Global and Planetary Change 135 (2015) 159–169

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

# Severe cooling episodes at the onset of deglaciations on the Southwestern Iberian margin from MIS 21 to 13 (IODP site U1385)

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ARTICLE INFO

*Article history:*
Received 27 March 2015
Received in revised form 3 November 2015
Accepted 5 November 2015
Available online 7 November 2015

*Keywords:*
North Atlantic
Iberian margin
Deglaciations
Millennial-scale SST variability
Pleistocene
Planktonic foraminifers

ABSTRACT

Here we reconstruct past sea surface water conditions on the SW Iberian Margin by analyzing planktonic foraminifer assemblages from IODP Site U1385 sediments (37°34.285′N, 10°7.562′W; 2585 m depth). The data provide a continuous climate record from Marine Isotope Stages (MIS) 21 to 13, extending the existing paleoclimate record of the Iberian Margin back to the ninth climatic cycle (867 ka). Millennial-scale variability in Sea Surface Temperature (SST) occurred during interglacial and glacial periods, but with wider amplitude (>5 °C) at glacial onsets and terminations. Pronounced stadial events were recorded at all deglaciations, during the middle Pleistocene. These events are recorded by large amplitude peaks in the percentage of *Neogloboquadrina pachyderma* sinistral coincident with heavy values of planktonic $\delta^{18}O$ and low Ca/Ti ratios. This prominent cooling of surface waters along the Portuguese margin is the result of major reorganizations of North Atlantic surface and deep-water circulation in response to freshwater release to the North Atlantic when ice sheets collapse at the onset of deglaciations. In fact, most of these cooling events occurred at times of maximum or increasing northern Hemisphere summer insolation. The slowdown of deep North Atlantic deep-water formation reduced the northward flow of the warm subtropical North Atlantic Drift, which was recorded on the Iberian margin by enhanced advection of northern cold subpolar waters. Following each episode of severe cooling at the onset of deglaciations, surface water experienced abrupt warming that initiated the climatic optimum during the early phase of interglacials. Abrupt warming was recorded by a sudden increase of the subtropical assemblage that indicates enhanced northward transport of heat through the North Atlantic Drift. At the onset of glaciations, SST along the Portuguese margin remained relatively warm while the surface waters of the North Atlantic experienced cooling, generating a large latitudinal SST gradient.



## 1. Introduction

The western Iberian margin has proven to be a crucial location for the comprehensive evaluation of millennial climate variability between hemispheres over the late Pleistocene, offering a direct comparison with Antarctic and Greenland ice core records (e.g. Shackleton et al., 2000; Martrat et al., 2007). A large number of studies have been conducted using piston cores from this area to partially characterize the last six climatic cycles (Cayre et al., 1999; Bard et al., 2000; de Abreu et al., 2003; Roucoux et al., 2005; Vautravers and Shackleton, 2006; Martrat et al., 2007; Rodrigues et al., 2011).

The western part of the Iberian Peninsula is very sensitive to variations in the North Atlantic surface circulation dynamics. The Iberian margin is located in a key region characterized by the interplay of subpolar waters brought by the Portugal Current, which constitutes the descending branch of the North Atlantic Drift, and subtropical waters brought by the Azores Current. Changes in the intensity of the northward flow of the North Atlantic Drift drive a deep impact on the north Atlantic subpolar and subtropical gyres, as well as on the position of the Polar, Arctic and subtropical fronts.

For the last climatic cycles various studies have illustrated the relationship between ice sheets instabilities in the northern Hemisphere and the southward migrations of the Arctic Front (AF) as far south as the Iberian margin (Bard et al., 2000) via the recirculation of cold water through the subtropical gyre eastern currents. Millennial-scale oscillations of Sea Surface Temperature (SST) at the Portuguese margin have been related to changes in North Atlantic surface circulation driven by freshwater perturbations at high latitudes (eg., Lebreiro et al., 1996, 1997; Zahn et al., 1997; Cayre et al., 1999; de Abreu et al., 2005; Vautravers and Shackleton, 2006; Martrat et al., 2007; Eynaud et al., 2009; Rodrigues et al., 2011). These oscillations also affected the continental climate across southern Europe via atmosphere–ocean coupling (Allen et al., 1999; Roucoux et al., 2005; Sánchez Goñi et al., 2008, 2013).

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http://dx.doi.org/10.1016/j.gloplacha.2015.11.001
0921-8181/

During the last glacial cycle a series of layers with high abundances of the polar species *Neogloboquadrina pachyderma* sinistral (Nps) were recorded along the Portuguese margin during Heinrich events (e.g., Lebreiro et al., 1997; de Abreu et al., 2003). In certain sites those layers also contained important amounts of Ice rafted debris (IRD) although the presence or absence of IRD rich layers off the Iberian margin during these events depends on the proximity to the shore. Sites located further offshore usually record IRD layers (Lebreiro et al., 1996; Bard et al., 2000) whereas sites nearshore rarely register them (Zahn et al., 1997).

At the same time, the Portuguese margin provides an excellent location to monitor past changes in deep water circulation and heat and salt exchange between Hemispheres (Hodell et al., 2013a). Millennial-scale oscillations in surface circulation recorded along the Portuguese margin were linked to significant changes in deep water circulation. Shutdown or reduced deep water formation in the North Atlantic in response to freshwater perturbations is registered in the SW Iberian margin by reduced flux of the North Atlantic Deep Water (NADW) and a rapid replacement by the northward flux of the Antarctic Bottom Water (AABW) (Shackleton et al., 2000; Skinner et al., 2003).

Before Integrated Ocean Drilling Program (IODP) Expedition 339 the existing sediment cores in the western Iberian margin only provided climatic and oceanographic reconstructions back to late Marine Isotope Stage 15 (e.g. Bard et al., 2000; Rodrigues et al., 2011). The sediment cores from Site U1385 (Shackleton Site), retrieved during Expedition 339, allow us to extend the record back to 870 ka and investigate the response of the mid-latitude eastern North Atlantic to climatic changes during the interval between 870 and 490 ka. In this work we studied planktonic foraminifer assemblages and combined them with the oxygen isotopes records from IODP Site U1385 to reconstruct the history of sea surface temperature on the southwest Iberian Margin from MIS 21 to MIS 13, thereby extending the existing record in the area back to the ninth climatic cycle.

Given that previous works suggested the Iberian Margin can play a pivotal role in understanding the millennial-scale climate variability during the last glacial cycle (Shackleton et al., 2000, Vautravers and Shackleton, 2006), in this work we aim to study the suborbital climate variability at this location during the last part of the middle Pleistocene transition (MPT, ~1250–700 ka; Clark et al., 2006) and state the influence that subpolar North Atlantic climatic oscillations and meridional SST gradients had on climatic events during and since the emergence of the 100-ka cycles.

## 2. Regional and oceanographic setting

IODP Site U1385 was drilled at the "Shackleton site", off the western Iberian margin (37°34.284′N, 10°7.562′W), at 2578 m water depth.

The western Iberian margin lies at present under the influence of several distinct water masses, which have been clearly identified and characterized (e.g. Fiúza et al., 1998; Peliz et al., 2005; Serra et al., 2010). These are, from top to bottom: the *North Atlantic Central Water* (NACW), reaching around 500–600 m depth and characterized by a complex circulation pattern; the *Mediterranean Outflow Water*, warm and very saline, between the NACW and 1500 m; the *Labrador Sea Water* (LSW) can reach 2200 m depth, depending on the density difference with the *Northeast Atlantic Deep Water* (NEADW), which flows down to 4000 m depth; and, across the lower slope and abyssal plains, the *Lower Deep Water*, composed mainly of Antarctic Bottom Water (AABW). The studied site (Fig. 1) is currently under the influence of NACW at the surface and NEADW at the sea floor. Surface water circulation in the area is determined by the eastern gyre of the North Atlantic (Eastern North Atlantic Central Water or ENACW) which consists of two branches, the Portugal Current in the north, of sub polar origin, and the Azores Current in the south, of subtropical origin. The general distribution of water masses is influenced by the seasonal migration of the Azores anticyclonic cell and its associated large-scale wind pattern. In summer, strong northerly Trade winds along west Iberia induce a coastal upwelling of the deeper layers of ENACW.

## 3. Material and methods

Sediments at Site U1385 define a single lithological unit dominated by calcareous muds and calcareous clays, with varying proportions of biogenic carbonate (23%–39%) and terrigenous sediment. Pelagic sedimentation prevails during interglacials, while terrigenous input is enhanced during glacials; however, sedimentation rates remain high (~10 cm/ka) for glacial and interglacial periods (Stow et al., 2012). Occasional occurrence of ice rafted debris (IRD) is also recorded. Cyclic variations in physical properties and color reflect cyclic changes in the proportion of biogenic carbonate and detrital material delivered to the site (Hodell et al., 2013b).

This study covers a section from the secondary splice U1385D/E (Hodell et al., 2013a) between 59.95 and 99.84 crmcd (corrected revised meters composite depth) (MIS 21–MIS 13). Samples for the microfaunal analysis were taken every 20 cm, providing an average estimated 1.76-ka resolution record. A total of 210 samples 1 cm thick were dried, weighed and washed over a 63 μm mesh sieve. The >63 μm residue was dried, weighed and sieved again to separate and weigh the >150 μm fraction. Census counts of planktonic foraminifera taxa and of planktonic foraminifer fragments were conducted on the sediment fraction larger than 150 μm, using a stereomicroscope. Each sample was successively split until a minimum of 300 specimens was obtained. A total of twenty-eight species and ten morphotypes (Kennett and Srinivasan, 1983) of planktonic foraminifers have been identified (Appendix A) and their relative abundances, calculated, as well as the number of specimens per gram of dry sediment. To monitor carbonate dissolution, planktonic foraminifer fragmentation index was calculated as percentage of test fragments related to the total amount of fragments plus specimens (Thunell, 1976).

Sea surface temperature (SST) values (annual, winter, summer and seasonality -difference between winter and summer parameters) were reconstructed according to the Artificial Neural Network (ANN) method, using a back propagation neural network system (Malmgren et al., 2001) to compare our fossil planktonic foraminifera assemblages with MARGO North Atlantic database. We used the commercial software NeuroGenetic Optimiser v2.6 (Biocomp), as described in Kucera et al. (2005), who calculate an error of prediction of 1.02 °C. The same set of 10 neural networks as in Kucera et al. (2005) was used in this study, providing 10 different SST reconstructions for each component (winter, summer, annual and seasonality). The average value of these ten estimations was used as the final SST reconstruction. Additionally, in order to calculate a similarity index and corroborate the ANN results, we applied a Modern Analog Technique (Prell, 1985) on the fossil data using the same MARGO modern dataset as was used for the training of the ANN (Kucera et al., 2005). The same methodology has been followed to reconstruct winter SST of Site U1314, using the same planktonic foraminifer assemblages as in Alonso-Garcia et al. (2011b). Site U1314 (~1 ka resolution) has been included in this work to better compare with the subpolar North Atlantic.

The age model of the studied section is based on the correlation of the benthic oxygen isotope record to the global benthic LR04 isotope stack (Lisiecki and Raymo, 2005) (see Hodell et al., 2015).

## 4. Results

Preservation in the studied interval is analyzed considering the planktonic foraminifer fragmentation index. This index remains generally lower than 20% (Fig. 2g), which informs of a very good preservation in the samples, except for some short intervals of increased dissolution. Nevertheless, the fragmentation index did not surpass the 40% threshold above which planktonic foraminifer assemblages

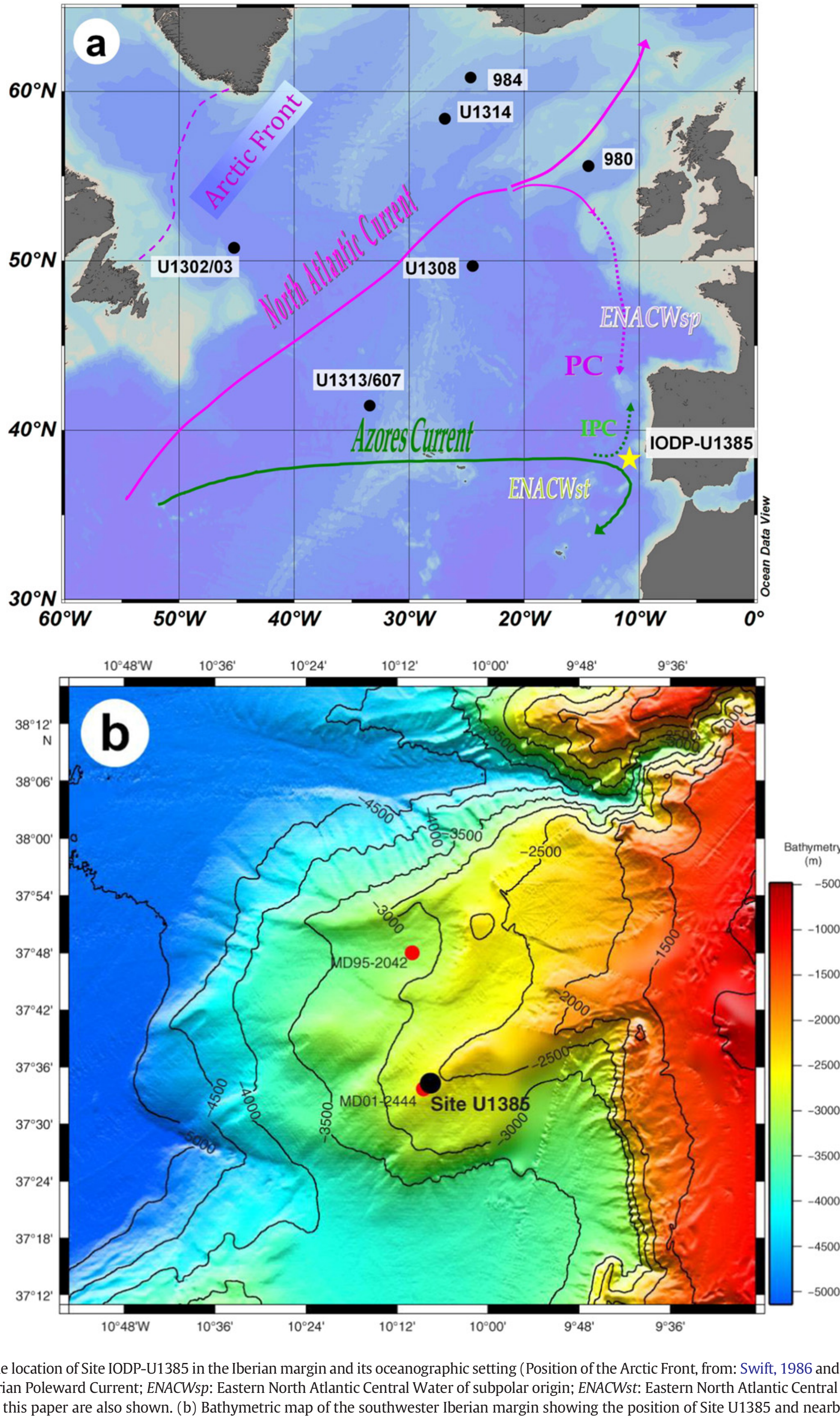



**Fig. 1.** (a) Map showing the location of Site IODP-U1385 in the Iberian margin and its oceanographic setting (Position of the Arctic Front, from: Swift, 1986 and Pflaumann et al., 2003). *PC*: Portugal Current; IPC: Iberian Poleward Current; *ENACWsp*: Eastern North Atlantic Central Water of subpolar origin; *ENACWst*: Eastern North Atlantic Central Water of subtropical origin. Other cores mentioned in this paper are also shown. (b) Bathymetric map of the southwester Iberian margin showing the position of Site U1385 and nearby piston Cores MD01-2444, located at approximately the same position as Site U1385, and MD95-2042 (After Hodell et al., 2013a).

begin to suffer modifications due to dissolution (Miao et al., 1994). Therefore, we can assume that the assemblages used for this work are not modified by dissolution and they are suitable to infer water mass properties.

Planktonic foraminifer accumulation rate ranges between 500 and 49,800 specimens per gram of dry sediment and ka, lowest values corresponding to levels of high bioturbation, where metallic deposits conform most of the coarse fraction of the sediment.

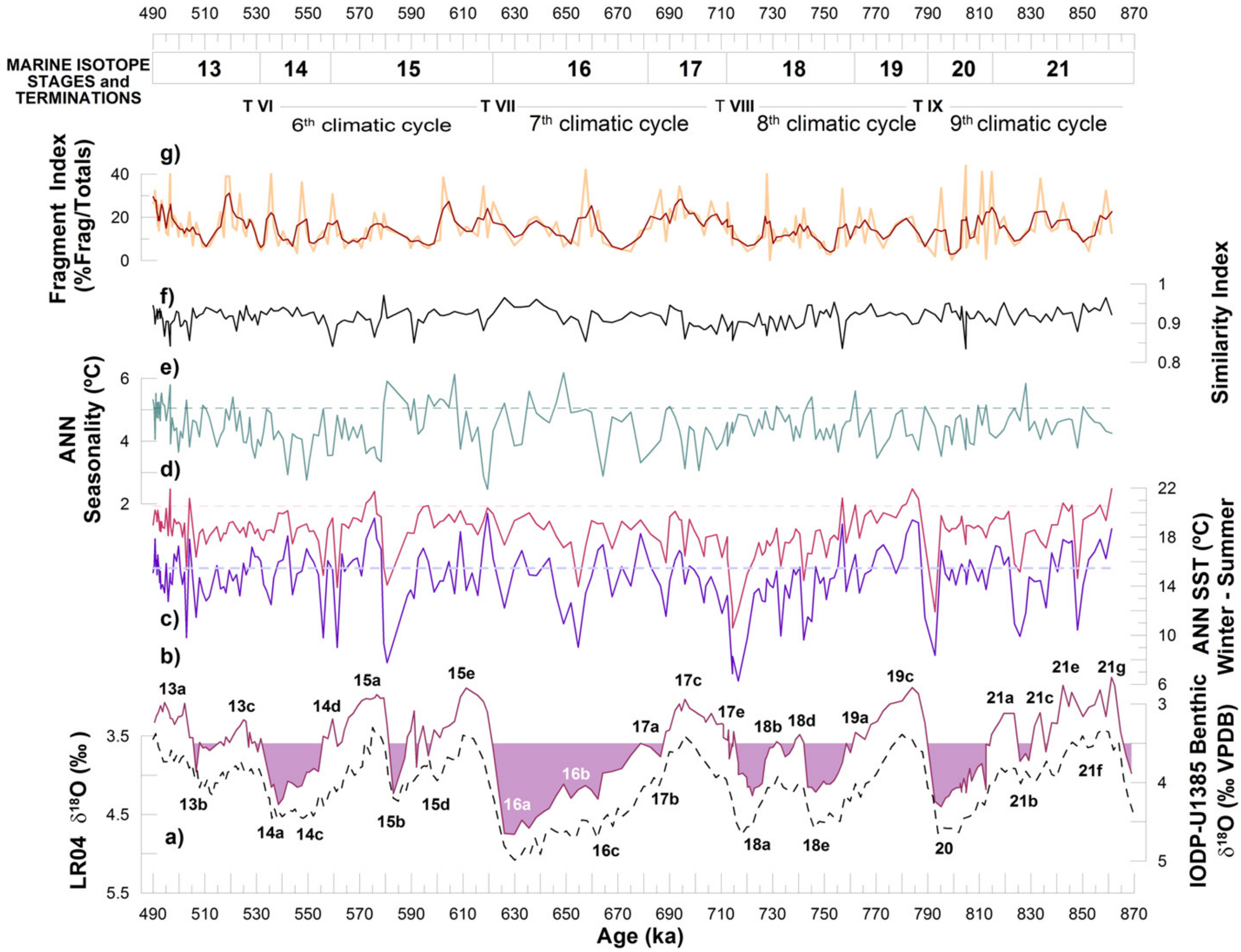



**Fig. 2.** Down-core results for stages 13 to 21 from IODP-U1385 and comparison with global LR04 benthic stack. (a) Age control points used to correlate both stacks (marked with crosses). (b) Benthic $\delta^{18}O$ profiles from LR-04 stack (Lisiecki and Raymo, 2005) in dashed line, and from U1385 (Hodell et al., 2015); filling enhances the ice volume threshold separating stable and unstable climatic regimes, which has been identified for the North Atlantic in $\delta^{18}O$ value of 3.5 ‰ (McManus et al., 1999). This threshold has been used to locate in the core the limits between glacial and interglacial conditions and determine the duration of climatic cycles. Substages are named according to Railsback et al. (2015). U1385 benthic $\delta^{18}O$ record shows a much higher variability and around 0.5 ‰ VPDB lower values than the global stack. (c) Winter ANN-reconstructed sea surface temperature. (d) Summer ANN-reconstructed sea surface temperature. Both winter and summer records are compared with present day temperatures on the site (horizontal dashed lines) from Locarnini et al. (2010). (e) ANN-reconstructed seasonality compared with present-day seasonality on the site (dashed line). (f) MAT-reconstructed similarity index (Prell, 1985) between fossil planktonic foraminifer assemblage in Site U1385 and MARGO dataset (Kucera et al., 2005). (g) Planktonic foraminifer fragmentation index (number of test fragments related to the total amount of fragments plus specimens) (Thunell, 1976) and averaged with a 3-point running mean.

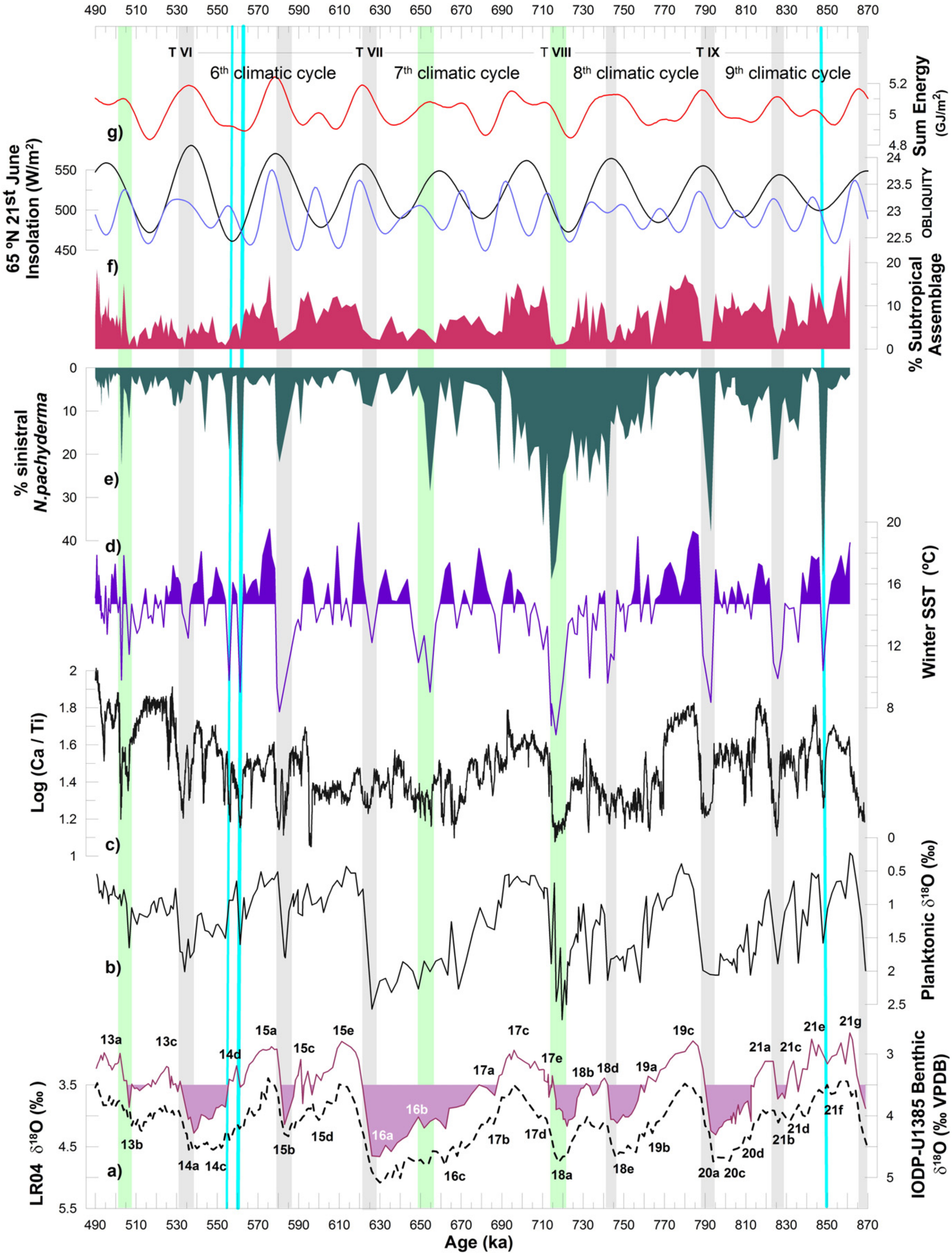
### 4.1. Planktonic foraminifer results

The microfaunal analysis focuses on species and assemblages that can be directly used to monitor any change in climatic or oceanographic conditions in North Atlantic surface water.

The species *Neogloboquadrina pachyderma* sinistral (Nps), with a temperature tolerance range between −1 and 8 °C and an optimum of 2 °C (Bé and Tolderlund, 1971; Tolderlund and Bé, 1971; Bauch et al., 1997; Pflaumann et al., 2003), is particularly abundant in the Arctic water (Johannessen et al., 1994). This species has been used to monitor southward penetrations of polar water masses, usually associated with iceberg discharges in mid-latitude North Atlantic (eg., Bond et al., 1992) as well as in the Portuguese margin (Cayre et al., 1999; de Abreu et al., 2003; Vautravers and Shackleton, 2006; Eynaud et al., 2009). This species ranges from 0% to a maximum of almost 50% during MIS 18. The species is more abundant before MIS 16 where high values occurred during interglacials, except for MIS 19, as well as glacials (Fig. 3e).

The subtropical assemblage (Ottens, 1991) consists mainly of species of *Globigerinoides* genus and it is usually linked to the subtropical

**Fig. 3.** Comparison between IODP-U1385 record and orbital parameters. (a) Benthic $\delta^{18}O$ profile: LR-04 stack (Lisiecki and Raymo, 2005) in dashed line, and record from U1385 (Hodell et al., 2015); filling enhances the ice volume threshold separating stable and unstable climatic regimes (McManus et al., 1999). Substages are named according to Railsback et al. (2015) (b) Planktonic foraminifer *Globigerina bulloides* $\delta^{18}O$ record from U1385 (Hodell et al., 2015). (c) Log Ca/Ti record from U1385 (Hodell et al., 2015) (d) Winter SST for Site U1385 (values above average are shaded). (d) Relative abundance of the planktonic foraminifer polar species *Neogloboquadrina pachyderma* sinistral in U1385. (e) Relative abundance of the subtropical assemblage (Ottens, 1991) in U1385. (g) Orbital parameters: obliquity (Laskar et al., 2004) (black) and 65 °N 21st June Insolation values (W/m$^2$) (blue) (Huybers, 2006) and integrated summer energy at 65 °N (>275 W/m$^2$) (red) (Huybers, 2006). Vertical bands mark pronounced cooling coinciding with deglaciations; gray bands mark events close to obliquity maxima and green bands mark the exceptions (no obliquity maxima or no deglaciation). Blue lines mark other pronounced cooling not linked either with deglaciations or with obliquity maxima.


T VI
T VII
T VIII
T IX
6th climatic cycle
7th climatic cycle
8th climatic cycle
9th climatic cycle
Sum Energy (GJ/m2)
65 °N 21st June Insolation (W/m2)
OBLIQUITY
% Subtropical Assemblage
% sinistral N.pachyderma
Winter SST (°C)
Log (Ca / Ti)
Planktonic δ18O (‰)
IODP-U1385 Benthic δ18O (‰ VPDB)
LR04 δ18O (‰)
Age (ka)
a)
b)
c)
d)
e)
f)
g)
13a
13b
13c
14a
14c
14d
15a
15b
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branch of ENACW, transported to the Northeast Atlantic by the Azores Current, which flows northward over the site during non-upwelling months (Peliz et al., 2005). Variations in the abundance of the subtropical assemblage (Fig. 3f) are consistent with climatic cycles. Variations in the subtropical assemblage resemble the planktonic $\delta^{18}O$ record, during both glacial and interglacial periods (Fig. 3).

*4.2. Sea surface temperature variations*

The similarity index of MAT (Fig. 2f) ranges between 0.9 and 1 for almost all the interval, suggesting that the studied samples are well represented in the modern dataset and that SST reconstructions (Fig. 2) are not affected by no-analog artifacts (Kucera et al., 2005).

In general, winter SST off the southwestern Iberian Margin resemble the planktonic oxygen isotope variations (Fig. 3, b and d). Minimum temperature occurred during Terminations or during glacial inceptions. SST in the area was generally colder during the studied interval (mean annual value, 16.6 °C) than at present (18 °C) (Locarnini et al., 2010), even during interglacials. During interglacial periods, summer SST (Fig. 2d) were on average 1 to 2 °C colder than at present and, during glacials, they were 2 to 4 °C colder. Nevertheless, during cooling episodes, summer SST dropped 6 °C below Holocene levels (18 °C, Bard et al., 2000) and those of previous interglacial, MIS 3, (17–18 °C, de Abreu et al., 2003; Vautravers and Shackleton, 2006). Winter SST (Fig. 2c) remained, on average, less than 1 °C lower than at present during all interglacials and during glacials MIS 20 and MIS 14, and were higher than today during most of MIS 19, in the warmest periods of MIS 21 and 15, and even in some very short spells during glacial stages MIS 18, MIS 16 and MIS 14. Only during MIS 18 winter SST were considerably lower (2.5 °C in average) than at present. The warmest period of the studied interval was MIS 19 and the coldest one was MIS 18. Isotope stages 17 and 13 were the coldest interglacial periods, with summer SST between 1 and 2 °C colder than at present and closer to the values recorded during glacial periods, and winter SST generally below modern values.

SST oscillations were, in general, less frequent and less pronounced during interglacials (less than 7 °C drop or rise) than during glacials (up to 11 °C oscillation), except for MIS 21f, that shows one of the steepest sea surface temperature oscillations (7.3 °C) of the whole studied interval.

ANN-reconstructed seasonality (Fig. 2e) during middle Pleistocene is lower than today and, in general, it shows small amplitude variability along the whole interval. Most of the deep oscillations in seasonality correspond to outstanding SST fluctuations. Increases in seasonality coincide with drops in winter SST and vice-versa. The highest seasonality values occurred in MIS 16b (6.2 °C), MIS 15e (6 °C) and 15b (5.9 °C). Since MIS 15a seasonality values were lower and show a slow increasing trend until the end of MIS 13, encompassing the cooling trend recorded by SST. During isotope stages 16 and 15 the amplitude of seasonality oscillations was between 1 and 2 °C higher than during the rest of the interval.

## 5. Discussion

*5.1. Sea surface cooling on the Portuguese margin at deglaciations during middle Pleistocene*

The planktonic foraminifer assemblages, SST and oxygen isotope data studied at Site U1385 indicate that during this period, and superimposed on the glacial-interglacial variations, suborbital millennial-scale climatic variability off Iberia reflects the influence of millennial changes in surface circulation in the NE Atlantic.

In order to identify millennial-scale climate events that may not be resolved with the resolution of our SST record we compare our data with the Ca/Ti record (Hodell et al., 2015), which provides an estimated resolution of 0.1 ka. Previous studies along the Portuguese margin reported that Ca/Ti reflects millennial-scale climate changes as well as sea level variations (Hodell et al., 2013a). Higher Ca/Ti ratios are linked to higher productivity of calcareous plankton during warmer periods and lower siliciclastic input from the continent (Hodell et al., 2013a).

Summer SST at the Portuguese margin remained relatively warm from MIS 21 to MIS 13, although lower than present-day summer SST, oscillating between 15 and 18 °C irrespective of the glacial or interglacial periods (Fig. 2d). This relatively warm temperature was, however, punctuated by abrupt SST cooling events, recorded throughout the record by pronounced peaks in abundance of Nps and sharp increases of *G. bulloides* $\delta^{18}O$ values, as well as very low values of the Ca/Ti ratio (Fig. 2, 3).

A close comparison of SST with the benthic $\delta^{18}O$ record for U1385 and the global benthic oxygen isotope stack (LR04) shows that all these cooling events were coetaneous with drops in the benthic $\delta^{18}O$. Longer and more pronounced cooling episodes in the Portuguese margin occurred at Terminations (Fig. 2a–c), particularly during Termination IX and VIII, but also at the transitions from glacial-interglacial substages MIS 21b to 21a, MIS 18e to 18d, and, especially, MIS 15b to 15a.

*5.1.1. MIS 21–20*

During the ninth climatic cycle (MIS 21–MIS 20) four main cooling events (6 to 8 °C drop) were recorded, all of them at transitions from higher to lower $\delta^{18}O$ values in the benthic oxygen isotope record. The amplitude and duration of these cooling episodes are related to the amplitude of the benthic isotope change (Fig. 2a–c). The most pronounced cooling occurred at Termination IX corresponding with a high amplitude change in the isotopes undoubtedly related to a major sea level rise and deglaciation. Another major cooling (6.4 °C) occurred at the transition MIS21b/a, also related to an important deglaciation and sea level rise. The first two cooling events recorded in this period also occurred at glacial/interglacial transitions, MIS 21f/e and MIS 21d/c. All these events of cool surface temperatures are also registered by heavier planktonic $\delta^{18}O$ and lower Ca/Ti values (Fig. 3b–d).

Based on the benthic $\delta^{18}O$ record climatic cycle MIS 21–20 encompasses two glacial, obliquity-driven cycles, the two more pronounced cooling events reflecting the culmination of these two glacial cycles. These cooling events were followed by remarkably warm intervals, showing the characteristic millennial-scale, stadial-interstadial climate oscillations (Fig. 3a,d,g). In particular, the four cool-warm oscillations recorded in MIS 21 have also been recorded in various sites of the North Atlantic (Flower et al., 2000; Kleiven et al., 2003; Hodell et al., 2008; Ferretti et al., 2010; Hernandez-Almeida et al., 2012) during the stage of progressive extension of the northern Hemisphere ice sheets during MIS 21. The cooling events off Iberia were marked by high percentages of the polar species Nps (Fig. 3e) but they were not linked to high IRD as has been reported for the same events at sites 984, 980 (Wright and Flower, 2002; hereafter, W&F02) and U1314 (Hernández-Almeida et al., 2013) in the North Atlantic.

*5.1.2. MIS 19–18*

During this cycle, sea surface waters along the Portuguese margin experienced a pronounced cooling during three episodes (Fig. 3d), being the greatest in amplitude (7.2 °C) and the coldest (6.2 °C, winter SST), the one recorded at Termination VIII. The other two cooling events were also linked to global drops in benthic $\delta^{18}O$ at the transitions MIS 18e/d and MIS 18b/c (Fig. 3a,d). Like in the previous climate cycle the amplitude of the cooling events is related to the amplitude of the deglaciations, being the cooling event associated to MIS 18b/c of lesser amplitude. Low Ca/Ti ratios, high planktonic $\delta^{18}O$ and high percentages of Nps also registered these cooling events that, with the exception of Termination VIII when SST increased gradually, were followed by abrupt warming (Fig. 3b–e).

Similar cooling episodes have been recorded in the subpolar North Atlantic at sites 980 (W&F02), U1314 (Alonso-Garcia et al., 2011a) (Fig. 4b) and U1302 (Channell et al., 2012), as well as at site U1308

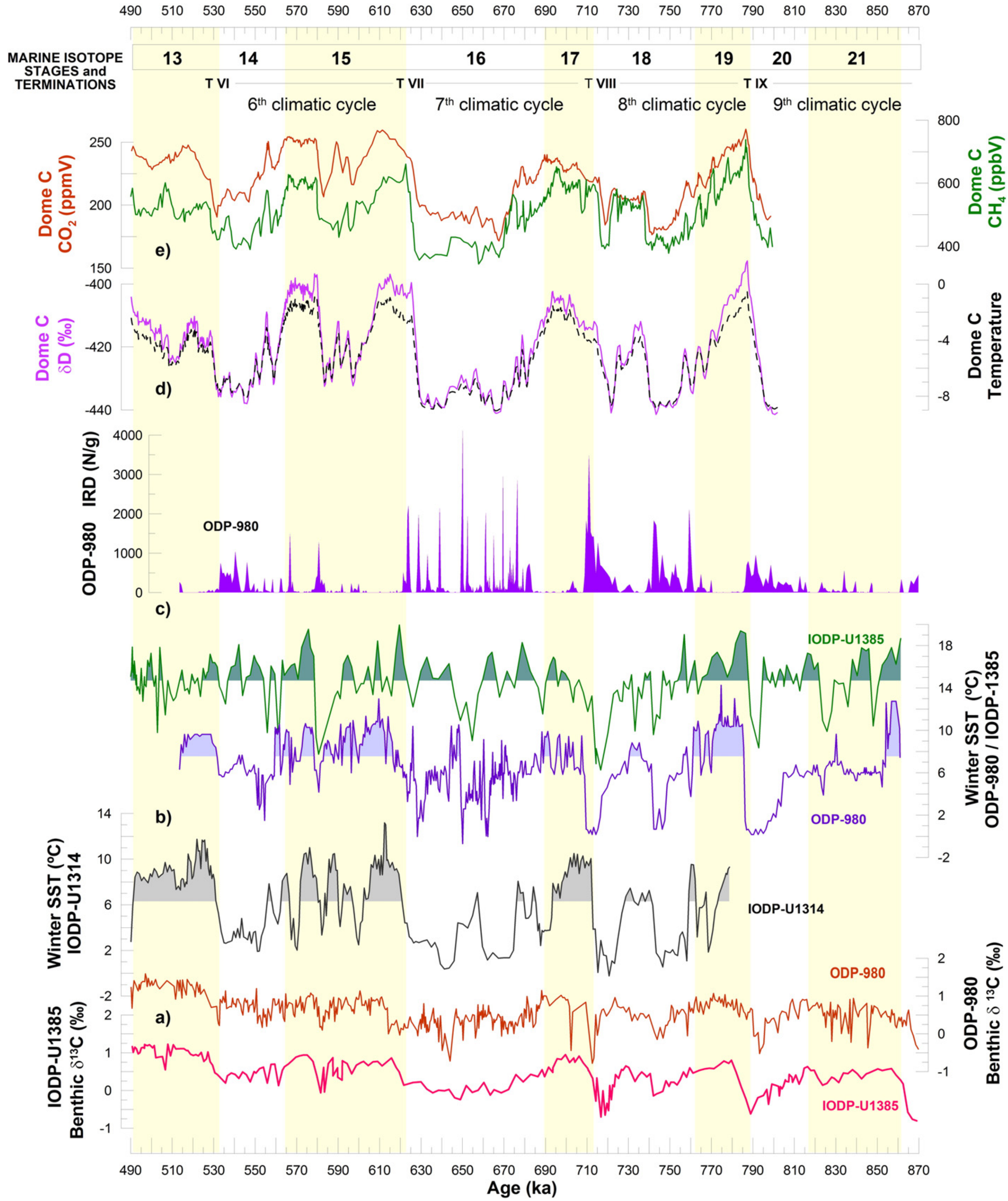


**Fig. 4.** Comparison between SST record from site IODP-U1385 (this work) and other climatic records from ninth to fifth climatic cycles. (a) Benthic $\delta^{13}C$ profile from U1385 (pink) and ODP-980 (W&F02) (brown). (b) Winter SST records from 58° N site U1314 (this work, gray), from 55°N site 980 (W&F02) (blue) and from site U1385 (green). SST above average for the interval are shaded in all the plots. (c) IRD content (in number of particles per gram of sediment) from site 980 (W&F02). The age model for site 980 has been recalculated according to LR04. (d) Antarctic Dome C δD record (purple) and reconstructed temperature (black dashed line) (Jouzel et al., 2007) (e) Content of greenhouse gases $CH_4$ (green) and $CO_2$ (red) in the Antarctic ice (Loulergue et al., 2008 and Lüthi et al., 2008, respectively).

(Hodell et al., 2008), but in that region they were associated to ice-rafting events (Fig.4c).

#### 5.1.3. MIS 17–16

Based on the global benthic Stack (LR04) MIS 16 was the longest and the most prominent glacial of the middle Pleistocene. Ice sheets grew continuously from 695 to 630 ka, with a lower rate of growth or retreat between 660 and 650 ka. It is at this time when surface waters in the Portuguese margin experienced a prominent drop (8 °C) in temperature (Fig. 3d). The beginning of this prominent cooling (659 ka) was synchronous with a low-amplitude warming phase recorded in Antarctic ice cores (Fig. 4b,d) and occurred nearly in phase with maximum obliquity of Earth's axis (Fig. 3d,g).

Unlike other Terminations, a weak cooling event (12.2 °C winter SST) was recorded at Termination VII, although this is one of the largest amplitude deglaciations. An also low amplitude drop in Ca/Ti reflects the small magnitude of this event (Fig.3c). Nevertheless, it coincided with IRD accumulation in site 980 (Fig. 4c) and was contemporaneous with Heinrich event 16.1 recorded at sites U1308 and U1302/03 (Hodell et al., 2008; Channell et al., 2012).

#### 5.1.4. MIS 15–13

In the upper part of our record, again SST experienced prominent cooling events at deglaciation between MIS 15b/a (7.7 °C winter SST) and at transition MIS 13b/a (11.4 winter SST). Two more short cooling events (9 and 9.7 °C winter SST) occurred at 561.35 and 555.87 ka, similar to those recorded in the subpolar cores 980 and U1314 (Fig. 4b).

A less pronounced cooling (5 °C drop) occurred at Termination VI that is also marked by a decrease in Ca/Ti (Fig. 3c-d).

### 5.2. Important reorganizations of North Atlantic circulation at the onset of northern hemisphere ice sheet retreats

While in other North Atlantic sites, especially those that are at higher latitude, SST remained relatively low during glacial times, the Portuguese margin was under the influence of relatively warm temperate waters during most glacial periods (Fig. 4b). The occurrence of temperate-warm surface waters at site U1385 during long time periods reflects the persistent influence of the North Atlantic Current (NAC) and its continuous advection of temperate-warm waters to the eastern margin of the subtropical North Atlantic gyre. The stadial-interstadial oscillations observed in this study were the result of enhanced/reduced advection of heat to the Southern Iberian Margin through the NAC. However, during most deglaciations a major reorganization of surface circulation in the North Atlantic reduced the northward flow of the NAC, promoting the southward expansion of cold subpolar waters along the western European margin.

The severe cooling episodes associated to most deglaciations were followed by a prominent warming event that marks the onset of a climate optimum interstadial event usually present in the first stage of interglacial periods. This climate optimum event was the warmest interstadial of each interglacial. Good examples of these high amplitude changes in temperature can be seen at Termination IX, when SST rose from 8.3 to 19 °C, and at transitions MIS 21f/e, MIS 21b/a, MIS 15b/a, etc. (Figs. 2c-d, 3d).

In parallel to the pronounced surface cooling events, the record of the Portuguese margin shows that deep-water circulation was also severely affected. A remarkable decrease in the benthic $\delta^{13}C$ is observed at deglaciations (Fig. 4a), especially in Terminations IX and VIII, but also at other glacial-interglacial transitions. These drops in benthic $\delta^{13}C$ have been recognized in other sites from the North Atlantic (W&F02; Hodell et al., 2008; Alonso-Garcia et al., 2011b; Ferretti et al., 2015). Drops in the benthic $\delta^{13}C$ have traditionally been attributed to slowdown of NADW formation triggered by lower sea surface salinities in the north Atlantic. In more recent climate cycles lower benthic $\delta^{13}C$ have been observed during Heinrich events that were triggered by freshwater discharge at times of ice sheet collapse (Shackleton et al., 2000; Skinner and Elderfield, 2007; Martrat et al., 2007). Pulses of repeated freshwater release to the North Atlantic originate the millennial-scale, stadial-interstadial oscillations of late Pleistocene caused by reduced/enhanced Atlantic meridional overturning circulation (AMOC) alternations. Events of reduced AMOC led to lower rates of heat transfer to the North Atlantic that resulted in decreased SST (e.g: Broecker et al., 1989; Stocker, 1999; McManus et al., 2004; Pisias et al., 2010). Although these millennial-scale climate oscillations are recorded at site U1385, the highest amplitude cooling/warming oscillations on the Portuguese margin coincided with deglaciations, both Terminations and the transitions from glacial to interglacial substages, and were marked by significant changes in the planktonic foraminifer assemblage from high percentages of Nps to increased relative abundance of subtropical species (Fig. 3e–f).

We interpret that the pronounced cooling events observed along the Iberian margin were triggered by freshwater released to the Atlantic at the onset of northern Hemisphere ice sheet retreats. The mechanism is similar to what happened during Heinrich stadials recorded at the end of the last two glacial periods (e.g. Rühlemann et al., 1999; Böhm et al., 2014), when the extension of the polar water and icebergs have been reported to reach the latitude of Southern Iberia (e.g., Skinner et al., 2003; Skinner and Shackleton, 2006). Although IRD were not recorded at site U1385 the advection of polar waters to the Portuguese margin only at deglaciations suggests that only freshwater perturbations of a certain magnitude, such as those related to ice-sheet retreats, had a profound effect on the SW Iberian margin.

The remarkable warming episodes that immediately followed deglaciations (Figs. 2a–c, 3a,d) were triggered by the resumption of NADW formation after the end of freshwater perturbations originated during ice sheet collapse. An increase in the strength of the AMOC led to invigoration of the NAC and the transport of warm surface waters to the Portuguese margin, which is recorded by a significant increase in the subtropical species in the planktonic foraminifer assemblage (Fig. 3f).

Ice sheets during Middle Pleistocene tended to collapse at times of high northern Hemisphere summer insolation that resulted from the combination of high obliquity and minimum precession (Imbrie et al., 1993; Huybers and Wunsch, 2003; Huybers, 2011). While obliquity mainly governed the time between deglaciations, precession determined the precise timing of deglaciations (Huybers, 2011) and ice discharge to the Ocean. This, in turn, triggered the major reorganizations of surface circulation in the North Atlantic and the advection of polar water to the Iberian margin. The coincidence in timing between these pronounced cooling events in Portugal with increasing northern Hemisphere summer insolation (Fig. 3d,g), strongly suggests a causal effect with ice sheet collapse events and deglaciations. Most of these events occurred at times of obliquity maxima when obliquity governs insolation at high latitudes. However there are two notable exceptions, the cooling episodes recorded at 650 and 710 ka when obliquity was relatively low or decreasing (Fig. 3g). Instead, these two cooling events occurred at times of increasing summer insolation driven by precession when the perihelion was aligned with northern Hemisphere summer solstice.

Recently it has been proposed that the energy received during summer (called integrated summer insolation, with summer defined as the period when insolation intensity exceeds the ~275 W/m$^2$ threshold) is the parameter that better reflects the amount of ice sheet melting (Huybers, 2006). The summer energy at 65°N (using the 275 W/m$^2$ threshold) shows high values during all terminations and transitions from glacial to interglacial substages (Fig. 3g), and may be advocated as the trigger for the major reorganizations in North Atlantic circulation observed in our Iberian margin record, in response to deglaciations.

### 5.3. North Atlantic SST gradient during ice sheet growth

One of the most characteristic features of the SST record in the Portuguese margin is that both the early phase of ice sheet growth, as recorded by the rapid increase in the benthic and planktonic $\delta^{18}O$, and glacial maxima, were coeval with warm SST at Site U1385 (Figs. 2a-c, 3a,b,d). In fact, off the Iberian margin none of the ice volume maxima corresponded to the lowest SST. When comparing SST records of this study with those from northern sites 980 and U1314 (Fig. 4b) an increasing N–S latitudinal SST gradient can be observed. After the pronounced warming recorded at the beginning of interglacials, millennial-scale climate changes are recorded both at high and at middle latitudes, but southern waters remained relatively warm, while the northern ones cooled as a result of the progressive extension of the northern Hemisphere ice sheets and associated southward advance of the AF (WF02; Alonso-Garcia et al., 2011a). This pattern is particularly noticeable at transitions MIS 19/18, MIS17/16 and MIS15/14. During the early phase of glacials, areas at latitudes of 37°N were influenced by the warm subtropical waters of the Azores current, as indicated by the presence of the subtropical assemblage in our Site (Fig. 3f). SST were similar during glacials, especially MIS 20, and interglacials, especially during MIS 20. A similar situation was observed in site U1313 during MIS 16, when warm and stratified surface waters coexisted with the presence of IRD layers produced by Heinrich-like Events (Naafs et al., 2011).

This lack of correspondence between SST and ice volume maxima was also recorded in the mid-latitude North Atlantic in more recent isotope stages, like MIS 6 (Martrat et al., 2007) and the Last Glacial Maximum, when surface water temperature was almost as high as today, according to SST reconstructions from the Portuguese margin (Cayre et al., 1999; de Abreu et al., 2003) and the North Atlantic at the same latitude (Chapman and Shackleton, 1998).

This mismatch between increasing global ice volume, cool SST in the northern latitudes and warm surface waters off Iberia supports the instrumental role that warm surface waters of mid-latitude North Atlantic had in building northern hemisphere ice sheets, providing an important source of water vapor to promote ice growth (Ruddiman and McIntyre, 1981; Sánchez Goñi et al., 2013).

## 6. Conclusions

Our study of the variation of planktonic foraminifers assemblages and SST, from the Shackleton site during the middle Pleistocene, as well as the comparison of our results with both benthic and planktonic $\delta^{18}O$ records and Ca/Ti data from the same Site (Hodell et al., 2015), allows the characterization of climatic conditions in the North Atlantic back to the ninth climatic cycle (867 ka). SST was generally colder during the middle Pleistocene than today off the southwestern Iberian margin, especially summer temperature, which was higher than today only during very short periods in some interglacials. During this period and superimposed on the glacial-interglacial variations, millennial-scale climatic variability was recorded.

All deglaciations on the Portuguese margin, both Terminations (particularly T IX and VIII) and the transitions from glacial to interglacial substages (MIS 21b/a, MIS 18e/d and especially MIS 15b/a), show a prominent (up to 10 °C in amplitude) cold-warm climate oscillation. This high amplitude variation in temperature during deglaciations is recorded by a remarkable change in the planktonic foraminifer assemblages from high relative abundance of the polar species Nps to high relative abundance of the subtropical association (Fig. 3e–f).

These high amplitude oscillations in temperature were the result of major reorganizations of Sea surface and deep water circulation in the North Atlantic triggered by freshwater releases to the Ocean when Ice sheets in the northern Hemisphere started to retreat. Reduced salinities at surface shutdown NADW formation and reduced the northward advection of heat and the transport of warm waters to the eastern margin of the subtropical gyre, causing the advection of subpolar waters to the SW Iberian margin. This scenario rapidly changed when the freshwater perturbation stopped. The reinitiating of NADW formation enhanced the strength of the AMOC leading to an intensification of the NAC and the flux of warm waters to the Iberian margin.

The comparison with SST records from higher latitudes of the North Atlantic reveals the development of a steeper latitudinal SST gradient between the sub-tropical and the sub-polar North Atlantic as ice sheets were growing in the northern Hemisphere, providing a source of water vapor that could promote the growth of ice sheets.

## Acknowledgments

We want to acknowledge the Integrated Ocean Drilling Program (IODP) for providing the sediment samples. Funding from Spanish projects GRACCIE (Consolider Ingenio 2011 CSD2007-00067, CGL2011-26493 and CTM2012-38248) is greatly acknowledged, as well as Castilla and Leon funding to "Grupo GR37" and project number SA263U14. MAG acknowledges the funding from the FCT fellowship SFRH/BPD/96960/2013. This research was also supported by the Natural Environmental Research Council Grant NE/K005804/1 and NE/J017922/1 to DAH. We also thank the kind help and useful comments from Dr. A. Voelker

## Appendix A. Planktonic foraminifer species and morphotypes identified

*Beella digitata*
*Candenia nitida*
*Globigerina bulloides*
*Globigerina falconensis*
*Globigerinella calida*
*Globigerinella siphonifera* (*aequilateralis*)
*Globigerinita glutinata*
*Globigerinita uvula*
*Globigerinoides conglobatus*
Globigerinoides ruber (pink)
*Globigerinoides ruber* (white)
*Globigerinoides sacculifer* (with sac)
*Globigerinoides sacculifer* (without sac)
*Globorotalia crassaformis* (dextral)
*Globorotalia crassaformis* (sinistral)
*Globorotalia hirsuta*
*Globorotalia inflata*
*Globorotalia scitula* (dextral)
*Globorotalia scitula* (sinistral)
*Globorotalia truncatulinoides* (dextral)
*Globorotalia truncatulinoides* (sinistral)
*Globorotaloides hexagonus*
*Globoturborotalita rubescens*
*Globoturborrotalita tenella*
*Neogloboquadrina dutertrei*
*Neogloboquadrina pachyderma* (dextral)
*Neogloboquadrina pachyderma* (sinistral)
*Orbulina universa*
*Pulleniatina obliquiloculata*
*Sphaeroidinella dehiscens*
*Tenuitella munda*
*Turborotalita humilis*
*Turborotalia quinqueloba*

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