Assessing the sensitivity of the Vanderford Glacier, East Antarctica, to basal melt and calving

Author Responses to Referee Comments

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Dear Cheng Gong:

We thank both reviewers for their comprehensive review of our manuscript and the improvements their constructive comments will bring to the manuscript. Here, we respond to comments from Tyler Pelle (Reviewer 2). Below, we respond (in blue) to each of their comments (in black). We respond to comments from Benjamin Getraer (Reviewer 1) in a separate document.

Sincerely,

Lawrence Bird and co-authors

Overview

In this manuscript, Bird et al. present an ice sheet modeling study that investigates the role of ice shelf basal melting and ice shelf calving in driving observed retreat of Vanderford Glacier in East Antarctica. The author's primary conclusions are that ice shelf basal melting (>50 m/yr) is the primary forcer of this observed retreat and that currently available satellite estimates of basal melting are insufficient to drive the magnitude of retreat observed over the past ~25 years. On the other hand, ice shelf calving had minimal impact on the dynamic retreat of Vanderford Glacier. Overall, I found this paper to be a pleasure to read! The ice sheet model and experimental set-up are meticulously described and the writing is free from any grammatical errors. Furthermore, I find that the conclusions are generally well supported by the results and that the authors make sure to highlight major sources of uncertainty. I also believe that the results of the paper will be important for future ice sheet modeling studies in this region, as this paper presents important constraints on the choice of ice sheet friction law as well as which forcing mechanisms to prioritize in the modeling of Vanderford Glacier. Below, I include suggestions that could improve the presentation and quality of the manuscript, but they are generally minor and should be relatively easy for the authors to address. Once this is done, I would be very supportive of this manuscript's publication in *The-Cryosphere*.

We are glad that the reviewer feels the paper will support future ice sheet modelling in this region and we thank them for their constructive feedback.

Both reviewers raise some good points around the clarity and cohesion between the methodology, discussion, and implications. We believe this may stem from the fact that in the original manuscript, the aims were not expressed clearly. As such, we have rewritten the aims to be more precise/correct, as follows (Lines 66-70):

"The aim of this study is to assess the sensitivity of mass loss and grounding line retreat at Vanderford Glacier to sub-ice shelf basal melt and calving. We use time-evolving numerical ice sheet model simulations to address the following research questions: 1) can satellite-derived estimates of basal melt and ice-front retreat generate the magnitude of observed grounding line retreat at Vanderford Glacier between 1996-2020; and, if not, 2) what magnitude of basal melt and/or calving is required to generate grounding line retreat of a similar magnitude to observed?

Although the aim of this study is not to directly replicate recent trends at Vanderford Glacier, by addressing the above questions, we are able to infer the likely driver(s) of recent historical changes in mass loss and grounding line retreat at Vanderford Glacier."

The rewording of the study aim above better reflects the original intention of the study, why the methodology was developed as it was, and is consistent with the findings presented in the manuscript. In light of this rewording, we have also adjusted the order of the first two paragraphs presented in the discussion for improved and consistent structure/readability.

Specific Comments

Ice sheet model spin-up: In the manuscript, you describe a 500 year spinup of the ice sheet model so that it relaxes to a pseudo steady state. I wonder about the implications of running the model to steady state given that you are trying to match observed patterns of grounding line retreat.

We thank the reviewer for raising this topic and agree that this is an important factor to explicitly comment on in the manuscript that is currently missing.

The focus of our study is to conduct a sensitivity analysis of different mass loss mechanisms on Vanderford Glacier, and not to match observed patterns of grounding line retreat (please see the reworded study aim in response to the reviewer's general comments). Therefore, we want to remove the influence of any other driver and remove any inertia that may exist within the present-day system, so a pseudo-steady state spin-up is appropriate.

A secondary aim is to assess the likely magnitude of basal melt required to generate grounding line retreat of similar magnitude to observations. Given the large uncertainties in basal melt estimates derived from satellite observations (see discussion on line 352-364), using a steady-state spin-up ensures that the influence of other mass loss drivers is removed, so that we can focus on assessing the magnitude of grounding line retreat directly in response to a given forcing (basal melt rate and ice-front retreat). We note that this approach means that we're not attempting to exactly replicate the patterns of observed retreat.

If Vanderford Glacier was not in steady state prior to the 18.6 km grounding line retreat, is this spinup to steady state really necessary (or appropriate)? Have you checked that the rate of ice mass change of Vanderford Glacier at the end of your spin-up is in somewhat of agreement with observations? How about the simulated velocities? You could test the impact of this steady state by perhaps performing an additional experiment that starts directly after the 2 year relaxation period and comparing the results to the corresponding experiment that started from steady state. Overall, I think that some justification of this spinup, discussion of its impacts on your results (possibly highlighted as an uncertainty in the later stages of the Discussion section), and a comparison of your steady-state model to present day observations (velocity and mass loss) would be very helpful.

Benjamin Getraer (Reviewer 1) had similar comments regarding the model spin-up. We provide the same response below to that provided in response to Reviewer 1.

We thank the reviewer for raising this point and agree that this is an important factor to explicitly comment on and that was missing in the original manuscript. The focus of our study is to conduct a sensitivity analysis of different mass loss mechanisms on Vanderford Glacier. Hence, we want to ensure that the system responds *only* to the perturbation applied to the different forcings and is not influenced by inherent trends associated with the model initialisation procedure. For this reason, we initialise the model to a pseudo-steady state using the 500-year spin-up (lines 143-147). We also simulate a *Ctrl* experiment using forcings consistent with the spin-up (lines 157-158), and in our analysis (Section 3), we present results with respect to the control (line 158-159), i.e., subtracting the control from the perturbation simulations, to remove any model drift, or influences on ice thickness or ice velocity that do not arise from our basal melt or calving perturbations. Present-day conditions at Vanderford Glacier are likely not in a steady-state; however, initialising our model to present-day conditions (e.g. with the observed trend in thickness over the historical period) would limit our ability to untangle the changes arising from basal melt and calving, and those that arise due to inertia in the system.

We have completed some additional model runs to assess the impact of our model initialisation choice on select basal melt perturbation experiments and discuss these below. Figure 1 displays results of additional model runs completed for M_{10} - M_{50} for each friction law, without the 500-year spin-up step. That is, we apply the perturbation period immediately after the initial 2-year relaxation step. We present these additional model runs in the first column and the corresponding model runs which use the 500-year spin-up step in the second column. Note that we have adjusted the presentation of grounding line retreat based on a later comment from the reviewer (Line 291 of this document).

Figure 1 shows that the relative change of GL_{flux}, grounding line position, VAF, and Ice volume, compared to a control experiment, does not differ considerably from our simulations that use a spin-up to pseudo-steady state. The largest differences are in the: 1) time it takes for the grounding line to re-advance to its original location, and 2) variability between the different friction laws. Figure 1 c-d show that with no spin-up, the grounding line takes longer to return to its initial location for some experiments than when the perturbation is applied to a system in pseudo-steady state. This result is expected since there is likely inherent inertia within the present-day system towards grounding line retreat that arises from the system response to previous basal melting and/or calving. The response to different friction laws shows a slightly different pattern than our original experiments, with Weertman experiments consistently generating the smallest change in VAF compared to other friction laws; however, all experiments yield the same pattern and magnitude of change as our original experiments.

Based on the results of these additional experiments, it is clear that the initialisation and spin-up procedure is appropriate in isolating the instantaneous effects of sub-ice shelf basal melt and ice-front retreat because they ensure that other trends in the system response to past forcings are removed. Given the aims of our study and that our sensitivity analysis uses a model configuration in pseudo-steady state, it is more appropriate to present the change in key variables (e.g. ice thickness, ice velocity, and grounding line flux) over the course of the spin-up period, rather than to compare the final model fields to observations. We have added a Figure to the Supplementary Information to show the evolution of these variables throughout the spin-up period.

We have made the following in-text adjustments to comment on our choice of model initialisation and to point to the additional figure in the Supplementary Information:

Line 146: *"At the end of this 500-year simulation, ice velocities and geometry are in pseudo-steady state (Fig. Sx), and these fields are used as the initial conditions for all perturbation experiments (Sect 2.3)."*

Line 464 (added): *"Our choice of model initialisation and spin-up to pseudo-steady state directly addresses the study aim, and ensures that the system responds only to the instantaneous perturbation applied to the different forcings and is not influenced by any inertia or trends within the system. This approach allows us to untangle the changes in grounding line flux, grounding line migration, volume above floatation, and ice volume that arise from basal melt and ice-front retreat, independently and in combination. Importantly, this approach limits our ability to comment on the current state of Vanderford Glacier (i.e. whether or not it may be undergoing irreversible grounding line retreat). To accurately assess the current state, or to comment on potential future behaviours at Vanderford Glacier, additional modelling simulations which use a present-day model initialisation (i.e. to accurately match recent trends in mass loss and spatial patterns of ice thickness, ice velocity, and grounding line position) are recommended. Simulations of present-day behaviour require improved observations of basal* *melt, particularly close to the grounding line, and a more accurate representation of bathymetry in ocean models used to parametrise sub-ice shelf basal melt is needed to support simulations of future behaviour."*

Reversibility of retreat: I was happy (possibly relieved) to see that in all of your experiments, simulated retreat and the grounding line flux stabilized back to conditions at the start of the simulation once the forcing was reverted back to what was applied in the spinup. I think that this is an important result and is worthy of being highlighted in the text! In your simulations, you show that retreat of Vanderford Glacier is not irreversible and that, in its current configuration, Vanderford is not undergoing MISI.

This is a good point, but has to be interpreted with caution. The focus of our study is to conduct a sensitivity analysis of different mass loss mechanisms on Vanderford Glacier, rather than to match observed patterns of grounding line retreat (please see the reworded study aim in response to the reviewer's general comments). As such, we cannot comment with certainty about the likelihood of irreversible retreat at Vanderford Glacier. Nevertheless, our simulations (with and without the spin-up to pseudo-steady state) suggest that the system can recover once perturbations are removed and the current grounding line may not be retreating irreversibly. Additional simulations with improved ocean forcing and bedrock topography, particularly close to and upstream of the current grounding line position, are required to accurately assess the reversibility of current grounding line retreat. For such a study, we'd recommend a different approach to the steady-state spin-up employed here; e.g., an initialisation/spin-up that embedded the historical trends into the simulated dH/dt.

Figure references: I noticed a couple of incorrect figure references. I tried to catch as many of them as possible in the line comments below, but also wanted to highlight it here in case I missed any. It would be great to double check these.

Thank you for highlighting these incorrect references. We have reviewed all figure references and made amendments where necessary.

Line Comments:

L57-60 How do these satellite estimates perform over heavily crevassed ice shelves? Would this be a factor as well? Also, what are their resolutions?

We further discuss the limitations of satellite-based basal melt estimates in the discussion section (Line 352-364). Regions of steep ice thickness gradients are conducive to regions of crevassing or other ice damage (Chartrand and Howat, 2023). We have added explicit mention of crevassing on Line 356:

"...In regions with steep ice thickness gradients (i.e. conducive to regions of heavy crevassing) and at..."

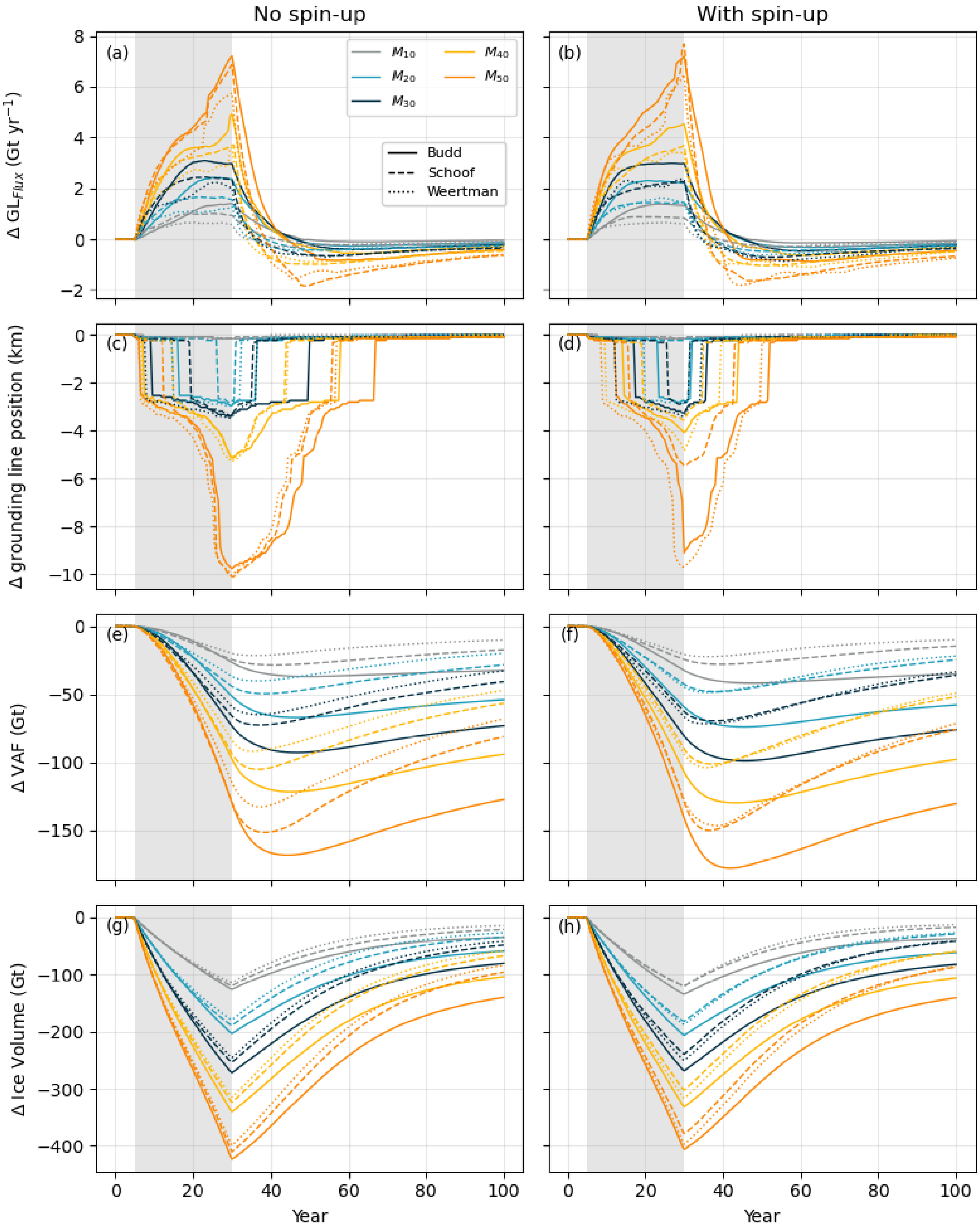

Figure 1: Comparison of perturbation experiments with different initialisation/spin-up conditions. Experiments without a 500-year spin-up to pseudo-steady state are presented in the first column. Experiments with a 500-year spin-up to pseudo-steady state are presented in the second column. Relative change (compared to the *Ctrl* experiment for each friction law) of: (a-b) Grounding line flux, (c-d) Grounding line position calculated along the central flowline show in Fig. 2c. Negative numbers represent grounding line retreat and positive numbers represent grounding line advance, relative to the Ctrl experiment. (e-f) Volume above floatation, (g-h) Ice volume. Grey shaded area denotes the perturbation period.

We have added mention of the typical resolution of satellite-derived basal melt estimates to Line 58:

"…basal melt estimates are derived at high resolution (i.e. 1-2 km) from satellite altimetry-based methods; however, these methods require various…"

L78-80 This might be a good place to point to figure-1, which shows the model domain.

We have moved the reference to Fig. 1 on Line 78 to point more directly to the model domain, rather than Vincennes Bay:

"We use the Ice-sheet and Sea-level System Model (ISSM; Larour et al., 2012) to run transient simulations of the Vincennes Bay drainage basin. The model domain (Fig. 1) covers the Vincennes Bay drainage basin…"

L146 In your steady-state runs, do you also check that mass loss is steady as well?

We consider the evolution of the grounding line flux, as well as changes in ice thickness and ice velocity throughout the spin-up period. We have added a Figure to the Supplementary Information to show the evolution of ice thickness, ice velocity, and grounding line flux throughout the spin-up period (line 146).

Is the steady state the same for all friction laws? We initialise each friction law separately (line 127 and 142) and subsequently perform the 500-year spin-up separately for each friction law. We have added an explicit statement to this effect on line 143:

"…we perform a 500-year spin-up simulation (Fig. 3) for each friction law where…"

How does the steady state geometry and ice velocity compare to the initial model state?

We have added a Figure to the Supplementary Information to show the evolution of ice thickness, ice velocity, and grounding line flux throughout the spin-up period (line 146). In summary, all fields display the largest changes over the first ~50 years before stabilising throughout the remainder of the spin-up period. The evolution throughout the spin-up period is similar across all friction laws.

Have you tested the impact of starting your perturbation experiments directly after the 2-year relaxation period (since Vanderford likely has not been in steady state). I'm wondering if this choice to spin up your model for such a long time feeds back on your results in some way?

This is a good point. We address the implications of our model spin-up in response to a previous comment from the reviewer (Line 52 of this document). Please refer to our additional model experiments, discussion above, and additional figure added to the Supplementary Information in response to this question.

L150 Change "simulate" to "perform"

Updated:

"…basal melt and calving, we perform a series of perturbation experiments."

L151 Perhaps it might be clearer to say "we simulate a series of perturbation experiments for each of the three friction laws that run for 100 years."

We have updated Lines 150-151 as follows:

"To assess the sensitivity of Vanderford Glacier to sub-ice shelf basal melt and calving, we simulate a series of perturbation experiments which run for 100 years, for each of the basal friction laws (Sect. 2.1)…."

If the model is spun-up for 500 years, why do you need to further spin up each experiment for another 5 years?

We include a short perturbation-free period during all experiments primarily to ensure that the timestepping of calving and basal melt perturbations were correctly aligned and that the timing of discrete perturbations aligned with the frequency of requested model output. The choice of 5 years is arbitrary, but given that our initial conditions are from a pseudo-steady state ice sheet, this is unlikely to have any impact on the results.

L158-159 What does it mean to remove the response of the control experiment from each perturbation experiment? Can you be more specific here? Is this specific to the grounding line flux, or does this also include the response of the grounding line as well?

For all reported timeseries of GL_{flux}, VAF, Grounding line retreat, and Ice volume, for each perturbation experiment, we remove the timeseries from the control experiment to isolate the effects of each perturbation. We have updated "Grounding line retreat" to be "Δ Grounding line position" to be consistent with other variables. The use of Δ in Fig. 6-8 represents the relative change of the perturbation experiment from the control experiment (i.e. the sole effect of the perturbation).

L230 Does this point to the fact that MISI is not in play here and that retreat of Vanderford is reversible if forcing decreases?

This is an interesting question. We comment on the reversibility of retreat/MISI in response to an earlier question (Line 146 above) - this response is also appropriate/relevant here.

Sec. 3.1 Also, do you know what caused this large jump in grounding line retreat in the Weertman $M_{Davidson}$ simulation (yellow dotted line in figure 6b)? It is odd that you see this spike in grounding line retreat, but do not see a corresponding jump in Delta-VAF or Delta-ice volume.

Benjamin Getraer (Reviewer 1) had the same comment. We provide the same response below to that provided to Reviewer 1.

Figure 2 shows the grounding line position at the beginning and end of the perturbation period (5 and 30 years, respectively), and the end of the simulation (100 years). Figure 2 also shows the change in ice thickness between the end of the perturbation period and the end of the simulation. A small change in ice thickness (i.e. < 30 m) in a localised region along the flowline used to calculate grounding line retreat suggests that the rapid retreat observed in the Weertman $M_{Davison}$ experiment is due to minimal ungrounding of a localised area and is not indicative of notable or widespread grounding line retreat. Since this region is so small and only experiences minimal thinning, this signal is not observed in Δ VAF or Δ Ice volume. Furthermore, due to only minimal thinning, ice re-grounds rapidly once the perturbation is removed, explaining the rapid re-advance of the grounding line.

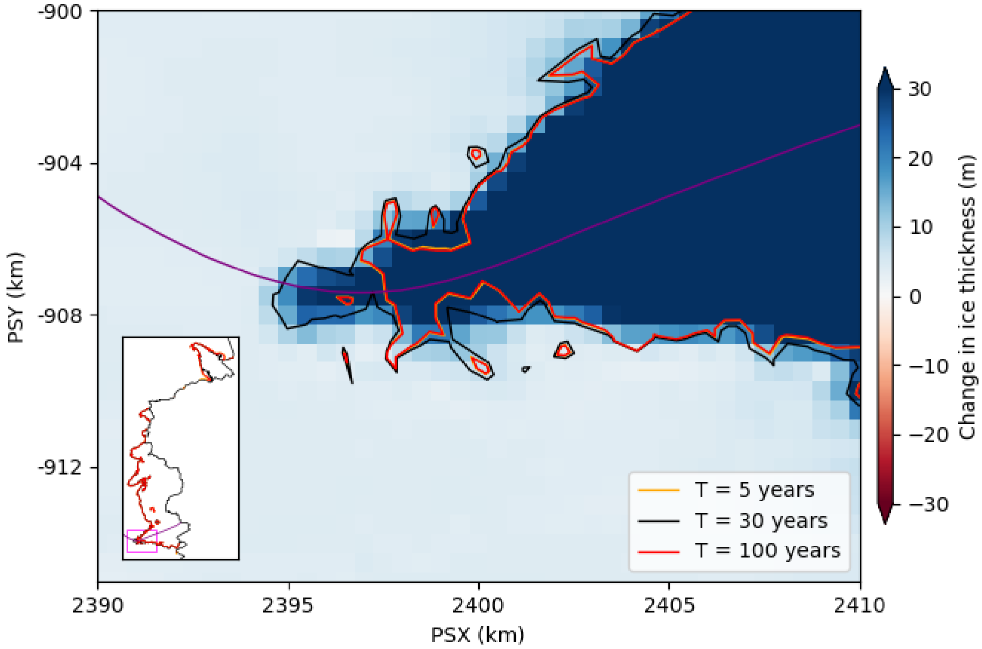

Figure 2: Weertman $M_{Davison}$ grounding lines and thickness change. Thickness change is shown as the difference between ice thickness at the end of the simulation period (T = 100 years) and at the end of the perturbation period (T = 30 years) when the grounding line is at its most retreated. Purple line denotes the flowline along which grounding line retreat is calculated.

L242 Figure pointer to 5c seems incorrect(this figure shows grounding line retreat in the linear calving experiments). Did you mean 5b? Same with pointer on L271 to fig. 7j (should this be 7i?)

We have corrected this figure reference to be Fig. 5b and the reference on Line 271 to be Fig. 7i. We have reviewed all figure references and made amendments where necessary.

L286 Fig. 7j references the basal melt perturbation experiments, do you mean fig. 7l? Same for figure reference in L294.

We have corrected both these figure references to be Fig. 7l. We have reviewed all figure references and made amendments where necessary.

L363 In addition to in situ measurements, what about the opportunity to back out high resolution ice shelf melt rate maps using techniques such as the one described in Zinck et al. (2023); https://tc.copernicus.org/articles/17/3785/2023/? Given that direct observations of ice shelf melt are difficult/costly to obtain, it might be worth discussing other avenues.

This is a great point and aligns with a similar comment made by Benjamin Getraer (Reviewer 1) about the appropriateness of collecting direct observations. As we discuss (Lines 354-364), satellite estimates often rely on the assumption of hydrostatic equilibrium; however, this assumption is challenged in regions such as Vincennes Bay. While satellite estimates provide a useful and convenient method to infer basal melt rates, current assumptions can limit their applicability to small dynamic systems in Antarctica. We have updated Line 362 as follows:

"...This highlights the need for improved estimates of basal melt across Vincennes Bay ice shelves. While recent advances in satellite-derived basal melt estimates (e.g. Shean et al., 2019; Paolo et al., 2022; Davison et al., 2023; Zinck et al., 2023) allow for high-resolution estimates of sub-ice shelf basal melt, some simplifying assumptions (e.g. hydrostatic equilibrium) have limited applicability in small dynamic systems such as Vincennes Bay, which highlights the ongoing need for direct observations (e.g., geophysical or oceanographic) to help constrain remotely-sensed estimates (McCormack et al., 2024)."

Figure Comments:

Fig. 2 In the caption, you say "current mass loss estimates for Vincennes Bay", but is this accurate since you are showing ice shelf melt rates and calving rates? Might consider removing this qualifying sentence.

We have updated the figure caption for clarity, as follows:

"Sub-ice shelf basal melt rates and ice-front migration for Vincennes Bay. (a) Long-term mean annual basal melt..."

Fig. 3 It is difficult to tell which experiments are bolded (I did not realize any were bold until I read the caption). Can you make this stick out more?

We have modified entries of basal melt and calving processing that are combined in hybrid experiments to improve readability of the figure.

Fig. 6 Is panel-b showing the location of the grounding line along the flowline (e.g., in the Weertman $M_{Davidson}$ experiment, the grounding line was ~2.5 km retreated inland from year 20-25, but then advanced back to its present day position at year 30), or is this the retreat rate? It might be nice to briefly mention this in the figure caption or corresponding section of the paper.

Fig. 6b and Fig. 7d-f show the position of the grounding line along the flowline, relative to the position of the grounding line from the corresponding control experiment. We have updated the axis label to be "Δ Grounding line position (km)" and inverted the numbers to represent retreat as negative numbers and advance as positive numbers. We have updated the figure captions as follows:

"Figure 6. … (b) Grounding line position calculated along the central flowline shown in Fig. 2c. Negative numbers represent grounding line retreat and positive numbers represent grounding line advance, relative to the Ctrl experiment. (c) …"

"Figure 7. … (d-f) Grounding line position calculated along the central flowline show in Fig. 2c. Negative numbers represent grounding line retreat and positive numbers represent grounding line advance, relative to the Ctrl experiment. (g-i) …"

Fig. 7 In the caption, I am a bit confused at your description of what the purple line is in panels d-f. Is the purple line the location of the 2020 grounding line along the flowline?

The purple line represents the position of the 2020 grounding line along the central flowline, relative to the position of the grounding line from the *Ctrl* experiments. Since the three different *Ctrl* experiments generate slightly different grounding line locations, we take the mean grounding line position from the three *Ctrl* experiments and calculate the 2020 grounding line position relative to this mean grounding line position. We have updated the figure caption as follows:

"… Purple horizontal line in (d-f) shows the location of the 2020 grounding line (Picton et al., 2023), along the central flow line shown in Fig. 2c., relative to the mean grounding line location from all three basal friction Ctrl experiments."

Fig. 10 The orange line is a bit difficult to see given the colormap used. Can you try to make these stand out a bit more?

We have updated Fig. 10 to improve readability.

References

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