Response to reviewer 1

> *We thank the reviewer for their comments and helpful suggestions for improving this manuscript. Our responses are italicized and indented below.*

The paper uses a model of subglacial hydrology to investigate processes of lake filling and drainage beneath a synthetic ice stream that resembles the Recovery Glacier System. The conclusion is that the system is characterized by (i) water accumulation at the bed that results in intermittent channel formation and meltwater drainage that leads to lake filling; (ii) subsequent steepening of downstream hydraulic gradients that drive increasing efflux from the lakes, (iii) downstream channel formation that allows lake drainage, and (iv) eventual shutdown of the channels as water supply decreases due to drainage of the stored water volume. It is also argued that the system is characterized by slow-moving pressure waves.

I found the story quite interesting, but since it is based largely on model results with limited observational constraints, I was left wondering how well it compares with reality. Certainly it provides a mechanism to explain the lake filling/drainage events that are suggested by altimetric studies (which show rapid uplift/subsidence cycles in restricted locations). However, I felt that the presentation lacked the depth of insight and understanding displayed by some other work on Antarctic subglacial meltwater drainage (such as that by Tulaczyk, Christoffersen and Bougamont). I think this is because the authors never really identify a set of well-posed research questions that they address with the model, so the whole paper has the feel of a report on the results coming out of a black box, and it isn't at all clear how the study advances knowledge and/or understanding of the system. The paper left me feeling intrigued by the problem, but unconvinced that it will influence thinking about these systems very significantly. It might provoke work that will, but I think the authors could make a lot more of their results than they do if they were really clear about what are the issues they want to resolve through conducting and publishing the work.

> *We appreciate that our previous introduction in the manuscript did not address the aims and objectives of our study as well as we had intended and we thank the reviewer for highlighting this lack of focus. We have made an effort to address this by including our aims and rephrasing the introduction so that our reasons for use of a synthetic model are clear. Below we elaborate on this in response to the specific reviewer comments above.*

In response to: "I found the story quite interesting, but since it is based largely on model results with limited observational constraints, I was left wondering how well it compares with reality."

> *The reviewer is correct in that our limited ability to directly access subglacial hydrological systems of Antarctic subglacial lakes and ice streams means there are few data to compare with model outputs. We suggest that it is for this reason that modeling is currently one of the most appropriate tools for exploring subglacial hydrological development. As we are using a synthetic model, we do not suggest that this can be directly compared with surface altimetry records, for example, and instead use the results of the model to encourage testing of hypotheses. In response to comments from the reviewer, we have emphasized this at the beginning of the discussion by saying: "by*

applying a 2D hydrology model, which produces lake filling and drainage through internal dynamics, we can make a step towards understanding and projecting the development of Antarctic subglacial drainage systems in addition to generating testable hypotheses.".

Because the process of hydrology modeling is complex and involves both distributed and channelized systems it is a valuable exercise to assess the development of the system without complicating it with realistic topography. This means that we can examine the controls on lake growth and drainage and also the sensitivity of the system to various parameterizations. The model will in future be applied to real topographic systems but prior to this it is useful to know what hydrological phenomena are common features in relation to lake dynamics and ice streams rather than unique to certain topographical situations. As a result, we maintain that the application of a synthetic model to this scenario is a useful and important step in understanding the causes of subglacial lake formation and drainage.

In response to: "I felt that the presentation lacked the depth of insight and understanding displayed by some other work on Antarctic subglacial meltwater drainage"

The works of Tulaczyk, Christoffersen and Bougamont are interesting advances in our understanding of controls on ice stream stability and dynamics. These papers use a 3D ice dynamics model and couple with a simplified till-based hydrology, with water either produced and refrozen in situ (and therefore not actively flowing through the system) or with Darcian flow alone. While this is very useful for establishing controls on ice dynamics from till characteristics, our approach and research questions are very different. We are interested in catchment-scale hydrological development and also the controls of lake drainage. Our model is the first to analyze 2D development of subglacial channels and the hydrological controls on lake drainage. The works of Tulaczyk, Christoffersen and Bougamont do not address either of these issues and it is therefore difficult to compare their research to ours. In the future we hope to develop the model to couple with ice dynamics and include till properties but for the moment we believe our findings of hydrological development are an interesting and highly relevant output that would enhance rather than contradict the findings of Tulaczyk, Christoffersen and Bougamont. In terms of insight, there is so little known about the subglacial hydrological systems of the Antarctic: what the substrate consists of, catchment-scale controls, whether channels can form and/or persist, controls on lake drainage, pressure etc. any advance we can make with modeling that will encourage further data collection and future modeling is important.

In response to: "I think this is because the authors never really identify a set of well-posed research questions that they address with the model, so the whole paper has the feel of a report on the results coming out of a black box…"

We have changed our introduction so that the final paragraph is now clear about our aims and research questions. We hope that this will allow readers to understand our motivation behind this research and why outputs from a synthetic model enhance *knowledge of subglacial drainage development in Antarctic ice streams. The final paragraph of the introduction 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.".

Detailed comments (referenced to page and line number)

3.4-3.8: over a period….has been found…. over a period

Changed

3.9: Is this interconnection permanent or intermittent? If permanent – I assume the flux itself is time-varying. I think discussing this issue more fully here will help provide more compelling motivation for the paper.

It is not yet clear whether the interconnection between lakes in Adventure subglacial trench is permanent or intermittent and we hope that our outputs from this synthetic modeling exercise will help address this question. We have added in "The mechanisms and longevity of hydrological connection are, however, not well understood." following this sentence to illustrate that it is an area of research worth pursuing.

3.15: "impact of subglacial lakes on hydrological development" – it could very well be that looking at this connection in reverse could be useful (i.e .the issue could be how hydrological evolution drives lake behaviour – rather than opposite). I think failure to look at the system in this way may be the biggest weakness of the paper (I recognize that feedbacks may be such that it is hard to figure out what the actual drivers for change and evolution are – but the paper just seems to sidestep the issue)

Much of the discussion of this paper is dedicated to assessing the drivers of lake growth and drainage. We discuss in detail the causes of lake growth due to the changing hydraulic potential gradients as a result of pressure wave movement. We also discuss the growth of channels on the downstream side of the lake due to large-scale downstream *hydrological development as a causal factor for lake drainage. In addition, we cover the impact that lake drainage has on downstream hydrological development. As a result, the focus of this paper is primarily on the causes of lake growth and drainage rather than the impact of lake drainage on hydrological development. To clarify that hydrological models in general can be used for this, we have changed the sentence from:*

"As an alternative, numerical models can be used to infer conditions at the ice-bed interface and to estimate the impact of subglacial lakes on hydrological development."

To

"As an alternative, numerical models can be used to investigate the causes of lake growth and drainage, and to estimate the impact of subglacial lakes on hydrological development."

We also change the final paragraph of the introduction to highlight our aims:

"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."

3.25: "assessing lake volume from altimetry is challenging" – I agree – it can suggest where lakes are, and surface height changes may suggest volume changes are underway, but quantifying this is really an inversion problem that has yet to be tackled. I agree with the final sentence of the paragraph but am not convinced that this paper really changes the situation.

The reviewer is correct that quantifying lake volumes from surface uplift and subsidence is an inversion problem. As we are presenting a synthetic model of catchment-scale hydrology and lake drainage dynamics we do not address this inversion problem in this manuscript. However, we believe that in order to quantify changes in lake volume in relation to surface records, a hydrological model, such as we have presented here, is necessary in addition to the inverse problem the reviewer suggests. We are open in the manuscript that there is still work to be done, for example coupling ice flexure and dynamics with hydrological models, in order to fully comprehend the system. We hope that the new introduction will clarify our aims for the synthetic model.

4.2: do you mean "drainage" in the generic sense here (i.e. water flow over the bed) or do you just mean "lake drainage" – important to be clear about this.

Changed to "lake drainage".

5.24: has been shown to have…(or maybe just "has up to 13…")

Changed to "has up to 13".

6.23: over a period of..

Changed.

7.18-19: I assume you mean the modeled water pressure, not "the model" as stated

Changed.

7.21-7.23: If you have low water pressures because the cavities do not fill with water, how are you sustaining the basal velocities at rates that keep the cavities open? Seems to be a feedback missing from the model somewhere.

In future versions of the model we hope to have a system where ice dynamics and hydrology are coupled so that these feedbacks are included. However, this is currently a hydrology model without a dynamic component and does not include temporal variation in basal sliding, which we discuss in the model limitations section. As a result, the basal sliding rate is fixed and not linked to water pressure. To clarify in the section referenced here, we change the phrasing from "there is not enough water to pressurize the distributed cavities for an ice speed of 100 m/a" to "there is not enough water to pressurize the distributed cavities for our fixed ice speed of 100m/a".

8.24: in terms of either the magnitude of the water pressure or its persistence

Changed.

11.9: I doubt the over-deepening itself forms and drains on these timescales. I assume you refer to the lake within it?

Changed to: "The larger overdeepening also allows a lake to form and drain slightly more quickly compared to lake in the standard overdeepening of 150 m."

11.11: We also vary…

Changed.

11.11: "When the rate is decreased." – the rate of what? Basal melt I assume?

Changed to "When the basal melt rate is decreased".

11.12 The depth of the lake is also smaller.....

Changed.

11.16: water levels fluctuate over a similar range

Changed.

11.21: and it therefore takes more time to reach near-overburden….

Changed.

11.24 conductivities within which the lake…

Changed.

11 – Section 5 – the range of parameter values used in the sensitivity analysis seems quite limited. It would be useful to explain this – is it based on physical reasoning , or just a means of limiting the number of model runs required? Either way, how did you settle on this specific range?

The parameter ranges were chosen both because of physical reasoning and to limit the time for model runs. To clarify, we have now elaborated on our choice of sensitivity parameter range in the text. In the case of the distributed conductivity, lower values caused the model to run too slowly to allow analysis of the system. For the water production rate, 2mm/year is double the value suggested for Recovery catchment by Fricker et al (2014) and we do not test greater values. We also now note that if the overdeepening depth is increased to 500 m, the model cannot run efficiently with the current mesh setup (i.e. running the model takes weeks rather than days) and so for deeper lakes a different model configuration would be necessary.

12.5: "a lake does not grow" – this implies a lake that maintains a stable volume – is this what you mean, or are you actually discussing whether or not a lake will form at all?

Changed to "lake does not form" for clarity

12.8: Little is known about the spatial and temporal evolution of the subglacial meltwater drainage systems of Antarctica and their…

Changed.

12.11: the system may be substantially…

Changed.

12.12: What do you actually mean by "and to some extent. Greenlandic outlet glaciers" – that they are only to some extent more closely studied, or that the difference between Antarctic subglacial systems and Greenlandic systems may be less than the difference between Antarctic systems and mountain glacier systems? It seems pretty obvious that systems fed by supraglacial inputs that vary seasonally and diurnally and also have extreme input events will be significantly different from systems fed primarily by basal melt and subglacial storage release events.

We have removed "to some extent" in order to fully differentiate the mountain and Greenlandic outlet glaciers from the Antarctic systems we are discussing. Indeed, the systems that are fed only by basal melt are likely different from those fed from seasonally-varying ice surface melting but, given that relatively little has been discussed about spatially and temporally developing hydrological systems in the Antarctic compared to other regions of the world, we believe it is a valid point to make.

12.13: features is that there is no water input… surface, so variability in water fluxes (and pressures?) does not occur on diurnal, weather-related, or seasonal timescales, but over years or even decades (BUT I think you need to discuss the sources of variability over these timescales – is it just drainage system instabilities?)

We have changed the phrasing as suggested. We agree that over the scale of years and decades that changes can happen in Antarctic systems other than internal hydrological development, including changes in ice dynamics due to ocean processes and mass change etc. The model is currently not configured to include ice flow and so we cannot address dynamic changes or mass changes that might impact the hydrological system. This, however, would be an interesting area for future research.

12.16: the phrase "basal hydrology develops" is tricky because you seem to be confounding the issues of time varying water fluxes with those of drainage network structure and channel morphology. I really think you need to be much more careful about this and think about each of these separate but connected issues clearly and distinctly – even if you do this solely in terms of what your model is simulating (which may or may not bear some resemblance to reality. I think the paper is struggling here simply because your thinking about the issues is not yet clear.

With this sentence we aimed to point out that the lack of knowledge about subglacial water production and the lack of available data about subglacial hydrology means that it is difficult to determine characteristics of the subglacial hydrological system in the Antarctic, which varies over years and decades and has no water input from the surface. We therefore clarify by changing the sentence from: "This characteristic causes two major difficulties when attempting to establish how Antarctic basal hydrology develops: (1) the subglacial production of water is based on modeled geothermal heat fluxes and modeled ice fluxes rather than measured water inputs rates from the surface and (2) available data records, particularly from satellite sources, are limited to the last couple of decades."

To: "These features cause two major difficulties when attempting to establish the characteristics of Antarctic subglacial hydrology: 1) estimates of subglacial water volumes are extrapolated from modeled geothermal heat fluxes and modeled basal friction from ice flux, rather than measured water inputs rates from the surface and 2) available data records, particularly from satellite sources, are limited to the last couple of decades."

In terms of our later analysis of basal hydrology development, we suggest that this 'development' encompasses changes in water flux, water pressure and network *development for both the sheet and channel. It precisely because of this complexity that the model outputs we present are new and exciting results in relation to lake dynamics and ice stream hydrology. Because these features of the hydrological system are all interconnected it puts us in a unique position to discuss channel growth in relation to water pressure, or increased flux out of the overdeepening causing channel growth that eventually allows the lake to drain. It is not possible to separate the examination of water fluxes from network development and we believe attempting to do so would hinder interpretation and discussion of the hydrological system development.*

12.17: surprising there is no mention of basal friction here (including friction between entrained debris and bedrock), or of the heat generated by the water flow itself – these terms are minor in temperate systems so are typically ignored – I'm not sure we can make the same assumption here.

We have clarified by changing the phrasing from "modeled ice fluxes" to "modeled basal friction from ice flux". Our water input rate to the system is based on estimates made in other studies about Recovery Ice Stream (Fricker et al., 2014) and attempting to quantify this estimate further is beyond the scope of this study. In addition, the additional flux from melting due the dissipation in water flow is always small and will likely not impact out outputs.

12.21: predicting the development of Antarctic subglacial drainage systems

Changed.

12.19-12.22: Need to recognise that the best you can do is generate testable hypotheses – until it is possible to do in situ measurements in these systems, the models will remain untested and their results no more than hypotheses

We acknowledge that a primary usage of models such as the one we present here is to generate testable hypotheses that will drive further research. To clarify this at the beginning of the discussion we have changed our last sentence to read: "...by applying a 2D hydrology model, which produces lake filling and drainage through internal dynamics, we can make a step towards understanding and projecting the development of Antarctic subglacial drainage systems in addition to generating testable hypotheses.". In addition, we have moved the model limitations section prior to the discussion so the readers will be aware of limitations of numerical modeling approaches while reading our analysis of the model outputs.

12.24: are forced by seasonally varying and weather-related water inputs

Changed to "forced to seasonally varying water inputs".

12.25: Do you know for sure there are no seasonal forcings on these systems - from snow loading variations for instance (self-organised criticality…) , or non melt-related sources (e.g. Kulessa, B., Hubbard, B. & Brown, G. (2003). Earth tide forcing of glacier drainage. *Geophysical Research Letters* 30(1)). These may be minor in alpine/Greenland systems but could become very significant where the surface melt signals are missing.

> *It is not possible to know absolutely that seasonal forcings do not impact the Antarctic hydrological systems and so we have rephrased to say "variability in subglacial water pressure and fluxes likely does not occur on diurnal, weather-related, or seasonal timescales". We think that snow loading likely does not impact the Antarctic hydrological systems that we are examining under very thick (2km) ice and our model is not currently configured to test this. In terms of tide forcing, we note that the boundary conditions include a static outlet pressure and that tidal influences are not included. While it would be interesting to see the influence of tides on the hydrology of the system it is beyond the scope of this study.*

13.2: water volume per unit area

> *Changed.*

13.4: the development of these hydrological systems will also be different

> *Changed.*

13.9: similar phenomenon

> *Changed.*

13.11: suggest that funneling

> *Changed.*

13.15: channels beneath the ice stream….therefore do not induce temporal…

> *Changed.*

13.18: channels is a key enabler of spatially propagating pressure waves

> *Changed.*

13.19: phenomenon that has ..

> *Changed.*

13.21: allow the waves to develop

> *Changed.*

13.22: realistic to assume a unidirectional relationship between hydraulic gradients and water fluxes. This whole sentence is pretty arm wavy and doesn't give the impression that the issues have been thought through clearly. I have a similar problem with the next sentence as well.

We think this is a misunderstanding due to our phrasing. We are not suggesting that the low hydraulic gradients are as a result of shallow surface slopes and low water fluxes etc. Instead we are saying that the reasons for the pressure waves are a result of a) hydraulic potential gradients, b) low water fluxes and c) funneling of water from a large catchment.

To clarify we have changed the sentence from: "These are low hydraulic potential gradients due to shallow surface slopes, relatively low water fluxes, and funneling of water from a large catchment"

To:

"These factors are: relatively low water fluxes; low hydraulic potential gradients due to shallow surface slopes; and funneling of water from a large catchment so that the water input rate is higher than the capacity of the ice stream."

We have also altered the following sentence for clarity (see below response).

13.24: it is water pressure gradients that drive water flow, not the pressure per se

We have clarified by changing the sentence from: "Our hydrological explanation for the waves is that water pressure builds up in the constricted system, followed by faster water flow resulting in temporary channel growth, which moves the excess water downstream."

To:

"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."

13.27: distributed system water thickness –but there seems to be an unstated assumption that the change in film thickness is directly/linearly related to the change in water pressure. Is this true?

The film thickness is directly related to the change in the water pressure in the cavity system. However, the pressure change does not allow more than 8cm increase in the distributed system thickness. We clarify by changing the phrasing to:

"Despite the pressure change, the water layer thickness of the cavity system only increases by a maximum of 8 cm".

14.2: might be identifiable at the surface.

Changed to "might be identifiable on the ice surface using feature tracking methods".

14.4: do arise in constricted systems

Changed.

14.7: for a period…

Changed.

14.18: pressure for between …surge-type

Changed.

14.21: do you mean transit, rather than transition?

Yes, we have changed this.

14.23: such bulls-eye patterns have also been found on outlet glaciers in northern Ellesmere Island by Laurence Gray (published too)

We apologize, we cannot identify the article that the reviewer is referring to. The Gray (2011) paper in GRL does mention regions of ice surface uplift and subsidence but does not discuss the state of the hydrological system (for example constricted vs. efficient) in reference to this, which is the primary link between our modeled pressure wave outputs and the analysis of the 'bullseye' patterns by Fatland and Lingle (2002).

14.24: period of 2 to 4.5 years…

Changed.

14.26: "due to similar criteria" is a strange way to say this.

We have changed this to "due to similar factors".

15.1-15.3: you seem to treat lake water volume and water pressure as synonymous here, but I don't think that is correct if the system is in contact with the ice and water outside the lake basin

Here we summarize the jokulhlaup theories of Nye (1976) and Fowler (1999) where leakage from the subglacial lake changes the downstream water pressure and hydraulic potential that eventually allows drainage. To clarify that we are not discussing our own outputs we now state: "The lake water accumulation in the latter type of system is driven by increased melt through volcanically-inducted heating. In these lakes, as the water builds up in the basin, some leakage seeds channel growth …"

15.15: can span two pressure waves

Changed.

15.16: pressure wave forms to conduct

We have changed the sentence to read "channels are efficient enough by the time the second pressure wave forms to conduct the extra water".

15.19: pressures from developing downstream

Changed.

15.20: wave passes…sizes of channels….are crucial….demonstrate that

Changed

15.25: how can a lack of cycles be similar to a model of cycles?

Here we intended to discuss a lack of repeating cycles rather than a lack of cycles altogether. For clarity we have changed our phrasing to "The lack of repeating cycles of lake growth and drainage is similar to the jokulhlaups modeled by…".

15.29: drainage cycles

Changed.

16.3: do you mean "linked to the passage of the wave"?

Changed.

16.8: not that 2-D hydrological networks exist in reality!

Changed from "…2D hydrological networks in addition to 1D models" to "…2D modeled hydrological networks in addition to 1D models".

16.11-16.12: rather than prevents it – but would this be geometry specific or general?

We have rephrased as suggested and to clarify we have added "the overdeepening in the current configuration" to illustrate that this is reliant on geometry.

16.16: exist at pressures slightly below…

Changed.

16.19: and at the top of the adverse slope is a key….

Changed.

16.24: data have been (data = plural of datum)

Changed.

16.26: where are these cycles seen?

We have added "…in various regions of Antarctica (e.g. Gray et al, 2005; Wingham et al, 2006; Fricker et al, 2007; Fricker et al, 2014)" to the end of this sentence in order to direct readers to some of the relevant literature.

16.28: and drainage demonstrated by the model..

Changed.

17.1: and to extend the record…. (but why no reference to CryoSat2 as a source of altimetry data?)

We now state that "Ice surface elevation data have been available from satellite-based sources such as ICESat and CryoSat2." and "It will require continued data from CryoSat2 and from systems such as ICESat2, due to launch in 2017, to extend the record and allow assessment of the system development over the next couple of decades".

17.3: forms in the overdeepening….basin to a depth of 150m

Changed.

17.4: for attempts to calculate

Changed.

17.7: water flux across a hydraulic equipotential surface

Changed.

17.15: are important for..

Changed.

17.19: rates inferred from altimetry.

Changed.

17.20: meters are also consistent with rates…..over Recovery

Changed.

17.22: The area of our lake is…

Changed.

17.25: and has an area of 60 km2

Changed.

17.26: directly with observations from the Recovery system which consists of many lakes within a region of complex topography (bed, surface or both?) . Should cite a source of information about this system

We have now specified that the basal topography is complex and have cited Fricker et al (2014).

17.28: increased in volume by…

Changed.

18.1: flux (not flux rate)

Changed.

18.2: yield lake growth…

Changed.

18.4: Final sentence of para needs rewriting (clearly your results are not **located** between the 2 lakes and, even if they were, this would have no bearing in their quality)!

We have clarified by writing as: "As a result, our model outputs lie within the range of the larger and smaller Recovery lake filling and drainage rates, which gives us confidence in our results."

18.9-10: This sentence needs rewriting – I don't think channels move water..

The sentence has been changed to "The channels are of sufficient size to propagate the high water pressure to ~50km downstream of the lake."

18.12: negative in the region around the lake

Changed.

18.14: I think this sentence needs some elaboration

We have re-written the sentence to say:

"As a result, periods of high water pressure (and by proxy, faster ice velocity) in the vicinity of the lake occur as the lake is growing rather than when it is draining; conversely, high water pressures due to lake drainage are found downstream."

18.17: I presume you mean measurements rather than calculations here? But you seem to be treating ice velocity and water pressure fluctuations as synonymous, which is not wise.

We have changed 'calculations' to 'measurements'. When discussing the impact of modeled hydrological development on ice dynamics, in the absence of a fully coupled model, it is common practice to use the effective pressure as a proxy for ice velocity. We now clarify this in our introductory aims by saying we examine "the impact of the lake drainage on downstream water pressures and, by proxy, ice dynamics". Also see above changes to sentence 18.14 where we reiterate this.

18.17: such high pressure…

Changed.

18.23: attain large sizes – (though the actual sizes reported are not especially large, given the size of the system being studied)

We have removed this phrase so the sentence now reads: "In our modeled Antarctic system, however, channels can persist for a number of years."

18.25: The faster rate of shrinkage, relative to the rate of channel growth, is (BUT is it not really just a consequence of the non-linear form of the flow law of ice and the fact that water pressures drop very rapidly when a channel ceases to be full of water?)

It is correct that the faster shrinkage rate is due to the non-linear form of the flow law. To clarify we now say: "The faster rate of shrinkage, relative to the rate of channel growth is a result of the non-linear creep of ice closing the channel once pressures drop below overburden."

19.1: as a pressure wave migrates through..

Changed.

19.4: that can cause channel growth over many years

Our phrasing was intended to imply that channels take many years to form due to constant water supply so we wish to have the sentence emphasis on the water supply *rather than the channel growth. We have added in punctuation to clarify so the sentence now reads: "that, over many years, can cause channel growth".*

19.5: smaller, so water flux through these systems will be lower during the winter months.

Changed.

19.11-19.15: Para is really irrelevant unless you make a case that channels incised into bedrock influence the pattern of drainage development and pressure wave propagation in subsequent years

We have removed this paragraph.

19.17: is highly simplified. For instance….rates, or variable

Changed.

19.19-19.20: but you only gain insight into the real system if the model simplifications don't significantly change the physics

With our approach of studying a synthetic system we do not change the physics of the hydrology equations that are being applied; instead we are limiting complications from aspects like highly variable topography or basal sliding rate that could cause the pressure wave and lake growth and drainage effects that we see. We now address this in the introduction by saying:

"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."

We plan to later apply the model to a system with variable topography and variable basal sliding included but, in order to best asses the outputs, a synthetic model is an excellent way to test the parameter space. As we discuss in the model limitations, it is possible that basal materials such as sediment could be present, which would require different equations that are not readily applicable in this type of model. We suggest that this is an area of future work.

19.22-19.24: The justification presented here is really weak

We are unclear what the reviewer is referring to here. If they are discussing the approach of using linked-cavity equations for a distributed drainage system we now elaborate on this in the model configuration section by saying:

"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 (Creyts & 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."

19.24: Why can't you have linked cavity systems at the surface of a sediment substrate, especially if it contains large clasts?

Yes, it is possible that linked cavity systems can exist on the surface of sediment, particularly with large clasts. This is demonstrated in the modeling work of Creyts and Schoof (2009) and is the study that we reference in our discussion here of the ability of GlaDS to emulate drainage in a sediment-based system.

20.1: tests to assess whether the pressure waves are …

Our tests were set up to make sure numerical artifacts were not causing the pressure waves and so we retain our wording.

20.4: obtain similar results as..

Changed.

20.4: "errors" – don't you mean differences – you have no idea what is reality so how can you refer to them as errors?

Changed to 'differences'.

20.8-20.19: The question raised by this paragraph is how value are the insights derived from the study given its obvious limitations?

All numerical models have limitations as they are merely a representation of nature. We are upfront about the limitations of our approach so that future approaches can expand on ours. Given the difficulty of in situ access to the subglacial systems of ice streams we are, however, limited at the present to primarily relying on models. As long as our readers are aware of what the model can and cannot address, the outputs can be used to drive future research and initiate hypotheses about the systems we discuss.

20.22: could allow downstream flow of water to occur….model, perhaps reducing the local…

Changed.

20.23: Why is it unlikely?

It is unlikely that the pressure waves would be entirely removed by including flexure in the model because the pressure wave propagates faster that the likely viscous response *time of ice. However, it is due to the fact that we cannot fully ascertain this that it is included in the model limitations. We clarify in the text by writing:*

"However, given the propagation speed of the pressure waves and a viscous response time of ice on the order of months, it is unlikely that flexure would entirely remove the pressure waves; instead it might change the downstream speed of the wave."

21.3: through internal dynamics alone.

Changed.

21.2-21.5: I would argue that the model results generate potentially testable hypotheses. As things stand we really have no idea whether we should believe them or not – so to argue they produce new insights seems like a stretch to me.

Our use of 'insights' is to ascertain likely features of the hydrological systems using the model, which can then be tested through data collection, rather than using a model to fully determining the basal hydrological conditions. We clarify by writing:

"The outputs therefore provide new insights and suggest directions of further research related to hydrological development and subglacial lake dynamics in Antarctic ice streams."

21.7: delete development – you aren't simulating how the drainage network develops as far as I can tell

As this is a spatially and temporally evolving model of subglacial hydrology it is primarily simulating drainage network development. It is this that allows pressure waves to migrate through the system and the lakes to grow and drain. We therefore retain our original phrasing. This is now clarified in our aims in the introduction.

21.11: efficient drainage networks

Changed.

21.13: delete "instead"

Changed.

21.16: water pressure peak

Changed.

21.18: can persist at such levels

Changed.

21.20: over scales similar to those observed beneath Antarctic ice streams.

Changed.

21.22: occurs only when

Changed.

21.25: do these pressure waves result in hydraulic jacking at the bed?

We address this when we discuss the possibility of ice flexure as a result of pressure waves. However, we also point out that the related change in water thickness is minimal and so that physical jacking is likely to be minimal.

22.3-22.5: Final sentence need rewriting

We have re-written the final paragraph. It now reads:

"The results from this synthetic ice stream hydrological experiment suggest that the Antarctic basal systems can be highly transient and variable with interactions between water pressure and channel growth that occur over a scale of years. These results encourage further analysis of Antarctic ice stream velocities, which could show an imprint of such a system. 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."

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' interupts the sentence. Remove. Also add in some citations of work studying these.

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

6556, lien 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 (Creyts & 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 jokulhaulp 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 acknowedged. 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 (Creyts & 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."

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Modeling Antarctic subglacial lake filling and drainage cycles

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Abstract. The growth and drainage of active subglacial lakes in Antarctica has previously been inferred from analysis of ice surface altimetry data. We use a subglacial hydrology model applied to a synthetic Antarctic ice stream to ~~determine~~ examine internal controls on the filling and drainage of subglacial lakes~~and their impact on ice stream dynamics~~. Our model outputs suggest that the highly constricted subglacial environment of the ice stream, combined with relatively high rates of water flow funneled from large catchments, can combine to create a system exhibiting slow-moving pressure waves. Over a period of years, the accumulation of water in the ice stream onset region results in a buildup of pressure creating temporary channels, which then evacuate the excess water. This increased flux of water ~~through~~ beneath the ice stream drives lake growth. As the water body builds up, it ~~too~~ steepens the hydraulic gradient and allows greater flux out of the overdeepened lake basin. Eventually this flux is large enough to create channels that cause the lake to drain. ~~Due to the presence of the channels, the drainage of the lake causes high water pressures around 50km downstream of the lake rather than immediately in the vicinity of the overdeepening. Following lake drainage, channels again shut down. Lake drainage~~ Lake drainage also depends on the internal hydrological development in the wider system and therefore does not directly correspond to a particular water volume or depth. This creates a highly temporally and spatially variable system, which is of interest for assessing the importance of subglacial lakes in ice stream hydrology and dynamics.

1 Introduction

Subglacial lakes store large quantities of water in bedrock overdeepenings and regions of hydraulic convergence underneath the Antarctic ice sheets, including the highly dynamic ice streams (e.g. Wingham et al., 2006; Wright and Siegert, 2012). The role of these water bodies in ice dynamics is largely unknown and limited by availability of data and knowledge of the basal hydrological regimes. The former has been ~~increasingly~~ addressed with satellite surface altimetry data products, allowing analysis of surface ice flexure in the region of subglacial lakes (e.g. Gray et al., 2005; Fricker et al., 2007). It has been found that many of the lakes in regions of fast flowing ice are active over ~~the~~ a period of <1-5 years causing ice uplift and subsidence related to the lake filling and draining (e.g. Fricker et al., 2010). The drainage of lakes have been found, in In the case of Byrd Glacier in the East Antarctic, the drainage of lakes has been found to cause significant downstream ice speed up of over the a period of 1-2 years (Stearns et al., 2008). Basal lakes also appear to be hydrologically interconnectedas . This is demonstrated by ice subsidence coincident with downstream ice uplift at lakes located 290 km apart in Adventure subglacial trench in the East Antarctic (Wingham et al., 2006). The mechanisms and longevity of hydrological connection are, however, not well understood.

In situ data of hydrological conditions at the bed of the Antarctic ice sheets are limited due to difficultly of access. As an alternative, numerical models can be used to infer conditions at the ice-bed interface and to estimate the impact of subglacial lakes on hydrological developmentinvestigate the feedbacks between hydrology and subglacial lake formation. To date, hydrological models of Antarctic subglacial lakes have been primarily diagnostic rather than prognostic and rely on ice surface uplift and subsidence data to determine the threshold switch between lake filling and draining (Carter et al., 2009, 2011; Carter and Fricker, 2012). Pattyn (2008) used a synthetic approach with a full Stokes ice flow model to assess triggers for Antarctic lake drainage. Those model outputs suggested that small changes in water input into a lake can cause episodic, although partial, drainage and related changes in the ice surface slope. An ice flow modeling approach was also used by Sergienko et al. (2007) to assess changes in the ice surface slope and local dynamics due to lake drainage. That study found that changes in lake depth are not directly translated to ice surface uplift and subsidence so that assessing lake volume from ice surface altimetry is challenging. These ice dynamics models begin to address the feedbacks between ice flow and subglacial lake filling and drainage, but did not include an active hydrological network, necessary to determine the larger, catchment-scale causes of lake stability.

Here we present the first application of a 2D basal hydrology model to analyze subglacial Antarctic lake stability and 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 drainage on ice stream hydrological development anddynamics. We use the lake drainage on downstream water pressures and, by proxy, ice dynamics. To achieve this, we apply GlaDS, a finite-element hydrological model, which incorporates both distributed and efficient drainage components. It has previously been applied to simulate drainage systems of synthetic ice sheet catchments and real Alpine glaciers (Werder et al., 2013) . We apply this model to a synthetic regime in Antarctica, designed to emulate Recovery Ice Stream, a region with up to thirteen active lakes (Fricker et al., 2014) , to assess the behavior and stability of subglacial lakes in the Antarcticbasal 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 and Fricker, 2012)~~, which~~ ; 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 the 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.

2 GlaDS model

GlaDS (Glacier Drainage System model) is a 2D finite element model that incorporates equations for subglacial R-channel growth and linked cavity system development. It has previously been applied to simulate drainage systems of synthetic ice sheet catchments and real Alpine glaciers (Werder et al., 2013) . The model configuration and application to synthetic ice sheet catchments and valley glacier systems is described fully in Werder et al. (2013); here we give a brief overview of the model. The effective pressure, N, in the system is

$$N = p_i - p_w, \tag{1}$$

where p_w is the water pressure and $p_i = \rho_i g H$ is the ice overburden pressure with ρ_i the ice density, g the gravitational acceleration, and H the ice thickness. Mass conservation in the distributed ~~linked-cavity~~ linked cavity system is described with

$$\frac{\partial h}{\partial t} + \frac{\partial h_e}{\partial t} + \nabla . q = m, \tag{2}$$

where h is the average thickness of the water layer, h_e is an effective storage layer thickness representing either an englacial or basal sediment aquifer, q is the water discharge and m is the prescribed source term for the distributed system representing, in this case, geothermal and frictional basal melt. Change in the water thickness is determined by cavity opening from sliding over basal bumps and closing through viscous ice deformation. Flux in the distributed system is related to the hydraulic potential gradient, $\phi = \rho_w g B + p_w$, where ρ_w is the water density and B is the bed elevation. Channels are modeled as semi-circular R-channels that grow due to melting and close due to viscous creep of ice. Mass conservation in the channels is described with

$$\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial s} = \frac{\Xi - \Pi}{\rho_w L} + m_c, \tag{3}$$

where S is the channel cross-sectional area, Q is the discharge through the channel, s is the horizontal distance along the channel, Ξ is the dissipation of potential energy, Π represents the change in sensible heat, L is the latent heat of fusion and m_c is the water that enters the channel from the surrounding distributed system. Model parameters are given in Table 1 and follow the same nomenclature as in Werder et al. (2013).

The model mesh is unstructured with channels calculated along the element edges to form a network. Water is exchanged between channel segments at the element nodes. The distributed system is calculated within and across the elements. Interaction between the two hydrological systems is determined by assuming the water pressure is the same in a channel and the distributed sheet immediately adjacent to it. Crucially for our application to subglacial lake development, the pressure calculated in the distributed system also includes the water thickness so that a body of water, such as a lake, will have a direct impact on the system hydraulic potential.

3 Model configuration

We configure GlaDS to represent a synthetic Antarctic system with characteristics similar to Recovery Ice Stream in the East Antarctic ice sheet. Recovery Ice Stream has been identified to have up to 13 active lakes that periodically fill and drain (Fricker et al., 2014). This system also has one of the largest catchments in the East Antarctic, draining 8% of the ice volume (Joughin et al., 2006), and is of considerable interest for analysis of lake drainage dynamics (Bell et al., 2007; Langley et al., 2011, 2014; Fricker et al., 2014). Our synthetic system is a simplified version of the Recovery region with a domain featuring a large catchment of area 5.4×10^5 km^2 feeding into an ice stream of width 50 km and length 300 km (see Fig. 1). The total area of the upper catchment equals the Recovery subglacial drainage catchment area feeding into the ice stream,. This was calculated using routing algorithms assuming water is at ice overburden pressure, applied to the BEDMAP2 basal and surface digital elevation models (DEMs) (Fretwell et al., 2013).

Two topographies are used within the model domain. The first has a planar basal slope of 0.06°. Due to the shallowing of ice surface slopes in the interior of Antarctic ice stream catchments, we construct a steeper surface slope of 0.29° in the ice stream and 0.11° in the catchment. This gives These values are based on average surface slopes in Recovery Ice Stream and give a maximum ice thickness of 3337 m. The second topography is identical to the first one except for an added overdeepening located 150 km upstream from the lower boundary. This overdeepening is created using a Gaussian formulation with a fixed radius of 7.5 km and maximum depth of 150 m overlain onto the basal planar slope; these values are consistent with medium-sized lakes in Recovery Ice Stream.

For the first topography, the model mesh in the ice stream has a minimum element edge length of 780 m, which increases to an average edge length of 1500 m in the catchment. In the second topography the mesh is the same but is refined within the overdeepening to a minimum edge length of 220 m, which allows accurate calculation of changes within the subglacial lake.

Water input to the distributed system is continuous across the domain, representing water production from both geothermal and frictional heating. Initially, we apply an input rate of 0.5 mm a^{-1}, a level that is likely too low for the Recovery region and is used to run the model to steady state. The second scenario uses the predicted water production rate for the Recovery catchment of 1 mm a^{-1} (Fricker et al., 2014). The model is ramped from steady state to this level of water input over the a period of 10 years, inducing a gradual change. In these model runs, the channel system has no direct input and channels are initiated from distributed-based flux, i.e. no pre-existing channels are assumed at the beginning of the model runs.

The upper and lateral boundary conditions are Neumann conditions set to zero inflow. The downstream boundary has a Dirichlet pressure condition set at ice overburden pressure to represent the ocean outlet of Recovery Ice Stream. Tidal influences on marginal water pressure are not included in this model set-up.

Our standard model parameters are listed in Table 1. Given lack of knowledge of the basal conditions in many regions of Antarctica, we perform sensitivity experiments to test the applicability of the model and also to assess controls on subglacial lake stability. These sensitivity parameters include tests on the overdeepening size, the conductivity of the distributed system versus the efficient system, and the volume of water produced at the bed. The variations of these parameters are given in Table 2. For each variation, the model is first allowed to run to steady state. 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 (Creyts and 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.

For the second topography, the model mesh is refined within the overdeepening to allow accurate calculation of changes within the subglacial lake. In these runs, the minimum element edge length is 220m in the overdeepening and 780m in the ice stream. These edge lengths increase to an average of 1500m in the upper catchment.

4 Results and analysis

4.1 Planar bed topography

We begin by examining the hydrological development of the ice stream assuming no overdeepenings and a fully planar bed configuration. The steady state solution for our model with low water production throughout the system causes the model water pressure to drop below overburden everywhere, including to 75% of overburden within the ice stream. This low pressure occurs because there is not enough water to pressurize the distributed cavities for an our fixed ice speed of 100 m a^{-1}. Antarctic systems likely operate close to overburden pressure due to the substantial ice thickness (Engelhardt and Kamb, 1997) and as a result, this steady state modeled solution is not realistic for the Recovery system.

In the second scenario, the water input rate is gradually increased over 10 years to that predicted for Recovery Ice Stream (i.e. 1 mm a^{-1}). The increased flux in the Recovery catchment initiates pressure waves in the ice stream where water is funneled from the large catchment into the narrower ice stream. We define a pressure wave as a ridge of water above ice overburden pressure, which propagates downstream. This is demonstrated in Fig. 2 where the change in effective pressure along the ice stream center line is plotted. In the Recovery system, these pressure waves repeat and by year 70 have settled into a periodic pattern as shown in Fig. 3a and b. This figure plots the average water pressure at locations 200 and 100 km from the margin, along with channel cross-sectional area. In these regions, the channels grow to $\sim$0.3 m^2 and reduce to $<$0.02 m^2 cross-sectional area over a pressure wave cycle. There is therefore a link between the pressure wave and the growth of channels. ~~It appears the~~ The pressure waves form because there is not enough hydrological capacity or hydraulic gradient ~~in the~~ at the bed of the ice stream to move water funneled from the large catchment downstream. The pressure of the water therefore increases, alters the hydraulic gradient and enhances downstream flux. This greater flux then encourages growth of channels. Once the pressure wave has passed, flux rates decrease and the channels close.

Figure 3c shows effective pressure, N, along the center line for a series of pressure waves moving through the system. The pressure waves have, on average, a speed of 220 m d^{-1} with an area of the domain remaining under pressures higher than overburden for up to two years. An example of one pressure cycle from year 85 to 88 is also plotted with the number of days the area is above overburden and the length scale affected by overpressure at that time (Fig. 3d). The longitudinal length affected by pressures above overburden varies on the timing of the wave cycle, increasing to a maximum of $\sim$170 km when the highest pressure is centered at a distance of $\sim$200 km from the downstream boundary of the ice stream (Fig. 3e). As a result, not all of the ice stream is equally affected by high pressures, both in terms of ~~duration and level of pressure~~either the magnitude of the water pressure or its persistence.

4.2 Overdeepened bed topography

We now run the same set of experiments using the bed topography that includes an overdeepening. With the low water input forcing, a steady state solution is reached where the pressure is again entirely below overburden, including in the overdeepening. In this steady state, no lake forms in the overdeepening as the volume of water entering the overdeepening always equals the volume of water exiting. If the pressure in the hydrological system was everywhere at overburden pressure, as is commonly assumed when no hydrological modeling capability is available, all water flow would be directed into the overdeepening and form a lake. However, with a fully coupled hydrology model, the system adapts rapidly so that the pressure conditions in the lake are precisely at the level to allow equal outflow for inflow, with pressures slightly lower on the ~~tip~~ rim of the reverse slope than in the overdeepening so that there is a positive downstream hydraulic potential gradient despite the adverse slope. As a result, the ~~downstream bedrock ridge~~ overdeepening reverse slope does not prevent water flow through the lake.

Using the above steady state as the initial condition and then ~~ramping up the~~ increasing the water input to the value representative of Recovery Ice Stream again causes pressure waves to occur (Fig. 4). ~~As shown in Fig. 4a and b, the overdeepening slightly changes~~ The overdeepening slightly alters the timing of pressure waves compared to the planar model runs (~~see Fig.~~ compare Fig. 4a,b with Fig. 3a,b). However, the range of pressure change upstream of the overdeepening is similar between the planar and the overdeepening runs.

~~In the overdeepening, a lake forms when the changing hydraulic gradients induced by~~ A lake forms in the overdeepening due to the altered hydraulic gradient from the pressure waves~~prevent adjustment of~~ ; the hydrological system ~~to the rate of water influx~~ cannot adjust rapidly enough to the increased water flux (Fig. 5). As the lake deepens, the hydraulic gradient over the ~~bedrock ridge~~ reverse slope is steepened and water flux over the ridge is increased. This greater water flux allows channels to form on the downstream ~~tip~~ rim of the overdeepening and lake drainage occurs when the channels downstream of the lake ~~reach a threshold size~~are sufficiently developed. Following lake drainage, water flux over the ~~bedrock ridge~~ reverse slope slows and the downstream channels close (Fig. 5). The lake begins to form again when ~~upstream hydraulic potential gradients change due to passage of~~ another pressure wave ~~,~~ passes, changing the hydraulic potential and driving more water into the overdeepening.

Multiple lake drainages occur over the period of 100 years. As shown in Fig. 6, the lake does not always fill to the same volume prior to drainage, and also has a variety of filling and drainage rates. On average, the maximum lake water depth and volume are 1.3 m and 0.86 km^3, respectively. Once the lake has drained, the average lake depth is 0.47 m (Fig. 6a, c). The lake filling times range between ∼1-3 years with an average of 1.65 years and drainage times between ∼0.8-2.75 years, with an average of 1.8 years. The lake filling and drainage rates peak for each cycle at an average of $\sim 1\,m^3\,s^{-1}$ and $1.5\,m^3\,s^{-1}$, respectively. The fastest lake drainage rate is $2.3\,m^3\,s^{-1}$ (Fig. 6d). The water pressure ranges between 0.95 and 1.04 as fractions of overburden (or 0.7 and -0.6 MPa effective pressure).

The changes in lake pressure do not always match the timing of lake growth and drainage and instead there is sometimes a pattern of two pressure waves for one lake drainage (Fig. 5). This is characterized by a pause in lake drainage as the pressure wave moves through the system, as ~~shown in~~ illustrated by the lake depth ~~output~~ plot in Fig. 5. The initial growth of the lake is driven by movement of the first pressure wave through the system. However, when the second wave moves through, the channels are sufficiently developed on the downstream region of the lake that they have capacity for the additional water driven into and out of the overdeepening. This channel capacity prevents the second pressure wave causing negative effective pressures downstream of the lake (Fig. 4c and Fig. 5). The pause in lake drainage is due to a combination of downstream channel pressurization and additional water flowing through the overdeepening. One lake drainage over two pressure wave cycles demonstrates that the pressure waves are not the only cause for lake growth and drainage but instead provide changing hydraulic conditions that prevent a steady state. As shown below in the sensitivity tests, the impact of the pressure wave on the lake growth and drainage timing depend on the conductivity of the system and the volumes of water in the hydrological networks.

Channel growth and shrinkage rates at the downstream margin of the lake are plotted in Fig. 7a along with the lake water level. During lake drainage, channels at the lake margin grow to a size of $\sim$0.07 m^2, although 10 km downstream they temporarily increase to a maximum of 17 m^2 (Fig. 7b). The channels are not always the same size when the lake drainage begins. ~~The main~~ One discernible pattern is that lower lake volumes at the end of drainage ~~and~~ coincide with the smallest channel sizes~~coincide~~. Beyond this, the rate of channel growth is also dependent on the pressure gradients downstream of the lake and on downstream channel size. As a result, exact controls for lake drainage timing are difficult to ascertain.

5 Sensitivity results

We tested the impact of overdeepening size on lake growth and drainage (Fig. 8 a). ~~We found that, when~~ When the overdeepening depth was decreased from 150 m to 50 m, very little water accumulated in the basin, with water depths increasing by $\sim$8 cm during a growth and drainage cycle. A deeper overdeepening of 250 m caused much greater water accumulation with lake depths up to 6 m. The larger overdeepening also ~~forms and drains~~ allows a lake to form and drain slightly more quickly compared to lake in the standard overdeepening of 150 m. If the overdeepening depth is increased to 500 m, the model mesh is not locally refined enough to allow efficient running of the model and so for deeper lake configurations the model setup would have to be altered.

We also ~~adapt~~ vary the volume of water produced at the bed. When the basal melt rate is decreased from 1 mm a^{-1} to 0.85 mm a^{-1} there is a delay in onset of lake formation (Fig. 8 b). ~~Also the~~ The depth of the lake is also smaller than with the standard melt input at $<$1 m. For input rates smaller than 0.85 mm a^{-1}, no lakes form and no pressure waves occur. With water production rate doubled to 2 mm a^{-1}, lake drainages and pressure waves occur more frequently and initiate earlier, although the lake water levels ~~are on~~ fluctuate over a similar range. As 2 mm a^{-1} is double the value of subglacial water production rates suggested for the Recovery catchment by (Fricker et al., 2014) we do not test the model with greater rates of water production.

Lowering the distributed system conductivity from 1×10^{-3} $m^{7/4}$ $kg^{-1/2}$ to 1×10^{-4} $m^{7/4}$ $kg^{-1/2}$ causes the a deeper lake to form, with lake growth and drainage occurring over a longer time scale

(Fig. 8 c). Lowering the conductivity further to 1×10^{-5} $m^{7/4}\,kg^{-1/2}$ caused the model to run too slowly to produce outputs over our analysis time period. When the conductivity is raised slightly from the baseline of 1×10^{-3} $m^{7/4}\,kg^{-1/2}$ to 1.1×10^{-3} $m^{7/4}\,kg^{-1/2}$, the lake takes longer to form than the standard run because the ice stream capacity is larger and ~~therefore it~~ it therefore takes more time to ~~achieve~~ reach near-overburden pressure and induce the pressure waves. With a higher distributed system conductivity, the system remains in steady state, no pressure waves develop, and no lake forms. There is therefore a narrow range of distributed system ~~conductivity where~~ conductivities within which the lake will form and drain. However, combinations of different parameters also allow stable lake growth and drainage. For example, a higher distributed system conductivity with greater water input allows lake formation.

When channel conductivity is lowered from 5×10^{-2} $m^{3/2}\,kg^{-1/2}$to 5×10^{-3} $m^{3/2}\,kg^{-1/2}$, no channels form at the margin of the lake and the pressure and lake level remain high throughout the model run (Fig. 8 d). With a high channel conductivity of 5×10^{-1} $m^{3/2}\,kg^{-1/2}$ the system capacity of the ice stream is increased so pressure features do not ~~form,~~ occur; the ice stream is mostly in steady state and a lake does not form. In this situation, the lake stabilizes around 96% of overburden.

6 ~~Discussion~~Model limitations

~~The subglacial systemsof Antarctica are regions where little is~~ Our modeled synthetic system has limitations due to its simplified nature. For example, it does not incorporate variable topography, spatially varying basal melt rates, or variable basal sliding parameters. However, the aim with this model is to gain insight into lake filling and draining characteristics without complicating the system. It is possible that including topography in the model could impact the pressure waves and therefore the rates of lake filling and draining. We also assume that water flows through a linked cavity system rather than a sediment based system, with the latter possibly being more prevalent in Antarctic ice streams. Water flux in sediments could be more restricted than in linked cavity systems. However, it is plausible that sediment-based systems have similar dynamics as linked cavity networks with sliding opening spaces between the ice and substrate and ice creep closing the space when water pressures drop (Creyts and Schoof, 2009) . Sediment deformation processes are, however, lacking in the model.

We have carefully conducted a series of tests to rule out, as far as possible, that the pressure wave features are numerical artifacts. We have performed tests to check that there is sufficient mesh convergence both in the planar and overdeepened topographies and obtain similar results as Werder et al. (2013) with differences in mean effective pressure and distributed water thickness on the range of 10^{-5} relative to a smaller mesh. The tolerances of the ordinary differential equation solver were also tested and selected accordingly.

Although likely not numerically induced, it is possible the pressure waves are not physical. The water pressures in the model do not exceed 1.04 $\times P_i$ (or N = -0.5 MPa) and are therefore not unreasonable. However, pressures above overburden can persist in one area for up to two years, which is a long period of overpressure. Including ice dynamics in the model might change the characteristics of the pressure waves. Feedbacks through faster ice flow and coincident cavity opening could allow greater water flux downstream and reduction of water pressure, as is seen by Hewitt (2013) . Ice physics such as those included in the models of Pattyn (2008) and Sergienko et al. (2007) where changing ice flux and ice surface slopes can influence lake drainage timing are also not incorporated into our model. It is therefore likely that more accurate predictions of lake filling and drainage require coupling of hydrology with ice dynamics models.

Including ice flexure and uplift could also impact the pressure waves and the rate of lake formation. For example, ice uplift at higher pressures could allow downstream flow of water to occur more rapidly than seen in the model, perhaps reducing local overpressure. However, given the propagation speed of the pressure waves and a viscous response time of ice on the order of months, it is unlikely that flexure would entirely remove the pressure waves; instead it might change the downstream speed of the wave. Future numerical experiments including ice flexure would provide insight into the likely persistence of the pressure waves observed in this hydrological model and the links between lake formation and the surface ice motion observed through satellite altimetry (e.g. Fricker et al., 2010) .

Despite the limitations of the current model configuration, this is the first 2D hydrological model to be applied to a synthetic system representing an Antarctic subglacial lake, which can produce lake drainage cycles through internal dynamics alone. The outputs therefore provide new insights and suggest directions of further research related to hydrological development and subglacial lake dynamics in Antarctic ice streams.

7 Discussion

Little is known about the spatial and temporal evolution of the ~~hydrological systems~~ subglacial meltwater drainage systems of Antarctica and their impacts on ice dynamics. With this hydrological modeling exercise we have produced outputs that suggest the system ~~is~~ may be substantially different from that of the more closely studied mountain ~~, and to some extent,~~ and Greenlandic outlet glaciers ~~.~~ ~~In the Antarctic~~(e.g. Iken and Bindschadler, 1986; Nienow et al., 1998; Bartholomew et al., 2012; Dow et al., 2015) . The Greenland Ice Sheet and mountain glaciers receive more than an order of magnitude more water volume per unit area from the surface than is produced at the bed of Antarctic ice streams through frictional and geothermal heating. In addition, one of the defining features ~~is that no water is~~ of the Antarctic is that there is no water input to the bed from the surface~~and therefore any variability at the bed is not driven on a seasonal scale but instead~~ , and so variability in subglacial water pressure and fluxes likely does not occur on diurnal, weather-related, or seasonal timescales, but over years or even decades. ~~This characteristic causes~~ These features cause two major difficulties when attempting to establish ~~how Antarctic basal hydrologydevelops~~the characteristics of Antarctic subglacial hydrology: 1) ~~the subglacial production of water is based on~~ estimates of subglacial water volumes are extrapolated from modeled geothermal heat fluxes and modeled ~~ice fluxes~~ basal friction from ice flux, rather than measured water inputs rates from the surface and 2) available data records, particularly from satellite sources, are limited to the last couple of decades. However, by applying a 2D hydrology model, which produces lake filling and drainage through internal dynamics, we can make a step towards understanding and ~~predicting the complex developments of subglacial Antarctic systems~~projecting the development of Antarctic subglacial drainage systems in addition to generating testable hypotheses.

7.1 Pressure waves

~~Greenland and mountain glacier hydrological systems are driven by seasonal water input from the ice surface whereas Antarctic ice streams have no seasonal hydrological signal. The Greenland Ice Sheet and mountain glaciers also receive more than an order of magnitude more water volume from the surface than is produced at the bed of Antarctic ice streams through frictional and geothermal heating. It is therefore to be expected that the hydrological development in these systems is also different.~~ In mountain glaciers, much work has been dedicated to identifying development of efficient drainage networks that cause a decrease in ice velocity following a speed up at the beginning of the melt season when water enters an initially constricted system (e.g. Iken and Bindschadler, 1986; Röthlisberger and Lang, 1987; Schoof, 2010). In Greenland, a similar ~~phenomena~~ phenomenon has been identified near the ice sheet margin (e.g. Bartholomew et al., 2012; Cowton et al., 2013; Joughin et al., 2013). In the Antarctic, our hydrology model outputs suggest that ~~the~~ funneling of water from a large catchment at the production rate expected for an ice stream like Recovery allows the water in the ice stream to flow continually at pressures close to and sometimes above overburden. Fast flow speeds in ice streams are strong evidence that this situation ~~does occur~~ likely occurs in reality (e.g. Rignot et al., 2011). The growth of channels ~~in~~ beneath the ice stream does diminish pressures but only to a level of $\sim 0.95 \times P_i$ and therefore ~~are not impacting~~ does not induce temporal changes in ice dynamics to the extent observed in mountain glaciers. However, growth of channels ~~are a key driver in allowing movement of the~~ is a key enabler of spatially propagating pressure waves.

The pressure waves are an interesting ~~phenomena that have~~ phenomenon that has not been a common feature of glacial hydrology models. From our sensitivity tests we find that a combination of factors ~~combine to~~ allow the waves ~~. These are low~~ to develop. These factors are: relatively low water fluxes; low hydraulic potential gradients due to shallow surface slopes~~, relatively low water fluxes,~~; and funneling of water from a large catchment so that the water input rate is higher than the capacity of the ice stream. Our hydrological explanation for the waves is that water pressure builds up in the ~~constricted system, followed by~~ upper region of the ice stream, increasing the hydraulic gradient. This leads to faster water flow resulting in temporary channel growth, ~~which moves~~ moving the excess water downstream. ~~There is therefore a close connection between the rate of~~ Despite the pressure change, ~~distributed water thickness and channel growth. Despite this, the water thickness in the cavities~~ the water layer thickness of the cavity system only increases by a maximum of 8 cm, suggesting that it would be difficult to see ~~such a pressure change~~ passage of the pressure wave in surface elevation data. However, the regions affected by high water pressure could cause an increase in ice velocity that might be identifiable ~~using surface~~ on the ice surface using feature tracking methods.

There is evidence from other glacial systems that transient regions of high pressure do arise in constricted systems~~do arise~~. Borehole data from Schoof et al. (2014) demonstrate that transient pressure oscillations ~~occur~~ occurred during the winter in a glacier in the Yukon Territory of Canada~~,~~. These were driven by low water flux rates in a constricted system. ~~These~~ The oscillations lasted over a period of days~~rather than years, as our model suggests could be occurring in~~, as opposed to the years in our model of Antarctic ice streams. Schoof et al. (2014) ~~model~~ modeled this system on an idealized flowline and ~~demonstrate~~ demonstrated that storage of water is an important control on the timing of internally-driven oscillations. Given the significant differences between a ~~Yukon~~ mountain glacier and an Antarctic ice stream it is not surprising that system oscillations would occur at different periodicities. However, it is encouraging that field evidence exists of internally driven transience when the basal hydrological system is expected to be highly constricted. ~~Further~~ Surging glaciers provide further evidence of pressure waves~~comes from surging glaciers~~. Interferometric analysis of the 1995 Bering Glacier surge in Alaska identified numerous '~~bull-eyes~~bull's-eyes' suggested to represent regions of surface uplift due to high pressure from water in a constricted system (Fatland and Lingle, 2002). This region remained under pressure for between 1-3 days as water moved downstream. Similar regions of temporary uplift were also observed on a nearby ~~non-surgetype~~ non surge-type glacier during the winter months when little water was moving through the system (Lingle and Fatland, 2003). Again, these pressure waves ~~transition~~ transit much more quickly than we suggest ~~for our~~ might occur in an Antarctic system but illustrate that such oscillations are observable in data.

7.2 Subglacial lakes

The hydrological model produces lake growth and drainage over a cumulative ~~range of 2-4.5~~ period of 2 to 4.5 years (Fig. 6). This cycle is driven by both the pressure waves and the growth of channels downstream of the lake. As such, the lake drains due to similar ~~criteria~~ factors that characterize jökulhlaups in regions like Grímsvötn, Vatnajökull, in Iceland. The lake water accumulation in the latter type of system is driven by increased melt through volcanically-inducted heating. ~~As~~ In these lakes, as the water builds up in the basin, some leakage seeds channel growth (e.g. Nye, 1976; Clarke, 1982). The 'seal' preventing lake drainage can be broken when the lake is at positive effective pressures depending on development and pressurization of the system downstream of the lake (Fowler, 1999). The jökulhlaup model of Fowler (1999) is based on there being the existence of a region of reverse hydraulic gradient downstream of the lake, which migrates upstream as the lake grows and alters the effective pressure gradient. In our modeled subglacial lakes in the Antarctic, the lake pressure is important in that it changes the hydraulic potential gradient driving water over the reverse bedrock slope, but there is no physical ‘seal’ of reverse hydraulic potential gradients. Insteadit is a threshold , it is channel size and overall system hydraulic gradient driven by changes further downstream that allow the lake to drain (Fig. 5). The In the synthetic Antarctic system, the lakes are not draining at the time of maximum pressure in the lake so that, while it is not fully realistic to not take account of ice flexure at times of water overpressure, it is not the overpressure alone that is causing lake drainage (Fig. 6). As shown in Fig. 5, one lake growth and drainage cycle can occur over span two pressure waves. This is because the channels are efficient enough by the time the second pressure wave forms to conduct the extra water driven into and out of the overdeepening. The second pressure wave therefore dissipates once it reaches the overdeepening and the channels prevent negative effective pressures from developing downstream of the draining lake. The fact that the lake does not grow and drain every time a pressure waves wave passes is further evidence that the size of channels both immediately downstream of the lake and further downstream in the system (creating the necessary hydraulic gradients) is are crucial for both lake growth and drainage. Our sensitivity tests with less conductive channels demonstrates that , demonstrate that the lake does not drain without the growth and shrinkage of channels , the lake does not drain (Fig. 8d).

The lack of repeatable repeating cycles of lake growth and drainage is similar to the jökulhlaup cycles kulhlaups modeled by Kingslake (2015). Based on the Nye (1976) equations, that model demonstrated his model demonstrates that lake floods driven by different rates of meltwater input had characteristics including chaotic dynamics (where the initial conditions strongly controlled control lake flood timing and cycles did do not repeat). Our lake filling and draining cycles reveals properties similar to the flood characteristics described by Kingslake (2015) . We In our simulations we see situations where meltwater input (driven by the pressure waves) causes a lake growth and drainage closely linked to the passage of the wave (see years 65 to 73 in Fig. 6). As describednoted above, we also have one lake drainage over some lake drainages spanning two pressure wave cycles. The lake growth and drainage is characteristics are non-repeating (Fig. 6a) even though, in the scenario without an overdeepening, the pressure wave settles into a stable pattern by 70 years (Fig. 3a and b). As a result, our outputs also suggest chaotic dynamics and demonstrate that this can be a condition of 2D modeled hydrological networks in addition to 1D models.

One important characteristic of the subglacial lakes to note is that , at no stage does the overdeepening in the current configuration fully prevent downstream flux of water over the reverse bedrock slope. The presence of a subglacial basin therefore only hampers water flux rather than preventing prevents it. This is because the hydrological system is rarely static at overburden pressure. Instead, when the system approaches overburden~~the pressure waves cause~~ , the development of pressure waves causes continual changes in water pressure. At all stages of the model runs, ~~the~~ water can flow up the adverse slope of the overdeepening~~because the~~ ; this is because water pressures at the ~~tip~~ rim of the overdeepening ~~can exist~~ are slightly below overburden ~~as a result of the~~ due to the presence of small channels. ~~This creates a gradient due to the~~ Combined with higher pressures in the lake, this creates a gradient that allows water to flow up the reverse slope (Werder, 2016) . The relative difference between the pressure in the lake and at the ~~adverse slope tip~~ top of the adverse slope is a key driver for how much water can exit the lake. In terms of lake dynamics, this process suggests that an instability must be present in the modeled system to allow lake growth and drainage~~, otherwise~~ . Otherwise, the system tends to steady state ~~and~~ with equal inflow and outflow through the overdeepening, and no lakes form. In our modeled system, the instability is caused by the pressure waves that continually change the hydraulic gradients in the system.

Ice surface elevation data ~~has~~ have been available from satellite-based sources such as ICESat ~~. The ice surface altimetry allows~~ and CryoSat2. These data have allowed identification of lake filling and draining cycles over the period of a decade in various regions of Antarctica (e.g. Gray et al., 2005; Wingham et al., 2006; Fricker The longevity of lake volume change means that it is not yet possible to determine whether the somewhat chaotic nature of lake growth and drainage~~as demonstrate~~ , as suggested by the model outputs, is also seen in nature. It will require ~~data from~~ continued data from CryoSat2 and from systems such as ICESat2, due to launch in 2017, to ~~continue~~ extend the record and ~~assess development~~ allow assessment of the system development over the next couple of decades.

The lake that forms in ~~our~~ the overdeepening is meters thick rather than filling the basin ~~of depth~~ to a depth of 150 m. This has important implications for attempts ~~of calculating~~ to calculate Antarctic-wide estimates of water budgets that include active lakes. Carter et al. (2011) and Carter and Fricker (2012) modeled water budgets for the Siple Coast region of the West Antarctic using water flux ~~over an hydropotential~~ across a hydraulic equiopotential surface and lake filling and drainage rates inferred from satellite altimetry data. This approach assumed that all water was flowing at overburden pressure and that overdeepenings prevented downstream water flux as the lakes were filling. Carter and Fricker (2012) adapted their model to allow for 'leaking' lakes that did not act as sinks but allowed ~~all water to throughflow~~throughflow of all water. This water budgeting method produced encouraging results linking the satellite altimetry data with estimated basal melt rates. Our model outputs suggest, however, that overdeepenings can allow downstream water flow at the same time as accumulating lakes, and also that varying water pressures in the system are ~~very~~ important for lake growth and drainage. This could impact the rates of filling and drainage of the Siple Coast lakes examined by Carter et al. (2011) and Carter and Fricker (2012), and perhaps constrain some of the discrepancies between modeled lake filling and drainage rate when compared with the ~~altimetry inferred rates~~ rates inferred from altimetry.

Changes of lake water level in the range of meters is are also consistent with the rates of ice surface uplift observed from altimetry measurements at over Recovery Ice Stream (Fricker et al., 2014)). Our lake area The area of our lake is 177 km^2 and located 150 km from the ice margin. It is therefore somewhat comparable to lakes 4 and 5 in Recovery Ice Stream (although these are both slightly larger in area at 220 and 273 km^2, respectively (Fricker et al., 2014)). Recovery lake 3 is 50 km downstream and is smaller with has an area of 60 km^2. It is difficult to compare our model results directly with the Recovery system because the latter is made up of many lakes and complex topographybasal topography (Fricker et al., 2014) . However, cumulatively lakes 4 and 5 were suggested to have increased in volume by 0.33 km^3 over four years. These then drained by 0.22 km^3 at a rate of 3.7 m^3 s^{-1}. In contrast, lake 3 drained by 0.07 km^3 with a flux rate of 0.57 m^3 s^{-1} over less than two years (Fricker et al., 2014)). Our typical model outputs for an overdeepening of area 177 km^2 with a depth of 150 m, has yield lake growth of $\sim$0.05 km^3 over 1.6 years at a rate of $\sim$1 m^3 s^{-1} and drainage over two years at a maximum rate of 1.5 m^3 s^{-1}. As a result, our model outputs lie somewhere in between the within the range of the larger and smaller Recovery lakes and lake filling and drainage rates, which gives us confidence in our results.

7.3 Impact on ice dynamics

Due to the growth of channels during subglacial lake drainage, there are rarely negative effective pressures directly downstream of the lake at the time of drainage. Instead, the channel are of sufficient size that they move the higher pressure water to around 50km downstream of the lake. However, due to the pressure waves moving through the entire ice stream there are occasions during lake *growth* when effective pressures are negative around the region of the lake, contributing to channel development on the tip of the reverse bedrock slope (Fig.3). As a result, there is a complex dynamical signal that is related more closely to the pressure waves than the lake drainage. This could be challenging to identify in ice surface velocity records although, given that few high temporal resolution velocity calculations have been made for areas like Recovery Ice Stream, it is possible that similar high pressure features have not yet been identified.

The growth and shrinkage of channels in mountain glacier and Greenlandic systems have been directly connected to changes in ice velocity (e.g. Iken and Bindschadler, 1986; Bartholomew et al., 2012). These channels are argued to form only during the summer melt-season and persist for several months before shutting down over winter. In our modeled Antarctic system, however, channels can persist for a number of yearsand can obtain large sizes. The largest channel in the run with no lake grows from 0.7-19.1 m^2 over four years and then collapses back to 0.2 m^2 in less than a year. The faster shrinking rate compared to rate of shrinkage, relative to the rate of channel growth is a result of the thick ice causing rapid creep into non-linear creep of ice closing the channel once pressures drop below overburden. This is an extreme example of a temporary channel in the modeled system. Instead most channels grow to $\sim$0.4 m^2 as the pressure wave transitions migrates through the region.

Although basal water is not produced in great volumes in these Antarctic systems, it is funneled from very large catchments into narrow ice streams and therefore provides a constant supply of water that, over many years, can cause channel growth. Basal catchments in Greenland are, on the other hand, at least an order of magnitude smaller~~and therefore water flux during the winter months in~~ , so water flux through these systems will be lower ~~. Also in Greenland, the~~ during the winter months. The influx of much higher volumes of water in the summer melt season in Greenland overwhelms any background hydrological system creating a much more temporally dynamic system~~so that~~ . As a result, the situation of constant water supply allowing system development is limited to a time period of less than a year.

~~The persistence of channels over a period of years in Antarctic ice streams may have impacts on basal erosion, particularly on the downstream side of lakes. It is possible that channels can be eroded into the bedrock or into basal sediment. Modeling these processes is beyond the scope of the current project but would be an interesting system to examine further.~~

7.4 ~~Model limitations~~

~~Our modeled synthetic system has limitations in that it is a simplified, for instance, it does not incorporate variable topography, spatially varying basal melt rates or variable basal sliding parameters. However the aim with this model is to gain insight into lake filling and draining characteristics without complicating the system. Including topography in the model could impact the pressure waves and therefore the rates of lake filling and draining. We also assume that water flows through a linked cavity system rather than a sediment based system, with the latter possibly being more prevalent in Antarctic ice streams. Water flux in sediments could be more restricted than in linked cavity systems. However, it is plausible that sediment-based systems have similar dynamics as linked-cavity networks with sliding opening spaces between the ice and substrate and ice creep closing the space when water pressures drop (Creyts and Schoof, 2009) .~~

~~We have carefully conducted a series of tests to rule out, as far as possible, that the pressure wave features are numerical artifacts. We have performed tests to check that there is sufficient mesh convergence both in the planar and overdeepened topographies and find similar outputs as Werder et al. (2013) with errors in mean effective pressure and distributed water thickness on the range of 10^{-5} relative to a smaller mesh. The tolerances of the ordinary differential equation solver were also tested and selected accordingly.~~

~~Although likely not numerically induced, it is possible~~ In our synthetic Antarctic system, due to the growth of channels during subglacial lake drainage, there are rarely negative effective pressures directly downstream of the lake at the time of drainage. Instead, the ~~pressure waves are not physical. The water pressures in~~ channel are of sufficient size to propagate the high water pressure to ~50 km downstream of the ~~model do not exceed 1.04 ×P_i (or N = -0.5 MPa) and are therefore not unreasonable. However, pressures above overburden can persist in one area for up to two years, which is a long~~

~~period of overpressure. Including ice dynamics in the model might change the characteristics of the pressure waves.Feedbacks through faster ice flow and coincident cavity opening could allow greater water flux downstream and reduction of water~~ lake. However, due to the pressure ~~, as is seen by Hewitt (2013) . Ice physics such as those included in the models of Pattyn (2008) and Sergienko et al. (2007) where changing ice flux and ice surface slopes can influence lake drainage timing are also not incorporated into our hydrological model. It is therefore likely that more accurate predictions of lake filling and drainage require coupling of hydrology with dynamics models.~~

~~Including ice flexure and uplift could also impact the pressure waves and the rate of lake formation. For example, ice uplift at higher pressures could allow flux of water downstream more rapidly than seen in the model and perhaps a reduction in local overpressure~~waves moving through the entire ice stream there are occasions during lake *growth* when effective pressures are negative in the region around the lake, contributing to channel development on the rim of the reverse slope (Fig.3). As a result, periods of high water pressure (and by proxy faster ice velocity) in the vicinity of the lake occur as the lake is growing rather than when it is draining; conversely, high water pressures due to lake drainage are found downstream. This complex dynamical signal could be challenging to identify in ice surface velocity records. However, ~~it is unlikely that flexure would entirely remove the pressure waves but might instead change the downstream speed of the wave. Future numerical experiments including ice flexure would provide insight into the likely persistence of the pressure waves observed in this hydrological model and the links between lake formation and the surface ice motion observed through satellite altimetry (e.g. Fricker et al., 2010) .~~ given that few high temporal resolution velocity measurements have been made for areas like Recovery Ice Stream, it is possible that such high pressure features have not yet been identified.

~~Despite the limitations of the current model configuration, this is the first 2D hydrological model to be applied to Antarctic subglacial lakes, which can produce lake drainage cycles through only internal dynamics. The outputs therefore provide new insights related to hydrological development and subglacial lake dynamics in Antarctic ice streams.~~

8 Conclusion

We have presented a 2D model of idealized Antarctic subglacial hydrology ~~development with analysis focused on the growth and drainage of a subglacial lake. The simulation uses a~~ evolution using a synthetic setup designed to represent a simplified Recovery Ice Stream and catchment with one overdeepening. Our analysis has been focused on the growth and drainage of a subglacial lake. The hydrological model incorporates both distributed and efficient drainage networks that develop internally.

Due to water influx from a large catchment into the relatively narrow ice stream, the system does not remain in steady state and ~~instead~~ pressure waves develop. Increases in pressure cause steepening of the hydraulic gradient, enhanced downstream flux, and growth of channels as the wave moves downstream. The speed of the pressure waves is $\sim$220 m d^{-1}. Following passage of the ~~pressure ridge~~water pressure peak, the channels shut down due to lack of water flux and pressures drop to levels slightly below overburden. Pressures can ~~exist at these~~ persist at such levels even in areas of thick ice because of the fast ice speed in the ice stream (100 m a^{-1} in our model runs) continually opening basal cavities.

Our model ~~also~~ reproduces lake growth and drainage over similar scales ~~as observed in~~ to those observed beneath Antarctic ice streams. Flux out of the lake is possible at all times due to sufficiently steep hydraulic potential gradients, although full lake drainage ~~only occurs~~ occurs only when channels at the adverse slope become large enough to ~~funnel~~ conduct the majority of the water from the overdeepening. Channels grow due to a combination of slow flux out of the lake and the pressure waves, although lake drainage is not always tied to the timing of the pressure waves.

The results from this synthetic ice stream hydrological experiment suggest that the Antarctic basal systems can be highly transient and variable with interactions between water pressure and channel growth that occur over a scale of years. These results encourage ~~greater data collection~~ further analysis of Antarctic ice stream velocities~~to examine multi-year flux changes and pressure waves~~, which could show an imprint of such a system. 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.

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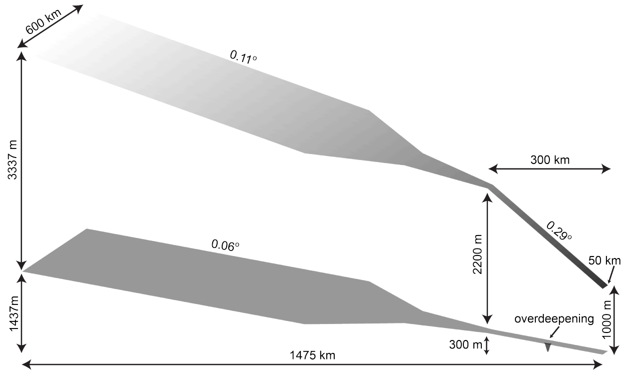

Figure 1. Model domain designed to emulate the catchment of Recovery Ice Stream. The overdeepening has a depth of 150 m. The slopes of the planar surfaces are noted with a steeper surface slope in the narrow ice stream portion of the domain.

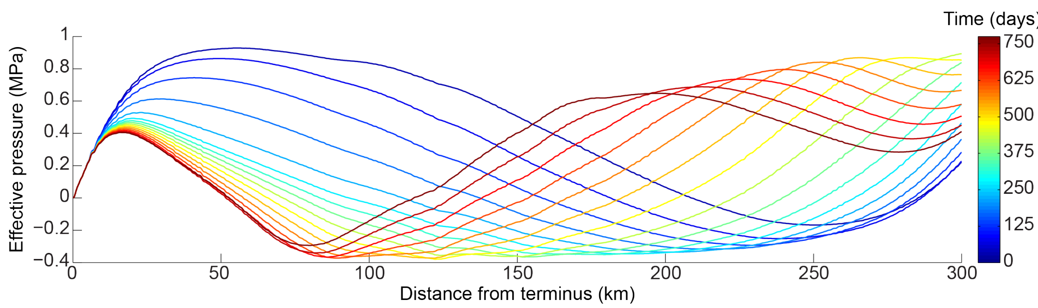

Figure 2. Effective pressure plotted for the ice stream in 50-day intervals, illustrating downstream movement of pressure waves. The outputs range from year 81 to year 83.

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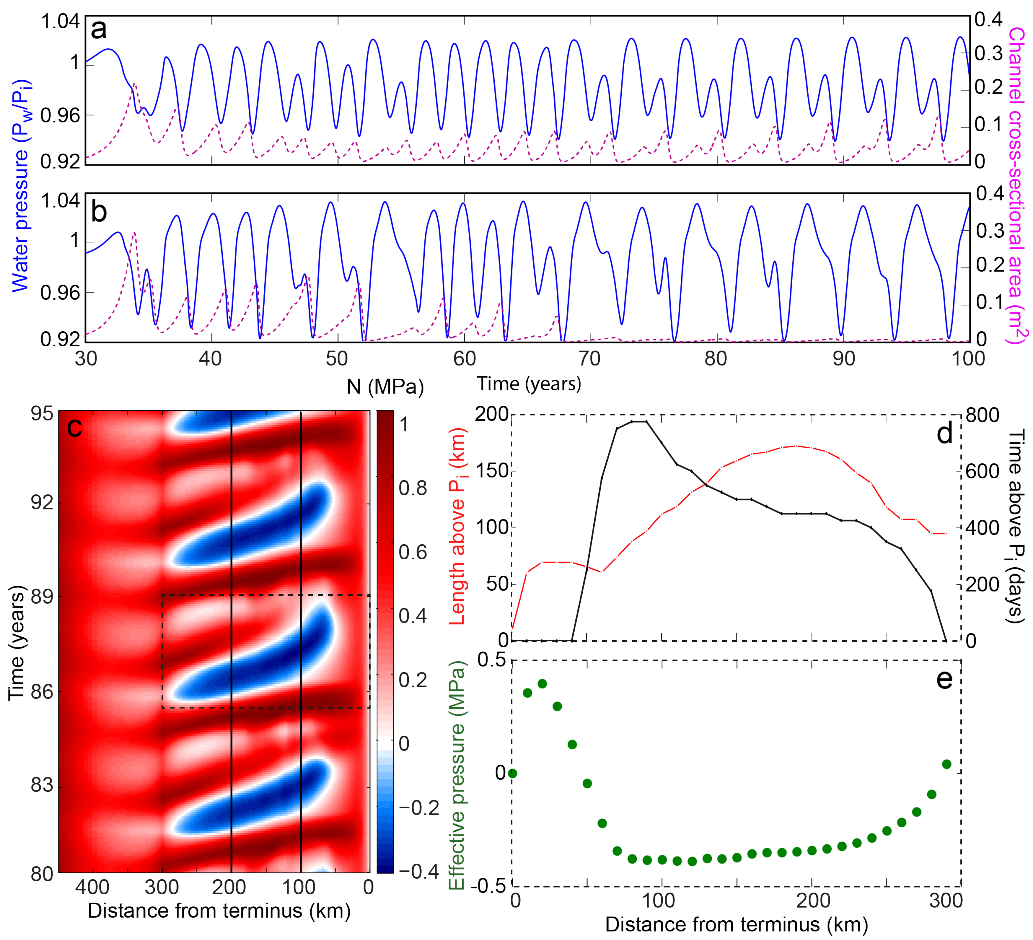

Figure 3. Model outputs from the system with no overdeepening. a) and b) Average water pressure (blue) and channel cross-sectional area (purple dashed) across the ice stream at a distance of 200 km and 100 km from the front, respectively, corresponding to the ~~colored bars~~ solid black lines in c). Prior to 30 years no pressure waves occur and so that time period is not plotted. c) Time-distance plot of center line effective pressure demonstrating several pressure waves. The dashed box shows the feature analyzed in d) and e). d) Longitudinal length affected by negative effective pressures at the time of pressure wave passing (red curve) and the time of an area below negative effective pressure (black curve) along the ice stream. e) Minimum effective pressure (green) along the ice stream.

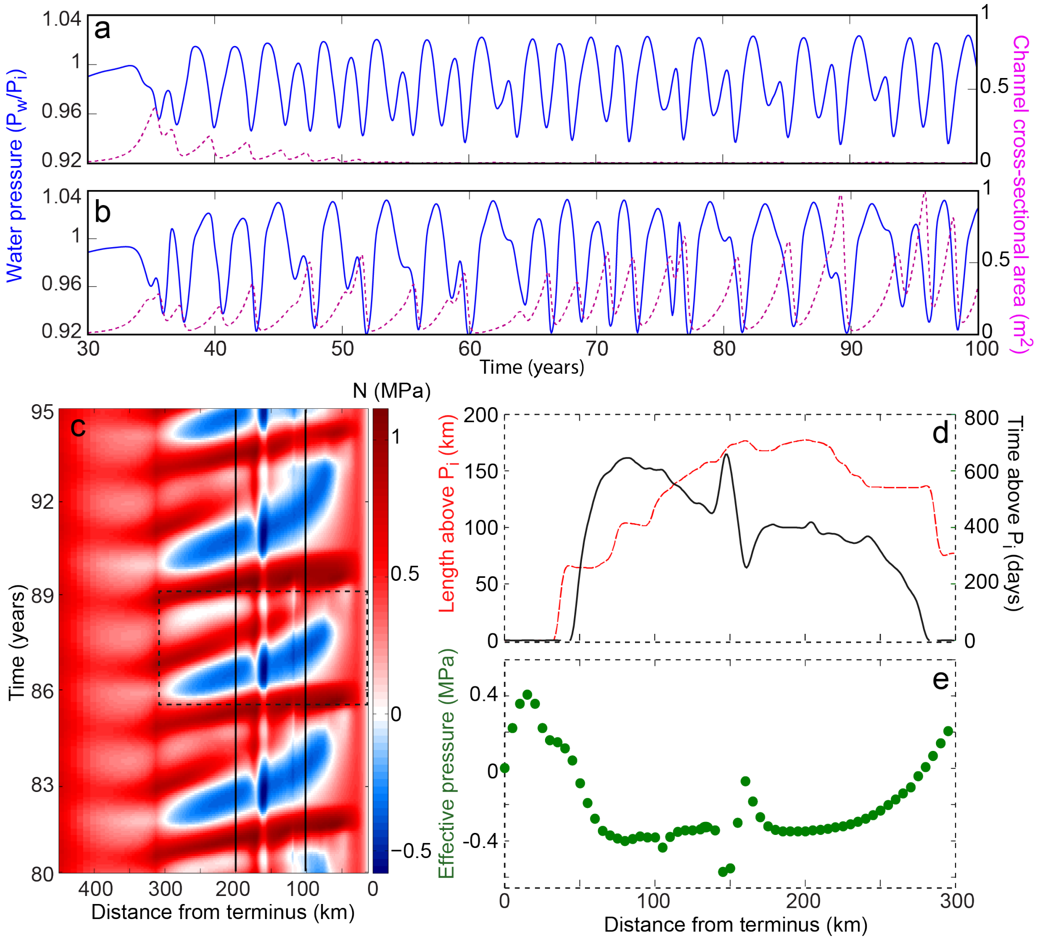

Figure 4. Model outputs from the system with the overdeepening. a) and b) Average water pressure (blue) and channel cross-sectional area (purple dashed) across the ice stream at a distance of 200 km and 100 km from the front, respectively, corresponding to the ~~colored bars~~ solid black lines in ~~e~~c). c) Time-distance plot of center line effective pressure demonstrating several pressure waves. The dashed box shows the feature analyzed in d) and e). d) Longitudinal length affected by negative effective pressures at the time of pressure wave passing (red curve) and the time of an area below negative effective pressure (black curve) along the ice stream. e) Minimum effective pressure (green) along the ice stream.

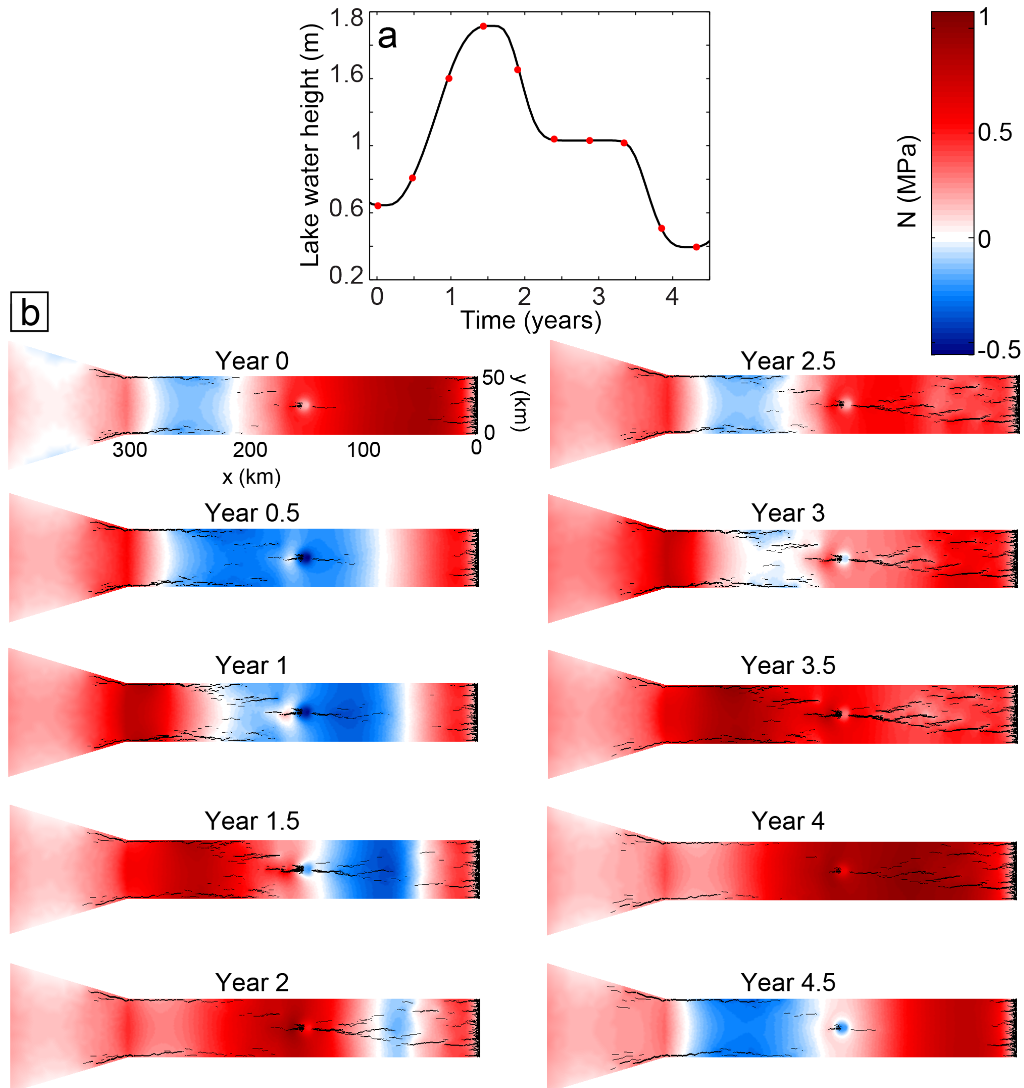

Figure 5. Changes in effective pressure in the ice stream (from years 48 to 52.5) over one lake filling and draining cycle, which occurs over two pressure wave cycles. a) Lake water level (black curve) with pressure plot timing indicated by the red dots. b) Pressure plots at six month intervals. Black lines indicate channels, with the line thickness illustrating channel size. The overdeepening is located 150 km from the terminus.

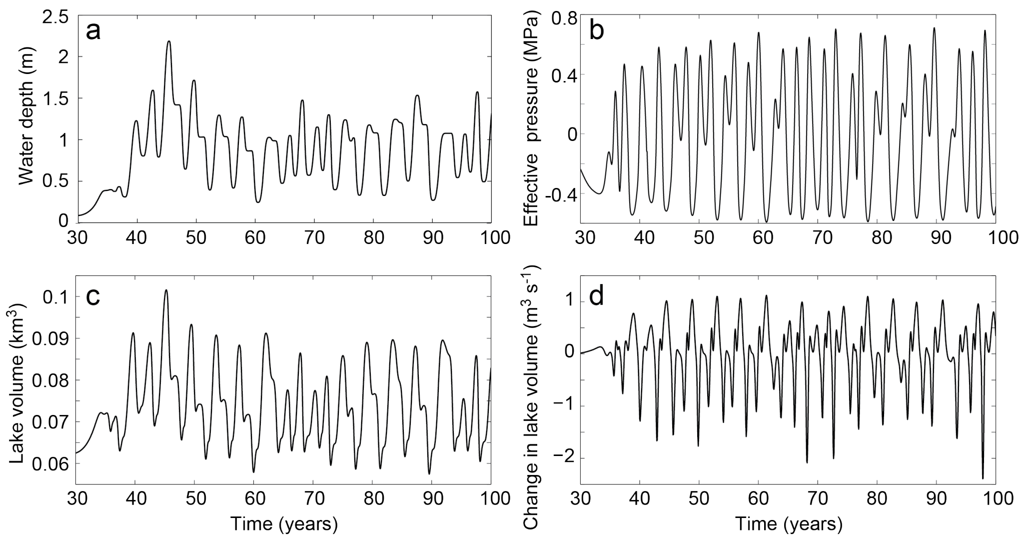

Figure 6. Conditions in the overdeepening over 100 years with a) the maximum lake water depth, b) the water effective pressure, c) the volume of the lake in the overdeepening and d) the filling (positive) and drainage (negative) rates of the lake.

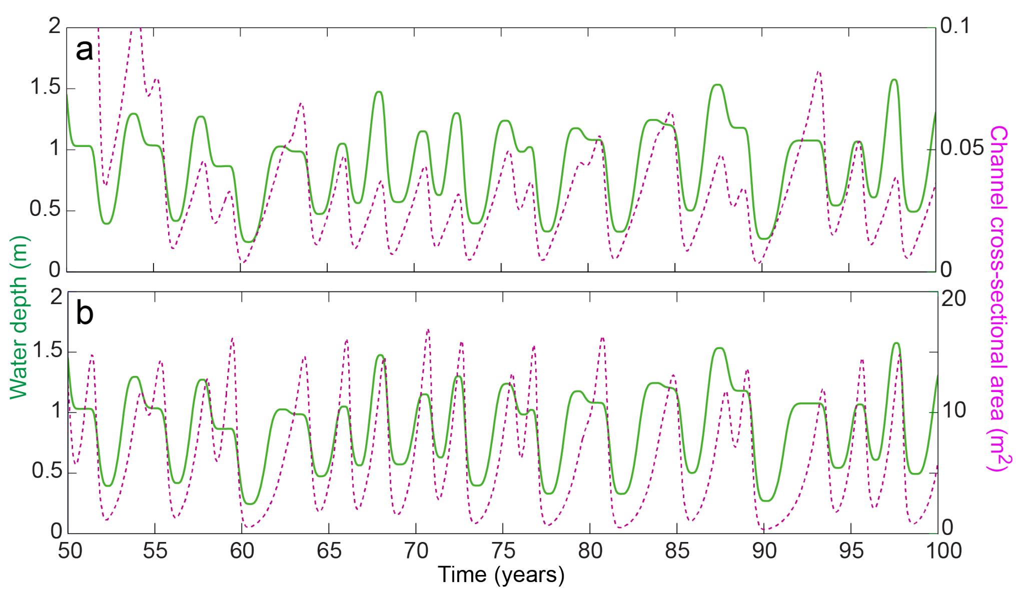

Figure 7. Maximum lake depth (green) and conduit cross-sectional area (purple dashed) at a) the ~~tip~~ rim of the overdeepening adverse slope and b) 10 km downstream from the overdeepening ~~tip~~rim, over 50 years. Lake depth is the same in each plot for direct comparison with channel size.

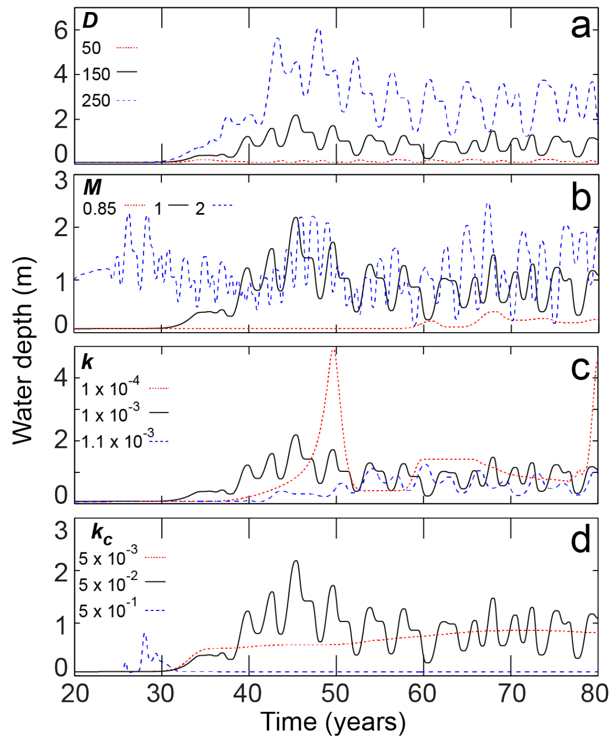

Figure 8. Maximum lake depth in the overdeepening from sensitivity testing. In each plot the black (solid) curve is the standard output. Tests of a) overdeepening depth, *D* (m), b) water input into the distributed system, *M* (mm a^{-1}), c) distributed system conductivity *k* ($m^{7/4}$ $kg^{-1/2}$) and, d) channel conductivity, k_c ($m^{3/2}$ $kg^{-1/2}$).

Table 1. Model parameters

Parameter	Symbol	Value	Units
Ice flow constant	A	2.5×10^{-25}	Pa^n s^{-1}
Englacial void ratio	e_v	10^{-5}	
Gravitational acceleration	g	9.81	m s^{-2}
Bedrock bump height	h_r	0.08	m
Latent heat of fusion	L	3.34×10^{5}	J kg^{-1}
Sheet width below channel	l_c	2	m
Cavity spacing	l_r	2	m
Glen's flow constant	n	3	
Basal sliding speed	u_b	100	m a^{-1}
Ice density	ρ_i	910	kg m^{-3}
Water density	ρ_w	1000	kg m^{-3}

Table 2. Sensitivity test variables

Parameter	Symbol	Base value	Variations	Units
Overdeepening depth	D	150	50, 250	m
Sheet conductivity	k	1×10^{-3}	1×10^{-4}, 1.1×10^{-3}	$m^{7/4}$ $kg^{-1/2}$
Channel conductivity	k_c	5×10^{-2}	5×10^{-1}, 5×10^{-3}	$m^{3/2}$ $kg^{-1/2}$
Sheet input	M	1	0.85, 2	mm a^{-1}