Modelling GNSS-observed seasonal velocity changes of the Ross Ice Shelf, Antarctica, using the Ice-sheet and Sea-level System Model (ISSM)
– Response to Reviewer 1 –

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Firstly, we would like to thank all three reviewers for their constructive and detailed comments. We agree with many points that were raised, especially the lack of discussion of our results in the context of recently published papers (e.g., *Klein et al.* [2020] & *Mosbeux et al.* [2023]). We have responded to each reviewer's comments below. All three reviewers' main comments included the need for additional discussion and consideration of *Klein et al.* [2020] and *Mosbeux et al.* [2023]. This is a good point that we will address throughout a revised manuscript, as we realize that we did not adequately motivate and contextualise our study, and these previous works deserved more recognition.

Novel contributions

Several reviewers questioned the novelty of aspects of our study. Here we briefly summarise aspects of our study which we believe are novel contributions.

- We present new GNSS time series from the Ross Ice Shelf that have not previously been published. These include sites near the calving front, near a significant pinning point, and in the deep interior of the ice shelf near the grounding line.
- Notably, our Site 2 is close to the calving front near the Ross Island region, which has been identified as observing high basal melt rates on a seasonal timescale (Stewart et al., 2019).
- We show that these measurements consistently show 2 peaks in ice shelf velocity every year (for Sites 1, 2 and 4, the newly collected datasets), contrary to previous measurements presented in *Klein et al.* [2020] and *Mosbeux et al.* [2023].
- We suggest that the seasonal variability of SSH (i.e., yearly cycle) may not be able to reproduce our GNSS seasonal velocity variability (i.e., semi-annual).
- We therefore turned to the potential role of basal melt and wanted to test *what it would take* to match velocity variations by changing the forcing as little as possible.
- Our approach of combining Automatic Differentiation and weekly MITgcm basal melt rates ([*Klein et al.*, 2020] used monthly basal melt rates) is also novel.

Sea surface height (SSH)

An area where the two previous studies should be discussed more in our manuscript is in regards to what other factors that could be driving the observed velocity variations on the ice shelf. [*Mosbeux et al.*, 2023] nicely shows that the seasonal variability of SSH can explain their observed seasonal variability of ice velocity.

To take this into account, we will rerun our simulations with the same SSH forcings implemented in [*Mosbeux et al.*, 2023] to consider this factor. However, we expect that the seasonal variability of SSH cannot explain our two-peaked seasonal velocity variability, as mentioned above. In our revised manuscript, we will also discuss other possible factors (tides, sea ice buttressing etc), that may also be good candidates to explain our new GNSS observations.

Basal melt rates

Melt rates are difficult to model and properly constrain, especially close to grounding lines, despite their critical role on ice dynamics. All reviewers commented on the realism of the basal melt rates. We agree that these basal melt rate perturbations we use are extremely high for the Ross Ice Shelf, today and in the future. However, this paper focuses on asking whether perturbations in basal melt rates *can* reproduce a similar velocity variability as observed by the GNSS units. We acknowledge that our contribution is a proof of concept, not a definitive answer to the question, and we will do our best to make this clear in the revision.

Multiple peaks in melt rate perturbation

Several reviewers questioned our use of multiple peaks in melt rate perturbation. Here we clarify our motivation for doing so. The baseline weekly MITgcm basal melt rates include a clear peak in the austral summer, and multiple other (much smaller) peaks throughout the year, highlighting that the basal melt rates have more variability than presented in [*Klein et al.*, 2020]. We also refer to [*Stewart et al.*, 2019] basal melt observations in our discussion, highlighting that they observe the largest peak in the austral summer, but also smaller peaks in the austral winter.

Klein et al. [2020] suggest that the actual total summer increase in the heat content of the AASW layer near the ice front is likely to be larger than the modelled increase, and the seasonal enhancement of the basal melting will continue further into autumn than in their model. [*Klein et al.*, 2020] extended the late melt period to April and found that it also shifted the timing of maximum velocity a month later, showing that a longer or later melt period at the front could align the modelled and observed velocity phases.

Our approach is to use multiple basal melt peaks as the basis for our phasing of the basal melt forcing, and we apply perturbations on this forcing until we reproduce a similar velocity variability to the GNSS observations. Through this, we can highlight that seasonal basal melt rates can reproduce the GNSS velocity variability on an interannual timescale for XX of the sites. We do not state or intend to imply that these perturbed basal melt rates are realistic for the Ross Ice Shelf. Our study instead serves as a proof of concept, motivated by Klein et al. "as-yet-unidentified seasonal processes". This overall aim will be clarified in the revised manuscript.

1 Reviewer 1

1.1 General comments

As stated in the submission guidelines for The Cryosphere, I strongly encourage the authors to deposit all scripts and configuration files for setting up and running the ISSM simulations in a FAIR-aligned repository, such as Zenodo.

We will include the scripts and configuration files for setting up and running the ISSM simulations in an FAIR-aligned repository when submitting the final manuscript.

Add to the introduction paragraph on lines 80-88 a brief description of how this present study differs from [*Klein et al.*, 2020] and [*Mosbeux et al.*, 2023] which, as described in the preceding paragraph, provide an explanation for the intra-annual velocity variations for the RIS.

This is a great point, see summary above.

Additionally, please add text in the Discussion that addresses why the conclusions of this present study differ from [*Klein et al.*, 2020], which claim that seasonal velocity variations are not driven by basal melt rate variability.

Again, this is a good point, hopefully addressed in the summary above.

Use "intraannual" throughout the text to refer to monthly to seasonal variability. For example, line 73 refers to monthly to seasonal variability as "interannual" but this should be changed to "intraannual". Please check the entire manuscript for other cases of this.

Done, this has been edited throughout the manuscript.

Add a map of observed velocities of the ice shelf to Figure 1.

Figure 1 shows the modelled surface velocity results after initialisation, we think that displaying the modelled surface velocity results is sufficient since ISSM used observed velocity from the MEaSUREs dataset to calibrate the model (modeled and observed velocity therefore look similar).

Remove Figure 3 because Figure 5 shows the same data.

We think that Figure 3 should still be included as it shows the raw *observed* velocities directly from the GNSS sites, whereas Figure 5 highlights the velocity variations. The observed velocities are important to show as they highlight at which sites the velocities are flowing faster, and the seasonal changes in these velocities.

It is not clear to me whether including both Figure 2 and Figure 4 is necessary and how the interpretation differs for the results shown in these two Figures. My understanding is that Figure 2 shows the sensitivity of the final velocity for a 6-month simulation and Figure 4 shows the sensitivity of the final velocity for a 2-year simulation. I also see that Figure 2 shows sensitivities that are above the selected threshold, whereas Figure 4 shows the full range of sensitivities. However, it seems like the text in Section 3.2, which describes the results in Figure 4, could also apply to the results in Figure 2. I may be wrong, in which case please feel free to disagree. If it is decided to keep both figures in the manuscript, please add text to Section 3.2 that explains why the results in the two figures are different and what additional information for interpretation is provided by Figure 4 that isn't already provided by Figure 2.

We agree with the reviewer that Figure 2 is not necessary, it will be removed.

Add a figure showing absolute modelled and observed velocities at each GNSS site to Supplementary Materials and reference this figure on line 266.

This figure will be added to the Supplementary Materials, although we are focusing on velocity variations, not absolute velocities.

The paragraph on lines 353-360 hypothesizes that perturbing the melt rate at the KIS grounding zone could modify driving stress at Site 4, through a modification of basal friction. Couldn't you use the ice sheet model to test this proposed process? ISSM simulates changes in driving stress and the corresponding change in basal friction due to the simulated melt rate perturbations. You could analyze the changes in the force balance at Site 4 to address this. Please either add this analysis to the paper or provide text explaining why this is not possible with your model configuration.

We will model the driving stress through time at Site 4, and analyse the results. If we think they are appropriate to include in the updated manuscript, we will add a figure and explanation in the discussion.

Wherever possible, begin each paragraph in the Discussion section with a topic sentence that describes the main result that is being discussed in the paragraph. For example, on line 312, change the topic sentence to: "We model a seasonal signal in velocity variability that is similar in phasing and magnitude at GNSS Sites 1 and 2 but not Sites 3 and 4." Another example is on line 362, where the topic sentence could be changed to: "The melt rate perturbations used in our modelling experiments are realistic for Sites 1 and 2 but less realistic for Sites 3 and 4." Please go through the Discussion to find other opportunities to make changes to topic sentences to clarify the result being discussed in the paragraph.

This is a great suggestion, and we will go through the discussion and begin each paragraph with a topic sentence in the updated manuscript.

1.2 Specific comments

[line 13] The word "today" seems out of place here. Can it be removed?

Done.

[line 126] I suggest adding a reference to https://doi.org/10.5623/geomat-2005-0004 to cite the CSRS-PPP specifically.

Done.

[line 175] Add a sentence to Section 2.4 stating that one set of simulations was run in which the basal melt rates were perturbed at locations where there was sensitivity in the velocities for any of the GNSS locations (as opposed to separate simulations where the melt rates were perturbed for each individual GNSS location).

We did not do this, and we apologize for the confusion. We only ran *one* set of simulations in which the basal melt rates were perturbed at locations identified as highly sensitive (using our threshold) for at least one GNSS site. We will clarify this in Section 2.4.

[line 181] Replace "raw" with "unperturbed".

Done.

[Figures 2 and 4] Is the black line showing the grounding line? If so, state that in the caption and change the passive ice outline from black to a different colour.

The caption has been edited to state that the black line is the grounding line. These figures will be edited in the updated manuscript, with a different colour for the passive ice outline.

[Figure 4] Add labels and arrows showing the locations of Roosevelt Island, Crary Ice Rise, Steershead Ice Rise, the Shirase Coast Ice Rumplus, Byrd Glacier and any other locations that are refered to in the text when describing this figure.

Thank you for this suggestion, we will add labels to Figure 1 to identify the locations that are referred to in the text in the updated manuscript.

[Figure 5] Color each dotted black line using the same colors as the solid lines to denote the melt rate perturbation magnitudes.

This will be implemented in the updated manuscript.

[line 264] The text states that "use of the lower sensitivity value did not significantly affect the final modelled velocity variations" and Figure 5 shows that is indeed correct for sites 1-3 but for site 4, it looks like the velocity peaks are about 30 percent larger for the highest perturbation magnitude. I suggest quantifying the differences between the two simulations that used different sensitivity thresholds.

While we agree with the reviewer that this statement should be toned down, we are a bit resistant to play with this threshold too much as the aim of this paper is not to try and match the GNSS and modelled velocities, but rather we are trying to determine if it is possible to reproduce similar velocity variations from basal melt alone, at least for some GNSS sites.

[lines 340-341] This sentence needs to be reworded: "Figure 2 highlights that basal melt rates are perturbed at the Ross Island region for Sites 1, 2 and 3." to something like "Figure 2 shows that velocities at Sites 1, 2, and 3 are most sensitive to basal melt rate perturbations at the Ross Island region."

Done.

[lines 350-352] This sentence is repetitive and states the same thing as the previous paragraph. Please delete this.

Done.

[line 361] Change this section heading to: "Comparison to observed basal melt rates beneath the Ross Ice Shelf".

Done.

[line 384] Please define what "short-term" basal melt rates are. This is the first mention of this term and it is not clear how this is defined.

The term "short-term" has been removed.

[Figure 6] Similar to the previous comment, please define the timespans that "short-term" and "mean" are covering in the figure caption.

The term "short-term" has been removed and the caption has been edited to replace "mean" with "average".

[lines 419-423] Are these "additional" experiments ones that are already described in the paper? If not, the configuration and results from these additional experiments need to be included in paper. They can be added to Supplementary Materials or an Appendix but please add figures of (1) the locations where melt rates were perturbed and (2) the resulting velocity variations.

These additional experiments will be included in the Appendix alongside the figures.

References

Klein, E., C. Mosbeux, P. D. Bromirski, L. Padman, Y. Bock, S. R. Springer, and H. A. Fricker, Annual cycle in flow of Ross Ice Shelf, Antarctica: Contribution of variable basal melting, *Journal of Glaciology*, *66*(259), 861–875, doi:10.1017/jog.2020.61, 2020.

Mosbeux, C., L. Padman, E. Klein, P. Bromirski, and H. Fricker, Seasonal variability in antarctic ice shelf velocities forced by sea surface height variations, *The Cryosphere*, *17*(7), 2585–2606, 2023.

Stewart, C. L., P. Christoffersen, K. W. Nicholls, M. J. Williams, and J. A. Dowdeswell, Basal melting of Ross Ice Shelf from solar heat absorption in an ice-front polynya, *Nature Geoscience*, *12*(6), 435–440, doi:10.1038/s41561-019-0356-0, 2019.