Comments to: Duration and Ice Thickness of a Late Holocene Outlet Glacier Advance near Narsarsuaq, South Greenland

Review 1:

This is a well planned and well conducted study. The manuscript is well written and well-illustrated. The main outcome of the paper is that the Narsarsuaq Stade began much earlier than previously suggested,

As mentioned in the paper the extensive Neoglacial Narsarsuaq advance, which was far greater than its advance during the Little Ice Age, is an unusual feature. Other nearby glaciers did not behave as Kiattuut Sermiat. Hopefully, future models can explain how this could be.

We thank you for your kind words and thoughtful review.

Line 23. suggest change: precipitation amounts to: snow fall.

We have changed "precipitation amount" to "snowfall" in line 22.

Line 44-45. suggest change middle and late Holocene to: Middle and Late Holocene. These are formal units (Walker et al. 2019).

We have changed all instances of lowercase "early, middle, and late Holocene" to "Early, Middle, and Late Holocene."

Line 48 etc. I think it is enough to mention the current spelling of the glaciers.

In line 48, we include old and new spellings because some papers we reference use an older spelling of the glacier name and we want to clearly show we are talking about the same glacier.

Line 84. Ma, not ma.

We have changed all instances of lowercase "ma" to "Ma."

Line 129. I am skeptical about "no adequate plant macrofossils were preserved". Usually, plant macrofossils are well preserved in Holocene lake sediments from Greenland. In line 190 it is noted "infrequent occurrence of terrestrial plant macrofossils in the lake sediments". In the relatively small lakes sampled, I would expect that terrestrial plant macrofossils might be quite common in Mid- and Late Holocene deposits. I wonder how much sediment was wet sieved to find terrestrial plant macrofossils? Often you need to sieve fairly large samples, which can be a problem if you want to date a thin sediment layer. If possible, several parallel sediment cores can be sampled, to get enough material for sieving.

We thank you for pointing out the confusing nature of this statement. There were no instances where the timing of transitions from glaciolacustrine (or till) to organic lake sediments (or vice-versa) in each lake were solely established using bulk sediment ages. However, there were some intervals in individual cores that did not preserve any aquatic moss or terrestrial plant remains (none were found upon wet sieving ~4 ccs of sediment at several 1 cm thick intervals (~16 ccs total in a given target depth range)). We collected several cores from each lake which allowed us to have enough sediment to usually find terrestrial or aquatic plant macrofossils. We have altered line 131-132as follows: "Bulk sediments were sampled as a last resort where no adequate plant macrofossils were preserved" to "Bulk sediments were sampled as a last resort where no adequate plant macrofossils were uncovered."

As far as the cause for some of the sediment core transitions not having terrestrial plant macrofossils (as described in lines 193-194), we believe that the organic lake sediment immediately above the glaciolacustrine sediment would likely have little to no terrestrial plant macrofossils as a result of the terrestrial community not being well established yet in the Early Holocene. It could also be related to the different basins the cores were collected from and how much surface runoff the shorelines closest to the core sites receive. In our research group's experience with lakes across Greenland, there are many sites like this one where terrestrial macrofossils are only rarely preserved/found.

Line 130. CALIB rather than Calib

We have replaced all instances of lowercase "Calib" with "CALIB."

Line 145. I suggest to label the oldest unit 1. It is a bit strange to describe unit 2 before unit 1.

We have labeled the uppermost Unit 1 so that all cores, regardless of the number of units they have, correspond to each other within LMEL and UMEL. Otherwise, for example, the similar units in 19-LMEL-N2 and 19-LMEL-U11 would be 2a and 1a respectively, instead of 1a and 1a. We believe that this approach makes our figures and in text discussion clearer for the reader. This also follows the convention of e.g., marine oxygen isotope stages.

Line 149. suggest layered rather than bedded.

We have replaced "bedded" with "layered" in line 152.

Line 150. Don't know what you mean by medium brown.

We have replaced "medium brown" with "brown" in line 153.

Line 150. fine-grained sediment rather than fine sediment.

We have changed "fine sediments" to "fine-grained sediments" in line 153.

Line 154. low MS values and low Ti concentrations.

We have added “low” before “Ti concentrations” in line 157.

Line 432. Here is mentioned “the unusual timing and magnitude of Kiattuut Sermiat’s late Holocene retreat”. And line 434: Another unusual, although not unique, feature of Kiattuut Sermiat’s history is that its advance during the Little Ice Age was notably lesser than the earlier Neoglacial Narsarsuaq advance.

The extensive Late Holocene Narsarsuaq advance is indeed a most unusual feature.

“In the future, high-resolution ice sheet models could be used to further determine what factors drove Kiattuut Sermiat retreat at this time, and what explained the relatively small magnitude of this outlet glacier’s Little Ice Age advance compared with the extensive late Holocene Narsarsuaq advance.”

We agree that these findings are very unusual and will hopefully be better understood with work building off ours and others.

Line 437. it is not only “unlike the response of many other glaciers in Greenland”. It is unlike almost all other glaciers in Greenland. However, a somewhat similar feature was reported from Sanddalen in NE Greenland by Bennike & Weidick (2008, Boreas vol. 30). I cannot just now remember other similar records from Greenland.

Thank you for pointing out this study to us. We restricted our survey of glaciers to the southern part of Greenland given the large differences in Late Glacial and Holocene climate change across the entire island. In line 454, we have changed “…unlike the response of many other glaciers in Greenland” to “…unlike the response of the vast majority of studied glaciers in Greenland”.

Line 441. Nuussuaq ice cores? Did not know about this ice core.

The Nuussuaq Ice Core was collected in 2015 from west Greenland and is described in Osman et al., 2021. It spans roughly the last 2,000 years.

Fig. 1A. This map should show the sea/ocean in light blue, ice free parts of Greenland in brown or green and ice-covered areas in white.

We don’t believe this is necessary, as the purpose of this panel is to simply highlight the overall region and the general location of the study site. The Kiattuut ice boundary is highlighted in the other panels of this figure.

Fig. 5. In my opinion the Early Holocene high temperatures recorded from Qipisarqo Lake is based on Alnus pollen from Labrador and Newfoundland, rather than from local sources. I suggest not to include curve C in the figure.

We agree that there are important questions about the interpretation of Alnus in the Qipisarqo core, but we prefer to include it as one of very few terrestrial summer temperature reconstructions available from this region. Furthermore, this record shows similarities to the chironomid-based temperature reconstruction by Wooller et al., 2004 from the same site, and excellent agreement (in terms of timing of peak inferred Holocene warmth) with the south Greenland mountain glaciers studied by Larocca et al. 2020a.

Table 1. Suggest including core length.

We have included core length in Table 1.

Review 2:

Puleo and Axford present a very interesting study from an outlet glacier in South Greenland. The manuscript merits publication, as it presents some unexpected results. I have only minor suggestions, comments and/or questions, as indicated in more detail below. Most important of these issues is a more detailed presentation and discussion of radiocarbon ages, potential reservoir effects and sedimentation rates. Such a discussion will not affect the overall story, but gives a broader background to the potential age uncertainties and may also provide new aspects of sedimentation conditions in similar lakes (e.g. low sedimentation rates, definition of ages of lithological changes etc).

We thank you for your thoughtful comments.

- line 14: Hard water or reservoir effect?

We have removed “hard water effect” in line 14 to avoid confusion and limit the length of the abstract. We now use the more general term “reservoir effect” throughout most of the text. Later in the paper text, where we discuss ^{14}C results, we now speculate that this is in fact a hardwater effect from the presence of carbonate-rich carbonatite rocks in the area.

- line 20: m above sea level?

We have updated line 20 to have “m a.s.l.” rather than simply “m” following the elevations.

- line 49: "a southernmost" sounds odd to me... "the southernmost" or "one of the southernmost"?

We have changed “a southernmost GrIS outlet glacier” to “one of the southernmost GrIS outlet glaciers.”

- lines 55-59: I suggest to include a very brief statement (and reference) how glacier elevation and maximum advance might be linked (higher outlet glacier elevation is not necessarily linked to maximum extend)

Good point that maximum elevation and maximum frontal extent did not necessarily coincide in time. However, we would argue (and our results support), both would have been part of the same general period of advance.

To help clarify this, we have changed “This valley was partly ice-dammed by the expanded outlet glacier during the Narsarsuaq advance” to “Geomorphological and sedimentological evidence suggest this valley was ice-dammed by the expanded outlet glacier during the Narsarsuaq advance. Sediment records from the two threshold lakes, which sit at slightly different elevations, also allow us to precisely constrain the maximum elevation of the outlet glacier surface (ice dam) during the advance” (lines 56-59).

- line 82: the vegetation cover in the watershed

We have changed “The vegetation cover” to “The vegetation cover in the watershed in line 84.”

- line 84: Ma

We have changed all instances of lowercase “ma” to uppercase “Ma.”

- line 85: metasedimentary gneiss should not contain high amounts of carbon, so the input of old carbon to the lakes should be relatively low. If the bedrock is used to discuss potentially too old radiocarbon ages in the lake, I miss some more detailed information on bedrock composition (occurrence of graphite?) and/or a discussion, why other reservoir effects (glacial meltwater, redeposition of organic matter etc) are excluded. In fact, later in the manuscript (Table 2), the very good correlation of some of parallel datings (eg samples 176113/176117; 176112/176109; 176111/176108) argues against substantial input of old carbon (graphite?; $CaCO_3$ is highly unlikely or needs further explanation..) from bedrock, as this cannot be used by aquatic moss, as far as I know.

Thank you for pointing out that we needed to clarify this. We agree that a more detailed description of the bedrock of the region is needed. Because of this, we have changed “The bedrock of the

Mellemlandet ridge is largely granite and granodiorite (~1800 Ma; Julianehåb igneous complex; Steenfelt et al., 2016) with some metasedimentary gneiss that may contribute ancient carbon to LMEL and UMEL." to "The bedrock of the Mellemlandet ridge is largely granite and granodiorite with some metasedimentary gneiss (~1800 Ma; Julianehåb igneous complex; Steenfelt et al., 2016) along with syenite, gabbro, and carbonatite dykes (~1300-1,140 Ma; Gardar Province; Upton et al., 2003), the last of which may contribute ancient inorganic carbon to LMEL and UMEL."

We have considered many possible explanations for the old ages on bulk and aquatic materials, and we believe it is most likely that old carbon is entering the lake DIC pools from the carbonatites, creating a hardwater effect that makes ages on aquatic mosses and bulk materials (which are likely dominated by aquatic organics) too old. Old carbon in clastic material from these rocks may also make up a small portion of the bulk sediment. Both factors would cause aquatic moss and sediment radiocarbon ages to appear older than terrestrial plants, which we argue yield accurate ages for sediment deposition.

We also added the following reference which provides more detail on the carbonate-bearing rocks:

Upton, B., Emeleus, C.H., Heaman, L.M., Goodenough, K.M., Finch, A.A.: Magmatism of the mid-Proterozoic Gardar Province, South Greenland: chronology, petrogenesis and geological setting. Lithos 68, 43-65, 2003.

line 120: ...organic content based on sediment color.. which color? Brownish? Provide more detailed information.

We have added a statement that clarifies how we evaluate color as a rough proxy for organic content. Line 123: ", where gray indicates lower organic content and brown indicates higher organic content)."

lines 174-176: Sentence sounds odd to me, please check wording.

We have rewritten this sentence into two sentences to make it clearer. "Unit 1 (79-0 cm) is similar to Units 1a and 1c in the LMEL cores, as it is brown, organic, laminated, fine-grained sediment containing abundant aquatic moss remains, and has relatively low MS values and Ti concentrations" has been changed to "Unit 1 (79-0 cm) has similar characteristics to Units 1a and 1c in the LMEL cores. It is made up of brown, organic, laminated, fine-grained sediment containing abundant aquatic moss remains with relatively low MS and low Ti values." Lines 178-180.

lines 189 ff: The presentation of 14C results and the discussion is confusing. Not all ages seem to be presented in Fig 4, but this would help to better evaluate the reliability of the individual ages. Also the succession of plots in Fig 4 is confusing (starting with the late Holocene, jumping into early Holocene and ending with a period in between). Although I can somehow understand the reasoning for the Y-axis, it is somehow meaningless to plot ages vs the distance of dated horizons to glacial sediments above or below. Much more important than the distance is the period included, which may vary a lot between individual cores sites due to highly differing sedimentation rates. I suggest to change Figure 4 by focusing on LMEL (only one age from UMEL is shown, and the important information from UMEL U2 is already given in Fig. 3). To better constrain and discuss potential reservoir effects, I suggest to provide a core composite, with the top of LMUL U11 (undisturbed) and a shift into LMUL N2 at the boundary between Units 1a and 1b. Then, transfer age information of cores LMEL N2, LMEL U5 and LMEL U11 into the core composite using optical information, MS and Ti data and show one x/y plot with composed depth vs ages. This also highlightens the broad range of ages for Unit 1c (varying between 3870 and 12070 cal yr BP!), probably also indicating an extremely low sedimentation rate.

Figures 2 and 3 and Table 2 provide a view of all 14C results together. We believe the approach you suggest is very similar to what already exists in Figures 2 and 3 (ages with depth on core images next to MS/Ti data. Here, the offsets and sedimentation rate changes between units and cores can be compared easily, as can all radiocarbon ages.

Our goal with Figure 4 is to summarize the dates that best constrain timing of the cores' sedimentary transitions and to show the temporal offsets of the different types of samples. This is why not all the dates are presented. The best approach to accomplish these goals we found was to plot the depth away from the transition zone vs. age. This is why the ordering exists the way it does, by transition type (sorted from samples above glacial sediment young to old then samples below glacial sediment). We do recognize that samples from different cores with the same depth away from the transition would not necessarily correspond in time due to differing sedimentation rates; however, we make direct comparisons between adjacent ages only when evaluating radiocarbon sample type age offsets between paired samples taken from the same core. Additionally, we do not want to omit UMEL because it provides a critical date for local deglaciation timing near the transition.

- line 191 ff: see comment above, you need to explain, why you think that old carbon provided by metasedimentary gneiss could be incorporated in aquatic moss; carbon should not be delivered as free CO_2 in this scenario. It might be included as small particles in bulk sediments, but in such a scenario, 14C sample processing needs to be discussed in more detail, e.g., how much old carbon (graphite particles??) are provided?, does sample preparation for 14C analyses include these particles?, how was cleaning of aquatic moss, etc).

Thank you for prompting us to clarify. We have clarified in this section that we attribute the reservoir effect to a hardwater effect from carbonatite bedrock in the region (and likely glacial drift including that rock type). We also expanded this paragraph to evaluate other possible causes of old ages in aquatic mosses and bulk sediments. We considered that reservoir effects in this setting could conceivably come from glacier meltwater influx (which we rule out because our ages do not come from glacially influenced sedimentary units) or incomplete exchange with atmospheric CO_2 due to perennial ice cover (but we argue that these lakes are not affected by perennial ice cover and are wind mixed). We rule out sample cleanliness as a potential issue, as samples were cleaned in the same manner for terrestrial and aquatic plant remains (under the microscope with DI water, needles, and tweezers). Therefore, we would expect terrestrial samples to also be contaminated with old carbon containing sediments if sample cleanliness were indeed the cause.

Old paragraph (start of section 4.2): "Radiocarbon sampling focused on constraining the ages of the sedimentary unit transitions described above. Due to the infrequent occurrence of terrestrial plant macrofossils in the lake sediments, combined with the occurrence of potentially carbon-bearing metasedimentary bedrock and/or metasedimentary glacial drift in the lakes' watersheds, we dated multiple organic material types and aimed to assess reservoir effects on ^{14}C in aquatic moss and bulk organic materials. In all cases and across a range of time periods, terrestrial plant samples yielded younger apparent ages than aquatic moss or bulk sediment samples from the same depth (Fig. 4; Table 2). We argue that this reflects a reservoir effect, which is consistent with the regional presence of metasedimentary rocks and causes aquatic moss and bulk sediment samples to appear older than they should. Thus, ages on aquatic mosses and bulk sediments are treated here as loose maximum estimates of depositional age, whereas ages on terrestrial plants provide tighter constraints on depositional age."

New paragraphs (start of section 4.2): "Radiocarbon sampling focused on constraining the ages of the sedimentary unit transitions described above. Due to the infrequent occurrence of terrestrial plant macrofossils in the lake sediments, combined with the mapped occurrence of potentially carbon-bearing bedrock and/or glacial drift in the region, we dated multiple organic material types and aimed to assess reservoir effects on ^{14}C in aquatic moss and bulk organic materials. In all cases and across a range of time periods, terrestrial plant samples yielded younger apparent ages than aquatic moss or bulk sediment samples from the same depth (Fig. 4; Table 2), leading us to suspect a lacustrine reservoir effect. We argue that this more specifically reflects a hardwater effect resulting from the regional presence of ancient carbon-bearing rocks, including carbonate-rich carbonatite (Upton et al. 2003). Inputs of ancient dissolved inorganic carbon to the lake via ice sheet meltwater could also cause ^{14}C reservoir effects (Björck and Wohlfarth, 2001), as could long-term perennial ice cover, but both are unlikely here. Glacial meltwater inputs would only have affected radiocarbon samples taken from times when glacier meltwater flowed into LMEL or UMEL. This would be the times of Narsarsuaq Advance (for LMEL) and the earliest deglacial period (for both lakes), neither of which were sampled to determine radiocarbon ages. As for ice cover limiting atmospheric CO_2 exchange, modern LMEL and UMEL experience many ice-free months in summer and these small, relatively shallow lakes are well mixed then by the wind. Thus, we infer a reservoir effect attributable to the regional presence of carbonatites and other carbon-bearing rocks. Because of this, ages on aquatic mosses and bulk sediments are treated here as loose maximum estimates of depositional age, whereas ages on terrestrial plants provide tighter constraints on depositional age."

We also added the following reference to facilitate the discussion of potential causes for the reservoir effect:

Björck, S., Wohlfarth, B.: 14C Chronostratigraphic Techniques in Paleolimnology in: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Change Using Lake Sediments. Volume 1: Basin Analysis, Coring, and Chronological Techniques. Kluwer Academic Publishers, Dordrecht, 205-245, 2001.

- line 244: differences in unit thicknesses are due to differences in sedimentation rates at the individual locations (sedimentation rates in Unit 1b seem to be primarily controlled by water depth, ie increasing water depth provides increasing sedimentation rate, in accordance with the suspension load in the water column).

We have changed this sentence from “Differences in unit thickness between the three LMEL cores are attributable to different sampling water depths and locations in the basin” to “Differences in unit thickness between the three LMEL cores are attributable to different sedimentation rates at the core site locations, which have different water depths.” Lines 261-262.

- line 257 ff: I fully agree that terrestrial macrofossils in general provide most reliable 14C ages. I also agree with the entire discussion of the deglaciation, but it would be nice to include other potential reservoir effects in the discussion (insufficient cleaning of aquatic moss, reservoir effects caused by glacial meltwater supply, ice cover etc).

We agree. Please see our updated discussion in section 4.2 where we address these concerns. In the paper text, we now address the possibility of reservoir effects from glacier meltwater influx or long-term ice cover. We do not discuss the contamination issue, because we argue it would equally affect terrestrial plant macrofossils, which were cleaned and inspected using the same procedures as our aquatic macrofossils.

- line 266: Can you fully exclude that the discrepancy is due to different elevations? If the lithological change in the studied lakes is caused by a retreating or lowering Kiattuut Sermiat, are the 10Be dated boulders and erratics not released somewhat later from the retreating (and lowering) glacier (depends on the location and/or if they are released from local ice caps)?

We cannot fully exclude that some of the discrepancy could be due to elevation differences. ^{10}Be ages on deglaciation in this region show little trend with elevation but are mostly from the outer to mid-fjord region (e.g., Carlson et al. 2021 QSR) so are not directly analogous to our high-elevation inland site. We are nearly certain that the radiocarbon ages that provide closest constraints on deglaciation timing are too old, as they are ages on bulk sediments and aquatic mosses, and other results from our study point to reservoir effects in these materials.

In response to your point, we have changed “Given that the demonstrated lake water ^{14}C reservoir effect at our sites can explain the discrepancy in local deglaciation timing, we argue the discrepancy is not due to small differences in elevation between the nearby ^{10}Be sampling sites (~560 m a.s.l.), other lake site (~600 m a.s.l.) and our lake sites (~670 m a.s.l.)” to “We strongly suspect that the demonstrated lake water ^{14}C reservoir effect at our sites explains the discrepancy in local deglaciation timing, but some of the offset may be due to small differences in elevation between the nearby ^{10}Be sampling sites (~560 m a.s.l.), other lake site (~600 m a.s.l.) and our lake sites (~670 m a.s.l.).” Lines 282-284.

- line 375: In summary, data indicate...?

We have changed “In summary, evidence indicates…” to “In summary, data indicate…” Line 392.

- line 384: .. which represents a lowering of the Kiattuut... (a lowering might be related to a retreat in length, but not necessarily).

We agree and have updated the text accordingly.

We have changed "One mixed terrestrial and aquatic plant radiocarbon sample 2.5 cm above the transition indicates that this retreat from the watershed occurred…" to "One mixed terrestrial and aquatic plant radiocarbon sample 2.5 cm above the transition indicates that the Kiattuut Sermiat surface elevation decrease occurred…" Lines 400-401.

- line 386: if we assume that the terrestrial plant remain ages are correct, there is a difference of ca 250 years between sample 176767 from 29.25 cm and sample 176114 from 31.5 cm depth in core N2. This difference suggests a rough estimation of the sedimentation rate of ca 100 years per centimeter. Such a low sedimentation rate would also roughly correspond to Unit 1c in the same core, where apparently ca. 2500 years are recorded in 15 cm or so. If there are 2.5 cm of organic sediments below the dated horizon of 1580 cal yr BP, extrapolating this sedimentation rate downcore in Unit 1a would provide an age of close to 2000 cal yr BP for the Late Holocene deglaciation. Please discuss this in more detail. It does not affect the entire story, but should be noted more clearly.

The samples you list there are from 19-LMEL-U11. We do not take this approach because radiocarbon sample 176114 at 31.5 cm depth in 19-LMEL-U11 contained both terrestrial plant and aquatic moss to reach enough mass for a radiocarbon measurement. This means we suspect that sample incorporates old carbon, making an extrapolation of the sedimentation rate inaccurate. We describe this further in the first paragraph of Section 5.4.

Fig 1: Please simplify the elevations scale (use m a.s.l., not m.a.s.l., corresponding with the text). Use (A) etc instead of A. according to fig caption (also for other figures). Provide source of DEM as reference (and include in Refs).

We have changed all instances of "A." etc. to "(A)" etc. in each figure.

We have rounded the elevation tick marks to the nearest 5 and changed "m.a.s.l." to "m a.s.l." in the legend of Figure 1.

We have also added the reference for the DEM that was provided in section 3.3 of the manuscript (Porter et al., 2018) to lines 67 (Section 2) and 75 (Figure 1 caption).

Fig 2: Figure caption: Mention (A), (B) and (C). It would be useful to include the water depth after the individual core names. Check and correct color of "1580" in Fig 2B.

We have referred to panels A, B, and C in Figure 2 and panels A and B in Figure 3. Line 159: Added “(A) Core 19-LMEL-N2. (B) Core 19-LMEL-U11. (C) Core 19-LMEL-U5.” Line 183/184: Added “(A) Core 19-UMEL-U2. (B) Core 19-UMEL-U1.”

We have added water depth in meters after the header core names and added the following statement in the Figure 2 and 3 captions: “Water depth is listed after the core name” (Lines 159/160 and 184).

The color of “1580” in Figure 2B is correct (half black and half blue), as it was a sample that had a mix of terrestrial plants and aquatic moss.

Fig 3: delete repetition in figure caption (Numbers and arrows....)

We thank you for spotting this and have removed the line “Numbers and arrows to the right of the depth axis indicate calibrated ages” from the caption of Figure 3. Lines 185-186.