

Holocene history of a southwest Greenland fjord: Exceptional Atlantic water influence under minimum ice-sheet extent

Corresponding Author: Ms Anna Kvorning

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

**** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors ****

Dear Ms Kvorning,

Your manuscript titled "Holocene history of a southwest Greenland fjord: modern conditions on path to deglaciation yet distinct from thermal maximum" has now been seen by 2 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

In particular, please ensure that the revised manuscript meets the following editorial thresholds:

- * Provide firm and sufficient evidence to demonstrate that your depth-age model is robust.
- * Communicate the limitations and uncertainties in your research and expand your discussion accordingly.
- * Discuss the effects of sediment accumulation rates on the studied bio and geochemical parameters.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Carolina Ortiz Guerrero, Ph.D.
Associate Editor
Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

SUMMARY & RECOMMENDATION:

The manuscript presents new proxy data that constrains Holocene marine environmental changes in southwest Greenland. The data come from a set of sediment cores and a sediment trap collected from Nuup Kangerlua. The interpretations regarding past environmental variability are justified and based primarily on results from multiple sedimentological, biogeochemical, geochronological, and micropaleontological proxies. Results, summarizing Holocene trends in marine productivity, marine/terrestrial input, and temperature/salinity, are clearly presented and discussed within the context of other relevant field studies. The authors highlight the regional significance of the research and make compelling connections to possible future environmental scenarios. The paper is well-organized and clearly written. I recommend publication following minor revision of the manuscript.

GENERAL COMMENTS:

The study contends that continued warming and ice-sheet retreat will plausibly cause stronger advection of Atlantic-derived water into the fjords of southwest Greenland. Based on the reconstructed Holocene framework of environmental variability, this seems logical. However, can the authors equally comment on how such a future switch may differ from that in the mid-Holocene. With a dramatically different sea-ice regime, significantly higher rates of change in ice-sheet mass balance (i.e. freshwater flux), and increasing frequency of extreme climate events, to name just a few variables, is it likely that increased advection of Atlantic-derived waters to west Greenland will proceed at the same pace and scale as during the mid-Holocene? What (if any) variables have the capacity to complicate or upend the historical analogy? I appreciate that a long, detailed discussion of these complexities is beyond the scope of the study. However, a short comment addressing some of the uncertainties regarding this paleoanalogue as a likely "landing spot" for near-future environmental change may highlight the need to both understand these paleoanalogues in greater detail and to consider them in the context of future projections.

SPECIFIC COMMENTS:

The majority of the specific comments below are suggestions aimed at increasing the clarity of the manuscript.

ABSTRACT

Line 24:

"... deglaciation from ~10 to 8 cal ka BP."

Line 26:

"... analogue from ~6.5 to 3 cal ka BP..."

INTRODUCTION

Lines 36-38:

The last sentence of this paragraph is somewhat awkward. Consider "... significantly impact fjord environments, including important marine ecosystems that constitute the basis for local fisheries and subsistence livelihoods."

Line 48:

I wonder if you can possibly be more precise with the timing here? End of this century?

Line 50:

"Marine climate variability in the Arctic is closely linked to..."

Lines 56-57:

"In the mid Holocene, a long period with a predominantly AO- phase^{18,28,29} has been identified..."

Line 64:

"... coastline¹⁸. The ice margin retreated from the outer coast to its present extent between..."

Line 65:

"... Nuup Kangerlua subsequently retreated further inland, reaching..."

Lines 75-76:

Consider a reference to Figure 1.

Line 85:

Have the authors investigated the history of post-glacial relative sea-level changes for the study area and considered how these may have affected the depth of the main sill (at a modern depth of 170 m) throughout the Holocene? For example, if relative sea-level in the fjord was higher/lower during the mid-Holocene could this have aided/precluded the advection of Atlantic-derived waters into the fjord? If known, I suggest that the depth of the sill be reported as a range, with reference to past relative sea-level changes.

Line 88:

"... varying from ~5 to 28 and reaching a minimum in mid-August, and..."

Lines 95-98:

"Sediment core studies covering the last ~3300 years have: i) shown that... and ii) linked increased..."

Line 125:

"... in which sustained warming would enhance inflow of..."

RESULTS

Lines 131-133:

"The fjord sediment analyzed in this study consist of a gravity core (SA13-ST6-40G) and a Rumohr-lot core (SA13-ST6-36R)."

The core coordinates, core length, and core water depth would be best summarized in a table, along with the CTD coordinates and water depths.

LINE 135:

Is "side branch" the same as an intra-fjord channel?

Line 144:

"... sedimentation rates ranging from 0.04 to 0.08 cm yr⁻¹..."

Lines 148-151:

For clarity, I suggest you split this up into a few sentences.

"Two peaks in magnetic susceptibility and IRD concentration are present in the core data. One from ~10.3 to 10.0 ka BP (553-536 cm) contains 20.9-46.4% of grains >63 µm. A second in the uppermost part of the core, from ~150 to -31 yrs BP (8-0 cm), has 2.5-4.5% of grains >63 µm."

What about the apparent peaks in IRD centred on ~360 cm, ~425 cm, and ~500 cm? Are these significant? Worth mentioning?

Lines 156-158:

"The BSi concentration increases from a minimum in the lowermost part of the core to a maximum at ~3.2 ka BP (208 cm), after which it sharply decreases and remains low to the top of the core."

Line 165:

"... increase upwards, reaching maximum values at..."

Lines 169-171:

" $\delta^{15}\text{N}$ values gradually decline towards the top of the core and vary from 2.8 to 8.3‰ (mean 5.5), with the greatest variation occurring in the early Holocene (Fig. 3)."

Line 172:

"C/N ratios and ..." or "The C/N ratio and..."

Line 175:

"... values vary from..."

Line 176:

"C/N ratios and ..." or "The C/N ratio and..."

Line 182:

"... dinocyst concentrations are ca. 1800-..."

Line 183:

"... while fluxes span 197-..."

Line 199:

"... has a similar composition to zone 6 of the gravity core."

Lines 207-208:

"... downward sediment flux consisted primarily of *I. minutum*..."

Line 208:

Consider "For this same period" instead of "At this time"

Line 210:

"... and the heterotroph *Brigantedinium* peaked."

DISCUSSION

Line 218-219:

"... Nuup Kangerlua by ~11.4-10.4 ka BP (Fig. 6), where the Kapisigdlit stade moraine was deposited ~10.4-10.0 ka BP (Fig. 1)."

Lines 220-221:

"... interpreted as IRD."

Lines 221-222:

"Low dinocyst concentrations and fluxes, low BSi and TOC levels, and relatively high C/N ratios, all indicate low productivity in the fjord when terrestrial inputs remained high."

Line 225:

The focus shifts here to a description of modern data from a sediment trap, then to a comparison between data from the sediment trap and the sediment cores. The juxtaposition would be more effective if stated more explicitly (i.e. A comparison with data from the sediment trap shows that Early Holocene dinocyst assemblages most closely resemble those of modern cold surface water conditions.)

Lines 227-228:

"When the sediment trap was collected..." Collected for the final time (i.e. retrieved)? May?

Lines 236-238:

"... indicate changing environmental conditions from deglaciation to ~8 ka BP..."

Lines 238-240:

"The change described by the GAMs primarily reflects the shift from heterotrophic species dominance to autotrophic species dominance..."

Line 241:

"... the site became more productive during this period, as evidenced by..."

Lines 249-250:

"Decreased IRD suggests a change from an ice-sheet proximal setting to a more marine environment during the Early Holocene, consistent with reduced terrestrial carbon flux to the coring site."

Lines 252-253:

"... summer months, when the highest dinocyst diversity and TOC are observed."

Line 256:

"... total assemblage), which can be associated with a stratified water column during summer."

Line 264:

"... reduced IRD and..."

Lines 274-275:

Consider a reference to Figure 8.

Line 284:

Consider new paragraph here.

Lines 284-286:

"... the ice sheet grounding line retreated inland from its present position and meltwater runoff to the study site was consequently reduced."

Lines 286-287:

"Ice sheet withdrawal would have enhanced freshwater runoff to the fjord, lowering its salinity, and resulting in unfavourable conditions..."

Line 291:

New paragraph

Lines 293-294:

Not sure of the reasoning here. If no *N. labyrinthus* cysts were found in the sediment trap, then how does this suggest advection of the species into the fjord by Atlantic waters at present? Do you mean intermittent advection in modern times, given that it is present at low abundances in modern seafloor sediments? This section from Line 291 to Line 296, discussing abundances of *N. labyrinthus* in modern sediments, somewhat disrupts the logic running from the sentence ending on Line 290 to the sentence starting on Line 296. Suggest Lines 291-296 constitute a separate paragraph.

Line 296:

New paragraph.

Lines 296-298:

Consider reference to Figure 6.

Line 297:

"... sediment records, and attributed..."

Line 299:

"... through Fram Strait..."

Line 310:

"... occurred farther north..."

Line 313:

Consider "...an important heat source for glacier mass balance..."

Lines 314-316:

"Evidence for mid Holocene tidewater glacier retreat is available from a site in Disko Bay, where an episode..."

Lines 316-317:

What is meant by "melt water surging"? Surging tidewater terminus induced by warmer water in the fjord? Surging tidewater terminus coincident with high meltwater discharge?

Lines 317-321:

Don't put it so mildly. Consider "We suggest that the exceptionally high *N. labyrinthus* abundances during this period reflect anomalous atmospheric and sea-surface warming."

Lines 319-322:

"Such warming is manifest in the NGRIP ice core as a 5-degree K positive temperature anomaly from ca. 4.4 to 3.9 ka BP. Further, positive temperature spikes are observed in the Agassiz ice core (Ellesmere Island) and in the Greenland Renland and Camp Century ice core between 4.29 and 3.79 ka BP."

Lines 329-330:

The cited increase in IRD content is quite subtle based on Figure 6.

Lines 331-332:

"... during the Neoglacial period."

Lines 334-336:

How would relative-sea level changes prior to and during this interval impacted the depth of the bathymetric sill at the fjord mouth? Could the sill have also been a factor in limiting the inflow of Atlantic-derived waters? Is this reasonable or can it be negated?

Lines 337-338:

"... Nuup Kangerlua suggest a mild climate during the early part of the Neoglacial, promoting glacial melt and leading to..."

Lines 338-339:

Do you think that you have the chronological resolution in the sediment core to make this distinction? This purported lag of 200 years is almost certainly within the age uncertainty.

Lines 339-341:

"... the period from ~1.8 to 1.5 ka BP coincides with a temporary increase productivity and Atlantic Water indicators (Fig. 6), and is consistent with..."

Lines 345-346:

"... from ~1 ka to the present, a transition to a new state is ongoing."

Lines 346-347:

"... and increased IRD content."

Line 348:

"...~1950 to the present..."

Lines 351-352:

"... studies of high-resolution..."

Lines 362-363:

"Our long-term record indicates that meltwater runoff has increased from ~1950 AD, as shown by the increased concentrations of the freshwater..."

Line 365:

"Biecheleria spp., both found..."

Lines 365-367:

Previously in the paragraph you cite the influence of increased (meltwater) runoff to explain the data. Here you refer solely to increased ice discharge. Do actually mean both? i.e. Freshwater input to the fjord in the form of both icebergs and meltwater?

Line 370:

"... the period following deglaciation, when a warmer..."

Line 371:

"... ice-sheet retreat and enhanced freshwater discharge."

Lines 371-373:

"Heterotrophic dinocyst species, which thrive during periods of ice melt, are dominant at present, and diatoms are the main..."

Line 373:

"The period between ~6.5 and 3 ka BP..."

Line 384-385:

"... it is plausible that the hydrography of Nuup Kangerlua will change due to..."

Line 387:

"... into the fjord, such as those for the mid-to-late Holocene described in this study."

TABLES

Table 1:

Median modelled ages should be reported to only 4 significant digits.

FIGURES

Figure 1:

Explain the small box in figure a), which I assume delineates the extent of figure b).

"The location of sediment cores and CTD's (SA13-ST6-36R, SA13-ST6-40G and SA13-ST6-41CTD - all named SA13-ST6) and the sediment trap (PPS 4/3 from 2017-18) analysed in this study are marked by yellow stars, situated within Kapisillit Kangerluat (KK)."

Figure 2:

"The relationship between depth and age are shown for both cores, SA13-ST-6-40G and SA13-ST6-36R (inset)."

"... (Supplementary table 1), blue dots denote 14C dates of polychaete tubes, and orange dots denote 14C dates from mixed benthic foraminifera."

Is the age-depth uncertainty 2-sigma?

Figure 3:

Would it be helpful to colour code the different plots using one colour for the proxies you associate primarily with productivity and a second colour for those you associate primarily with marine input?

For example, the $\delta^{15}\text{N}$ plot lies in the middle and, from the figure alone, readers may not intuit its primary value vis-a-vis productivity/marine input.

Figure 4:

The scale for core SA13-St6-36R, ranging from -0.02 to 0.02 ka BP is not consistent with the age-depth model for the core shown in Figure 3. Was only the uppermost part of this core analyzed?

"... taxa in cores..."

Figure 6:

The interval associated with minimum ice-sheet extent and increased salinity is cited as ~6.5 to 3 ka BP in the text.

However, in the figure the grey bar denoting this interval spans 6.5 to ~3.2 ka BP. Is this a minor drafting error or is ~3.2 ka BP a more accurate constraint for the end of this interval?

Reviewer #2 (Remarks to the Author):

This paper presents a Holocene marine sediment record from southwestern Greenland based on analyses of grain-size, biochemical parameters, and microfossils. Interpretations are supported by new sediment trap data near the study site covering one year. Arctic Holocene records may offer modern analogues for the current warming observed in the Arctic today or help elucidate future climate projections. The paper is based on a fjord record offering a high temporal resolution and additionally from a geographical region that has been less investigated. Thus, the paper could be of interest for a wider audience.

The depth-age model is less than robust. Two types of material (polychaete tubes and mixed benthic foraminifera) have been dated, and even though they originate from the same environment, they may not reflect the same environmental conditions, e.g., the animals have different life spans. How has this been assessed?

Sediment accumulation rates have not been considered when using concentrations, please refer to lines 264-265, lines 339-341, and Figure 6 (BSi, *N. labyrinthus*). During the time interval 6.5-3 cal ka BP, sediment accumulation rates are low (lowest values of the record). Do the increased concentrations of BSi and *N. labyrinthus* reflect a higher productivity or the decreased sediment accumulation rates?

Flux of TOC has been calculated for the sediment trap data, but TOC from the sediment cores is presented as relative abundance of TOC (%). It would be useful to compare modern-day and past values directly (either as flux or %).

The major finding of the paper is that the period 6.5-3 cal ka BP does not look like the present and may represent an analogue for the future. This should be made clear in the title. This should also be considered in the introduction making the text more pointed towards this.

The paper holds detailed descriptions of geoscience data that does not seem to be of interest for a wider field. The paper may benefit if this is removed to methods or supplementary material. This would also enable the paper to be shorter with less figures.

Figure 2: It is not possible to see how the calibrated ages correlate when the individual ranges are not shown. It is also not possible to see the reversal very well (radiocarbon dates from core depths 355.5 and 377.5 cm).

Figure 3: Variations of the data are not shown very well due to the small x-axes. Consider to present data in two panels enabling more space for each x-axis.

Figure 6. Move figure 6f to the bottom of the figure next to the panel labelled "Atlantic water influence in other records" or

combine them as data presented in 6f are not part of the current study from Nuup Kangerlua.

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Version 1:

Decision Letter:

**** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors ****

Dear Ms Kvorning,

Your revised manuscript titled "Holocene history of a southwest Greenland fjord: modern conditions on path to deglaciation yet distinct from thermal maximum" has now been seen by our original reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

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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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Carolina Ortiz Guerrero, Ph.D.
Associate Editor
Communications Earth & Environment

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I have reviewed the revised manuscript, as well as the author's responses to my comments. I confirm that all of my concerns have been addressed.

Reviewer #2 (Remarks to the Author):

Thanks to the authors, who have carefully addressed all my previous concerns. I have a minor technical comment; Figure 1 seems to have a low resolution.

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Point-by-point response to the reviewers' comments.

Reviewer 1

SUMMARY & RECOMMENDATION: The manuscript presents new proxy data that constrains Holocene marine environmental changes in southwest Greenland. The data come from a set of sediment cores and a sediment trap collected from Nuup Kangerlua. The interpretations regarding past environmental variability are justified and based primarily on results from multiple sedimentological, biogeochemical, geochronological, and micropaleontological proxies. Results, summarizing Holocene trends in marine productivity, marine/terrestrial input, and temperature/salinity, are clearly presented and discussed within the context of other relevant field studies. The authors highlight the regional significance of the research and make compelling connections to possible future environmental scenarios. The paper is well-organized and clearly written. I recommend publication following minor revision of the manuscript.

GENERAL COMMENTS: The study contends that continued warming and ice-sheet retreat will plausibly cause stronger advection of Atlantic-derived water into the fjords of southwest Greenland. Based on the reconstructed Holocene framework of environmental variability, this seems logical. However, can the authors equally comment on how such a future switch may differ from that in the mid-Holocene. With a dramatically different sea-ice regime, significantly higher rates of change in ice-sheet mass balance (i.e. freshwater flux), and increasing frequency of extreme climate events, to name just a few variables, is it likely that increased advection of Atlantic-derived waters to west Greenland will proceed at the same pace and scale as during the mid-Holocene? What (if any) variables have the capacity to complicate or upend the historical analogy? I appreciate that a long, detailed discussion of these complexities is beyond the scope of the study. However, a short comment addressing some of the uncertainties regarding this paleoanalogue as a likely "landing spot" for near-future environmental change may highlight the need to both understand these paleoanalogues in greater detail and to consider them in the context of future projections.

Answer: We thank the reviewer for their thorough review and valuable feedback, which have significantly contributed to the improvement of the manuscript.

In response to your concern, we have incorporated the following paragraph into our manuscript: "There are, however, significant differences between the HTM and ongoing warming. While the HTM was driven by increased boreal summer insolation, the unprecedented modern-day warming is primarily caused by elevated greenhouse gas concentrations in the atmosphere. Furthermore, present-day warming is occurring at an unprecedented rate at high latitudes, making it the fastest observed warming during the entire Holocene period^{6,85}. During the HTM, the ice sheet retreated inland, reaching a minimum extent farther inland than its current position. The significant warming predicted for this century is expected to drive even faster ice mass loss than what has been modeled for the last 12,000 years including the HTM^{6,86}. When considering this, the increased advection of

Atlantic-derived waters to West Greenland will likely proceed at a faster pace during this century than during the mid-Holocene. Enhanced advection of warmer, saltier Atlantic-derived waters will drive significant changes in the distribution of ocean heat and salinity. These changes are expected to accelerate ice sheet retreat, amplify sea ice loss and intensify water column stratification. Such shifts will have profound and potentially detrimental impacts on marine ecosystems, disrupting biodiversity and altering food web dynamics.”

SPECIFIC COMMENTS: The majority of the specific comments below are suggestions aimed at increasing the clarity of the manuscript.

ABSTRACT

Comment: Line 24: “... deglaciation from ~10 to 8 cal ka BP.”

Answer: Comment has been included.

Comment: Line 26: “... analogue from ~6.5 to 3 cal ka BP...”

Answer: Comment has been included.

INTRODUCTION

Comment: Lines 36-38: The last sentence of this paragraph is somewhat awkward. Consider “... significantly impact fjord environments, including important marine ecosystems that constitute the basis for local fisheries and subsistence livelihoods.”

Answer: Comment has been included.

Comment: Line 48: I wonder if you can possibly be more precise with the timing here? End of this century?

Answer: We thank the reviewer for the comment. We have altered the sentence to “Still, this period has been considered a potentially useful analogue for near-future conditions²¹ with global surface temperatures between 2011-2020 already reaching ~1.1 °C relative to 1850-1900 CE (IPCC, 2023)”

Comment: Line 50: “Marine climate variability in the Arctic is closely linked to...”

Answer: Comment has been included.

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Answer: Suggestion has been included.

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Answer: We appreciate the reviewer for highlighting the discussion point. The relative sea-level changes have been examined at two distinct sites along the outer coast, where both records indicate that the majority of post-glacial isostatic uplift (approximately 100 m) occurred rapidly between 11 and 10 cal. ka BP at Godmouth and Nuuk (Lecavalier et al., 2014). This initial phase of uplift was followed by a more gradual rise around 40 m from approximately 10 to 4 cal. ka BP. Given that the majority of isostatic uplift took place prior to 10 ka, we conclude that it is unlikely it has influenced the paleoceanographic conditions described.

Comment: Line 88: "... varying from ~5 to 28 and reaching a minimum in mid-August, and..."

Answer: Comment has been included.

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Answer: Suggestions have been included.

Comment: What about the apparent peaks in IRD centred on ~360 cm, ~425 cm, and ~500 cm? Are these significant? Worth mentioning?

Answer: Thank you for the comment. We now describe all peaks with >6 % of grains >63 µm.

Comment: Lines 156-158: "The BSi concentration increases from a minimum in the lowermost part of the core to a maximum at ~3.2 ka BP (208 cm), after which it sharply decreases and remains low to the top of the core."

Answer: Comment has been included.

Comment: Line 165: "... increase upwards, reaching maximum values at..."

Answer: We have added a comma.

Comment: Lines 169-171: "δ¹⁵N values gradually decline towards the top of the core and vary from 2.8 to 8.3‰ (mean 5.5), with the greatest variation occurring in the early Holocene (Fig. 3)."

Answer: Comment that we have included.

Comment: Line 172: "C/N ratios and ..." or "The C/N ratio and..."

Answer: Comment has been included.

Comment: Line 175: "... values vary from..."

Answer: Comment has been included.

Comment: Line 176: "C/N ratios and ..." or "The C/N ratio and..."

Answer: Comment has been included.

Comment: Line 182: "... dinocyst concentrations are ca. 1800-..."

Answer: Comment has been included.

Comment: Line 183: "... while fluxes span 197-..."

Answer: Comment has been included.

Comment: Line 199: "... has a similar composition to zone 6 of the gravity core."

[Answer: Comment has been included.](#)

Comment: Lines 207-208: "... downward sediment flux consisted primarily of *I. minutum*..."

[Answer: Comment has been included.](#)

Comment: Line 208: Consider "For this same period" instead of "At this time"

[Answer: Comment has been included.](#)

Comment: Line 210: "... and the heterotroph *Brigantedinium* peaked."

[Answer: Comment has been included.](#)

DISCUSSION

Comment: Line 218-219: "... Nuup Kangerlua by ~11.4-10.4 ka BP (Fig. 6), where the Kapisigdlit stade moraine was deposited ~10.4-10.0 ka BP (Fig. 1)."

[Answer: Comment has been included.](#)

Comment: Lines 220-221: "... interpreted as IRD."

[Answer: Comment has been included.](#)

Comment: Lines 221-222: "Low dinocyst concentrations and fluxes, low BSI and TOC levels, and relatively high C/N ratios, all indicate low productivity in the fjord when terrestrial inputs remained high."

[Answer: Comment has been included.](#)

Comment: Line 225: The focus shifts here to a description of modern data from a sediment trap, then to a comparison between data from the sediment trap and the sediment cores. The juxtaposition would be more effective if stated more explicitly (i.e. A comparison with data from the sediment trap shows that Early Holocene dinocyst assemblages most closely resemble those of modern cold surface water conditions.)

[Answer: Thank you for the comment and suggestion. We agree that this makes it more effective so the suggestion is incorporated.](#)

Comment: Lines 227-228: "When the sediment trap was collected..." Collected for the final time (i.e. retrieved)? May?

[Answer: Thank you for the comment. We have rewritten the part for clarification. The trap was retrieved in May \(end of the one year deployment\).](#)

Comment: Lines 236-238: "... indicate changing environmental conditions from deglaciation to ~8 ka BP..."

[Answer: Comment has been included.](#)

Comment: Lines 238-240: “The change described by the GAMs primarily reflects the shift from heterotrophic species dominance to autotrophic species dominance...”

Answer: [Comment has been included.](#)

Comment: Line 241: “... the site became more productive during this period, as evidenced by...”

Answer: [Comment has been included.](#)

Comment: Lines 249-250: “Decreased IRD suggests a change from an ice-sheet proximal setting to a more marine environment during the Early Holocene, consistent with reduced terrestrial carbon flux to the coring site.”

Answer: [Comment has been included.](#)

Comment: Lines 252-253: “... summer months, when the highest dinocyst diversity and TOC are observed.”

Answer: [Comment has been included.](#)

Comment: Line 256: “... total assemblage), which can be associated with a stratified water column during summer.”

Answer: [Comment has been included.](#)

Comment: Line 264: “... reduced IRD and...”

Answer: [Comment has been included.](#)

Comment: Lines 274-275: Consider a reference to Figure 8.

Answer: [Thank you for your suggestion. We decided to add a reference; however, we found a reference to Supplementary Figure 5 suitable.](#)

Comment: Line 284: Consider new paragraph here.

Answer: [Suggestion has been included.](#)

Comment: Lines 284-286: “... the ice sheet grounding line retreated inland from its present position and meltwater runoff to the study site was consequently reduced.”

Answer: [Comment has been included.](#)

Comment: Lines 286-287: “Ice sheet withdrawal would have enhanced freshwater runoff to the fjord, lowering its salinity, and resulting in unfavourable conditions...”

Answer: [Comment has been included.](#)

Comment: Line 291: New paragraph

Answer: [Comment has been included.](#)

Comment: Lines 293-294: Not sure of the reasoning here. If no *N. labyrinthus* cysts were found in the sediment trap, then how does this suggest advection of the species into the fjord

by Atlantic waters at present? Do you mean intermittent advection in modern times, given that it is present at low abundances in modern seafloor sediments? This section from Line 291 to Line 296, discussing abundances of *N. labyrinthus* in modern sediments, somewhat disrupts the logic running from the sentence ending on Line 290 to the sentence starting on Line 296. Suggest Lines 291-296 constitute a separate paragraph.

Answer: We have re-phrased this paragraph for clarity. Indeed, since modern sediments from the fjord have extremely low abundances of this cyst taxon (maximum 2% of the total assemblage), and no cysts of this species were found in the sediment trap, we interpret its presence as possibly due to intermittent advection in modern times.

Comment: Line 296: New paragraph.

Answer: Comment has been included.

Comment: Lines 296-298: Consider reference to Figure 6.

Answer: Suggestion has been included.

Comment: Line 297: "... sediment records, and attributed..."

Answer: Comment has been included.

Comment: Line 299: "... through Fram Strait..."

Answer: Comment has been included.

Comment: Line 310: "... occurred farther north..."

Answer: Comment has been included.

Comment: Line 313: Consider "...an important heat source for glacier mass balance..."

Answer: Suggestion has been included.

Comment: Lines 314-316: "Evidence for mid Holocene tidewater glacier retreat is available from a site in Disko Bay, where an episode..."

Answer: Comment has been included.

Comment: Lines 316-317: What is meant by "melt water surging"? Surging tidewater terminus induced by warmer water in the fjord? Surging tidewater terminus coincident with high meltwater discharge?

Answer: Thank you for the question. We have changed the sentence and used the term meltwater discharge event instead.

Comment: Lines 317-321: Don't put it so mildly. Consider "We suggest that the exceptionally high *N. labyrinthus* abundances during this period reflect anomalous atmospheric and sea-surface warming."

Answer: Comment has been included.

Comment: Lines 319-322: “Such warming is manifest in the NGRIP ice core as a 5-degree K positive temperature anomaly from ca. 4.4 to 3.9 ka BP. Further, positive temperature spikes are observed in the Agassiz ice core (Ellesmere Island) and in the Greenland Renland and Camp Century ice core between 4.29 and 3.79 ka BP.”

Answer: Comment has been partly included, we changed the last part to “Agassiz ice core (Ellesmere Island), Greenland Renland ice core and Camp Century ice core between 4.29 and 3.79 ka BP.” instead.

Comment: Lines 329-330: The cited increase in IRD content is quite subtle based on Figure 6.

Answer: We have deleted IRD from the sentence.

Comment: Lines 331-332: “... during the Neoglacial period.”

Answer: Comment has been included.

Comment: Lines 334-336: How would relative-sea level changes prior to and during this interval impact the depth of the bathymetric sill at the fjord mouth? Could the sill have also been a factor in limiting the inflow of Atlantic-derived waters? Is this reasonable or can it be negated?

Answer: Thank you for the comment. As we mentioned in a previous response, the majority of isostatic uplift occurred before 10 ka. Therefore, variations in the sill depth can be ruled out as having significantly influenced the inflow of Atlantic-derived water.

Comment: Lines 337-338: “... Nuup Kangerlua suggest a mild climate during the early part of the Neoglacial, promoting glacial melt and leading to...”

Answer: Comment has been included.

Comment: Lines 338-339: Do you think that you have the chronological resolution in the sediment core to make this distinction? This purported lag of 200 years is almost certainly within the age uncertainty.

Answer: We thank the reviewer for the question and we agree that this age distinction was within the age uncertainty, so we rephrased the sentence to “Our findings support decreased productivity from ~3 ka BP”

Comment: Lines 339-341: “... the period from ~1.8 to 1.5 ka BP coincides with a temporary increase productivity and Atlantic Water indicators (Fig. 6), and is consistent with...”

Answer: Comment has been partly incorporated, we keep the “in” prior to “productivity and Atlantic Water indicators (Fig. 6), and is consistent with...”

Comment: Lines 345-346: “... from ~1 ka to the present, a transition to a new state is ongoing.”

Answer: Comment has been incorporated and we have added a “BP” after “~1 ka”.

Comment: Lines 346-347: ‘... and increased IRD content.’

Answer: Comment has been included.

Comment: Line 348: ‘...~1950 to the present...’

Answer: Comment has been included.

Comment: Lines 351-352: ‘... studies of high-resolution...’

Answer: Comment has been included.

Comment: Lines 362-363: ‘Our long-term record indicates that meltwater runoff has increased from ~1950 AD, as shown by the increased concentrations of the freshwater...’

Answer: Comment has been included.

Comment: Line 365: ‘Biecheleria spp., both found...’

Answer: We have added a comma.

Comment: Lines 365-367: Previously in the paragraph you cite the influence of increased (meltwater) runoff to explain the data. Here you refer solely to increased ice discharge. Do you actually mean both? i.e. Freshwater input to the fjord in the form of both icebergs and meltwater?

Answer: We thank the reviewer for making us aware of this. We meant freshwater discharge and have now rewritten the sentence as “Our results support the idea that cooling of the surface waters result from increased freshwater runoff including meltwater and ice discharge into Nuup Kangerlua during the last decades.”

Comment: Line 370: ‘... the period following deglaciation, when a warmer...’

Answer: Comment has been included.

Comment: Line 371: ‘... ice-sheet retreat and enhanced freshwater discharge.’

Answer: Comment has been included.

Comment: Lines 371-373: ‘Heterotrophic dinocyst species, which thrive during periods of ice melt, are dominant at present, and diatoms are the main...’

Answer: Comment has been included.

Comment: Line 373: ‘The period between ~6.5 and 3 ka BP...’

Answer: Comment has been included.

Comment: Line 384-385: ‘... it is plausible that the hydrography of Nuup Kangerlua will change due to...’

Answer: Comment has been included.

Comment: Line 387: ‘... into the fjord, such as those for the mid-to-late Holocene described in this study.’

Answer: Comment has been included.

TABLES

Comment for Table 1: Median modelled ages should be reported to only 4 significant digits.

Answer: Comment has been included.

FIGURES

Comment for Figure 1: Explain the small box in figure a), which I assume delineates the extent of figure b).

Answer: We have added the sentence “The black box delineates the extent of figure b.”

Comment for Figure 1: “The location of sediment cores and CTD’s (SA13-ST6-36R, SA13-ST6-40G and SA13-ST6-41CTD - all named SA13-ST6) and the sediment trap (PPS 4/3 from 2017-18) analysed in this study are marked by yellow stars, situated within Kapisillit Kangerluat (KK).”

Answer: Comment has been included except for “CTD’s” here we wrote “CTD”

Comment for Figure 2: “The relationship between depth and age are shown for both cores, SA13-ST-6-40G and SA13-ST6-36R (inset).”

Answer: Comment has been included.

Comment for Figure 2: “... (Supplementary table 1), blue dots denote 14C dates of polychaete tubes, and orange dots denote 14C dates from mixed benthic foraminifera.”

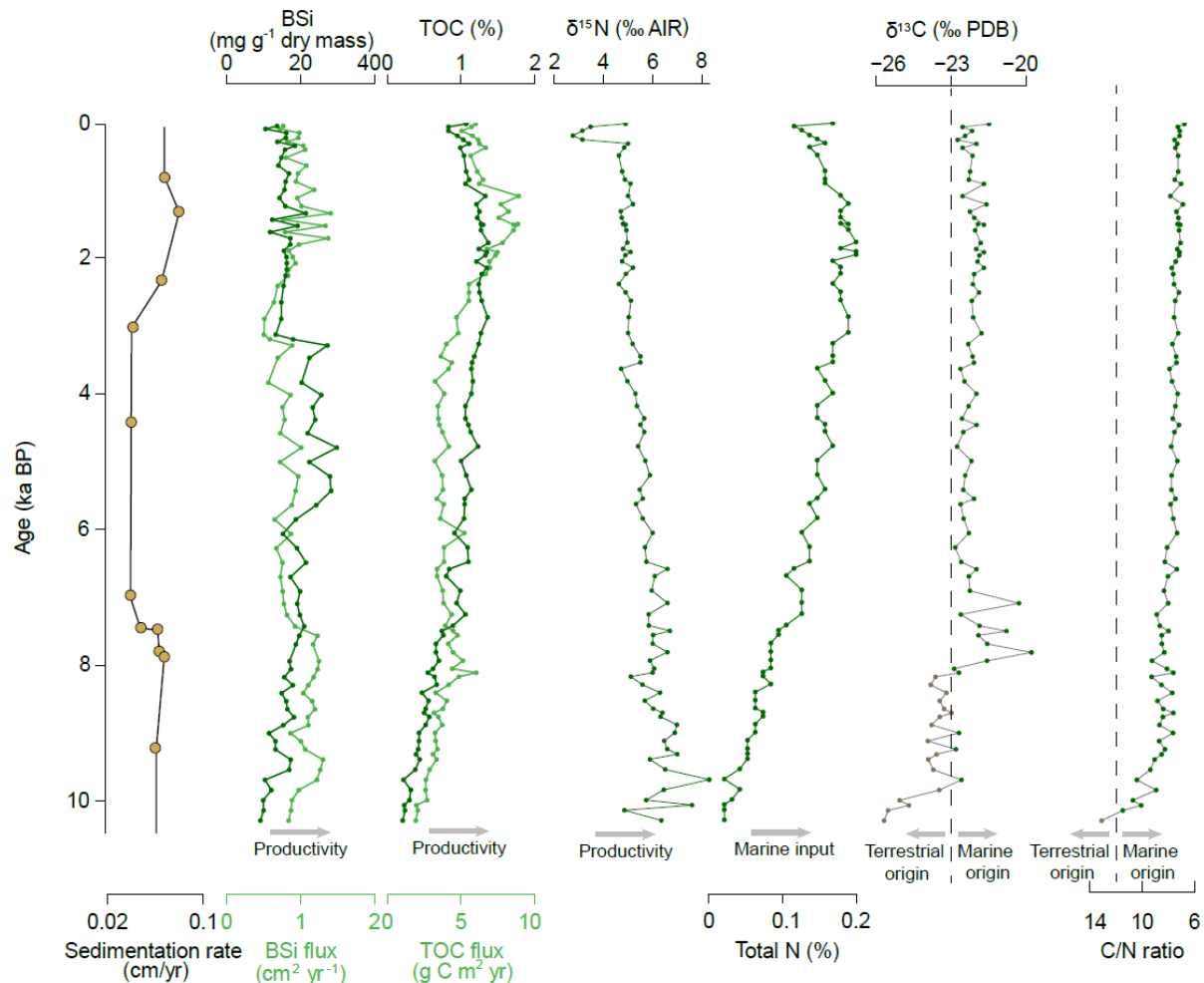
Answer: Comment has been included.

Comment for Figure 2: Is the age-depth uncertainty 2-sigma?

Answer: Yes and we have added that in the figure text.

Comment for Figure 3: Would it be helpful to colour code the different plots using one colour for the proxies you associate primarily with productivity and a second colour for those you associate primarily with marine input? For example, the $\delta^{15}\text{N}$ plot lies in the middle and, from the figure alone, readers may not intuit its primary value vis-a-vis productivity/marine input.

Answer: We thank the reviewer for the suggestion. In response, we have enhanced the visualization by adding an arrow with descriptive text at the base of each plot for clarity. For the final two plots, where the data can represent either a marine or terrestrial source depending on the values, we implemented color coding (green for marine and brown for terrestrial) to differentiate the sources. Additionally, we included dashed lines to visually separate the two categories, further improving interpretability.



Comment for Figure 4: The scale for core SA13-St6-36R, ranging from -0.02 to 0.02 ka BP is not consistent with the age-depth model for the core shown in Figure 3. Was only the uppermost part of this core analyzed?

Answer: We thank the reviewer for the comment. It is correct that we show the entire age-depth model for core SA13-St6-36R in Figure 2 and exclusively show dinocyst data from the top ca. 15 cm. Based on the detection of 210Pb and a similar dinocyst assemblage in the upperpart of both records we assume there is considerable overlap between the two and have thus only included the top of the 36R core.

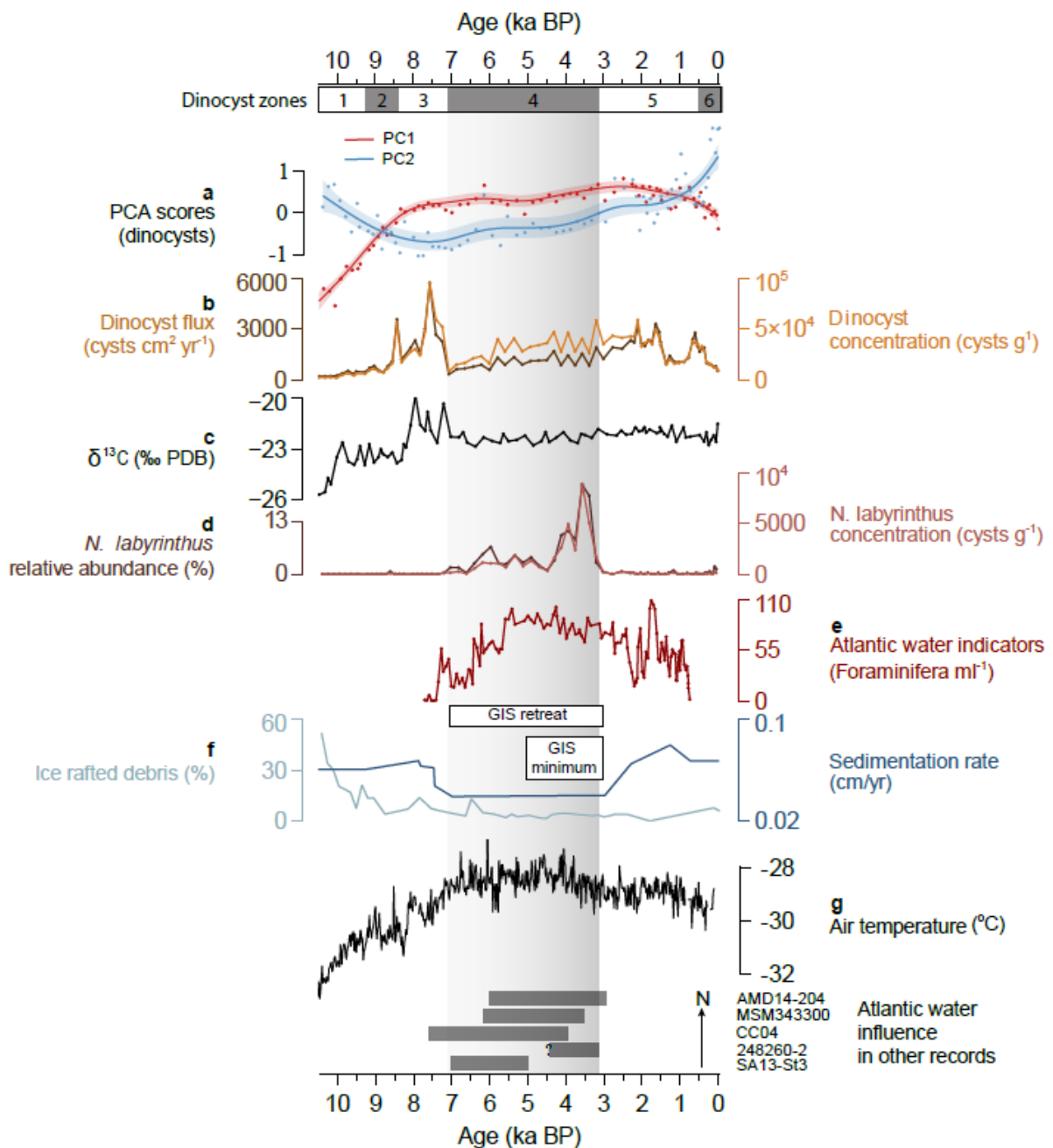
Comment for Figure 4: “... taxa in cores...”

Answer: Comment has been included.

Comment for Figure 6: The interval associated with minimum ice-sheet extent and increased salinity is cited as ~6.5 to 3 ka BP in the text. However, in the figure the grey bar denoting this interval spans 6.5 to ~3.2 ka BP. Is this a minor drafting error or is ~3.2 ka BP a more accurate constraint for the end of this interval?

Answer: We thank the reviewer for raising this question. The glacier retreated between ~7 and 3 ka BP and reached minimum at ~5 ka BP, this is shown in Fig. 6 as the small white

boxes named “GIS retreat” and “GIS minimum”. The grey bar is covering the period with enhanced influence of Atlantic Water based on dinocyst zone 4 and the abundance of *N. labyrinthus*.



Reviewer #2 (Remarks to the Author):

This paper presents a Holocene marine sediment record from southwestern Greenland based on analyses of grain-size, biochemical parameters, and microfossils. Interpretations are supported by new sediment trap data near the study site covering one year. Arctic Holocene records may offer modern analogues for the current warming observed in the Arctic today or help elucidate future climate projections. The paper is based on a fjord record offering a high temporal resolution and additionally from a geographical region that has been less investigated. Thus, the paper could be of interest for a wider audience.

Comment: The depth-age model is less than robust. Two types of material (polychaete tubes and mixed benthic foraminifera) have been dated, and even though they originate from the same environment, they may not reflect the same environmental conditions, e.g., the animals have different life spans. How has this been assessed?

Answer: We thank the reviewer for raising this concern and for providing feedback that has helped improve the manuscript. Constructing age-depth models for marine sediment cores from the Arctic region is often challenging due to the limited availability of calcareous fossils. Despite laborious and extensive screening of the entire record for foraminifera, we were only able to collect sufficient material for radiocarbon dating at the specific depths. This limitation led us to include two different types of material (foraminifera and polychaete tubes) in constructing the age-depth model. To ensure the reliability of using polychaete tubes, we conducted radiocarbon measurements on both materials at several depths to verify their consistency. Additionally, a published study from the same region has also successfully combined polychaete tubes and foraminifera in age-depth model construction (Oksman et al., 2024).

We have now added further details to the methods section: “Polychaetes burrow into the sediments, and careful assessment was made to determine the uppermost layer penetrated by the tube, as this represents the layer inhabited by the polychaete.”

Moreover, we address the age reversal in the results section: “A minor reversal in the radiocarbon dates was observed at 377.5 cm, based on dating of benthic foraminifera. The very small sample size of this date, however, was associated with a large error of ~330 years, making it compatible with surrounding dates and it was therefore not treated as an outlier. There was also strong agreement between the two dates conducted on different materials at 400.5 cm and 403.5 cm.”

Finally, we emphasize that our aim is to describe changes occurring over centuries rather than decades. Given this scope, we believe the age-depth model is sufficiently robust for the purpose of this study.

Comment: Sediment accumulation rates have not been considered when using concentrations, please refer to lines 264-265, lines 339-341, and Figure 6 (BSi, *N. labyrinthus*). During the time interval 6.5-3 cal ka BP, sediment accumulation rates are low (lowest values of the record). Do the increased concentrations of BSi and *N. labyrinthus* reflect a higher productivity or the decreased sediment accumulation rates?

Answer: We thank the reviewer for the comment. In the revised manuscript, we have included the BSi flux alongside the concentration. As noted, while the BSi concentration is elevated, the flux remains relatively low. To address this, we present the abundance of *N. labyrinthus*, which is unaffected by sedimentation processes. Notably, we observe a significant increase in *N. labyrinthus* abundance, exceeding 20%, which is unaffected by sedimentation processes

Comment: Flux of TOC has been calculated for the sediment trap data, but TOC from the sediment cores is presented as relative abundance of TOC (%). It would be useful to compare modern-day and past values directly (either as flux or %).

Answer: We have calculated and added the flux of TOC from the sediment core in Fig. 4.

Comment: The major finding of the paper is that the period 6.5-3 cal ka BP does not look like the present and may represent an analogue for the future. This should be made clear in the title. This should also be considered in the introduction making the text more pointed towards this.

Answer: We thank the reviewer for raising this concern, however, we find that the original title clearly states the difference between modern and future conditions.

Comment: The paper holds detailed descriptions of geoscience data that does not seem to be of interest for a wider field. The paper may benefit if this is removed to methods or supplementary material. This would also enable the paper to be shorter with less figures.

Answer: We acknowledge the reviewer's comment but we feel that the detail given is necessary for supporting our findings. We have followed the word limit and formatting requirements of the journal.

Comment: Figure 2: It is not possible to see how the calibrated ages correlate when the individual ranges are not shown. It is also not possible to see the reversal very well (radiocarbon dates from core depths 355.5 and 377.5 cm).

Answer: Thank you for bringing up this point. We have included the original age-depth model in the appendix, here the uncertainties associated with each individual radiocarbon date are clearly illustrated, together with the reversed age. The reversed age has a very large uncertainty, making it compatible with surrounding dates and it was therefore not treated as an outlier.

Comment: Figure 3: Variations of the data are not shown very well due to the small x-axes. Consider to present data in two panels enabling more space for each x-axis.

Answer: Thank you for the feedback regarding figure 3. We have enhanced the visualization by adding an arrow with descriptive text at the base of each plot for clarity. For the final two plots, where the data can represent either a marine or terrestrial source depending on the values, we implemented color coding (green for marine and brown for terrestrial) to differentiate the sources. Additionally, we included dashed lines to visually separate the two categories, further improving interpretability.

Comment: Figure 6. Move figure 6f to the bottom of the figure next to the panel labelled “Atlantic water influence in other records” or combine them as data presented in 6f are not part of the current study from Nuup Kangerlua.

Answer: We appreciate the reviewer’s suggestion. In Fig. 6, our goal is to compare the *N. labyrinthus* concentration (and now abundance) with the foraminifera dataset, and we believe this comparison is most effectively achieved by placing the two panels close together. Similarly, in Fig. 6g, we aim to compare our data with glacier position findings from another study, so positioning these panels side by side provides greater clarity. That said, we have streamlined the figure by removing the biogenic silica concentration, and we hope these adjustments have resulted in a clearer visualisation.

References:

Lecavalier, B. S. *et al.* (2017) ‘High Arctic Holocene temperature record from the Agassiz ice cap and Greenland ice sheet evolution’, *Proceedings of the National Academy of Sciences of the United States of America*, 114(23), pp. 5952–5957. doi: 10.1073/pnas.1616287114.

Axford, Y., De Vernal, A. and Osterberg, E. C. (2021) ‘Past warmth and its impacts during the holocene thermal maximum in greenland’, *Annual Review of Earth and Planetary Sciences*, 49, pp. 279–307. doi: 10.1146/annurev-earth-081420-063858.

Oksman, M. *et al.* (2024) ‘Climate Variability and Glacier Dynamics Linked to Fjord Productivity Changes Over the Last ca. 3300 Years in Nuup Kangerlua, Southwest Greenland’, *Paleoceanography and Paleoclimatology*, 39(3). doi: 10.1029/2023PA004710.

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I have reviewed the revised manuscript, as well as the author's responses to my comments. I confirm that all of my concerns have been addressed.

Answer: We sincerely thank the reviewer for reviewing the manuscript again. The reviewer's revision has been extremely helpful in improving the manuscript.

Reviewer #2 (Remarks to the Author):

Thanks to the authors, who have carefully addressed all my previous concerns. I have a minor technical comment; Figure 1 seems to have a low resolution.

Answer: Thank you to the reviewer for the thorough revision. The reviewer's thorough revision has been extremely helpful in improving the manuscript. We have attached high-resolution versions of all figures for this final submission.