Author's response to Anonymous Referee 1 (RC1) egusphere-2023-2690

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1 Review

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

- *The fact that Nix is a 2D model significantly limits its potential as a community code, in my opinion. Although the model is well-described, which is expected for GMD, all components (physical models, numerics) employ well-known techniques that are already implemented in many other community glacier/ice sheet models in 3D (e.g., PISM, Elmer/Ice, CESM, ISSM, Bisicles, to name a few). Without offering anything distinctly new, I question the rationale behind publishing a 'model development' paper on the Nix model.*

We believe that the present work strongly adheres to those defined by "*Model description papers*" (in agreement with Referee #2, Tijn Berends), for that it meets the Geoscientific Model Development journal definition of a "*detailed, complete, rigorous and accessible description of a numerical model*" (see `https://www.geoscientific-model-development.net/`). It is well known that different models behave distinctly, and it is thus important to document them. Information about the real world is not only obtained from spatially explicit models and simpler models allow the investigation of the relevance of specific processes. Even though Nix model has a number of novelties (elaborated below), it should not be a requirement to be published as a "*Model description papers*" in GMD.

The main goal of this work is to present and describe an ice-sheet model that aims at overcoming the inevitable trade-off between a sophisticated physical description and fast computations. Compared to other 2D models, Nix provides the following novelties (summarised in Table 1):

1. **Thermomechanical coupling**. Nix explicitly resolves the energy balance by solving for the ice temperatures assuming a number of processes in the heat equation: vertical diffusion, horizontal and vertical advection, strain dissipation and basal frictional heat. As a result, the ice viscosity is thus temperature dependent. Moreover, the basal friction coefficient is also coupled to the thermal state of the base, thus accounting for a potential friction reduction if the pressure melting point is reached.
2. **Fast computations**. It combines a higher-order stress balance with active thermodynamics, while keeping extremely fast computations that allow for statistical studies with thousands of simulations involved, otherwise prohibited by 3D models.
   - **2a.** For wall-clock times of the order of minutes, Nix allows for resolutions of $\Delta x = 0.1$ km (needed to properly resolve the grounding line) and simulated times of order

$t \sim 10^3$ kyr. This extremely low computational cost allows for statistical studies with thousands of simulations involved, otherwise prohibited by 3D models.

2b. Parallelisation. Nix users can optionally select parallel computing (supported by Eigen library), particularly convenient for high resolutions in the Blatter-Pattyn approximation, where large sparse matrices must be inverted. Moreover, it is possible to use Eigen's matrices, vectors, and arrays for fixed size within CUDA kernels.

2c. It is hard to give a one-to-one comparison since other models that solve for the same higher-order momentum balance coupled with a thermodynamical solver use 3D solvers (partially providing Nix novelty). To give an estimation, the MALI ice-sheet model (Hoffman et al., 2018) control simulations averaged 5.26 simulated years per wall-clock hour. On the contrary, MISMIP experiments run with Nix reach $\sim 10^5$ simulated years per wall-clock hour on average. Thus, there is a 5-order magnitude difference in terms of computational time.

3. **Time stepping**. Unlike other models, Nix offers an adaptive time stepping based on the convergence of Picard's iteration in the velocity solution solver. This approach differs from the standard proportional-integral (PI) methods (e.g., Cheng et al., 2017) and strongly contributes to its fast computational performance in Nix.

4. **Friendly usage**. As a combination of low computational demands, a 2D setup and a clean structure, Nix can be even run on a regular laptop. Installation, compilation and execution are controlled from a simple Python program. This allows Nix to be used without deep knowledge of the C programming language (low-level, procedural and statically-typed). Even though Nix simulations can run on a personal computer, the user can exploit parallelization on a High Performance Computing cluster.

Table 1: Summary of Nix capabilities.

Requirement	Nix capability
Fast computations	Low dimensionality, adaptive time-stepping, parallelization
Higher-order description	Blatter-Pattyn model
Thermomechanical coupling	Temperature-dependent ice viscosity and basal friction
Easy usage	Python wrapper

These capabilities constitute a notable difference from other ice-sheet models. Even so, we are fully aware of the limitations of a 2D setup. We do not aim at describing a highly sophisticated 3D ice sheet and we are thus conscious of the narrower range of possible applications of a 2D set-up, but we believe our model can provide additional insight for more comprehensive model studies. Two-dimensional models have tremendously helped in understanding ice-sheet dynamics both from a theoretical (e.g., Schoof, 2005; Schoof, 2006; 2007a; b) and a modelling perspective (e.g., Payne, 1995; Hindmarsh and Le Meur, 2001; Vieli and Payne, 2005; Pattyn et al., 2006). Moreover, 2D models are also capable of providing valuable insight on mechanisms such as buttressing (Dupont and Alley, 2005; Schoof, 2007; Jamieson et al., 2012, Robel et al., 2014; 2018). We have included a statement of the clear intended applications of Nix.

- *On the other hand, the MISMIP experiments incorporating active thermo-mechanics in response to oceanic and atmospheric forcings seem novel to me (has this been done before?). However, the findings are not thoroughly discussed, particularly in terms of connecting with existing literature, and the implications are barely addressed.*

To the authors' knowledge, this approach is indeed novel. We have further exploited these results, thus expanding the connection of our findings with existing literature. Moreover, we have addressed the potential implication of the results better in the discussion section. This will be incorporated into the new version of the manuscript.

- *In conclusion, I believe the originality of the manuscript resides more on its application than in model development. Therefore, I recommend shifting the focus of the paper to highlight the results more prominently, relegating the thorough yet unoriginal model description to an extensive appendix. By providing deeper discussions and a clearer emphasis on the results, a submission to a more applied journal, such as the Journal of Glaciology, The Cryosphere, or Frontiers, would be more fitting. I hope my comments are useful.*

As mentioned above, Nix's novelty lies in its fast computational capabilities and a low memory demand, thus allowing for high resolutions while explicitly solving the associated heat problem. In a broader framework of spatially explicit ice-sheet models, it can potentially provide important insight into grounding line dynamics in comprehensive 3D models. In addition, unlike other 2D models, Nix provides full thermomechanical coupling with both ice flow and basal friction.

Several of Nix's capabilities thus constitute a notable difference from other ice-sheet models and we are inclined to think that our model can provide valuable insight for more comprehensive studies. Nonetheless, we agree that our application of the model to the MISMIP experiments with coupled thermodynamics constitute interesting and novel results.

The corresponding analysis in the revised text has been consequently expanded. We believe that the manuscript now represents a more valuable contribution in this way.