Review of Coupling between ice flow and subglacial hydrology enhances marine ice-sheet retreat

Anonymous Referee

1 General Comments

This work employs a 1D channel subglacial hydrology model to study the effects of dynamically determined effective pressure on ice sheet stability at the grounding line of a flowline ice sheet model. The model employed in this study is a reduced version of the model presented by Kingslake and Ng (2013) (omitting lake evolution and distributed drainage system). The experimental design is an extension of that of Brondex et al. (2017) to include a dynamically determined effective pressure. The authors perform a dimensional analysis on the subglacial hydrology equations to study relative contribution from the involved processes. In the steady state, the authors find that effective pressure reaches a local maximum in the vicinity of the grounding line. The authors state that dynamically determined effective pressure results in faster and farther grounding line retreat than a perscribed effective pressure profile.

This study suffers from three foundational shortcomings: a lack of novelty, an overly simplistic model/experimental design, and non-physical treatment of the static effective pressure in the second transient experiment which forms the foundation for inferring that subglacial hydrology enhances marine ice-sheet retreat. Shoring up these shortcomings will require a non-trivial amount of work but will be a worthwhile contribution for understanding the impact of subglacial hydrology on grounding line positioning.

2 Specific Comments

The key finding that effective pressure exhibits a local maximum close to the margin is not itself novel. Others have found an increase in effective pressure toward the ice stream terminus (around 10/13 models, de Fleurian et al., 2018) or grounding line (Dow et al., 2018). It does, however, give the reader more confidence in the model to see it replicate known behaviour.

The inclusion subglacial hydrology to more realistically capturing margin retreat has been done before (e.g. Brondex et al., 2017). The authors state that studies which invert for sliding coefficient on the basis of measured surface velocities underestimate the potential for grounding line retreat and that the inclusion of dynamically determined effective pressure from a subglacial hydrology model reveals enhanced grounding line retreat versus static bed conditions. This conclusion may be a consequence of comparing against a static bed condition which imposes an effective pressure profile which does not change as the ice at a given location thins. This means that the static bed condition case is stabilized by an effective pressure condition from previously thicker ice. These experiments should be redone to reflect ice thinning, for example by imposing an effective pressure as a fraction of overburden as detailed in the response to Fig 7 below. Furthermore, it should be shown that these findings are robust to varied choices of parameters. For example, how does grounding line retreat differ for the static and dynamic cases for different accumulation rate? This study would benefit from a sensitivity analysis of the conclusions to scale decisions in the experimental design (flow law constant, accumulation rate, additional water source term, and input water flux boundary condition). Or better yet, an internally consistent calculation of some of those quantities.

It is a worthwhile exercise to examine the marginal contribution of isolated processes to overall system behaviour by turning off other interacting processes. In the earth system, however, neglecting fundamental processes and their interactions breaks the relation between model and true system. Here the authors employ a subglacial hydrology model forced with prescribed melt input. In the true earth system, this melt input comes from strain heating, basal frictional heating, and surface melt sources. This model is missing an important set of feedbacks between temperature dependent ice stiffness, basal melt production, hydrologically controlled basal friction, and ice-thermomechanics. Including thermomechanics in this model is feasible given its simplicity and would allow extension of model behaviour closer to the true system.

The perturbation used in the transient experiments is not physical. The time scale for surface temperatures to propagate to the full thickness of the ice body is given by the thickness over the accumulation rate. Given your ice thickness of 1000 m and realistic spatio-temporal mean Holocene accumulation rates for West Antarctica of 0.27 m/a (Bodart et al., 2023) or up to 0.40 m/a modern accumulation rates closer to the coast of West Antarctica (Kaspari et al., 2004), it would take about 2.5 kyr for surface warming to propagate through the ice column – far longer than the 10 yr period examined in the transient experiments. A more realistic approach would be to impose a change in buttressing at the grounding line to simulate ice shelf break up, allowing self-consistent evolution of the ice stiffness with thermomechanics. This would also allow for comparison of the importance of subglacial hydrology to buttressing for Antarctic mass balance and grounding line stability. In the context of the processes which determine grounding line position, where does subglacial hydrology rank?

The summary accumulation rates discussed above also point to an issue with the parameter ranges in the experimental design. No justification is given for those values and in the case of accumulation, the upper bound for the sensitivity experiments is far too high (10 m/a) and the mean value used in the other experiments is too high (1 m/a). Because of the sampling methodology used in the sensitivity analysis, the realistic accumulation rates are undersampled. This is also the region (your Fig. 2) where your model displays the greatest sensitivity to accumulation rate – in terms of effective pressure, ice thickness, and grounding line position. The parameter ranges in this study need to be revisited, adequately justified, and more appropriately sampled (see note below for line 190).

The dimensional analysis in steady state of the model processes was a welcomed inclusion and served to highlight important model components. In all figures other than Fig 5, however, showing the non-dimensionalized versions of the variables made their interpretation cumbersome. These should be changed to the dimensional versions.

3 Itemized Review

Numbers refer to line numbers unless otherwise indicated

- 21: Seroussi et al. (2020) does not discuss subglacial hydrology, they only refer to de Fleurian et al. (2018), please remove.
- 27: Also see Alley et al. (1994)
- 33: Drew and Tarasov (2023) shows varied ice sheet behaviour by parameterization and inclusion of varied hydrologies.
- 38: But there are plenty of examples of other subglacial hydrology models of varying degrees of complexity from intermediate (Bueler and van Pelt, 2015; Drew and Tarasov, 2023) to high (Werder et al., 2013; Sommers et al., 2018). I think this sentence could be removed.
- 50: Consider discussing Dow et al. (2018) application of GLADS to marine terminating ice stream but for one-way coupled unsteady conditions. They also find increased effective pressure at grounding line.
- 80: citation needed
- 102: add e.g. to citation
- 167: remove respectively
- 170: a plot of the relative positioning of hydrology and ice dynamic variables and their grids would help here
- 190: How were these parameter ranges decided upon? Please provide justification/citation.
- 190: how was the base vector selected? Did you try multiple base vectors? One at a time sensitivity analyses can be very sensitive to fixed values and is problematic for non-linear coupled models (Saltelli et al., 2019).
- 190: 100 values is quite a lot for a one-at-a-time sensitivity analysis. If able to run the experiment for this density then the sensitivity analysis would benefit from including interaction terms. See for example (Saltelli, 2002). Also, a uniformly spaced sampling is not valid for sampling across several orders of magnitude (Q_{in} varies across 4), the lowest value sampled is actually 0.1 not 0.001 as stated in the text. The plots in fig. 2 show the greatest change at the lower values of each parameter range. Likely the zone of greatest sensitivity has not been sampled and is not displayed (e.g. A_s is stated to be varied between 0.01 and 100 but the lowest value actually sampled would be 1. Log uniform is more appropriate.
- 190: a table of the variables probed and their ranges would help here, perhaps an additional column in Table 2.
- 198: is this hydrology resolution in agreement with table 1?
- table 3: it would be helpful to see the equations in the centre column reduced to the constants in table 2 and the imposed scales in the first 3 rows. This would help to follow the scale choices through to the impact on process.

- 235: It looks as though these results are past the CFL limit for an explicit time step length. Taking your hydrology grid resolution as 100 m and the water velocity as $Q_0/S_0 \approx 0.5m/s$, your time step should be less than 200 s ($\approx 6e-6$ yr), but in your transient experiments you are using time steps of 5 yr and 0.05 yr.

  You are, however, solving via implicit backward Euler which is stable at larger Courant numbers. How sensitive are these results to your time step length? Do they converge under decreasing time steps? At such large Courant numbers time convergence needs to be checked when dealing with highly-non linear systems.

- 244: Holding N constant for the T2 experiments neglects any change in coupling due to ice thinning and removes an important positive feedback. Perhaps a more reasonable approach would be to hold N as a fraction of overburden determined by the steady state conditions prior to perturbation? Then you could include that critical positive feedback of ice thinning in your T2 experiments.

- Fig. 2: please change horizontal axes to log scale for those parameters which vary over several orders of magnitude. Also changing the distance to actual physical distance instead of normalized distance would help the reader to recall the scales involved.

- 317: It is not appropriate to call the ice and hydrology fully coupled here, as no melt from basal, englacial, or surficial surfaces is included in a self consistent way here (e.g. strain heating or surface melt due to lowering below the equilibrium line altitude). Also S2 is not coupled to an ice model but forced with a profile (Eq. 19) and constant velocity.

- 325: It does not follow that the region of higher basal shear stress is caused by the higher effective pressure. If no hydrology were included (e.g. Weerman sliding) you would still get this increase in basal shear stress here because of the higher driving stresses.

- Fig 7: This grounding line stability in the T2 versus T1 model setups may be a consequence of assuming an effective pressure which is independent of ice sheet thickness. For example if one assumes SIA – $\tau_b = \tau_d$ – and compares the effect on ice velocity from effective pressure proportional to ice sheet thickness ($N = aP_{ice}$) or constant then using your Budd sliding law you get $u = \rho_i g h \frac{\partial h-b}{\partial x}/C_b N_{const}$ versus $u = \frac{\partial h-b}{\partial x}/C_b a$. In the constant effective pressure case the velocity reduction due to ice thinning will be much greater than in the effective pressure proportional to overburden case. Furthermore, as the margin retreats into steadily increasing effective pressure you are effectively reducing the sliding coefficient. In this plot your velocity increase from the ice stiffness perturbation is at least half (plot seems to be cut off) in your T2 scenario versus T1. This disparity should likely be much less and is possibly the reason for the grounding line bifurcation.

- 359: The driving stress does not decrease because of the lower longitudinal stress increase, driving stress is determined by surface slope. In your Budd sliding equation the basal shear stress increases to balance the driving stress. This means velocity increase and ice thinning. Please restate.

- 361: Again, this higher N near the boundary is non-physical given thinner ice from retreat.

- paragraph starting at 390: I am confused by the logic here. Applying Eq 21 “which holds for most of the ice sheet far from the grounding line” to conditions right at the grounding line and inferring “that the advection term must grow large near the grounding line.” Perhaps the reasoning here can be better expounded in another way or reworded?
- 397: This reasoning feels circular in context of previous paragraph. Also, generally one would expect that as channel cross section gets bigger, flux gets bigger, and effective pressure gets bigger. Effective pressure drops because the ice is thinning toward the margin.
- 399: do you mean $\psi \approx -\frac{\partial N}{\partial x}$?
- 414: which results?
- 404: “also be explained by coupling” – what aspect of the coupling?
- 430: Again, this is may be simply a consequence of the choice of effective pressure profile.
- 435: “holding it static is similar...” – but it is not, when the ice retreats into the region of non-physically higher effective pressure you are effectively reducing the sliding coefficient, not just holding it constant.

References

Alley, R. B., Anandakrishnan, S., Bentley, C. R., and Lord, N.: A water-piracy hypothesis for the stagnation of Ice Stream C, Antarctica, Annals of Glaciology, 20, 187–194, https://doi.org/10.3189/1994aog20-1-187-194, 1994.

Bodart, J. A., Bingham, R. G., Young, D. A., MacGregor, J. A., Ashmore, D. W., Quartini, E., Hein, A. S., Vaughan, D. G., and Blankenship, D. D.: High mid-Holocene accumulation rates over West Antarctica inferred from a pervasive ice-penetrating radar reflector, The Cryosphere, 17, 1497–1512, https://doi.org/10.5194/tc-17-1497-2023, 2023.

Brondex, J., Gagaliardini, O., Gillet-Chaulet, F., and Durand, G.: Sensitivity of grounding line dynamics to the choice of the friction law, Journal of Glaciology, 63, 854–866, https://doi.org/10.1017/jog.2017.51, 2017.

Bueler, E. and van Pelt, W.: Mass-conserving subglacial hydrology in the Parallel Ice Sheet Model version 0.6, Geoscientific Model Development, 8, 1613–1635, https://doi.org/10.5194/gmd-8-1613-2015, 2015.

de Fleurian, B., Werder, M. A., Beyer, S., Brinkerhoff, D. J., Delaney, I., Dow, C. F., Downs, J., Gagliardini, O., Hoffman, M. J., Hooke, R. L., Seguinot, J., and Sommers, A. N.: SHMIP The subglacial hydrology model intercomparison Project, Journal of Glaciology, 64, 897–916, https://doi.org/10.1017/jog.2018.78, 2018.

Dow, C. F., Werder, M. A., Babonis, G., Nowicki, S., Walker, R. T., Csatho, B., and Morlighem, M.: Dynamics of Active Subglacial Lakes in Recovery Ice Stream, Journal of Geophysical Research: Earth Surface, 123, 837–850, https://doi.org/10.1002/2017jf004409, 2018.

Drew, M. and Tarasov, L.: Surging of a Hudson Strait-scale ice stream: subglacial hydrology matters but the process details mostly do not, The Cryosphere, 17, 5391–5415, https://doi.org/10.5194/tc-17-5391-2023, 2023.

Kaspari, S., Mayewski, P. A., Dixon, D. A., Spikes, V. B., Sneed, S. B., Handley, M. J., and Hamilton, G. S.: Climate variability in West Antarctica derived from annual accumulation-rate records from ITASE firn/ice cores, Annals of Glaciology, 39, 585–594, https://doi.org/10.3189/172756404781814447, 2004.

Kingslake, J. and Ng, F.: Modelling the coupling of flood discharge with glacier flow during jökulhlaups, Annals of Glaciology, 54, 25–31, https://doi.org/10.3189/2013aog63a331, 2013.

Saltelli, A.: Making best use of model evaluations to compute sensitivity indices, Computer Physics Communications, 145, 280–297, https://doi.org/10.1016/s0010-4655(02)00280-1, 2002.

Saltelli, A., Aleksankina, K., Becker, W., Fennell, P., Ferretti, F., Holst, N., Li, S., and Wu, Q.: Why so many published sensitivity analyses are false: A systematic review of sensitivity analysis practices, Environmental Modelling & Software, 114, 29–39, https://doi.org/10.1016/j.envsoft.2019.01.012, 2019.

Seroussi, H., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe-Ouchi, A., Agosta, C., Albrecht, T., Asay-Davis, X., Barthel, A., Calov, R., Cullather, R., Dumas, C., Galton-Fenzi, B. K., Gladstone, R., Golledge, N. R., Gregory, J. M., Greve, R., Hattermann, T., Hoffman, M. J., Humbert, A., Huybrechts, P., Jourdain, N. C., Kleiner, T., Larour, E., Leguy, G. R., Lowry, D. P., Little, C. M., Morlighem, M., Pattyn, F., Pelle, T., Price, S. F., Quiquet, A., Reese, R., Schlegel, N.-J., Shepherd, A., Simon, E., Smith, R. S., Straneo, F., Sun, S., Trusel, L. D., Van Breedam, J., van de Wal, R. S. W., Winkelmann, R., Zhao, C., Zhang, T., and Zwinger, T.: ISMIP6 Antarctica: a multi-model ensemble of the Antarctic ice sheet evolution over the 21st century, The Cryosphere, 14, 3033–3070, https://doi.org/10.5194/tc-14-3033-2020, 2020.

Sommers, A., Rajaram, H., and Morlighem, M.: SHAKTI: Subglacial Hydrology and Kinetic, Transient Interactions v1.0, Geoscientific Model Development, 11, 2955–2974, https://doi.org/10.5194/gmd-11-2955-2018, 2018.

Werder, M. A., Hewitt, I. J., Schoof, C. G., and Flowers, G. E.: Modeling channelized and distributed subglacial drainage in two dimensions, Journal of Geophysical Research: Earth Surface, 118, 2140–2158, https://doi.org/10.1002/jgrf.20146, 2013.