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Geoscientific Model Development Discussions

Interactive comment on "A continuum model of ice mélange and its role during retreat of the Antarctic Ice Sheet" *by* David Pollard et al.

J.M. Amundson (Referee)

jmamundson@alaska.edu

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Overview

In this study the authors modify a set of equations used to model ice shelves in order to model the flow of ice mélange and to test its impacts on the behavior of the Antarctic Ice Sheet. Over the past decade or so, several observational papers have highlighted the relationship between ice mélange mobility and the seasonal advance and retreat cycle of marine-terminating glaciers. Few studies have attempted to model ice mélange, and only a couple have attempted to model ice mélange using continuum models. Development of continuum models of ice mélange is necessary for implementation into prognostic glacier/ice sheet simulations that commonly run for centuries to millenia. Thus, this paper is an important step toward implementing ice mélange into climate

models.

My primary concerns revolve around the choice of the constitutive relationship for ice mélange. Essentially, the authors use Glen's Flow Law, which describes the viscous deformation of glacier ice, to model the motion of a granular material. The modifications that they make are based on knowledge of granular materials (little/no resistance to divergence) and sea ice (compression becomes difficult when the thickness becomes large). It's possible that these modifications are sufficient to yield a good approximation of ice mélange behavior, but I'm not sure. Unfortunately, there is very little data with which to test *any* constitutive relation for ice mélange, and so the approach adopted here seems about as good as any other, especially since the architecture is already in place for solving the flow equations. That said, the results from the model need to be interpreted with caution, which I think the authors have done.

An additional uncertainty in the model is the lack of seasonality. In the model ice mélange generally exhibits extensional flow due to glaciostatic pressure gradients (similar to ice shelves). However, ice mélange flow in winter is often quasi-static, with all icebergs moving at the same speed as the glacier terminus. (In other words, pressure gradients are completely balanced by shear stresses along the fjord walls.) Ultimately, what this means is that the model equations used here probably underestimate ice mélange resistance in winter and overestimate it in summer. I would like to be convinced that this produces similar results to a model in which the ice mélange is really stiff in winter and weak in summer. On a related note, I'm not entirely sure if the boundary condition at the end of the mélange is correct, since it implies that gravitational spreading should occur even when the ice is very thin. Sea ice models are generally able to ignore this effect since sea ice typically moves very quickly; however, in models of landfast sea ice (e.g., Leppäranta, 2012) the constitutive relation is modified to ensure that gravitational spreading doesn't occur for thin ice by including a pressure term similar to the P_p term that the authors use to inhibit compression of thick mélange. It may be that the boundary condition is fine since the authors aren't modeling winter mélange and are just trying to capture the net annual effect. I'm just not really sure how to think the boundary condition in this case.

Comments

- Please replace the reference to Amundson et al. (2016) with Burton et al. (2018). The former is not a peer-reviewed article, and the latter includes the same material (and more). A notable result of Burton et al., which is relevant here, is that ice mélange resistance is related exponentially to the ice mélange length-to-width ratio (L/W). (Note that we have also found similar results using a continuum approach and assuming a Coulomb-like rheology, though that work is currently in review.) Assuming parallel-sided fjords and ignoring any potential binding effects of sea ice, we found that ice mélange was only capable of inhibiting calving when $L/W > 3$. This is consistent with the results from this study, which indicate the ice mélange doesn't have much effect on the wide ice shelves found in Antarctica. It could be interesting to compare — what is the length-to-width ratio of fjords in Antarctica for which the model predicts that ice mélange will affect the rate of retreat?
- I think the modifications to the constitutive relationship could be made more compact and transparent. I think you could write something like this:

  $$\tau' = 2\eta\dot{\epsilon}_{ij}(1 + (f - 1)\delta_{ij}) - P_p\delta_{ij} \tag{1}$$

  As it currently stands, the reader has to get through some other details before reading about these modifications, which to me are really the most important parts of the paper. P_p kind of appears out of nowhere, since it wouldn't naturally arise from vertical integration of the stress balance equations unless it appears

  in the constitutive relation, and the description of f is buried several paragraphs after it is first introduced.

  By formulating the constitutive relation similarly to how I have here, you can immediately point out that (i) the equation is identical to the standard equations for glacier flow when $i \neq j$, (ii) there is low resistance to extension when $i = j$, and (iii) the P_p term prevents $\dot{\epsilon}_{xx}$ or $\dot{\epsilon}_{yy}$ from becoming highly negative (compressive) when the mélange is thick.

Detailed Comments

P. 1, L. 10: Its not clear that ice melange noticeably affects glacier velocities directly.

P. 2, L. 9: This statement makes it sound like ice mélange is often just icebergs connected by sea ice, and not a densely-packed granular material.

P. 3, L. 23: Also probably affected by currents, wind, and tides (which would have an asymmetric influence).

P. 4, L. 5: Should be Vankova and Holland.

P. 4, L. 25: I agree that large icebergs are never overriden, but there could be some small scale rotation occurring, resulting in storage of gravitational potential energy.

References

Burton, J.C., J.M. Amundson, R. Cassotto, C.-C. Kuo, and M. Dennin (2018), Quantifying flow and stress in ice mélange, the world's largest granular material. Proc. Nat. Acad. Sci., https://doi.org/10.1073/pnas.1715136115

Leppäranta, M. (2012), The drift of sea ice, 2 ed. Springer-Verlag, Berlin and Heidelberg.