We appreciate the thoughtful and constructive comments by the reviewers.

Both reviewers agree that the description of the subsurface warming events found uis very general, and there are some exceptions that have to be noted. The reviewers also list a number of technical/typing errors, and minor changes in the figures, which we have been changed according to the reviewer, unless is specified.

Below we respond to the comments by each reviewer.

Anonymous Referee #1

This manuscript presents new Mg/Ca and d18O results from IODP Site U1314 on the planktonic foraminifer N. pachyderma (sin) for the Early Pleistocene MIS 31-19. N. pachyderma was selected to reconstruct changes in subsurface water mass conditions. The records show warmer and saltier conditions just before and during the maximum occurrences of IRD deposition. These results are interpreted as representing a similar mechanism which was suggested for MIS 3 in the N-Atlantic that accumulated warmer and saltier water leads to instability of the ice sheets and accordingly to the release of ice bergs. The manuscript is well written and provides an interesting addition to the growing collection of records which show the link between subsurface warming in the N-Atlantic, rapid climate oscillations, and ice sheet instability. I only have a few comments, which are detailed below. In summary, I recommend this manuscript for publication in Climate of the Past after minor revisions have been made.

A first main question which came up is “Why MIS31-19?” What makes this interval specifically interesting to perform these reconstructions on?

This interval, between MIS31-19, was chosen because we wanted to demonstrate that persistent suborbital-scale variability in North Atlantic sea-surface and deep-water hydrography were already recognisable and operating at this time, independently of the duration of glacial–interglacial cycles as in the MIS3, and responded to the same mechanism as in the Late Pleistocene (link to equatorial and tropical regions).

In general I do agree that subsurface warming regularly occurs during IRD events, it nevertheless also seems to be quite random. For some events it fits perfectly, but for other maximum temperature events no IRD occurs or a maximum in IRD is accompanied by minimum temperatures (e.g. 960 ka). Even though intensity/duration of each separate event may have been different and therefore the responses may have been different, I wonder if this is not also a case of small age model mismatches and/or the result of the different responses which were found in Mignot et al. (2007). They argue that they only find subsurface warming when intermediate water formation also ceased along with NADW formation. As long as intermediate water formation continued no subsurface warming developed.

This comment agrees with the second reviewer. While we agree that a more detailed description of the features observed in each proxy during the IRD events, we do not think can be called ‘random’. In the example indicated by reviewer (960 ka) indeed there is a maximum of subsurface temperatures at the beginning and during the IRD discharge. The cooling occurs at the IRD maxima, but we do not think that this does not agree with the mechanism proposed here (subsurface warming triggering ice-sheet instability). Following suggestion from Reviewer #2, we provide a more elaborated description of the subsurface warming events.

Mg/Ca on N. pachyderma has never been straightforward to interpret. Therefore, I think it is essential to include the actual Mg/Ca data into the paper/supplement. It is mentioned that Mn/Ca was <0.5 mmol/mol. Such values still seem relatively high. Was there a correlation between Mn/Ca and Mg/Ca or were any samples identified as outliers with high Mn/Ca?

Mg/Ca data has been included in the Supplementary data, and a vertical axis has been included in the Figure 2, next to the Mg/Ca based temperatures. Mn/Ca ratios are bellow 0.5 and the average value is 0.2 mmol/mol. These values are well bellow to those previously shown to be problematic for Mg/Ca-temperature reconstructions (Pena et al., 2005). In addition, the fact that any significant correlation occur between the Mn/Ca and Mg/Ca record (R^2=0.2) and the absence of outliers support that the studied samples do not have any relevant Mg contamination problem associated to the presence of Mn-rich phase.

Minor comments:

Page 4034-13: Change to “Subsurface accumulation of warm waters” 4035/4043: I suggest adding a recent paper by Ezat et al. (2014) who used benthic foraminifer Mg/Ca to show warming during such stadials in the Nordic Seas. Also, Naafs et al. (2013) provide a review of IRD events since the Pliocene, including the studied interval in here.

4036-19: “allow”

4037-8: should be westwards 4037: Properties of the Irminger Current seem to contradict each other between the 2nd and 3rd paragraphs.

This section has been rewritten.

4037-24: “shell”; rephrase the sentence, it seems that it should be two separate sentences. 4038-3: delete “to”; “planktonic”; -6: “on a . . .”

4038-26: The reference “Hernández-Almeida et al., 2013b” is missing.

4039-13: “overestimate”;

-16: delete “ratio”;

-27: delete “the iceberg”

4041-7-10: Please rephrase; the order seems wrong; shouldn’t it be that because of the accumulation of subsurface heat you destabilize the water column which then leads to the increased calving, and then finally AMOC speeds up again?

We think the chronology of events is right. During the weakened AMOC, heat accumulates at subsurface, causing inversion in the water column (Shaffer et al. 2004). Once there is enough heat to melt the ice-sheet, this retreats. According to Mignot et al. (2007), strong vertical temperature inversion facilitates destabilization the water column, inflowing warm Atlantic water is in contact with the surface, and there is an efficient release of heat to the atmosphere, starting convection shortly after the end of the perturbation. We have rephrased last sentence to clarify it.

4042-3: “intensifications”

-22: “orbital-scale”: It would be interesting to show this, is temperature changing similar to the other proxies as shown in Hernandez-Almeida et al. (2010)?

This comment is not clear; do not know what it means with similar change in temperature as in Hernández-Almeida et al. (2010).

4044-9: “at the expense of”

Fig.2-4: Add error bars, both on d18Osw and Mg/Ca of pachyderma these can be quite significant.

The external reproductibility of the Mg/Ca of pachyderma is indicated in the methods section: ‘External reproducibility for Mg/Ca ratio is estimated at 1.8%’

Fig. 3: add MIS numbers to the plots.

Suggested References: Ezat, M., T. Rasmussen, J. Groeneveld (2014). Persistent intermediate water warming during cold stadials in the SE Nordic seas during the last 65 kyr. Geology, doi:10.1130/G35579.1 Naafs, B.D.A., J. Hefter, R. Stein (2013). Millennial-scale ice rafting events and Hudson Strait Heinrich (-like) Events during the late Pliocene and Pleistocene: a review. Quaternary Science Reviews 80, 1-28

Anonymous Referee #2

Review Hérnandez-Almeida et al. Subsurface North Atlantic warming as a trigger of rapid cooling events: evidences from the Early Pleistocene (MIS 31-19). Hérnandez-Almeida et al. present a new record of Mg/Ca-derived temperature of the subsurface dweller Neogloboquadrina pachyderma sinistral for core U1304 for the time interval 1069-779 ka. The Mg/Ca-derived record is furthermore used to deconvolved the sea water d18O and temperature component from the previously published N. pachyderma d18O record and obtained indirect indications about subsurface salinity changes. These new records (subT, d18Osw) are used in combination with previously published (by the same authors and collaborators) records of planktonic and benthic stable isotopes and IRD counts to infer increases in subsurface temperature and salinity in connection with IRD events due to reorganizations of the AMOC. Similar subsurface developments have been reported during MIS 3 also in relation to IRD discharges and AMOC reorganization. To my knowledge, this is the 1st time that such events are described for the around-MPT world and show that climate instability is the norm rather than the exception of glacial times. The manuscript will be of interest for a wide audience of Climate of the Past and I recommend publication after moderate revisions. I find that the main point of the manuscript, warmer+saltier subsurface water accompanying IRD events can be more elaborated to describe differences between different periods. It seems tricky to make a generalization of this mechanism to all the IRD events since some of them happen during interglacials, when maybe there was indeed no sea ice cover for the warm subsurface waters to flow underneath and destabilize.

Although some of the IRD occur during interglacials, the benthic d18O clearly shows that they took place during periods of increased ice volume. The mechanism proposed here does not imply sea-ice formation, but involves large ice-shelves on continents. The subsurface warming would melt and destabilize the ice-sheets, and then those would release the IRD. Sea-ice do not necessary imply IRD discharge.

For example 4040-6 “many of the IRD events”, it is probably more precise to leave it more open, “a number of the IRD events”, “some of the IRD events” and subsequently try to group them and describe which fit in that mechanism of which do not. You could prepare a table in which the information listed below is included (and other info you consider relevant).

IRD ca 1060-1050 ka (MIS 30): warming yes, salt yes, increase plk d13C (=ventilation) yes, also increase in plk d18O (not seen in benthic d18O), likely related to salinity. IRD started before, during cooling.

IRD ca 1033 (MIS 29): warming no, salt yes? (difficult to see in Fig.2), ventilation yes, also increase in plk d18O not seen in benthic d18O, likely related to salinity

IRD ca 1020 (MIS 29): warming no, salt yes, ventilation yes, also increase in plk d18O

IRD ca 1012 (MIS 28): warming very small, salt very small, ventilation yes, no really increase in plk d18O,

IRD ca 1008 (MIS 28): warming yes, salt yes, ventilation yes, before IRD discharge

IRD ca 995 (MIS 27): warming yes, salt yes, ventilation yes, before IRD discharge,

IRD ca 817 (very small, MIS 20): warming yes, salt yes, ventilation yes, no increase in plk d18O

IRD ca 800 (MIS 20): warming no, salt yes, ventilation yes, increase in plk d18O

Table has been included, but instead of included cualitative changes (yes/not), we have included the change in Mg/Ca, d18Osw and d13Cplanktonic.

On view of this listing, my impression is that the subsurface mechanism operated during glacial periods or mild interglacial periods (pre-MPT) when the ice sheets were still close to the critical mass defined by McManus (ben d18O 3.5 per mil) for instability. The IRD events during MIS 21 do not relate with subsurface warming and were more likely caused by the surface cooling described in the 2012 paper. In that paper all IRD were related to surface cooling so it would be good to integrated both interpretations here, for example playing with the critical mass of ice sheets, how a big ice sheet allow to growth sea ice, do we then need the subsurface warming to break that sea ice? Can any of the salt anomalies be related to brine rejection and not to entering of subsurface subtropical derived waters? In general I miss the integration of the nicely presented previous records (MAT-SST, radiolaria and opal for productivity) and I think that the discussion could benefit from some mentioning to those. I suggest a bit more of elaboration on the differences of the events rather than putting them all in the same box.

First of all, thank you for the comments and the suggestion of a table describing the different events. For the IRD events during MIS 21, only the ones at ~ 832 and 828 ka do not show very clear Mg/Ca warming. However, they do show the other features attributed to the general mechanism proposed here: increase in the d18Osw and higher planktonic d13C-smaller planktonic-benthic d13C gradient, which indicate better ventilation at subsurface-intermediate depths. Would the brine rejection favour this better conditions at subsurface? It is a possibility, although we do not have any proxy that may reflect the sea-ice formation and brine rejection. We added this option for events ~ 832 and 828 ka.

We think that including other proxies, especially radiolarians and opal, which are related to productivity, would drift from the main point of the manuscript; subsurface warming.

Comments to the text:

4034: Please note that paleoceanographers have a tendency to use the term AMOC as a synonym of NADW convection. Sensu stricto AMOC refers to latitudinal transports in the Atlantic and there is such latitudinal transport at surface and subsurface (northward) and at depth (southward), being both connected. In this regard it is contradictory to say (4034-10) “enhanced northward transport of subsurface waters in periods of reduced AMOC”. You probably mean here periods of reduce NADW/NAIW (NCW) formation. If this is the case, I have difficulties understanding the mechanism that would lead to increase transport of subsurface waters to the north; to my understanding the more NADW convection, the more feeding waters are needed to be transported to the north and subsequently sunk. To me it would make more sense to think that the warm, salty subsurface waters accumulate below the sea ice because they do not sink as NCW (and it is not necessary that more volume is transported). Idem for 4041-17,18

Yes, we agree that there is a period of reduced NADW formation, as we indicate in 4041, due to the increased sea-ice and insulation of surface ocean. Afterwards, are changes in the AMOC that control the events. According to Shaffer et al. (2004) some heat is transported by weak circulation, creating a growing temperature inversion in the northern North Atlantic ‘; and Mignot (2007) links subsurface warming to a intermediate convection in high latitudes; keeping an weak AMOC and transport warm and salty waters northwards. This situation is what we described in the discussion: shutdown of the NADW, shoaling of convection to intermediate depths and more GNAIW, keeping AMOC transporting warm subsurface waters to the north, that accumulate below ice-sheets. In summary, we think that using the term AMOC it is right. Maybe the words enhanced and reduced in the same sentence can look contradictory (4034-10), so we have changed them.

4036-10, I think that 200 m is the top of the thermocline and not the base (which is at some 1000 m according to your figure 1). Please rephrase.

Yes, it is upper thermocline

4037-25. Idem, according to figure 1 N. pachy inhabits (200 m), the upper thermocline.

4037-27. at the upper thermocline

Same

4041-14. Sensu stricto you cannot speak here of intermediate waters because your Dd13C gradient is between subsurface (ca 200 m) and deep waters and not between intermediate and deep waters. Please rephrase.

Typos, minor edits and rewording:

Please remove the spaces in Mg / Ca, i.e. write Mg/Ca throughout.

4034-5/6, rephrase, it is repetitive, for example: We used Mg/Ca-based temperatures of Neogloboquadrina pachyderma sinistral, a deep dwelling planktonic foraminifera, and paired measurements of Mg/Ca-based temperatures and d18O to estimate d18O of sea water at site U1314.

4034-19, spell out MIS in 1st use in abstract and main text

4035-20, symbol in d18O is missing

4037-3, sensu estricto this referencing is not correct because Paillard and Yiou, 1996 do not present Analyseries 2.0 but 1.0, you can circumvent that by saying only using the Analyseries software.

4037-19, southwards

4037-27, phrase does not read correct. Rephrase, for example "on deep dwelling plk foraminifera N. pachy sin. which inhabits and calcifies. . ."

4038-3. Wording. "Around 50-60 well-preserved test of plk foraminifera N. pachy sin. (> 150 micras) were analysed in 542 samples for Mg/Ca ratio following Pena's et al (2005) procedure"

4038-4, I infer that you used N. pachy sin. non encrusted? Please mention, this information is also missing in the 2012 paper and encrusted and non-encrusted may represent different environmental conditions.

4038-16 to 26, is this detailed description necessary? The records are published and the methods described in the original publications. It would be enough with a sentence referring to those publications otherwise it is misleading and it seems that these records are also new here.

We have removed the description of the analyses, referring the original publications. We keep in which species were made the stable isotopes.

4038-28. Reword. Example: Seawater d18O was calculated introducing paired Mg/Cabsed temperatures and calcite d18O in the paleotemperature equation of Shacklenton (1974).

4039-21,22: it is not clear what you mean, since MIS 25 d18Osw increased by 0.5per mil and T by 0.5◦C, towards present?

Rephrased

4039-27: Wording. Shortly after the iceberg discharge started

4040-27. they exhibit?

4043-14,15, wording + please see considerations about AMOC above

Modified

4044-14. Wording, divide sentence.

Caption Figure 2. For c) benthic d13C the reference Hernández-Almeida et al. 2013a (P3) is missing. Both, Hernández-Almeida et al. 2013a (P3) and 2013b (Boreas) are missing in the reference list.

Figure 3. vertical axis:Mg/Ca (a is missing in Ca)

Figure 4. A running mean though the curve would help readers to pick up the general trends. A color shading for either glacial or interglacial times would also be helpful to evaluate whether there are tendencies with G-I cyclicity (this also for figure 2).

Running mean of the gradient between planktonic and benthic d13C in Fig. 4 has been added. The G-I cyclicty is in the top of the plots; a color shading would interfere with the shading of the subrsurface warming events.

Thanks again for the helpful comments and suggestions.

Iván Hernández-Almeida and co-authors

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

I. Hernández-Almeida[1]; F-J. Sierro[2]; I. Cacho[3]; J-A. Flores[2]

[1] {Institute of Geography and Oeschger Centre for Climate Change Research, University of Bern, Erlachstrasse 9a, CH-3012 Bern, Switzerland}

[2] {Department of Geology, University of Salamanca. Plaza de la Merced s/n, Salamanca 37008, Spain}

[3] {Department of Stratigraphy, Paleontology and Marine Geosciences, University of Barcelona, C/Martí i Franquès s/n, 08028 Barcelona, Spain}

Correspondence to: I. Hernández-Almeida (ivan.hernandez@giub.unibe.ch)

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 δ^{18}O of seawater at Site U1314. 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 δ^{18}O of seawater suggest increased 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 and salt stored at subsurface 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 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 and/or through freshwater perturbations causing changes in the dynamics of the North Atlantic subpolar gyre that controls the meridional heat and salinity transport (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;Shaffer et al., 2004;Rasmussen and Thomsen, 2004;Liu et al., 2009;Marcott et al., 2011;Mignot et al., 2007;Moros et al., 2002;Peck et al., 2008;Jonkers et al., 2010b;Ezat et al., 2014;Naafs et al., 2013). 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 events such as Heinrich and Dansgaard-Oeschger (D-O) cycles.

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 δ^{18}O is controlled by temperature and δ^{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 paleoceanographic studies using these proxies have been produced (Jonkers et al., 2010b;Peck et al., 2008;Peck et al., 2006). 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.

Although the paleo-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 transitions between cold (stadial) and warm (interstadial) phases of the D-O cycles as those found during the Last Glacial period.

To further evaluate 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 temperatures (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 and during the iceberg events, indicating clear 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 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 δ^{18}O provides a record δ^{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 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.

Formatted: Superscript

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 δ^{18}O and +0.6‰ for δ^{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 δ^{18}O and 0.02‰ for δ^{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 δ^{18}O was calculated introducing paired Mg/Ca based temperatures and calcite δ^{18} O from *N. pachyderma* sin. in the paleotemperature equation of~~following~~ Shackleton (1974).~~ from paired Mg/Ca δ^{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 overestimate~~d~~ 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°C~~reaching 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).

Formatted: Not Superscript/ Subscript

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, 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 inflow in the 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 (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.

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

Field Code Changed

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 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).

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 would increase at the expenses of NADW. ~~Enhanced p~~Poleward transport of warm and salty subsurface subtropical waters during these episodes would thin and destabilize ice-shelves creating pulses of ice-rafted debris. ~~Deep water convection sites shifted south of the Polar Front and production of GNAIW would increase at the expenses of NADW.~~ Salt and heat accumulated at the subsurface would be suddenly released 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.

Acknowledgements

This work was funded by Ministerio de Ciencia e Innovación Project GRACCIE (CONSOLIDER-INGENIO CSD2007–00067) and CGL2011–26493. IC thanks the ICREA Academia funding form the Generalitat de Catalunya. We are grateful to Leopoldo Pena and Gemma Herrera for their assistance with laboratory work at the University of Barcelona, and to Martin Grosjean for his comments and suggestions on the manuscript. This research used samples from IODP Expedition 306.

References

Aagaard, K., and Carmack, E. C.: The role of sea ice and other fresh water in the Arctic circulation, Journal of Geophysical Research: Oceans, 94, 14485-14498, 10.1029/JC094iC10p14485, 1989.

Alvarez-Solas, J., Charbit, S., Ritz, C., Paillard, D., Ramstein, G., and Dumas, C.: Links between ocean temperature and iceberg discharge during Heinrich events, Nature Geosci, 3, 122-126, 2010.

Alvarez-Solas, J., Charbit, S., Ramstein, G., Paillard, D., Dumas, C., Ritz, C., and Roche, D. M.: Millennial-scale oscillations in the Southern Ocean in response to atmospheric CO_2 increase, Global and Planetary Change, 76, 128-136, 2011.

Antonov, J. I., Locarnini, R., Boyer, T., Mishonov, A., Garcia, H., and Levitus, S.: World Ocean Atlas 2005 Volume 2: Salinity, NOAA Atlas NESDIS, 62, 2006.

Banderas, R., Álvarez-Solas, J., and Montoya, M.: Role of CO2 and Southern Ocean winds in glacial abrupt climate change, Climate of the Past, 8, 1011-1021, 2012.

Bartoli, G., Sarnthein, M., and Weinelt, M.: Late Pliocene millennial-scale climate variability in the northern North Atlantic prior to and after the onset of Northern Hemisphere glaciation, Paleoceanography, 21, PA4205, 10.1029/2005pa001185, 2006.

Bauch, D., Carstens, J., and Wefer, G.: Oxygen isotope composition of living *Neogloboquadrina pachyderma* (sin.) in the Arctic Ocean, Earth Planet. Sci. Lett., 146, 47-58, 1997.

Bianchi, G. G., and McCave, I. N.: Hydrography and sedimentation under the deep western boundary current on Björn and Gardar Drifts, Iceland Basin, Mar. Geol., 165, 137-169, 2000.

Bintanja, R., and van de Wal, R. S. W.: North American ice-sheet dynamics and the onset of 100,000-year glacial cycles, Nature, 454, 869-872, 2008.

Bolton, C. T., Wilson, P. A., Bailey, I., Friedrich, O., Beer, C. J., Becker, J., Baranwal, S., and Schiebel, R.: Millennial-scale climate variability in the subpolar North Atlantic Ocean during the late Pliocene, Paleoceanography, 25, PA4218, 10.1029/2010pa001951, 2010.

Brady, E., and Otto-Bliesner, B.: The role of meltwater-induced subsurface ocean warming in regulating the Atlantic meridional overturning in glacial climate simulations, Climate Dynamics, 37, 1517-1532, 10.1007/s00382-010-0925-9, 2011.

Broccoli, A., and Manabe, S.: The influence of continental ice, atmospheric CO2, and land albedo on the climate of the last glacial maximum, Climate Dynamics, 1, 87-99, 1987.

Charles, C. D., Pahnke, K., Zahn, R., Mortyn, P., Ninnemann, U., and Hodell, D.: Millennial scale evolution of the Southern Ocean chemical divide, Quat. Sci. Rev., 29, 399-409, 2010.

Clark, P. U., Marshall, S. J., Clarke, G. K., Hostetler, S. W., Licciardi, J. M., and Teller, J. T.: Freshwater forcing of abrupt climate change during the last glaciation, Science, 293, 283-287, 2001.

Dansgaard, W., Johnsen, S., Clausen, H., Dahl-Jensen, D., Gundestrup, N., Hammer, C., Hvidberg, C., Steffensen, J., Sveinbjörnsdottir, A., and Jouzel, J.: Evidence for general instability of past climate from a 250-kyr ice-core record, Nature, 364, 218-220, 1993.

Elderfield, H., and Ganssen, G.: Past temperature and δ^{18}O of surface ocean waters inferred from foraminiferal Mg/Ca ratios, Nature, 405, 442-445, 2000.

Eynaud, F., de Abreu, L., Voelker, A., Schönfeld, J., Salgueiro, E., Turon, J.-L., Penaud, A., Toucanne, S., Naughton, F., Sánchez Goñi, M. F., Malaizé, B., and Cacho, I.: Position of the Polar Front along the western Iberian margin during key cold episodes of the last 45 ka, Geochem. Geophys. Geosyst., 10, Q07U05, 10.1029/2009gc002398, 2009.

Ezat, M. M., Rasmussen, T. L., and Groeneveld, J.: Persistent intermediate water warming during cold stadials in the southeastern Nordic seas during the past 65 k.y, Geology, 10.1130/g35579.1, 2014.

Ferretti, P., Crowhurst, S. J., Hall, M. A., and Cacho, I.: North Atlantic millennial-scale climate variability 910 to 790 ka and the role of the equatorial insolation forcing, Earth Planet. Sci. Lett., 293, 28-41, 2010.

Ganopolski, A., and Rahmstorf, S.: Rapid changes of glacial climate simulated in a coupled climate model, Nature, 409, 153-158, 2001.

Grousset, F. E., Cortijo, E., Huon, S., Hervé, L., Richter, T., Burdloff, D., Duprat, J., and Weber, O.: Zooming in on Heinrich Layers, Paleoceanography, 16, 240–259, 10.1029/2000pa000559, 2001.

Hátún, H., Sandø, A. B., Drange, H., Hansen, B., and Valdimarsson, H.: Influence of the Atlantic Subpolar Gyre on the Thermohaline Circulation, Science, 309, 1841-1844, 10.1126/science.1114777, 2005.

Heinrich, H.: Origin and consequences of cyclic ice rafting in the Northeast Atlantic Ocean during the past 130,000 years, Quatern. Res., 29, 142-152, 1988.

Hernández-Almeida, I., Sierro, F. J., Cacho, I., and Flores, J. A.: Impact of suborbital climate changes in the North Atlantic on ice sheet dynamics at the Mid-Pleistocene Transition, Paleoceanography, 27, PA3214, 10.1029/2011pa002209, 2012.

Hernández-Almeida, I., Bjørklund, K. R., Sierro, F. J., Filippelli, G. M., Cacho, I., and Flores, J. A.: A high resolution opal and radiolarian record from the subpolar North Atlantic during the Mid-Pleistocene Transition (1069–779 ka): Palaeoceanographic implications, Palaeogeogr., Palaeoclimatol., Palaeoecol., 391, Part A, 49-70, http://dx.doi.org/10.1016/j.palaeo.2011.05.049, 2013a.

Hernández-Almeida, I., Sierro, F. J., Flores, J.-A., Cacho, I., and Filippelli, G. M.: Palaeoceanographic changes in the North Atlantic during the Mid-Pleistocene Transition (MIS 31–19) as inferred from planktonic foraminiferal and calcium carbonate records, Boreas, 42, 140-159, 10.1111/j.1502-3885.2012.00283.x, 2013b.

Hillaire-Marcel, C., de Vernal, A., and McKay, J.: Foraminifer isotope study of the Pleistocene Labrador Sea, northwest North Atlantic (IODP Sites 1302/03 and 1305), with emphasis on paleoceanographical differences between its "inner" and "outer" basins, Mar. Geol., 279, 188-198, 2011.

Horikawa, K., Asahara, Y., Yamamoto, K., and Okazaki, Y.: Intermediate water formation in the Bering Sea during glacial periods: Evidence from neodymium isotope ratios, Geology, 38, 435-438, 10.1130/g30225.1, 2010.

Jonkers, L., Brummer, G.-J. A., Peeters, F. J. C., van Aken, H. M., and De Jong, M. F.: Seasonal stratification, shell flux, and oxygen isotope dynamics of left-coiling N. pachyderma and T. quinqueloba in the western subpolar North Atlantic, Paleoceanography, 25, PA2204, 10.1029/2009pa001849, 2010a.

Jonkers, L., Moros, M., Prins, M. A., Dokken, T., Dahl, C. A., Dijkstra, N., Perner, K., and Brummer, G.-J. A.: A reconstruction of sea surface warming in the northern North Atlantic during MIS 3 ice-rafting events, Quat. Sci. Rev., 29, 1791-1800, 2010b.

Kaspi, Y., Sayag, R., and Tziperman, E.: A “triple sea-ice state” mechanism for the abrupt warming and synchronous ice sheet collapses during Heinrich events, Paleoceanography, 19, PA3004, 10.1029/2004pa001009, 2004.

Kleiven, H. F., Hall, I. R., McCave, I. N., Knorr, G., and Jansen, E.: Coupled deep-water flow and climate variability in the middle Pleistocene North Atlantic, Geology, 39, 343-346, 2011.

Kohfeld, K. E., Fairbanks, R. G., Smith, S. L., and Walsh, I. D.: *Neogloboquadrina pachyderma* (sinistral coiling) as paleoceanographic tracers in polar oceans: rvidence from northeast water polynya plankton tows, sediment traps, and surface sediments, Paleoceanography, 11, 679-699, 1996.

Kozdon, R., Eisenhauer, A., Weinelt, M., Meland, M. Y., and Nürnberg, D.: Reassessing Mg/Ca temperature calibrations of *Neogloboquadrina pachyderma* (sinistral) using paired $\delta^{44/40}$Ca and Mg/Ca measurements, Geochem. Geophys. Geosyst., 10, Q03005, 10.1029/2008gc002169, 2009.

Li, C., Battisti, D. S., Schrag, D. P., and Tziperman, E.: Abrupt climate shifts in Greenland due to displacements of the sea ice edge, Geophys. Res. Lett., 32, 10.1029/2005GL023492, 2005.

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

Liu, Z., Otto-Bliesner, B. L., He, F., Brady, E. C., Tomas, R., Clark, P. U., Carlson, A. E., Lynch-Stieglitz, J., Curry, W., Brook, E., Erickson, D., Jacob, R., Kutzbach, J., and Cheng, J.: Transient Simulation of Last Deglaciation with a New Mechanism for Bølling-Allerød Warming, Science, 325, 310-314, 10.1126/science.1171041, 2009.

Locarnini, R. A., Mishonov, A. V., Antonov, J. I., Boyer, T. P., Garcia, H. E., Baranova, O. K., Zweng, M. M., Paver, C. R., Reagan, J. R., Johnson, D. R., Hamilton, M., and Seidov, D.: World Ocean Atlas 2013, Volume 1: Temperature, Washington, D.C., 40, 2013.

MacAyeal, D. R., Scambos, T. A., Hulbe, C. L., and Fahnestock, M. A.: Catastrophic ice-shelf break-up by an ice-shelf-fragment-capsize mechanism, Journal of Glaciology, 49, 22-36, 10.3189/172756503781830863, 2003.

Malmberg, S. A.: The water masses between Iceland and Greenland, Journal of Marine Research Institute, 9, 127–140, 1985.

Manabe, S., and Stouffer, R. J.: Coupled ocean-atmosphere model response to freshwater input: Comparison to Younger Dryas Event, Paleoceanography, 12, 321-336, 10.1029/96pa03932, 1997.

Marcott, S. A., Clark, P. U., Padman, L., Klinkhammer, G. P., Springer, S. R., Liu, Z., Otto-Bliesner, B. L., Carlson, A. E., Ungerer, A., Padman, J., He, F., Cheng, J., and Schmittner, A.: Ice-shelf collapse from subsurface warming as a trigger for Heinrich events, Proceedings of the National Academy of Sciences, 108, 13415–13419, 10.1073/pnas.1104772108, 2011.

Marshall, S. J., and Koutnik, M. R.: Ice sheet action versus reaction: Distinguishing between Heinrich events and Dansgaard-Oeschger cycles in the North Atlantic, Paleoceanography, 21, PA2021, 10.1029/2005pa001247, 2006.

McClymont, E. L., Rosell-Melé, A., Haug, G. H., and Lloyd, J. M.: Expansion of subarctic water masses in the North Atlantic and Pacific oceans and implications for mid-Pleistocene ice sheet growth, Paleoceanography, 23, PA4214, doi: 10.1029/2008pa001622, 2008.

Mignot, J., Ganopolski, A., and Levermann, A.: Atlantic Subsurface Temperatures: Response to a Shutdown of the Overturning Circulation and Consequences for Its Recovery, Journal of Climate, 20, 4884-4898, doi:10.1175/JCLI4280.1, 2007.

Mix, A. C., and Fairbanks, R. G.: North Atlantic surface-ocean control of Pleistocene deep-ocean circulation, Earth Planet. Sci. Lett., 73, 231-243, 1985.

Moros, M., Kuijpers, A., Snowball, I., Lassen, S., Bäckström, D., Gingele, F., and McManus, J.: Were glacial iceberg surges in the North Atlantic triggered by climatic warming?, Mar. Geol., 192, 393-417, 2002.

Naafs, B. D. A., Hefter, J., and Stein, R.: Millennial-scale ice rafting events and Hudson Strait Heinrich(-like) Events during the late Pliocene and Pleistocene: a review, Quat. Sci. Rev., 80, 1-28, http://dx.doi.org/10.1016/j.quascirev.2013.08.014, 2013.

Nürnberg, D.: Magnesium in tests of *Neogloboquadrina pachyderma* sinistral from high northern and southern latitudes, Journal of Foraminiferal Research, 25, 350-368, 10.2113/gsjfr.25.4.350, 1995.

Nyland, B. F., Jansen, E., Elderfield, H., and Andersson, C.: *Neogloboquadrina pachyderma* (dex. and sin.) Mg/Ca and δ^{18}O records from the Norwegian Sea, Geochem. Geophys. Geosyst., 7, Q10P17, 10.1029/2005gc001055, 2006.

Oppo, D. W., and Lehman, S. J.: Mid-Depth Circulation of the Subpolar North Atlantic During the Last Glacial Maximum, Science, 259, 1148-1152, 1993.

Paillard, D. L., and Yiou, P.: Macintosh program performs time-series analysis, Eos Transactions, American Geophysical Union, 77, 379, doi:10.1029/96EO00259, 1996.

Peck, V. L., Hall, I. R., Zahn, R., Elderfield, H., Grousset, F., Hemming, S. R., and Scourse, J. D.: High resolution evidence for linkages between NW European ice sheet instability and Atlantic Meridional Overturning Circulation, Earth Planet. Sci. Lett., 243, 476-488, 2006.

Peck, V. L., Hall, I. R., Zahn, R., and Elderfield, H.: Millennial-scale surface and subsurface paleothermometry from the northeast Atlantic, 55–8 ka BP, Paleoceanography, 23, PA3221, 10.1029/2008pa001631, 2008.

Pena, L. D., Calvo, E., Cacho, I., Eggins, S., and Pelejero, C.: Identification and removal of Mn-Mg-rich contaminant phases on foraminiferal tests: Implications for Mg/Ca past temperature reconstructions, Geochem. Geophys. Geosyst., 6, Q09P02, 10.1029/2005gc000930, 2005.

Petersen, S. V., Schrag, D. P., and Clark, P. U.: A new mechanism for Dansgaard-Oeschger cycles, Paleoceanography, 28, 10.1029/2012PA002364, 2013.

Rasmussen, T. L., and Thomsen, E.: The role of the North Atlantic Drift in the millennial timescale glacial climate fluctuations, Palaeogeogr., Palaeoclimatol., Palaeoecol., 210, 101-116, 2004.

Rignot, E., and Jacobs, S. S.: Rapid Bottom Melting Widespread near Antarctic Ice Sheet Grounding Lines, Science, 296, 2020-2023, 10.1126/science.1070942, 2002.

Risebrobakken, B., Dokken, T., Smedsrud, L. H., Andersson, C., Jansen, E., Moros, M., and Ivanova, E. V.: Early Holocene temperature variability in the Nordic Seas: The role of oceanic heat advection versus changes in orbital forcing, Paleoceanography, 26, PA4206, 10.1029/2011pa002117, 2011.

Ruddiman, W. F.: Late Quaternary deposition of ice-rafted sand in the subpolar North Atlantic (lat 40º to 65ºN), Geol. Soc. Am. Bull., 88, 1813-1827, 1977.

Ruddiman, W. F., and McIntyre, A.: The North Atlantic Ocean during the last deglaciation, Palaeogeogr., Palaeoclimatol., Palaeoecol., 35, 145-214, 1981a.

Schlitzer, R.: Ocean Data View, http://odv.awi.de, 2008.

Schmidt, M. W., Spero, H. J., and Lea, D. W.: Links between salinity variation in the Caribbean and North Atlantic thermohaline circulation, Nature, 428, 160-163, 2004.

Schmidt, M. W., Vautravers, M. J., and Spero, H. J.: Rapid subtropical North Atlantic salinity oscillations across Dansgaard-Oeschger cycles, Nature, 443, 561-564, 2006.

Schmidt, M. W., Chang, P., Hertzberg, J. E., Them, T. R., Ji, L., and Otto-Bliesner, B. L.: Impact of abrupt deglacial climate change on tropical Atlantic subsurface temperatures, Proceedings of the National Academy of Sciences, 109, 14348-14352, 10.1073/pnas.1207806109, 2012.

Shackleton, N.: Attainment of isotopic equilibrium between ocean water and the benthonic foraminifera genus Uvigerina: isotopic changes in the ocean during the last glacial, Colloques Internationaux du CNRS, 219, 203–209, 1974.

Shaffer, G., Olsen, S. M., and Bjerrum, C. J.: Ocean subsurface warming as a mechanism for coupling Dansgaard-Oeschger climate cycles and ice-rafting events, Geophys. Res. Lett., 31, L24202, 10.1029/2004gl020968, 2004.

Simstich, J., Sarnthein, M., and Erlenkeuser, H.: Paired δ^{18}O signals of *Neogloboquadrina pachyderma* (s) and *Turborotalita quinqueloba* show thermal stratification structure in Nordic Seas, Mar. Micropaleontol., 48, 107-125, 2003.

Smith, L. M., Andrews, J. T., Castañeda, I. S., Kristjánsdóttir, G. B., Jennings, A. E., and Sveinbjörnsdóttir, Á. E.: Temperature reconstructions for SW and N Iceland waters over the last 10 cal ka based on δ^{18}O records from planktic and benthic Foraminifera, Quat. Sci. Rev., 24, 1723-1740, 2005.

Thornalley, D. J., Elderfield, H., and McCave, I. N.: Holocene oscillations in temperature and salinity of the surface subpolar North Atlantic, Nature, 457, 711-714, 2009.

Vaughan, D. G., and Doake, C. S. M.: Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula, Nature, 379, 328-331, 1996.

Venz, K. A., Hodell, D. A., Stanton, C., and Warnke, D. A.: A 1.0 Myr Record of Glacial North Atlantic Intermediate Water Variability from ODP Site 982 in the Northeast Atlantic, Paleoceanography, 14, 42-52, 1999.

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

Volkmann, R., and Mensch, M.: Stable isotope composition (δ^{18}O, δ^{13}C) of living planktic foraminifers in the outer Laptev Sea and the Fram Strait, Mar. Micropaleontol., 42, 163-188, 2001.

Zweng, M. M., Reagan, J. R., Antonov, J. I., Locarnini, R. A., Mishonov, A. V., Boyer, T. P., Garcia, H. E., Baranova, O. K., Johnson, D. R., Seidov, D., and Biddle, M. M.: World Ocean Atlas 2013, Volume 2: Salinity, Washington, D.C., 39, 2013.

FIGURE CAPTIONS

Table 1. Summary of the changes in Mg/Ca, $\delta^{18}O_{sw}$ and planktonic δ^{13}C during the IRD events.

Formatted: Subscript

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 δ^{18}O (Hernández-Almeida et al., 2012); (c) benthic δ^{13}C (Hernández-Almeida et al., 2013a); (d) planktonic δ^{13}C (red) (Hernández-Almeida et al., 2013b) vs. benthic δ^{13}C from Site 982 (blue) (Venz et al., 1999); (e) $\delta^{18}O_{sw}$ reconstruction from paired Mg/Ca-δ^{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 vertical bars indicate IRD discharge associated with subsurface warming.

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).