Summary and comments on the manuscript entitled

Grounding-line flux formula applied as a flux condition in numerical simulations fails for buttressed Antarctic ice streams

presented on 30.12.2016
by

R. Reese et al.

Summary

As reported in several studies, resolution is key for an appropriate representation of grounding line migration in ice-flow models. Yet for continental-scale forward simulation, a trade-off has to be made between resolution and computational costs. On longer time-scales, the mesh has furthermore to be adapted and updated according to the migration of the grounding line. Avoiding these mesh issues, boundary layer theory allows to infer ice-flux values across the grounding line (Schoof, 2007). This flux relation (Eq. 1) has since been implemented as an internal boundary condition in several ice-sheet models using coarse resolution (¿5km). Intercomparison studies confirmed the utility of this parameterisation. Yet the effect of ice-shelf buttressing, which can be included in the parameterisation, did not receive much attention. The authors of this study try to shed light on the applicability of the buttressing correction term (buttressing factor) in the flux parameterisation at the grounding line. For this purpose, a state-of-the-art ice-flow model is applied over Antarctica. Ice velocity observations are matched by a bi-variate inversion for the basal slipperiness and the rate factor. For this setup, it is reported that the computed buttressing factor shows high spatial variability along the grounding line of the two largest ice-shelves in Antarctica. Moreover, negative values are widespread, which leads to unphysical flux values in the parameterisation. The authors therefore strongly question the applicability of this correction term.
The study is soundly structured, to the point and well written. Yet I have major questions and concerns on important details of the methodology and on theit interpretation. As the simultaneous inversion of two parameters is not well posed, their quantification is under-determined. Thus, essential parameters for the flux parameterisation are not well constrained. Further issues concerning the buttressing factor θ come from uncertainties in the exact location of the grounding line, which might have severe consequences for the interpretation. Therefore, I recommend that this manuscript undergoes a major revision. I advise the editor to only consider publication of this article, if the authors were able to adequately address the comments below.

Main comments

Buttressing factor

- As you seek to infer flux values at the grounding line, special attention has to be given to its positioning in the model. Errors in the positioning can have large impacts on the flux formula. I therefore highly appreciate the effort to correct the ice density by firn information from a regional climate model. Yet in regions of high inflow from outlet glaciers, the used flotation criterion is possible not very accurate. Certainly in light of the fact that the Bedmap2 thickness values near the grounding line are subject to large uncertainties. For any mismatch of the grounding line position or in ice thickness, the inversion has to compensate by accordingly adjusting the basal slipperiness (C) and the rate factor (A) such that observed velocities are reproduced. I cannot foresee what effects this might have on the stress regime and ultimately on the buttressing parameter (θ).

- Considering uncertainties in the grounding line position, you could rely on Antarctic-wide grounding line observations (e.g. Rignot et al., 2011), rather than using a flotation criterion. Bedmap2 also comprises a flotation mask. A sensitivity assessment to the grounding line position might indeed be valuable.

- You nicely explain how you retrieve the grounding line position. For the calculation of the buttressing factor θ and the flux parameterisation (Eq. 1), you interpolate the relevant stress and thickness values within the corresponding mesh element. Any grounding-line mesh element will by definition include nodal information from the grounded side. Therefore, your buttressing calculation is biased by a stress regime that is influenced by basal friction. From how I understand the buttressing factor, it should represent the stress regime on the ice shelf-side only because it is this side which exerts buttressing upstream. Unfortunately, this is highly uncharted research territory and there are certainly no best practices. From my experience, some spatial smoothing of the shelf-side deviatoric stress regime is beneficial.

- Using your three buttressing definitions, you compute the 'analytical' parameter θ all along the grounding line. Yet these values remain uncontested or unvalidated. You concentrate on the fact that negative values are widespread and that the flux parameterisation would yield 'unphysical' results.Buttressing can however be estimated in another way for comparison. The idea is that you should remove the ice shelf entirely and recompute the associated unbuttressed velocity field. Then, you can directly compute the ratio between ice fluxes in the buttressed and unbuttressed case. These values would be very informative to quantify the buttressing effect along the grounding line. Moreover, the variability could be compared to the θ values.

With some luck the two values show a significant correlation, which you might want to exploit for an improved/adjusted quantification of buttressing in the flux formula.

Flux formula

- Similar to above, any uncertainties in the location and ice thickness of the grounding line will affect the inferred parameters (C,A). Moreover, it was shown by (Arthern and Gudmundsson, 2010) that a similar bi-variate inversion for C and A is highly underdetermined. This means that multiple combinations of C and A (on grounded ice) are possible. As both parameters enter the flux parameterisation, with different weighting, these two issues cannot be ignored. I even fear that the usage of the flux parameterisation in such a situation is almost a vain exercise. An option to prove me wrong would be the following: (1) Infer A and C using velocity observations. (2) Remove all ice shelves, either by reducing the computational domain or by setting the ice-shelf thickness to a very small value. Then compute the corresponding velocity field for this unbuttressed case (3) Compare modelled ice flux with the 'analytical' flux parameterisation. I fear that no consistency will be found in the unbuttressed flux values between the 'modelled' and 'analytical' values. This is certainly a very useful and informative exercise.

Unbuttressed situation

- I understand why you strongly focus on highly buttressed ice shelves. In this way, your evaluation of the buttressing parameter θ is deliberately biased to the buttressed cases. I would therefore suggest to add an unconfined ice-shelf setup. An example could be the Thwaites Glacier area, though there might be some complication from a pinning point not present in the Bedmap2 geometry. The pinning point might however not matter to much, as the western portion of the floating tongue is certainly not much buttressed. In such a clearly unconfined setup, I would expect θ values consistently close to 1.0 or even above.

Specific comments

P7L21-23 I suppose that you compute the 'modelled' ice flux over the grounding line by using the velocity component perpendicular to the grounding line. Is that right?

P8L12-13 I do not see the velocity decrease along the central flowline of Institute Ice Stream in Fig. 1. A velocity profile, as an inset to Fig. 1 or 3, would help.

Eq. 14 I wonder how you compute the velocity mismatch in the cost function. Do you do this on the model mesh nodes or directly at the location of each velocity observation. This matters, because you have refined your grid near the grounding line. So the nodal difference computation would introduce a strong bias in the cost towards the grounding line area. This might even be desirable in your case.

Fig.1 The vectors in this plot are hard to discern. I would prefer a 2D magnitude plot of the velocity fields with superposed streamlines. As mentioned above, an along-flow profile of velocity magnitudes would help to see the velocity decrease upstream of the grounding line.

Fig.3b, 5,B2 Use a different colour map for the flux difference because the colours are very similar to the buttressing parameter θ.

Fig. B3-B5 Legend entries are too tiny. Please take a larger font size.

Fig.S.3. A comparison of the inferred viscosity field on Ronne Ice Shelf by Larour et al. (2005), I miss well imprinted weak zones along the lateral ice-shelf margins. Do you have any explanation for that?

References

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