Clim. Past Discuss., https://doi.org/10.5194/cp-2018-30
Manuscript under review for journal Clim. Past
Discussion started: 21 March 2018
© Author(s) 2018. CC BY 4.0 License.

Climate of the Past
Discussions

Role of the North Atlantic circulation in the mid-Pleistocene transition

Gloria M. Martin-Garcia[1], Francisco J. Sierro[1], José A. Flores[1], Fátima Abrantes[2]

[1] Department of Geology, University of Salamanca, Salamanca, Spain

[2] Marine Geology and Georesources (DivGM), Portuguese Institute for the Sea and Atmosphere, Lisbon, and Centre for Marine Sciences at University of Algarve, Portugal

Correspondence to: G. M. Martin-Garcia (gm.martin@usal.es)

Abstract

The southwestern Iberian margin is highly sensitive to changes in the distribution of North Atlantic currents, and to the position of oceanic fronts. In this work, the evolution of oceanographic parameters from 812 to 530 ka (MIS20-MIS14) is reconstructed, based on the analysis of planktonic foraminifer assemblages from site IODP-U1385 (37º34.285´N, 10º7.562´W; 2585 mbsl). By comparing the obtained results with published records from other North Atlantic sites between 41 and 55 ºN, basin-wide paleoceanographic conditions are reconstructed. Variations of assemblages dwelling in different water masses indicate a major change in the general North Atlantic circulation during MIS16, coinciding with the definite establishment of the 100-ky cyclicity associated to the Mid-Pleistocene Transition. In surface, this change consisted in the re-distribution of water masses, with the subsequent thermal variation, and occurred linked to the northwestward migration of the Arctic Front (AF) and the increase in the North Atlantic Deep Water (NADW) formation. During glacials prior to MIS 16, the NADW formation was very weak, which drastically slowed down the surface circulation; the AF was at a southerly position and the North Atlantic Current (NAC) diverted southeastwards, developing steep south-north, and east-west, thermal gradients and blockading the arrival of warm water, with associated moisture, to high latitudes. During MIS16, the important

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-30
Manuscript under review for journal Clim. Past
Discussion started: 21 March 2018
© Author(s) 2018. CC BY 4.0 License.

increase in the meridional overturning circulation, in combination with the north-westward AF shift, allowed the arrival of the NAC to subpolar latitudes, multiplying the moisture availability for ice-sheets growth, which worked as a positive feedback to prolong the glacials towards 100-ky cycles.

Keywords: Mid-Pleistocene Transition (MPT); North Atlantic circulation; North Atlantic Current (NAC); Planktonic foraminifers; Iberian margin; IODP-U1385; Glacials.

1 Introduction

Climate in the North Atlantic region is characterized by the continuous poleward heat flow carried out by the oceanic circulation. Warm and salty surface water originated in the tropical region is transported by the Gulf Stream and North Atlantic Current (NAC) towards the polar ocean and the northeast Atlantic, along the western European margin, transferring heat and moisture to the atmosphere during the process. Surface circulation and associated heat flow is pumped by sinking of surface water in the subpolar region and formation of the North Atlantic Deep-water (NADW). As a matter of fact, the Atlantic Meridional Overturning Circulation (AMOC) is responsible for ~50% of the total poleward heat advection (Sabine et al. 2004; Adkins, 2013).

The NAC forms the transition zone between the cold and productive waters located north of the Arctic Front (AF) (eg., Johannessen et al., 1994), and the warm and oligotrophic waters from the subtropical gyre in the South. Each water mass has distinct physic-chemical characteristics and specific planktonic foraminiferal assemblages (eg., Bé, 1977; Ottens, 1991; Cayre et al., 1999). Various studies have shown that surface water characteristics in the mid-latitude North Atlantic depend on the strength and position of the NAC and associated oceanic fronts (Calvo et al., 2001; Naafs et al., 2010; Voelker et al., 2010). During Pleistocene glacials, the AF migrated southward into mid-latitude North Atlantic (Stein et al., 2009; Villanueva et al., 2001), cold polar waters expanded to lower latitudes and the NAC did not reach as far North as during interglacials (e.g., Pflaumann et al., 2003).

© Author(s) 2018. CC BY 4.0 License.

After MIS21 a northwestward shift in the position of the AF began, both during interglacials (Hernandez-Almeida et al., 2013) and glacials (Alonso-Garcia et al., 2011), which culminated after MIS16 in a position similar to today (Wright and Flower, 2002 – henceforth W&F02). Coinciding with the final stage of this shift in the AF position, a major reorganisation of the meridional overturning circulation developed, resulting in increased NADW formation since MIS17 (Poirier and Billups, 2014). Both processes could have been related with the mid-Pleistocene transition (MPT), the major change in climate that occurred when the Earth´s climate system switched from a linear orbital (41 and 23 ky cycles) response, to a non-linear 100 ky forcing since ~650 ka (e.g., Ruddiman et al., 1989; Imbrie et al., 1993). Related with the shift in the AF position, warm and salty surface water reached subpolar latitudes during glacials, which would have provided the necessary humidity to prolong the growth of ice sheets, as well as enhanced meridional overturning – both processes acting as feedback mechanisms partly responsible for the change of the climate system phasing (Imbrie et al., 1993).

Over the last glacial cycle, the Iberian margin recorded both peak displacement events of the AF and periods of greater influence of subtropical water from the Azores Current (AzC) (eg., Martrat et al., 2007; Eynaud et al., 2009; Salgueiro et al., 2010). There is also evidence that polar to tropical planktonic foraminifers assemblages co-occurred in a latitudinal band around 35º – 40ºN during the Last Glacial Maximum (McIntyre et al., 1972), which suggests that the limit between both water masses was located slightly southwards than it is today (Fiúza et al., 1998; Peliz et al., 2005). Site IODP-U1385 (37º34´N) is located within this oscillating boundary, which makes it a privileged location to study changes in surface North Atlantic circulation through glacial-interglacial periods. The objective of this work is to study the evolution of the sea surface circulation in the North Atlantic from MIS20 to MIS14, and explore its possible influence in the MPT and the change in cyclicity of the Earth´s climate system. Analyses of planktonic foraminifer assemblages are used to identify the different water masses, and results from IODP-U1385 are compared with published data from other North Atlantic latitudes to obtain basin-wide conclusions.

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-30
Manuscript under review for journal Clim. Past
Discussion started: 21 March 2018
© Author(s) 2018. CC BY 4.0 License.

2 Materials and Methods

2.1 IODP Site U1385

The Southwestern Iberian margin is a focal location for paleoclimate and oceanographic research over long time periods (Hodell et al. 2013). Site IODP-U1385 was drilled at the so-called Shackleton Site (37º34.284´N, 10º7.562´W), at 2589 metres water depth (Fig. 1). In surface, this area lies under the influence of the *North Atlantic Central Water* (NACW), with a complex circulation pattern; in depth, the NADW flows between ~2,200 and 4,000 meters, above the *Antarctic Bottom Water* (AABW).

Today´s surface water circulation in the North Atlantic (Fig. 1a) consists of two different branches. The NAC, after reaching the subpolar ocean drifts southwards along Europe transporting the Eastern North Atlantic Central Water of sub polar origin (ENACWsp), formed north of 46º (Brambilla and Talley, 2008). In the south, the AzC, of subtropical origin (ENACWst) and formed along the Azores Front (Rios et al., 1992), drifts eastwards and bifurcates when approaching the continental margin. The ENACWst is saltier, warmer, less dense than the ENACWsp and overflows it along Iberia with a decreasing lower limit from south to north until ~42.7 ºN (Fiúza et al., 1998).

Sediments at Site U1385 define a single lithological unit with a high sedimentation rate (~10 cmky^{-1}), very uniform and dominated by calcareous muds and calcareous clays, with varying proportions of biogenic carbonate (23% - 39%) and terrigenous sediments (Stow et al., 2012).

2.2 Foraminiferal study

This study covers a section comprised between 67.2 and 94.6 crmcd (MIS14 - MIS20). The age model (Hodell et al., 2015) is based on the correlation of the benthic oxygen isotope record to the global benthic LR04 isotope stack (Lisiecki and Raymo, 2005).

Sampling was performed every 20 cm, providing a 1.76–ky resolution in average. A total of 147 samples 1 cm-thick were freeze-dried, weighed and washed over a 63-μm mesh. The >63 μm residue was dried, weighed and sieved again to separate and

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-30
Manuscript under review for journal Clim. Past
Discussion started: 21 March 2018
© Author(s) 2018. CC BY 4.0 License.

weigh the >150 μm fraction. Planktonic foraminifers taxa were identified (Kennett and Srinivasan, 1983) in aliquots of this last fraction containing a minimum of 300 specimens.

3 Results

The microfaunal analysis focused on species and assemblages that can be associated to North Atlantic surface water masses.

Neogloboquadrina pachyderma sinistral (Nps) is an indicator of polar water (Cayre et al., 1999; Pflaumann et a., 2003; Eynaud et al., 2009). At site U1385, this species is generally present during glacials MIS20, MIS18 (when highest percentages occurred), and the first half of MIS16 (Fig. 2b). Since ~650 ka, including maximal glacial conditions of MIS16 and MIS14, the presence of Nps is generally lower, with somewhat higher abundances associated to deglacial events, as inferred from sharp decreases in $\delta^{18}O$ (Fig.2a-b).

Turborotalita quinqueloba (Tq) dwells in cold waters and is usually associated with the AF (Johannessen et al., 1994; Cayre et al., 1999). Its percentage in U1385 is lower before MIS16 than since then (Fig. 2c). Highest values occur at ~650 ka and during MIS15b, the glacial interval that interrupted interglacial MIS15.

The NAC assemblage (Ottens, 1992; Appendix A) (NACass) is the most abundant one at this site. Previous to ~650 ka, its variation mirrors that of Nps and values are higher during interglacial conditions than during glacial periods (Fig. 2d). Since then it is the opposite, the highest percentages coinciding with full glacials MIS16a and MIS14a.

The warm surface assemblage (Vautravers et al., 2004; Appendix B) (WSass) is typical of the subtropical water transported eastwards by the AzC. In U1385, during glacials previous to MIS16, this assemblage is fairly abundant (MIS18) or even more abundant than during interglacials (MIS20); during MIS16, its percentage reduces as the glacial advances, and in MIS14, values are generally lower than in previous glacials (Fig. 2e).

5 Discussion

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-30
Manuscript under review for journal Clim. Past
Discussion started: 21 March 2018
© Author(s) 2018. CC BY 4.0 License.

5.1 North Atlantic circulation during glacials prior to MIS16

The location of sites 607 and 980 along the main core of the NAC towards the high latitudes of the North Atlantic, allowed us to monitor past changes in the northward heat transport, using planktonic foraminifer assemblages and SST estimations from both sites. By contrast, planktonic foraminifer assemblages at site U1385 are more influenced by the advection of heat to the northeastern Atlantic through the easternmost branches of the NAC, and especially by the AzC, that originates in the tropics and flows towards Iberia following the northern margin of the subtropical gyre. In consequence, with these three strategic sites, we can monitor changes in the main circulation systems of the NE Atlantic during the mid-Pleistocene, and estimate the heat advection to the north (SST gradient between site 607 and 980) and to the northeast Atlantic (SST gradient between site 607 and U1385) (see Fig. 4c-e).

During glacials MIS18 and MIS20, progressive cooling is recorded in sites 607 and 980. Though the cooling is more pronounced in the higher latitude, the SST gradient between both sites is relatively small and decreases largely towards the end of the glacials. In contrast, the Iberian margin remained relatively warm during most of MIS20 and a large part of MIS18, which undoubtedly reflects a continuous flow of the AzC to this region and the easternmost branches of the NAC.

At the subpolar latitude of site 980, the presence of polar water increased rapidly as glacial conditions advanced, as informed by very high percentages of Nps (Fig. 3c). During this time, the heat flow of the main core of the NAC, that transfers heat to these high latitudes, was interrupted or largely reduced, as can be inferred from the low temperatures registered in the Azores region (site 607, Fig. 4d). This reduced advection of warm water from the tropics triggered the southward advance of the AF, that surpassed 50 ºN during both glacials (W&F02). All this occurred at a time when the ice volume was very low (MIS18) or relatively low (MIS20) (Fig.3a).

While the heat flow to the latitude of site 980 decreased progressively along the glacials, and almost shut down at glacial maxima (MIS20a, MIS18e and MIS18a), the heat flow to the Iberian margin continued in the early part of glacial MIS18 and, especially, during MIS20, indicating a very active AzC and some southern branches

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-30
Manuscript under review for journal Clim. Past
Discussion started: 21 March 2018
© Author(s) 2018. CC BY 4.0 License.

of the NAC, during both glacials. These currents advected warm water eastward and deflected northward along the Iberian margin, probably overflowing the polar water mass, similarly to today´s IPC (Fig. 1a). The advection of the warm AzC to site U1385, according to WSass data, was only interrupted at Terminations TIX, TVIII, and at deglaciation MIS18e/d, when surface waters in the area were invaded by polar species, such as Nps (Fig. 2e,b). The negative thermal gradient between sites 607 and U1385 (Fig. 4d-e), that lie at approximately the same latitude, indicates that, an important fraction of the heat reaching the Iberian margin did not flow through the site 607 region, which suggests a significant contribution of the AzC at the northern margin of the subtropical gyre during glacials MIS20 and MIS18, as it occurs today.

During glacial maxima MIS20a, MIS18e and MIS18a, SST at the mid-latitude site 607 was very similar to that at the high-latitude site 980, which suggests either a complete shut-down of the NAC core flux, or a southward or southeastward migration of this current (Fig. 4c-d). In consequence, the southward migration of polar and subpolar fauna was recorded by increasing percentages of Nps in site 980 (W&F02) (Fig. 3c) and decreasing SST in site 607 (Ruddiman et al., 1989) (Fig. 4d). Nevertheless, site U1385 registered gradual cooling from the MIS19 interglacial optimum until TVIII (Martin-Garcia et al., 2015) (Fig. 4e), implying that the SW Iberian margin was always under the influence of the warmer water of the AzC. The presence of water masses of very different origin off Iberia, at the same time, is illustrated by the co-occurrence of relatively high percentages of Nps and WSass during MIS18 (Fig. 2b,e).

5.2 Changes in the North Atlantic circulation starting at glacial MIS16

MIS16 was a very prolonged glacial with extensive ice sheets; nevertheless, polar waters did not generally extend to the mid-latitude ocean, as suggested by the low percentages of Nps in ODP-607 (Ruddiman et al., 1989) and U1385 (Fig. 2b). As may be seen in figure 4c-d, the SST gradient between sites 607 and 980 increased after MIS18, and was significantly high during MIS16 and MIS14, in contrast to that observed during MIS20-18. This important SST decrease, between sites 607 and

© Author(s) 2018. CC BY 4.0 License.

980, must be the result of a significant heat loss to the atmosphere along the path of the NAC at that time and, consequently, a release of water vapour to the air in the North Atlantic.

In the mid-latitude ocean, a small negative SST gradient between sites 607 and U1385 still prevailed during MIS16-14 (Fig. 4d-e), indicating a continuous flux of heat to southern Portugal, that remained under the influence of the subtropical water transported by the AzC during most part of glacials MIS16 and MIS14. Contrary to previous glacials, the NAC kept vigorous during MIS16 – with an exception ~655 ka – and increased its strength as the glacial advanced, as inferred from microfaunal assemblages (Fig. 2d-e); this pattern repeated during MIS14. While in glacials MIS20 and18 surface water at the latitude of site 980 progressively cooled towards glacial maxima, without significant millennial-scale oscillations, in glacials MIS16 and MIS14, the surface ocean circulation was very unstable and the Arctic water migrated northward-southward site 980 very frequently. During short time periods, the NAC reached this subpolar site, conveying heat to the northern-latitude Atlantic (W&F02). However, this oscillation of the AF never affected middle latitudes, according to the fairly mild SST recorded both in the open ocean and in the continental margin during MIS16-14 (Ruddiman et al., 1989; Martin-Garcia et al., 2015) (Fig.4 c-d).

Contrary to that observed in MIS18 and MIS20, when SST was much colder at site 607 than at site U1385, the absence of a pronounced east-west thermal gradient in the mid-latitude ocean suggests a larger influence of the NAC to the Portuguese margin, as corroborated by microfaunal data (Fig. 2d). Glacial SST patterns observed in site 607 during MIS16 and MIS14 are also very different from those recorded in MIS20 and MIS18 (Fig. 4d). While in the older glacials SST gradually decreased towards the glacial maximum, in MIS16 and MIS14 this trend is not observed. In contrast, warmer waters were recorded during glacial maxima in both sites U1385 and 607 that were only replaced at TVII and TVI by short cold episodes of arctic water.

5.3 Implications of changes in the North Atlantic circulation associated to the MPT

© Author(s) 2018. CC BY 4.0 License.

Assuming a close correlation between the rate of AMOC and benthic $\delta^{13}C$ levels (Zahn et al, 1997; Adkins et al., 2005; Hoogakker et al., 2006), data from the subpolar North Atlantic (W&F02; Hodell et al., 2008) document enhanced NADW formation since MIS17, which resulted in decreased presence of AABW in mid-latitude and subtropical sites during glacials (e.g., Poirier&Billups, 2014; Hodell et al., 2015) (Fig. 3b). The increased production of NADW triggered the advection of relatively-warm NAC towards subpolar latitude, providing additional humidity to the area and, thus, enhancing the growth of ice sheets, which led to the prolonged and extreme glaciation of MIS16, one of the first and most prominent glacials of the "100-ky world". In addition, the intermittent advection of this warm water made ice sheets more vulnerable to internal instabilities, with the subsequent release of icebergs registered in the North Atlantic during MIS16 (e.g., W&F02; Hodell et al., 2008). The interaction between a more intense AMOC and ice sheet instabilities, recorded by rapid migrations of the AF north and south of site 980, resulted in punctual events of complete collapse of the NADW formation, like that at ~655 ka that coincided with one of the southernmost positions of the AF, according to the Tq record in site 980 (W&F02), and was also registered in U1385 by peaks in Nps and Tq, and very low percentage of NACass (Fig. 3b-e). Both this episode and the outstanding one ~650 ka, with the lowest $\delta^{13}C$ value since MIS18 in middle latitudes in coincidence with very high abundance of the NACass in high latitudes (Fig. 3b,e), points to an exceptionally vigorous but shallow NA overturning cell, underlain by significant volumes of southern-sourced water, similarly to the situation at the end of TII (Böhm et al., 2014). This mode of AMOC, according to benthic $\delta^{13}C$ records, maintained during glacial stages MIS16, MIS15b, and especially during MIS14, when the subpolar site 980 recorded > 0.25 ‰ higher $\delta^{13}C$ than southerner sites (W&F02; Hodell et al., 2015, 2016).

This vigorous AMOC mode recorded in MIS14 was the culmination of a sequence of increasing deepening of the overturning circulation cell that initiated in MIS22, and was registered by a tendency towards higher benthic $\delta^{13}C$, both in high and mid-latitude sites U1308 and U1313, from MIS22 to MIS14 (Hodell and Channell, 2016),

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-30
Manuscript under review for journal Clim. Past
Discussion started: 21 March 2018
© Author(s) 2018. CC BY 4.0 License.

and was especially noticeable during glacial stages. During MIS20 and MIS18, ice sheets collapses (W&F02) produced a continuous flux of meltwater pulses that kept very weak NADW formation; the deep North Atlantic being occupied by southern-sourced waters, according to very low benthic $\delta^{13}C$ recorded both in middle and high latitudes (W&F02; Hodell et al., 2015; 2016). During these glacials, the almost shutdown AMOC maintained the AF at a southern position and prevented the northward flux of the necessary moisture for the growth of ice sheets, which could not work as a positive feedback and extend glacial stages over obliquity and precessional (41- and 23 ky) cycles, as they worked during MIS16, one of the first and most prominent glacials of the "100-ky world".

6 Conclusions

By studying planktonic foraminiferal assemblages from the Iberian margin (IODP-U1385) for the interval 812–530 ka and comparing them with records from other sites between 41 and 55 ºN, we are able to trace paleoceanographic conditions across the North Atlantic from MIS20 to MIS14 and draw the following conclusions:

Variations of microfaunal assemblages associated to surface currents indicate a major change in the general North Atlantic circulation during this interval, coinciding with the definite establishment of the 100-ky climate phasing. In surface, this change consisted in the re-distribution of water masses and associated SST that happened linked to the northwestward migration of the AF during MIS16, and was related with the increasing NADW formation trend that initiated in MIS22.

Prior to MIS 16, the AMOC rate was very low, especially during glacials, the AF was at a southerly position, and the NAC diverted southeastwards, developing steep south-north and east-west thermal gradients, and blockading the arrival of warm water, with associated moisture, to the high latitude North Atlantic.

During MIS16, the NADW formation increased in respect to previous glacials, especially during glacial maxima, which resulted in the north-westward AF shift and enhanced surface circulation, allowing the arrival of the relatively-warm NAC to subpolar latitudes and increasing the moisture availability to continuing the ice sheets

© Author(s) 2018. CC BY 4.0 License.

growth, which would have worked as a positive feedback to prolong the duration of glacials to 100-ky cycles.

Appendix A: North Atlantic current assemblage (Ottens, 1991)

Globigerina bulloides
Globigerinella siphonifera (aequilateralis)
Globorrotalia inflata
Neogloboquadrina pachyderma dextral

Appendix B: warm surface assemblage (Vautravers et al., 2004)

Beela digitata
Globigerina falconensis
Globigerinella siphonifera (aequilateralis)
Globigerinoides ruber
Globigerinoides sacculifer
Globoturborotalita rubescens
Globoturborotalita tenella
Orbulina universa
Pulleniatina obliquiloculata

References

Adkins, J. 2013: The role of deep ocean circulation in setting glacial climates. Paleoceanography, 28, 539-561

Adkins, J.F., Ingersoll, A.P., Pasquero, C., 2005: Rapid climate change and conditional instability of the glacial deep ocean from the thermobaric effect and geothermal heating. Quat. Sci. Rev., 24, 581–594

Alonso-Garcia, M., Sierro, F.J., Flores, J.A., 2011: Artic fronts shifts in the subpolar North Atlantic during the Mid-Pleistocene (800-400 ka) and their implications for ocean circulation. Palaeogeogr. Palaeoclimatol. Palaeoecol., 311, 268-280

Bé, A.W.H., 1977: Recent planktonic foraminifera. Oceanic Micropaleontology, 1, Ramsay, A.T.S., Ed., Elsevier, New York, pp. 1-100.

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-30
Manuscript under review for journal Clim. Past
Discussion started: 21 March 2018
© Author(s) 2018. CC BY 4.0 License.

Böhm, E., Lippold, J., Gutjahr, M., Frank, M., Blaser, P., Antz, B., Fohlmeister, J., Frank, N., Andersen, M.B., Deininger, M., 2014: Strong and deep Atlantic meridional overturning circulation during the last glacial cycle. doi:10.1038/nature14059

Brambilla, E., Talley, L.D., 2008: Subpolar Mode Water in the northeastern Atlantic: 1. Averaged properties and mean circulation. J. Geophys. Res. 113, C04025, doi:10.1029/2006JC004062

Calvo, E., Villanueva, J., Grimalt, J.O., Boelaert, A., Labeyrie, L., 2001: New insights into the glacial latitudinal temperature gradients in the North Atlantic. Results from $U^{k'}_{37}$ sea surface temperatures and terrigenous inputs. Earth Planet. Sci. Lett., 188 (3-4), 509-519, doi:10.1016/S0012-821X(01)00316-8

Cayre, O., Lancelot, Y., Vincent, E., 1999: Paleoceaanographic reconstructions from planktonic foraminifera ogg the Iberian Margin: Temperature, salinity and Heinrich events. Paleoceanography, 14 (3), 384-396

Expedition 339 Scientists, 2012: Mediterranean outflow: environmental significance of the Mediterranean Outflow Water and its global implications. IODP Prel. Rept., 339. doi:10.2204/iodp.pr.339.2012

Eynaud, F., de Abreu, L., Voelker, A., Schonfeld, J., Salguerio, E., Turon, J.L., Penaud, A., Toucanne, S., Naughton, F., Sanchez-Goñi, M.F., 2009: Position of the Polar Front along the western Iberian margin during key cold episodes of the last 45 ka. Geoch. Geoph. Geosystems 10, Q07U05, doi:10.1029/2009GC002398

Fiúza, A.F.G., Hamann, M., Ambar, I., Díaz del Río, G., González, N. Cabanas, J.M., 1998: Water masses and their circulation off western Iberia during May 1993. Deep-Sea Research 45, 1127-1160

Hernandez-Almeida, I., Bjoklund, K.R., Sierro, F.J., Filippelli, G.M., Cacho, I., Flores, J.A., 2013: A high resolution opal and radiolarian record from the subpolar North Atlantic during the Mid-Pleistocene Transition (1069-779 ka): Paleoceanographic implications. Palaeogeogr. Palaeoclimatol. Palaeoecol., doi:10.1016/m.palaeo.2011.05.049

© Author(s) 2018. CC BY 4.0 License.

Hodell, D.A., Channell, J.E.T., 2016: Mode transitions in Northern Hemisphere glaciation: co-evolution of millennial and orbital variability in Quaternary climate. Clim. Past 12, 1805-1828, doi: 10.5194/cp-12-1805-2016

Hodell, D.A., Channell, J.E.T., Curtis, J.H., Romero, O.E., Röhl, U., 2008: Onset of "Hudson Strait" Heinrich events in the eastern North Atlantic at the end of the middle Pleistocene transition (~640 ka)? Paleoceanography 23, doi:10.1029/2008PA001591

Hodell, D., Crowhurst, S., Skinner, L., Tzedakis, P.C., Margari, V., Channell, J.E.T., Kamenov, G., Maclachlan, S., Rothwell, G., 2013: Response of Iberian Margin sediments to orbital and suborbital forcing over the past 420 ka. Paleocean. 28 (1), 185-199, doi: 10.1002/palo.20017

Hodell, D., Lourens, L., Crowhurst, S., Konijnendijk, T., Tjallingii, R. and the Shackleton Site Project Members, 2015: A reference time scale for Site U1385 (Shackleton Site) on the Iberian Margin. Global and planetary Change 133, 49-64, doi:10.1016/j.gloplacha.2015.07.002

Hoogakker, B.A., Rohling, E.J., Palmer, M.R., Tyrrell, T., Rothwell, R.G., 2006: Underlying causes for long-term global ocean $\delta^{13}C$ fluctuations over the last 1.20 Myr. Earth and Planet. Sci. Lett. 248 15-29, doi:10.1016/j.epsl.2006.05.007

Johannessen, T., Jansen, E., Flatoy, A., Ravelo, A.C., 1994: The relationship between surface water masses, oceanographic fronts and paleoclimatic proxies in surface sediments of the Greenland, Iceland, Norwegian seas. NATO ASI Series, 117, Zahn, R. et al. Eds., Springer-Verlag, New York, 61-85

Imbrie, J. et al., 1993: On the structure and origin of major glaciation cycles 2: The 100,000 year cycle. Paleoceanography 8, 699-735, doi:10.1029/93PA02751

Kennett, J.P., Srinivasan, M.S., 1983: Neogene Planktonic Foraminifera. A Phylogenetic Atlas. Hutchinson Ross Publishing Company, New York

Lisiecki, L.E., Raymo, M.E., 2005: A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography, 20, PA1003, doi:10.1029/2004PA001071

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-30
Manuscript under review for journal Clim. Past
Discussion started: 21 March 2018
© Author(s) 2018. CC BY 4.0 License.
Climate of the Past Discussions

Martin-Garcia, G.M., Alonso-Garcia, M., Sierro, F.J., Hodell, D.A., Flores, J.A., 2015: Severe cooling episodes at the onset of deglaciations on the Southwestern Iberian margin from MIS 21 to 13 (IODP site U1385). Global and Planetary Change 135, 159-169, doi:10.1016/j.gloplacha.2015.11.001

Martrat, B., Grimalt, J.O., Shackleton, N.J., de Abreu, L., Hutterli, M.A., Stocker, T.F., 2007: Four Climate Cycles of Recurring Deep and Surface Water Destabilizations on the Iberian Margin. Science, 317 (5837), 502-507, doi:10.1126/science.1101706

McIntyre, A., Ruddiman, W.F., Jantzen, R., 1972: Southward penetrations of the North Atlantic Polar Front: faunal and floral evidence of large-scale surface water mass movements over the last 225,000 years. Deep-Sea Res. 19, 61-77.

McManus, J.F., Oppo, D.W., Cullen, J.L., 1999: A 0.5-million.year record of millennial. scale climate variability in the North Atlantic. Science 283 (5404), 971-975, doi:10.1126/science.283.5404.971

Naafs, B.D.A., Stein, R., Hefter, J., Khélifi, N., De Schepper, S., Haug, G.H., 2010: Late Pliocene changes in the North Atlantic Current. Earth and Planetary Science Letters 298, 434-442, doi:10.1016/j.epsl.2010.08.023

Ottens, J.J., 1991: Planktic foraminifera as North Atlantic watermass indicators. Oceanol. Acta, 14, 123-140

Pflaumann, U., Sarnthein, M., Chapman, M., de Abreu, L., Funnell, B., Huels, M., Kiefer, T., Maslin, M., 2003: Glacial North Atlantic: sea-surface conditions reconstructed by GLAMAP 2000. Paleoceanography 18, 1065, doi:1010.1029/2002PA000774

Peliz, A., Dubert, J., Santos, A.M.P., Oliveira, P.B., Le Cann, B., 2005: Winter upper ocean circulation in the Western Iberian Basin - Fronts, eddies and poleward flows: an overview. Deep Sea Research Part I: Oceanographic Research Papers 52, 621-646, doi:10.1016/j.dsr.2004.11.005

Poirier, R.K., Billups, K., 2014: The intensification of northern component deepwater formation during the mid-Pleistocene climate transition. Paleoceanography 29, 1046-1061, doi:10.1002/2014PA002661

© Author(s) 2018. CC BY 4.0 License.

Railsback, L.B., Gibbard, P.L., Head, M.J., Voarintsoa, N.R.G., Toucanne, S., 2015: An optimized scheme of lettered marine isotope substages for the last 1.0 million years, and the climatostratigraphic nature of isotope stages and substages. Quat. Sci. Rev. 111, 94–106

Rios, A.F., Perez, F.F., Fraga, F., 1992: Water Masses in the Upper and Middle North-Atlantic Ocean East of the Azores. Deep-Sea Res. Pt. A, 39, 645-658

Ruddiman, W.F., Raymo, M.E., Martinson, D.G., Clement, B.M., Backman, J., 1989: Sea surface temperature reconstruction of DSDP Site 94-607 in the North Atlantic. doi:10.1594/PANGAEA.52373

Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., Wanninkhof, R., Wong, C. S., Wallace, D. W. R., Tilbrook, B., Millero, F. J., Peng, T. H., Kozyr, A., Ono, T. & Rios, A. F. 2004: The oceanic sink for anthropogenic CO_2. Sci., 305, 367-371

Salgueiro, E., Voelker, A.H.L., de Abreu, L., Abrantes, F., Meggers, H., Wefer, G., 2010: Temperature and productivity changes off the western Iberian margin during the last 150 ky. Quaternary Science Reviews 29, 680-695, doi:10.1016/j.quascirev.2009.11.013

Stein, R., Hefter, J., Grützner, J., Voelker, A., Naafs, B.D.A., 2009: Variability of surface water characterstics and Heinrich-like events in the Pleistocene midlatitude North Atlantic Ocean: Biomarker and XRD records from IODP Site U1313 (MIS 16-9). Paleoceanography 24, doi:10.1029/2008PA001639

Stow, D.A.V., Hernández-Molina, F.J., Alvarez-Zarikian, C.A., and Expedition 339 Scientists, 2012: Mediterranean outflow: environmental significance of the Mediterranean Outflow Water and its global implications. IODP Preliminary Report, 339, doi:10.2204/iodp.pr.339.2012

Vautravers, M.J., Shackleton, N.J., Lopez-Martinez, C., Grimalt, J.O., 2004: Gulf Steam variability during marine isotope stage 3. Paleoeanography 19, PA2011, doi:10.1029/2003PA000966

Villanueva, J., Calvo, E., Pelejero, C., Grimalt, J.O., Boelaert, A., Labeyrie, L., 2001: A latitudinal productivity band in the Central North Atlantic over the last 270 kyr:

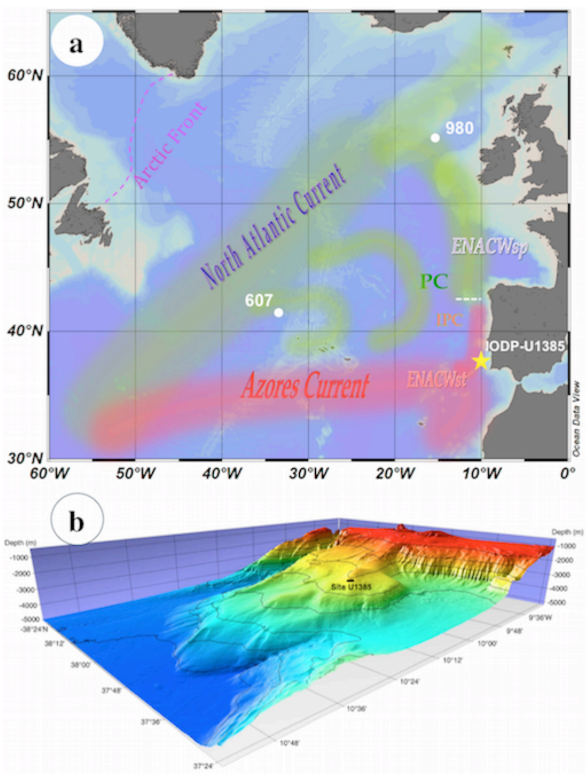
Clim. Past Discuss., https://doi.org/10.5194/cp-2018-30
Manuscript under review for journal Clim. Past
Discussion started: 21 March 2018
© Author(s) 2018. CC BY 4.0 License.

an alkenone perspective. Paleoceanography 16, 617-626, doi:610.1029/2000PA000543

Voelker, A.H.L., Rodrigues, T., Billups, K., Oppo, D., McManus, J., Stein, R., Hefter, J., Grimalt, J.O., 2010: Variations in mid-latitude North Atlantic surface water properties during the mid-Brunhes (MIS 9-14) and their implications for the thermohaline circulation. Clim. Past 6, 531-552, doi:10.5194/cp-6-531-2010

Wright, A.K., Flower, B.P., 2002: Surface and deep ocean circulation in the subpolar North Atlantic during the mid-Pleistocene revolution. Paleoceanography 17, 1068, doi:10.1029/2002PA000782

Zahn, R., Schönfeld, J., Kudrass, H.R., Park, M.H, Erlenkeuser, H. Grootes, P., 1997: Thermohaline instability in the North Atlantic during meltwater events: Stable isotope and ice-rafted detritus records from core SO75-26KL, Portuguese margin. Paleoceanography 12, 696-710



© Author(s) 2018. CC BY 4.0 License.

Figure 1. (a) Modern surface circulation in the North Atlantic and location of IODP-U1385 and other sites discussed in this paper. *ENACWsp* Eastern North Atlantic Central Waters of subpolar origin; *ENACWst*, Eastern North Atlantic Central Waters of subtropical origin; *IPC*, Iberian Poleward Current; *PC,* Portugal Current. The white dashed line represents the today´s approximate surface limit between *ENACWsp* and *ENACWst* (Fiúza et al., 1998). (b) Regional bathymetry of the SW Iberian margin, showing site U1385 (Expedition 339 Scientists, 2012).

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-30
Manuscript under review for journal Clim. Past
Discussion started: 21 March 2018
© Author(s) 2018. CC BY 4.0 License.

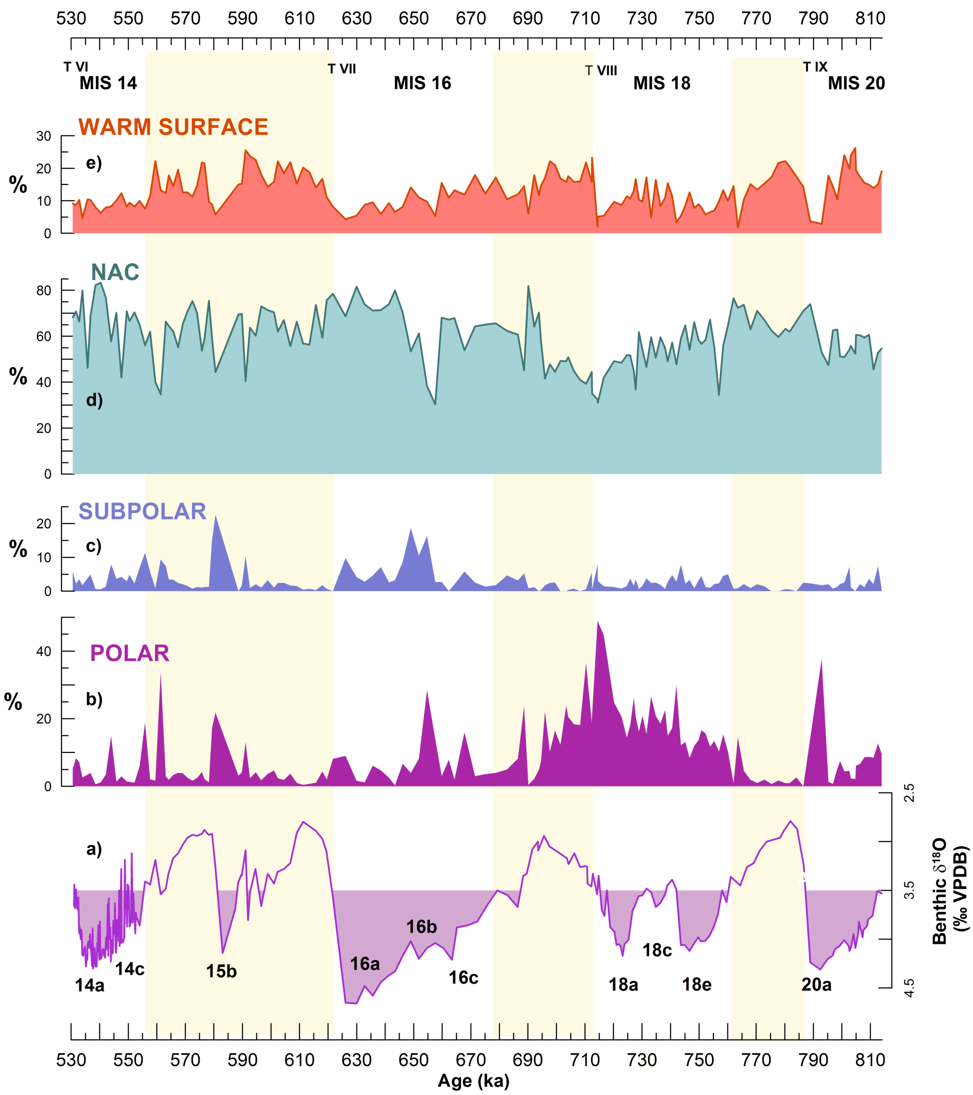


Figure 2. Relative abundance of planktonic foraminiferal species and assemblages in IODP-U1385 through MIS 14-20, and comparison with benthic isotope data from the same site. (a) Benthic δ^{18}O record (Hodell et al., 2015) with filling enhancing glacial conditions according to the threshold for the North Atlantic (McManus et al., 1999); glacial substages are named according to Railsback et al. (2015). Relative abundance of: (b) polar species *N. pachyderma* sinistral; (c) subpolar species *T. quinqueloba*; (d) NAC assemblage (as defined by Ottens, 1991); and (e) warm

© Author(s) 2018. CC BY 4.0 License.

surface assemblage (as defined by Vautravers et al., 2004). Yellow bands highlight interglacials. Terminations (T) are marked in roman numerals. IODP-U1385 isotopic record is from Hodell et al. (2015).

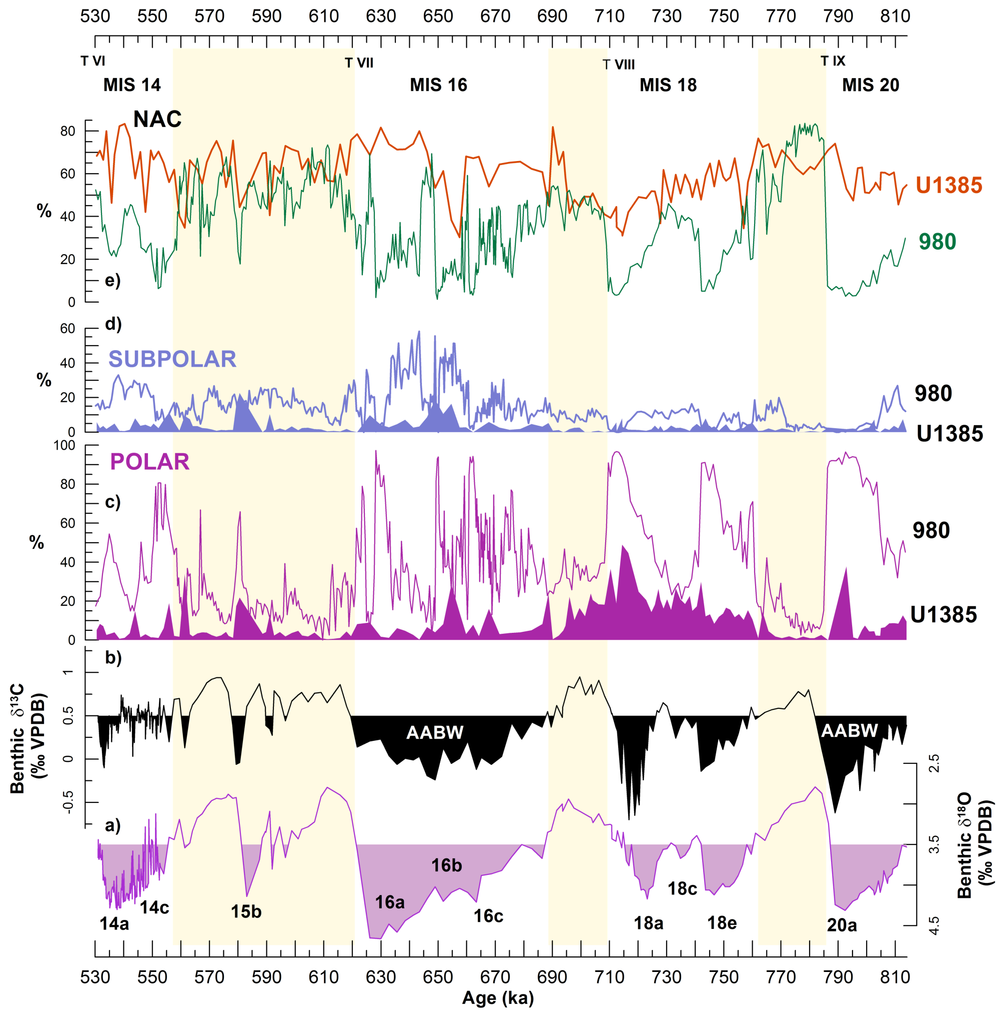


Figure 3. Comparison of faunal assemblages in the mid-latitude (IODP-U1385) and subpolar (ODP-980) North Atlantic. Benthic $\delta^{18}O$ (a), and $\delta^{13}C$ (b) from U1385 (Hodell et al., 2015); filling in (b) enhancing ^{13}C-depleted values typical for Antarctic bottom water (AABW) (Adkins et al., 2005). (c) Percentage of *N. pachyderma* sinistral in sites U1385 (filled) and 980. (d) Relative abundance of *T. quinqueloba* for sites U1385 (filled) and 980. (e) Relative abundance of the NAC assemblage (as defined by

© Author(s) 2018. CC BY 4.0 License.

Ottens, 1991) in sites U1385 (red) and 980 (green). Site 980 faunal data are from W&F02; for this work, the NAC assemblage of site 980 has been calculated using the published census counts, and its age model, re-calculated using the LR04-stock. IODP-U1385 isotope records are from Hodell et al. (2015). Yellow bands highlight interglacials. Terminations (T) are marked in roman numerals.

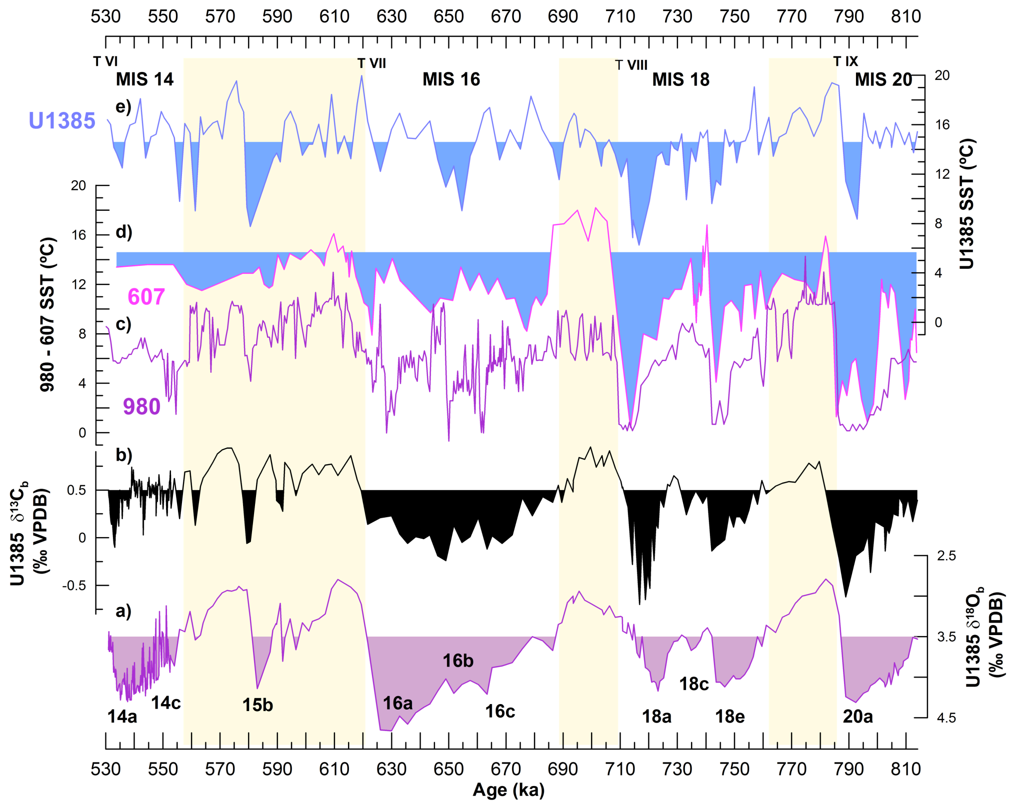


Figure 4. Reconstruction of the North Atlantic latitudinal and longitudinal thermal gradients. Benthic $\delta^{18}O$ (a) and $\delta^{13}C$ (b) from U1385 (Hodell et al., 2015). (c) SST from ODP sites 980 (purple) (W&F02) and 607 (pink) (Ruddiman et al., 1989), represented in the same axis. (d) SST from U1385 (blue) (Martin-Garcia et al., 2015). Filling in records from both U1385 and 607 enhances values lower than 14.5 ºC, the average SST in U1385 for the study interval.