The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2019-326-AC3, 2020

The Cryosphere
Discussions
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Interactive comment on "Results of the third Marine Ice Sheet Model Intercomparison Project (MISMIP+)" *by* Stephen L. Cornford et al.

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Received and published: 13 April 2020

Response to Prof. Pattyn's review

We thank Prof. Pattyn for this supportive and thorough review, and acknowledge all of the points made. We reply to each point made (black text) below using blue text.

Overall assessment

This paper reports on a follow-up of a series of marine ice sheet model intercomparisons (MISMIP) in which particular attention is paid to the effect of buttressing on the stability of grounding lines on retrograde slopes. The geometry of the experiment is taken from Gudmundsson et al (2013), i.e., a narrow overdeepened channel in the marine portion of the grounded ice sheet. Several models, from full Stokes to models of intermediate complexity (including membrane stresses in a variety of ways) participated in the experiment that consist of applying sub-shelf melt starting from an initial steady-state configuration on a retrograde bedrock slope. All participating models show the same qualitative behaviour, meaning that a steady-state configuration across a retrograde section of the bed is obtained due to buttressing and grounding line retreat is initiated when sub-shelf melt is applied. The paper is definitely interesting for publication in TC and will become a benchmark for future model development.

Nevertheless, I have a few points that need some clarification. From the start (abstract) the authors promote the experiment as a test for the treatment of viscous stress sufficient for buttressing. However, throughout the paper, the emphasis is on the response of the different models in relation to basal sliding rules and differences in stress balance, but further discussion on buttressing remains absent. What are the implications of the results in our understanding of buttressing of ice flow on retrograde slopes?

This is a good point, but we would suggest that the common points and differences between the models do not reveal much about buttressing per se, beyond results that are already known: buttressing can lead to steady equilibrium with the grounding line crossing a partially retrograde bed, and the loss of that buttressing through ice shelf thinning can lead to grounding line retreat. We have rephrased and expanded the abstract (below, with deletions and additions highlighted) to make this clear

'We present the result of the third Marine Ice Sheet Intercomparison project, MISMIP+. MISMIP+ is intended to be a benchmark for ice flow models which include fast sliding marine ice streams and floating ice shelves and in particular a treatment of viscous stress that is sufficient to model *buttressing*, where upstream ice flow is restrained by a downstream ice shelf. A set of idealized experiments first test that models are able to maintain a steady state with the grounding line located on a retrograde slope due to buttressing and then explore scenarios where a reduction in that buttressing causes ice stream acceleration, thinning, and grounding line retreat. The majority of participating models passed the first test and then produced similar responses to the loss of buttressing. We find that the most important distinction between models in this particular type of simulation is in the treatment of sliding at the bed, with other distinctions – notably the difference between the simpler and more complete treatments of englacial stress, but also the differences between numerical methods – taking a secondary role.'

It is also important to note that all models qualitatively show the same results. It is not necessary to dive immediately into their differences. It is important to highlight that models are capable of reproducing stable grounding lines on retrograde bed slopes in case of strong buttressing, irrespective of sliding rules or approximation to the stress balance.

Agreed - we now state this in the abstract (see previous response), and also begin the discussion with a the details of this important point

Another point is that the majority of models are from the intermediate complexity group,i.e. higher-order models that include membrane stresses one way or the other. Theauthors particularly focus on two outliers, a HySSA model and two full Stokes models(Elmer/Ice and ISSM). Most of the attention goes to the HySSA model, but the similar behaviour of the two FS models is intriguing but left out without further discussion, especially since these are the models containing most of the physics. Both FS models are different and use different sliding laws/rules.

We have added text to both the results and discussions sections, and a figure fig.1

in this response) considering the differences within the Stokes models and with their nearest non-full-Stokes models (those using the same code and sliding law). The picture is not quite as simple as saying the Stokes models are different and better (though that is of course one possibility). Notably, although there are point of disagreement between the Stokes and non-Stokes models, there are also differences of similar magnitude between the two Stokes models (Elmer/Ice FS and ISSM FS). Elmer/Ice FS shows essentially the same rate of retreat in Ice1r as the SSA/HO/L1Lx models, while ISSM FS shows the same average rate but a much greater initial rate and lower final rate. Elmer/Ice FS shows no re-advance at all, which seems likely to be a numerical issue, while ISSM FS shows re-advance that is slower than many models but similar to ISSM SSA.

One of them also solves for L1Lx and has a comparable behaviour to the other L1Lx models, showing that numerical issues should not be the culprit.

We suggest (but of course do not know) that numerical issues could still be the culprit. The full Stokes and SSA/L1Lx/HO problems are different, with the Stokes problem being more difficult, even if other aspects of the numerical treatment are the same. Stokes models must solve for the scalar pressure to satisfy $\vec{\nabla}.\vec{u} = 0$ (while lesser models have it easy, so to speak) and also solve a more complicated contact problem. See e.g Gagliardini 2015 for a case where a numerical decision affects Elmer/Ice quite strongly at even 50 m resolution in MISMIP3d

The minor advance in the Ice1ra experiment therefore requires more discussion in the context of why the other (L1Lx) models advance so much more in this particular experiment when sub-shelf melt is halted. It could inform more on viscous stress important in buttressing, for instance.

A discussion has been added (see above)

Detailed remarks

Line 3: what is meant by 'sufficient' buttressing? Please also state what is meant by the testing of the models. What is tested and what for? It is not clear what the precise goal of the experiments is, especially in relation to buttressing (see major remark).

We meant that the models were sufficient, rather than the buttressing. To clarify this, we changed the phrase to "a treatment of viscous stress that is sufficient **to model** buttressing. We also clarified the remainder of the abstract to say what is tested (see response to major remark) and what is explored, which we think then makes the goal clearer.

Line 40: strongly buttresses instead of buttresses

Agreed, and done

Line 47: configurations

corrected

Line 60: This was also the case for the MISMIP3d experiments

Noted, with citation

Line 104: suggest to continue the sentence: where u is the horizontal ...

Done

Line 105: Weertman (1957) sliding law/rule

added "sliding law"

Line 107: is continuous

Yes

Line 109, eq 4: define α

We added detail on α^2, the coefficient of friction in a Coulomb friction law.

Line 130: this is not the definition of steady-state. can it be mentioned over what time scales the models were run to reach the 'pseudo steady state'?

Added some wording to make this point clear, and also added 'Participants were free to produce the initial state by any method; the majority of participants chose to evolve their models with the stated parameters for ~ 10 ka in order to approach steady state'

Line 188: Has this controversial modification been applied by any of the participating models? In either case, it should be stated.

Yes, though the models in question have in general avoided the modification since. We added 'Several participants employed such a modification in these exercises, with clear consequences in the Ice2 experiments (Sec. 4.3)'

Line 244: 'the use or otherwise': I don't understand this sentence. Moreover, it is not clear where and how this transformation is applied and Bueler et al (2015) does not shed further light on this. Some more details should be given, as this is also mentioned further down in the manuscript.

This is described in the cited text (Beuler et al 2005) in section 5.2 (Regularization of the margin by a transformation). We noted the section in the text.

Line 274: in comparison with the other models, this description is really short. For the sake of balance, some more details should be given.

A more comprehensive description was included.

Line 286-289: Any reason why this is the case? This should be mentioned.

There is more explanation in the individual sections - this paragraph is an overview before the detailed results

Line 297: Last sentence: does this apply to the Ice0 experiment?

The sentence 'Not every submission included this test, although the majority did?'. Yes - one or two submissions omitted Ice0, notably the Elmer/Ice full Stokes model. I (SLC) judged that the Elmer/Ice full Stokes contribution was too important to exclude on these grounds.

Line 349-350: See major remark. It is not because they are underrepresented that you are loath to make much of these differences. I would say that L1Lx models are over-represented in this case.

A fair point - see the response to the major remark, but in brief we have added some more discussion of the full Stokes models

Line 355-356: Or there are too many models of a particular category.

Too many L1Lx/SSA models? We agree that this class of model is common

Line 388: This doesn't seem to apply to the FS models it seems.

A fair point - see the response to the major remark, but in brief we have added some more discussion of the full Stokes models

Line 396-397: See major remark: It is important to note that all models qualitatively show the same results and to highlight that models are capable of reproducing stable grounding lines on retrograde bed slopes in case of strong buttressing, irrespective of sliding rules or approximation to the stress balance. Even the HySSA qualitatively shows a similar behaviour; its exception is can then be further discussed as is done in this paragraph.

Agreed - the discussion now begins with a paragraph emphasising that point.

Line 422-425: There is also no Coulomb-limiting factor in MISMIP3d. Furthermore, the friction coefficient in MISMIP3d leads to a sharp contrast between grounded and floating ice (higher friction that in this experiment).

We added the details on friction. There are as many MISMIP+ models that do not employ the Coulomb limit as do, so that in itself does not explain the difference.

Discussion: more discussion on the FS models is needed as well as buttressing in general (see major remark).

A fair point - see the response to the major remark, but in brief we have added some more discussion of the full Stokes models

Line 439-440: I wouldn't say that the distinction between FS and other models is minor.The Ice1ra experiment proves otherwise.

A fair point - see the response to the major remark, but in brief we have added some more discussion of the full Stokes models

Line 442: Either add that HySSA has qualitatively the same behaviour, or more general state in the summary that all models exhibit qualitatively the same behaviour and are capable of reproducing stable grounding lines on retrograde slopes in case of strong buttressing.

Agreed - we added this note, but also began the discussion (as suggested above) by noting the important point that models were more similar than different (with the possible exception of the Stokes models

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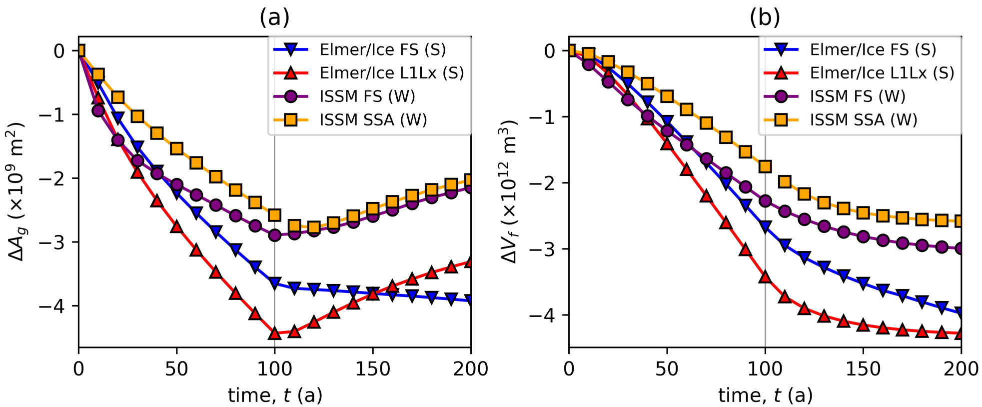

Fig. 1. Comparison of full Stokes and vertically integrated models in the Ice1r and Ice1ra experiments. Panel (a) shows the change in grounded area, panel (b) the change in volume above flotation.