

## **Review: The organisation of subglacial drainage during the demise of the Finnish Lake District Ice Lobe – Hepburn et al.**

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### **General comments**

I think this is a much improved manuscript from the version I saw last (first version). The logic of the paper is much better presented, clear to follow, and much of the heavy language and confusing constructions have been addressed and resolved. I think the work is a good illustration of how the geomorphological record of former glaciation can be used to test ice sheet/hydrology models and give confidence in their wider utility, as well as shed light on patterns observed in the landform record.

I see that you've given some attention to refining how you formulate your overall aim, and I think that it now works ("explore the ability of GLaDS, a process-based subglacial hydrology model, to explain murtoo formation in both space and time"). I read this, and your manuscript, as testing whether GLaDS can generate the right conditions in the right place for murtoo formation, and then learn something about how these conditions compare to other meltwater landforming settings. I think you could be a bit clearer about what your comparisons can provide, and what they can't. The comparison of distributions is somewhat circular because of the widespread and time-integrated distribution of murtoos in Finland: murtoos are hypothesised to form under high pressure in an area near the onset of channelisation, and the model produces a high overburden zone upstream of channelisation. We could conclude the model is good. Yet, if the conceptual model is wrong and they can form under different settings, then we could look to a different zone in the model output, still find murtoos, and therefore also conclude that the model is good. We can't confirm the hypothesis. In this context, the comparison of model seasonal behaviour against sedimentology is really important, because there are multiple predictions in a sequence that the model must achieve. A good match for sedimentology makes this a genuine test of the physical and conceptual models, and I think some words to this effect in section 5.2 and/or in the conclusions would strengthen the paper.

I think Section 5.3 needs a bit more work – there are passages I still find confusing, and passages where I think important findings are lost that should be brought forward more clearly. Some of these findings draw from section 5.2 also. In particular, I'm concerned that a key argument that is made, that there is a significant biannual difference between murtoo routes and meltwater routes, mixes two sets of findings and hasn't been explicitly demonstrated itself. I expand on this further below with some suggestions for how to improve the clarity of the arguments made in these sections. I think an additional figure that illustrates the spatial distribution of contrasting modelled drainage behaviours would really help the narrative (also explained further below).

### **Specific and technical comments, by line**

14-17: "Our model outputs match many of the predictions" would be a stronger (and appropriate) statement than the rather vague "represent". I think you can say more here about what you've actually found and discussed, and importantly, include that the model matches what we would expect from murtoo sedimentology (as above). For example: "Our model outputs match the general distribution of channelised drainage landforms such as esker and meltwater routes. Many of the predictions for murtoo formation are produced by the model, including the location... and,

importantly, the seasonal sequence of drainage conditions inferred from murtoo sedimentology. These conclusions are largely robust to a range of parameter decisions, and we explore seasonal and inter-annual drainage behaviour associated with murtoo zones and meltwater pathways.”

32: “analyses... have been applied”

39-40: to better fit the development of ideas in this paragraph, I would move the phrase beginning “potentially including” to line 45, which would then flow “...ideal targets against which to evaluate subglacial hydrology models, potentially including processes variable at sub-annual scales and across the distributed-channelised transition”. (Note, wherever it is place, suggest replace “those” with “processes”, for clarity.)

46: landform genesis uncertainty arises from both fundamentally different concepts of how a landform is formed, and also spatial and temporal scales of formation.

59: odd punctuation: write out “length and spacing scaling relationships”

65-67: suggest deleting “modern” from “modern subglacial hydrology models” – unless there is a particular reason for this word, to compare with others?

73: I suggest changing the wording to “and likely represent time-transgressive formation over decades-millennia” – the current wording suggests that there is esker building taking place along the full length of a >10km esker over millennia, which I don’t think is what is meant.

74: typo – glaciofluvial

84: published as Peterson et al. 2017

91: “closer than 40-60km to the...”

93-116: in this paragraph, could you add references to the numbered developmental stages in Table 1, at the relevant point in the text? You begin this way (line 97: represents the first stage...), but it would be helpful throughout. E.g. change text in parentheses on line 99 to “developmental stage 2: Table 1”, and thereafter at the relevant point just (Stage 3), (Stage 4)...

107: does “disappearance” mean erosion or non-deposition?

111-113: there are 3 phrases here beginning “final” or “finally” – suggest rephrasing so that only one event is “final”.

132: “however” in this construction is not being used as a parenthetical aside. Suggest change to “...in the centre of the ice lobe where thin sediment cover may have limited...”

158-162: I’m not sure these sentences accurately describe what you present in the results and discussion. In my view, you: examine catchment-scale hydrology parameters and compare to murtoo formation predictions and distribution of channelised landforms (eskers); you specifically explore seasonal and inter-annual drainage parameters in the zone where murtoos are hypothesised to form; you investigate differences in modelled hydrology between observed murtoo and meltwater routes, and where no glaciofluvial landforms exist; and you test the sensitivity of your results to a range of parameters.

173: suggest delete “uniform” – it seems to contradict being allowed to change diameter

221: spell out MAT (mean annual or monthly air temp?)

242-3: “Monthly melt was kept fixed annually” – sounds a bit confusing, do you mean that it was kept fixed year on year, i.e. no inter-annual variability, each month’s temp was the same each year?

245: again, “total monthly melt was converted to yearly melt rates” – this is also confusing, I’m not sure here what you’ve done or why

260-1: while the variables subject to sensitivity testing are clearly listed in the Appendix Table 1, and nicely explained through the following paragraphs, I would have found it helpful to have a clear summary list of those variables in the text. Consider adding a summary sentence here, or modifying line 206-1, along the lines of “Sensitivity testing was performed on: basal melt rate, moulin density and distribution, conductivity of sheet and channelised water, englacial storage, basal ice velocity, land or water-terminating ice, basal bump height, bed topography surface, and mesh geometry.”

306: delete “between”

324-5: “and each peaks... and remains...” Here, I also wonder why the peak in sheet discharge and water velocity occurs *adjacent* to a channel?

325-326: typo –  $V_w$  not  $W_v$  (three instances)

326: delete one “to”

327: you do have constraints (= landforms) on your model output, so I suggest amending to “Without independent constraint against which to compare our model output”

330: for more emphasis, I would suggest deleting “and”, and breaking the sentence. Catchment hydrology “remains consistent across most of the sensitivity tests. Furthermore, sensitivity test results remain consistent with predictions for moraine genesis.”

331-3: I would delete the additional descriptors for each parameter (e.g. variable, modified, differences in...). It’s redundant in the context of sensitivity testing, and risks confusing between an experiment in which a parameter varies spatially/temporally, vs one that has a uniform distribution of the parameter but it differs from the baseline experiment.

334: I got a little confused here and the next paragraph, since you’ve just stated that almost all parameters showed relative insensitivity but then go on to discuss how several parameters affect channel location. It would help to start a new paragraph on line 334, and open with a clear statement differentiating catchment-scale results with channel-scale results. E.g. “While catchment-scale trends are robust, the exact location of channels, and their length and local overburden%, vary between sensitivity tests.”

336: “differences in channel location”

341: again to help the narrative, suggest open with “Besides channel location, channel length and overburden% vary considerably”. And I would also be specific here about which sensitivity tests, not just “six of”. E.g. “...vary considerably in our testing of sensitivity to conductivity”.

347: again to help the narrative, suggest open with “For the other end member”

347: does the “and” in this line mean that both conditions are met (minimum sheet  $k$  at the same time as maximum channel  $k$ ), or that this result arises when either one of those conditions is met? I’m guessing the latter since each has a separate figure reference. I wonder if there’s a way to clarify this. (Same for line 351.)

357-60: I think a clearer way to argue this is that excessively long or short channels are considered 'invalid', on the basis of modern Greenland observations, and that an anomalous overburden% distribution is considered invalid on the basis of the conceptual model for murtoo distribution, and therefore the baseline terms are considered most plausible.

366: "the pressure conditions... are notably different"

367: suggest breaking the sentence to make it clear which channels (modelled or observed) you refer to in the final clause. "In Greenland, channels exist at lower pressure..., and the resultant hydraulic potential gradient..."

376: typo – FLDIL

## Section 5.2

From your description of sites D&E, I struggle to see the difference in landform/hydrological context. You start with E, and describe it as being representative of channel onset nearby, and conclude that the model drainage behaviour is consistent with murtoo development phases (although murtoos themselves aren't evident here). Then you describe D as being located at the head of two channels, and near murtoos, and interpret that 1 of the 2 modes of drainage here is consistent with murtoo formation. I see that the drainage behaviour differs at sites D&E, but both can allow for murtoo formation and both have some relationship with channel onset, so I think this part of section 5.2 (e.g. lines ~389-406) would be better packaged if you instead: introduce D&E as both being in the zone hypothesised to favour murtoo formation, and that both display drainage behaviour that could accommodate murtoo formation, but they show different interannual behaviour; and note also that one node is close to an observed murtoo while the other is not.

I think this would better frame the later discussion of absence of murtoos where they're predicted, and the discussion of the biannual behaviour and its relationship to landform distribution.

Here and below: a figure, perhaps plotted in map view, of nodes that display biannual behaviour vs annual behaviour would really help this discussion and that in section 5.3.

392: wording is a bit awkward – I suggest "representative of nodes surrounding the onset of a channel" ?

402-5: there's a few awkward phrases here. Consider: "before quickly dropping to an overburden% that is elevated relative to the previous winter." "Years with an elevated overburden% are associated with lower  $Q_c$ ...". Put commas round "approaching  $1 \text{ m}^3 \text{ s}^{-1}$ ". Replace odd-numbered years with "We consider that the latter case is more consistent with..."

410: double "maximum"

411: "the channel remains active over winter".

418-9: suggest you add to the end of the sentence "that have been invoked to explain murtoo sedimentology".

422: since GLaDS is pervasively connected and therefore can't produce the rapid changes in flow that you describe, is this limitation more widely a problem for other modelling questions? Of course the model is a necessary compromise on certain aspects in order to be manageable, but does your work flag that this is actually important to implement more fully?

### Section 5.3

Is the heading appropriate? I think something like “Comparing murtoo and meltwater route hydrology” is a closer description of what this Section considers.

Paragraph 1 is overcomplicated, and I think it is mis-framed as an evaluation of GLaDS ability to represent meltwater pathways – you do something more specific than that and it raises an interesting discussion about different types of behaviour. It could be much more succinct and clear if you frame the opening to this Section as: You further explore drainage behaviour in the zone hypothesised to be relevant for murtoo formation. You group all the nodes in this zone according to whether they are located among murtoos, meltwater routes, or neither. Murtoos and meltwater route distribution are based on Ahokangas et al, and you include eskers with meltwater routes, though you acknowledge there is no age control to say if they all form simultaneously (and in the relevant time-slice).

Line 448: “winter minima”

449: “do not intersect mapped glaciofluvial geomorphology”

450: “... are lower...”

P3 could be more impactful, and it’s missing a clear discussion of all elements in Fig 6 – in the second half of the paragraph, you overlook Fig 6 and only talk about what’s in the Appendix. I suggest, for all parameters, first comment on what is shown in Fig 6, then comment on what differences are apparent during specific months.

I also think there’s some interesting behaviour in Fig 6 that you haven’t commented on (but here would be the place for it), and I wonder if it would contribute to your discussion of biannual behaviour and/or differences in drainage mode within the same ‘murtoo-favouring zone’. For all parameters, the murtoo data has a bimodal distribution, while the channels either have a single peak or are also bimodal – is this something you can comment on?

P4-P6 – I still find it hard to work through the arguments relating to the biannual drainage signal. It’s an interesting behaviour, but I’m still not really sure what you are saying about it in relation to either space or landforms (or whether it’s a model artefact that wouldn’t be present in reality). I think there’s a missing link in your arguments that relates to the statements on lines 472-3 and 481-2: that there is a spatial component to the biannual signal in murtoo route outputs, and a significant biannual difference between murtoo routes and meltwater routes.

I don’t believe you’ve demonstrated a significant biannual difference between murtoo routes and meltwater routes. Section 5.2/Fig 3 show that two nodes in the hypothesised murtoo forming zone have different signals – one annual, and one biannual. You’ve concluded that both behaviours are suited to murtoo formation (albeit only one of the two modes in the biannual case). Section 5.3/Fig 6 show that murtoo and melt routes differ in behaviour within a season/year, but you don’t demonstrate here that one or the other is characterised by a biannual signal. Therefore, your statements on lines 472-3 and 481-2 combine these two results, without demonstrating that the biannual signal is landform-specific.

I think paragraphs 4-6 (i.e. remainder of Section 5.3, from line 467), ought to be revised to sharpen the discussion about the biannual signal, its spatial distribution, and how it might relate to a specific landform type. As above, I think that a figure that demonstrates the “spatial component to the biannual signal” would really help – whether or not this spatial biannual pattern also has a connection to a specific landform type. This could be a map – nodes with an annual/biannual signal.

And/or an equivalent to Fig 6, but plotted for the two lateral or central parts of the lobe instead of by landform type?

Some further specific writing amendments...

In P4, there are far too many ideas all stuffed into one paragraph:

- I would move the opening to conclude P2 and open P3: murtoo & meltwater routes are both very different to where there are no landforms, and in this way GLaDS faithfully represents FLDIL drainage patterns. // This is further evident when plotted as a PDF. Here, however, you also see subtle differences between murtoos and meltwater routes.
- Start P4 by posing the problem that murtoos are absent where the model (both conceptual and physical) suggests they ought to form. Offer your geological/data reasons for this. Then...
- Alternatively, murtoo distribution could be related to biannual channel discharge behaviour (reported in section 5.2, Fig 3). Biannual signal is interpreted as due to channels persisting through winter; they likely influence the nearby system the following summer, when the initial melt input would be discharged by an already established efficient pathway. There is also a spatial component to the biannual signal in our model output. When channels in the central third of the FLDIL persist over winter, those in the outer two thirds do not – and vice versa. Murtoo distribution – absent in the central third – could be a reflection of this spatial control on winter channel operation.

This sets up the whole of the final part of your discussion in the context of murtoo formation (presence/absence), and there is a clear purpose to the biannual discussion, rather than discussing a quirk that seems to have emerged from your modelling whose connection to your research question isn't really apparent.

P5 – I also think this is unnecessarily wordy and buries the point of the argument. Consider re-ordering (and trimming) the ideas:

The appearance of winter channels isn't surprising: they are evident on Greenland. Yours operate at very low discharges (below an arbitrary threshold for classifying a "channel") but nonetheless exhibit this behaviour. However, the spatial pattern of winter persistence is unexpected. There is spatial variability in your climate forcing, which translates into spatial variability in meltwater input, though your input has no interannual variability that would explain a biannual signal in channel Q and overburden.

This leads directly into the next paragraph, in which you offer a solution.

Line 503 – if this difference between murtoo and meltwater routes that you refer to here is the presence of a biannual signal, then as above, I don't think you have demonstrated this. (If you only mean that they differ, as in Fig 6, then this is ok.)

504: "divergence... appears to..."

506: be specific – which portions of the model have channels that resist closure during winter? A figure would really help this spatial discussion. Where/how do these portions relate to flow divergence?

508-9: but even if the very regular biannual signal isn't evident any more, do certain sectors have more of a tendency for over-winter channel persistence than others? I'm not sure you intended to conclude this discussion with 'it's a model artefact', but that's how it reads.

509-514: this is a really interesting idea, that the sub-lobes approximately match the pattern of winter channel persistence. Again, could a figure that illustrates this be combined with one as suggested above, or would the same figure serve both aspects of this discussion? And can you offer a concluding sentence that might explain why large eskers bound zones with different winter persistence of channels? In terms of the writing structure, I would break these lines off into a new, final paragraph.

#### Section 5.4 to end

517: I think you've actually explored drainage in relation to more than one glaciofluvial landform – suggest pluralise

520: the absence of topography is an awkward concept. Suggest amend to “including the absence of any relief”

523: the wording here is a bit confusing about the direction/trend of change (up/down or forward/backward in time) – suggest something like “Assuming this area has been uplifted by a maximum of ~100m, the volume of melt... would have been higher during the YD due to higher temperatures at lower altitude.”

537-539: this seems very specific and a poor final sentence – is it necessary or can you move it earlier in the paragraph? It seems more natural to end with the future work sentence.

In this section you focus on all the things that you haven't included. But you have done some fairly extensive sensitivity testing. I think it would be entirely appropriate to note that you haven't included all these factors and this introduces some uncertainty, but that you have tested many parameters and your findings are largely robust.

544: “The alternating sedimentological sequence”

557: delete “extending”, you've already said the channels extend

#### Appendix:

Make sure the title of the article matches the final title.

Fig A15. I think the caption ought to read ‘comparison of basal melt  $7 \times 10^{-3}$ ... against baseline  $1 \times 10^{-3}$  ?