

Review: Reorganisation of subglacial drainage processes during rapid melting of the Fennoscandian Ice Sheet – Hepburn et al.

General comments – see main review comment box.

Problematic text

The title doesn't seem appropriate: neither "reorganisation" nor "rapid" melting are explicitly examined or discussed.

Introduction – there is useful and relevant content here, but its presentation is disjointed and doesn't build towards a specific research question. The murtoo section is important but reads like a fact dump, while the rest of the hydrology overview flags various unknowns without us really knowing which, if any, of these you hope to address. From your "In this paper" statement, I am not sure what you hope to achieve or what you will actually do: "exploring conditions for murtoo formation" and "evaluating models" are rather vague ideas. I suggest: (i) pull out the bulk of the murtoo background and move that to the Study Area section (e.g. "Study area and significance of murtoos for basal hydrology"), leaving just a brief intro and summary of the significance of murtoos for your study in the Introduction; and (ii) revise the remaining sections to build a more coherent narrative that poses a problem and sets out a specific goal of this work.

At the end of the *Study area* section, I am still not clear on what the purpose of murtoos is to this study. Are you testing the conceptual (sedimentology-based) models of how they form? Are you testing numerical model performance, if we accept the sedimentology conceptual model? What is the purpose and scope of this work? Given that scope and research question, what murtoo traits are specifically important to your study, and in what way? Why is e.g. distribution with respect to lineations important, since you don't return to this later in the Discussion? In presenting murtoos as a tool for understanding hydrology, make explicit what information they give and what's important to your study... and come back to this in the Discussion.

Method section 3.2 – here, as above, I still don't follow what the actual research question or strategy is. What are you looking for when you "compare the GLaDS output to geomorphological evidence"? Are you trying to learn something about the landforms or the modelled hydrology? Why are you choosing a select zone in which to make model-landform comparisons? The Method should outline what you are trying to achieve and why, as well as how.

Results - most of the substance (that's developed in the discussion) comes from the baseline model. For greater clarity, consider splitting the baseline experiment results into two subsections, with the split at line 373: 4.1.1 – model behaviour; and 4.1.2 – hydrology in the hypothesised murtoo formation zone.

The sensitivity reporting in 4.2 reports trends, but in neither this section of the results nor in the Discussion is there any *evaluation* of the sensitivity tests. In the absence of any evaluation or any narrative connecting the results to a research question, it is difficult to see what the work contributes. (In this regard, it doesn't help that all the figures are supplementary.) Your Abstract and your Conclusions state that sensitivity testing leads you to a specific parameter space for murtoo formation, but you haven't demonstrated this through any evaluation of sensitivity test outcomes. Which parameter space do you find most plausible, and why? Which parameter space best produces features that fit the geomorphological record (channels/meltwater routes and murtoos), and which best matches the sedimentological interpretation for murtoos – and do these preferred parameter spaces align?

In the *Discussion*, there is some repetition (summary) of results but little “so what” exploration that explicitly follows, while other parts of the Discussion are framed around how well the model performs, rather than what the model finds and what insights that gives us. The discussion of biannual patterns seems like it could be an important finding, but is confusing: one paragraph argues this behaviour is a model artefact, but the next gives a glaciological explanation for it – what’s your argument? Some key ideas are lost in heavy text.

The *Conclusions* focus on what you’ve done rather than what you’ve found, and consequently fall flat. Could you revise to e.g. We assume murtoo formation near the headward onset of channelisation, where we find the following conditions: i, ii, iii, iv... Murtoos aren’t universally present where those conditions exist, which we interpret in the following way... / which we interpret to mean they also need conditions a, b...

Line by line technical comments

17: unless I’ve missed something in the manuscript, I don’t recall “water depths in terrain surrounding murtoos fields” being explored or discussed – what does this refer to?

28: delete one instance of “as”

34: wall melt and channelisation will lower the *water* pressure, which *raises* the effective pressure

43-58: the specific topic(s) of this passage and the problem areas or unknowns shift back and forth, making it hard to follow what the limitations are and what “however”, “instead”, “yet” actually refers to in each instance. E.g. basal hydrology – topography – hydraulic properties – hydraulic connectivity (same meaning?) – back to subglacial hydrology (does “instead” contrast directly with hydraulic properties of sediments, or all knowledge of basal hydrology?) – channelised drainage extent (relation to previous points?) – bed characteristics – “basal parameters”. With this rather vague term ending the passage, I’m not sure what the key point was or what the “fundamental challenge” is.

50: “However” should start a new sentence in this construction. (Also line 241, 365)

59: change to glaciofluvial, as elsewhere in the manuscript

60: delete “during periods of rapid ice loss” – this requires a confident and explicit link between a glaciofluvial landform and specific (high) mass loss estimates, which aren’t given.

62: define “meltwater routes” – listed here, they sound as if they are different from eskers and tunnel valleys – are these not also meltwater routes?

64-66: this sentence about distributed systems sits out of place with both preceding and subsequent passages dealing with channelised

65: with high *water* pressures (give low effective pressure)

73: awkward wording, suggest “assumptions about the water pressure, prescribing...”

86: here you define meltwater routes (needed earlier) but this idea was formulated long before Dewald et al. 2022 – use a more appropriate reference (e.g. Utting, Peterson, Lewington, Ahokangas...)

93: delete “closely associated” – it’s redundant here

98-99: several ideas need further explanation or definition here: transition to – or from?; what is “semi-distribution drainage”?; why does the spatial proximity of murtoos with eskers “therefore” indicate “repeated and brief pulses of meltwater”?

103 and other instances throughout: reference should be Peterson Becher & Johnson 2021

105-6: here do distal and proximal refer to across a single landform, or the field of murtoos?

106: for consistency with rest of the sentence structure – “proximally is comprised of glaciofluvial deposits with structures such as current ripples....”.

116: Stage 2 – what about the diamict that is interbedded?

123: define “upper flow regime”

131: why does laminated mud indicate sudden cessation of murtoo formation? What’s the environment for that mud settling from suspension? This sounds unlikely in a subglacial environment, which is presumably where the murtoo is forming. Why should the water in channels or linked cavities be sufficiently still for suspension settling?

132: sudden decay of what?

135: “comprising a main body”

139: “interbedding... is suggested to result from”

141-2: the “small size” of murtoos hasn’t yet been presented, and the “onset of channelization” is an interpretation (rather than observation) that murtoos form synchronously with eskers, but upstream. I think this point needs to be rehearsed more fully since it is a fundamental assumption you draw on in interpreting your model output. What supports synchronous formation of murtoos and downstream eskers, rather than murtoo formation at a later stage (i.e. the whole landform assemblage is time-transgressive)?

147: you have a study area, not one specific site that you focus on – revise this header to Study Area (and murtoo significance...)

150: suggest insert “in south-central Finland” after “moraines”

155: “the lateral margins”

158: study area

160: you refer to the other margins (next sentence) as lateral, so for clarity I would here write “bound at its terminal margin” (or distal)

167: typo drumlins

173: “complex landform assemblage” is vague, and what does its complexity have to do with surface melting?

174: revise to “accompanied by calving into the Baltic Sea” – Greenwood et al. 2017 (also 2023, if you find this relevant) find plenty of iceberg scours indicative of an actively calving margin

176: I think it is relevant to note in this section that the ice margin was (shallow) sub-aquatic and not land-terminating.

177-188: this passage is hard to work through – it’s very difficult to visualise spatially what’s being described. Some information isn’t necessary, several sentences give qualifying information before we even learn what’s being qualified, and language such as “association between”, “borders”, variably described sectors/bands/routes is vague. E.g. in the upstream trunk murtoos occur with rm + hummocks in two (?) longitudinal bands, each bounded by a band of lineations. In the northeastern band, murtoos and eskers... (describe arrangement). Downstream, where the FLDIL splays out, murtoo distribution is

fragmented and terrain is more dominated by hummocky moraine. Murtoos are sparse within 40km of the Salpausselkä.

195: somewhere in the methods, note that GLaDS is used with only one-way coupling, i.e. there is no feedback of hydrology on the ice sheet.

203, Table 1 + other initial instances: since the manuscript deals with both an ice sheet and a water sheet, I suggest using the phrase “water sheet” where this is intended and the term first introduced, to avoid confusion

206: “cross-sectional area of which” is a bit confusing – what does “of which” refer back to?

Grammatically, it refers to edges, but do you mean channels? Are these the same thing, conceptually? (In which case, how does an edge have a cross-section area?)

210: should be ρ_i not p_i (?) – also in Table 1.

213-14: is this threshold just a matter of classification or does a different equation apply (Eqn 2) above the threshold? Please clarify.

220: I stumbled over “surface elevation” on first reading, since you’ve just been referring to ice parameters. Suggest “We anticipate that the modern topography (bed elevation) is not representative... and we therefore subtract...”

229: can you finish off this comment on base level change with a suggestion of what effect omitting GIA is anticipated to have?

233: typo except

247: an adaptive

274: delete “around”

282: “nodes were pressured”? Could you add a few words to explain why this is necessary? And what does the velocity of 30 m/yr apply to? Table 1 lists ice velocity as 100-200 m/yr.

291: do you mean the final configuration? “End-member” implies one alternative, at the end of a spectrum of possibilities towards another, opposing, alternative.

298 (and Table 1): what is the basal bump height? If the basal topography is taken from the modified DEM, what is this additional basal elevation variable?

303: note that a shallow water body better replicates the palaeo setting

311: “masked” is ambiguous – did you select these nodes for analysis or exclude them?

322: (overburden%);

327: does the median include or exclude the 10 years of adjustment time?

327: suggest deleting “pressure expressed as a percentage of overburden” – you’ve already defined overburden%

328: should be Q_c for channel discharge

329: since observed murtoos are shown on the plots, I would clarify that the black solid lines are *modelled* channels, not observed/mapped ones.

331-3: the comments about in/efficient drainage here veer towards interpretation, rather than straight reporting of results. It would make it easier to read and digest if you remove these comments and just report overburden%. I also suggest starting a new paragraph after the overburden sentences – there is a lot of info in this paragraph and splitting it up would make it easier to digest.

333-6: “Towards the ice margin” and “60km from the ice margin” in the same sentence is confusing. I can’t follow the description, without looking at the figure. The next two sentences also confused me, since the difference in channels appears to suggest a contrast between summer and winter, but spatially I’m not sure whether you’re trying to express a contrast or not. Does the following (paraphrased) work? q_s is orders of magnitude higher in the zone within 60km of the ice margin than further upstream, in both summer and winter. In summer, high q_s is found in patches within the channelised zone. In winter, q_s is much lower, and its peak is shifted to a zone headward of the uppermost channel reach, 40-60km from the margin. (?)

337: as earlier, comments about channels confuse the issue, which is about velocity in sheet water. What does “reflects the concentration of drainage” mean, in this context? It is an interpretation of a mechanism that would account for a particular trait of V_w , but would help if it were explicitly presented this way. Focus on presenting the patterns in the main variable, and being clear in expressing spatial relationships – I’m not sure if you are reporting a contrast between summer and winter or not, in either spatial terms or velocity magnitude. I suggest also using the same units/terms as used in the figure, i.e. 15×10^{-4} rather than 1.5×10^{-3} .

341-2: superscript s^{-1} . Also lines 348, 352, 369 – check elsewhere.

342: Can you be more specific about the channels that persist over winter – how many? Or what proportion of the summer total?

343/4: suggest move the two sentences about Fig 3A to here, and open with it. By closing the reporting of fig 3 with a “nothing to see” case, all the interest and power of the findings about biannual signals is lost – much better to end with these interesting cases.

351: sharp increase in overburden% - not overburden pressure. There are numerous cases in the next paragraph(s) also where “overburden” or “overburden pressure” ought to be “overburden%”, or alternatively “water pressure”.

351: “trends towards” – can you say if this is an increase or decrease or values hover around one value?

353: with only a small increase in overburden% ... and little taken up by sheet flow?

356: this is confusing, suggest “with no overwinter channels evident in the central area while lateral margin channels persist over winter” .

357 + throughout: I strongly suggest sticking to expressing pressure either as water pressure or as overburden%. It is enough with two alternative ways of expressing the same thing. There is no particular need to express the same thing in terms of effective pressure – it’s confusing at best and erroneous at worst. Replace here with e.g. “a persistent area of high basal water pressure (overburden% approaches and exceeds 100%)...”

360: increase in water pressure to 120% of overburden

360: “associated with” is vague, it’s not clear what you actually mean in either case you refer to. Suggest delete this phrase here and be more specific later, where necessary. E.g. node 3842, located on a channel onset site. E.g. node 16402, located in between channel onset areas.

371: “remaining at 80% of overburden” – no need for another way of expressing pressure!

373: "To explore behaviours potentially associated with murtoo formation..." ??

375: "...of a mapped meltwater route that also hosts...". Can you also give $n=?$ in each case with the definition of the group (i, ii, iii)? You should also note again here that these meltwater routes are taken from Ahokangas et al., and note how you treat eskers (part of a meltwater route, or separate?).

377: does "throughout the year" mean "mean annual"?

382: is the statistical difference between groups significant for each of the 4 variables, considered separately? Or in combination?

388, 393, 396: could you be more specific where you state a variable is "significantly higher" or lower? In this context, it is easy to misinterpret significantly higher for substantially higher; a difference can be small, but statistically significant. What is meant here? Generally, the blue/orange variables in Fig 4, 5, A32 look pretty similar to each other, so any differences seem like they would be small, but statistically significant – can you express this more accurately and specifically in the written text?

400: what do you mean, "to best apply the model to a palaeoglacial setting"?

404: "water is efficiently evacuated" (or, water pressure is dissipated??)

406 + throughout: as above, express pressure in terms of either water pressure or overburden%

408: "At a minimum sheet conductivity of 10^{-5} ..." – symbol not needed since you wrote out in words

411: K_C should be k_c (small letters)

411 + throughout Section 4.2: Table 1 gives units for k_s as $m^{7/4} \text{ kg}^{-1/2}$ and for k_c as $m^{3/2} \text{ kg}^{-1/2}$. These are muddled and inconsistent (7/4 or 3/2) through the Section.

412: "low pressure" – which variable? (Also line 429)

420: "the location of which" – what does "of which" refer back to?

448-455: superscript yr^{-1} . Note that elsewhere in the text the unit for years is given as a.

452: what do you mean by "more tightly constrains the observed summer water pressure..." ? I don't follow.

Section 4.2 overall: see comment above (problematic text) – this sections reports the end member behaviour and selected middle option of the range of sensitivity tests, but doesn't anywhere *evaluate* these outputs. How stable/robust are the results presented for the baseline case? What do we learn from these sensitivity tests?

5.1 header: seasonal drainage is implicit in some parts of your discussion in which you compare winter and summer conditions, but seasonality isn't a trait you explicitly dwell on and explore. This doesn't seem a particularly appropriate header (or could be made more so by extracting aspects of seasonality for dedicated discussion).

460: "...demonstrated by Kirkham et al., who evaluated hypotheses..." – in its present formulation, I moved onto the next phrase + reference as a new item, not connected to Kirkham.

472: do papers by Hewitt, Schoof etc not include transitions between channelised + distributed systems (and compare to landform-based predictions of geometry)?

474: does "as" mean because, where, when, ... in this context?

475: what does “define a parameter space for basal hydrology models” mean, specifically, in this context?

479: I’m having trouble visualising “vertically arcuate along a comparable path to the surface” – can you rephrase?

483: delete “Instead” – doesn’t seem like there’s a contrast

485: “...gradients limit the growth of channels...” (?)

486: permit (delete s)

490: “Across the full domain <70km from the margin” sounds like you’ve got two mutually exclusive areas. I think you perhaps mean within the width of the domain and within 70km of the margin ?

494: suggest deleting “when plotted as a summer average” and change previous line to “summer water pressure”

494: Elsewhere *in the downstream zone*, water pressure ... ?

496: insert ii) since you started a list with item i) – and ii) the limited... dropping below 75% of overburden

502 and next two paragraphs: these read more like a summary of the results than a discussion. What’s new, what key insights have you gained into murtoo formation and/or murtoo vs channel hydrology? What about all the murtoos upstream of the 40-60km band?

506: if “channel discharge” is only ever close to but not exceeding the threshold for being designated a channel, how does that entity have a “channel discharge” and be measured as Q_c ? In fact, I should have asked this earlier with the presentation of results and figures e.g. Fig 3, 4, 5 – if a channel isn’t a channel until it has a discharge of $1 \text{ m}^3/\text{s}$, then how can a channel have discharge Q_c below that?

515: what is it that suggests that cavity expansion necessary for murtoos is captured in your model? Expand on “which suggest”. I think you also need to expand on the argument that murtoo formation requires the existence of small channels, as a pre-requisite. Is that the case, or have I extracted the wrong idea from what I think you’re alluding to? (This is sort of stated in the introduction to murtoo sedimentology, and on the previous page you refer to cavity enlargement, but does a cavity or conduit mean – in model terms – a small channel?)

526: “such landforms relating to meltwater drainage have been mapped...”

531: there is quite a lengthy history of data-model comparison with regards to eskers, and some of that work is likely relevant here (also in the opening of the Discussion, where you also address data-model comparison) e.g. papers by Boulton 2007-2009, by Hewitt 2011, Hewitt & Creyts 2019; work by Flavien Beaud 2016, 2018 among others

535-6: repetitive – suggest “...grid-based models, but the exact location...”. “The spacing of channels, however, remains robust...”. Delete the early part of the second sentence.

539: does this contradict the earlier result that I flagged in my general comments, that channel discharge is higher outside mapped meltwater routes?

541: presumably the baseline run was selected in order to match the Greenland geometry, though – it’s not really a result that this is the case, is it?

542: consistent language with earlier: “In the baseline model run, small channels...”

558: “between our model results and the observations beneath Greenland” ? – “those” implies model results beneath Greenland...

561: “in these systems” – does “these” refer back to the distributed system, channels, or both? Be specific.

571-2: this sentence repeats the opening sentence of the paragraph, but more specifically and concisely – suggest delete the opener or replace it.

572: overburden%

576: as above, if the “channel” has discharge orders of magnitude below the threshold to be a channel, how can these be considered channels?

583-4, + preceding + following paragraph: you argue biannual behaviour in the model output is a consequence of internal model dynamics (i.e. an artefact) yet then offer an explanation for it in glaciological terms. What is your argument? And what is the relation to a patchy murtoo distribution?

623: study area

631: while you have performed some sensitivity runs, neither your Results nor Discussion section explicitly analyses or evaluates those outputs, so it is false to say that “By sensitivity testing... we demonstrate...”. You have selected the baseline run as your favoured answer.

635: that murtoos arise because of “consecutive years of elevated meltwater volumes” has not been clearly demonstrated or argued in the Discussion. Your Discussion has presented biannual behaviour linked to winter persistence of some channels, and implied some related cavity/channel growth behaviour (although see above, 583-604), but your Discussion does not explicitly tie this to murtoo formation. “Elevated meltwater volumes” is also an ambiguous phrase: volume is not considered, as a model variable – do you mean pressure, discharge or velocity?

Figures & Tables

Table 1

- channel conductivity: the main text refers to experiments with values 0.001, 0.05, 0.5
- ice velocity: given the inference of ice streaming, a tested velocity range of 100-200 m/yr seems rather limited, and low – why?

Fig 1

I don’t think that slope visualisation of terrain models is the most intuitive way to illustrate and distinguish murtoo morphology, especially for those not accustomed to working with terrain models or unfamiliar with these landform types. I would suggest a conventional hillshade, with illumination best suited to each panel.

Also consider rotating the triangle symbols in the direction of murtoos?

Caption: change to *study area*.

A) “Murtoo fields identified by Ahokangas...”.

D) If murtoo fields are adjacent to the esker, then murtoo fields have not undergone an “abrupt downstream transition” to an esker – please revise, the description of a transition is misleading.

E) “within the centre” – delete “at”

Fig 2

- give units for q_s , V_w and Q_c
- In the caption, move the sentence about channels as black lines to after (C), and say that this is the case in panels A-C. (Not just A)
- murtoo triangles aren't visible at this scale (appear as dots), nor is channel scaling for discharge (appear as black lines). I'd remove the murtoo/channel legend, and simply add to the last line of the caption that black dots are murtoo fields, from (which ref?).

Fig 3

- label A, B, D, E next to coloured dots on panel C.
- consider flipping the inset graph so that distance = 0 to the right, for consistency with the map plot?
- caption: opening sentence, suggest "at four nodes over model years 15-25 in the baseline model run". And panel C) ... "in model year 19 (arbitrarily selected)."
- caption final sentence, should be q_s

Fig 4

- give units for q_s , V_w and Q_c
- colours: the red and orange are rather close, and the pink too – could you choose more distinct colours? Also, the legend shows solid pink while the graphs show dashed, and the legend describes as dashed purple. Please revise one or an other to be consistent.
- "Meltwater routes that do not contain murtoo fields (murtoo hosting)" ... "routes which do host murtoos (murtoo free)" – both of these phrases in the caption are internally inconsistent. They are also (possibly?) inconsistent with the legend. Please revise.

Fig 5

- give units for q_s , V_w and Q_c
- same errors for murtoo hosting / murtoo free – the caption is internally inconsistent, and please check consistency with legend.
 - I note that I have not checked legends/captions for all appendix figures, but at least A32 has the same error – please revise, and check other figures thoroughly.

Fig 6

- caption line 2: delete "against"