Author's response to Editors Comment 1

August 24, 2023

1 General Comment

[Thank you for submitting a revised version of your article draft. Although you addressed most of the concerns and suggestions raised by the reviewers and myself, I feel another and hopefully final round of minor modifications would be needed to have the manuscript in good shape for publication. You'll find in the attached file a version of your latest manuscript highlighted including notes for various issues one still would need to address prior to publication.

The minor revision should focus on: - Removing research question list style (Q1-11) and rather use the other grouping already implemented into 3 or 4 subsections, discussing these points in a logical and systematic fashion. This would add clarity and allow to remove some repetition. - Maybe be more explicit that all this stud arises from using existing software that creates limitations where there may not be any if another approach was employed. For example, the fact that the PISM results significantly depend on the number of cores used for the simulation is something that should not happen. I feel some of the issues arise also because of the various parametrisation of physical processes used in the target software. Reflecting a this in, e.g., the conclusion would be valuable. - Some additional work is needed on polishing the technical notification and equations. Only variables should be in italic, and ideally one could define concise variable for some of the long terms that show up in the equations.]

We thank the editor for their constructive comments. We have addressed all the editor's comments and revised the text accordingly. A point-by-point reply is reported below, with referee comments in orange and our replies in black.

As all general comments are also addressed by detailed comments, please refer to the detailed comments sections for our replies.

2 Detailed comments

Responses to comments requiring a detailed response are listed below. Otherwise we have fully implemented the specific suggestions of the editor and do not list them below.

[Title: change "issues" to "challenges"] To better describe the content of this manuscript and include all of our experiments, we updated the title from: *Numerical issues when modeling thermally and hydraulically driven ice stream surge cycling*

to: *Modeling sensitivities of thermally and hydraulically driven ice stream surge cycling*

[Ln 19: could also be called "spontaneous localisation".] The sentence *This is especially important in the case of abrupt changes.* was removed entirely, as it is a repetition of *This is especially true when modeling the highly non-linear ice sheet surge instability, which has significant implications not only for the ice sheet itself but also for the climate.*

[Ln 80: This needs more details. The terminology here is already specific to the models and gives no information to the reader. What are you doing, running ensembles, running more nonlinear solver iterations, else?] We do not fully understand this comment, as there is no terminology specific to the models in this sentence and *high variance ensemble* explicitly states that we are running ensembles. However, we slightly updated this sentence from: *In order*

to partly address potential non-linear dependencies of surge cycling on model parameters, we run each of our numerical experiments with a high variance ensemble of 5 GSM and 9 PISM parameter vectors.

to: *To partly address potential non-linear dependencies of surge cycling on model parameters, we run each numerical experiment with a high variance ensemble of 5 GSM and 9 PISM parameter vectors instead of just a single run.*

Furthermore, we updated the first sentence of this paragraph from *In terms of ice flow models, we primarily use the 3D glacial systems [GSM, Tarasov et al., 2023].*

to: *In terms of ice flow models, we primarily use the 3D glacial systems model with hybrid shallow shelf/ice physics [GSM, Tarasov et al., 2023].*

[Ln 181: To me this seems to be among the most meaningful metric one could use in a study like this one and do not fully get how it is different from them MNEEs you are proposing] As stated in the cited line, the difference between results for different resolution (or different configurations) is the metric. The MNEEs are the minimal threshold for determining if these differences are significant. We've noted the text was confusing in this regard, and have now replaced the word *metric* with *threshold* when associated with the MNEEs: *This is a new metric that aims to minimally resolve whether a change in surge characteristics due to changes in the model configuration is significant (see Sec. 2.3 for details).*

to: *This is a minimal threshold to resolve whether a change in surge characteristics due to changes in the model configuration is significant (see Sec. 2.3 for details).*,

*We compute the new '**M**inimum **N**umerical **E**rror **E**stimates' (MNEEs) metric by examining the model response to changes in the model configuration that are not part of the physical system.*

to: *We compute the new '**M**inimum **N**umerical **E**rror **E**stimates' (MNEEs) threshold by examining the model response to changes in the model configuration that are not part of the physical system.*, and

Therefore, it is crucial to determine MNEEs (or a comparable metric) to minimize the possibility of interpreting numerical errors as a physical response to a change in model setup.

to: *Therefore, it is crucial to determine MNEEs (or a comparable threshold) to minimize the possibility of interpreting numerical errors as a physical response to a change in model setup.*

[Ln 369: How would changing the number of cores used result in a different matrix based solver? How does this reflect to the stricter numerical convergence criteria used in GSM, i.e., can't one do both for both codes?] To avoid confusion, we removed the part about the matrix based solver. The sentence now reads *The MNEEs are defined as the percentage differences in surge characteristics when applying a stricter (than default) numerical convergence in the GSM and changing the number of processor cores used in PISM.* and we moved up one sentence from the results section: *The differences between PISM runs with different numbers of processor cores can be caused by, for example, a different order of floating point arithmetic operations and the processor-number-dependent preconditioner used in PISM [PISM 2.0.6 documentation, 2023].*

While we tested stricter numerical convergence criteria for PISM (Sec. 3.2), they led to an unreasonable increase in the model run time beyond the run-time limit of the computational cluster. Furthermore, as mentioned in our last response to Referee 2, *many readers will expect the same or at least similar results for different numbers of cores. We decided to use the number of cores for two reasons. 1) To emphasize that in a highly non-linear system such as the one examined here, even the smallest differences can lead to substantial differences in surge characteristics. 2) To show the potential numerical sensitivity of the default PISM setup, likely blindly used by many ice sheet modellers, to prompt the community to pay more attention to numerical issues.*

[Ln 440: what does this mean? Is the outer loop the nonlinear solver? ideally, you monitor linear and nonlinear resduals, and make sure they all converge.] We updated this sentence from: *In a second experiment, we additionally increase the maximum iterations from 2 to 3 for the outer Picard loop (ice dynamics) and from 2 to 4 when solving the non-linear elliptic SSA*

equation.

to: *In a second experiment, we additionally increase the maximum iterations from* 2 *to* 3 *for the outer Picard loop solving for the ice thickness and from* 2 *to* 4 *when solving the non-linear elliptic SSA equation for horizontal ice velocities.*

[Ln 654: what is Pa?] Pa is the unit Pascal, as indicated in the text: *We enforce that* N_{eff} *never falls below* 10 kPa *(denominator in Eq. (21), similar results for* $N_{\text{eff,min}} = 5$ kPa*).*

[Results Summary and Discussion: I would remove the Q-based layout and use the same 3 group you proposed in the introduction. Also, part of the discussion could be slightly srteamlined further in order to avoid repetition.] We removed parts of the MNEEs and basal temperature ramp paragraphs in the discussion section to further streamline the summary. However, the manuscript is already structured according to the three groups (minimum numerical error estimates (MNEEs), sensitivity experiments, and convergence study). The research questions mainly split the otherwise 10 pages long sensitivity experiment results section into further subgroups, providing additional guidance for the reader. Especially given the number of research questions, we feel strongly about retaining this structure (and wish it was more common when there are more than a few research questions in one paper).

[Conclusions: Maybe good to highlight here that agood part of the issues you encountered are actually due to models themselves, and that less parametrised models with correct multicore parallelisation should by construction avoid most of the issues and challenges you are reporting here.] We agree that some of these issues would be irrelevant in an ideal world (e.g., models with 50 m grid resolution). However, such high grid resolutions are currently unfeasible and will likely remain unfeasible for the foreseeable future. Therefore, all state-of-the-art ice sheet models, including the GSM and PISM, require some level of parameterization.

The processor-number-dependent preconditioner used by PETSc's KSP is critical to its parallel scalability [PISM 2.0.6 documentation, 2023]. Furthermore, the GSM avoids any parallelization issue (only single core usage) yet still shows numerical challenges.

As increasing the awareness of numerical challenges that must be considered when modeling surges is one of the key takeaways, we prefer not to include the proposed statement and avoid giving the reader a false sense of security.

References

PISM 2.0.6 documentation. Petsc options for pism users, August 2023. URL `https://www.pism.io/docs/manual/practical-usage/petsc-options.html`.

Lev Tarasov, Kevin Hank, and Benoit S. Lecavalier. Gsmv01.31.2023 code archive for lissq experiments, February 2023. URL `https://doi.org/10.5281/zenodo.7668472`.