Response to the comments of Reviewer 2

Summary

This manuscript offers a novel approach to understanding the role of proglacial lake level changes on ice dynamics under a range of different scenarios. It is generally well written and well referenced although some paragraphs require some rewording. The manuscript reveals how both long- and shorter-term increases in lake level result in increased ice velocities and higher rates of thinning compared to a land terminating scenario. The glacier response to changing water levels is shown to be non-linear with grounding line mass flux dramatically increasing once flotation occurs. The authors also show that shorter term reductions in lake level can lead to high tensile and compressive stresses at the terminus that could drive significant crevassing, however they suggest that slow drainage could act as a viable geoengineering strategy to mitigate GLOF risk and lower glacier retreat rates. At present there remain a number of limitations that require significant revision that I have immediately addressed below.

AP: *Thank you for your thoughtful review. We address our line-by-line comments below.*

Major comments

The most significant limitation, which the authors have acknowledged, is the exclusion of calving and subaqueous melting. In real lake-terminating systems, thermal undercutting and calving are primary drivers of mass loss. By omitting these to isolate hydrostatic buoyancy, the model represents a highly conservative estimate of glacier sensitivity. If there is a way to incorporate subaqueous melt, relative to changes in lake temperature (which is likely to vary significantly seasonally, with lake volume, and be influenced by the presence of icebergs and inflow from non-glacial water sources), this studies results would be greatly strengthened. The lack of removal of ice through calving is most likely resulting in unrealistically thin ice tongue formation that may presumably be acting to stabilise ice/reduce velocities behind the grounding line thus resulting in underestimations of glacier change.

AP: *We appreciate this comment and fully agree that frontal ablation — primarily calving and subaqueous melting — is a critical process that influences glacier dynamics, likely to a far greater extent than lake level alone, and that omitting these processes yields conservative estimates of glacier sensitivity. We intentionally and consciously exclude explicit treatment of these processes, in part to focus on the sensitivity to lake level and its hydrostatic effects, and in part because the processes of calving into proglacial lakes (style, geometry, rate, appropriate calving law formulation) and the subaqueous melt rates (and relationship to temperature, melting and water stratification) are poorly constrained and would require significant sensitivity testing themselves. For example, there is no consensus on an appropriate calving law for well-studied marine terminating systems* (e.g., Barnett et al., 2026)*; applicability of a marine-suited calving law to lake cases is entirely unclear. These are obvious and important next lines of enquiry. We explicitly state our approach in the manuscript(Line 89): "****We conduct a series of controlled experiments on a semi-synthetic model domain, designed to isolate the role of lake level change by holding other parameters constant (e.g., surface mass balance, bed geometry, and calving parameterisations)***.", and acknowledge the limitations (Line 505): "****Our exclusion of calving and subaqueous melting likely leads to conservative estimates of glacier sensitivity, as these processes can account for a substantial proportion of mass loss in lake-terminating systems (Carrivick & Tweed, 2013; Minowa et al. 2021; Caldwell et al. 2025). Incorporating these processes would likely amplify the lake level effects we identify, through delivering more water into the proglacial basin, and could reveal additional instability mechanisms.*** *" We will further incorporate our comment above into the manuscript under section 2.2. Mass balance and boundary conditions.*

While glacier dynamics are primarily governed by geometry, mass balance, and frontal ablation — factors that are well-studied globally and similarly applicable to lake-terminating glaciers — the defining characteristic of lake-terminating glaciers is that their lake levels can fluctuate through filling and drainage events or cycles, potentially influencing glacier dynamics. Quantitatively assessing this influence is the central aim of our study.

*To isolate this effect, our experiments are deliberately designed to control for other influencing factors. However, we note that fixing the ice front position in our experimental set-up does not imply the exclusion of ice flux across it. Ice flux through the front continues, allowing ice to move from upstream to downstream, and ice is removed from the model as it passes through the frontal position. We simply do not permit frontal retreat driven by frontal ablation, such that we do not explicitly model calving or subaqueous melting. We state this in the manuscript (Line 152): "****Our experiments use a fixed glacier front, across which ice is lost without explicit consideration of calving and subaqueous melting, while allowing the glacier to develop a floating extension."*** *Our experiments confirm that the glacier remains dynamic and does not produce unrealistically thin terminal ice.*

The paper frames Experiment 3 as testing a GLOF like scenario, however the time period of drainage is on a magnitude of years rather than hours or at the most days which real life GLOF events typically occur. I think this is therefore misleading and the authors either need to cite examples of GLOFs which have undergone drainage in this style or reframe what this experiment is trying to demonstrate. It would also be great to see an experiment showing very rapid lake level changes that compare to an observed real world GLOF.

AP: *Thank you for raising this important point. Our experiments were designed through a paleo-ice sheet lens, in which "rapid" lake drainages can typically be constrained to a season or 1-2 years. The geological record does provide evidence of incremental drainage* (Teller et al., 2002; Tweed & Russell, 1999) *and also of larger drainage events that necessarily take longer to release a larger volume of water*(Clarke et al., 2004; Glasser et al., 2016) *, but we acknowledge that the best estimates of drainage duration may also reflect the temporal resolution of the record and not the actual process. We admit that the durations of typical GLOFs in contemporary and smaller-scale settings is much faster than we have captured in our experimental design.*

We note that our model operates at a monthly temporal resolution. Thus, although a 100 m drop is applied over one year, the actual change per timestep is approximately 8 m per month; the total stress response after the end of the drainage is plotted. Nevertheless, we acknowledge that this does not fully replicate a rapid glacial lake outburst flood (GLOF) scenario.

We believe there is still value in our original experiment, which shows the qualitative and quantitative response to the rate of drainage (1-4 years) and the importance of whether the initial state is floating or grounded. These timescales may be relevant to larger, paleo-cases of lake drainage. We propose to include an additional experiment in our revised manuscript, designed with a higher temporal resolution and a more realistic lake level drop to better capture GLOF-like conditions. Figure R2, below, shows the same qualitative behaviour with a 10-day model time-step and drainage over 15-30 days; the model crashes at higher resolution and becomes computationally challenging. Nonetheless, we find high stress response with rapid lake drainage.

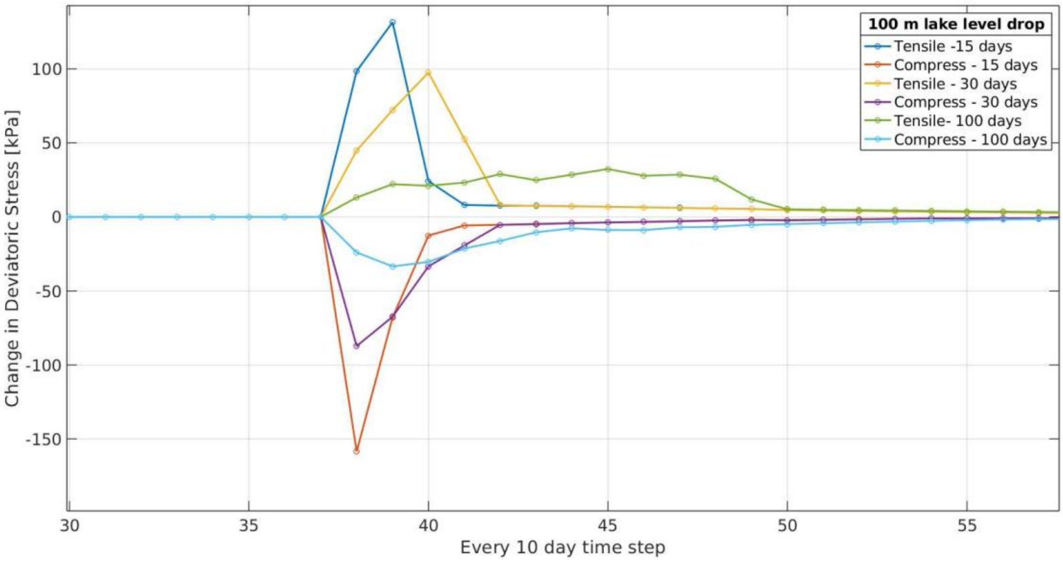

Fig R2 – model results of high temporal resolution experiments show similar qualitative behaviour as our earlier “rapid” experiments and similar order of magnitude stress response.

During Experiment 3, the model shows stress peaking and then relaxing back to equilibrium within 5 to 10 years due to the viscoelastic nature of ice. However, because the model lacks a fracture mechanics or calving law component, it assumes the ice simply "absorbs" this stress and relaxes. In reality, stresses that high (exceeding typical ice tensile strength of ~300 kPa) would result in physical breakage and therefore calving rather than just mathematical stress relaxation, this needs to be properly addressed in the manuscript.

AP: *Since fracture mechanics and calving laws are not incorporated in our model configuration, our analysis is restricted to characterizing the nature of the stress response generated. We have cautiously highlighted plausible follow-up mechanisms without drawing definitive conclusions, noting that the magnitude of the stress response may be sufficient to trigger calving and ice fracturing — processes that warrant further dedicated investigation. We note that due to the implementation of a drainage event longer in duration (e.g. 1 year) than an individual timestep (1 month), stresses have been summed, so the instantaneous stress response – which would be important to a fracture mechanics analysis – is not clear; this underpins our cautious interpretation.*

With our higher resolution experiment, modelling a faster drainage event, the stress responses are of a similar order of magnitude. We therefore agree with the reviewer that these stresses would lead to mechanical failure of the ice front (calving). While our model (lacking fracture mechanics) relaxes after the drainage event, given the magnitude of the stress response, we interpret that calving would ensue.

In the revised manuscript, we will discuss our results under the new set of higher resolution simulations.

--

Minor comments

L38: The language in this sentence could be a bit more precise; Lakes can form without having a major impact on ice dynamics, particularly when they are small. Maybe frame as → increasing lake growth can result in glaciers becoming increasingly detached from climatic drivers on ice dynamics.

AP: *Thank you for the suggestion. We will rephrase the sentence in the revised manuscript as **"Once a lake forms and grows at the glacier terminus, the glacier's behaviour may become increasingly influenced by interactions between the lake and the ice front, which can surpass the effects of climate conditions alone on glacier dynamics"***

--

L61: Replace semicolon with full stop.

AP: *We will correct it.*

--

L75-78: The last part of this paragraph feels like a different message to the first part, maybe remove discussion of significance of glacial lake outburst floods to the following paragraph or a new paragraph as it doesn't quite fit with the discussion on ice dynamics above.

AP: This paragraph addresses the occurrence and the impacts of proglacial lake presence and lake drainage. Lakes have impacts on the glacier system but their drainage additionally has downstream impacts, on the ocean and on the terrestrial landscape (including human infrastructure). The next paragraph then goes on to comment on the likely trajectory of change – lake damming is becoming more frequent, and the aforementioned impacts are therefore becoming a greater concern. We will adjust the wording to better reflect this narrative.

--

L96-107: This reads well.

AP: *Thank You*

--

L142: "Poorly unknown" double negative, amend to something like 'poorly quantified' or just 'unknown'.

AP: *Thank you, this should have said "poorly known"; we will correct it.*

--

L160-162: The way this is worded makes it a little tricky to follow.

AP: *We rephrase the sentence as "**Our experiments describe lake water depths relative to the lake floor** ~~**, which therefore has 0 m water depth**~~**, i.e., water depth is 0 m at the lake floor.** "*

--

L174: Consistency with the formatting compared to the below experiments, other experiments have "and" after the semi col whereas this line doesn't.

AP: Added 'and' in the revised manuscript.

--

L206: Define extent of "lake region" how was this region determined?

AP: *The lake region is delineated using the BedMachine data. BedMachine classifies an area around and upstream of the present-day lake as "ocean", though it does not actually have a marine terminus. The original lake has two part of glacierized basins, and we wanted to restrict the downstream extent of the lake within our study glacierized basin. The upstream* *extent of lake is extended to the area where from lake-terminating tributary starts (green contour of Fig. 1).*

--

L207: A 20% difference between lake and land terminating velocities does not seem to be “modest”.

AP: *This difference is not for the whole glacier, but only for the terminus part, and it happens over the period of 100 years.*

--

L215/Fig 4: This plot could be improved, the figures are quite small, and it is hard to make out the bits of the glacier we are interested in i.e. the terminus regions, maybe full glacier plots could be put in the supplementary so this plot can focus on the terminus region?

AP: *We agree that the changes in the terminal region are quite small on the page, and that it is difficult to discern changes in the upper catchment. However, these upstream changes are present and we find this a relevant result. We will modify the colour range in these figure panels to better highlight the upstream changes, and will provide an extra inset figure for each variable at year 100 focussed only on the terminal region, with appropriate colour range for the magnitude of changes there. We take the same approach to Figs 7 & 8.*

--

L230: Again, what is meant by “lake area” here, I am not sure how much glacier this refers to, could we say within x m of the terminus or a point that is fixed? A map showing this lake area could also solve this problem.

AP: *The lake extent is shown in Fig. 1c (green contour), which encompasses glacier ice where the bed elevation lies below sea level. As shown in Fig. 2b, the bed elevation below sea level extends considerably further upstream. However, we restrict the potential lake extent in our model to the lake-terminating tributary. If a “lake” extended further upstream, it would in fact connect to the ocean. The defined lake area, as in Fig 1C, is the only area in our model domain where lake level changes influence subglacial water pressure.*

To address this confusion, we add clarification of how the lake area is defined to our Methods section 2.3 (Experimental design). (We additionally note its role in how subglacial water pressure is distributed, in response to Reviewer 1’s concerns.)

--

L236-240: These sentences currently don’t read so well, change “lake terminus” to something like “while the glacier was still lake terminating”.

AP: *We have changed it accordingly in the revised manuscript.*

--

L251/Fig 7: Same as comment for fig 4.

AP: *We address Figs 7 & 8 in the same way as we amend Fig 4.*

--

L256-259: We could do with a plot like fig 6 to show this velocity stabilisation as this transition point is not clear from fig 7.

AP: *It is shown in Fig. 9.*

--

L274-313: This feels like a totally different experiment and is very interesting in its own right, it should therefore be described as such earlier on.

AP: *We referred to a further subset of follow-up experiments in Section 2.3 but, in hindsight, this could be profiled better. Thanks for the feedback. We will explicitly outline these experiments in the Methods (as Experiment set 2a and set 2b), and amend the narrative in the opening to the Results sections for these Experiment sets.*

--

L277: What are these lake levels?

AP: *As above – we will describe the different lake levels considered for this experiment in the Methods (Experimental design, 2.3).*

--

L308-311: This feels better placed in the discussion.

AP: *For better readability, we think it is justified to place the explanation here as a signpost to the discussion.*

--

L314: Although the focus of this section is on the stress response, it would also be interesting to see the velocity/thinning response included to allow for comparison with the other experiments.

AP: *Thank you – we agree, but the number of results figures in the manuscript is already rather high and we plan to include an additional figure with a higher temporal resolution rapid drainage experiment. We could add panels to Fig 12, though as the focus here is on a shorter time frame, a direct comparison with the other experiments is not applicable. Consistent with the other lake level fall experiments, the velocity is expected to decrease rapidly in response to a rapid lake level drop.*

--

L351: Please define these or make clear what these “unstable feedbacks” are here.

AP: *By ‘Unstable feedbacks’, we mean MICI (Marine Ice Cliff Instability) like scenario. However, we feel that would be an overstatement without further investigation and incorporation of fracture and calving. Thus, we remove the “unstable feedbacks” from this sentence.*

--

L387-389: This opening sentence could do with improvement in readability and how it sets up the coming paragraph.

AP: These lines are not an opening sentence, but rather a closing sentence of a paragraph. Perhaps the reviewer meant 397-399? We will review the narrative flow of these closing and opening sentences

--

L406-408: Given that ice discharge (calving?) is not quantified in this study, this sentence needs a citation.

AP: *This sentence intended to draw on the grounding line flux results, plotted in Figs 10 & 11. We will change “discharge” to “flux”, and refer to the figures.*

--

L410-414: I am not sure how quickly ice advancing over the grounding line would result in a change in lake level? I imagine it wouldn’t be too hard to quantify and also work out how much this would change the discharge of the lakes outlet stream. I feel that any displacement of water by ice flowing into the lake would be quickly offset by increasing drainage from the lakes outlet.

AP: *Ultimately this depends on the topography peripheral to the lake basin, and the location of the lake outlet relative to the (advancing) grounding line. If the basin is not supply-limited and is already filled to its threshold, there should be no lake level change (the displacement would be offset, as the reviewer suggests). However, if grounding line advance blocks the earlier threshold (e.g. on a retrograde slope and/or where the threshold is proximal to the ice-dam), lake level may rise to a new threshold. We consider rephrasing this paragraph in the revised manuscript. The analysis provided here may or may not be significant, but requires separate investigation.*

--

L412-414: Do we have any examples of such rapid lake rise?

AP: *We do not have any examples of such scenarios. This is short term phenomena which may happen at the lake growth stage coincident with glacier retreat. But, this is physically possible and can vary in magnitude, but probably difficult to capture with observation.*

--

L422-424: Describe these examples of where this has happened.

AP: *This has been observed at Russell glacier in West Greenland. We will mention that in the revised manuscript along with the reference.*

--

L438-439: This sentence doesn't read well at the moment from "however" onwards, not clear what it's trying to say.

AP: *We would rephrase the sentence as "Thinning trends of such systems appears almost universal ~~, however, widely observed whether the terminus lake is~~ irrespective of the nature of the lake terminus: stable or evolving, newly formed or long-established"*

--

L456-457: This sentence is confusing, not sure where lake-contact margins come into this.

AP: We rephrase this sentence to: "Our results suggest that even temporary lake level increases can commit glaciers to prolonged mass loss; mass which may be lost not only at the lake-terminating interface itself but more widely across the catchment. This finding emphasises…"

--

L470: "propagate also" → also propagate.

AP: *Corrected*

--

L485: I would be cautious about linking these results to these poorly constrained historical events especially given that this study doesn't quantify the glacier response to sub annual changes in lake levels.

AP: *We argue that these geological events are exceptionally well-constrained in timing and magnitude, and exhibit repeated occurrence (both in the same catchment and across neighbouring catchments: Regnéll et al. 2023, 2025; Høgaas & Longva 2018 – referred to in the original manuscript). These drainage events are large, high-magnitude, and more prevalent than in many contemporary settings, and indeed motivated this work. We consider it very relevant to refer to these palaeo-examples in light of what we learn here, especially since we also now include a model experiment that addresses sub-annual lake drainage.*

--

L505-508: Could be a good point to discuss how icebergs would affect water temperature and the energy balance at the terminus and what would mean for thinning rates.

AP: *We would add a line with that in the revised manuscript.*

--

L544: Would this be considered rapid, most would assume rapid refers to a GLOF style event i.e. hours? South Lohnak could be a good case study here for examining how the stress changes at the terminus resulted in crevassing/acceleration etc if we are to discuss mountain systems.

AP: *We will qualify our language regarding "rapid" here in the Conclusions, while referring to additional studies earlier in the manuscript (e.g. Discussion). As addressed in the major comments #2, we will be redesigning our experiment 3 with shorter time-resolution to address GLOF style events.*

--

References

Barnett, J., Holmes, F. A., Greenwood, S. L., Morlighem, M., Kirchner, N., & Jakobsson, M. (2026). Comparing calving laws at Greenland's three largest ice shelves. *EGUsphere*, *2026*, 1–27. https://doi.org/10.5194/egusphere-2026-436

Clarke, G. K. C., Leverington, D. W., Teller, J. T., & Dyke, A. S. (2004). Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8200BP cold event. *Climate System History and Dynamics: The Canadian Program in Eart h System Evolution*, *23*(3), 389–407. https://doi.org/10.1016/j.quascirev.2003.06.004

Glasser, N. F., Jansson, K. N., Duller, G. A. T., Singarayer, J., Holloway, M., & Harrison, S. (2016). Glacial lake drainage in Patagonia (13-8 kyr) and response of the adjacent Pacific Ocean. *Scientific Reports*, *6*(1), 21064. https://doi.org/10.1038/srep21064

Teller, J. T., Leverington, D. W., & Mann, J. D. (2002). Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation. *Quaternary Science Reviews*, *21*(8), 879–887. https://doi.org/10.1016/S0277-3791(01)00145-7

Tweed, F. S., & Russell, A. J. (1999). Controls on the formation and sudden drainage of glacier-impounded lakes: Implications for jökulhlaup characteristics. *Progress in Physical Geography: Earth and Environment*, *23*(1), 79–110. https://doi.org/10.1177/030913339902300104