Authors' response
EGUSPHERE-2023-2690

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Note: Reviewers' comments are given in italic font whereas the authors' responses read in regular font.

1 Editor's remarks

The authors are thankful to the editor (Ludovic Räss) for his comments, thus allowing an improved version of the paper. We have addressed the main points raised by the editor:

- Better define, motivate and showcase the applicability of Nix's new features when compared to existing models.
- Explain potential discrepancies with the previous version.
- Updated GitHub repository link: `https://github.com/d-morenop/nix`.
- Removed typos.

The result of this revision is evident in a clearer and more convincing version of the paper. Nix thus presents itself as an extremely versatile model combining usage simplicity, low computational costs and high-order physics at extremely high resolution ($\Delta x < 0.1$ km).

2 Tijn Berends

The authors are grateful to the reviewer for their constructive comments. We now provide our answers (regular font) to the main concerns raised by the reviewer (italic).

Major comments

- *Applicability. I think you could still do a better job of convincing the reader of the practical value of the Nix model. The experiments presented in the manuscript used "a horizontal resolution of Δx = 2 km and 35 vertical layers". These numbers would not pose any difficulty in terms of performance for existing 3-D models (PISM, CISM, Elmer, UFEMISM, etc.) when using a flow-band set-up, so the added value of Nix in this application does not really stand out. However, in your rebuttal, you state that "For wall-clock times of the order of minutes, Nix allows for resolutions of Δx = 0.1 km ... and simulated times of order $t \sim 10^3$ kyr.". This resolution is 20 times higher than what is used in your experiments. Such a high resolution likely cannot be easily matched by existing 3-D models (at least, not without using reallylarge numbers of CPU cores), and so there the added value of Nix would be much more noticeable. I think that providing some numbers to demonstrate Nix's performance at such high resolutions, including some (hypothetical) examples of experiments where such a high resolution would be necessary, would help convince the reader of why (as I asked in my first review), they should use Nix instead of any of the already existing ice-sheet models.*

We thank the reviewer for pointing out Nix high computational speed. Appendix H has been updated by including a figure that shows the computational speed time at high resolutions, i.e., up to $\Delta x =$ 0.05 km, far beyond existing 3D models (see Fig. 1 in this document and Appendix H of the updated manuscript).

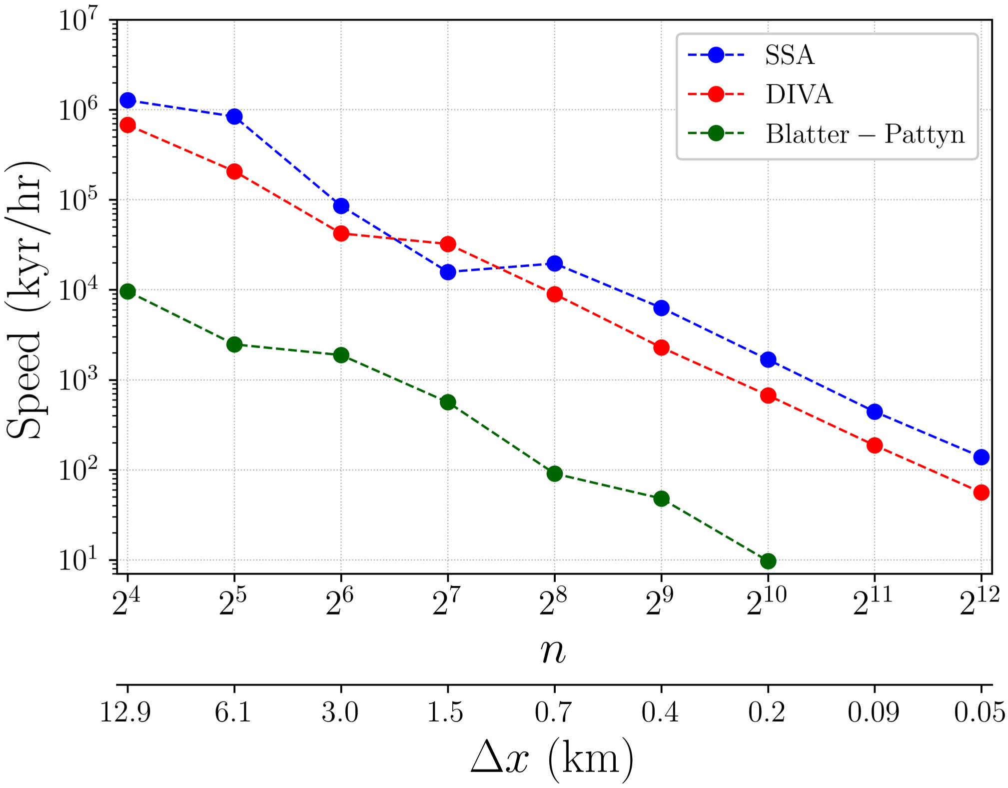

Figure 1: Nix computational speed for the three solvers available. The double x-axis represents the number of horizontal grid points n and the corresponding resolution at the grounding line Δx. Note that Nix allows for an unevenly-spaced stretched grid that explicitly tracks the grounding line position. This figure is now part of Appendix H.

Furthermore, the practical use of Nix ice-sheet model does not solely lie on its high-resolution performance, but also in the gap filled in the model hierarchy spectrum. Nix is a 2D marine-terminating ice-sheet model described by the higher-order Blatter-Pattyn stress balance and fully thermodynamically coupled. Unlike previous existing 2D models, Nix solves for the ice temperatures and evaluates the importance of ice thermomechanics for stability and grounding line migration by forcing with physical variables: air temperatures and oceanic anomalies. To the authors' knowledge, this represents a novel result and sheds light on the stability of marine-terminating ice sheets. Previous studies, such as those focused on attribution exercises to anthropogenic-induced ice-sheet retreat (e.g., Christian et al., 2022), use simplified physics that neglect the thermochemical coupling and are consequently biased by unrealistic constant temperatures both in space and time. Other examples of neglected thermal effect on ice viscosity also involve Heinrich Events triggered by oceanic warming (Bassis et al., 2017).

Nix usage stands out for its simplicity. Highly complex 3D ice-sheet models (e.g., ElmerIce, ISSM) require large efforts for installation, computational resources and careful preparation of input fields. On the contrary, only two command lines are enough to run Nix:

```
$ git clone https://github.com/d-morenop/nix
$ python run_nix.py
```

This will run the desired experiment (within a few minutes) solving the higher-order Blatter-Pattyn stress balance. Then, simply by running the script nix_plot.py, the user can visualize the output saved in the NetCDF file "*nix.nc*". Alternatively, one can employ the ncview tool for a direct inspection of the simulation output.

- *Discrepancies with new results.*

This point was already noted by the authors in the previous response (see the uploaded document "Relevant changes made in the manuscript"; 10th of May, 2024). We quote here what was already written for clarification: "*[...] the authors further noted a misconception on the previous diagnosis of the thermomechanically coupled simulations [...]. Results are now correctly interpreted and both Section 6.2.2 and Fig. 6 have been updated accordingly showing that the hysteresis loop in overdeepening beds is in fact widen when thermodynamics is considered*".

In the old manuscript version, results corresponded to simulations in which ice temperatures were calculated, but the viscosity was not updated accordingly. This led to a different hysteresis loop. All figures and results were updated as it was already noted in the last review. This explains all figures discrepancies between the last two versions.

- *In Sect. 6.2.,1 I see that you added an altitude dependency to the surface temperature forcing, why was this done? Also, in the authors' response, you mention "both adiabatic and moist lapse rates", but only one value of 9.8 K/km is given in the manuscript. Also, in the previous version, you needed to reduce the surface temperature by about 80 K to cause the ice sheet to advance, whereas now you only need a 30 K change. Can you explain this difference?*

In the first manuscript version, the applicability and realism of the modeled were criticized. To overcome this issue, an adiabatic lapse rate was simply included to further improve realism and applicability. The corresponding value of the moist lapse rate has been included in the manuscript.

The difference in temperature amplitude to produce advance in the ice sheet shares the same answer that we elaborated above: old results corresponded to simulations in which ice temperatures were calculated, but the viscosity was not updated accordingly. Now that the ice viscosity is also updated with the new temperatures, the ice velocity adjusts accordingly and the amplitude in the atmospheric forcing necessary to produce advance is thus reduced.

- *In the new version of Fig. 5, large parts of the ice in panel E (the lower left, near the bedrock and near the ice divide) seem to be about 20 to 30 K colder than in panel A. In the text, you claim that the 30 kyr steps are long enough to "ensure thermal quasi-equilibrium", and since the geometries in these two panels are identical, the temperature profiles should be identical too. Can you explain where these substantial temperature differences come from?*

Thank you for the comment. Fig. 5e did not correspond to the very last frame for the forcing. As the reviewer notes, the temperatures profiles are expected to be identical given the boundary conditions of the problem. We have updated accordingly the figure.

Minor comments

- *L76-77 "... though differences are particularly notable for resolutions below 20 km." The differences between the DIVA and the BPA arise when the scale of subglacial bedrock topography is smaller than 20 km (in the ISMIP-HOM experiments). This has nothing to do with resolution, nor with any other numerical model parameter. It is a consequence of the neglected strain rates in the DIVA, making the velocity errors increase faster with the aspect ratio of the ice than they do in the BP.*

The text does not discuss the physical reason why these differences appear. It is simply stated that such deviation only becomes noticeable for resolutions higher than 20 km. As the reviewer later elaborates: "*[...] the velocity errors increase faster with the aspect ratio of the ice than they do in the BP*". Consequently, DIVA and Blatter-Pattyn stress balances are virtually equivalent for resolutions coarser than 20 km within the ISMIP-HOM experimental setup.

- *L87 "... ice high-quality spatially distributed observations..." unclear what you mean by this.*

Remote sensing has important limitations in terms of spatially distributed observations of basal conditions. This poses a restriction on how we constrain ice-sheet models in fast flowing regions. We refer the reviewer to Bueler and Brown (2009) for further details. The manuscript has been updated for clarification.

- *L307 "This melt rate is included as an additional term in the ice flux computation (Eq. 7 and 18)" Please provide the modified versions of these two equations including M.*

We have updated the Discretization scheme (Eq. D3) to account for this potential additional term.

- *L397 "... (Fig. 3c and 3c)..." I think these are 3c and 3d.*

Indeed. The typo has been fixed.

- *L439 "...panels 5a, 5b 5e..." I think these are 5a, 5c, and 5e.*

Indeed. The typo has been fixed.

- *L550 "...the required calving at the grounding line..." I thought M was supposed to represent some sort of melt?*

Following Christian et al., (2022), we simply interpret this term as flux anomalies at the terminus driven by variable ocean conditions. In real glaciers, these anomalies could be driven by variable calving, submarine melt, or a combination. This is now explicitly stated in the manuscript (Lines 307-309).

References

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