Dear editor,

Please find below our detailed replies and associated modifications of our manuscript consequently to the comments and advice formulated by both reviewers and Dr. Lukas Jonkers.
Enclosed to this letter are (i) the “normal” revised version of the manuscript, and (ii) the same revised version of the manuscript with major modifications highlighted in red.

We hope we successfully complied with the whole remarks and managed to improve the quality of our paper.

Anonymous Reviewer #1

REV#1: Wary and co-authors present a study combining various proxy records to understand hydrographic changes during the millennial-scale climate oscillations of the last glacial period in the northern North Atlantic. The paper shows interesting new data and concepts that are interesting for the paleoclimate community and merit publication. However, the paper needs major revisions before it could be accepted for publication in Climate of the Past.
First of all, a manuscript should focus on the new data produced and added to the already published data. Thus –as far as I can tell– the methods and results sections should purely focus on the planktonic foraminifer derived records and on the grain size data. The dinocyst reconstructions have been published previously and should therefore only be integrated into the discussion. Deleting the dinocyst-relevant text from the methods and results section will also shorten the manuscript.
Reply: We strongly reduced the part related to dinocysts and palynological analyses from the methods section (see Sect. 3.3, lines 218 to 232, where we now only mention the provenance of data, the precise data reused in our study and the associated method uncertainties) and from the results section (see Sect. 4, lines 275-278, lines 286-292, and lines 305-311 where we only describe data stemming from dinocysts but exclusively produced for the present study).

One of the major problems of the paper is that it is treating the planktonic foraminifer reconstruction data as indicator for subsurface water conditions. Currently, I, as a reader, can support this assumption only for the δ18O and δ18Ow data because those two values are truly related to the living/ calcification depth of N. pachyderma (s), although the authors never mention which depth range they assume the N. pachyderma (s)-derived data reflect [the authors could include the following reference to strengthen their interpretation on a regional level: Peck et al. 2008. Millennial-scale surface and subsurface paleothermometry from the North East Atlantic, 55-8 kyr BP. Paleoceanography 23, PA3221, doi:10.1029/2008PA001631].
Reply: We added information about the depth range inhabited by *N. pachyderma*, as well as the suggested reference plus others to strengthen the discussion (see lines 207-209).

For the temperature reconstruction the authors are referring to a publication by Eynaud et al. (2013) that for most readers (including me) is impossible to access.
Reply: Reviwer #2 also mentioned this. We are really sorry with the fact that this article is not freely accessible. To remedy this situation, we added references where the method has been intensively described (lines 166-167) and included in the text a brief but complete summary of the technical aspects of the transfer function applied to planktonic foraminifera assemblages (lines 167-184).

Because the manuscript does not mention from which water depth the modern analog data for the Eynaud transfer function is, I can currently not support the statement of the authors that the planktic foraminifer derived temperatures are subsurface temperatures. Most modern analog files for planktic foraminifer reconstructions are for a water depth of 10 m – the same depth as used for the dinocysts transfer function. Even if the planktonic foraminifers themselves might live over a wider depth range, by using the transfer function you relate all the information to the water depth provided by your modern analog data, i.e. 10 m???. In case the Eynaud et al. (2013) modern analog database is for a water depth deeper than 10 m not only the water depth chosen needs to be clearly stated but there should also be some additional information provided on why that exact water depth was chosen and how reliable reconstructions for the chosen water depth are in the region of the study area. See for example: Telford, R.J., Li, C., Kucera, M., 2013. Mismatch between the depth habitat of planktonic foraminifera and the calibration depth of SST transfer functions may bias reconstructions. Clim. Past 9, 859-870.
Reply: This remark, also done by Dr. Lukas Jonkers in his short comment, is totally well-founded and raises a fundamental point. The method we used, its results and our interpretations are defensible with robust arguments (already mentioned in our replies to reviewer 1 and to Dr. Jonkers).
We created a Supplementary Information and Method document, in which we explain our whole argumentation, based on ecological as well as technical arguments, strengthened by references (including references suggested by reviewer #1 and Dr. Jonkers).
We also added some of these arguments (the ecological ones) in the text, lines 361-370.
We also added some lines where we clearly specify that F-Temp are not interpreted as absolute subsurface temperatures, but as subsurface relative estimations of temperature (lines 373-378).

In the methods and results, the authors list biodiversity indices/data. What is importance of this data is for the current study? The data are mentioned nowhere in the discussion and thus treated by the authors themselves as not relevant. I therefore recommend deleting this data from the paper.
Reply: Actually, diversity and dominance indices are clearly mentioned in the first section of the discussion (Sect. 5.1, lines 331-345). We consider these data as very important since they attest that fauna are not reworked and therefore that derived reconstructions do not reflect allochthonous signals. Hence, we did not delete them from the text.

Issues related to “stratigraphy”: 1) I recommend using GI as abbreviation for Greenland Interstadials because for the scientists from the ice-core community GIS stands for Greenland ice sheet. GI is also used within the INTIMATE community and the nomenclature of GI/GS (e.g., Rasmussen et al., 2014 in QSR “A stratigraphic framework for abrupt climatic changes during the Last Glacial period. …”).
Reply: GIS replaced by GI in the whole document.

2) The interval marked for Heinrich event 3 is too broad. Normally, only the last cold phase is linked to H 3 (e.g., Hall et al., 2011 for a nearby record). With the broad interval used by the authors they are including a Greenland Interstadial = GI 5.1 (e.g., Rasmussen et al., 2014) into H3 and it is therefore not astonishing that they see a three-phased pattern in their paleoclimatic records.
Reply: We did not change the limits of this interval (because this interval corresponds to **Heinrich Stadial 3** – and not Heinrich Event 3 – with age limits defined following Wolff et al. (2010), i.e. end of GI5 to beginning of GI4). However, we now propose to divide the HS3 interval in three parts: HS3a, GI 5.1, HS3b (see lines 635-636 + lines 648-655).

3) H 2 timing: the general view is that Heinrich events precede a GI (e.g., Bond et al., 1993; van Kreveld et al., 2000; Hall et al., 2011). So H 2 should directly precede GI 2 and not fall into the middle of GS 3 as marked by the authors in their figures and previously by Caulle et al. (2013). Grousset et al. (2000) showed that deep-sea cores from the European margin recorded an earlier event

with European-sourced IRD (and thus in the strictest sense is not a Heinrich event) that sometimes is referred to as H 2.2. So from the timing in relation to the NGRIP record the authors seem to have marked and are discussing this older H 2.2. event and not H 2 per se. However, looking at the % G. bulloides record shown in Fig. 2 I am not sure if there is not a problem in the core's age model. Normally, I would contribute the % G. bulloides peak following the marked H 2 interval to GI 2. Thus in the paleoclimate records the H 2 level might be correct; it is just too old in relation to the NGRIP chronology. To clarify this issue the authors might try to align their % N. pachyderma (s) record with those shown Austin, W.E.N., Hibbert, F.D., Rasmussen, S.O., Peters, C., Abbott, P.M., Bryant, C.L., 2012, The synchronization of palaeoclimatic events in the North Atlantic region during Greenland Stadial 3 (ca. 27.5 to 23.3 kyr b2k). Quaternary Science Reviews 36, 154-163.
Reply: We did not change any of that and kept on using the same age limits for HS2 as Caulle et al. (2013), i.e. 26-24.7 ka (delimited by authors according to maximum LLG concentrations and high percentages of *N. pachyderma*), for consistency and also because these age limits are very close to HS2 definition given by Sanchez-Goñi and Harrison (2010; i.e. 26.5-24.3 ka cal BP, GICC05 chronology).
Indeed, even if it is true that there might be some small problems with the age model of the upper section of the core (given that it is only constrained by ^{14}C dates in this part), it is not true that Heinrich stadials (and thus Heinrich events) always directly precede a GI, and particularly HS2 as some subdivisions structure them in a much more complex and subtle way (see. Sanchez-Goñi and Harrison, 2010).

Issues related to the modern (past) oceanography: 1) I recommend using the term of ISOW = Iceland Scotland Overflow Water instead of NSOW. ISOW is the term used by oceanographers and includes contributions by both the Norwegian Sea Deep Water and the intermediate/deep waters formed north of Iceland.
Reply: NSOW replaced by ISOW in the whole document.

I would like to see a reference to a modern oceanography study included in the reference list on page 2082 line 5.
Reply: Reference to Hansen and Osterhus, 2000 has been added (line 103/104).

It would also be important to mention that only a minor part of the ISOW exiting through the Faeroe-Shetland Channel crosses the Wyville-Thompson ridge (see Hansen and Østerhus 2000) and therefore affects the core site. This aspect is highly important for the past records when convection in the Nordic Seas was reduced or shallower and thus the overflow potentially weaker.
Reply: Done (line 103).

2) Terminology: the authors use several time the phrase "Atlantic inflow" in relation to the NAD but this is not correct for the location of their core site. Inflow refers to the waters entering the Nordic/Norwegian Sea and thus to the Atlantic water current north of the Faeroer islands.
Reply: The term "Atlantic inflow" has been replaced by "northward Atlantic flow" or "Atlantic water northward flow" (lines 40/41, 411, 421/422, 522, 602).

3) Convection: for the discussion of the past hydrographic conditions the authors are also mixing up regions or convection depths. Modern and likely GI **deep convection took place in the Nordic Seas and thus way north of the studied site and not above/close to the site as implied by the text and the schemes in Fig. 6**. Nowadays, the site is, however, located at the northern edge of the area where subpolar mode (central) water is formed/convected (see for example Brambilla, E., Talley, L.D., Robbins, P.E., 2008. Subpolar Mode Water in the northeastern Atlantic: 2. Origin and transformation. Journal of Geophysical Research 113, doi:10.1029/2006jc004063), but this an subsurface/intermediate depth water mass. On the other hand, the Rockall Plateau south of the

core site is the area indicated where deep convection might have taken place during the last glacial maximum (e.g., Sarnthein et al., 1994, Changes in east Atlantic deepwater circulation over the last 30,000 years: Eight time slices reconstructions. Paleoceanography 9, 209-267. or Gherardi, J., Labeyrie, L., Nave, S., Francois, R., McManus, J.F., Cortijo, E., 2009. Glacial - interglacial circulation changes inferred from 231Pa/230Th sedimentary record in the North Atlantic region. Paleoceanography 24, doi:10.1029/2008PA001696.) So overall, the **authors need to be more precise in indication how deep and where the convection took place they are mentioning in the discussion**.

Reply: We do agree that the convection site was certainly located way north of our study area during GI.

Concerning Fig. 6 (conceptual scheme): (i) we replaced the confusing term “Faeroes” by “Nordic Seas”, and (ii) we would like to highlight the fact that this figure has purely been designed to illustrate the **sequential evolution of hydrological processes** occurring throughout a typical DO cycle at a regional scale.

Concerning the text, (i) as already stated in our reply to Reviewer #1, **we deeply think that we cannot be more precise** about the depth of convection considering our set of proxies, and (ii) concerning its location, we specified in the text (line 547) that we are talking about convection occurring north of our study site.

4) you cannot per se assume that the NAD was also present/flowing over/near your core site, in particular during Heinrich events and may be some of the GS. The NAD as a surface current might have been diverted to the south, i.e. towards the area(s) where deep convection took place, by the expanded subpolar gyre. Thus I would be very careful to use the term intensity in relation to a paleo-NAD. It might also be good to give evidence from cores along the NAD flow path or along the British margin (such as Hall or Peck papers) to support a NAD presence throughout the intervals discussed.

Reply: As replied to Reviewer #1, such evidences have unfortunately been very rare up to now. We propose that the NAD might have been present **close to** our study area during **some very occasional and atypical stadials** such as HS2, because our data as well as previous studies suggest the possibility of such a pattern (Elliot et al., 2002, Voelker et al., 2006, and Dokken et al., 2013, already cited in the original submitted version + reference to Scourse et al., 2009 added to strengthen again our argumentation, see lines 629-634).

Concerning the use of the term “intensity”, we consider that a greater influence of the NAD over the study area might most of the time be related to a stronger intensity of the NAD.

The subsurface Atlantic inflow seen by Rasmussen and co-workers does not necessarily have to be a subducted NAD but could also be in the form of a mode water –although we currently cannot distinguish this in the past.

Reply: We already suggested in the original submitted version (now at lines 572-576 in the revised version) that the Atlantic inflow seen by Rasmussen et al. might represent a continuous stadial flow of Atlantic intermediate waters unrelated to the NAD. We do not want to be more categorical in our formulation because, as also mentioned by Reviewer #1, we do not have any evidence or argument to do so.

So I am currently not sure if the water mass signals (NAD vs/plus meltwater) as outlined in the top paragraph of page 2094 are fully correct or not –but this also goes back to the water depth reconstructed with the planktic foraminifer transfer function. Based on the modern oceanographic conditions around Greenland I would associate iceberg-calving with fresher surface waters and thus the existence of a halocline.

Reply: The assumption taken for foraminifera transfer function is the most reasonable one (see the Supplementary Information). Iceberg calving are for sure related to the existence of the near-surface halocline, but as soon as the halocline disappear the very-surface meltwater propagates within the subsurface layer, where the δ^{18}O NPS capture the meltwater signal.

Additional comments in order of page numbers: 1) in the abstract and following pages it should be “the Faeroers/ Faeroer Islands”

Reply: We do not think the spelling proposed by Reviewer #1 is correct since English dictionaries do not repertory any “Faeroers/ Faeroer Islands” but do repertory “Faeroes/Faeroe Islands”. Moreover, almost all studies (in paleoceanography, sedimentology, modern oceanography, etc.) conducted in the region use the terms “Faeroes” and “Faeroe Islands”. Therefore, we kept these latter terms.

2) page 2080 top: the base of the Holocene was defined as 11.65 ka BP or 11.7 b2k in Walker at al. (2009; Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records. Journal of Quaternary Science 24, 3-17.) so the top age for the glacial period should be adjusted to 11 ka BP at minimum.

Reply: We deleted the mention to the rough age limits of the last glacial period, because while the base of the Holocene has been clearly defined, there is no general consensus concerning the base of the last glacial (is this linked to the glacial inception after MIS5.5, or is it synchronous to the MIS4 onset?).

3) page 2080, 2082 and 2091 the word “preconized” does not exist in English; at the bottom of page 2082 is should be “combined with”

Reply: Preconized has been replaced by “considered” (line 66) and by “recommended” (lines 129, 338).

4) page 2085 paragraph on δ18Ow calculation: the correction of -2.5 °C was introduced to adjust for the 10 m depth estimate for the planktic foraminifer transfer function based temperatures. So if the modern analog temperatures used by Eynaud et al. (2013) would be from a deeper water depth, this correction might no longer be valid.

Reply: As clarified in the text (line 178) and in the Supplementary Information, SST are extracted at 10 m water depth in the modern database used for the transfer function, so the correction of -2.5 °C is valid.

5) page 2088: following the genotype analyses N. pachyderma (d) is now referred to as N. incompta.

Reply: *N. pachyderma* sinistral coiling/ *N. pachyderma* s. has been replaced by *N. pachyderma*, and *N. pachyderma* dextral coiling has been replaced by *N. incompta*.

6) page 2090: header should be changed to Deep-water proxies
7) page 2093 line 8: substitute “comforts” with “supports”
8) page 2096 line 23: I assume you mean “shallower” instead of “deeper” AMOC
Reply: Terms changed.

9) page 2098 a) line 13: NAD re-intensification or being present again?
Reply: Extending northward again. Clarified (line 543).

b) line 14: you don’t have a surface halocline; do you mean “near surface”?
Reply: “Surface halocline” replaced by “near-surface halocline”.

c) line 15 ff: what depth of convection do you mean? Mode water or deep water??? You get density increases with colder temperatures and higher salinity; so even if your water might be “too warm” they could have a higher salinity that could allow convection. Anyhow for the GI this whole process takes

place in the Nordic Seas and you can therefore not use evidence –but there is data out there from the Nordic Seas that you can refer to.
Reply: As mentioned in the original submitted version, we talk about convection of deep water, as we have deep-water proxies and no proxies indicative of convection of intermediate waters.

In line 19: heat exchange between what? Surface and subsurface? Surface and atmosphere (thus enabling atmospheric cooling)?
Reply: Both, subsurface and surface, and surface and atmosphere. Clarified in the text (lines 549/550).

For the GS/HS did you think about that some of the bottom current evidence might be related to an Atlantic-sourced water mass? Hansen and Østerhus mention on page 167 that in your study region a large Atlantic water component was observed. So if you would have deep convection over the Rockall Plateau, could that water not influence your site as well? In particular, if convection in the Nordic Seas was diminished and thus the overflow?
Reply: We are not really sure of what Reviewer #1 means in this comment. Surely, he talks about our suggestion that the meridional convection was more active/extending more northward during HS2 than during the other HS.
But basically, we can see four (rather three) possibilities concerning bottom conditions during GS/HS:
1) The presence of southern-sourced deep water masses (depleted in $\delta^{13}C$) over our study site when ISOW was inactive, as evidenced in some studies during some Heinrich events (e.g. Vidal et al., 1997; Elliot et al., 2002). But these water-masses have never been associated to a deep current efficient enough in the subpolar North Atlantic to explain the atypical grain-size distribution and MS signature observed during HS2 (indeed, low magnetic susceptibility values are associated with these benthic $\delta^{13}C$ depleted events, with both records obtained from the same core, see e.g. Elliot et al., 2002).
2) The presence of $\delta^{18}O$ depleted bottom waters formed in the Nordic Seas by brine rejection. Some studies (Dokken and Jansen, 1999; Dokken et al., 2013) suggested the existence of such a deep water mass on the basis of benthic foraminiferal isotopic content. However, the periods with the lowest $\delta^{18}O$ evidenced in Dokken and Jansen (1999)'s record are also associated to the lowest magnetic susceptibility values. Hence, if such deep water-masses were present during HS, they were not associated with a bottom current efficient enough to explain the atypical MS signature recorded in our core during HS2.
3) The hypothesis (maybe?) suggested by Reviewer #1: deep-water formed by convection south of our site (on the Rockall Plateau) that would be present upstream. We read additional papers focused on deep convection processes, but did not find any mention of such a process. And as mentioned in our reply to Reviewer #1, a true deep current with sufficiently high velocities is needed to induce such a reorganization of the sediment composition. Hence this hypothesis still sounds very unlikely.
4) The hypothesis we defend (the only one remaining, somewhat surprising but the one we believe to be the most coherent and which conciliates all of our proxies): a more active/extending more northward Atlantic meridional overturning circulation.

We did not mention the above three first hypotheses in our revised version because the first two cannot explain our signals and the third one seems very unlikely. Finally ours is the most intuitive.

10) page 2100 line 13: add "water" after "fresh"
Reply: Done (line 596).

11) page 2102 line 4 ff: is there evidence for this from any of the cores along the British ice sheet margin? E.g. papers by Peck; Hall; Knutz; Austin etc.
Reply: This comment concerns the hypothesis of additional iceberg calving from European ice-sheets during HS3/GI 5.1. There might be some (arguable) evidence for this. But, we deleted this part

because it was not adding force to our arguments but simply referring to another hypothesis already advanced by Elliot et al. (2002).

12) figures 3 and 5: add arrows indicating direction of salinity change for δ18Ow data and increase in LLG. Mention in legends when data is shown on reversed scale (such as δ18O N. pachyderma (s)).
Reply: Indication of the direction of salinity and IRD concentration changes has been added. We specified that LLG were plotted on a reverse scale, but not the δ^{18}O *N. pachyderma* since it is not.

There are additional minor language mistakes throughout the text that a spell/grammar check of the manuscript should pick up.
Reply: We have checked again, but will be pleased to benefit from the English copy-editing services offered by Climate of the Past.

Anonymous Reviewer #2

REV#2: General appreciation
This paper presents foraminifera-based analyses combined with previously published data on dinoflagellate cyst-based transfer functions results to document the episodic changes in surface/subsurface circulation patterns in the North Atlantic during the late Pleistocene, in relation to the episodic warm and cold episodes associated with Greenland stadials and interstadials, Heinrich events, etc.
The manuscript is well written in correct English, but I made a few suggestions to improve the language. The manuscript should be read by someone with good English prior to the final submission.
Reply: As mentioned above, we have checked again, so we will wait for the English copy-editing services correction.

It follows a logical progression, and presents interesting new data on the mechanisms responsible for such changes at secular/millennial timescales in the North Atlantic Ocean. However, in its present form, I failed to see the novelty of the data as the emphasis is placed on previously published data (dinocyst-derived reconstructions) rather than on the new foraminifers data. Therefore, I suggest the paper to be modified to place the emphasis on the new data. The conclusions are supported by the data presented, although some aspects of the methodology and trends in the foraminifera data need more detailed explanations. The figures are well drafted and all useful for the comprehension of the text. However, some need modifications as suggested in the detailed comment section. I think that the mechanism put forward by the authors to explain the changes between warm and cold episodes (GIS–GS) is really interesting and definitely deserves to be published, following major (I would rather qualify them as moderate) revisions.
Reply: As detailed below, we followed his/her advice.

Referee #2: Detailed comments

- The paper presents new data on FORAMINIFER and uses previously published data on dinocyst assemblages and transfer functions results, and this is not obvious from neither the abstract nor the Material and methods section. This is particularly evident in the introduction (lines 79-82) where dinocyst data from two previously published studies are mentioned BEFORE the new data presented in this manuscript: "...Our study uses a direct proxy of surface sensu stricto conditions, i.e. dinoflagellate cyst (dinocyst) assemblages, coupled to other proxies that give access to subsurface (foraminifera assemblages and geochemical analyses on their shells) and deep water mass dynamics (sediment grain-size measurements and magnetic susceptibility)." I suggest focusing on the new data only in the material and methods section.

Reply: We strongly reduced the material and methods section related to dinocysts, we deleted results already presented in Zumaque et al. (2012) and Caulle et al. (2013), we presented foraminifera-related sections before dinocyst-related ones as often as possible. The abstract (lines 28-29), introduction (lines 85-87) and conclusion (lines 683-685) have been slightly modified to clarify this point

Incidentally, the information on the foraminifera database is not readily available and more information should be added to the Material and methods section regarding this matter.

Reply: As written previously for Rev. #1 "We are really sorry with the fact that this article is not freely accessible. To remedy this situation, we added references where the method has been intensively described (lines 166-167) and included in the text a brief but complete summary of the technical aspects of the transfer function applied to planktonic foraminifera assemblages (lines 167-184)".

Foraminifera are presented here as "subsurface proxies" (figure 5), but no indication as to which depth range they represent.

Reply: It was already mentioned in the discussion section (now line 366), but we have also added the information in the material and method section (lines 154-159).

Presently there is more information on dinocyst reconstructions than on foraminifera reconstructions.

Reply: It is not the case anymore (see lines 163-184).

- I do not see very well the concordance between dinocyst-based reconstructed salinities and that derived from the foraminfera-based δ^{18}OSW (figure 3), although both seem to vary at millennial timescales.

Reply: Nor we do. We do not mention any such concordance in our manuscript.

- Lines 452-459: The authors state that higher magnetic susceptibility and higher concentrations of benthic foraminifera both indicate higher bottom water energy or higher bottom current intensity. However, in their diagrams 4g and 4h, the maximum signal of both indicators occur at different periods, the maximum magnetic susceptibility occurring during the LGM, with a general increasing trend toward the top of the record, while maximum benthic foraminifera concentrations occur much earlier in their records (below HS3), with a decreasing trend toward the top of the record. Wouldn't one expect to see both indicators varying together rather than at different time periods and with opposing trends like it is the case presently?

Reply: conform to our online reply to Reviewer #2, with additional information marked with *:

"In the study area, magnetic susceptibility is clearly related to bottom current strength (Kissel et al., 1999). Benthic foraminifera concentrations are related to bottom conditions, i.e. oxygenation (through ventilation by newly formed bottom flows in our case) AND bottom productivity (e.g. Rasmussen et al., 1999)*. Rasmussen et al. (2002) evidenced similar trends of benthic concentrations in a nearby core (ENAM33, located southwest off Faeroes) and one retrieved from the Reykjanes Ridge (DS97-2P) and interpreted them as the result of decreasing bottom productivity during the late MIS3 and MIS2. The decreasing trend observed in our core is thus also probably related to decreasing bottom productivity.

Furthermore, Rasmussen et al. (1997, 1999, 2002)** and Rasmussen and Thomsen (2004) deeply investigated the changes in composition (and concentration/fluxes) of benthic foraminifera fauna in many cores retrieved in the study area (southern Norwegian Sea and northeastern North Atlantic) with focus on the millennial climatic variability of the last glacial period. They all evidenced, during GI, high benthic concentrations and the occurrence of peculiar species that they related to bottom conditions similar to the present ones, i.e. characterized by active bottom current and high supply of food. They evidenced a reverse scheme during GS, with low concentrations and the occurrence of an "Atlantic species group" typifying a stop of the overflow and the intrusion of Atlantic Intermediate Water. Hence, in the study area, changes in benthic foraminifera concentrations during DO, even if influenced by changes in bottom productivity, seem to be related to changes in the bottom current activity."

* Already mentioned in the initial submitted version (now at lines 476-479).

** Reference to Rasmussen et al., 2002 and Rasmussen et al., 2007 added in the revised manuscript to strengthen this interpretation at a regional scale (lines 475-476).

- The concentrations of Pediastrum are illustrated on figure 3, and very briefly mentioned in the text (lines 153 and 312), but no explanation is given on their usefulness in the present work.

Reply: Mention to *Pediastrum* spp. line 153 (now line 227) has been kept (in the material and methods brief section about palynological data reused in our study). Mention line 312 has been deleted (result previously described in Zumaque et al. and Caulle et al.). But we a mention to *Pediastrum* spp. in the discussion section (lines 390-393).

Remarks made by Reviewer #2 concerning language errors, reformulation, figure modification, etc., (see below) have all been taken into account in the revised manuscript:

- Line 82: I would not call this "a high temporal resolution". I suggest modifying the sentence as follows: "Analyses were conducted at centennial to millennial time scales on core MD99-2281 located southwest off Faeroes Islands." Corrected, see lines 87-88
- Lines 208-209: "...not fully understood and discrepancies still exist**~~ing~~** between the various sea-level reconstructions..." Corrected, see lines 211-212
- Line 254-255: "...all data will be here presented and discussed **according to a cal BP age scale**." Corrected, see lines 274-275
- Line 354: "...derived hydrological signals share **common** features **~~in common~~** but also differ in some points ..." Corrected, see line 349
- Lines 439-441: "**Beside**, grain-size analyses on pretreated samples were **~~besides~~** conducted on the core section where the content of CaCO3 (data not shown) **~~displays~~** the largest variations and attains its maximal..." Corrected, see line 459 ("displays" not deleted because needed)
- Line 462: "**~~This~~** **These** results are in accordance with findings..." Corrected, see line 482
- Not being a fan of acronyms, this papers contains too many of them. Also, the same expression is used in different forms throughout the text: Dansgaard-Oeschger events are referred to as DO, DO cycles, and DO events, which contributes to the confusion with the acronyms. "DO cycles" and "DO events" replaced in the whole document by just "DO"
- Line 515: "However, a **detailed** ~~scrupulous~~..." Corrected, see line 535

- Line 575: “...depicted during GS, and characterized by the presence of a fresh **water** lid...” Added
- Lines 618-619: with classical disruptions of the overturning circulation at the **~~end and the~~** beginning **and the end** of the event interrupted Corrected, see line 647
- Lines 650-651: Once again, the emphasis is place on dinoflagellate cyst assemblages despite the fact that the present study is about foraminifera analyses. Please rephrase to put the emphasis on the new analyses presented here, and coupled to dinocyst transfer functions results done as already mentioned above (conclusion, lines 683-685)
- Figure 2: the choice of colors for the curves and titles of these curves should be revised. The pale blue and light brown-orange (diagrams c, e and f) make it difficult to see on the screen, even more on paper. Try using more contrasting colors and/or thickening the curves. On that same figure, diagram a, the significance of acronyms (LGM, HS1, etc.) and numerals 1 through 10 on the curve should be indicated in the figure caption. done
- Figure 3. The same comment about the color choice in figure 2 applies to this figure, especially the pale yellowish-green and pale blue, and also in figures 4-5. Try using more contrasting colors and thickening the curves. done
- The addition of raw foraminifer counts would be nice, possibly in “additional material” section added in the form of a table in the Supplementary Information and Material

Dr. Lukas Jonkers’ short comment

My comments are on some of the methodological aspects of this paper and focus mainly on the planktonic foraminifera proxies. I think these issues need to be addressed before the data can be interpreted in terms of stratification.

Planktonic foraminifera assemblage based temperature estimates.

The authors argue that the MAT temperature estimates (F-Temp) reflect temperature at the depth where the planktonic foraminifera lived. While I don’t disagree that planktonic foraminifera occupy a depth range similar to the 0-300 m the authors state, the argument that the F-Temp estimates reflect subsurface temperatures is not correct. This is because MAT approach used by the authors yields temperatures at 10 m depth by design (the down core assemblages are compared to core-top assemblages and modern temperatures at 10 m depth). Without going into the details on the accuracy of the reconstructions (which should be addressed in a revised manuscript), this basically means that the present reconstruction of stratification is based on two estimates of sea surface temperature, which cannot be right. If the authors want to reconstruct temperature deeper in the water column, then they need to i) demonstrate that the modern assemblages in the training set are better described/explained by temperature variability over say the upper 300 m (instead of the surface; see e.g. [Pflaumann et al., 1996]) and ii) ‘recalibrate’ the MAT by comparing the fossil assemblages to temperatures at this depth range. If i) can be demonstrated then this will change the F-Temp

estimates considerably because temperatures at depth are generally lower than at the surface and less variable (i.e. resulting in a less steep calibration curve so to say). To summarise, while part (and not all) of the planktonic foraminifera population may live deeper in the water column, the authors need to demonstrate that subsurface temperatures are a better predictor of assemblage variability in the core top data set and if so repeat the MAT with sub surface temperatures rather than SST. Simply inferring that the foram-based SSTs actually reflect subsurface temperatures because they are lower and show a smaller seasonality (but see below) than the dynocyst-based SSTs is not sufficient to reconstruct stratification.
Reply: As already mentioned in the present reply in reponse to Reviewer #1's comment, **we created a Supplementary Information and Method document**, in which we explain why our interpretations are robust despite the use of a modern database with SST extracted at 10 m water depth. We also added some lines about that in the manuscript (lines 361-370; lines 373-378, + also stated again in the Supplementary Information) where we clearly **specify that F-Temp are not interpreted as absolute subsurface temperatures, but as subsurface relative estimations of temperature.**
Details on the accuracy of the reconstructions were already mentioned in the initial manuscript (now lines 183/184).

Seasonality

Seasonal temperatures in the modern ocean are highly correlated, thus impeding independent reconstruction using transfer functions [Kucera et al., 2005]. The estimates of seasonality are thus not independent and should not be used as an indicator for the depth reflected by the temperature estimates.
Reply: We do not completely agree on this point. The strong differences exhibited by foraminifera-derived and dinocysts-derived seasonality signals do not indicate different depth habitats, but they are an argument in favor of the fact that they do not inhabit the same water mass. And that is what we say in the manuscript (lines 359-363).

(Also, the estimates for past seasonality are ~8 x (forams) and ~5 x (dynocysts) larger than modern observations, which would require some additional discussion/questioning.)
Reply: We added some lines in the discussion about the strong difference between modern and reconstructed surface seasonality values (lines 379-388).

Seawater δ18O estimates

N. pachyderma generally lives in the subsurface and its major flux pulse is somewhere in spring-summer. However, the calcification depth and season of N. pachyderma are likely to have varied through time (perhaps as a function of climate) e.g. [Jonkers and Kuˇcera, 2015]. The estimates of δ18Osw based on the MAT derived sea surface temperatures are thus inherently flawed because they do not (necessarily/always) reflect calcification temperature of N. pachyderma.
Reply: we do not agree, cf. our reply (replaced just below) to Dr. Jonkers about this point where we explained why interpreting our δ18Osw in terms of relative variations of local subsurface salinity is robust:
"Then, concerning δ18Osw estimates, as isotopes and foraminiferal counts are made on several specimens from a sediment sample that represents several (tens of) years, we believe that intra- and probably inter-annual variations in growth period and calcification depth are softened. Furthermore, according to Telford et al. (2013) "*For cores north of 25°N, the* [paleo]*reconstructions from different*

depths and seasons resemble one another, with an offset" and winter, summer, spring, autumn and annual F-Temp reconstructed from our PF assemblages provide indeed synchronous and similar variations. Hence, whatever the depth and season considered for the reconstructed F-Temp signal, the reconstructed δ18Osw signal would resemble the one presented in the present manuscript.

Now, concerning changes in calcification depth and season as a function of climate, they are probably inherent to all reconstructions based on PF (including geochemical ones). Concerning changes in seasonality, Jonkers and Kucera (2015) evidenced that warmings as well as coolings always result in underestimation of the amplitude of environmental change in PF records, but they did not mention any reverse environmental change in PF records due to changes in seasonality. Concerning changes in calcification depth, every study dealing with PF-derived reconstructions (MAT, δ18O, Mg/Ca, …) assumes, as first postulate, that changes in temperature resulting from changes in calcification depth are largely inferior to changes in temperature resulting from environmental changes (e.g. Peck et al., 2008). In our case, it is very likely that changes in depth accentuated the recorded environmental changes: during stadials the low saline surface layer forces PF to migrate down and thus to record colder temperatures, and during interstadial the reduction of upper stratification enables PF to migrate up and to record warmer temperatures. All of this implies that, despite biases linked to changes in calcification depth and growth season through time, and despite the fact that these biases are probably accentuated because we combined PF assemblages-derived temperatures to PF monospecific δ18O measurements, the relative variations of the reconstructed δ18Osw signal are thought to be robust in terms of trends and timings (the only way we discuss them) and similar to the ones we could have obtained using a temperature signal derived from monospecific PF samples (such as Mg/Ca)."

Stratification of surface waters during the last glacial millennial climatic events: a key factor in subsurface and deep water mass dynamics.

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Abstract

The last glacial period was punctuated by abrupt climatic events with extrema known as Heinrich events and Dansgaard-Oeschger cycles. These millennial events have been the subject of many paleoreconstructions and model experiments in the past decades, but yet the hydrological processes involved remain elusive. In the present work, high resolution analyses were conducted on the 12-42 ka BP section of core MD99-2281 retrieved Southwest off Faeroes, and combined with analyses conducted in two previous studies (Zumaque et al., 2012; Caulle et al., 2013). Such a multiproxy approach, coupling micropaleontological, geochemical and sedimentological analyses, allows us to track surface, subsurface, and deep hydrological processes occurring during these rapid climatic changes. Records indicate that the coldest episodes of the studied period (Greenland stadials and Heinrich stadials) were characterized by a strong stratification of surface waters. This surface stratification seems to have played a key role in the dynamics of subsurface and deep water masses. Indeed, periods of high surface stratification are marked by a coupling of subsurface and deep circulations which sharply weaken at the beginning of stadials while surface conditions progressively deteriorate throughout these cold episodes; at the opposite, periods of decreasing surface stratification (Greenland interstadials) are characterized by a coupling of surface and deep hydrological processes, with progressively milder surface conditions and gradual intensification of the deep circulation while the vigor of the subsurface northward Atlantic flow remains constantly high. Our results also reveal different and atypical hydrological signatures during Heinrich stadials (HS): while HS1 and HS4 exhibit a "usual" scheme with reduced overturning circulation, a relatively active North Atlantic circulation seems to have prevailed during HS2, and HS3 seems to have experienced a re-intensification of this circulation at mid-event. Our findings thus bring valuable information to better understand hydrological processes occurring in a key area during the abrupt climatic shifts of the last glacial period.

Keywords

Dansgaard-Oeschger cycles, Heinrich events, surface stratification, halocline, North Atlantic Drift, Norwegian Sea Overflow water.

1 Introduction

The last glacial period is characterized by abrupt climate oscillations. This millennial to sub-millennial climatic variability was first evidenced in Greenland atmospheric temperature records as oscillations occurring every 1-4 ka and known as Dansgaard-Oeschger events (DO) (Dansgaard et al., 1993, Bond et al., 1993). DO are characterized by a rapid transition occurring in a few decades from cold (Greenland stadial – GS) to warm (Greenland interstadial – GI) conditions. These events have been widely identified in marine archives from the subpolar North Atlantic Ocean and adjacent seas as coeval changes in surface and deep hydrology (e.g. Rasmussen et al., 1996a,b; Kissel et al., 1999; Van Kreveld et al., 2000; Rahmstorf, 2002). Moreover, during GS (including the most massive, i.e. Heinrich stadials – HS), increases of iceberg and ice-rafted debris (IRD) delivery from the boreal ice-sheets are recorded (e.g. Heinrich, 1988; Bond et al., 1993; Bond and Lotti, 1995; Elliot et al., 2001). Despite a large number of paleoreconstructions and model experiments focusing on this millennial climatic variability, processes involved still remain elusive and different mechanisms are invoked. Most of the considered theories involve changes in the meridional overturning circulation, either as the cause (e.g. Alvarez-Solas et al., 2010) or the consequence (e.g. Manabe and Stouffer, 1995; Ganopolski and Rahmstorf, 2001; Levine and Bigg, 2008) of these periodic ice-sheet instabilities.

In order to better understand these phenomena, the importance of working on high resolution records coming from key locations has been highlighted. Previous studies of marine cores located around major sills in between the North Atlantic Ocean and the Nordic Seas have shown the strong potential of this buffer area to track this variability (see references herein). Most of these studies agree with coeval oscillations of the meridional overturning circulation, depicted as weaker loop of Atlantic inflow and deep overflow from the Nordic Seas during GS and HS and inversely during GI (e.g. Rasmussen et al., 1996a,b, 2002a; Moros et al., 1997, 2002; Kissel et al., 1999, 2008; Van Kreveld et al., 2000; Elliot et al., 2002; Rasmussen and Thomsen, 2004; Ballini et al., 2006; Dickson et al., 2008). Some of them (Rasmussen et al., 1996a,b; Rasmussen and Thomsen, 2004; Van Kreveld et al., 2000; Dokken et al., 2013), on the basis of indirect proxies of sea surface conditions, suggest a strong stratification of the water column and the presence of a halocline during GS, which might have affected the oceanic circulation at greater depths.

Our study uses proxies that give access to (sub)surface (foraminifera assemblages and geochemical analyses on their shells) and deep water mass dynamics (sediment grain-size measurements and magnetic susceptibility), coupled to previously published reconstructions of sea-surface sensu stricto conditions obtained from dinoflagellate cyst (dinocyst) assemblages (Zumaque et al., 2012, Caulle et al., 2013). All analyses were conducted at centennial to millennial time scales on core MD99-2281 located southwest off Faeroe Islands. This multiproxy approach allows us (i) to directly evidence the past structure of the upper water column and especially if stratification did occur, (ii) to track this stratification evolution during the millennial abrupt events, and (iii) to evaluate its interaction with subsurface and bottom circulations.

2 Environmental setting and paleoceanographic interests

Core MD99-2281 (60.3418°N, -9.4557°E, 1197 m water depth) was retrieved during the IMAGES V – GINNA cruise on the RV Marion Dufresne (Labeyrie et al., 1999). The coring site is located southwest off Faeroes, at the southern foot of the Faeroe Bank and north of the Rockall Trough (Fig. 1).

This area constitutes a nodal point regarding modern oceanic circulation, as it is influenced by (i) the warm and salty Atlantic surface waters (T>5 °C, S>35.0; Hansen and Osterhus, 2000) conveyed by the poleward current of the North Atlantic Drift (NAD), and (ii) the intermediate and deep, cold and less saline waters (T<3 °C, S<35.0; Hansen and Osterhus, 2000) overflowing from the Nordic Seas (e.g. Kuijpers et al., 1998a,b, 2002; Hansen and Osterhus, 2000) (Fig. 1). These intermediate and deep water masses are formed within the Nordic Seas and are usually grouped under the name of Iceland Scotland Overflow Water (ISOW; Borenäs and Lundberg, 2004). At present, a branch of ISOW exits the Norwegian Sea by flowing southward through the Faeroe-Shetland Channel and then is divided into two branches: a northern, major and permanent branch, and a southern, minor, and non-permanent one (Fig. 1b). Our site is located beneath the southern branch, which intermittently crosses the Wyville-Thompson Ridge (a topographic barrier culminating at around 600 meters water-depth) and flows southward (e.g. Boldreel et al., 1998; Kuijpers et al., 1998a,b, 2002; Hansen and Østerhus, 2000). Nevertheless, according to Boldreel et al. (1998), the coring site is located within the area unaffected by strong current activities, with sedimentation resulting from pelagic sediments deposited in a low-energy, deep-water environment.

This system of water-mass exchange is known to have been very sensitive to the millennial-scale climatic variability of the last glacial period (e.g. Rasmussen et al., 1996a,b, 2002a;

Moros et al., 1997, 2002; Kissel et al., 1999, 2008; Van Kreveld et al., 2000; Elliot et al., 2002; Eynaud et al., 2002; Rasmussen and Thomsen, 2004, 2008; Ballini et al., 2006; Dickson et al., 2008; Zumaque et al., 2012; Caulle et al., 2013). This is particularly true for the Faeroe region which was then under the direct influence of the proximal European ice-sheets (i.e. the Fennoscandian and the British-Irish ice-sheets; Fig. 1a) whose decays/built-up have modulated the oceanic and climatic dynamics. Therefore, core MD99-2281 is expected to have recorded changes in the vigor of the NAD penetration and ISOW overflow in relation to European ice-sheets history.

3 Material and methods

3.1 Stratigraphy of the core

The age model of core MD99-2281 conforms to the previous published one from Zumaque et al. (2012) and Caulle et al. (2013). As recommended by several paleoceanographic studies in this area (e.g. Kissel et al., 1999, 2008; Laj et al., 2000; Elliot et al., 2002; Eynaud et al., 2002; Ballini et al., 2006; Rasmussen and Thomsen, 2009; Dokken et al., 2013), the age model is constrained by AMS ^{14}C dates (in the case of our study, 10 dates measured on planktonic foraminifera monospecific samples), combined to additional tie-points (18 in our case) obtained by comparing the magnetic susceptibility record of core MD99-2281 to the δ^{18}O signal of NGRIP ice-core (GICC05 time scale; Andersen et al., 2006; Svensson et al., 2008; Wolff et al., 2010; see Figs. 2, 3, 4 and 5 where dates are illustrated by red stars and tie-points by blue stars along the age axis). The age model was finally established on the basis of a linear interpolation between ages and tie-points (see Zumaque et al., 2012 for further explanations). It is important to note that supplementary stratigraphic control points, independent from climate, were retrieved from the record of the changes in the Earth's magnetic field (analysis performed at the LSCE), namely the Mono Lake and the Laschamps events. Those additional tie points give confidence in the established age model (see Fig. 4 in Zumaque et al., 2012).

The coring site experienced relatively high sedimentation rates during the last glacial period (between 23 and 408 cm.ka^{-1}, with a mean around 61 cm.ka^{-1} for the studied section, i.e. 300-2090 cm or ~ 12-42 ka cal BP, cf. Fig. 4). These rates, combined to our sampling frequency (every ~ 10 cm on the studied section for all analyses except for grain size analyses on a short portion of the core and for magnetic susceptibility measurements, cf. Sect. 3.5.), lead to appropriate degrees of temporal resolution (between ~ 25 and ~ 525 years, with a mean of ~ 165 years) to study the last glacial rapid climatic variability at an infra-millennial scale.

3.2 Planktonic foraminifera

Planktonic foraminifera analyses were performed on the > 150 µm fraction, on the same samples as those used for dinocyst analyses. A minimum of 350 specimens per sample were counted, and thirteen taxa were identified in the studied section. The dominant and major subordinate species are usually classified as surface/mid- to mid/deep dwelling taxa (*Neogloboquadrina pachyderma* (sinistral coiling), *Globigerina bulloides*, *Turborotalita quinqueloba*, *N. incompta* and *Globigerinita glutinata*) potentially living between 0 and 300 meters water depths according to literature (e.g. Schiebel et al., 2001, Table 3 in Staines-Urías et al., 2013 and references therein). Abundances of each species were calculated relative to the total sum of planktonic foraminifera. Counts of total benthic foraminifera were also performed, and planktonic and benthic foraminifera total concentrations (number of specimen g^{-1} of dried sediment) were calculated.

Quantitative reconstructions of foraminifera-derived temperatures (hereafter "F-Temp") were obtained using a transfer function applied to planktonic foraminifera assemblages. This transfer function has been developed by Eynaud et al. (2013). It has already been described in several previous studies (e.g. Matsuzaki et al., 2011; Penaud et al., 2011; Sánchez Goñi al., 2012, 2013; Mary et al., 2015), but hereafter is a brief summary of the technical aspects of this method. The modern analogue technique (MAT, see Guiot and de Vernal, 2007, 2011a,b for a review of this technique) was applied and performed with the R software (R version 2.7.0; http://www.r-project.org/), using the ReconstMAT script developed by J. Guiot (BIOINDIC package, https://www.eccorev.fr/ spip.php?article389). The modern planktonic foraminifera database used here combines two databases previously developed within the MARGO framework (Kucera et al., 2005; Hayes et al., 2005). It includes modern assemblages and modern hydrological parameters from 1007 sites distributed over the North Atlantic Ocean and Mediterranean Sea. Modern hydrological parameters are annual and seasonal (mean winter: January/February/March, mean spring: April/May/June, mean summer: July/August/September, and mean fall: October/November/December) oceanic temperatures extracted at 10 meters water depth (with the WOA Sample tool especially built for the MARGO exercise, i.e. Schäfer-Neth and Manschke, 2002). Statistical treatments rely on the calculation of dissimilarity indexes between the fossil and modern spectra, leading to the selection of the five best analogues. Quantifications rely on a weighted average of temperature values associated with the five best modern analogues. For the present study, we will use the mean summer and mean winter F-Temp reconstructed with RMSEP of 1.3 °C and 1.2 °C respectively.

Stable oxygen isotope measurements ($\delta^{18}O$) were also performed on monospecific samples of *Neogloboquadrina pachyderma* (some previously reported in Zumaque et al., 2012 and Caulle et al., 2013, as well as new measurements). For each sample (the same as those used for F-Temp reconstructions), 5 to 6 specimens (i.e. ~ 65 µg mean weight aliquots) were hand-picked from the 200-250 µm size fraction. From 300 to 1190 cm (~ 12-27 ka BP, 90 samples) measurements were done at LSCE laboratory using a Finnigan MAT 251 mass spectrometer. The mean external reproducibility of carbonate standard NBS19 was ± 0.05‰. From 1200 to 2090 cm (~ 27-42 ka BP, 90 samples), measurements were performed at EPOC laboratory with an Optima Micromass mass spectrometer. Reproducibility of NBS19 was ± 0.03‰. Those two spectrometers are inter-calibrated thus allowing us to directly compare both records. In both cases, values are given versus Vienna Pee Dee Belemnite (VPDB) standard.

To estimate past changes in seawater isotopic composition ($\delta^{18}O_{SW}$), we used the paleotemperature equation developed by Epstein and Mayeda (1953) and Shackleton (1974) which links the $\delta^{18}O_{SW}$, the isotopic composition of calcareous shells ($\delta^{18}O_{C}$) and the calcification temperature (T) as follows: $T = 16.9 - 4.38 (\delta^{18}O_{C} - \delta^{18}O_{SW}) + 0.13 (\delta^{18}O_{C} - \delta^{18}O_{SW})^2$. Following Duplessy et al. (1991), we used $\delta^{18}O$ measurements on *N. pachyderma* as $\delta^{18}O_{C}$, and mean summer F-Temp corrected by 2.5°C as T. We then followed the method recently described in Malaizé and Caley (2009) to extract the $\delta^{18}O_{SW}$ signal. Variations of this signal depend on past fluctuations of local salinities as well as on the global isotopic signal related to changes in continental ice-sheet volume. We used the global $\delta^{18}O$ signal of Waelbroeck et al. (2002) to remove $\delta^{18}O$ variations due to glacial-interglacial ice volume changes. We thus obtained a local $\delta^{18}O_{SW}$ signal that can be used as an indicator of local salinities changes in the depth range where *N. pachyderma* calcifies, i.e. from a few tens of meters to around 250 meters water depth (e.g. Carstens et al., 1997; Simstich et al., 2003; Peck et al., 2008; Jonkers et al., 2010). Nevertheless, it should be kept in mind that this signal is not corrected from the rapid ice volume fluctuations associated with Marine Isotopic Stage 3 (MIS3) collapse events, as those fluctuations still remain not fully understood and discrepancies still exist between the various sea-level reconstructions (Siddall et al., 2008). Quantitative estimations of salinities were not carried out as large uncertainties remain concerning the temporal stability of the relation linking local $\delta^{18}O_{SW}$ to salinity, even if a recent study, using atmospheric isotopic model, tends to minimize these uncertainties within our study area (Caley and Roche, 2013).

3.3 Dinocysts

Dinocyst specific determination, counting, and estimates of past sea-surface estimates (through transfer function applied to dinocyst assemblages) were performed within the framework of two previous studies: Caulle et al. (2013) for the 12-27 ka BP section of the studied core, and Zumaque et al. (2012) for the 27-42 ka BP section. Methods for palynological preparation, identification, counts, calculation of abundances, and dinocyst transfer function are described in these two studies. Data stemming from those analyses and reused in the present study are the concentration of modern (i.e. Quaternary) dinocysts (number of cysts cm^{-3} of dried sediment), the relative abundances of some selected dinocyst species, the concentration of coenobia of freshwater micro-algae *Pediastrum* spp. (number cm^{-3} of dried sediment), and quantitative reconstructions of mean summer (July-August-September) and mean winter (January-February-March) sea-surface temperatures (SST) (with root mean square errors of prediction – RMSEP – of 1.5 °C and 1.05 °C respectively), mean summer and mean winter sea-surface salinities (SSS; respective RMSEP of 2.4 and 2.3 psu; see Caulle et al., 2013 and Zumaque et al., 2012 for further details).

3.4 Ecological indices

Some ecological indices were calculated both on dinocyst and planktonic foraminifera assemblages. Diversity is represented by the H index: $-\sum_{i=1}^{s}[(n_i/N) \times \ln(n_i/N)]$, where n_i is the number of specimens recorded for taxa i, s the total number of taxa and N the total number of individuals counted for each sample (Shannon and Weaver, 1949). Dominance corresponds to $(n' + n'') / N$ where n' is the number of individuals of the more abundant species, n'' the number of individuals of the second more abundant species, and N the total number of specimens counted for each sample (cf. Goodman, 1979).

3.5 Sedimentological proxies

Grain-size measurements were performed on a Malvern MASTER SIZER S at EPOC laboratory (University of Bordeaux). Subsamples of bulk sediment were taken every ~ 10 cm between 40 and 2170 cm (~ 11-43 ka BP), except between 1791.5 and 1940.5 cm (~ 37-40 ka BP) where sampling was done every centimeter (371 samples in total); those subsamples did not receive any chemical pretreatment before being analyzed. But to ensure that results obtained from non-pretreated sediment adequately reflect grain-size variations of the terrigenous fraction in our study area, a second set of analyses was conducted on carbonate-free and organic-free subsamples (pretreatment with HCl 10% and H_2O_2 35%) taken every ~ 10 cm from 1593 to 1791 cm (~ 33.6-37 ka BP, same depth as the non-pretreated subsamples). Results derived from the bulk subsamples will be further represented as a mapping of the relative percentages of the different grain-size fractions along core. Some grain-size parameters were additionally calculated: median (D50), percentiles 10 and 90 (D10 and D90), mean grain size of the 10-63 µm fraction, mode, and silt ratio. The mode corresponds to the mean diameter of the most abundant size fraction. The silt ratio, reflecting size variations in the silt fraction, corresponds to the ratio of the percentage of the coarse silt fraction (26-63 µm) over the percentage of the fine silt fraction (10-26 µm).

Large Lithic Grains (LLG) concentrations (nb. of grains g^{-1} of dry sediment) were determined in the > 150 µm sediment fraction of the studied core, in the same samples as those used for foraminifera and dinocyst analyses. As in many works conducted in the study area (e.g. Elliot et al., 1998, 2001; Rasmussen et al., 2002a; Scourse et al., 2009), we assume that LLG contain a large proportion of ice-rafted debris, and thus consider this proxy as an indicator of floating ice (i.e. icebergs or coastal sea-ice) delivery to the site.

Magnetic Susceptibility was measured onboard every 2 cm with a GEOTEK Multi-Sensor Core Logger (Labeyrie and Cortijo, 2005). More detailed magnetic analyses were performed at the LSCE with a 45-mm diameter MS2-C Bartington coil on the MIS 3 section (see Zumaque et al., 2012). However, as the present study also focuses on MIS 2, we chose to present the continuous onboard signal which is furthermore very similar to the low field magnetic susceptibility record obtained at the LSCE (see Fig. 3 in Zumaque et al., 2012).

4 Results

As the age model and some raw data have already been shown in Zumaque et al. (2012) and Caulle et al. (2013), all data will be here presented and discussed according to a calendar BP age scale. Furthermore, those two previous studies already provided a detailed description of dinocyst assemblages and derived hydrological reconstructions. Therefore, except for the ecological indices and seasonality signals which are inherent to the present work, we will not describe these data here again.

4.1 Micropaleontological assemblages characteristics

Planktonic foraminifera concentrations vary from 0 to 2500 individuals/g of dry sediment, with a mean value of around 400, and highest values recorded during GI (Fig. 2c). Assemblages are clearly dominated by the polar taxon *N. pachyderma* (relative abundance ranging from 20 to nearly 100%, Fig. 2b), peaking during GS and HS. *G. bulloides*, *T. quinqueloba*, *N. incompta* and *G. glutinata* are major subordinate species in some intervals, in particular GI and the Last Glacial Maximum (LGM).

Dinocyst and foraminifera ecological indices fluctuate in phase with the abrupt climatic oscillations of the last glacial period (Figs. 2e and 2f). Planktonic foraminifera diversity and dominance are always negatively correlated, with low values of diversity and high values of dominance during GS and HS, and inversely during GI. Dinocysts diversity and dominance variations are mostly opposite, with generally higher values of diversity and lower values of dominance during GS and HS compared to GI; they appear covariant only along three very short intervals during the LGM around 20.7, 21.2 and 22.9 ka BP.

4.2 Sea-surface hydrological parameters

Planktonic foraminifera-derived mean summer temperatures (or mean summer F-Temp; Fig. 3b) vary between 2.5 and 10 °C, on average around 7 °C, and mean winter F-Temp range from -0.6 to 6.1 °C with a mean around 3 °C. These reconstructed F-Temp are lower than modern SST over the studied area which are around 11.7 and 8.6 °C on average for summer and winter seasons respectively (WOA09 data; Locarnini et al., 2010). Despite the gap of nearly 4 °C between these two signals, they both show similar trends with higher F-Temp during GI and lower values during GS and HS (Fig. 3b).

Local $\delta^{18}O_{SW}$ signal derived from foraminifera (here used as an indicator of local salinity changes) also responded to the millennial-scale variability (Fig. 3g). Values vary between around -2 and 1‰, the lowest ones being recorded during HS1 and HS4 and the highest ones during GI, the LGM and towards the Holocene.

Seasonality signals derived from dinocysts and planktonic foraminifera (calculated as mean summer minus mean winter temperatures, Fig. 3c) are clearly different from each other. The dinocyst-derived seasonality record displays large variations, with higher values during GS and the LGM (maximum of 15.1 °C, for an average of 13.6 °C) and lower ones during GI (minimum of 5.7 °C). On the contrary, the foraminifera-derived seasonality signal does not exhibit any comparable variation throughout the studied period since values vary between 2.4 and 5.1 °C with a mean value of 4.1 °C.

LLG concentrations describe a general scheme rather similar to the local $\delta^{18}O_{SW}$ and F-Temp signals (Fig. 3). They are generally higher during GS and HS than during GI. Only two noticeable exceptions exist: a high LLG concentration during the second half of GI8, and very few LLG during most of HS3.

4.3 Deep-water proxies

The millennial-scale variability has also been well captured by proxies related to bottom conditions as shown in Fig. 4. Compared to stadials (i.e. GS and HS), GI are characterized by higher sedimentation rates, coarser grain-sizes (marked by D50 values up to 5 phi and D90 values up to 2.5 phi, and also evidenced on the grain-size mapping in Fig. 4c through the displacement towards the right, i.e. towards coarser grain-sizes, of the most abundant grain-size fractions, i.e. the ones colored from light blue to red), a higher proportion of the coarse silt fraction relative to the fine silt fraction, a coarser dominant fraction, higher magnetic susceptibility values, and higher benthic foraminifera concentrations. Among stadials, only HS2 exhibits a signature comparable to GI one. Note that except for magnetic susceptibility (and sedimentation rate), all the other deep-sea proxies seem to increase gradually throughout GI. It is visible for GI 11, 10 and 7, and particularly noticeable for GI 8; for shorter GI, this progressive trend is hardly or not distinguishable.

5 Discussion

5.1 A reworked signal?

Considering the size of micro-organisms used in this study and the sedimentary processes occurring in the area, one could object that assemblages may not result from local deposition only but also from lateral advections including reworking of previously deposited material on proximal areas. In this case, our reconstructions would not reflect local surface and subsurface hydrology but a combination of allochthonous and autochthonous signals, furthermore mixed throughout time.

To identify and circumscribe these problems, we used the methodology recommended by Londeix et al. (2007) to identify reworked intervals in sedimentary records by combining diversity and dominance indices in microfossil communities. Indeed, according to these authors, ecologically inconsistent covariance between these two indices is attributed to mixing processes. In core MD99-2281, diversity and dominance are negatively correlated all along the 12-42 ka BP studied section regarding both planktonic foraminifera and dinocysts (except for three very short episodes during the LGM, a period not discussed in this study, and only for dinocysts, Fig. 2e and 2f), and so do not reveal any evidence of reworking.

5.2 Interpretation of proxies

5.2.1 Proxies of surface and subsurface hydrology

As shown in Fig. 3, hydrological signals derived from planktonic foraminifera (F-Temp and local $\delta^{18}O_{SW}$) and from dinocysts (SST and SSS) share common features but also differ in some points through the studied period. Firstly, winter SST, winter F-Temp and summer F-Temp display similar variations and similar amplitudes of variation (with nonetheless noticeable discrepancies, e.g. during the LGM and between 32 and 27 ka cal BP), but are clearly different from dinocyst-derived summer SST. Indeed, summer SST show a clear opposite trend to the three other reconstructed temperature signals (with higher values during GS and HS), and they display values well above the ones of the three other signals as well as above the modern mean ones. Secondly, at stadial-interstadial transitions, dinocyst-derived SST and SSS display gradual increases/decreases whereas foraminifera-derived temperatures and local $\delta^{18}O_{SW}$ show more abrupt variations despite identical resolutions (Figs. 3b and 6a). Lastly, dinocysts mainly recorded a large seasonality with significant variations over the studied period whereas planktonic foraminifera recorded a low seasonality with very low or even nil fluctuations (Fig. 3c). As suggested in previous studies (e.g. de Vernal et al., 2005, 2006; Penaud et al., 2011), such discrepancies may result from differences in depth habitat of these organisms. Indeed, dinoflagellates are restricted to the photic layer while planktonic foraminifera may live deeper. This is particularly true for the dominant and subordinate foraminifera species identified in this study, since they do not bear any symbiont. According to literature, the depth habitat of these species potentially ranges between 0 and 300 meters water depth (see Table 3 in Staines-Urías et al., 2013 and references therein). Besides, dinocyst-derived SSS are very low throughout most of the studied period (means of 31 and 32 psu for summer and winter SSS), and the main planktonic foraminifera species identified in our assemblages barely tolerate such salinities (Tolderlund and Bé, 1971). Therefore, we can reasonably consider here that dinocysts provide a record of the surface sensu stricto, whereas planktonic foraminifera recorded hydrological conditions of a larger section of the upper water column that we call hereafter the subsurface for simplicity. It is worth noting that F-Temp reconstructions cannot be considered as subsurface absolute reconstructions since temperatures in the modern database used for the transfer function are extracted at 10 meters water depth. However, interpreting them as subsurface relative estimations is coherent if we consider previous works focused on transfer functions applied to planktonic foraminifera assemblages (see Supplementary Information).

Seasonality values derived from dinocysts (averaged value over the studied period of ~ 13.6 °C, Fig. 3c) are ~ 4 times higher than the modern sea-surface seasonality value over the study area (~ 3.2 °C; calculated from WOA09 data as mean summer minus mean winter oceanic temperatures; Locarnini et al., 2010). It might seem surprising, but similar values are presently recorded in several areas around the world (at the outlet of the Gulf of St Lawrence, in the Baltic Sea and outlets of the bordering gulfs, in the Sea of Japan, the East China Sea, the Black Sea, and the Caspian Sea, according to WOA09 data, Locarnini et al., 2010). For some of these areas, such high seasonality contrasts are related to a stratification of the upper water column marked by the presence of a halocline (e.g. the Baltic Sea, Kullenberg, 1981; the outlet of the Gulf of St Lawrence, Banks, 1966). Indeed, the very low SSS recorded by dinocysts (which are well below the modern ones over the study area, equal to 35.3 psu according to WOA09 data, Antonov et al., 2010; Fig. 3d), as well as the presence of the freshwater micro-algae *Pediastrum* spp. (a marker of freshwater advection in surface; e.g. Eynaud et al., 2007), support the existence of a thin freshwater surface layer of low thermal inertia overlying the study area during most of the studied period. Similarly to present situations, this freshwater layer would have certainly been responsible for a strong stratification of the water column due to the presence of a halocline. Such a pattern is also qualitatively consistent since the most abundant dinocyst species is *B. tepikiense*, a taxon which displays a strong affinity for stratified surface waters characterized by a large seasonality (Rochon et al., 1999). Furthermore, this interpretation explains why dinocyst (i.e. surface) signals are noisier than planktonic foraminifera ones.

Iceberg calving and associated meltwater inputs are potential initiator and feeder of this halocline. Ice-rafted debris have mainly been used as tracers of these iceberg surges. Here, we use LLG concentrations and assume, as generally admitted, that LLG are mainly constituted of IRD. Our LLG signal is indeed very similar to IRD records coming from many studies and sites in North Atlantic (e.g. Bond and Lotti, 1995; Elliot et al., 1998, 2001; Van Kreveld et al., 2000; Rasmussen and Thomsen, 2004; Dickson et al., 2008) which described higher ice-rafted debris concentrations during GS and HS and variable concentrations during the LGM. This supports the assumption that our LLG signal can be used as an indicator of iceberg delivery to the studied site. In this case, the resemblance between LLG concentrations and local $\delta^{18}O_{SW}$ and subsurface temperature (F-Temp) signals suggests that these latter signals are at least partly forced by iceberg calving and melting and associated cold freshwater releases. However, variations in the warm and salty northward Atlantic flow could also play a major role in the fluctuations of these signals. Many freshwater model experiments (e.g. Manabe and Stouffer, 1995; Ganopolski and Rahmstorf, 2001; Levine and Bigg, 2008) have indeed shown that these two processes are clearly linked, in the sense that (i) freshwater release weakens the Atlantic meridional overturning circulation and limits the northward extension of the NAD, and (ii) the larger the amount of released freshwater is, the more weaken the oceanic circulation is. Moreover, the correspondence between LLG and foraminifera-derived signals is only partial. Some delays (e.g. during H4, GS8, GS6) and incoherencies (e.g. the relatively long periods before and after HS2 with considerably low $\delta^{18}O_{SW}$ but almost no LLG) can indeed be noticed. This leads us to think that paleo-fluctuations of our foraminifera-derived signals are the result of the combined two phenomena: the warm and saline Atlantic water northward flow and its southward retreat, and the episodic cold and fresh water release associated with iceberg surges. Respective contributions of these two phenomena could seem difficult to dissociate, but in this study, dinocyst data provide valuable clues. Indeed, as mentioned above, dinocyst-derived SSS and seasonality signals are indicators of surface stratification. Then we can suppose that during periods of high surface stratification (i.e. periods when the halocline strongly hampers or even prevents mixing between surface and subsurface waters), variations of F-Temp and local $\delta^{18}O_{SW}$ should be principally due to variations in the NAD intensity. At the opposite, during periods of weaker surface stratification, and when iceberg calving occurred, variations of planktonic foraminifera-derived parameters should be the result of the combination of meltwater inputs from the surface and NAD variations; but during periods of low stratification and without iceberg calving, subsurface hydrological variations should be due to NAD fluctuations only.

5.2.2 Proxies of deep water currents

Reconstructing past variations of the ISOW dynamics deserves to be attempted in this study as our multi-proxy approach provides various indicators of bottom current activities (Fig. 4). The first type of bottom flow proxy corresponds to parameters derived from grain-size measurements. These parameters (listed in Sect. 3.3 and below) have been widely employed in reconstructions of bottom current activity (e.g. McCave et al., 1995a,b; McCave, 2007; Bianchi and McCave, 1999; Hodell et al., 2009). Their use is based on the fact that bottom currents preferentially affect the silt fraction (10-63µm) by size-sorting, such as stronger currents induce a coarsening and an increase of the relative proportion of this size fraction. Basically, an intensification of the ISOW will be depicted as a coarsening of D10, D50, and D90 (Fig. 4c), an increase of the mean size of the 10-63 µm fraction (Fig. 4d) and of the silt ratio (Fig. 4e), a coarsening of the dominant mode towards values corresponding to the silt fraction or even coarser (Fig. 4f), and a grain size distribution showing a coarsening and an increase of the relative proportion of this coarse fraction (Fig. 4c). It is important to note that in the glacial North Atlantic Ocean, IRD < 150 µm could constitute a potential source of silt-size particulates which could bias the use of these parameters as bottom flow proxies (Prins et al., 2002). Nevertheless, in our case, LLG concentrations are generally higher during GS, i.e. when grain-size distribution and parameters indicate a general finning of the total sediment fraction – including silt fraction – and a predominance of the < 10 µm fraction. As the supplies of IRD > 150 µm (i.e. LLG) and < 150 µm are supposed to be synchronous, the impact of IRD inputs (fine as well as coarse ones) on the grain-size distribution seems to be minor, and so do not seem to bias the use of grain-size parameters as indicators of the bottom current strength. In a similar way, biogenic inputs could also influence grain-size distribution and bias the grain-size proxies. However, Fig. 4d, e and f show that the calculated grain-size parameters for the bulk samples and for the pretreated ones exhibit the same variations in terms of timing as well as in amplitude. Besides, grain-size analyses on pretreated samples were conducted on the core section where the content of $CaCO_3$ (data not shown) displays the largest variations and attains its maximal value over the studied portion of the core. This confirms that in our study area, grain-size variations of bulk sediment almost exclusively reflect changes in the terrigenous fraction and so can be directly interpreted in terms of fluctuations of the bottom current intensity.

The second type of bottom flow proxy used in this study is the magnetic susceptibility (Fig. 4g). Kissel et al. (1999, 2009) have shown that, in areas distributed along the path of the deep water-masses feeding the North Atlantic Deep Water, magnetic susceptibility fluctuations are directly related to variations in the relative amount of magnetic particulates within the sediment; as those magnetic minerals principally originates from a unique source (the Nordic basaltic province), changes in magnetic susceptibility reflect changes in the efficiency of their transport mode from the source area to the study site, i.e. changes in the intensity of bottom currents. Hence, in our study area, higher values of magnetic susceptibility reflect higher ISOW energy.

Our last type of indicator of bottom flow activity corresponds to benthic foraminiferal concentrations (Fig. 4h). Indeed, in the study of different cores located in the study area, Rasmussen et al. (1997, 1999, 2002a) related this parameter to the activity of the ISOW, with high concentrations of benthic foraminifera associated with relatively strong bottom current influence and increased ventilation and supply of food, and conversely low benthic abundances related to more quiet deep-sea conditions with reduced fluxes of organic matter.

When looking at the evolution of all these proxies in core MD99-2281, it clearly appears that they all tend to the same general scheme: the ISOW was relatively active during GI and relatively reduced during GS (Figs. 4 and 5). These results are in accordance with findings from previous studies (e.g. Moros et al., 1997, 2002; Van Kreveld et al., 2000; Elliot et al., 2002; Rasmussen and Thomsen, 2004; Ballini et al., 2006). Besides, the higher sedimentation rates recorded during GI (Fig. 4b) indicate that in our study area and during the studied period, the ISOW was responsible of a higher supply of sediment during episodes of high activity rather than of a winnowing of the clay fraction (< 10 µm).

One could argue that since the age model of the studied core is based on correlations between our magnetic susceptibility record and the $\delta^{18}O$ signal of NGRIP ice-core (i.e. on the assumption that the ISOW was reduced during GS), we cannot make any supposition about the timing of changes in deep current intensity. This would be obviously true in the case of studies intending to precisely compare the timing of these changes relatively to the timing of Greenland atmospheric variations. But this is not the case of our study, which aims to compare the timing of deep circulation changes with the one of surface and subsurface hydrological variations (as deduced from the same sedimentological archive), and to compare the trends of all those fluctuations (progressive *versus* abrupt).

5.3 Hydrological signature during Dansgaard-Oeschger events and implications

MD99-2281 records are in general agreement with the usual climatic scheme depicted in previous studies and described in the introduction of this paper, i.e. iceberg surges and a weaker or shallower Atlantic meridional overturning circulation during GS, and conversely warmer surface conditions linked to a more northerly inflow of Atlantic surface waters and associated active deep water convection in the Nordic Seas during GI (cf. Fig. 5). This is especially noticeable with the strong and striking correlation between dinocysts, planktonic and benthic foraminifera abundances throughout all the studied period, which furthermore suggests a coupling of the productivity at the different layers of the water column.

However our records also reveal unusual features, such as the strong stratification of surface waters during GS. Previous studies from the subpolar North Atlantic (e.g. Rasmussen et al., 1996a,b, Rasmussen and Thomsen, 2004 and Dokken et al., 2013 at study sites close to MD99-2281 site, Van Kreveld et al., 2000 in the Irminger Basin) already indirectly deduced from planktonic foraminifera data the presence of a halocline and a stratified water column during GS. In our study, dinocyst assemblages and dinocyst-derived surface hydrological parameters provide direct evidences of the presence of a thin freshwater surface layer and stratified surface waters during stadials, and therefore confirm the previous assumption based on indirect proxies (rather subsurface proxies).

Our records also show atypical progressive trends that can be depicted within GS and most of all within GI (Figs. 3, 5 and 6a). During GS, dinocyst data indicate a deterioration of surface conditions characterized by a more or less gradual decrease of winter SST (depending on the GS considered) while summer SST, surface stratification and seasonality remain high. Foraminifera-derived subsurface hydrological parameters and grain-size data show rapid transitions at the beginning of GS (especially noticeable for GS 10 and 8 for example) which denote an abrupt slowing down of the northward Atlantic flow (sharp decreases of F-Temp and local $\delta^{18}O_{SW}$) and of the deep ISOW (marked decreases in grain-sizes, silt ratio and mean size of the silt fraction) at that time. Throughout GI, dinocyst data reveal progressively milder surface conditions marked by a gradual increase of winter SST in parallel with a gradual decrease of stratification and seasonality. Grain-size data also indicate a gradual intensification of the ISOW flow with a maximal intensity at the end of these periods (particularly noticeable when looking at the silt ratio and the mean size of the 10-63 µm fraction, and highlighted by red arrows on Fig. 5). At the opposite, planktonic foraminifera data show that the subsurface reactivation of the NAD at the GS-GI transitions was more abrupt than shown within proxies of surface and deep-sea dynamics.

At first sight, our set of proxies thus denotes a decoupling between surface, subsurface, and deep-sea hydrological processes during DO. This is in agreement with previous studies which already suggested a decoupling between surface and subsurface (Moros et al., 2002) or subsurface and deep circulations (Rasmussen et al., 1996b). However, a detailed examination of our records reveals that subsurface and deep circulations are coupled during GS, i.e. when surface waters are highly stratified, and that surface and deep circulations are coupled during GI, i.e. when the stratification is reduced. This leads us to think that the surface stratification is a determinant factor for hydrological processes occurring at greater depth around the study area. We can therefore propose the following scenario which conciliates our records and highlights the importance of the water-column organization during millennial scale climatic events (Fig. 6b):

At the end of GS, the NAD rapidly extends northward again. However, the water column is still highly stratified and the near-surface halocline prevents heat exchange towards the atmosphere; heat is thus stored in the subsurface layer below the halocline. Subsurface waters are consequently not dense enough because too warm to sink and deep convection is nil or very limited (at least north of our study site). Then, at the beginning of GI, the halocline starts to be unstable (probably because of the accumulation of heat below). The stratification is then progressively reduced, and heat exchange (between subsurface and surface, and surface and atmosphere) becomes possible again. Subsurface Atlantic waters progressively mix with low salinity surface waters which progressively get saltier. They become sufficiently dense to sink, and deep convection is thus re-activated and progressively intensifies throughout the GI. As a consequence, the ISOW activity progressively strengthens and reaches its maximal vigor at the end of this period. Then, at the beginning of GS, iceberg discharges occur. The associated meltwater has several consequences on the stadial hydrology. First, the freshwater input rapidly propagates in the mixed surface-subsurface layer, lowers its salinity, strongly reduces deep convection, and thus weakens the NAD and the ISOW flows. Secondly, it contributes to the re-establishment of the freshwater surface layer and the associated halocline, and to the progressive slight strengthening of the stratification. NAD and ISOW flows remain weak until the end of GS.

Rasmussen et al. (1996a,b) and Rasmussen and Thomsen (2004) proposed a similar scenario where an accumulation of heat below the fresh surface layer is responsible for the destabilization of the halocline and the abrupt release of a large amount of heat to the atmosphere, then causing the sudden Greenland atmospheric warming. On the basis of benthic assemblages from various cores located around Faeroe Islands (e.g. ENAM93-21; 62.7383°N; -3.9987°E; 1020 m water depth – ENAM33; 61.2647°N; -11.1609°E; 1217 m water depth), they suggested that relatively warm Atlantic intermediate waters keep on flowing into the Nordic Seas below the halocline during GS, and they attributed these warm Atlantic waters to the NAD. However, our results derived from planktonic foraminifera data do not indicate any significant flow of NAD directly below the halocline during GS (Rasmussen et al., 1996a,b and Rasmussen and Thomsen, 2004 recorded indeed a total dominance of *Neogloboquadrina pachyderma* during stadials), but enables such a flow at deeper water depth. In this case, both the reactivation of the subsurface NAD at the end of GS and the continuous northward flow of Atlantic intermediate waters during GS may have participated in the accumulation of heat below the halocline, the destabilization of this latter, and then the sudden release of heat to the atmosphere at the GS-GI transition.

Dokken et al. (2013) also proposed a similar scenario for GS, with a fresh surface layer, a halocline, and an active Atlantic inflow just below it. This scenario was inferred from planktonic foraminifera data in core MD99-2284 (62.3747°N; -0.9802°E; 1500 m water depth). Considering the location of their study site close to the continental shelf edge, this shallow Atlantic inflow is not contradictory to our results which allow the presence of a narrow warm Atlantic inflow flattened against the shelf edge by the Coriolis force. Such a narrow flow would not be recorded in cores located further away from the shelf such as ours.

The observed gradual intensification of the ISOW flow during GI constitutes the most unusual and salient feature revealed by our data. However, a previous study from the Reykjanes Ridge (Snowball and Moros, 2003) also depicted a very similar pattern in magnetic susceptibility data and quartz to plagioclase ratio in cores LO09-18GC (58.9674°N; -30.6832°E; 1460 m water depth) and SO82-05GGC (59.1857°N; -30.9047°E; 1420 m water depth), with a progressive intensification of the Iceland-Scotland Overflow Water during GI followed by an abrupt reduction.

5.4 Different hydrological patterns during Heinrich stadials

Figure 5 clearly shows that the four HS recorded in the studied section of core MD99-2281 (HS1, HS2, HS3 (which can be divided in HS3a and HS3b, see below) and HS4) do not exhibit the same hydrological patterns. The only common feature corresponds to the harsh surface conditions deduced from dinocyst data and also depicted during GS, and characterized by the presence of a fresh water lid, a high seasonality and a relatively strong stratification of the water column. On the contrary, planktonic foraminifera data and deep-sea proxies show different signals, in amplitude or in trend, thus suggesting different subsurface and deep water mass dynamics (see Table 1).

HS1 and HS4 appear such as HS are usually described in the literature, i.e. with very low local $\delta^{18}O_{SW}$ values indicative of very low salinities in the subsurface layer, and strongly reduced or even shut down northward Atlantic flow and deep-water overflow (according to foraminifera-derived data and grain-size data respectively). Compared to GS, our data indicate a more drastic reduction of the meridional overturning circulation and a more southerly location of the deep convection center during HS1 and HS4, in agreement with previous studies (e.g. Elliot et al., 2002; Rahmstorf, 2002).

At the opposite, HS2 presents a very atypical hydrological signature: grain-size data, in agreement with the magnetic susceptibility signal, indicate a relatively active ISOW; in parallel, subsurface records show F-Temp and local $\delta^{18}O_{SW}$ comparable to most of GS ones but higher than the “classical” HS1 and HS4 and even than some GS. These results indicate the presence of saltier (and so denser) and slightly warmer subsurface waters bathing our study site, and thus denotes a slightly more active meridional overturning circulation and a more northerly center of convection during HS2 compared to “classical” HS. This would be besides in agreement with previous paleoreconstructions: in core Na 87-22 (located on the eastern banks of the Rockall Plateau; 55.4833°N; -14.6833°E; 2161 m water depth), Elliot et al. (2002) found benthic $\delta^{13}C$ values during HS2 which are higher than HS1 and HS4 values and similar to GS values; according to the interpretation of this proxy made by the authors, it suggests that the reduction of deep-water formation and the northward migration of $\delta^{13}C$ depleted southern source deep waters were less important during HS2 and stadials than during HS1 and HS4. Much farther away from our study area, in the Gulf of Cadiz, core MD99-2339 (35.88°N, -7.53°E; 1170 m water depth; Voelker et al., 2006) also provides indirect evidence of a more active North Atlantic overturning circulation. Indeed, paleoreconstructions of the strength of the Mediterranean Outflow Water (or MOW, which overflows from the

Mediterranean Sea to and within the Gulf of Cadiz) have shown that this bottom current has been particularly active during periods of weak Atlantic meridional overturning circulation such as GS and HS (e.g. Cacho et al., 2000; Voelker et al., 2006; Toucanne et al., 2007). Grain-size data of core MD99-2339 show indeed a clear intensification of the MOW during HS1, HS4, HS5, and most GS. However they do not indicate such a strengthening during HS2 (and HS3), and so could denote a more vigorous North Atlantic circulation. Furthermore, Scourse et al. (2009) evidenced higher IRD fluxes during HS2 (compared to other HS) in cores located west and north off Great Britain. According to the authors, these strong fluxes typify the maximal extent of the British Irish Ice-Sheet. In such a context, an Atlantic flow extending more northerly as compared to the other HS might have also contributed to enhance iceberg release from the British Irish Ice-Sheet.

Concerning HS3 (defined, as usually, as the interval starting at the end of GI 5 and ending at the start of GI 4), grain-size data tend to indicate a low ISOW activity throughout the interval. However, foraminifera-derived subsurface parameters show a tripartite structure with (i) low F-Temp and local $\delta^{18}O_{SW}$ values indicative of a weak NAD at the beginning and the end of the event and (ii) higher values pointing to a stronger NAD in the central part of the event. Besides, the magnetic susceptibility record shows two peaks around 29.5 and 30.5 ka BP coeval with high F-Temp and local $\delta^{18}O_{SW}$ values. Benthic foraminifera concentrations also display a peak concomitant with the first MS peak. Furthermore, Elliot et al. (2002) found a two-phased incursion of southern sourced waters (at the onset and the termination of the event) in core Na 87-22 from the Rockall Plateau and core SU90-24 from the Irminger Basin (62.0667°N; -37.0333°E; 2100 m water depth). Hence, all of these records suggest that HS3 might have been a three-phased event with classical disruptions of the overturning circulation at the beginning and the end of the event, interrupted by a significant resumption of this circulation. The beginning of the period of resumption of this circulation is concomitant with the short interstadial phase defined as GI 5.1 by Rasmussen et al. (2014). Since both intervals before and after GI 5.1 have previously been related to HS3 (e.g. Sanchez Goñi and Harrison, 2010; Hall et al., 2011) we propose to follow Rasmussen et al. (2014) and to divide the usual HS3 period in three phases: HS3a, GI 5.1, and HS3b such as indicated in Fig. 5. In this way, HS3a and HS3b can be considered as two periods of relatively weak Atlantic meridional overturning circulation, separated from each other by a phase of re-intensification of this circulation also detectable in Greenland ice core records as a milder phase (GI 5.1). The absence of clear evidence of ISOW reactivation in grain-size data during GI 5.1, and its discrete and arguable evidence in the magnetic susceptibility and benthic concentration records is puzzling if we consider, as advanced previously, that subsurface and deep circulations should be coupled due to the strong surface stratification. However, the Wyville-Thompson Ridge could have acted as a topographic barrier (even more than at present) that would have prevented a too weak deep flow to influence our study site by constraining it into the Faeroe Bank Channel (cf. Fig. 1).

6 Conclusion

Analyses carried out within the framework of this study confirm that the area southwest off Faeroe Islands has been very sensitive to the last glacial millennial-scale climatic variability. Our multiproxy approach allows us to track hydrological processes at different key water depths, and reveals a partly and episodically coupling of surface, subsurface and deep water mass dynamics controlled by surface stratification during rapid climatic shifts. Indeed, GI are characterized by a decreasing stratification and a coupling of surface and deep hydrological processes, with progressively milder surface conditions and gradual intensification of the ISOW while the activity of the subsurface NAD flow remains constantly high. At the opposite, GS experienced a high surface stratification and coupled subsurface and deep circulations marked by a sharp weakening of the NAD and the ISOW at the beginning of GS, while surface conditions progressively deteriorate throughout the GS. These results led us to propose a scenario describing the evolution and interactions of hydrological processes during DO and taking into account the determining role of the surface stratification. Our records also denote different hydrological signatures during Heinrich stadials. HS1 and HS4 appear as "classical" HS with strongly reduced Atlantic meridional overturning circulation. On the contrary, HS2 probably experienced a relatively active North Atlantic circulation. Finally, HS3 seems to be a three-phased event marked by a re-intensification of the overturning circulation in the middle of the event.

Our study highlights the importance of coupling near-surface reconstructions of oceanic conditions to avoid misinterpretation of data, particularly in areas affected by changes in the structure of the upper water column. It illustrates the potential of such high resolution multi-proxy paleoreconstructions, especially in areas close to glacial ice-sheets when aiming to track hydrological processes occurring during the still so enigmatic rapid climatic oscillations of glacial periods. It also encourages model experiments to take into account stratification artifacts and 3D-oceanic scenarios, and to test the robustness of the hydrological mechanisms and interactions proposed in this work.

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Figure captions

Figure 1. (a) General map of the studied area, showing the location of the studied core MD99-2281 (red cross) and of nearby cores referred to in the present study (black dots; ENAM93-21 and ENAM33, *Rasmussen et al.*, 1996a,b, *Rasmussen and Thomsen*, 2004; MD99-2284, *Dokken et al.*, 2013; LO09-18GC and SO82-05GGC, *Snowball and Moros,* 2003; Na87-22 and SU90-24, *Elliot et al.*, 2002). The hatched areas represent the maximal last glacial extension of the proximal ice-sheets (after *Ehlers and Gibbard*, 2007; FIS: Fennoscandian Ice-Sheet; BIIS: British-Irish Ice-Sheet). The yellow arrows indicate the major pathways of the warm and saline surface water conveyed by the North Atlantic Drift (NAD, after *Orvik and Niiler*, 2002 and *Stanford et al.*, 2011). Purple square indicates the area shown in Fig. 1b. Blue line indicates the location of the profile shown in Fig. 1c. (b) Detailed physiography of the studied area. Bathymetry is from GEBCO (www.gebco.net, isobaths every 200 m). Remarkable sub-marine structures are indicated (bathymetric heights: FB, Faeroe Bank; BBB, Bill Bailey Bank; LB, Lousy Bank; WTR, Wyville-Thompson Ridge – trough: RT, Rockall Trough – and channels: FSC, Faeroe-Shetland Channel; FBC, Faeroe Bank Channel). Purple arrows show the major (full lines) and intermittent (dotted lines) deep Iceland Scotland Overflow Water (ISOW) pathways, after *Boldreel et al.*, (1998), *Kuijpers et al*. (1998b, 2002), and *Howe et al*. (2006). Blue line indicates the location of the profile shown in Fig. 1c. (c) East-west profile of oceanic temperatures. Temperature data are derived from WOA09 (*Locarnini et al*., 2010) and plot using Ocean Data View (*Schlitzer*, 2012); bathymetric data are from GEBCO (www.gebco.net). Locations of the studied core and of the main sub-marine structures are indicated. *Geographic coordinate system: WGS 1984 – Projection: Mercator 55°N.*

Figure 2. Evolution of index micro-planktonic assemblages compared to (a) NGRIP-GICC05 $\delta^{18}O$ record: (b) Relative abundances of the dominant planktonic foraminifera species – (c) Absolute abundances (nb. of specimen in the sediment) of dinocysts and planktonic foraminifera – (d) Relative abundances of dominant dinocyst species – (e) Planktonic foraminifera diversity and dominance (see calculations in Sect. 3.2.) – (f) Dinocyst diversity and dominance. Red stars indicate AMS ^{14}C dates used, and blue stars show the tie-points obtained by comparing the MD99-2281 magnetic susceptibility record to the NGRIP $\delta^{18}O$ signal (see *Zumaque et al.*, 2012). GS and HS are highlighted by light and dark grey bands

respectively (age limits after *Wolff et al*., 2010). DO are numbered according to corresponding GI numbers in Dansgaard et al. (1993), except for GI 5 which was divided in GI 5.2 and GI 5.1 according to Rasmussen et al. (2014). LGM is for Last Glacial Maximum, BA for Bølling-Allerød, and YD for Younger Dryas.

Figure 3. Reconstructed hydrological parameters derived from dinocyst and planktonic foraminifera assemblages compared to (a) NGRIP-GICC05 δ^{18}O record: – (b) Temperatures – (c) Seasonality (mean summer minus mean winter temperatures) – (d) SSS derived from dinocysts – (e) Abundances of coenobia of the freshwater algae *Pediastrum* spp. – (f) δ^{18}O measured on *N. pachyderma* – (g) Local $\delta^{18}O_{SW}$ derived from δ^{18}O on *N. pachyderma* – (h) Large Lithic Grains (LLG) concentration, plotted on a reverse scale. Stars, bands, DO number and acronyms: same legend as Fig. 2.

Figure 4. Evolution of oceanic bottom conditions. (a) NGRIP-GICC05 δ^{18}O record – (b) Sedimentation rate (calculated between two consecutive tie-points) – (c) Grain-size distribution on the background, and D10, D50, and D90 represented as black curves in the foreground – (d) Mean size of the silt (10-63 µm) fraction for bulk samples and pretreated samples (carbonates and organic matter removed) – (e) Silt ratio between 26-63 µm and 10-26 µm fractions for bulk and pretreated samples – (f) Mean diameter of the dominant grain-size mode for bulk and pretreated samples – (g) Magnetic susceptibility record – (h) Absolute abundances of benthic foraminifera. Stars, bands, DO number and acronyms: same legend as Fig. 2.

Figure 5. Comparative figure showing the evolution through time of proxies indicative of the ISOW bottom dynamics (left framed panel), the subsurface NAD intensity (middle framed panel), and the surface sensu stricto conditions (right framed panel). Absolute abundances of benthic foraminifera, planktonic foraminifera, and dinocysts are shown in the middle unframed panel. NGRIP δ^{18}O record is shown at the far left to illustrate the chronological framework. Stars, bands, DO number and acronyms: same legend as Fig. 2. Red arrows highlight the progressive trends.

Figure 6. Synthetic figure illustrating the hydrological processes occurring during Dansgaard-Oeschger cycles at the study site. (a) Zoom in on DO 8, 7, 6 and 5 showing the evolution of some selected proxies shown in Fig. 5, as well as the schematic evolution through DO of the ISOW activity, the NAD vigor, the intensity of mixing between surface and subsurface waters, and the degree of surface stratification. (b) Conceptual representation of the hydrological processes occurring during the different phases of DO as depicted in Fig. 6a.

Table

Table 1. Synthesis of the main hydrologic features depicted at the study site during Heinrich stadials (HS) 1 to 4.

Event	**Bottom (ISOW)**	**Subsurface (NAD)**	**Surface**	**Interpretations**
HS1 & HS4	Weak or stopped	Weak or stopped	High stratification - No mixing between surface and subsurface waters	As usually described HS
HS2	Relatively active	More active than during HS1 & HS4		"Atypical" HS Relatively active overturning circulation, center of deep convection located more northerly
HS3	Three-phased or weak	Three-phased (↓↑↓)		Three-phased event (HS3a, GI 5.1, HS3b)