Editor Initial Decision: Publish subject to minor revisions (review by Editor) (02 Mar 2015) by Dr. Thorsten Kiefer

Comments to the Author:

Dear Dr. Hernández-Almeida and co-authors,

First, apologies for taking so long to arrive at an editor decision. Partly this was caused be the required handover from editor Andrea Dutton to me. The rest is due to me not finding the time to go through all documents for a full overview.

However, I finally have read the manuscript, the reviews, and your author response. The referee reports had been relatively favourable. You addressed some of the points the referees mentioned and rebutted others. I think the manuscript is close to being acceptable. However, there are many small points I would still like you to address and one major point that relates to key point of publications, i.e. how well the data support the stated findings and conclusions. I would therefore ask you to revise the manuscript once more.

Thank you, with best regards,

Thorsten Kiefer

Thanks for the comments, the replies point-by-point are below each comment in bold.

* THE MAJOR POINT *

Even after your revisions I still share the concern of both referees who noticed that the relationship between IRD, T, and d18Osw is not as clear in the data as the text might imply. The revised text has changed a little to mention some exceptions, but you don't provide any statistical analysis. Moreover, figure 2 is not very transparent. I tried to follow what the vertical red-yellow bars are supposed to mean. The Fig. 2 caption says they "indicate IRD discharge associated with subsurface warming." This is too vague and subjective, and accordingly was done in an inconsistent way. For example, around 960 ka the bar seems defined by the d18Osw, at 980 ka by the IRD peak. As a minimum increase of transparency I ask therefore you to re-draw the vertical bars in a consistent way, either hinging all on d18O or all on (probably more logically) IRD, so that at least readers can assess more easily for themselves how robust the described relationship is. Figure 3 needs to be adjusted then as well to be consistent with Fig. 2. Moreover, as some semi-quantitative statistical visualisation I suggest that you colour-code the new table 1. You can, for example, colour fields in red where a significant warming occurred together with the IRD. You could even distinguish between a light red and darker red depending on how significant the warming occurs. Same with d18Osw and d13C. If doing such a significance analysis, please explain exactly how you did it, so that one can see that the analysis is clear, objective, and reproducible.

For inspiration, I recommend to look at Lang and Wolff, 2011, CP http://www.clim-past.net/7/361/2011/cp-7-361-2011.html

All events have been defined by the d18Osw maxima before or during IRD events, which is reflects the hydrological changes at subsurface (salt and temperature increase at subsurface). The IRD are the final consequence of the subsurface warming and iceberg discharge, so we do not expect to be simultaneous in all cases with subsurface warming and ventilation. In the text, we describe these

subsurface warming and salinity increases occurring 'prior to or during' the IRD events. The timing of the IRD peaks depends on more factors that cannot be constrained in this paper (e.g. ice-shelf thickness), so we show that the changes in the d18Osw occur immediately before or during the IRD discharge. Anyway, although the maxima of d18Osw sometimes is in the middle of the IRD peak, this one is preceded by a increasing trend in d18Osw that indicate a change in the conditions in the subsurface.

The values of table 1 have been calculated from the difference between the lowest d18Osw values at the beginning of the IRD, up to the d18Osw maxima during the event. This time interval has been used also for d13Cplanktonic and Mg/Ca. This is explained in the figure caption.

* MINOR BUT RELEVANT POINTS TO ADDRESS *

ABSTRACT

p1 line 17: remove or fill the empty "()"

Changed

p1 line 18 "at Site U1314": add location info like "from a sediment core from Gardar Drift in the subpolar North Atlantic" instead of site name, or in addition if you think the site number is relevant in the abstract.

Changed

p1 line 21 "temperatures and salinities": Where? *subsurface* I assume, but please be unambiguous by saying so.

Changed

p1 lines 22/23 "during periods of weaker Atlantic Meridional Overturning Circulation (AMOC) reduction": I guess you mean either "weaker AMOC" or "AMOC reduction" but NOT "weaker AMOC reduction".

Changed

TEXT

p2 lines 9/10 "insulating effect of extensive ice-shelves": Not sure what is meant here. How can the ice shelves themselves insulate? What do they insulate from what from what?

It means ice-shelves insulate the surface ocean from the atmosphere, allowing air temperature to decrease further. We have added 'insulating effect of extensive ice-shelves and sea-ice on the air-sea fluxes' to be more clear.

line 10: Replace "through" with "to".

p2 line 11 "in the dynamics of the North Atlantic subpolar gyre that controls the meridional heat and salinity transport": That sounds incorrect or at least imprecise. The meridional transport is controlled by the MOC, the subpolar gyre alone just circulates it in the northern North Atlantic. Maybe you mean the transport to the high-latitude northern North Atlantic or to the Nordic Seas? Please me more precise.

Changed, 0changes in the heat and salinity transport to the high-latitude northern North Atlantic'

p2 line 19/20 "This mechanism involves the coupling of the AMOC with ice-sheet dynamics, by an increase of the heat and salt export from low latitudes": This is the key hypothesis you are testing with data. Following the concern of Referee#2, I ask you to be clearer in describing the mechanism hypothesised. This does not need to be elegantly formulated, but clear. The missing link at the moment seems to be why a weaker AMOC should necessarily result in heat and salt export from low latitudes (in the subsurface layer, I suppose …). Either explain the hypothesised mechanism or give an indication that it is observed but not understood.

The mechanism is explained, according to the observations made by model simulation studies.

p2 line 23 "for abrupt climate events such as Heinrich and Dansgaard-Oeschger (D-O) cycles": This is the first time you mention Heinrich and Dansgaard-Oeschger (D-O) cycles. Two remarks: They should be mentioned in paragraph 1 already. And: cycles are not abrupt. And in fact Heinrich events are not occurring in a particularly cyclic way. So maybe better something like: "…for abrupt climate shifts such as those associated with Heinrich and Dansgaard-Oeschger (D-O) events".

Changed

p2 line30/31 "However, only few paleoceanographic studies using these proxies have been produced (Jonkers et al.,31 2010b;Peck et al., 2008;Peck et al., 2006).": In fact plenty of paired Mg/Ca and d18O studies have been produced. Therefore, please either specify this statement or delete it.

We meant studies using pared Mg/Ca d18O on N. pachyderma sin for older time intervals, beyond the MIS 3. Now it is specified.

p3 line 2: "out of" does not work. Replace with "other than" or "beyond"

Changed

p3 line 3 "paleo-community": Avoid such sloppy language in a paper. Paleoscience community or paleoclimate community or paleoceanographic community …

Changed by paleoceanographic community

p3 line 7 "high-quality/resolution": No lazy writing please. This is no ratio, therefore avoid the /. Reformulate and or replace.

Changed by high-resolution

p3 line 11 "similar structure transitions": Do you mean "similarly structured transitions … line in the D-O…"?

Changed by 'similar structure during transtions'

p3 line 13 "evaluate": You don't evaluate, you study or specify or constrain or elucidate …

Changed by constrain

p3 line 19: "temperatures": remove the plural-s

Changed

p3 line 25 “preceding”: Change to “prior to”.

Changed

p3 line 26 “indicating clear evidence”: Either a suggestive “indicating” or a firm “providing (clear) evidence”, but no mixture, please. My own suggestion would be to definitively avoid the “clear” because you are inly making inferences, not studying the ice shelf yourself.

Changed by ‘providing evidence’

p4 line 1 “rates average 9.3 cm/kyr from 1069 to 779 ka”: Decide on one abbreviation for year, either a or y or yr, and use throughout.

Changed by ka

p4 line 28 “a record d18O of seawater ”: Change to “a record of seawater d18O”.

Changed, a throughout the text.

p4 line 31: replace the with “a” in “the reductive cleaning step” or specify “as originally introduced by …”

Changed

p8 line 30 “Atlantic inflow”: Unclear: what inflow exactly?

Changed by ‘Atlantic inflow to the Nordic Seas’

p9 line 1 “salt inflow in the North Atlantic”: As above, this is unclear. What inflow exactly?

Changed by ‘higher salinity at subsurface depths in the subpolar North Atlantic’

p10 line 11/12 “destabilize ice-shelves creating pulses of ice-rafted debris”: In this description of the scenario please add the logical step of iceberg discharge. The mentioned IRD is only the expression of the discharged and melted icebergs. If ou keep IRD in here, note that no pulses of IRD exist, but layers of IRD or pulses of IRD release (or pulses of IRD deposition).

Change by ‘pulses of iceberg dischage’

p10 line 13 “suddenly released”: Released to where?

Subsurface heat is released to the atmosphere

CONCLUSIONS

The conclusion contains a lot of “would” formulations, which are not suitable here. Please formulate the conclusions you are confident to put forward. Moreover, please reconsider whether the last half-sentence referring to “the 100-kyr climate cycles of the Late Pleistocene” is a good and well-formulated conclusion. It is the first mentioning of the 100-yr cycle in tis entire paper. I think it should either prepared and discussed somewhere earlier in the paper, reformulated in the conclusions chapter, or deleted.

'Would formulations' deleted from the conclusion. The last sentence about 100-ka cycle has been removed, it is said that 'reflecting that rapid switches of the AMOC also occurred during the Early Pleistocene'

TABLE, FIGURES

Table 1: Consider colour-coding as I suggested. In caption be clearer what the number mean.

Table 1 has been colour-coded, and the explanation has been included in the caption

Fig. 2: Place the letters A-F more clearly so that they are unambiguously assigned to a curve or panel. Very confusing as it is. And in caption say what the green and grey sections mean in the benthic 13C curve.

Letters moved, green and grey sections (Cibicidoides and M. pompilioides, respectively) explained in the figure caption

Fig. 3 Caption: Mention what is "specific" about the intervals chosen.

They are just four close-up examples of the timing of the events.

SUPPLEMENT

Please (1) add a Table caption that also contains more metadata so that the table becomes more meaningful if used without the paper at hand. (2) Makes sure that the final version of the table fits the width of one table (in the current version the last column is on a separate page).

Subsurface North Atlantic warming as a trigger of rapid cooling events: evidences from the Early Pleistocene (MIS 31-19)

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Abstract

Subsurface water column dynamics in the subpolar North Atlantic were reconstructed in order to improve the understanding of the cause of abrupt IRD events during cold periods of the Early Pleistocene. We used paired Mg/Ca-δ^{18}O measurements Mg/Ca-based temperatures on *Neogloboquadrina pachyderma* sinistral of , a deep-dwelling (*Neogloboquadrina pachyderma* sinistral) planktonic foraminifera, and paired Mg/Ca-δ^{18}O measurements to to estimate the subsurface temperatures and seawater δ^{18}O of seawater at Site U1314from a sediment core from Gardar Drift, in the subpolar North Atlantic. Carbon isotopes on benthic and planktonic foraminifera from the same site provide information about the ventilation and water column nutrient gradient. Mg/Ca-based temperatures and seawater δ^{18}O of seawater suggest increased subsurface temperatures and salinities during ice-rafting, likely due to enhanced northward subsurface transport of subtropical waters during periods of weaker Atlantic Meridional Overturning Circulation (AMOC)AMOC reduction. Planktonic carbon isotopes support this suggestion, showing coincident increased subsurface ventilation during deposition of ice-rafted detritus (IRD). Subsurface accumulation of warm waters Warm waters accumulated at subsurface would result in basal warming and break-up of ice-shelves, leading to massive iceberg discharges in the North Atlantic. Release of heat stored at subsurface to the

atmosphere would help to restart the AMOC. This mechanism is in agreement with modelling and proxy studies that observe a subsurface warming in the North Atlantic in response to AMOC slowdown during the ~~MIS3~~Marine Isotope Stage (MIS) 3.

1 Introduction

Rapid climate events in marine and continental sediments, as well as ice-core records are a pervasive feature during the Last Glacial period (Dansgaard et al., 1993; Heinrich, 1988). Millennial-scale oscillations (Dansgaard–Oeschger –D-O- and Heinrich events) are characterized by abrupt shifts between warm/cold conditions, associated to ice-sheet oscillations, as evidenced by major ice-rafting events recorded in the North Atlantic sediments (Grousset et al., 2001; Heinrich, 1988). The mechanism responsible for these fluctuations is not fully understood. Most accepted hypotheses relate rapid oscillations in the Atlantic Meridional Overturning Circulation (AMOC) to insulating effect of extensive ice-shelves and sea-ice on the air-sea fluxes and/or ~~through~~ to freshwater perturbations causing changes in the ~~dynamics of the North Atlantic subpolar gyre that controls the meridional~~ heat and salinity transport to the high-latitude northern North Atlantic (Ganopolski and Rahmstorf, 2001; Clark et al., 2001; Hátún et al., 2005; Li et al., 2005).

More recently, a number of studies ~~and climate models~~ have proposed that increased iceberg discharge during cold stadial events may have resulted from the destabilization of marine ice-shelves by a ~~strong subsurface~~basal melting caused, in turn, by enhanced subsurface oceanic warming (Alvarez-Solas et al., 2010; Rasmussen and Thomsen, 2004; Marcott et al., 2011; Moros et al., 2002; Peck et al., 2008; Jonkers et al., 2010b; Ezat et al., 2014; Naafs et al., 2013). Model simulations indicate that weakening of deep convection at high latitudes in the North Atlantic results in a slow warming of intermediate depths (above 2500 m) by downward diffusion of heat at low latitudes (Rühlemann et al., 2004). This heat is accumulated at subsurface and wind-induced circulation enables northward transport of warm and salty waters in the northern North Atlantic (Shaffer et al., 2004; Mignot et al., 2007; Liu et al., 2009). This mechanism involves the coupling of the AMOC with ice-sheet dynamics, by an increase of the heat and salt export from low latitudes, warming of subsurface waters that would act as a positive feedback in the ice-shelf collapse. General agreement between model and proxy evidences support this explanation for abrupt climate shifts such as those associated with ~~events such as~~ Heinrich and ~~Dansgaard-Oeschger (~~D-O~~) cycles~~events.

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Application of Mg/Ca paleothermometry to deep-dwelling planktonic foraminiferal species constitutes a potential recorder of subsurface conditions (Kozdon et al., 2009; Simstich et al., 2003; Volkmann and Mensch, 2001) to test the feasibility of this hypothesis. Moreover, as foraminiferal $\delta^{18}O$ is controlled by temperature and~~-~~ seawater $\delta^{18}O$ ~~of seawater~~ ($\delta^{18}O_{sw}$), combining foraminiferal Mg/Ca temperature reconstructions with δ~~d~~^{18}O from the same species and samples allow to reconstruct $\delta^{18}O_{sw}$ as a proxy for salinity (Schmidt et al., 2004). ~~However, only few~~Several paleoceanographic studies using paired $\delta^{18}O$ and Mg/Ca measurements ~~paleoceanographic studies using these proxies~~ have been produced for the Marine Isotope Stage (MIS) 3 (Jonkers et al., 2010b; Peck et al., 2008; Peck et al., 2006). However, ~~. Therefore, more~~ studies with a similar approach are still required to understand subsurface temperature and circulation changes linked to AMOC reorganizations~~, especially for time periods out of the Marine Isotope Stage (MIS) MIS 3.~~ during older time intervals, such as the Early Pleistocene.

Although the paleo~~-community~~ceanographic community has extensively studied climate disruptions during most recent time scales, relatively little attention has been devoted to high-frequency climate variability in earlier periods when large Northern Hemisphere (NH) ice-sheets were same size as in the Late Pleistocene. Part of the gap of the study of these rapid climate oscillations in older time scales was due to the absence of high-~~quality/~~resolution paleoclimate records. However, during the last years, several studies carried out in International Ocean Drilling Project (IODP)~~IODP~~ cores have found robust evidences of abrupt climate events, (Bolton et al., 2010; Ferretti et al., 2010; Kleiven et al., 2011; Hernández-Almeida et al., 2012; Bartoli et al., 2006), with similar structure during transitions between cold (stadial) and warm (interstadial) phases of the D-O cycles as those found during the Last Glacial period.

To further ~~evaluate~~ constrain the relationship between subsurface ocean temperature and ice-sheet instabilities during the Early Pleistocene, we present here a new millennial-scale reconstruction of the temperature and $\delta^{18}O_{sw}$ of the subsurface Atlantic inflow using paired Mg/Ca and $\delta^{18}O$ measurements on the planktonic foraminifera *Neogloboquadrina pachyderma* sinistral (sin.) from IODP Site U1314. This is the first Mg/Ca temperature record produced in the subpolar North Atlantic for the Early Pleistocene. Previous paleo-~~SST~~ sea surface temperature~~s~~ (SST) records in the region are derived from planktonic foraminifera-based transfer functions (Hernández-Almeida et al., 2012) or alkenones (McClymont et al., 2008), but none of them give information about the thermocline conditions. The location of this core is at ideal latitude for monitoring changes in ice-sheet mass balance, and Mg/Ca values derived from *N. pachyderma* sin. allow~~s~~ to record changes in the subsurface temperatures (~~base of the~~ upper thermocline, ~200 meters depth) (Nürnberg, 1995) associated with oscillations in the AMOC. Our data suggest subsurface warming and salinity increases ~~preceding~~ prior to and during the iceberg events, ~~indicating clear~~providing evidence of coupling between basal melting and ice-sheet collapse as a mechanism controlling the millennial-scale events in the Early Pleistocene.

2 Study site and materials

Records were made using sediments from IODP Site U1314 (56.36°N, 27.88°W, 2820-m depth) from the southern Gardar Drift in the subpolar North Atlantic (Fig. 1A). Sedimentation rates average 9.3 cm/~~kyr~~ ka from 1069 to 779 ka, dated by tuning our benthic $\delta^{18}O$ curve to the benthic isotope stack of Lisiecki and Raymo (2005) (hereinafter referred to as LR04) by using AnalySeries ~~2.0~~ software (Paillard and Yiou, 1996) ~~(See Hernández-Almeida et al.~~ (See Hernández-Almeida et al., 2012 for further details)~~. for further details).~~

Site U1314 lies in the path of an extension of the North Atlantic Current (NAC), the Irminger

Current (IC), which splits from the NAC and turns toward the Greenland coast. The core of this relatively warm and salty water mass is distinguishable by its properties vertically down to 700 m depth. As the IC travels ~~eastwards~~ westwards it mixes with the colder ~~(≤ 0 °C)~~ and fresher ~~(< 34.4‰)~~ waters of the East Greenland Current (EGC), becoming less saline and colder (Malmberg, 1985)~~-~~.

Although today the limit of winter sea-ice (Arctic Front) lies north of Site U1314, it is known to have migrated southward during glacials of the Pleistocene bringing much cooler waters and potentially also sea-ice south of 60°N. (Ruddiman, 1977). Today, modern hydrographic conditions at Site U1314 are characterized by seasonal water temperatures ranging between 11.7 and 7.7 °C at 10 m depth and 8-7.4 °C at 200 m (Locarnini et al., 2013) with nearly constant salinity of 35.1-35.2 practical salinity units (p.s.u.) (Antonov et al., 2006) (Fig. 1B).

Winter convection of the cooled Atlantic surface waters in the Nordic Seas results in the formation of North Atlantic Deep Water (NADW), which flows south-ward as the Iceland-

Scotland Overflow Water (ISOW) (Figure 1a). This water mass flows at Site U1314 depth (Bianchi and McCave, 2000).

Subsurface water column conditions were determined through Mg/Ca ratios and stable isotopes measured on deep dwelling planktonic foraminifera *N. pachyderma* sin. This species inhabits and calcifies its shell~~f~~ in the subpolar North Atlantic at ~~water depths below the~~the upper thermocline, at ~200 m depth, (Kohfeld et al., 1996; Simstich et al., 2003; Nürnberg, 1995; Volkmann and Mensch, 2001). Therefore we assume that ~~*N. pachyderma* sin.~~ $\delta^{13}C$ on deep dwelling foraminifera *N. pachyderma* sin., which inhabits and calcifies at the upper thermocline, provides information on the ventilation rates of the subsurface water mass ~~at the thermocline~~(Hillaire-Marcel et al., 2011), while Mg/Ca measurements on the same species reflect water temperature changes and combined with $\delta^{18}O$ provides a record of seawater $\delta^{18}O$ ~~of seawater~~ (sw) of the subsurface ocean (Peck et al., 2006).

Around ~~to~~ 50-60 well-preserved tests of planktonic~~ic~~ foraminifera *N. pachyderma* sin.~~–~~ (>150 µm size fraction, non-encrusted~~–~~ tests) were ~~(>150 µm size fraction)~~ analysed in 542 samples for Mg/Ca ratio following Pena et al. (2005) procedure which includes ~~the~~ a reductive cleaning step. Dissolved samples were analysed on a Perkin Elmer Elan 6000 Inductively Coupled Plasma Mass Spec- trometer (ICP-MS) at the Scientific and Technological Centers of the University of Barcelona (CCiT-UB). External reproducibility for Mg/Ca ratio is estimated at 1.8% (2σ) based in the analysis of high-purity gravimetrically prepared standard solution (1.629 mmol/mol) measured routinely every four samples. Elemental ratios of Mn/Ca and Al/Ca ratios were analysed in parallel as quality controls for clay and Mn-rich mineral content. The recorded low values (Mn/Ca<0.5 mmol/mol; Al/Ca<0.15 mmol/mol) and their low correlation with the Mg/Ca ratios (R^2=0.2 and 0.004 respectively) indicate that the cleaning protocol satisfactorily removed most of the contaminant phases. Final Mg/Ca values were converted into temperatures values according to Elderfield and Ganssen (2000) equation.

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Stable isotopes (carbon and oxygen) records from benthic and planktonic foraminifera correspond to Hernández-Almeida et al. (2013b; 2012; 2013a). Analyses were carried out on planktonic foraminifera *N. pachyderma* sin. and on benthic foraminifera *Cibicidoides* spp. (mainly *Cibicidoides wuellerstorfi*) and *Melonis pompilioides* when former was absent. An adjustment factor (-0.11‰ for $\delta^{18}O$ and +0.6‰ for $\delta^{13}C$) calculated from replicates along the core was then applied to the *M. pompilioides* isotope values to produce a uniform isotope data set. . Analyses were carried out on a Finnigan MAT 252 mass spectrometer fitted with a CarboKiel-II carbonate preparation device at the CCiT from the University of Barcelona. Calibration to the Vienna Pee Dee Belemnite (VPDB) standard scale (Coplen, 1996) was made through the NBS-19 standard, and the analytical precision was better than 0.06‰ for $\delta^{18}O$ and 0.02‰ for $\delta^{13}C$.. Oxygen isotope values were then ice-volume corrected by scaling to the sea-level curve of LR04 using an LGM to late Holocene sea-level change of 120 m (Bintanja and van de Wal, 2008). Seawater $\delta^{18}O$ was calculated introducing paired Mg/Ca based temperatures and calcite δ^{18} O from *N. pachyderma* sin. in the paleotemperature equation offollowing Shackleton (1974). from paired Mg/Ca $\delta^{18}O$ on *N. pachyderma* sin.

It has been widely demonstrated that planktonic species do not always precipitate calcite in equilibrium. Based on the $\delta^{18}O$ measurements on seawater and *N. pachyderma* sin. tests from the Icelandic continental shelf, Smith et al. (2005) observed a $\delta^{18}O$ disequilibrium offset of 0.25‰. Others authors have also observed a disequilibrium offset in the oxygen isotope composition of *N. pachyderma* sin. of ~ 0.6‰ associated with post-gametogenic processes and thermal stratification of the water column in the Nordic Seas (Nyland et al., 2006). However, Jonkers et al. (2010a) did not find any offset in sediment trap samples from the Irminger Sea. Taking into account that samples used in this study are very close to Site U1314, we did not apply any correction factor to our calculated $\delta^{18}O_{sw}$. Contradicting studies indicate that this issue is not well constrained, with a need for further studies. Due to the uncertainties in *N. pachyderma* sin. vital effect and low SST during the MPT Mid-Pleistocene Transition that may overestimated the $\delta^{18}O_{sw}$ values, we suggest caution when interpreting in absolute terms.

3 Results

Mg/Ca ratio ranges between 0.7-1.25 mmol*mol^{-1} and Mg/Ca derived paleotemperatures range between 1.9 and 12.3°C (Fig. 2). The Mg/Ca and $\delta^{18}O_{sw}$ records show different patterns after and before MIS 25. From MIS 31 to MIS 25, the amplitude of the glacial-to-interglacial (G-IG) changes is low; temperatures and $\delta^{18}O_{sw}$ are stable, only punctuated by frequent millennial-scale oscillations, with temperature decreases of ~ 3°C and $\delta^{18}O_{sw}$ increases up to 1 ‰. Since MIS 25, amplitude of hydrographic changes was larger, with $\delta^{18}O_{sw}$ increased by ~1-0.5‰, and temperature by only 0.5°Creaching maxima up to 12°C during MIS 25 and 21,. with (between 5- 9°C) (Fig. 2). During this interval, there is also a pervasive suborbital variability, especially during glacial onset and during MIS 21. Ice-rafting episodes are characterised by relatively warm and saltier subsurface waters at the Gardar Drift. Rapid temperature and $\delta^{18}O_{sw}$ increases are observed before the IRD deposition, e.g. at 1060, 995, 924, 880 ka, or shortly after the iceberg discharge the iceberg started (Fig. 3). There are exceptions, and some events do not show this pattern, like at ~ 832 and 828 ka, subsurface warming is not observed, but there is increase in $\delta^{18}O_{sw}$ (Table 1).

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The most important feature of the difference between benthic and planktonic $\delta^{13}C$ ($\Delta\delta^{13}C$) are the abrupt decreases of ~1‰ during IRD events, when values are around 0‰. During warmer periods, $\Delta\delta^{13}C$ ranges between +1-1.4‰ (Fig. 4).

4 Discussion

Paleotemperature estimates based on Mg/Ca of *N. pachyderma* sin. at Site U1314 indicate that many of the IRD events were characterised by an abrupt subsurface warming (Fig. 2). The magnitude of this warming is not always the same across the studied interval, ranging between 2.5-8°C. The $\delta^{18}O_{sw}$ shows repeatedly higher values, indicating saltier waters during IRD deposition. Although these changes in temperature and salinity were simultaneous to the IRD events, in some cases (e.g. at 995 ka), subsurface waters started to warm up and to become saltier even before the ice-rafting. The positive excursions of the $\delta^{13}C$ signal from *N. pachyderma* sin. during these events were interpreted to indicate increasing subsurface ventilation in the North Atlantic (Hernández-Almeida et al., 2013b) (Fig. 2). Similar conditions of better ventilation at intermediate depths during IRD deposition are also evident from benthic $\delta^{13}C$ in Site 982 on the Rockall Plateau (Venz et al., 1999), which was suggested to be related to changes in the production of GNAIW (Fig. 2). Strong coupling between the Mg/Ca temperatures and $\delta^{18}O_{sw}$ fluctuations and subsurface circulation may reflect a change in the AMOC.

The accumulation of subsurface warming during ice-rafting events would correspond with a rapid development of the thermocline that stabilizes the water column and via intense basal melting and thinning of marine ice-shelves provokes a large-scale instability of the ice-sheets and retreat of the grounding line. With destruction of ice-shelves, ice streams may surge, leading to increased iceberg production. The ice-sheets located in regions with relatively mild conditions and high precipitation rates, such as Scandinavia and Iceland, are indeed very sensitive to millennial climate variability, and then respond quickly to warmer conditions pr~~u~~oducing iceberg discharges ~~exhibit a brief and rapid increase in iceberg flux during warmings~~ (Marshall and Koutnik, 2006). The difference between benthic and planktonic $\delta^{13}C$ ($\Delta\delta^{13}C$), used to indicate the nutrient gradient between subsurface and bottom water (Charles et al., 2010), gives additional information about the ventilation of subsurface and deep waters. The short-term periods of low $\Delta\delta^{13}C$ values (~0‰) during IRD discharges suggest water column vertical mixing and formation of Glacial North Atlantic Intermediate Water (GNAIW) ~~GNAIW~~ south of the Arctic Front.

After iceberg calving decreased, sudden release of heat accumulated at subsurface, broke the upper stratification (Mignot et al., 2007). Inflowing warm and salty Atlantic waters are again in contact with the surface ocean, and there is an efficient release of heat to the atmosphere, ~~and destabilized the water column (Mignot et al., 2007). Saltier and warmer water brought to the surface from below resulted~~ resulting in an intensified AMOC~~,~~ characterized by deeper and stronger deep-water circulation (Schmidt et al., 2006; Liu et al., 2009). Onset of deep convection in the Nordic Seas and NADW production led to a shut-down of GNAIW production (Venz et al., 1999). The nutrient gradient profile shows rapid increases up to 1.4‰ reflecting the establishment of a strong nutricline between deep and ~~intermediate~~ subsurface waters (Fig. 4). The switch to deep convection and a strong AMOC overshooting caused a decrease in subsurface temperatures and $\delta^{18}O_{sw}$, suggesting the return toward a 'normal water column' state.

Although the mechanism that characterizes the subsurface climate instabilities involves higher Mg/Ca temperatures, planktonic $\delta^{13}C$ and $\delta^{18}O_{sw}$, some of the events are missing some of these features. At ~ 832 and 828 ka, IRD events are not accompanied clear by subsurface warming, while changes in $\delta^{13}C$ and $\delta^{18}O_{sw}$ are evident (Table 1). This could imply that more active subsurface depth ventilation was due to by brine rejection during the wintertime sea-ice production, as occurs in high-latitude seas (Aagaard and Carmack, 1989; Horikawa et al., 2010). However, this alternate mechanism to explain the eventual higher density of subsurface waters in absence of warmer waters is speculative, and more robust evidences of brine rejection during sea-ice formation are needed.

We are still uncertain about the driving mechanism that ~~enhanced~~ drives northward transport of warm and salty subsurface waters during episodes of weak AMOC. We suggest that analogous mechanisms involving ice-shelf and sea-~~-~~ice expansion in the NH that are invoked to explain D-O cycles during the Last Glacial period (Petersen et al., 2013), operated also during the Early Pleistocene. Growing ice-shelves in the subpolar North Atlantic during the onset of glaciations would change land surface albedos producing a reduction of air sea temperature (Broccoli and Manabe, 1987). This cooling would increase the extent and thickness of sea-–ice, resulting in a higher insulation of the surface ocean (Li et al., 2005; Kaspi et al., 2004), causing convection shutdown in the high latitude North Atlantic and reduced NADW formation. A weakened subpolar gyre circulation would supply less cold and fresh water to the Atlantic inflow to the Nordic Seas, making it saltier (Thornalley et al., 2009; Hátún et al., 2005). Warm and salty waters accumulating at the subsurface would be eventually transported poleward,– as there is still convection but at intermediate depths, and finally causing causes a temperature inversion and salt inflowhigher salinity at subsurface depths in the subpolar North Atlantic (Shaffer et al., 2004). Alternatively, abrupt slowdown of the AMOC may respond to different mechanisms including internal oscillation regulated via atmospheric CO_2 concentration and Southern Ocean wind intensifications (Banderas et al., 2012; Alvarez-Solas et al., 2011).

Several modelling and paleoclimate studies also show intermediate or subsurface warming in the North Atlantic during IRD events as a response to AMOC reorganizations (Liu et al., 2009; Mignot et al., 2007; Brady and Otto-Bliesner, 2011), accompanied by a southward shift in the convection cell from the Nordic Seas to the subpolar North Atlantic (Brady and Otto-Bliesner, 2011; Venz et al., 1999; Voelker et al., 2010; Oppo and Lehman, 1993). This scenario characterized by a temperature inversion, would represent an analogous situation to modern conditions in Arctic Ocean. In this region, Atlantic waters flowing via the West Spitsbergen Current cause an Atlantic-derived temperature and salinity maximum at 200-500 m water depth, under the permanent sea-ice cover (Bauch et al., 1997).

Temperature sensitive proxies from other North Atlantic sites display similar features that are interpreted as subsurface warming conditions prior to ice-rafting events and deglaciations during the Last Glacial period and the Holocene. Risebrobakken et al. (2011) documented intensified subsurface warming in the Nordic Seas using planktonic foraminifera faunas as a response to a reduced strength of the AMOC through the deglaciation and the early Holocene. Mg/Ca derived temperatures from *N. pachyderma* sin. in two cores from the Northeast Atlantic also support the inferred warming during Heinrich events. These records show upper ocean stratification and high subsurface temperatures initiated during ice-rafting events

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(Jonkers et al., 2010b; Peck et al., 2008). Jonkers et al. (2010b) explained the low planktonic $\delta^{13}C$ values of *N. pachyderma* during these events as a result of reduced ventilation of subsurface waters due to the insulating effect of a meltwater lens and/or a sea-ice layer. Our high planktonic $\delta^{13}C$ values during these rapid cooling events, however, indicate that more intense subsurface ventilation and/or nutrient depleted subtropical waters were exported to the subpolar North Atlantic, which is supported by the similarity with the intermediate water $\delta^{13}C$ signal from Site 982 (Venz et al., 1999) (Fig.2). We argue that such disagreement between planktonic $\delta^{13}C$ profiles could be explained by the southward shift of the Polar Front as far as 42°N during cold periods of the Late Pleistocene (Ruddiman and McIntyre, 1981a; Eynaud et al., 2009), limiting the fraction of nutrient depleted subtropical waters exported northward (Mix and Fairbanks, 1985) compared to the Early Pleistocene.

Similar warm conditions during Heinrich events and stadials are also evident from benthic faunas and Mg/Ca ratios in benthic foraminifera from the Nordic Seas, indicating that warming was probably extended to intermediate depths (below 1000 meters) by downward diffusion of subtropical ocean heat during times of slow North Atlantic overturning (Rasmussen and Thomsen, 2004; Marcott et al., 2011; Ezat et al., 2014) . These results are in agreement with subsurface warming events at the subtropics during Heinrich 1 (Schmidt et al., 2012). All of these observations suggest that subsurface warming was a basin-wide phenomenon during periods of reduced AMOC in ~~response to a reduction in the AMOC during~~ MIS3. To better ~~evaluate~~ constrain this scenario for the Early Pleistocene, more subsurface marine records situated in key regions from the North Atlantic are required. The proposed scenario is in agreement with modelling studies that reveal basal melting of the ice-shelf and periodic pulses of iceberg discharge as a response to strong reduction of the AMOC (Mignot et al., 2007; Shaffer et al., 2004; Alvarez-Solas et al., 2010; Manabe and Stouffer, 1997).

Finally, from the similarity of the paleoclimatic records with the model simulations and modern observations, we argue that observed increased subsurface ocean warming could play a leading role in ~~the ice-sheet's increasingly negative mass imbalance over the next decades in the Arctic region,~~ ~~and~~ the massive break-up of ice-shelves in the Antarctic Ocean (Vaughan and Doake, 1996; Rignot and Jacobs, 2002; MacAyeal et al., 2003).

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5 Conclusions

The Mg/Ca derived paleotemperature and $\delta^{18}O_{sw}$ oscillations prior and during IRD discharges at Site U1314 across the Early Pleistocene (MIS 31-19) are related to changes in subsurface circulation. The mechanism operating during episodes of rapid-climate coolings consists in a reduction in the AMOC during periods of extensive ice-shelves and sea-~~-~~ice in the subpolar North Atlantic. Deep water convection sites shifted south of the Polar Front and production of GNAIW increased at the expenses of NADW. ~~Enhanced p~~Poleward transport of warm and salty subsurface subtropical waters during these episodes ~~would~~ thinned and destabilize ice-shelves creating pulses of ~~ice-rafted debris~~iceberg discharge. ~~Deep water convection sites shifted south of the Polar Front and production of GNAIW would increase at~~ the ~~expenses of NADW. Salt and h~~Heat accumulated at the subsurface ~~would be~~was suddenly released to the atmosphere when the ice-sheet collapsed, resulting in an intensified AMOC. Analogous mechanisms based on subsurface warming as a trigger for millennial-scale climate variability were proposed for Heinrich events or D-O cycles recorded during Late Glacial period (Alvarez-Solas et al., 2010; Shaffer et al., 2004), reflecting that rapid switches of the AMOC also occurred ~~before the establishment of the 100-kyr climate cycles of the Late Pleistocene.~~ during the Early Pleistocene.

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FIGURE CAPTIONS

Table 1. Summary of the changes in Mg/Ca, $\delta^{18}O_{sw}$ and planktonic $\delta^{13}C$ during the IRD events. The amplitude of the change is calculated from the difference between the point where $\delta^{18}O_{sw}$ starts to increase prior to the IRD event and the $\delta^{18}O_{sw}$ maxima during the IRD event. The events are colour-coded, being deep red the strongest change, and white the weakest.

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Figure 1. (a) Location of IODP Site U1314. Modern surface (red), and deep circulation (blue) in the North Atlantic: East Greenland Current (EGC), North Atlantic Current (NAC), Irminger Current (IC), Iceland Scotland Overflow Water (ISOW), North Atlantic Deep Water (NADW). (b) Plots of temperature (ºC) (red) and salinity (p.s.u.) (blue) versus depth obtained from the World Ocean Atlas 2013 (Locarnini et al., 2013; Zweng et al., 2013). Map generated with Ocean Data View v.3.4.3. software (Schlitzer, 2008).

Figure 2. Data for IODP Site U1314 spanning marine isotope stages (MIS) 31-19 vs. age. From top to bottom: (a) benthic (Hernández-Almeida et al., 2013a) and (b) planktonic $\delta^{18}O$

(Hernández-Almeida et al., 2012); (c) benthic $\delta^{13}C$ (Hernández-Almeida et al., 2013a) (*Cibicidoides* spp., green; adjusted *M. pompilioides*, grey); (d) planktonic $\delta^{13}C$ (red) (Hernández-Almeida et al., 2013b) vs. benthic $\delta^{13}C$ from Site 982 (blue) (Venz et al., 1999); (e) $\delta^{18}O_{sw}$ reconstruction from paired Mg/Ca-$\delta^{18}O$ measurements on the planktonic foraminifera *Neogloboquadrina pachyderma* (sin.); (f) derived Mg/Ca-paleotemperature calculated using exponential temperature equation of Elderfield and Ganssen (2000). (g) IRD/g (Hernández-Almeida et al., 2012). ~~Red v~~Vertical bars indicate ~~IRD~~ maxima of the $\delta^{18}O_{sw}$ associated with each subsurface heat and salt increase. ~~discharge associated with subsurface warming.~~

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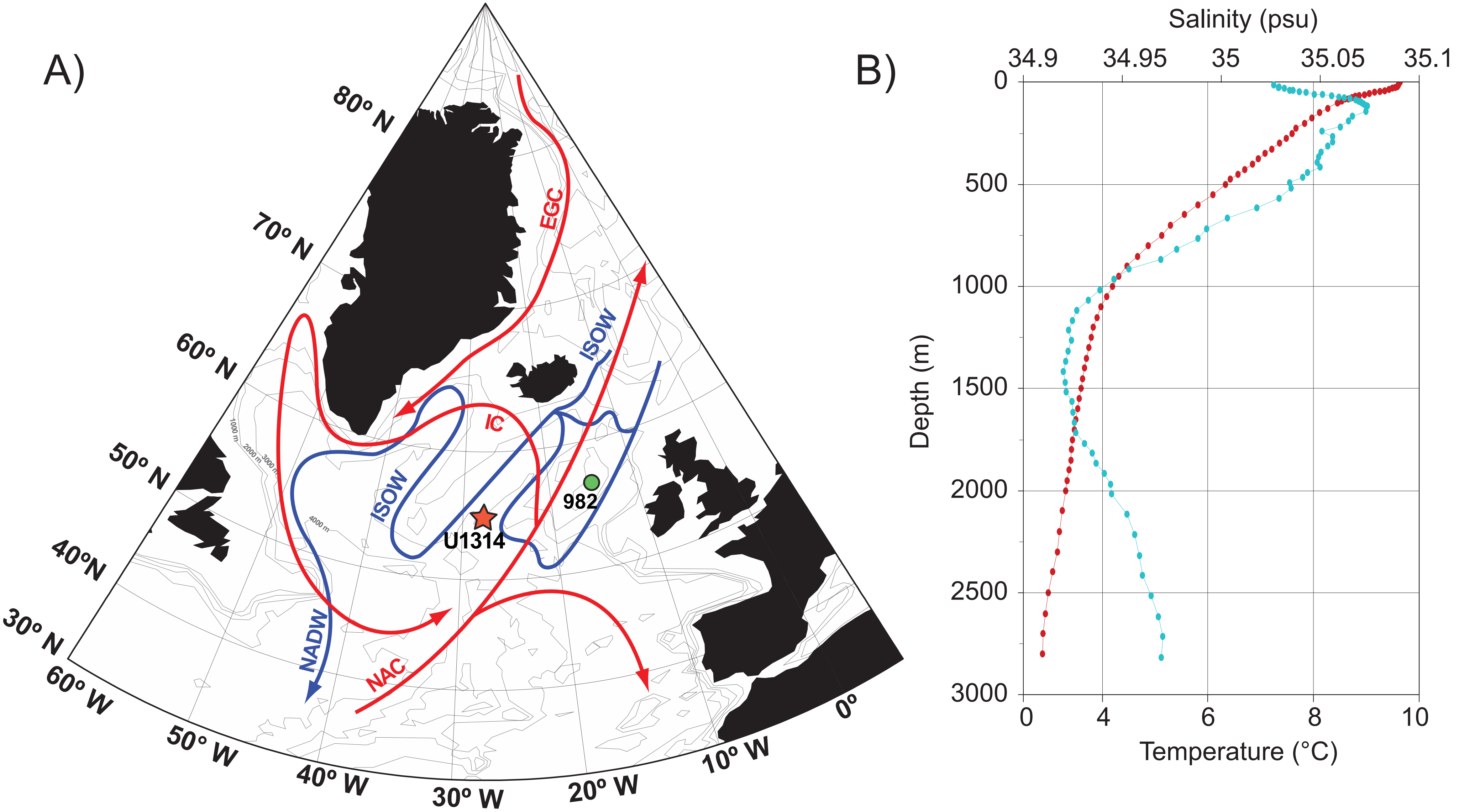
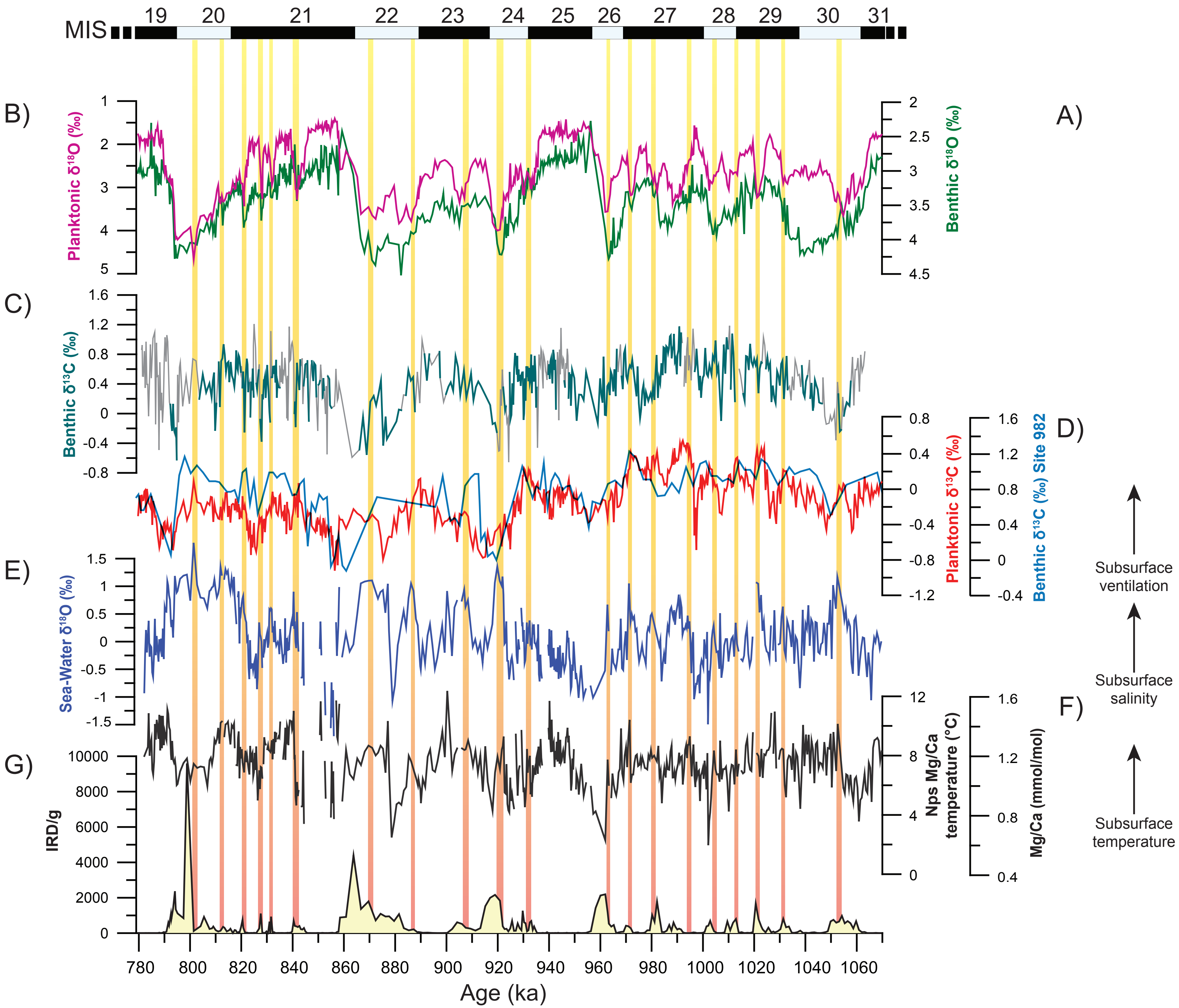
Figure 3. Comparison between ~~SST~~ Mg/Ca-paleotemperature, $\delta^{18}O_{sw}$, planktonic $\delta^{13}C$ ~~planktonic foraminifera~~ and IRD/g for Site U1314 during specific intervals.

Figure 4. Data for IODP Site U1314 spanning marine isotope stages (MIS) 31-19 vs. age. (a) $\Delta\delta^{13}C_{b-p}$ (b-benthic, p-planktonic) (i.e. *C. wuellerstorfi*/*M. pompilioides*-*N. pachyderma* sin.); (b) IRD/g (Hernández-Almeida et al., 2012).

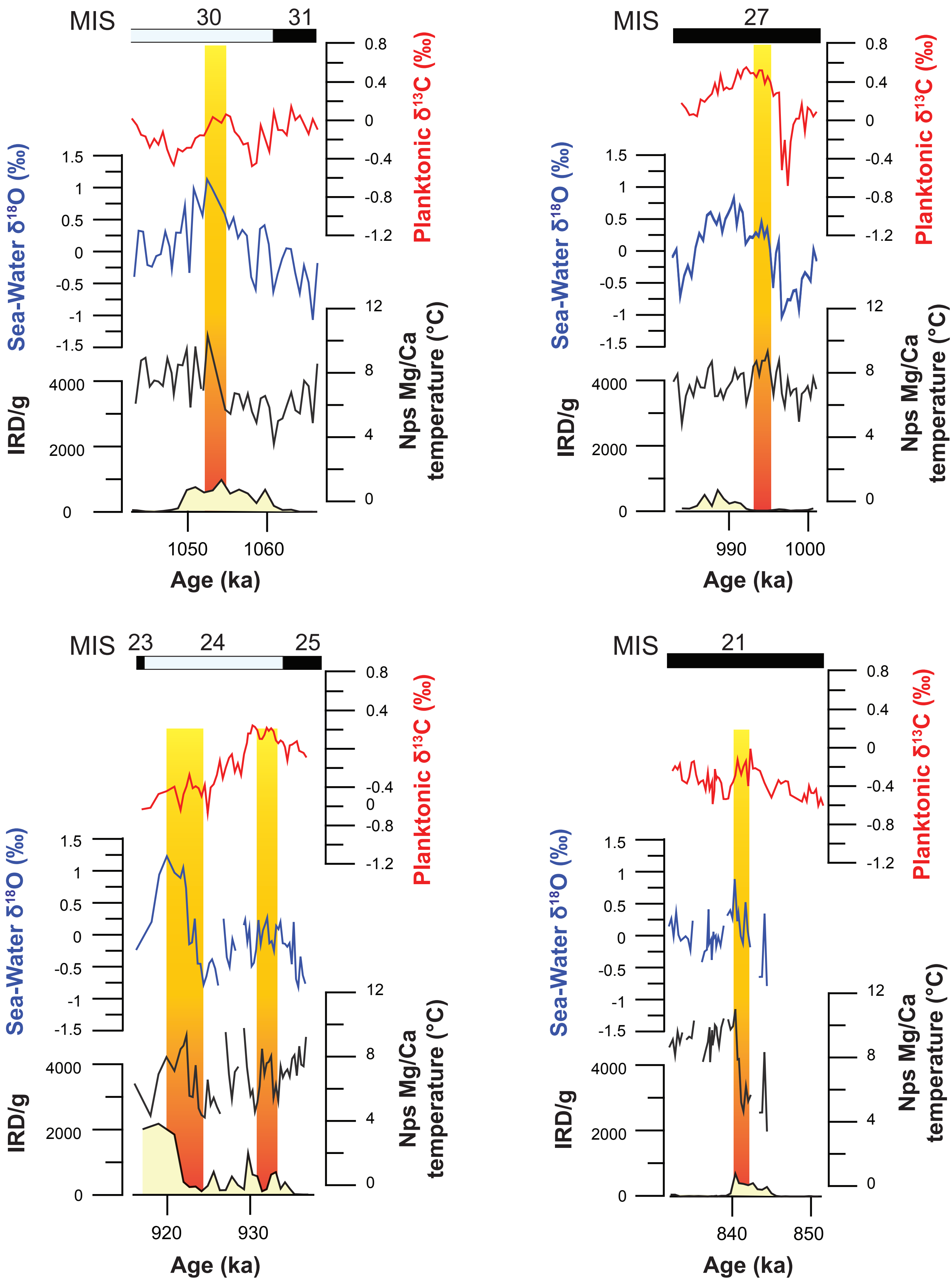
IRD Event	Warming Mg/Ca (°C)	Salinity $\delta^{18}O_{sw}$ (‰)	Ventilation $\delta^{13}C_{plank}$ (‰)
MIS 30 (~1052 ka)	5.4	1.7	0.4
MIS 29 (~1033 ka)	4	1.4	0.4
MIS 29 (~1020 ka)	0.92	1.3	0.7
MIS 28 (~1012 ka)	1.7	0.7	0.4
MIS 28 (~1004 ka)	6.2	0.9	0.5
MIS 27 (~995 ka)	2.9	1.5	0.9
MIS 27 (~981 ka)	3.6	1.1	0.3
MIS 27 (~970 ka)	3.1	1.5	0.3
MIS 26 (~961 ka)	1.8	1.2	0.02
MIS 24 (~931 ka)	2.8	0.7	0.3
MIS 24 (~924 ka)	4	1.8	0.2
MIS 23 (~910 ka)	2.9	1.3	0.5
MIS 22 (~888 ka)	3.2	1.5	0.1
MIS 22 (~870 ka)	6.3	2	0.4
MIS 21 (~842 ka)	6.4	1.6	0.4
MIS 21 (~830 ka)	0.1	0.6	0.4
MIS 21 (~828 ka)	0.5	0.8	0.3
MIS 21 (~820 ka)	1.7	1.1	0.5
MIS 21 (~815 ka)	3	0.8	0.2
MIS 21 (~805 ka)	1.5	1.2	0.3



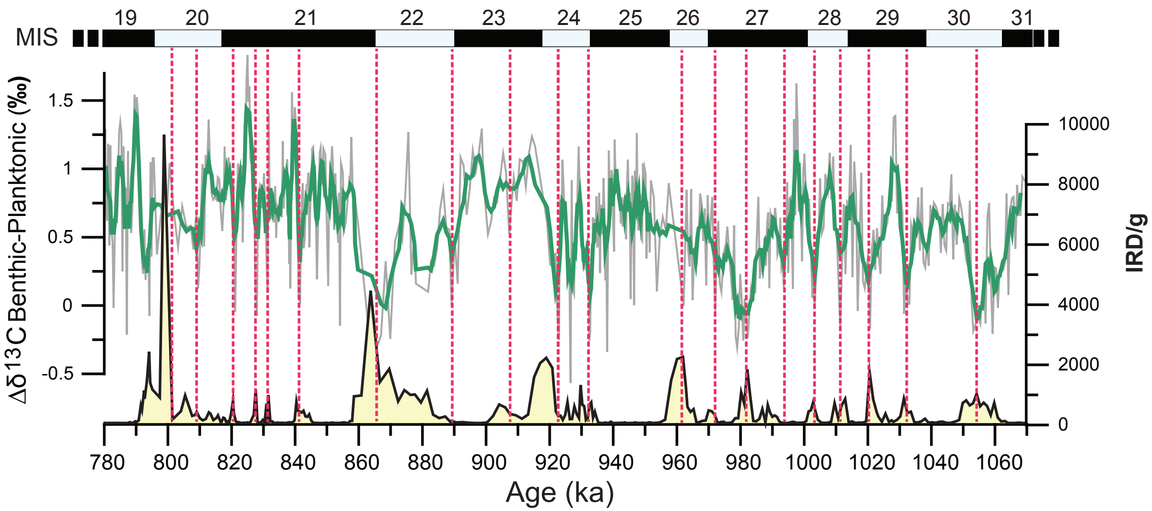
A)
80° N
70° N
60° N
50° N
40°N
30° N
60° W
50° W
40° W
30° W
20° W
10° W
0°
EGC
IC
ISOW
ISOW
NADW
NAC
U1314
982
B)
Salinity (psu)
34.9
34.95
35
35.05
35.1
Depth (m)
0
500
1000
1500
2000
2500
3000
Temperature (°C)
0
4
6
8
10



MIS
19
20
21
22
23
24
25
26
27
28
29
30
31
A)
B)
C)
D)
E)
F)
G)
Planktonic δ18O (‰)
Benthic δ18O (‰)
Benthic δ13C (‰)
Planktonic δ13C (‰)
Benthic δ13C (‰) Site 982
Sea-Water δ18O (‰)
Nps Mg/Ca temperature (°C)
Mg/Ca (mmol/mol)
IRD/g
Age (ka)
Subsurface ventilation
Subsurface salinity
Subsurface temperature



MIS
30
31
27
23
24
25
21
Planktonic δ13C (‰)
Sea-Water δ18O (‰)
Nps Mg/Ca temperature (°C)
IRD/g
Age (ka)
1050
1060
990
1000
920
930
840
850



MIS
19
20
21
22
23
24
25
26
27
28
29
30
31
Δδ13C Benthic-Planktonic (‰)
1.5
1
0.5
0
-0.5
IRD/g
10000
8000
6000
4000
2000
0
780
800
820
840
860
880
900
920
940
960
980
1000
1020
1040
1060
Age (ka)