

Response to reviewer 2

Many thanks to the reviewer for their comments and helpful suggestions for improving this manuscript. Our responses are italicized and indented below.

This manuscript addresses important and interesting questions surrounding the interaction of Antarctic subglacial lakes with the hydrologic system. The authors are the first to apply a 2D hydrology model such as the GlaDS one here to a synthetic subglacial lake system.

The work presented in this paper is novel and interesting, and in my opinion should be published after a few revisions are made. In particular, I found that on first reading the paper was lacking in a clear motivation/aim/scientific questions it was trying to answer. It was only on second reading that things became more clear and I thought the paper really had good purpose. I think, therefore, that the authors need to work on improving the introduction and motivation. The summary at the end of 6.4 and in the conclusions are very good, and while you don't want to give the result away at the start of the paper, you do want to lay out the questions that you then have answers to.

With this in mind, I would add a short paragraph at the end of the introduction summarizing more explicitly what you aim to address with the model ('behaviour and stability of subglacial lakes' is quite vague). Furthermore, explicitly state 'In section 2 we give a brief summary of the model before describing the model setup and configuration in section 3. etc etc.' This will also help make clear to the reader that you just describe results that the model produces in section 4 and only then discuss their *relevance* and application in section 5.

Thank you for the suggestions for how to improve our introduction to this manuscript. We have substantially altered our final paragraph of the introduction to address the lack of motivation and aim within the introduction of the previous version. This now reads:

“Our primary aims are to examine a) the hydrological conditions that allow subglacial lake growth and drainage on a catchment scale, and b) the impact of the lake drainage on downstream water pressures and, by proxy, ice dynamics. To achieve this, we apply GlaDS, a finite-element basal hydrology model, to a synthetic system designed to represent an idealized Antarctic ice stream with one overdeepening. Using this simplified system allows us to identify hydrological controls on lake dynamics and examine the wider catchment without complications of highly variable basal topography. Our approach is novel as it does not require any external forcing to fill and drain the lakes (c.f. Carter et al, 2012); this instead occurs due to internal model dynamics. We begin, in section 2, by giving a brief summary of the model and, in section 3, our application of the model to our idealized ice stream. This is followed, in section 4, by an exploration of the model outputs for an ice stream without and with an overdeepening, and the differences between the two setups. Section 5 gives an outline of results from sensitivity tests of the model and section 6 covers the limitations of the modeling approach. We discuss the relevance and application of the model outputs in section 7 before concluding in section 8.”

Comments

Abstract, line 5 You don't actually really get as far as the impact of the lakes on ice stream dynamics. So I wouldn't write this in the abstract...

We have removed the mention of lake impact on ice dynamics.

Abstract and throughout I am not sure of your use of the word 'funneled' throughout the manuscript. Not a word conventionally used to describe water flow beneath ice sheets. Use 'drawn down/in' perhaps, as you're really referring to the water flowing down gradients in hydraulic potential. Funneled, to me, suggests something only based on bed slope.

Our use of the word "funneled" is to describe the domain constricting to a narrow region from a wider region. Our tests indicate that the narrowing of the flow path 'neck' from the wide catchment to the narrow ice stream is important for producing the pressure waves. As a result we use the word to describe the domain geometry rather than the condition of the hydraulic potential surface. To clarify this, the first time we use "funneled" in the main text we have added: "water is funneled from the large catchment into the narrower ice stream". We believe that, since it is widely known that water flow under glaciers is impacted by both bed slope and surface slope, using the word "funneled" will not confuse interpretation of our phrasing.

Abstract line 11 Flux of water 'through' the ice stream... water is flowing at the bed. Using 'through' implies within the ice. So change to 'at the bed of' or 'beneath'

Changed to "beneath".

Abstract line 12 Delete 'too'

Changed.

Abstract I find the middle section of the abstract a bit dry and long-winded. Cut down to only what is absolutely necessary. e.g. Line 14 re-write 'In turn, this drainage mechanism causes high water pressures 50km downstream of the lake' (no need for first or last part of sentence in the abstract).

We have removed this and some other sentences in order to cut down the content of the abstract and retain only what is necessary.

6547, line 1 'has been increasingly' is confusion of tenses (has implies past, and increasingly implies present).

"Increasingly" removed.

6547, line 6-7 Don't use subclauses like this unless have to, as ruins the flow. Re-write 'In the case of Byrd Glacier..., the drainage of lakes *has* been found to cause... '

Changed.

6547, line 8-11 Long sentence with no punctuation- not easy to read.

We have divided this into two sentences.

6547, line 12-15 Numerical models are also used to assess the impact of hydrology on formation of lakes (i.e. the other way round). Maybe change 'impact' to 'feedbacks between hydrology and lake formation'.

This has been changed to: "...numerical models can be used to investigate the feedbacks between hydrology and subglacial lake formation."

6547, line 18-end Nice summary of others' work.

Thank you.

6548, line 1 'Here' is a weak start to a sentence. Perhaps 'In this manuscript'.

This paragraph has been re-written and this section removed.

section 2 Nice summary of model.

Thank you.

6550, line 5-9 Long sentence. Split into 2.

We have split this into two sentences.

6550, line 11- 17 Can you justify these values of surface slope and radius slightly more, since they are not included in the sensitivity study?

The slope values are based on average values from the ice stream trunk and catchment region of Recovery Ice Stream. We have now stated this in the text. The radius of the overdeepening represents a medium-sized lake in Recovery Ice Stream. We also now clarify this in the text.

6551, line 10 - 13 Have you said mesh details for first topography? Assuming 780m in ice stream and 1500m upper catchment. State explicitly.

We have changed this paragraph so that the mesh for both topographies is now stated.

6552, line 11 Change 'funnelled'. 'Incoming water from upstream' would seem to me to be a better description. 'hydraulic gradient in the ice stream' also isn't a particularly good description-

I presume you mean the hydraulic gradient *at the bed* of the ice stream isn't large enough (due to the surface slope of the ice stream not being large enough). Re-write this sentence. The rest of this paragraph provides a very nice clear and concise description.

At our first instance of using 'funneled' in the text, we now state that this is "water is funneled from the large catchment into the narrower ice stream". Having clarified that we are describing geometrical funneling rather than in relation to the hydraulic gradient we believe that the use of funneled in this instance is now clear.

We have rephrased the remainder of the sentence as suggested.

Figure 3 Nice figure. Why the different coloured boxes around a and b? Only adds confusion introducing more colours, so if no meaning just change both of these to black. Same for fig 4.

Thank you. The different colors around a and b were to match the colored lines in c, showing where the water pressure and channel growth outputs are located in the domain. However, to avoid confusion we have removed the colored boxes in Figures 3 and 4.

6552, line 17 'an area' change to 'an area of the domain'.

Changed.

6553, line 11 I find the use of the phrase 'ramping up' throughout the paper slightly too informal. Change to '...then increasing the water input...'

Changed.

6553, line 13 This change is not explicitly shown in Figure 4. Say 'The overdeepening does alter the time of pressure waves... (compare Fig 4a,b with Fig 3a,b).

We have made this change.

6553, line 14 insert comma after 'however'.

Changed.

6553, line 17-19 Very long-winded first sentence, difficult to take in a main point. Perhaps use a semicolon to split it up? 'A lake is able to form in the overdeepening due to the altered hydraulic gradient from the pressure waves; the hydrological system is not able to adjust rapidly enough to the increased water flux.'

We have changed this sentence as suggested.

6553, line 22 'a threshold size'- what exactly do you mean by that?

For clarity we have changed this sentence from:

“lake drainage occurs when the channels downstream of the lake reach a threshold size.”

to:

“..lake drainage occurs when the channels downstream of the lake are sufficiently developed.”

6553, line 24-25 Describe in sequence of events. i.e. `...when another pressure wave passes, changing the hydraulic potential and driving more water into the overdeepening'.

We have changed this to the suggested sentence.

Figure 6 V nice.

Thank you.

6554, line 11 Change to `as illustrated by the lake depth plot in Figure 5'.

Changed.

Fig 7 Legend in b being horizontal is slightly confusing at first glance as continuous and no spaces between each colour. Better to just keep vertical and overlap with first part of graph?

We think that you mean Figure 5 here? We have rearranged the figure so that the legend for (b) is now vertical. Due to space constraints we keep the legend above the water pressure maps.

6555, line 6 Delete `we found that'. Unnecessary and don't want to many uses of `we'.

Changed.

6555, line 12 Don't start sentence with `also'. `Furthermore' instead?

This has been changed to 'The depth of the lake is also smaller...'

6556, line 4 replace comma with semicolon.

Changed.

Section 5 Nice. A clear, concise summary of the sensitivity tests.

Thank you

6556, line 11-12 'to some extent' interrupts the sentence. Remove. Also add in some citations of work studying these.

We have removed 'to some extent' and added in citations.

6556, line 12-22 Very nice summary.

Thank you

6556, section 6.1 You are repeating what you have just said at the start of this section. I would add your comment about order or magnitude difference in water input to the summary at the start of section 6 and start this section around line 5. Or at the very least get rid of the repetition in the first sentence.

We have removed lines 1-5 and integrated them into the introductory paragraph of the discussion.

6557, line 11, 22 'Funneling' change to 'draw in'??

As we explain above, we have clarified our use of 'funneled' for geometrical description of the domain and so we retain our wording here.

6557, line 14-15 I think it's decidedly uncomfortable that you reach this stage of the manuscript and state that there is 'strong evidence that this situation does occur in reality' without having discussed at all how actually this might not be best hydrology model (e.g. deformable sediment-much more evidence out there for this than for any channels at all). I know later you do justify this briefly (start of 6.4) but a bit more detail would be good earlier in the paper (even in intro or model description). I'm not saying it takes away from the worth of the work at all, but does deserve discussion.

For clarity and openness about the limitations of the model, we have moved section 6.4 to its own 'limitations' section following sensitivity results and prior to the discussion. In this way, the discussion is now in context of the limitations of our (and any modeling) approach. We also expand on the lack of deformable sediment in the model configuration so that it is clear that, although there is likely deformable sediment in the ice streams, the model in its current configuration cannot include these characteristics. In the model configuration we now say:

"GlaDS is primarily set up to deal with distributed linked cavity systems. However, a sediment based distributed basal drainage system may behave in a similar fashion (Creys & Schoof, 2009). By testing a range of conductivities in the distributed system we can emulate Darcian flow through sediment along with more conductive cavity-type systems. Sediment deformation processes, which could be important in ice stream hydrology and dynamics cannot, however, be taken into account with this model configuration."

We also reiterate in the limitations section that: “Sediment deformation processes are, however, lacking in the model.”

6557, line 25 'followed by' doesn't work well in sentence here. Change to '...system, before faster water flow then results in temporary channel growth, moving the excess...'

We have split up the sentence following comments from reviewer 1. It now reads: “Our hydrological explanation for the waves is that water pressure builds up in the upper region of the ice stream, increasing the hydraulic gradient. This leads to faster water flow resulting in temporary channel growth, moving the excess water downstream.”

6557, line 26 Change to 'there is a resultant close...'

This sentence has been removed following comments from the other reviewer.

6558, line 4-8 Long sentence. Split into two - '...Canada. These are driven by...'. Alter next sentence slightly as well e.g. 'The oscillations lasted over a period of days, as opposed to the years in our model of Antarctic ice streams',

Changed.

6558, line 14. Didn't read as a complete sentence on first reading. Switch order so subject right at start. 'Surging glaciers provide further evidence of pressure waves'.

Changed.

6558, line 21-22 change to 'than we suggest might occur in an Antarctic system'

Changed.

6559, section 6.2 Nice comparison with jokulhault model.

Thank you.

6559, line 23-24 Another unnecessary subclause in sentence. Re-write as '...demonstrates that the lake does not drain without the growth and shrinkage of channels'

Changed.

6559, line 26-27 '...his model demonstrates...'

Changed.

6559, line 28 Change 'controlled' to 'control' and 'did not' to 'do not'.

Changed.

6560, line 1 Change 'the flood characteristics' to 'these flood characteristics...' since you have just been describing them.

Changed.

6560, line 3 'As described' unnecessary.

Changed.

6561, line 11 change to 'allowed throughflow of all water'.

Changed.

6561, line 5-20 Nice comparison with Carter work.

Thank you.

6562, line 14-17 Long sentence. Split into two.

Changed.

6563, line 23 A channel doesn't 'obtain' a size. Change wording e.g. reach, grow to.

This has been removed following comments from the other reviewer.

6563, line 2 'funneled' change to 'drawn down/in'

As we explain above, we have clarified our use of 'funneled' for geometrical description of the domain and so we retain our wording here.

6563, line 6-10 Don't start sentence with 'also' and split this long sentence into two.

Changed.

6563, line 16-19 bad sentence structure. change. maybe to 'has limitations due to its simplified nature. For example, it does not incorporate...'

Changed.

6563, line 19 Comma after however.

Changed.

6563, line 22-27 THIS IS A KEY POINT that needs acknowledged. Please give it a bit more emphasis and also mention it earlier in the paper when you introduce model.

We have added the following into the model configuration section to emphasize the point that the model cannot deal with sediment deformation processes:

“GlaDS is primarily set up to deal with distributed linked cavity systems. However, a sediment based distributed basal drainage system may behave in a similar fashion (Creys & Schoof, 2009). By testing a range of conductivities in the distributed system we can emulate Darcian flow through sediment along with more conductive cavity-type systems. Sediment deformation processes, which could be important in ice stream hydrology and dynamics cannot, however, be taken into account with this model configuration.”

We have also moved the model limitations section prior to the discussion so that this point about lack of equations describing water flow through sediment in the model is reiterated at the end of the results.

6564, line 17 Change to `our model' rather than `our hydrological model' Since what you describe would require a coupled model of both hydrological type and the ice.

Changed.

6564, line 24 Re-structure sentence. `...remove the pressure waves; it might instead...'

Changed.

6565, lines 1-5 Careful here. You have not actually applied it to Antarctic lakes. Make clear synthetic situation, trying to simulate a situation comparable to Antarctic lakes. You should outline something similar to this in the introduction too so that the work as the purpose summarised here from the start.

We have clarified by changing the first sentence to say: “We have presented a 2D model of idealized Antarctic subglacial hydrology evolution using a synthetic setup designed to represent a simplified Recovery Ice Stream and catchment with one overdeepening.”

Section 7 Great summary. Perhaps you could also add a paragraph in about future work. Do you plan to implement this model over a real domain/ include some ice dynamics/include ice flexure etc in the foreseeable future?

Thanks for the comments. We have added the following to the end of the conclusion to indicate that we are applying the model to realistic topography and aim to include ice dynamics in the future:

“Future work will involve applying this model to Recovery Ice Stream using realistic topography in addition to adding in ice flexure and ice dynamic components to the model setup.”