographic conditions
IODP Site U1385 (37°34.285′N, 10°7.562′W), or “Shackleton Site”, was drilled on the lower slope of the SW Iberian margin at 2578 m below sea level (Fig. 1) (Expedition 339 Scientists, 2013; Hodell et al., 2013). At present, the site is under the influence of North Atlantic Deep Water (NADW), although during glacial and cold episodes the contribution of southern-sourced Antarctic bottom water increased (Duplessy et al., 1988; Skinner and Elderfield, 2007). Above the NADW, the intermediate depth is dominated by the Mediterranean Outflow Water, and the upper water column by the Portugal Current and the Azores Current, depending on the atmospheric circulation (Fiúza, 1984; Pérez et al., 2001; Peliz et al., 2005). In winter, the northward, warm surface Iberian Poleward Current is dominant, whereas in spring and summer strong northerly winds induce coastal upwelling and the southward transport of the recently upwelled waters by the Portugal Current. This seasonal surface layer is underlain by the subtropical Eastern North Atlantic Central Water, composed of two branches of subtropical or subpolar origin with the subtropical overlying the subpolar branch (e.g., Rios et al., 1992; Fiúza et al., 1998).

2.2. Modern climate and vegetation
The climate of SW Iberia is Mediterranean with warm/dry summers and cool/wet winters (annual precipitation (Pann): 350–600 mm; annual Temperature (Tann): 13–17 °C with minimal winter temperatures between 5 and 1 °C), with an important influence of Atlantic moisture on its westernmost side (Peinado Lorca and Martinez-Parras, 1987; Gimeno et al., 2010). The summer dryness is predominantly driven by the northeastward expansion of the subtropical Azores High, which is associated with the descending branch of the Hadley cell (Lionello et al., 2006), while the winter precipitation is directly affected by the position and strength of the North Atlantic westerlies and related changes in the North Atlantic Oscillation and North Atlantic storm tracks (e.g., Hurrell, 1995; Trigo et al., 2004).

The western Iberian margin pollen spectra provide an integrated image of the regional vegetation from the adjacent landmasses because the Tagus and, to a lesser extent, the Sado rivers are the main pollen suppliers to the SW Iberian deep-sea sediments (Naughton et al., 2007). The vegetation distribution and composition of the Tagus and Sado watersheds, which belong to the Mediterranean region, are mainly influenced by precipitation and thermal gradients related to orography and maritime influences (Peinado Lorca and Martinez-Parras, 1987; Quezel, 1989; Blanco Castro et al., 1997). While the lowland areas of the western part of the basin are dominated by deciduous oak (Quercus) and cork oak (Quercus suber) woodlands due to increased moisture availability,
evergreen oak develops (Quercus rotundifolia and Q. coccifera) towards the east and south. In the montane forests, deciduous Quercus dominates areas at mid-altitude and conifers (Pinus woodland with Juniperus) at the highest elevations. Mediterranean shrub vegetation is characterized by heathers (Ericaceae) in the wettest areas (Pann: >600 mm), and by rockroses (Cistaceae) in drier environments (Peinado Lorca and Martinez-Parras, 1987; Loidi et al., 2007).

3. Material and methods

Deep-sea Site U1385 was retrieved from the structural high “Promontorio dos Príncipes de Avis”, using an advanced piston corer system, during the IODP Expedition 339 (Mediterranean Outflow) on board D/V JOIDES Resolution (Fig. 1) (Expedition 339 Scientists, 2013; Hodell et al., 2013). Five Holes (A–E; 67 cores in total) were drilled and correlated on the basis of core scanning XRF at 1-cm resolution to provide a continuous composite section covering the past 1.5 My (Hodell et al., 2015). The recovered sediments form a homogeneous lithologic unit dominated by hemipelagic mud and claystone (Expedition 339 Scientists, 2013).

3.1. Chronostratigraphy

For the studied interval, between MIS 32 and early MIS 30 (120.06–125.09 corrected revised meter composite depth (crmcd)), two age models were produced by Hodell et al. (2015): (1) the oxygen isotope age model derived by correlating the low resolution (20–cm) benthic oxygen isotope record (δ18O b) of Site U1385 to the LR04 δ18O b stack (Lisiecki and Raymo, 2005), and (2) the astronomically (precession)-tuned timescale produced by tuning sediment lightness (L*) peaks to the precession minima assuming a lag of ~3 ky based on new radiocarbon reconstructions at the nearby core MD99-2334K (Skinner et al., 2014) (Table 1). A third chronology has been proposed based on the revision of the LR04-derived chronology (F. Jimenez-Espejo et al., in progress) through the correlation of the high resolution δ18O b of Site U1385 to the one from IODP Site U1308 (Table 1), which has also an age model related to the LR04 stack (Hodell et al., 2008).

The LR04-derived chronology shows good agreement with the precession-tuned timescale (Hodell et al., 2015; F. Jimenez-Espejo et al., in progress), within the estimated uncertainty for the LR04 stack (~6 ky; Lisiecki and Raymo, 2005). However, since the studied interval is marked by one of the strongest precession cycles of the last 1.5 My (Laskar et al., 2004) the astronomical timescale is probably more accurate than the LR04-derived age model. The good agreement between the Mediterranean sapropel cyclostratigraphy (Konijnendijk et al., 2014) and the precession-tuned age model (Hodell et al., 2015) supports its robustness. Age-depth modeling was based on linear interpolation between four age control points between ~1048 and 1111 ka (Table 1). High sedimentation rates (Table 1), between 9.4 and 17.8 cm/ky, provide an average temporal resolution of ~350 yr for the pollen record and of ~250 yr for the δ18O SST profile.

3.2. Pollen analysis

IODP Site U1385 Holes E and D were subsampled for pollen
analysis at 0.02–0.08 crmcd intervals from 120.08 to 125.09 crmcd, except for the transition between the Holes where the sample spacing was of ~0.19 crmcd. From each 1-cm thick sample slice, 2.5–5 cm$^2$ of sediment were prepared following the conventional palynological procedure for marine samples (described in detail at http://ephe-paleoclimat.com/ephe/Pollen%20sample%20preparation.htm). After coarse-sieving (150 μm mesh) and carbonate destruction (attack with cold HCl successively at 10%, 25%, and 50%), silica and silicates were eliminated by chemical digestion (cold HF at 45% and 70%). Fluorosilicates were removed with a final treatment with cold HCl at 25%. The obtained residue was sieved through a mesh of 10 μm and mounted unstained in glycerol to allow rotation of the pollen grains.

Pollen analysis on 134 samples was carried out under a Nikon light microscope at ×500 and ×1000 (oil immersion) magnification and identification followed two well-known European pollen atlases (Moore et al., 1991; Reille, 1992) and the pollen reference collection available at UMR EPOC, University of Bordeaux. Each pollen sample comprised 20 to 29 pollen morphotypes and reached a total sporo-pollen sum between 142 and 487, with a minimum of 100 pollen grains excluding Pinus, aquatics and Pteridophyta spores. Due to the Pinus over-representation in marine sediments, the genus was excluded from pollen percentage calculations (Heusser and Balsam, 1977; Naughton et al., 2007). Also excluded were Cedrus, because it is an exotic pollen grain that likely originates from the North African cedar forest (Magri, 2012), aquatic plants, spores and indeterminable pollen grains. Pinus and Cedrus percentages were estimated from the main sum plus their indistinguishable pollen. A synthetic pollen percentage diagram of major pollen taxa and ecological groups versus depth is presented in Fig. 2. Following previous pollen studies off southern Iberia (e.g., Fletcher and Sánchez Goni, 2008; Sánchez Goni et al., 2008, 2016; Chabaud et al., 2014; Oliveira et al., 2016), the pollen types were grouped into three main categories: semi-desert plants (Artemisia, Chenopodiaceae and both Ephedra types), Mediterranean sclerophylls (Quercus evergreen-type, Cistus, Olea, Phillyrea and Pistacia) and temperate forest (TF; Mediterranean sclerophylls and all temperate trees and shrub taxa, excluding Pinus, Cedrus and Cupressaceae). The temperate forest category corresponds to the commonly used Mediterranean forest (MF), however, here we designate it by temperate forest because the vegetation composition displays a marked Atlantic character throughout the pollen record (Fig. 2).

Pollen zones were defined by visual inspection of the pollen diagram (Birks and Birks, 1980) and constrained hierarchical cluster analysis (Fig. 2). This analysis was performed using the function clust of the package rioja (Juggins, 2009) in R environment v. 3.1.1 (R Core Team, 2014).

### 3.3. Molecular biomarker analyses

Biomarkers analyses were carried out in 205 levels from Holes E and D between 120.08 and 125.44 crmcd at ~0.01–0.06 crmcd intervals, except in the transition between Holes (sample spacing of 0.18 crmcd). Analyses were performed at the laboratory of IDAEA-CSIC, Barcelona, and followed the procedure described in detail in Villanueva et al. (1997). Samples were freeze-dried and extracted with dichloromethane in an ultrasonic bath. After saponification with 10% potassium hydroxide in methanol, the neutral lipids were extracted with hexane and dried under a nitrogen atmosphere, and finally derivatized with bis(trimethylsilyl)trifluoroacetamide. Alkenones were quantified with a Varian gas chromatograph (model 450) equipped with a septum programmable injector, a flame ionisation detector and a CPSIL-5 CB column coated with 100% dimethylsiloxane (film thickness of 0.12 mm). Hydrogen was used as the carrier gas at 50 cm/s. The concentrations of each compound were determined using n-nonadecan-1-ol, n-hexatriacontane and n-dotriacontane as internal standards. Alkenone-based sea surface temperature ($U_{37}^{CPT}$-SST) reconstruction was based on the $U_{37}^{C}$ index (Brassell et al., 1986; Prahl and Wakeham, 1987) and converted into annual mean SST values following the global core-top calibration (Müller et al., 1998). Reproducibility tests showed that analytical uncertainty in the alkenone unsaturation index determination is lower than 0.0165 (±0.5 °C) (Villanueva et al., 1997).

### 3.4. Time series analysis

Cross-correlation function (CCF) analysis was implemented using the R package stts (R Core Team, 2014) in order to identify and quantify lead/lag relationships between the TF record and orbital parameters. Given the strong response of heathland to precession in the Iberian Peninsula (Roucoux et al., 2006; Margari et al., 2007, 2014; Fletcher and Sánchez Goni, 2008; Chabaud et al., 2014), the CCF analysis was also applied to these two time series. For this analysis, the unevenly spaced time series were interpolated with the Akima-spline at a regular time step of 300 yr and the linear trend was removed. The correlation coefficients ($r$) indicate the degree of similarity between two time series with values ranging from −1 to 1. The existence of a lag reveals the time offset between both time series.

Fourier spectral analysis for unevenly spaced palaeoclimate
Fig. 2. Percentage pollen diagram of selected morphotypes and ecological groups from Site U1385 plotted against depth. Ecological groups include temperate forest (TF) which here includes the Mediterranean sclerophylls and all temperate trees and shrub taxa, excluding Pinus, Cedrus and Cupressaceae; Mediterranean sclerophylls: Quercus evergreen-type, Cistus, Olea, Phillyrea and Pistacia; and semi-desert plants: Artemisia, Chenopodiaceae, Ephedra distachya-type and Ephedra fragilis-type. On the right of the diagram are represented the pollen zones and results of the cluster analysis. Pollen zones are labelled as following: Site U1385 - MIS (Marine Isotopic Stage) — number of the pollen zone. Shaded areas indicate open vegetation phases associated with the glacial sections of MIS 32 and MIS 30 bracketing the terrestrial counterpart of MIS 31 in SW Iberia.
time series was performed to detect potential periodicities in the TF pollen and $^{18}$O records. The REDFIT methodology and software package was used for this analysis. REDFIT allows testing for statistically significant spectral peaks that could indicate periodicities in non-constantly sampled time series against a red-noise background (Schulz and Mudelsee, 2002).

4. Results and interpretations

4.1. MIS 31 definition

Following Hodell et al. (2015) who defined the onset of interglacials at the terminal stadial event and its demise where $\delta^{18}$O drops and millennial variability of log(Ca/Ti) starts, MIS 31 lasted 32 ky, from ~1094 to 1062 ka (Fig. 3). Although the onset of MIS 31 at Site U1385 is 13 ky earlier than defined by Lisiecki and Raymo (2005) for the LR04 stack, it is consistent with recent studies off southern Iberia that used the $\delta^{18}$O and SST records to recognize the beginning of interglacial climate (Voelker et al., 2015) (Fig. 3). This earlier onset of the MIS 31 interglacial also agrees with the benthic foraminifera $\delta^{13}$C record of North Atlantic Site U1308 that indicates the resumption of strong AMOC (Hodell et al., 2008) within the traditional definition of MIS 32 (Lisiecki and Raymo, 2005). Moreover, recent publications have emphasized the need to reconsider the positioning of the MIS 31 lower boundary defined by Lisiecki and Raymo (2005) due to the unusual weak character of glacial MIS 32 in terms of length and/or intensity (Teitler et al., 2015; de Wet et al., 2016, and references therein).

4.2. Pollen-based reconstruction of vegetation and climate dynamics in SW Iberia

Results of pollen analysis are presented in the percentage pollen diagram (Figs. 2 and 3). Three pollen superzones are identified and distinguish the two main phases of open vegetation expansion during MIS 32 and MIS 30 glacial stages from the interglacial forest development during MIS 31 (Figs. 2 and 3). These superzones are additionally divided into zones to characterize the dynamics of the vegetation cover and composition (Figs. 2 and 3). Millennial-scale events of forest decline are indicated in Fig. 4 as they are not systematically represented by distinctive pollen zones.

4.2.1. Long-term vegetation and climate change

MIS 32 and MIS 30 are characterized by open vegetation cover (zones U1385-32-1 and U1385-30-1, respectively), dominated by Pinus, Taraxacum-type, Poaceae and semi-desert plants, while TF and heather are represented by values below 20% (Figs. 2 and 3). Based on the present day ecology of the dominant vegetation types, these intervals were marked by prevailing cold and dry conditions (Polunin and Walters, 1985; Prentice et al., 1996).

The second superzone corresponds to the terrestrial interglacial counterpart of MIS 31 in SW Iberia, which we named Sado, and comprises five zones (zones U1385-31-1 to 5) (Figs. 2 and 3). As documented for SW Iberian interglacials of the middle-to late Pleistocene (Sánchez Goni et al., 1999, 2016; Tedéakis et al., 2004; Roucoux et al., 2008; Oliveira et al., 2016), a rapid expansion of the TF (pollen percentages above 20%) and Isoetes also marks the onset of the Sado interglacial, at ~1094 ka, and ends at ~1060 ka with the dominance of semi-desert plants (Figs. 2 and 3). While the beginning of Sado is contemporaneous with the beginning of MIS 31 as defined by Hodell et al. (2015), its demise occurred two millennia after the end of MIS 31 (Fig. 3). This 34 ky-long, floristically diverse terrestrial interglacial is characterized by well-developed TF (pollen percentages up to 55%, average 30%) and low expansion of Mediterranean sclerophylls (pollen percentages up to 14.8%, average 4.6%), indicating overall warmth and moisture availability in SW Iberia but reduced climate seasonality (Figs. 2 and 3).

The earliest interval of the Sado corresponds to a transition phase from ~1094 to 1087.7 ka (U1385-31-1) marked by a relatively low development of the TF, mainly composed of deciduous Quercus woodland, and a characteristic ‘M’ structure in the TF pollen percentage record. Relatively high values of semi-desert plants, suggest that limited moisture availability may have restricted forest expansion (Figs. 2 and 3). During the ensuing interval, between ~1087.7 and 1079.5 ka (U1385-31-2), semi-desert plants contract and the vegetation cover is dominated by mixed deciduous woodland with small quantities of diverse summer drought-intolerant trees (Carpinus betulus, Castanea, Corylus, Fagus and Fraxinus excelsior-type) and abundant heathland (Ericaceae) (Figs. 2 and 3). Since these summer drought-intolerant taxa require relatively warm winters and warm-cool but wet summers (Polunin and Walters, 1985; Blanco Castro et al., 1997; Gallardo-Lanchon, 2001; Tallantire, 2002) and heath also requires sustained humidity-year-round (e.g., Loidi et al., 2007), these vegetation changes reflect the establishment of a temperate and humid climate regime with precipitation distributed evenly all over the year. The weak expansion of Isoetes (Figs. 2 and 3), fern ally, further supports the interpretation of reduced seasonality contrast as their optimal development requires periods of flooding alternating with desiccation in wintertime (Prada, 1986; Salvo Tierra, 1990).

During the major forest development (TF% between ~30 and 55%) (U1385-31-3), from ~1079.5 to 1072.5 ka, a deciduous Quercus expansion accompanied by the occurrence of various temperate trees and relatively low representation of the Mediterranean sclerophylls (average 7.8%), reflect a temperate and humid climate regime in SW Iberia with low seasonal contrast (Figs. 2 and 3). Nevertheless, the reduction of Ericaceae, large increase of Isoetes and modest expansion of the Mediterranean sclerophylls indicate that this interval was marked by increased warmth and the highest seasonality (slightly warmer and drier summers) within Sado interglacial. A prominent feature of this interval is the asymmetric “M” shape depicted by the TF pollen percentage curve, which points to the occurrence of two warm and humid phases separated by a short-lived and low-amplitude cooling and drying episode between 1076.8 and 1075.2 ka (Fig. 3). This warmest phase ends with a strong and rapid TF decline occurring within ~200 yr. A progressive contraction of the TF (U1385-31-4 to ~5) follows suggesting a cooling trend up to the end of Sado interglacial (Fig. 3). The TF long-term decrease was associated with the expansion of dry-grasslands (in particular Taraxacum-type and Poaceae) between ~1072.5 and 1067.5 ka (U1385-31-4), and with a distinct heathland development from ~1067.5 to 1060 ka (U1385-31-5) indicating a climate shift to wetter conditions and lower seasonality (Figs. 2 and 3).

Cross correlation analysis reveals that the TF pollen record is not correlated to the precession (Fig. 5a), but shows a strong positive correlation statistically significant (95% confidence interval) around lag-0 ($r = 0.78$) with obliquity (Fig. 5b). This indicates that, within the chronological uncertainties, the two time series are in phase with no apparent offset. Ericaceae shows a positive correlation with precession statistically significant at lag-0 ($r = 0.70$). The highest correlation coefficient takes place at lag ~3 ($r = 0.75$) suggesting that maximum correlation also occurs with nearly no apparent lag (lag of ~1000 yr) within the age model error (Fig. 5c).

4.2.2. Suborbital vegetation and climate variability

The pollen sequence of Site U1385 reveals persistent abrupt climate variability throughout the record with repeated millennial-to-centennial scale vegetation changes superimposed on the long-
term evolution (Fig. 4). Ten forest decline events (U1385-32-fe-1 to -30-fe10), reflecting atmospheric cooling and drying, were identified as significant reductions of the TF pollen percentages, between 8 and 24%, occurring at least across two consecutive samples (Fig. 4). These TF setbacks took place over a period of time ranging between ~205 yr (U1385-31-fe7) and ~900 yr (U1385-31-fe2) and lasted between ~600 and 3580 yr (U1385-31-fe3 and -fe10, respectively) (Fig. 4).
Fig. 4. Site U1385 direct land-ocean comparison between the millennial-scale temperate forest (TF) decline events and oceanic surface changes in the context of eastern North Atlantic changes. From the bottom to the top: Selected pollen percentage curves of (a) semi-desert plants (orange), Ericaceae (blue) and (b) TF (green), UK 1ρ-SST of (c) Site U1385 (black) and (d) Site U1387 from the Gulf of Cadiz (Voelker et al., 2015) (brown), (e) IRD discharges inferred from the Si/Sr ratio of Site U1308 (Hodell et al., 2008) (black) and IRD% of Site U1314 (Hernández-Almeida et al., 2013) (blue), (f) Iceland–Scotland overflow strength based on the K/Ti record of Site U1314 (Grützner and Higgins, 2010) (blue), (g) Benthic δ13C of Site U1308 reflecting changes in NADW formation and the AMOC (Hodell et al., 2008) (dark green; bold 3-point moving average), (h) δ18O records of Site U1385 (Hodell et al., 2015) (purple), Site U1308 (Hodell et al., 2008) (black) and LR04 (Lisiecki and Raymo, 2005) (light blue). Dashed line designates the ice volume threshold of McManus et al. (1999). Marine Isotope Stages (MIS) following Hodell et al. (2015) are shown at the top. Numbered blue bands mark the millennial-scale TF decline events labelled as following: Site U1385 - MIS (Marine Isotopic Stage) - number of the event. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
The coldest and driest events, U1385-32-fe1 (centered at ~1096.4 ka) and -30-fe10 (~1053.6 ka), occurred during glacial MIS 32 and MIS 30, respectively, and are represented not only by severe forest declines (TF% minima < 10%) but also by maximal expansion of semi-desert plants and very low abundances of heaths (Fig. 4). These long-lasting phases, ~2 and 3.6 ky, respectively, are however complex. They both encompass two episodes of forest contraction separated by a short-lived recovery of the TF and heathland at the expense of semi-desert plants. This internal variability reflects a tripartite climatic oscillation marked by cold/dry-warmer/wetter-cold/dry conditions in SW Iberia. Afforestation at the MIS 32/31 transition is briefly interrupted at ~1094.5 ka (U1385-32-fe2 event) revealing a discrete shift to cool and dry conditions on land (Fig. 4).

The interglacial climate variability during the Sado forest stage is marked by six forest decline events, U1385-31-fe3 to -fe8, with TF minima centered at ~1091.7, 1088.3, 1080, 1076.6, 1070.6 and 1063.3 ka, respectively (Fig. 4). These forest setbacks are characterized by important increases of semi-desert plants (up to ~24%) and relatively low values of TF minima (~15%), implying cool and dry conditions. In contrast, the subsequent forest decline event U1385-31-fe6 is associated with higher TF values (~29%) and weaker expansion of semi-desert plants (to ~14%), indicating that a cool and dry climatic oscillation of low amplitude interrupted the TF maximum development during MIS 31 in SW Iberia. This long-lasting phase of major TF expansion ended abruptly with a strong contraction of the forest (~24% change) comprising a short-lived forest recovery before the minimum percentages of TF, event U1385-31-fe7 (Fig. 4). These changes reflect a rapid vegetation response to colder and drier conditions interrupted by a brief warming and moisture increase. The subsequent long-term decrease in the TF, end of Sado interglacial and the onset of MIS 30, was punctuated by two additional TF setbacks, events U1385-31-fe8 and -30-fe9, associated with similar TF values (~15%) but different changes in herbaceous composition (Fig. 4). During the event U1385-31-fe8 Ericaceae dominance indicates a cooling with higher annual humidity, while during U1385-30-fe9 (TF% minima at ~1059.7 ka) a strong expansion of semi-desert plants suggests a shift to cold and dry conditions at the end of the Sado interglacial.

Spectral analysis of the TF record using the REDFIT method (Schulz and Mudelsee, 2002) shows a peak around 6 ky with significance at 90% on both precession-tuned (Fig. 6a) and LR04-based chronologies (Fig. 6b). These similar results ensure that the identification of ~6 ky cyclicity is independent of the chosen age model.

Fig. 5. Cross-correlation analysis between: a) the temperate forest (TF) pollen percentage record and precession parameter; b) TF record and obliquity; c) Ericaceae (heathland) pollen percentages and precession parameter. The Lag (x-axis) multiplied by the sampling interval (300 yr) indicates the offset between two time series. Dashed blue lines display the 95% confidence interval. Orbital solutions provided by Laskar et al. (2004). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
5. Discussion

5.1. MIS 31, a “super interglacial” around the world?

The Site U1385 pollen-based vegetation record shows that Sado interglacial was a 34 ky-long forested interval characterized overall by moderate expansion of temperate trees and very reduced development of Mediterranean sclerophylls (Figs. 2 and 3). This interglacial was not extremely warm but rather temperate and humid with reduced seasonal contrast. The MIS 31 conditions found here for the subtropical latitudes of the North Atlantic region were similar to those indicated by the low resolution western and central Mediterranean pollen records, where the arboreal pollen is not particularly prominent (Joannin et al., 2008, 2011), and the pollen-derived quantitative estimates reveal a peculiar wet character and reduced seasonality in temperature and precipitation (Joannin et al., 2011). Particularly wet MIS 31 conditions are also supported by calcareous nannofossil assemblages at the Montalbano Jonico section from southern Italy (Girone et al., 2013). Comparison of Sado with SW Iberian terrestrial interglacials dominated by 100-ky periodicity shows that the maximum expansion of forest (maximum of 55%) was considerably lower than reported for MIS 5e and the Holocene (maximum ~70 and 77%, respectively) and slightly larger than MIS 19c, 11c and 9e (maximum ~50, 44 and 53%, respectively) (Sanchez Goni et al., 1999, 2016; Chabaud et al., 2014; Desprat et al., 2016; Oliveira et al., 2016). In contrast, all these interglacials exhibited higher development of Mediterranean sclerophylls (MIS 19c: 24%, MIS 11c: 17%, MIS 9e: 24%, MIS 5e: 21% and Holocene: 23%) than MIS 31 (% up to 15%). This comparison highlights that the Sado interglacial does not stand out for its forest extent and warmth but rather for the particular weak precipitation seasonality.

In line with the atmospherically driven changes, the Iberian margin SST record is not characterized by exceptionally high temperatures during MIS 31 (Fig. 3). Although the SST optimum is slightly warmer than the Holocene, similar maximum SSTs of 20 °C were also recorded at Site U1385 during the last 1.1 My (MIS 19c, 17e, 15e, 9e and 5e) (Rodrigues et al., 2016). These conditions are also reflected in the recently published planktonic δ^{18}O record of the same site (Hodell et al., 2015) and the nearby Site U1387 UK 37°-SST profile (MIS 34 to 29) (Voelker et al., 2015). Thus, although in the high-latitudes there is consistent proxy data and model evidence of exceptionally high oceanic and atmospheric temperatures during MIS 31 (e.g., Flores and Sierra, 2007; Scherer et al., 2008; Maiorano et al., 2009; Naish et al., 2009; DeConto et al., 2012; Melles et al., 2012; Tarasov et al., 2013; Coletti et al., 2015; Teitel et al., 2015; de Wet et al., 2016), the land-sea comparison from Site U1385 clearly shows that this interglacial was not unusually warm in the subtropical eastern North Atlantic. Only in a very small extent, which indicates cooler atmospheric conditions. After ~1067.5 ka, the SSTs continuously decreased from interglacial values towards MIS 30 glacial conditions paralleling the reduction in the TF (Fig. 3).
number of North Atlantic records does it stand out from the warmest middle-to late Pleistocene interglacials (Ruddiman et al., 1989; McIvyst et al., 2008; Hillaire-Marcel et al., 2011). In contrast, most of the records evidence that MIS 31 was warmer than the present interglacial (Helmke et al., 2003; Lawrence et al., 2010; Naafs et al., 2013; Billups and Scheinwald, 2014; Aubry et al., 2016).

Besides highlighting that the warmth magnitude achieved during MIS 31 is not spatially coherent, our study supports the extended duration of this warm stage compared to the oxygen isotope chronology of Lisiecki and Raymo (2005), which places MIS 31 between 1081 and 1062 ka, i.e. lasting for 19 ky (Fig. 3). The precise identification of MIS 31 onset is not straightforward because there is no sharp and rapid glacial-interglacial transition in the δ^{18}O records (Fig. 3). However, it is clear from our combined analyses of marine and terrestrial tracers that the interglacial climate regime started several millennia before 1081 ka in the SW Iberia region (Fig. 3). As in other regions over the globe (Teitler et al., 2015; de Wet et al., 2016 and references therein), western and central Mediterranean palaeoclimate records also show that interglacial conditions were established prior to the LR04-assigned boundary for MIS 31 onset (Joannin et al., 2008; Maiorano et al., 2010; Girone et al., 2013; Hodell et al., 2015; de Wet et al., 2016). Such observations lend support to recent work from the high-latitudes of both northern and southern hemispheres showing that a substantial warming started well before the MIS 32/31 transition as defined in the LR04 stack (Teitler et al., 2015; de Wet et al., 2016). Moreover, our multiproxy reconstruction shows that MIS 31 interglacial conditions persisted for at least 32 ky (Fig. 3), an unusually long duration, but comparable to the one estimated for the longer interglacials of the past 800 ky (28 ± 2 ky: MIS 17, 13a and 11c) (Tzedakis et al., 2012). Tzedakis et al. (2012) suggest that the longer duration of these interglacials could be due to a nearly antiphase relationship between obliquity and precession, with the first summer insolation minimum occurring during maximum obliquity, which is not the case for MIS 31 (Fig. 3). Alternatively MIS 31 prolonged interglacial warmth may be attributed to its unique insolation pattern, with the first SH insolation maxima leading to the weak character of MIS 32 through interhemispheric climate teleconnections related to WAIS melting and consequent changes in the palaeoceanographic and atmospheric circulation (Melles et al., 2012; de Wet et al., 2016).

5.2. Astronomical factors controlling the MIS 31 vegetation and climate in SW Europe

Given the exceptional insolation (precession) forcing during MIS 31, an extensive Mediterranean forest cover in SW Iberia below 40°N with a prominent development of Mediterranean sclerophylls consistent with the precessional influence on seasonal contrast, was likely to be expected. Paradoxically, pollen-based vegetation and atmospheric changes (Fig. 3) and CCF analysis (Fig. 5a) do not show the influence of precession on TF development. The early phases of the Sado interglacial, from 1084 to 1079.5 ka, provide a clear evidence for this non-linear response with the TF progressive development occurring throughout the descending branch and minima of the summer insolation curve (inverse to precession) (Fig. 3). Moreover, even if there is a slight increase of Mediterranean sclerophylls near the MIS 31 precession minima (Fig. 3), their expansion remains weaker compared to younger interglacials marked by high or low precession forcing such as MIS 5e and MIS 11c, respectively (Sanchez Goñi et al., 1999; Oliveira et al., 2015). The weakness of the Mediterranean sclerophylls response to precession forcing ~1073 ka may be also linked to the impact of millennial-scale climate dynamics in ending the increasing trend of sclerophyll taxa in U1385-31-fe7 (Fig. 4). Interestingly, the major expansion of the forest cover, which corresponds to the strongest expression of the temperate and humid climate regime (pollen zone U1385-31-3), is coincident with the MIS 31 obliquity maxima (Fig. 3). The potential influence of obliquity on TF development, and therefore on the hydrologic conditions of southern Iberia throughout MIS 31 is testified by the unambiguous significant positive correlation without time lag given by the CCF analysis (Fig. 5b). These findings are in agreement with recent climate model simulations for the precession and obliquity forcing on the Mediterranean freshwater budget (Bosmans et al., 2015), using the extreme values of both orbital parameters of the last 1 My (Berger, 1978). These climate simulations suggest increased winter precipitation during obliquity maximum and precession minimum across the Mediterranean basin including adjacent regions such as SW Iberia. However, at times of obliquity maximum the summer precipitation is also relatively high, supporting the low seasonality in precipitation inferred from our pollen record and the predominant role of obliquity on TF development. Bosmans et al. (2015) proposed that the increase of winter precipitation over the Mediterranean basin is primarily due to an air-sea thermal contrast inducing locally convective precipitation, while in southern Iberia and Morocco it is mainly driven by highlatitude precipitation associated to increased storm track activity as it is also in current climate (Sousa et al., 2016). The position and strength of the winter storm track are strongly influenced by the North Atlantic climate dynamics, in particular latitudinal temperature gradients (Brayshaw et al., 2011). Reduced meridional winter temperature gradient (warmer high-latitudes temperatures due to maxima in obliquity) would weaken the flow of the temperate westerlies allowing their southward migration into SW Iberia, and therefore the increase of moisture. Because the summer climate regime in southern Iberia is mainly controlled by subtropical climate dynamics (Lionello et al., 2006), enhanced summer precipitation during obliquity maxima may be related to a more northern position of the North Atlantic Subtropical High which could have led to less summer aridity at subtropical latitudes. We speculate that the unexpected wetter conditions and muted seasonality indicated by SW Iberian vegetation during MIS 31 may also be a result of the higher amount of moisture available in the atmosphere, due to reduced ice-sheets, as demonstrated by high-latitudes proxy data and model studies (Schwar et al., 2008; Naish et al., 2009; Pollard and DeConto, 2009; DeConto et al., 2012; Melles et al., 2012; Coletti et al., 2015). This would have produced enough atmospheric humidity in summertime that counterbalanced the strong precession forcing determining high seasonality and allowing for summer drought-intolerant trees to develop in SW Iberia during MIS 31, but constraining the expansion of Mediterranean sclerophylls (Fig. 3).

The pervasive influence of obliquity on the TF development in SW Iberia during MIS 31 is in line with the growing body of evidence that shows an obliquity-forced climate before ~900 ky (e.g., Maasch and Saltzman, 1990; Berger and Jansen, 1994; Mudelsee and Schulz, 1997; Mudelsee and Stattegger, 1997; Maslin and Ridgwell, 2005; Maslin and Brierley, 2015). This obliquity signal is also evident in the western Mediterranean marine pollen record of ODP Site 976, which displays five obliquity-driven botanical successions through MIS 31-23 underlying the eight short-lasting precessional vegetation cycles (Joannin et al., 2011). Pollen analysis from the central Mediterranean region (southern Italy) also show a similar vegetation response to both obliquity and precession parameters during other time intervals of the 41-ky world (MIS 43-40: Joannin et al., 2007; MIS 37-23: Joannin et al., 2008). Similarly, although obliquity plays a dominant role on TF development and composition in the SW Iberian region between MIS 32 and early MIS 30, Ericaceae shows a clear imprint of precession
with two major phases of heathland expansion coinciding with precession maxima (Fig. 3). The precession forcing apparent in the Ericaceae pollen record of Site U1385 is constrained statistically significant correlation, even if the highest correlation shows a lag of ~1000 yr (Fig. 5c). The expansion of Ericaceae in southern Iberia during intervals of precession maxima (summer insolation minima) has been documented for glacial and interglacial periods across the late Pleistocene as a taxon-specific response to lower rainfall seasonality (reduced summer dryness) (Roucoux et al., 2006; Margari et al., 2007, 2014; Fletcher and Sánchez Goñi, 2008; Chabaud et al., 2014). This work shows that the influence of precession forcing on heathland development also occurred in the 41-ky world, thereby supporting that this taxon-specific response is pervasive and independent of the climatic background state. The fern spore Isoetes, which displays a similar (inverse) trend to the Ericaceae (Fig. 3), also shows a precession signal that may relate to the dependence of Isoetes on seasonally flooded ground (Prada, 1986; Salvo Tierra, 1990), as opposed to Ericaceae preference for year-round moisture (e.g., Loidi et al., 2007).

5.3. Land - sea interaction on millennial timescales

5.3.1. Millennial-scale variability during glacials MIS 32 and MIS 30

Site U1385 pollen-based vegetation record reveals that the coldest and driest atmospheric conditions occurred during the MIS 32 and MIS 30 glacial stages, forest decline events U1385-30-fe1 and -32-fe10, concomitantly with abrupt and severe SST cooling at the SW Iberian margin (Fig. 4). Besides their particular long duration, these extreme events display an interesting common tripartite climatic pattern characterized by cold/dry-warmer/wetter-cold/dry conditions (Fig. 4). Cold and dry conditions during both glacial stages are also reported in other western and central Mediterranean (Joannin et al., 2008, 2011; Girone et al., 2013; Hodell et al., 2015; Voelker et al., 2015) and North Atlantic records (e.g., Ruddiman, 1989; Toucanne et al., 2009; Lawrence et al., 2010; Naafs et al., 2013; Voelker et al., 2015). Nevertheless, apart from Voelker et al. (2015), those previous studies do not have a sufficiently high temporal resolution to allow for a detailed investigation of the short-lived internal climate variability. Voelker et al. (2015) document a similar tripartite climatic pattern during the extremely cold SST events of MIS 32 and MIS 30 in the Gulf of Cadiz (Fig. 4). This pattern is also evident in the mid-latitude North Atlantic DSDP Site 607 during the abrupt MIS 30 event (Lawrence et al., 2010), however, the SST warming phase is represented by a unique sample, which requires a resolution increase.

The climatic imprint of the most intense MIS 32 and MIS 30 events in the Iberian ecosystems resemble some of the last glacial Heinrich stadials (HS) with regard to the magnitude and duration of the weak forest episodes (TF pollen percentages remain below 10% for ~2–3 ky), severe cooling of surface waters (SSTs absolute minima of 8.5–10 °C) and climatic structure (three main phases) (e.g., Bard et al., 2000; Sánchez Goñi et al., 2000; Fletcher and Sánchez Goñi, 2008; Naughton et al., 2009, 2016). Recent studies off western Iberia have also documented the occurrence of Heinrich (H)-type events throughout the middle-to late Pleistocene (Martrat et al., 2007; Voelker et al., 2010; Rodríguez et al., 2011; Palumbo et al., 2013; Marino et al., 2014; Maiorano et al., 2015). However, a complex tripartite climatic pattern was only noticed in the MDO3–2699 U^13C_{37}-SST profile during the cold spell of Termination V (Rodrigues et al., 2011). In analogy to the HS and H-type events displaying a tri-phase climatic pattern, meltwater-induced reduction in AMOC together with rapid southward shifts in the position of the Polar Front and Atlantic jet-stream during the early and late phases (e.g., Naughton et al., 2009, 2016; Rodríguez et al., 2011) appear as plausible underlying mechanisms for explaining the MIS 32 and MIS 30 extreme cold phases. Within age uncertainties, disruption of the AMOC by meltwater discharge is supported by coincident decreases of benthic δ^{13}C values at Site U1308 and S-rich IRD events, although these IRD were not derived from the Hudson Strait as the “classic” HS but rather from northern Europe, Greenland and/or Iceland (Hodell et al., 2008) (Fig. 4). Site U1314, located in the subpolar gyre, provides additional evidence for a perturbation of the AMOC during the MIS 30 event, as revealed by an increase in K/Ti that is inferred to reflect a reduction in the Iceland–Scotland Overflow Water (Grützner and Higgins, 2010), and related ice-rafting (Hernández-Almeida et al., 2013). On the contrary, the MIS 32 event is coincident with low K/Ti ratios (Fig. 4). Considering the Site U1385 pollen record of MIS 38 (Tzedakis et al., 2015) and the MIS 41–37 palaeoceanographic study (Birner et al., 2016) evidence for similar millennial-scale variability during the early Pleistocene and the Dansgaard–Oeschger (D–O) events of the last glacial, we propose that Heinrich-type mechanisms may have been also operating in the 41-ky world, notwithstanding the origin of the iceberg pulses (Hodell et al., 2008; Bailey et al., 2012; Naafs et al., 2013) and the reduced extent of the ice-sheets and shorter duration of the glacial (e.g., Lisiecki and Raymo, 2005; Elderfield et al., 2012).

The weak and short-lived event U1385-32-fe2 is associated with a slowdown of the SST increasing rate in the subtropical gyre, but no AMOC change is indicated (Fig. 4). However, it is worth highlighting that a small decrease of the forest before the onset of the terrestrial interglacial, a potential Younger Dryas-type event, has also been documented by other Iberian margin vegetation records from Terminations I to IV (Desprat et al., 2007) and Termination IX (Sánchez Goñi et al., 2016). A substantial drop in SSTs, from 16.3 to 12.4 °C, is coeval with event U1385-30-fe9 (Fig. 4). This event is also recorded in the U^13C_{37}-SST profile of Site U1387 (Voelker et al., 2015) and it may be linked to the progressive AMOC reduction during the MIS 31/30 transition, as suggested by the benthic δ^{13}C decrease at Site U1308, and the increasing IRD recorded in the subpolar gyre (Hodell et al., 2008; Hernández-Almeida et al., 2013) (Fig. 4).

Our study strengthens previous evidence, from SW Iberian margin (Hodell et al., 2015; Tzedakis et al., 2015; Birner et al., 2016) and North Atlantic deep-sea sediments (Raymo et al., 1998; Hodell et al., 2008; Grützner and Higgins, 2010), for persistent abrupt climate variability during the glacial climate of the early Pleistocene. Moreover, the present direct land-sea comparison shows that the most intense millennial-scale cooling and drying events in the SW Iberia, events U1385-32-fe1, -30-fe9 and -30-fe10, only occurred when the δ^{18}O_{oceans} exceeded 3.5‰ (Fig. 4). This observation is consistent with the critical ice volume threshold needed to amplify the magnitude of millennial-scale variability after the MPT (McManus et al., 1999) and, most particularly, for the enhancement and/or extended duration of the Iberian vegetation changes (Desprat et al., 2005, 2009; Margari et al., 2010; Oliveira et al., 2016), although lower δ^{18}O_{ocean} thresholds (3.2‰ and 3.3‰) have been suggested for the early Pleistocene (Raymo et al., 1998; McIntyre et al., 2001; Bailey et al., 2012; Hodell et al., 2015; Birner et al., 2016). Because changes in the δ^{18}O_{oceans} are not only driven by ice volume but also by deep-water temperature (Shackleton, 1987; Skinner and Shackleton, 2005), caution is required when applying the concept of ice volume thresholds.

5.3.2. Intra-interglacial climate variability during MIS 31

Our pollen record shows pervasive millennial-scale atmospherically driven changes in SW Iberian vegetation throughout MIS 31 (Fig. 4), which contrasts with the proposed suppression of suborbital variability during interglacial stages (δ^{18}O_{oceans} > -3.3 – 3.5‰) over the past 1.5 My (Hodell et al., 2015; Birner et al., 2016). Six
temperate forest declines (U1385-31-fe3 to -fe8) indicate repeated atmospheric cooling and drying episodes, whereas SST remained warm off the western Iberia (Fig. 4). The observed land-sea decoupling at millennial timescales during MIS 31 is supported by the absence of coincident SST reversals in the UK\textsuperscript{37}-SST reconstruction of the nearby Site U1387 (Fig. 4) (Voelker et al., 2015). The only exception is the cold spell that appears associated with the forest event U1385-31-fe8, however this SST decrease is characterized by a single sample at Site U1387 while in our UK\textsuperscript{37}-SST record the warming trend is well-resolved (Fig. 4). Moreover, it is noticeable that no Si/ Sr peaks at Site U1308 occur during MIS 31 (Fig. 4), suggesting that the SW Iberian millennial-scale forest declines during the Sado interglacial are not driven by North Atlantic freshwater forcing. Regrettably, comparison with the other currently available North Atlantic and Mediterranean records is hampered by their lack of temporal resolution (i.e., centennial-scale) to investigate in detail the MIS 31 intra-interglacial climate variability (Ruddiman et al., 1989; Helmke et al., 2003; Tzedakis et al., 2006; Joannin et al., 2008, 2011; McClymont et al., 2008; Toucanne et al., 2009; Lawrence et al., 2010; Maiorano et al., 2010; Hillaire-Marcel et al., 2011; Girone et al., 2013; Naafs et al., 2013; Hodell et al., 2015).

The spectral analysis of the TF record carried out to explore the nature of MIS 31 variability on millennial timescales revealed a significant dominant cyclicity around 6 ky (Fig. 6a and b), which may be linked to the fourth harmonic of the precessional component of the insolation forcing (5.5 ky cycles) (Berger et al., 2006). Although it has been argued that the amplitude of precessional-derived cyclicity decreases rapidly from the equator to high-lattitudes (Short et al., 1991; Berger et al., 2006), the cycles related to the half and fourth precessional components have been recognized in palaeoclimate records from the mid-to-high latitudes in the North Atlantic throughout the Pleistocene (Wara et al., 2000; Weirauch et al., 2008; Ferretti et al., 2010, 2015; Billups et al., 2011; Amore et al., 2012; Hernández-Almeida et al., 2012; Palumbo et al., 2013; Billups and Scheinwald, 2014). Most particularly, based on a new land–sea comparison of MIS 19 at Site U1385, Sánchez Goni et al. (2016) revealed the occurrence of 5 ky cycles of cooling and drying in the SW Iberian region associated with warm SSTs in the eastern North Atlantic subtropical gyre also related to the fourth harmonic of precession. The suggestion for a low-latitude insolation forcing is primarily based on the fact that in low-latitudes the incoming daily irradiation over a year is characterized by a double maximum, which leads to a larger latitudinal latitude insolation forcing is primarily based on the fact that in low-latitudes the incoming daily irradiation over a year is characterized by a double maximum, which leads to a larger latitudinal

6. Conclusions

This new multiproxy record of the early Pleistocene at Site U1385, is the first to document the SW Iberian vegetation and surface oceanic conditions in the eastern subtropical gyre at orbital and suborbital timescales over the 1100–1050 ka interval (from MIS 32 to early MIS 30), which includes the “super interglacial” MIS 31. The MIS 31 extreme insulation (precession) forcing was favorable for an anomalously warm interglacial characterized by enhanced seasonality in the SW Iberia region. However, our study shows that, unlike other locations at higher latitudes, atmospheric and sea-surface temperatures were not exceptionally high in the context of other middle-to-late Pleistocene interglacials. Moreover, the Site U1385 pollen-based vegetation record reveals for the first time an unexpected temperate and humid climate regime marked by low abundance of Mediterranean sclerophylls and the development of diverse summer drought-intolerant trees. This muted seasonality during MIS 31 is consistent with analysis of vegetation dynamics and cross-correlation coefficients showing a dominant influence of obliquity on the forest development rather than precession. Prevailing obliquity-driven vegetation and climatic changes, in agreement with modeling experiments, are likely associated to a decrease in the seasonal distribution of rainfall in SW Iberia resulting from higher summer precipitation associated to obliquity maxima rather than to precession minima. The response of Ericaceae (heathland), in contrast to the temperate forest, is strongly imprinted by precession forcing, with major expansions occurring during the two precession maxima of the studied interval. Apart from revealing both obliquity and precession forcing during MIS 31 in SW Iberia, our study shows an unusual prolonged period of interglacial conditions starting ~13 ky earlier than defined in the LR04 stack, which supports the need for a redefinition of the lower boundary of MIS 31.

Superimposed on the orbital-scale driven changes, persistent millennial-scale climate variability is shown by ten forest decline events reflecting cooling and drying episodes in SW Iberia from MIS 32 to early MIS 30. The Site U1385 direct land–sea comparison reveals the different expression of the millennial-scale cooling, in terms of magnitude, character and duration, under the distinct glacial/interglacial boundary conditions. The particularly long,
coldest and driest atmospheric events are synchronously detected in the marine realm by large SST decreases and concur with the larger ice volume conditions of glacial MIS 32 and MIS 30. These extreme events are related to North Atlantic cooling and enhanced iceberg discharges, supporting the key role of northern ice-sheet instability and associated changes in the deep-water circulation in amplifying the intensity and duration of suborbital cooling in SW Iberia throughout the Pleistocene. Comparison of the high intensity MIS 32 and MIS 30 events with Heinrich events reveals close similarities regarding the imprint on terrestrial and marine Iberian ecosystems and the tripartite climatic structure. In the light of this strong resemblance, we suggest that Heinrich-type mechanisms, despite the source of the icebergs, may have also been operating during the glacial climate of the 41-ky world. Finally, our work provides detailed evidence for MIS 31 intra-interglacial instability in SW Iberia. Rapid forest decline events indicating recurring cool and dry atmospheric episodes with no concurrent SST change reveal a land-sea decoupling during MIS 31. Spectral analysis results show that these repeated atmospheric shifts contain a significant suborbital variability at periods of 6 ky, likely corresponding to the fourth harmonic of the precession cycle. We propose that the observed millennial-scale climate variability at Site U1385 during MIS 31 might have been driven by low-latitude insolation forcing, which led to meridional tilts in the temperate westerlies and consequent cooling and drying in SW Iberia. To better constrain the processes and mechanisms involved in rapid climate change during the different background climate states of early Pleistocene, additional high-resolution studies in key regions from the North Atlantic are required.

Acknowledgments

Financial support was provided by WarmClim, a LEFE-INSU IMAGO project, and the Portuguese Foundation for Science and Technology (FCT) through the project CLIMHOL (PTDC/AAC-CLI/100157/2008), D. Oliveira’s doctoral grant (SFRH/BD/9079/2012), F. Naughton’s postdoctoral grant (SFRH/BPD/108712/2015) and A. Voelker’s IF contract. JM. Polanco-Martinez was funded by a Basque Government post-doctoral fellowship (Ref. No. POS_2015_1_0006) and B. Martrat by a Ramón y Cajal contract (RYC-2013-14073). This research used samples provided by the Integrated Ocean Drilling Program (IODP, Expedition 339. We would like to thank the scientists and technicians of IODP Expedition 339 and the Bremen Core Repository, L. Devaux for technical assistance and A. Rebotim for comments and editing. The editor, José Carrión, and an anonymous reviewer are acknowledged for their constructive and insightful comments.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2017.02.013.

References


