nature portfolio

Peer Review File

Last deglacial abrupt climate changes caused by meltwater pulses in the Labrador Sea

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

24th Aug 22

Dear Mr You,

Your manuscript titled "Abrupt climate changes caused by meltwater pulses in the Labrador Sea during the last glacial termination" has now been seen by 3 reviewers, and I include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

In particular, please ensure that the revised manuscript meets the following editorial thresholds:
Provide a discussion of the discrepancy between your local record and those of other regional records
Add more dynamical explanation to link the four millennium-scale cold events with the freshwater pulse

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter) and the completed checklist:
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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

Please do not hesitate to contact me if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the

opportunity to review your work.

Best regards,

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Locum Chief Editor
Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript entitled “Abrupt climate changes caused by meltwater pulses in the Labrador Sea during the last glacial termination” by You and co-authors presents a set of high-resolution and well-dated proxy records from a sediment core from the Eirik Drift, eastern Labrador Sea, spanning over the past 23 ka from the LGM to the Holocene. On the basis of the new data, the authors characterized mainly the four cold/four warm events during the last deglaciation and the early-Holocene, and possible underlying mechanisms. Overall, while the new data are interesting and valuable, the interpretations remain tentative. A major revision is necessary pending on which I recommend acceptance of this paper.
Major concerns:
(1) The hydroclimatic variability revealed by the new dataset does not appear to be tuneful with those recorded by a large number of ice core, marine sediment and terrestrial records from the North Atlantic regions. For instance, the vital discrepancy is very obvious regarding the timing and structure of the 8.2 ka event, YD and B/A. This is possibly an important observation, but I did not see a convincing explanation of it in the current manuscript. It seems to me that the new records, if robust, have a distinct nature, reflecting a ‘local’ climate variability, which is significant different from the current interpretation framework of climate variation history over the last deglaciation and the Holocene in the North Atlantic. In other

words, an in-depth discussion of the discrepancy is essential.
(2) The apparent "problems" associated with the new data themselves require explanations. For example, the glacial SST in some periods (around the HS1) is similar to the Holocene, and the SSTs during the four cold events is equivalent to or lower than the glacial values. Especially, the SST during the C4 event is the lowest, which is difficult to image. In contrast, the less sea ice and the higher SST in the HS1 than in the C1-C4 events appear to be strange. The %C37:4 of C1 suggests more freshwater injection than that of C4, whereas the SST during C1 seems less cool than C4.
Minor issues:
(1) In abstract and conclusion, the abrupt changes of meltwater pulses and SST are described to occur within a few decades. However, the dating uncertainties and sample resolution of the records are about 100-years or larger (?). As such, a detailed evaluation of the uncertainties associated with the conclusion should be included in the method section. Similarly, in the line of 251, for example, the duration of "360 years" should also give an uncertainty.
(2) The main scientific issue focused here need to be explained better and clearer in the introduction. A large part of the current introduction is about the AMOC, but the AMOC seems not an important issue discussed in the main text (not event encompassed a comparison with AMOC proxies), although it is highly relevant.
(3) The authors provided 10 proxies, including IP25, PDIP25, Uk37 SST, HBI-III, Alkenoes, Dinosterol, Si/Sr, Zr/Rb, % C37:4 and SS, but some of them are rarely mentioned or used in the text.
(4) Any replications available to test the robustness of the new records?

Reviewer #2 (Remarks to the Author):

Review: You et al

In agreeing to review this paper I expected that given Stein's early experience and contributions on the East Greenland margin [1]that a significant fraction of the paper would be devoted to the contributions of sediment and meltwater contributed from that margin to the Erik Drift. This would certainly be reasonable as Hatfield et al [2]showed that this was a notable source of sediment in core MD99-2227 for the last interglacial, which was also extracted from a nearby site (57.533°N, -48.733°W at 3491 m wd). Winsor et al [3] also studied several aspects of the sediment record at the MD99-2227 site---I did not see any mention of research on this nearby site nor references to published studies on the glacial history of S/SW Greenland [4, 5]. In line 288 they mention both the LIS and GIS but my reading of the paper indicates that the primary focus was directed westward rather than the nearby ice sheet,
The number of radiocarbon dates is impressive and the resulting depth/age model is totally convincing. However, I wonder why they did not search for key Icelandic tephras (e.g. Vedde and Saksunavatn) as their identification would be critical in determining the OCR. Even in the 1980's Icelandic tephra was identified in cores from further north on the SW Greenland margin [6] and several tephras have been identified in cores from the East Greenland margin [7, 8] would which assist in deciding whether a constant OCR was appropriate.

Given their data and the effort to link it with the NGRIP isotope record it is worth noting that papers from “upstream” areas suggest caution should be applied in linking an atmospheric record from 3 km with climate and ocean data. Bjorck et al [4] for example present land-based evidence from S Greenland for a mild YD while Jennings et al [5] [9, 10] present marine isotope data from ~68°N East Greenland that a considerable meltwater signal characterized the YD---this may have been sourced from the Laurentide Ice Sheet via the Arctic Ocean [11] However, the possible contributions from these source(s) are nearly invisible on the schematic figure 5 and rather the focus of the paper is much more clearly on LIS and the export of sediment via meltwater and icebergs from Hudson Strait.
Figure 5 indicates that their main meltwater source was Hudson Strait and this was certainly the conclusion reached by Hesse and co-workers working on the meltwater sediment records and linked to the NAMOC [12-14] so the question is: what proxies in core MSM12/2-5-1 record meltwater that can be associated with the LIS versus meltwater associated with the GIS? Many workers have noted the glacial and meltwater outflow from a Hudson Strait ice stream is characterized by large fractions of detrital carbonate and Fig. 5 indicates a transport path to the site. Jennings et al [15] argued that sites off SW Iceland contained carbonate from Hudson Strait and it would seem reasonable that detrital carbonate from Hudson Strait might be a tracer in MSM12/2-5-1 . However, even though they employ XRF to measure chemistry they do not mention Ca and that has been shown to be a reliable measure of H-events along the western Labrador Sea margin [16, 17]. Since they have detailed grain size data I found it puzzling that they use the Zr/Rb ratio as a measure of meltwater plumes (line 155) or at least did not compare it with some ratio included in the grain size----such as: coarse silt/very fine silt.
I must admit that I find my review more critical than I expected. Part of this is not the authors fault but is due to the fact that in order to fully understand the paper the reviewer is compelled to (at least glance at) a plethora of Suppl. Data and figures. This invariably leads one to wonder whether science would not be better served by publishing in a longer format----a long standing debate! Having said all that it is certainly evident that the proxies record abrupt events and the proxies link these to a variety of environmental changes including sea ice, but I found the link to meltwater pulses less compelling.

1. Stein, R., et al., Latest Pleistocene to Holocene changes in glaciomarine sedimentation in Scorsby Sund and along the adjacent East Greenland Continental Margin: Preliminary results. Geo-Marine Letters, 1993. 13: p. 9-16.
2. Hatfield, R.G., et al., Interglacial responses of the southern Greenland ice sheet over the last 430,000 years determined using particle-size specific magnetic and isotopic tracers. Earth and Planetary Science Letters, 2016. 454: p. 225-236.
3. Winsor, K., et al., Evolution of the northeast Labrador Sea during the last interglaciation. Geochemistry Geophysics Geosystems, 2012. 13.
4. Winsor, K., et al., Rapid last-deglacial thinning and retreat of the marine-terminating southwestern Greenland ice sheet. Earth and Planetary Science Letters, 2015. 426: p. 1-12.
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6. Fillon, R.H. and J.C. Duplessy, Labrador Sea bio-, tephro, oxygen isotopic stratigraphy and Late Quaternary paleoceanography trends. Canadian Journal of Earth Sciences, 1980. 17.
7. Jennings, A.E., et al., Holocene tephra from Iceland and Alaska Record in SE Greenland

Shelf sediments, in Marine tephrachronology., W.E.N. Austin, et al., Editors. 2014, Royal Society of London Special publication 398. p. 157-193.
8. Voelker, A.H.L. and H. Haflidason, Refining the Icelandic tephrachronology of the last glacial period - The deep-sea core P52644 record from the southern Greenland Sea. Global and Planetary Change, 2015. 131: p. 35-62.
9. Bjorck, S., et al., Anomalously mild Younger Dryas summer conditions in southern Greenland. Geology, 2002. 30: p. 427-430.
10. Jennings, A.E., et al., Freshwater forcing from the Greenland Ice Sheet during the Younger Dryas: Evidence from Southeastern Greenland shelf cores. Quaternary Science Reviews, 2006. 25: p. 282-298.
11. Tarasov, L. and W.R. Peltier, A calibrated deglacial drainage chronology for the North American continent" evidence for an Arctic trigger for the Younger Dryas. Quaternary Science Reviews, 2006. 25: p. 659-688.
12. Chough, S.K., R. Hesse, and J. Muller, The Northwest Atlantic Mid-Ocean Channel of the Labrador Sea. IV. Petrography and provenance of the sediments. Canadian Journal Earth Sciences, 1987. 24: p. 731-740.
13. Hesse, R. and S. Khodabakhsh, Anatomy of Labrador Sea Heinrich layers. Marine Geology, 2016. 380: p. 44-66.
14. Hesse, R., Ice-proximal Labrador Sea Heinrich layers: a sedimentological approach. Canadian Journal of Earth Sciences, 2016. 53(1): p. 71-100.
15. Jennings, A.E., J.T. Andrews, and L. Wilson, Detrital Carbonate Events on the Labrador Shelf, a 13 to 7 kyr Template for Freshwater Forcing From the Laurentide Ice Sheet Quaternary Science Reviews, 2015. 107: p. 62-80.
16. Mao, L., et al., Labrador Current fluctuation during the last glacial cycle
. Marine Geology, 2018.
17. Rashid, H., et al., Fine scale sediment structure and geochemical signature between eastern and western North Atlantic during Heinrich events 1 and 2. Quaternary Science Reviews, 2012. 46: p. 136-150.

Reviewer #3 (Remarks to the Author):

Freshwater pulse is considered to be the main cause of abrupt climate change; however, the lack of high-resolution marine evidence hampers in-depth understanding of the mechanism of abrupt climate events since the last glacial maximum. Based on high-resolution biological and element proxy indicators of a marine core retrieved from the Eastern Labrador Sea cores, this paper reveals that four millennium-scale abrupt events occurred from the last deglaciation to the middle Holocene, accompanied by sea ice expansion and sea surface temperature decrease. These four abrupt events generally correspond to the cooling events in the Greenland ice core, implying the impact of freshwater input caused by the collapse of the Laurentian-Greenland ice sheet. This study provides the precise timing and relative magnitudes of four abrupt events that are critical to understanding rapid climate changes during the last deglaciation over the high-latitude Northern Hemisphere. This topic is suitable for possible publication in Communications. Several suggestions that may help readers to better understand the broad significance and possible dynamics of abrupt climate changes are as follows.

1. Regional correlation: Two cores (21GGC and U1305) are very close to the study site as shown in Fig.1. I wonder whether the lithology and proxy variations are quite similar or not between these sites. It's very necessary to present convincing evidence to show that four millennial events are well presented in the sensitive region.
2. Amplitude difference: Figure 3 shows the changes in sea ice extent and sea surface temperature. It seems that relative amplitude of these four abrupt events are quite difference as shown by the three proxy indicators (Fig. 3a-c). For example, the magnitude of the C3b event is significantly higher in IP2.5 than the other three events; however, the extent of sea ice from C1 to C4 is gradually decreasing (Fig.3b), in contrast to the gradually cooling of SST from C1 to C4 (Fig.3c). A brief explanation on the amplitude difference between four events as inferred by different proxies is welcome.
3. Trend difference: The magnitudes of these four cold events shown by the element ratios in Fig. 4 are gradually weakened, which is consistent with C37:4 and PDIP2.5, but is obviously different from the gradual cooling of the temperature. This trend difference also needs to be explained.
4. The four cooling events found in this paper are very meaningful, but their expressions are quite different from the cold events revealed in the Greenland ice core record (Fig. 4). Neither the magnitude of the change (i.e. 8.2-kyr vs. C4) nor the duration (YD vs. C2) is different between marine and ice-core proxies. Moreover, C1 and C3 have no obvious corresponding events in the Greenland ice-core. These discrepancies suggest that the features of different abrupt events might not be similar, and thus their impacts are spatially different, which should be properly clarified in the main text.
5. Figure 5 presents a conceptual model of four cold events, e.g. C1-2 and C3-4 were separately grouped as two types. As described in the fourth comments, such a classification might not be insufficient to reflect the differences between the four events. It is suggest that the source, and extent and impacts of the four similar events can be refined on the basis of an intensive synthesis of marine records in the high-latitude North Atlantic.
6. The focus of this paper is to discuss the four millennium-scale cold events, rather the YD, BA, and HS1, so these events should be clearly highlighted in Figs. 3 and 4.

Author response to reviewers' comments on the manuscript entitled "Abrupt climate changes caused by meltwater pulses in the Labrador Sea during the last glacial termination" (COMMSENV-22-0619-T) by D. You and coauthors

We many thank the three reviewers for their constructive and helpful comments and suggestions. All comments have been carefully considered and most of them incorporated into the revised manuscript. We believe the current version has been significantly improved based on the comments. The main points we have revised are as follows:

1) For clarification and to avoid misunderstanding, we have exchanged the term "cold event" by "meltwater event (MW)" for naming the abrupt events in our records. We want to highlight several meltwater events resulting in cold phases in the Labrador Sea/subpolar regions, which have a close relationship with the classical cold events such as the YD and 8.2 ka BP cold event. Furthermore, the term "warm interval" has been deleted and described as "intervals without strong meltwater discharge".
2) We have reorganized and added the necessary discussion about correlation/comparison between four meltwater events in our records and classical events (i.e., B/A, YD, etc.), which is the main concern of Reviewer 1 and 3. Proxy records of comparison between MW4 and 8.2 ka BP cold event are shown in the main text (Fig. 5).
3) Our SST record was compared with the newly published subsurface temperature record from the southern Labrador Sea, indicating (sub-)surface ocean warming in the Labrador Sea preceded the occurrence of meltwater events. Ocean warming might trigger collapse of surrounding ice sheets, resulting in meltwater pulses and abrupt changes in surface characteristics.
4) In order to help readers to better understand the process of abrupt events, we have revised and integrated the schematic figure and focused on the common characteristics (Fig. 6).
5) Reference records about the decay of the LIS and GrIS have been added, further supporting the correlation between the collapse of surrounding ice sheets and meltwater pluses. According to the comment from Reviewer 2, we have also emphasized significant contribution of meltwater inflow from the GrIS in the text and relevant information (GrIS exposure ages and Ca-corrected Ti record) have been added in Figure 4.
6) Furthermore, we have restricted the time interval of our study to 1.5-19 ka BP where we have a robust age control based on numerous AMS ^{14}C ages. That means, we mainly focus on the abrupt changes during the last deglaciation. Consequently, we have changed the title of the manuscript to "Last deglacial abrupt climate changes caused by meltwater pulses in the Labrador Sea".

Please find our point-by-point response (in blue) to the reviewers' comments (in black) below.

Reply to Reviewer #1:

The manuscript entitled "Abrupt climate changes caused by meltwater pulses in the Labrador Sea during the last glacial termination" by You and co-authors presents a set of high-resolution and well-dated proxy records from a sediment core from the Eirik Drift, eastern Labrador Sea, spanning over the past 23 ka from the LGM to the Holocene. On the basis of the new data, the authors characterized mainly the four cold/four warm events during the last deglaciation and the early-Holocene, and possible underlying mechanisms. Overall, while the new data are interesting and valuable, the interpretations remain tentative. A major revision is necessary pending on which I recommend acceptance of this paper.

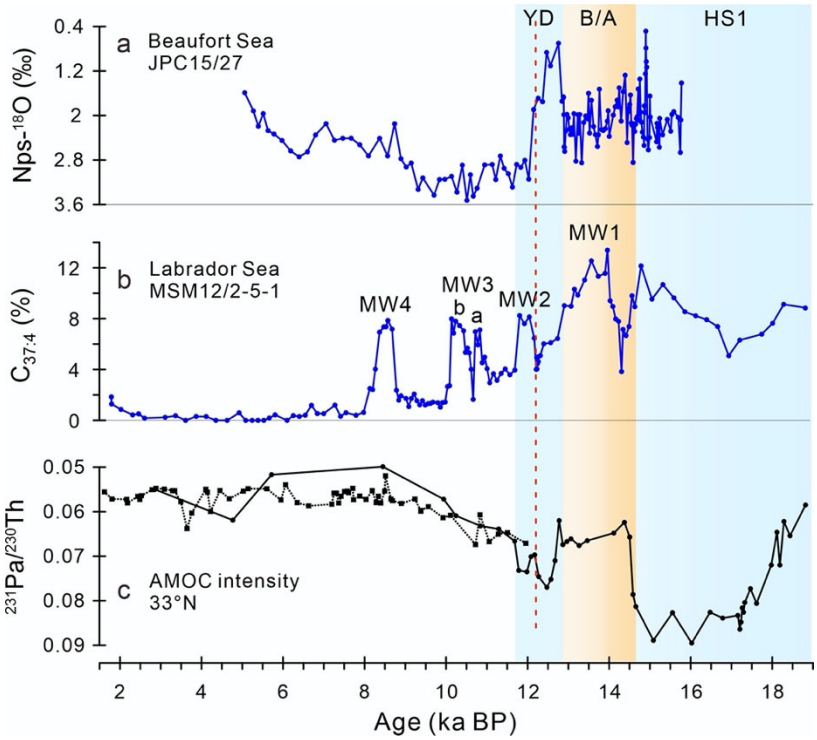
Major concerns:

1.1 The hydroclimatic variability revealed by the new dataset does not appear to be tuneful with those recorded by a large number of ice core, marine sediment and terrestrial records from the North Atlantic regions. For instance, the vital discrepancy is very obvious regarding the timing and structure of the 8.2 ka event, YD and B/A. This is possibly an important observation, but I did not see a convincing explanation of it in the current manuscript. It seems to me that the new records, if robust, have a distinct nature, reflecting a 'local' climate variability, which is significant different from the current interpretation framework of climate variation history over the last deglaciation and the Holocene in the North Atlantic. In other words, an in-depth discussion of the discrepancy is essential.

Reply 1.1: Thanks for the reviewer's constructive comment. We realised that the terminology "cold event" might be misleading. For clarification and to avoid misunderstanding, we have exchanged the term "cold event" by "meltwater event" (MW) in the revised manuscript. Furthermore, we added more discussion about the relationship between the four meltwater events and the "classic" events such as the B/A, the YD, and the 8.2 ka BP cold event, etc. Please see the related discussion in **lines 226 to 287**.

Based on correlations with other published records in the high-latitude North Atlantic regions (please see new supplementary Fig, 7), MW1, MW2, and MW4 were not just local events, and they show close linkages to prominent intervals such as the Allerød period, late YD, and the 8.2 ka BP cold event. MW3, on the other hand, might have been more a local event that had a relatively weak influence on the wide-range North Atlantic Ocean/atmosphere system. Compared to extremely cold intervals (i.e., HS1 and YD), the Bølling/Allerød interval is a relatively warm period as shown in the NGRIP ice core record. However, the Allerød period is a relatively cold interval in contrast to the Bølling warm period (Rasmussen et al., 2006), including two major meltwater-related cold intervals (i.e., the Older Dryas stadial and Intra-Allerød Cold periods) (Thornalley et al., 2010). MW1 occurred around 14 ka BP correlating with lighter $\delta^{18}O$ in the NGRIP record, decreased subsurface temperatures in the southern Labrador Sea (Max et al., 2022) and the northeastern Atlantic (Peck et al., 2008; Benway et al., 2010), surface freshening and reduced ventilation in the north Atlantic (Thornalley et al., 2010; Thornalley et al., 2011) (Supplementary Fig. 7). These correlations/similarities indicate that meltwater inflow into the Labrador Sea/subpolar regions might have caused the cooling during the Allerød period (more details see **lines 226 to 243**). As for MW2, its duration is not equivalent to the YD. As we already discussed in the text (**lines 244 to 254**), MW2 coincided with the Heinrich event 0, which has been documented on the Labrador Shelf (Jennings et al., 2015) and other North Atlantic regions (Andrews et al., 1995). Furthermore, the occurrence of MW2 is in line with the second weakening of the AMOC during the late YD (see the following plot), which might have contributed to a sustained cold phase during the YD. The identification of MW4 is consistent with the prevailing opinion that surface freshening occurred in the

Labrador Sea around 8.5 ka BP (Lochte et al., 2019). The freshwater discharge might have perturbed the AMOC about 145-320 yr. and resulted in the development of the 8.2 ka cold event (Lochte et al., 2019; Renssen et al., 2001). Thus, it is reasonable that MW4 occurred preceding widespread atmosphere cooling during the 8.2 ka BP cold event (Fig. 5). Please see **lines 269 to 287** and Supplementary Fig. 8 for details. Due to relatively modest changes in the ice core records (Fig. 4b) and low-amplitude variations in the wide-range North Atlantic regions (Supplementary Fig. 7), WM3 might be more like a local event, and significant changes in surface characteristics were most likely restricted to the proximal Labrador Sea (e.g., Max et al., 2022; Jennings et al., 2015; this study) (Fig. 4). More details please see **lines 255 to 268**.



Comparison between freshwater pulses and AMOC intensity during the YD

a) Nps-^{18}O record from Core JPC15/27, Beaufort Sea indicating deglacial flooding preceding the YD (Keigwin et al., 2018); **b)** %$C_{37:4}$ record from Core MSM12/2-5-1, Labrador Sea showing meltwater inflow during the last deglaciation (this study); **c)** integrated ^{231}Pa/^{230}Th records from 33°N North Atlantic indicating AMOC intensity (McManus et al., 2004; Lippold et al., 2019). Red dashed line divided the YD into two parts.

1.2 The apparent "problems" associated with the new data themselves require explanations. For example, the glacial SST in some periods (around the HS1) is similar to the Holocene, and the SSTs during the four cold events is equivalent to or lower than the glacial values. Especially, the SST during the C4 event is the lowest, which is difficult to image. In contrast, the less sea ice and the higher SST in the HS1 than in the C1-C4 events appear to be strange. The %C37:4 of C1 suggests more freshwater injection than that of C4, whereas the SST during C1 seems less cool than C4.

Reply 1.2: Thanks for the comments. The SST reconstruction is based on the correlation between UK37 and summer temperatures in the subpolar regions. In the low-temperature range <<10 °C, the calibration

equation becomes less precise (Filippova et al., 2016). Thus, absolute SST values of different meltwater should be interpreted more cautiously, and we focus more on the abrupt changes per se. The related statement has been added to Methods in **lines 377 to 379**). Reconstructed SSTs are high during the early HS1, which are similar to high temperatures during the Bølling warm period, the early YD, and the early Holocene. Such high/increased SSTs might be explained by enhanced warm Atlantic Water inflow/Irminger Current and reduced meltwater inflow. Please see **lines 288 to 302** for details. $C_{37:4}$ is a qualitative proxy indicating meltwater inflow, which means it cannot provide quantitative and accurate estimates for meltwater volumes (Bendle et al., 2005; Bard et al., 2000). Therefore, it might be better to focus on qualitative/abrupt changes during the meltwater events rather than absolute values.

Minor issues:

1.3 In abstract and conclusion, the abrupt changes of meltwater pulses and SST are described to occur within a few decades. However, the dating uncertainties and sample resolution of the records are about 100-years or larger (?). As such, a detailed evaluation of the uncertainties associated with the conclusion should be included in the method section. Similarly, in the line of 251, for example, the duration of "360 years" should also give an uncertainty.

Reply 1.3: Thanks for the comment. We agree that dating uncertainties and sample resolution can influence the assessment of rates of abrupt changes and durations of meltwater events. For durations of the events, assessments based on median age and age range (minimum to maximum, 95% confidence interval) have been provided in the text (**lines 138 to 142**). Due to a 200 yr. error that we used for uncertainties of reservoir correction (i.e., $\triangle R=0\pm200$) is very cautious/conservative compared to some studies in the north Atlantic regions using $\triangle R=0$. Thus, possible durations (95% confidence intervals) of meltwater events might be relatively larger, which could only provide an approximate estimate. (MW1: 14.08-12.93 ka based on median age, 14.62-12.67 ka (95%); MW2: 12.23-11.87 ka based on median age, 12.52-11.45 ka (95%); MW3a: 11.07-10.78 ka based on median age, 11.51-10.48 ka (95%); MW3b: 10.64-10.15 ka based on median age, 10.96-9.81 ka (95%); MW4: 8.74-8.33 ka based on median age, 9.05-8.01 ka (95%)). Considering the abrupt changes occurred from one extreme to the other (e.g., SST record, Fig. 4e) within two samples located close to each other, and the very high sedimentation rates we have, such changes should/might have occurred within a few decades (**lines 203 to 206**). From this point of view, we would like to keep the statement like "such events could occur within a few decades" in the text.

1.4 The main scientific issue focused here need to be explained better and clearer in the introduction. A large part of the current introduction is about the AMOC, but the AMOC seems not an important issue discussed in the main text (not event encompassed a comparison with AMOC proxies), although it is highly relevant.

Reply 1.4: Thanks for the comment. In the revised introduction, AMOC is only mentioned in the first paragraph which is closely related to abrupt climate changes during the last glacial cycle, probably caused by freshwater perturbations. In the second paragraph, we emphasize that the last deglaciation is an ideal period to study abrupt climate change and uncertainties remain regarding the timing, pathway, mechanism, and influence of meltwater discharge. In the following two paragraphs, we present the

importance of the study area and the main findings. Please see **lines 30 to 69** for the revised introduction.

1.5 The authors provided 10 proxies, including IP25, PDIP25, Uk37 SST, HBI-III, Alkenones, Dinosterol, Si/Sr, Zr/Rb, % C37:4 and SS, but some of them are rarely mentioned or used in the text.

Reply 1.5: Thanks for the comment. We think all these proxies are necessary for the paper and should be involved in the text. For example, P_DIP_{25} values have been calculated based on concentrations of IP_{25} and dinosterol. Whereas for the intervals characterized by zero or minimum concentrations of IP_{25} or dinosterol, P_DIP_{25} cannot be calculated. Thus, it is necessary to show changes in sea ice algae production (IP_{25}) and open water productivity (dinosterol), which could better reflect changes in sea ice extent. Furthermore, in order to help our readers better understand changes in the coarse fraction, >63 μm/% and IRD abundance have been added in the main text, which are classic proxies for coarse versus fine-grained matter. In any case, all proxies are mentioned in the text.

1.6 Any replications available to test the robustness of the new records?

Reply 1.6: Thanks for the comment. In a reasonable timeframe, it is certainly not possible to get another very high-resolution and well-dated set of all the biomarker records from surrounding areas for testing the robustness of the records from Core MSM12/2-5-1 as well as their interpretations. There is, however, a biomarker record from the southern Labrador Sea (Max et al., 2022) that supports our interpretations quite well. This record we have included in Figure 4 and Supplementary Figure 7 and in our discussion. Nevertheless, more work still needs to be done in the future.

Reply to Reviewer #2:

2.1 In agreeing to review this paper I expected that given Stein's early experience and contributions on the East Greenland margin [1] that a significant fraction of the paper would be devoted to the contributions of sediment and meltwater contributed from that margin to the Erik Drift. This would certainly be reasonable as Hatfield et al [2] showed that this was a notable source of sediment in core MD99-2227 for the last interglacial, which was also extracted from a nearby site (57.533°N, -48.733°W at 3491 m wd). Winsor et al [3] also studied several aspects of the sediment record at the MD99-2227 site---I did not see any mention of research on this nearby site nor references to published studies on the glacial history of S/SW Greenland [4, 5]. In line 288 they mention both the LIS and GIS but my reading of the paper indicates that the primary focus was directed westward rather than the nearby ice sheet.

Reply 2.1: Thanks for the comment. We agree that, besides the LIS, we should consider the impacts of the nearby GrIS on abrupt changes in surface characteristics in our study area. In order to better present the decay history of the GrIS, the Ca-corrected Ti record from Core MD99-2227 and exposure ages based on ^{10}Be measurements from southern/southwestern/southeastern GrIS have been added in Figure 4. And the core MD99-2227 location has been shown in Figure 1. As shown in the Ca-corrected Ti record and exposure ages, the decay of the GrIS was increased between 14 to 10 ka BP, which might

have significantly contributed to the surface freshening in MW1 to MW3. Furthermore, high Si/Sr ratios and relatively low dolomite content during the MW2, MW3, and MW4, probably indicating that detrital sediment was input along with meltwater discharge from the LIS superimposed by the GrIS (Fig. 4g). The related revision please see **lines 44 to 45, 161 to 164, 207 to 225**.

2.2 The number of radiocarbon dates is impressive and the resulting depth/age model is totally convincing. However, I wonder why they did not search for key Icelandic tephras (e.g., Vedde and Saksunavatn) as their identification would be critical in determining the OCR. Even in the 1980's Icelandic tephra was identified in cores from further north on the SW Greenland margin [6] and several tephras have been identified in cores from the East Greenland margin [7, 8] would which assist in deciding whether a constant OCR was appropriate.

Reply 2.2: Thanks for the comment. We added the tephra abundance, IRD abundance, and coarse fraction (>63 μm) content in Figure 4. The tephra peak found in 1123 cm core depth and dated to around 12.6 ka BP (based on our current age model) might be the Vedde Ash layer dated to 12.12 ka BP (Abbott and Davies, 2012) (Figs. 2 and 4 with question marks). However, without further geochemical analyses on tephra fractions and possible impact from ice-rafted tephra, this tephra layer cannot be attributed to the Vedde Ash unambiguously. Furthermore, if this tephra layer is Vedde Ash for sure, this would imply a local reservoir age correction of about 450 yr. (△R=450). However, we cannot determine for which time interval this local reservoir age correction has to be considered. Thus, we have not used the Vedde Ash layer as an extra age control point to establish our age model, but only marked it in Figures 2 and 4 (more details see Methods in **lines 324 to 330** and Supplementary Table 1).

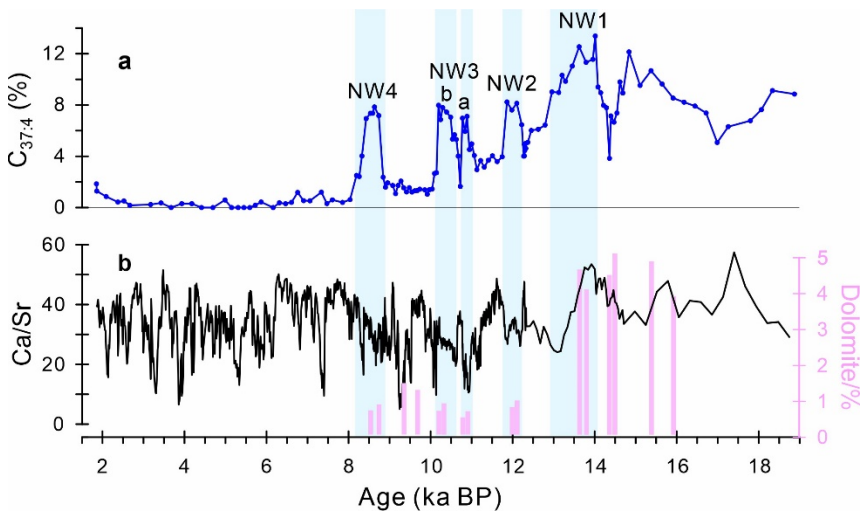
2.3 Given their data and the effort to link it with the NGRIP isotope record it is worth noting that papers from "upstream" areas suggest caution should be applied in linking an atmospheric record from 3 km with climate and ocean data. Bjorck et al [4] for example present land-based evidence from S Greenland for a mild YD while Jennings et al [5] [9, 10] present marine isotope data from ~68°N East Greenland that a considerable meltwater signal characterized the YD---this may have been sourced from the Laurentide Ice Sheet via the Arctic Ocean [11]. However, the possible contributions from these source(s) are nearly invisible on the schematic figure 5 and rather the focus of the paper is much more clearly on LIS and the export of sediment via meltwater and icebergs from Hudson Strait.

Reply 2.3: Thanks for the comment. We agree that there were multiple sources of meltwater inflow into our core site during the deglaciation (i.e., from the LIS, the GrIS, and the Arctic Ocean). We outlined this in the discussion (third paragraph, **lines 207 to 225**). We have also emphasized that the GrIS was the important source of meltwater inflow during the meltwater events superimposed by the LIS (more details see **Reply 2.1**). Furthermore, we added more marks (blue arrows) in Figure 6 indicating possible/different sources of meltwater input. In general, we think our biomarker records can reflect the local/surrounding environment despite the water depth of the sediment core being above 3 km (see **lines 91 to 98**). Thus, it makes sense to compare changes in surface characteristics in our study area with ice core records. In the revised Discussion part, we reduced some discussion about surface freshening on changes in atmospheric temperatures and focused more on comparisons between meltwater events and classical intervals.

2.4 Figure 5 indicates that their main meltwater source was Hudson Strait and this was certainly the conclusion reached by Hesse and co-workers working on the meltwater sediment records and linked to the NAMOC [12-14] so the question is: what proxies in core MSM12/2-5-1 record meltwater that can be associated with the LIS versus meltwater associated with the GIS? Many workers have noted the glacial and meltwater outflow from a Hudson Strait ice stream is characterized by large fractions of detrital carbonate and Fig. 5 indicates a transport path to the site. Jennings et al [15] argued that sites off SW Iceland contained carbonate from Hudson Strait and it would seem reasonable that detrital carbonate from Hudson Strait might be a tracer in MSM12/2-5-1. However, even though they employ XRF to measure chemistry they do not mention Ca and that has been shown to be a reliable measure of H-events along the western Labrador Sea margin [16, 17]. Since they have detailed grain size data, I found it puzzling that they use the Zr/Rb ratio as a measure of meltwater plumes (line 155) or at least did not compare it with some ratio included in the grain size----such as: coarse silt/very fine silt.

Reply 2.4: Thanks for the comment. We have known that XRF-Ca/Sr is widely used in the western Labrador Sea/subpolar regions to indicate detrital carbonate deposition from the LIS. The Ca/Sr ratios from Core MSM12/2-5-1 can be found below. Three peaks of Ca/Sr ratios can be found clearly at around 17.5 ka BP, 16 ka BP, and 14 ka BP in line with the high content of XRD-dolomite, which indicates increased detrital carbonate input. However, there are no significant peaks in the upper part of the record, which may suggest that there was no large detrital carbonate deposition. Another possibility is that the Ca/Sr ratios were affected by increased biogenic productivity (Fig. 2e, 2f).

Doing detailed analyses of the grain-size distribution (especially the silt fraction) would be beyond the PhD study that concentrates on the biomarker and XRF scanning records. Thus, the time resolution of our grain-size records is relatively low in comparison to the other proxy records we have produced. Following the comment of Reviewer 2, however, we have exchanged the Zr/Rb proxy record by lower resolution records of the coarse fraction concentration (>63 μm) and IRD content in the main text and Figure 4. Furthermore, in Figure 5 a direct comparison of the coarse fraction concentration (>63 μm) and the Zr/Rb ratios is shown indicating that the Zr/Rb record represent the amount of coarse/fine fraction quite well. The entire Zr/Rb record of Core MSM12/2-5-1 (in combination with other grain-size records) is presented in Supplementary Figure 5.



Comparison between %C37:4 and XRF-Ca/Sr (Core MSM12/2-5-1)

2.5 I must admit that I find my review more critical than I expected. Part of this is not the authors fault but is due to the fact that in order to fully understand the paper the reviewer is compelled to (at least glance at) a plethora of Suppl. Data and figures. This invariably leads one to wonder whether science would not be better served by publishing in a longer format----a long standing debate! Having said all that it is certainly evident that the proxies record abrupt events and the proxies link these to a variety of environmental changes including sea ice, but I found the link to meltwater pulses less compelling.

Reply 2.5: Thanks for the comment. In order to help highlight the interaction between the ocean and the ice sheets, other records regarding the GrIS and LIS dynamics and subsurface temperatures from the Labrador Sea have been added to Figure 4. High detrital carbonate input on the Labrador Shelf (Core MD99-2236) during MW2, MW3, and MW4 coincided with increased meltwater inflow, increased sea ice extent, and reduced SSTs in our records. Furthermore, according to exposure ages in southern/southeastern/southwestern Greenland and the Ca-corrected Ti record from Core MD99-2227, the retreat of the Greenland Ice Sheet also contributed significantly to the meltwater discharge during the last deglaciation. Thus, we think low-salinity and low-temperature surface water promoted sea ice formation and decreased SSTs. Higher (sub-)surface ocean temperatures in the Labrador Sea were found preceding the occurrence of meltwater events (Fig. 4e, f), indicating ocean warming probably caused the collapse of surrounding ice sheets (Figure 6a) (please see **lines 288 to 302** for details), and following meltwater pulses induced abrupt changes in sea surface characteristics in the subpolar regions (Figure 6b, c).

To reduce the number of Supplementary Figures, some of them have been removed, and we have referred to related data that can be found in PANGAEA.

Reviewer #3 (Remarks to the Author):

Freshwater pulse is considered to be the main cause of abrupt climate change; however, the lack of high-resolution marine evidence hampers in-depth understanding of the mechanism of abrupt climate events since the last glacial maximum. Based on high-resolution biological and element proxy indicators of a marine core retrieved from the Eastern Labrador Sea cores, this paper reveals that four millennium-scale abrupt events occurred from the last deglaciation to the middle Holocene, accompanied by sea ice expansion and sea surface temperature decrease. These four abrupt events generally correspond to the cooling events in the Greenland ice core, implying the impact of freshwater input caused by the collapse of the Laurentian-Greenland ice sheet. This study provides the precise timing and relative magnitudes of four abrupt events that are critical to understanding rapid climate changes during the last deglaciation over the high-latitude Northern Hemisphere. This topic is suitable for possible publication in Communications. Several suggestions that may help readers to better understand the broad significance and possible dynamics of abrupt climate changes are as follows.

3.1 Regional correlation: Two cores (21GGC and U1305) are very close to the study site as shown in Fig.1. I wonder whether the lithology and proxy variations are quite similar or not between these sites.

It's very necessary to present convincing evidence to show that four millennial events are well presented in the sensitive region.

Reply 3.1: Thanks for the comment. Unfortunately, we did not find other high-resolution and well-dated records representing the whole last deglaciation on the Eirik Drift, which could be compared with our records. Some grain size data from cores U1305 and 21GGC representing at least parts of the last deglaciation, are presented in Supplementary Figure 5. Unfortunately, the main focus of IODP Site U1305 was on longer-timescale records. Thus, almost no comparable proxy records of the last deglaciation are available. For the B/A to YD time interval, a relatively high-resolution $\overline{SS}$ record from IODP Site 1305 is available (Henderson, 2009). However, due to the lack of AMS 14C dates the age model is quite weak and does not allow a detailed comparison with our records (see Supplementary Fig. 5). The high-resolution $\overline{SS}$ record of Core 21GGC only dates back to the mid-late Holocene, which shows decreased grain size/bottom current intensity in the core site in line with our Zr/Rb ratios (Supplementary Fig. 5).

3.2 Amplitude difference: Figure 3 shows the changes in sea ice extent and sea surface temperature. It seems that relative amplitude of these four abrupt events are quite difference as shown by the three proxy indicators (Fig. 3a-c). For example, the magnitude of the C3b event is significantly higher in IP25 than the other three events; however, the extent of sea ice from C1 to C4 is gradually decreasing (Fig.3b), in contrast to the gradually cooling of SST from C1 to C4 (Fig.3c). A brief explanation on the amplitude difference between four events as inferred by different proxies is welcome.

Reply 3.2: Thanks for the comment. The concentration of IP_{25} does not represent the sea ice extent but is a proxy for sea ice algae productivity. The semi-quantitative proxy for sea ice extent is PIP_{25} index (Fig. 4 and Supplementary Fig. 4) that is based on the combination of IP_{25} and the open-water phytoplankton biomarker (e.g., dinosterol as used in our case; more details see Methods in **lines 353 to 356**). The PIP_{25} values are quite similar for the meltwater events 2, 3a, 3b, and 4 (PIP_{25} cannot be calculated for Event 4; see Supplementary Fig. 4 for further explanation), suggesting marginal to extended sea ice conditions. For these events, the SST values are very low (i.e., between 1 and 3 °C). As for this low-temperature range, the calibration equation becomes less precise, and it is not possible/useful to interpret the SSTs as "a gradual cooling trend". The SSTs just indicate very low SSTs, coinciding with extended sea ice conditions for all three events. The related statement has been added in Methods (**lines 377 to 379**).

3.3 Trend difference: The magnitudes of these four cold events shown by the element ratios in Fig. 4 are gradually weakened, which is consistent with C37:4 and PDIP2.5, but is obviously different from the gradual cooling of the temperature. This trend difference also needs to be explained.

Reply 3.3: Thanks for the comment. As explained in **Reply 3.2**, the SST change from 3 to 1 °C in the meltwater events cannot be interpreted as a cooling trend. That means, during the deglaciation the three proxies $C_{37:4}$ (maxima suggesting huge pulses of meltwater discharge), SST (distinct minima due to the cold meltwater discharge), and P_DIP_{25} (maxima indicating extended sea ice cover due to cold and low saline surface waters) are perfectly in line with our interpretation. After the final decay of the LIS at the

end of the deglacial, meltwater discharge decreased significantly, and further sea ice formation was not possible. With this, also the extreme SST minima disappeared, and the SST displayed a cooling trend during the middle-late Holocene that followed the decrease in summer insolation, a well-known trend observed in many other records in the North Atlantic.

3.4 The four cooling events found in this paper are very meaningful, but their expressions are quite different from the cold events revealed in the Greenland ice core record (Fig. 4). Neither the magnitude of the change (i.e., 8.2-kyr vs. C4) nor the duration (YD vs. C2) is different between marine and ice-core proxies. Moreover, C1 and C3 have no obvious corresponding events in the Greenland ice-core. These discrepancies suggest that the features of different abrupt events might not be similar, and thus their impacts are spatially different, which should be properly clarified in the main text.

Reply 3.4: Thanks for the comment. As outlined in **Reply 1.1**, it was misleading that we have used The term "cold events" instead of "meltwater events". Please see **Reply 1.1** for details. For the relationship between meltwater events and "classical" events, please see the related discussion in **lines 226 to 287.**

The impact of each event might be spatially different, which contributed to different signals in the NGRIP ice core record. However, it is difficult to reconstruct the exact extent of surface freshening in the subpolar regions during these meltwater events. More high-resolution and well-dated records are needed to constrain the distributions. The schematic plot has been simplified and integrated, showing common characteristics of these meltwater events in Figure 6b and 6c. Furthermore, it should also be considered that the influence of freshwater forcing is different under different climatic conditions (stable interglacial vs. unstable deglaciation). Differences in magnitude between marine and ice core records at MW3 and MW4 might be related to the relatively stable interglacial state. Please see **lines 261 to 268** for details.

3.5 Figure 5 presents a conceptual model of four cold events, e.g., C1-2 and C3-4 were separately grouped as two types. As described in the fourth comments, such a classification might not be insufficient to reflect the differences between the four events. It is suggested that the source, and extent and impacts of the four similar events can be refined on the basis of an intensive synthesis of marine records in the high-latitude North Atlantic.

Reply 3.5: Thanks for the comment. We agree that the source, extent, and impact of four meltwater events might be different and it could be better to refine these issues for every event. However, it is quite difficult to know the exact scope of impact of these events due to the lack of high-resolution records in the subpolar regions spanning the full last deglaciation, especially in the central high-latitude North Atlantic (e.g., Irminger Sea). More high-resolution and well-dated records are needed to constrain distributions. Furthermore, based on the proxies we used, we cannot distinguish the exact source of meltwater inflow but can only say it mainly originates from the surrounding ice sheets (LIS and GrIS). Distinguishing sources of meltwater is beyond the scope of the paper. In order to help readers to better understand the correlation between meltwater discharge and abrupt changes in surface characteristics and emphasize interactions among ocean warming, decay of ice sheets, and cooling atmosphere, we

simplified and integrated the schematic figure (Fig. 6) which only shows general characteristics of intervals with or without strong meltwater inflow during the last deglaciation.

3.6 The focus of this paper is to discuss the four millennium-scale cold events, rather the YD, BA, and HS1, so these events should be clearly highlighted in Figs. 3 and 4.

Thanks for this very important comment. The four meltwater events, the focus of this paper, have been highlighted in each figure. This makes it much more easier for the reader to correlate the different proxies and to follow the story.

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24th Jan 23

Dear Mr You,

Please allow us to sincerely apologise for the long delay in sending a decision on your manuscript titled "Last deglacial abrupt climate changes caused by meltwater pulses in the Labrador Sea" has now been seen by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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REVIEWERS' COMMENTS:

Reviewer #3 (Remarks to the Author):

The authors have made detailed responses to my comments, some of which have been incorporated in the revision. Four meltwater (ME) events presented in this work are important for understanding the characteristics and effects of abrupt climate changes from the last deglaciation to the Early Holocene. After reading through the revision, I think that there are two points needing additional clarification. First, MEs 1 and 3 are well recognized in Greenland ice core and North Atlantic marine sediments, whereas MEs 2 and 4 seem to be unobvious in other records. Please clarify whether the latter two events are regional signals? Second, ME1 leads to the 8.2-ka events, but ME3 occurred in the late YD. Please briefly explain why the timing of these MEs is different from two well-constrained cooling events.

Reviewer #4 (Remarks to the Author):

First, I apologize for being overdue. I had to go on field works on short notice and could not respond. The manuscript “Last deglacial abrupt climate changes caused by meltwater pulses in the Labrador Sea” by Dr. You and co-authors present well-dated and high-resolution marine multi-proxy from the

eastern Labrador Sea sediment core. Based on the new data, the authors observed four millennial-scale cooling events in association with surface–subsurface water warmings and resultant meltwater discharges. This manuscript is a revised version after the first round of the peer review process. I think that the manuscript is revised well following the comments by all three reviewers, and is almost close to publishing. I believe that the new marine data across the last deglaciation in the eastern Labrador Sea will be of interest to many readers of the Communications Earth and Environment, and will contribute to revealing the paleoclimatic and paleoceanographic variations during the last deglaciation.

Minor comments

Lines 92–93: This is unclear to me. I would like to suggest adding a detailed explanation using one or two sentences if the letter limit permits.

Fig. 3a, d, e, and f: Please add descriptions of what line and area plots indicate in the caption or graph.

Author response to reviewers' comments on the manuscript entitled "Last deglacial abrupt climate changes caused by meltwater pulses in the Labrador Sea" (COMMSENV-22-0619A)

We many thank the reviewers' comments and suggestions. All comments have been carefully considered. Please find our point-by-point response (in blue) to the reviewers' comments (in black) below.

In addition, we have added one biomarker proxy record supporting our identification of meltwater pulses:
In order to further support our interpretation that $\%C_{37:4}$ can be used as a proxy for meltwater discharge, the stable hydrogen isotope composition of palmitic acid (δD_{PA}) has been measured in a selected set of samples representing Meltwater Pulse 4. These data points have been included in Figure 5a. In this record, lower δD_{PA} values (correlating with lower salinity, see Sachs et al., 2018) correlate with higher $\%C_{37:4}$ suggesting that higher $\%C_{37:4}$ values are caused by increased meltwater discharge. In **Lines 139-147, 287-290, and 398 to 411,** a few sentences have been added for discussion and methods, respectively. For carrying out the δD_{PA} measurement and evaluation, we would like to include Enno Schefuß as co-author.

Reply to Reviewer#3:

The authors have made detailed responses to my comments, some of which have been incorporated in the revision. Four meltwater (ME) events presented in this work are important for understanding the characteristics and effects of abrupt climate changes from the last deglaciation to the Early Holocene. After reading through the revision, I think that there are two points needing additional clarification. First, MEs 1 and 3 are well recognized in Greenland ice core and North Atlantic marine sediments, whereas MEs 2 and 4 seem to be unobvious in other records. Please clarify whether the latter two events are regional signals? Second, ME1 leads to the 8.2-ka events, but ME3 occurred in the late YD. Please briefly explain why the timing of these MEs is different from two well-constrained cooling events.

Reply: Thanks for the comments. If I understand correctly, the reviewer used different numbers to name the meltwater events in our records (i.e., ME1 here is MW4 in our paper, whereas ME2 is MW3, ME3 is MW2, and ME4 is MW1 actually). Thus, the first questions are why MW3 and MW1 are unobvious in other records and whether they represent regional events. Probably not clear enough, we thought we have already explained this question in the last response letter and manuscript. MW1 occurred around 14 ka BP correlating with lighter $\delta^{18}O$ in the NGRIP record, decreased subsurface temperatures in the southern Labrador Sea (Max et al., 2022) and the northeastern Atlantic (Peck et al., 2008; Benway et al., 2010), surface freshening and reduced ventilation in the North Atlantic (Thornalley et al., 2010; Thornalley et al., 2011) (please see the records in Supplementary Fig. 7). These correlations/similarities suggest that meltwater inflow into the Labrador Sea might have caused a wider range of surface

freshening in the subpolar regions and have caused the cooling during the Allerød period. However, MW3 might be more a local event, and significant changes in surface characteristics were most likely restricted to the proximal Labrador Sea (e.g., Max et al., 2022; Jennings et al., 2015; this study) and caused less cooling in the atmosphere.

The other main question is why the timing of MW4 and MW2 are not consistent with the 8.2 ka BP cold event and YD, respectively. The meltwater events identified in our records have caused cold phases in the Labrador Sea/subpolar regions, which closely related to the classical cold events. The identification of MW4 is consistent with the prevailing opinion that surface freshening occurred in the Labrador Sea around 8.5 ka BP (Lochte et al., 2019). The freshwater discharge might have perturbed the AMOC about 145-320 yr. and resulted in the development of the 8.2 ka cold event (Lochte et al., 2019; Renssen et al., 2001). Thus, it is reasonable that MW4 occurred preceding widespread atmosphere cooling during the 8.2 ka BP cold event (Fig. 5, Supplementary Fig. 8). To further support our interpretation of the high $\%C_{37:4}$ values as meltwater signal, hydrogen isotopes of palmitic acid (δD_{PA}) (a proxy for changes in salinity with lower values implying lower salinity; see Sachs et al., 2018) were measured from selected samples around MW4. The good correlation between (higher) $\%C_{37:4}$ and (lower) δD_{PA} indicates that $\%C_{37:4}$ reflects meltwater discharge quite well (Fig. 5a). Related description has been added to the text (**Lines 139-147**). MW2 is not equivalent to YD. MW2 coincides with the Heinrich Event 0, which has been documented on the Labrador Shelf (Jennings et al., 2015) and other North Atlantic regions (Andrews et al., 1995), corresponding to a wide range of surface freshening in the subpolar regions during the late YD (Supplementary Fig. 7). Furthermore, the occurrence of MW2 is in line with the second distinct weakening of the AMOC during the late YD (McManus et al., 2004). Thus, MW2 might have contributed to a sustained cold phase for the late YD, whereas freshwater from the Arctic Ocean (e.g., Keigwin et al., 2018; Wu et al., 2020) might have merely triggered the cold phase of early YD. More details please see **Lines 257-267**.

Reply to Reviewer#4:

First, I apologize for being overdue. I had to go on field works on short notice and could not respond. The manuscript "Last deglacial abrupt climate changes caused by meltwater pulses in the Labrador Sea" by Dr. You and co-authors present well-dated and high-resolution marine multi-proxy from the eastern Labrador Sea sediment core. Based on the new data, the authors observed four millennial-scale cooling events in association with surface–subsurface water warmings and resultant meltwater discharges. This manuscript is a revised version after the first round of the peer review process. I think that the manuscript is revised well following the comments by all three reviewers, and is almost close to publishing. I believe that the new marine data across the last deglaciation in the eastern Labrador Sea will be of interest to many readers of the Communications Earth and Environment, and will contribute to revealing the paleoclimatic and paleoceanographic variations during the last deglaciation.

Minor comments

Lines 92–93: This is unclear to me. I would like to suggest adding a detailed explanation using one or

two sentences if the letter limit permits.

Reply: Thanks for the comment. We have revised this sentence (**Lines 93-97**).

Following Mollenhauer et al. (2011), radiocarbon age differences between biomarker (alkenones) and planktic foraminifera in records from the Gardar Drift (close to Eirik Drift) are negligible, suggesting that marine organic matter has been deposited quite rapidly or only transported over very short lateral distance. Therefore, we interpret our biomarker records to reflect predominantly surrounding environmental conditions.

Fig. 3a, d, e, and f: Please add descriptions of what line and area plots indicate in the caption or graph.

Reply: Thanks for the comment. We have add the necessary information in the caption.

Supplementary references

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