# Response to reviews: "Reorganisation of subglacial drainage processes during rapid melting of the Fennoscandian Ice Sheet"

## Reviewer 1

We thank reviewer 1 for their encouraging and helpful comments. Below we detail our response to each and in turn the changes we have made to our manuscript. We believe that these changes have improved the manuscript.

### General comments

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**Comment 1.1:** I found the title a bit misleading about the topic of the paper. I think the manuscript speaks to the past location of hydraulic conditions below the glacier, but I found little in the manuscript about "reorganisation of subgalacial drainage processes". Maybe "organisation of subglacial processes." Additionally, "rapid melting" does not seem like a big part of the paper, especially by reading the abstract.

**Reply**: Both reviewers queried the appropriateness of the title, we have modified the title to now be:

"The organisation of subglacial drainage during the demise of the Finnish Lake District Ice-Lobe".

We hope this better reflects the contents of the paper.

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**Comment 1.2:** Throughout, but especially in the abstract and introduction, the authors make statements of "parame- terizing and testing models of subglacial hydrology", "basal hydrology in models", or "basal hydraulic conditions." These conditions or parameterizations can cover a wide range of features describing sub- glacial processes, include channel size or shape, water pressure, sediment transport, water velocity, distributed or channelized drainage. I believe the authors must be more specific and deliberate in describing the specific subglacial hydraulic features they aim to examine and link these features to murtoo development and persistence.

**Reply**: We have altered the abstract and introduction as suggested to be more explicit about our approach and aims. . Particularly with regard to our aims. The aims now state:

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- Compare the subglacial hydrological conditions proposed for murtoo genesis and their associated land-forms against model outputs from GlaDS.
- Sensitivity test GlaDS across a range of possible parameter values to explore the influence of these parameters on our outcomes in order to evaluate the potential of such models to be used to interrogate palaeo-hydrological systems more broadly and in turn motivate future work in this area.

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**Comment 1.3:** Related to the last point, it seems that the description of murtoo formation could be improved. At times, it seems that hydraulic processes associated with different stages of murtoo development are in contradiction. An examples are given below.

**Reply**: We have addressed this by responding to the specific comments below.

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**Comment 1.4:** Section 3.1.1: From my reading of this section, it seems that no diurnal forcings were used. While this makes sense in a paleo setting, I am concerned about the impact on results. For instance on the GrIS, hydraulic head can very over 150m and bed separation can be in excess of 25cm (Andrews et al., 2014). It seems like such short temporal changes in subglacial hydrology could impact the formation of murtoos and move from one murtoo sequence to another over a very short time period (stages mentioned in Introduction, Hovikoski et al., 2023). I realize that application of such variable water discharges to hydraulic models can be difficult and in many scenarios not necessary. However, it seems like it could be important in this application.

**Reply**: Yes, we did not include any diurnal forcing. In reality, diurnal forcing may well be extremely important in murtoo formation right at the very onset of channelisation and is absolutely a target for future work on this subject. We have added it to our limiations. However, for the work presented here which aims primarily to describe the catchment scale processes in hydrological development, we note that in Werder et al., 2013, their diurnal experiment results in channels that largely follow the same spatial expression as in other runs. They do experience large fluctuations in discharge and pressure throughout the 24H cycle, however, at distances greater than 2 km from channels (and moulins), pressure fluctuations are minimised by the englacial storage term, which reduces the spatial influence of changing meltwater inputs at short timescales. Within the murtoo forming zone then, we expect that the pattern of pressure across the full-width of the domain (especially when averaged seasonally) would likely be comparable to our forcing runs without diurnal fluctuations, with changes in the pattern restricted near to channel heads and specific moulin inputs.

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**Comment 1.5:** To the best of my knowledge GlaDS uses a semicircular channel geometry that is fixed (i.e. shape of the channel does not evolve). However, it seems that a key feature of murtoo development is low broad channels, potentially with changing channel shape. This seems to be discussed in Hovikoski et al., 2023 and in the manuscript at lines 511 to 523. Hooke et al., 1990 speaks to the effects of channel shape on subglacial hydraulics. I am aware that certain trade offs can be made between the friction factor and channel shape to end up with similar hydraulic characteristics. In some applications this may minimize the impact of the semicircular assumption. However, because sediment transport relationships are scaled to unit width of the channel, sediment deposition can be sensitive to the width of the channel floor, and thus the general shape of the channel. However, please comment on how this may impact the results. Is this such a consideration with the development of the drainage system? What are the impacts of the semi-circular and potentially fixed channel shape on the formation of murtoos?

**Reply**: GlaDS does indeed model channels as semi-circles, and we have added a line to this effect in the methods (Line 245) which reads:

"channelised flow—describing uniform, semi-circular Röthlisberger channels (R-channels) that are allowed to change diameter—along element edges".

Because GlaDS does not include any explicit treatment of sediment dynamics we are not truly modelling murtoo formation. Instead, we are attempting to reproduce the conditions associated with murtoo formation, particularly water pressure throughout the melt season. It is therefore difficult to evaluate what effects changing the channel geometry may have on murtoo formation. Further, without a detailed understanding of exactly how channel geometry varies in both space and time it is difficult to imagine how we might robustly explore this. Nonetheless, we have also more explicitly raised this as a limitation of our work. This can be found in Section 5.4.

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**Comment 1.6:** More out of curiosity, how do the murtoo fields persist given the retreat of the glacier and the presumptive movement of the channelized drainage area up the glacier? Might retreat have occurred too rapidly to "destroy" the murtoos?

**Reply**: That is an interesting question, and one subject to ongoing investigation, but it is beyond the scope of this manuscript.

## Specific comments

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**Comment 1.7:** Ln 46: to the best of my knowledge Werder et al. (2013) examines hard bedded characteristics below glaciers, "subsurface material" needs clarifying. Would an alternative be sediment floored channels or canals.

**Reply**: We have replaced this reference with one more appropriate, specifically Chu, V.W., 2014. Greenland ice sheet hydrology: A review. *Progress in Physical Geography*, 38(1), pp.19-54.

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**Comment 1.8:** Ln 59-71: the modeling work of F. Beaud is likely relevant here, as is the manuscript Hewitt and Creyts (2018) about eskers. Consider adding.

**Reply**: We have added the references to both in an expanded portion detailing previous modelling work in the palaeo setting, as well as work by Boulton et al. This can be found on Lines 88–100.

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**Comment 1.9:** Ln 87: what does "more dynamic" mean also, I can imagine what "interlobate joints" are, but please clarify.

**Reply**: We have changed this sentence to clarify that 'more dynamic' means faster, and removed the reference to interlobate joints in response to a comment by Reviewer 2, the sentence now (Line 163) reads:

"...which are in turn concentrated in faster flowing, *warm-based* sectors of the FIS including the FLDIL..."

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**Comment 1.10:** Enumerated 1-4 in Intro: I found this useful, and closely linked to Figure 10 in Hovikoski et al. 2023. Would the authors consider applying the cartoon in this manuscript? Additionally, it was difficult for me extract in the enumerated section the model output that would be indicative of this process in murtoo development. Please clarify. Might a table with one column of subglacial hydrology model output help?

**Reply**: Thank you for this suggestion. We have added a table (Table 1) linking the murtoo developmental stages to expected model outputs, and added callbacks to this table in our results and discussion. We have referenced the Hoviloski et al., paper more explicitly, but have not included their specific figure so as to avoid any copyright reproduction issues.

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**Comment 1.11:** About points 1-2, I am a little curious about the idea that there is sediment deposition at the onset of melt. It seems that the conduit could be small, thus increasing water follow could increase sediment transport capacity, rather than cause sediment deposition. Although available observations of sediment transport are from the terminus, there can often be an increase in sediment transport at this time of the season.

**Reply**: We envisage that the subglacial water flow is in pulses against an overall backdrop of increasing discharge through the melt season. When flow fluctuates parts of broadening/low conduits become rapidly clogged by sediment-rich flows in shallow flow space and sediments are periodically slightly deformed by ice. During conduit widening, the marginal channels of murtoos seem to have the highest transport capacity. We have clarified our stages 1–2 to reflect this. Stages 1–2 are now:

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1. With the onset of spring melt, pulses of water deposit the murtoo body within an increasingly large conduit. As each pulse increases in discharge and then wanes they promote the deposition of sand lenses, sinusoidally stratified sand, and poorly-sorted gravel, with silt commonly draping ripple-scale features. In this phase of formation, cobbles are the largest clast size, which places an upper limit on water depth of $\sim 25\,\mathrm{cm}$ (Hovikoski et al., 2023).

2. As the melt season continues through summer, an increasingly enlarged pond forms in response to higher discharge. In turn, the increasing grain size indicates higher water velocity and sediments on the upper slope appear consistent with high velocity, upper-flow-regime deposits and the boulder size-distribution suggest a maximum flow space of 1 m (Hovikoski et al., 2023).

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**Comment 1.12:** Ln 120: "higher water velocity" and "development of an englacial pond." To me these processes should not happen at the same place and time. Also, please define "upper-flow-regime."

**Reply**: Our original phrasing was a little muddled, though we note our original manuscript contained "development of an *enlarged* pond..." and not an "englacial pond". The expectation is that the pond already exists before higher velocity flows reach and form upper-flow regime structures. We have corrected the text to reflect this:

"3. As the melt season continues through summer, an increasingly enlarged pond forms in response to higher discharge. In turn, the increasing grain size indicates higher water velocity and sediments on the upper slope appear consistent with high velocity, upper-flow-regime deposits and the boulder size-distribution suggest a maximum flow space of 1 m"

Regarding the definition of sedimentological terms, in this section we briefly describe the sedimentological architecture of murtoos as background, referencing several papers with this as their main focus. Accordingly, we have not defined upper- (or lower-) flow regimes, both of which are relatively common concepts in sedimentology but whose specific meaning is adjacent to the main focus of our study. However, we have adjusted the section such that the deposits we reference are more specifically linked to the regime in which they form so that the line (189–192) now reads:

"proximally is comprised of alternating sequences of glaciofluvial deposits, with current ripples (formed in low discharge, lower flow regimes) giving way to transitional cross-bedding (transitional flow regimes), and antidunal sinsuoidal lamination (formed in higher discharge, upper flow regimes;..."

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**Comment 1.13:** Figure 1: Could estimated glacier flow lines be added?

**Reply**: Yes, we have added arrows indicating the approximate ice flow direction to each panel in Figure 1 and updated the caption accordingly.

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**Comment 1.14:** Ln 195: "modified digital elevation model"... can the section where this is described be referenced?

**Reply**: We have added the section reference so that the line (Line 235) now reads:

"Then, using GlaDS parameterised by this input ice geometry and a modified digital elevation model (DEM) of the region (see Section 3.1.1)"

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**Comment 1.15:** Table 1: I am curious if "mean annual velocity" is really an "input" or a model result or output, given the coupling with ISSM.

**Reply**: In this work, we are not using GlaDS coupled to ice dynamics. Instead, ice velocity (and other ISSM parameters, such as the ice rheological properties) are effectively model inputs. We have clarified this in response to one of Reviewer 2's comments (Comment 2.52:). The line to this effect (Line 270–271) now reads:

"Finally, in the iteration used here, GlaDS is not coupled two-ways to a model of ice dynamics, and instead we prescribe an ice velocity and geometry that is not variable in response to hydrological forcing"

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**Comment 1.16:** "Fixed cross section" or "to the bed at every node." Does this go well here? or is somehow part of experimental design?

**Reply**: We have left these in place, as we are describing the GlaDS model design and believe this to be the most relevant section for this.

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**Comment 1.17:** Ln 361: "At node 3,842": maybe make clear that these nodes are representative of their surrounding.

**Reply**: We have added a clarification to this effect. The sentence now reads:

"At node 3,842, chosen to be representative of surrounding nodes,..."

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**Comment 1.18:** Figure 3c: should "D" be written as distance? also it seems like this is the end of the melt season of one year. Would it make sense for an "average" to be represented? Also would it make sense to add A-E in the plot in C as to clarify which plots go with which points?

**Reply**: We have changed the inset plot in what is now Figure 4C to read 'Distance from the ice margin (km)'. We have also added A–E labels into the plot as was also suggested by reviewer 2. We chose to illustrate the end of the melt season to give an idea of what channels looked like spatially at the end of the melt season and to give context to the time-series plots from four points. We also note that the summer average model condition is shown in what is now Figure 3.

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**Comment 1.19:** Ln 505–506: why $10^0$ in one line and 1 in the next?

**Reply**: Thank you for noting this, we have changed the former to keep consistency.

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**Comment 1.20:** Ln 515: "limited cavity expansion" might this be channel floor width?

**Reply**: We have changed the line (now 584–586) to now read: "however the agreement in dimension suggests that the limited cavity expansion or restricted channel floor width within which murtoo form is captured within our model"

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**Comment 1.21:** Ln 520: "The reason... sediment supply..." My initial reaction upon reading this is that I normally do not consider a distributed drainage system able to transport large amounts of sediment, thus I am unsure about how sediment supply up glacier could impact the results here.

**Reply**: Murtoos occupy a semi-distributed environment where movement of subglacial sediment is an important factor as indicated by the sedimentological studies of murtoos. We have expanded on this idea within our rewritten discussion, which can be found on Line 690–696:

"Murtoos appear to form within a semi-distributed drainage environment, and sedimentological studies indicate the movement of sediment is important in murtoo formation (Peterson Becher and Johnson, 2021; Mäkinen et al., 2023; Hovikoski et al., 2023). The reason that murtoos are not present in an area of the FLDIL where our modelling suggests they should form may be a preservation issue or due to limited sediment supply. Sediment cover in this area is very thin, and the large areas of exposed bedrock likely limited the supply of sediment from which murtoos could form (Figure A1B), an interaction not yet accounted for in our modelling. Modern lakes are also abundant in the centre of the FLDIL and may also act to mask murtoo routes."

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**Comment 1.22:** Ln 524: "More broadly" good pun after speaking of broad channels... "More generally"

**Reply**: The pun was unintended and we have changed the text as suggested.

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**Comment 1.23:** Ln 544-549: I might be missing something. However, melt water input location also seems like a control. For instance, Gagliardini and Werder 2018 may speak to this.

**Reply**: We have added this reference and a pointer to lower crevasse density at higher elevation also inhibiting meltwater input. The line (570) now reads:

"shallow surface gradients engender low hydraulic potential gradients, while low crevasse density limits meltwater input to the bed (Gagliardini and Werder 2018)"

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**Comment 1.24:** Ln 558-567: From reading this paragraph, the authors seem to point out the differences between GrIS and the runs here. However, I seem to miss the analysis of the causes of this difference between the two systems.

**Reply**: We expect that the difference arises because of the low-relief of our domain. We have added a sentence to this effect on Line 621–623 which reads:

"The FLDIL is relatively low-relief compared to the steep margins of Greenland (e.g., Wright et al., 2016), and the shallow topography may act to reduce the hydraulic gradient between distributed and channelised drainage."

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**Comment 1.25:** Ln 593: "sub-lobes they bound" something funny grammatically, also I am not sure what is meant.

**Reply**: We have modified the sentence (now on Line 720) to read:

" As a result, landforms within the FLDIL have previously been divided into three sub-lobes. The boundaries between these three sub-lobes are demarcated by particularly large esker deposits suggesting a concentration..."

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**Comment 1.26:** Ln 606: "1-2 day. . . walltime?"

**Reply**: Yes, thank you for noting this. We have clarified to this effect which now reads: "could run to completion *with a walltime* of 1–2 days while"

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**Comment 1.27:** Ln 613: $\sim$0.75°C how much more water does this result in?

**Reply**: Raising the model MAAT by a uniform $\sim$0.75°C changes the mean moulin discharge (at every non-zero moulin through the full model run) by $\sim$10% from 2.544 to 2.774 $m^3s^{-1}$ (an upper limit based on running our PDD scheme 5 times). However, this represents an upper limit because uplift and tilting was non-uniform in our domain and the actual change in domain-wide MAAT is likely to be lower. We have not reported this in the manuscript, but we have changed the wording to make clear that the $\sim$0.75°C is confined to the areas of highest uplift. These changes can be found in both the methods (Line 280–285) and the limitations (Line 730–734) sections.

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**Comment 1.28:** Ln 627: "macro conditions" what are these precise conditions?

**Reply**: In response to several comments from Reviewer 2 we have significantly changed our Conclusions section, in doing so removing this term and defining the conditions to which we are referring.

**Comment 1.29:** Figure A2. what is a median discharge? Also, it seems like units are missing.

**Reply**: Thank you for noting this, we have rectified both the missing units and clarified what is meant by median discharge.