

## General comments from reviewers

We would like to thank the two reviewers for the useful feedback provided which has greatly assisted in improving the clarity and quality of our manuscript. We will address the general comments of the two reviews in order and then the specific comments of each to follow, detailing changes made.

Reviewer 1, Dr Todd, notes concern about the different mesh resolutions and time steps used for the two different sliding models. In both these cases we looked to getting convergent and self-consistent behaviour and used a time step that would allow that. We would also like to draw attention to the mesh resolution tests performed, the results of which are shown in Appendix 1 of the manuscript. For both sliding laws we ran tests with different mesh resolutions. We found that for the "cavitation" sliding law the resulting trajectory of the grounding line was unchanged between the 1km and 500m mesh resolution cases, while the 2km case had shown different results. Hence we concluded that finer mesh spacing was not required to be confident in resolving the grounding line position. The need for fine mesh resolution for models with a retreating grounding line is documented in previous studies for the Weertman sliding case and does indeed converge [1]. The concave shape of the grounded transition zone for the Cavitation sliding law, versus the steep gradients at the start of the ice shelf for the Weertman case remains consistent throughout all the mesh resolution test, hence we are confident that the regrounding behaviour is in general more likely for the cavitation sliding law case.

Dr Todd also notes that the forcing using effective channel width may not reflect any hypothesised real-world drivers of ice sheet collapse. We agree that forcing by the altering the smb or applying basal melting would be necessary for more realistic models. However, our model is already highly idealised and aiming only to investigate qualitative differences in the behaviour of the ice sheet purely due to the choice of sliding relations used, without further complications from other drivers of change. Certainly such experiments would be of interest but would form the basis of a different study than is in the scope of what we have presented here.

Reviewer 2 has 3 main points of concern. Firstly, they have highlighted the recent publication by [2] on a similar topic, using the same ice sheet model code, Elmer/Ice, which should be referenced. At the time of our submission of our paper it was not yet published. It is clearly highly relevant to our paper and we have cited it in our revised manuscript where appropriate.

The second point of concern for reviewer 2 is with our method of spinning up the system and then performing experiments using spatially uniform parameters for the two friction laws. We agree that, as highlighted by the reviewer, the resulting profile and the regrounding behaviour after retreat is a consequence of both the initial state of the ice sheet after spinup and the choice of friction law. While other studies, such as [2] have tuned the parameters of the sliding relations they use so that the distribution of basal shear stress is identical across all experiments initially, we have chosen here to use parameter values which will result in key properties of the system to be similar in both cases. In this case it is the initial grounding line position that we aim to begin with in a similar position. While tuning for identical initial states will allow for a directly comparable quantification of future changes, that is not the aim of our paper. In this paper (and perhaps other similar papers to some extent as the reviewer

points out) the ice sheet profiles have a distinct qualitative nature determined by the physics of the sliding relation. Tuning one sliding relation to match the state given by a different sliding relation provides an initial state that is inconsistent with the physics of the sliding relation. Our method of obtaining the initial state tuning the parameters to with similar values for  $k_e$  allows us to then compare modes of behaviour.

The final major concern of reviewer 2 is that the "dynamic regrounding" is sensitive to the value of  $C$  ( $C_{max}$  in our revised notation). We agree that a full sensitivity study would be of interest, but such is clearly a very large undertaking and beyond the scope of this work. We don't see an argument why  $C$  should be especially important. It should also be noted that the reviewer is concerned that our value of  $C$  is very low. We note that a higher value of  $C$  would lead to thicker grounded ice, and that it is the downstream advection of this thicker ice that causes the regrounding. So it could be argued that regrounding would be more likely with higher values of  $C$ .

In addition to these general comments, we have addressed the specific comments from the reviewers below, including those regarding inconsistencies and confusion in the formulation of the sliding laws in the original manuscript noted by both reviewers. These are detailed below.

## Specific Comments from reviewers

### Reviewer 1

*The comparison of the Weertman-style sliding vs cavitation sliding seems to centre on the fact that Weertman sliding is tricky to implement in models, but this isn't the only shortcoming of sliding laws which neglect effective pressure, surely? Can the authors not also make the case that Weertman sliding is fundamentally unsuitable for systems with significant water pressure at the base?*

We agree that for systems with significant water pressure at the base the Weertman sliding relation is unsuitable to use and recent modelling work on marine ice sheets especially shows that the results can vary widely depending on the friction law used. Our aim in this paper is not to provide evidence on the validity (or not) of Weertman sliding. This comparison, however, aims to point out qualitative differences in terms of ice sheet geometry rather than to try to claim that one sliding relation is "better" than the other.

*I guess water pressure at the base is simply defined by sea level? This should be explicitly stated in the methods, I think. Is this what you mean by P3L15: based on the assumption of full connectivity between the subglacial hydrologic system and the ocean?*

Yes, the water pressure is indeed defined by sea level. The paragraph around P3L15 has been edited to reflect this explicitly and now reads "The effective pressure  $N$  is calculated based on the sea level and the assumption of full connectivity between the subglacial hydrologic system and the ocean"

*I think you could be clearer on how lateral drag is implemented. You describe the lateral resistance parameter  $K$  but don't explain how that modifies the Stokes solution. Also, when you say ... which we use to modify the lateral drag from*

*high to low, do you mean that the channel width varies through space or time? This becomes clear later on, but it would be good to avoid confusion here.*

Please see our response to the similar comment from reviewer 2 below where we improve our explanation of the implementation of the lateral drag and clarify that we are varying the drag in time, rather than space.

*Also, on the issue of lateral drag and channel width, the parameter  $W$ , as used by Gagliardini et al. (2010) refers to the half-width, rather than the width. Comparing your Eq. 6 with their supporting material, I see that you've adapted the equations somewhat, so I am unsure whether this should still be half-width or if your adaptation accounts for this.*

In our original manuscript we used an equation for  $K$  as it is calculated in the Elmer/Ice online documentation, which varies by some factors (including  $\rho_i$ ) than what is given in the supplementary material of Gagliardini et al. (2010) which first introduces the implementation of the lateral drag function. For consistency, in the manuscript we will use the same form and  $W$  should be the half-width of the channel. We have corrected the manuscript throughout so that  $W$  now refers to a channel half-width.

*I like how you've presented the results in Figs. 2 and 4, but I found myself flicking back and forth between them for comparison. Perhaps you could reformat to show 2a alongside 4a, 2b alongside 4b, etc.?*

We appreciate the feedback on the presentation of the results but feel that we have ordered the plots in the best way possible to convey the information. When the manuscript is compiled in two column-format these plots are meant to stack on top of each other so that the horizontal axes align and features in the plots at co-incident times are clearer to see.

*The velocity plots in Figure 3b are strange, and, I guess, indicative of mesh dependency? At any rate, the high frequency variability should be explained.*

The amplitude of these high frequency fluctuations is expected to be a function of mesh resolution (amongst other things). Each jump in velocity probably corresponds to grounding line movement retreat to the next element. Ungrounding of an element significantly reduces the basal friction, allowing speed-up. This does not happen with the Cavitation sliding law because the dependence on effective pressure means that the basal shear stress is in any case close to zero for elements that are newly ungrounded. We have added this explanation in a paragraph added in section 3.2 referring to this velocity plot.

*P2L1: and when focusing on retreating glaciers such as Pine Island Slightly odd wording?*

Yes, this paragraph has been edited and now reads: "Marine ice sheets have been investigated widely with Pattyn (2017b) providing a recent review of development in modelling their dynamics. They have been the subject of recent model intercomparison projects such as MISMIP (Pattyn 2012), MISMIP3d (Pattyn 2013) and MISMIP+ (Asay-Davis 2016) looking at idealised systems. Retreating glaciers showing a geometry making them susceptible to MISI, such as Pine Island Glacier, have been also been a particular focus (Gladstone 2012, Joughin 2010, Favier 2014). More recent analysis has shown that stable grounding line

configurations may be possible on retrograde sloping bedrock when the buttressing of floating ice shelves and 3D geometry of the system is included (Katz 2010, Gudmundsson 2012, Gudmundsson 2013).

*P2L11: Elmer has a few sliding relations implemented, including Weertman and Budd.*

We have added references to Gladstone et al. (2017) and Brondex et al. (2017) who have used the other sliding laws implemented in Elmer/Ice which include an effective pressure dependence.

*Fig 1,2,3,4: Missing a,b,c labels*

These labels have now been added on all these figures.

*P3L14: C is the max value of  $T_b/N$ , I believe.*

This has been corrected in the manuscript.

*P3L18: is the non-linear Weertman-type?*

This line now reads "is a non-linear, Weertman type friction law"

*P3L20: Why not redefine  $m$  to something else to avoid confusion with  $m$  in Eq. 3*

As noted below by reviewer 2, the  $m$  in Eq. 3 is an error and should in fact be  $n$ , so there is no longer with the  $m$  in Eq. 5 any confusion. The words "in this case" have been removed.

*P3L22 and elsewhere: Perhaps lateral buttressing or lateral drag would be clearer? When I think of 'buttressing' I think of melange or sea-ice buttressing.*

We have clarified this by altering the text to read "A buttressing-like force due to friction along glacier side walls is included by using a parametrisation of lateral friction by Gagliardini et al. (2010)".

*P4L28: Here you state that you increase  $W$  from 100km to 350km, but I think you also run 400 and 500km (Fig. 3), right?*

Yes, the text is amended to read "from 100km to values equal to 350km, 400km and 500km "

*P9L1: "iceshelf" → "ice shelf"*

This has been corrected in the manuscript.

## Reviewer 2

*From P1 L21 to P2 L1: I don't understand this sentence, is there a problem with the end of it: "and when focusing on retreating glaciers such as Pine Island" We agree this sentence was unclear, please see response above to a similar comment by the other reviewer.*

*P2 L4: Brondex and others (2017) have also shown that tuning the spatial distribution of the Weertman friction coefficient to match the basal shear stress produced by a Schoof law could also lead, under certain circumstances, to steady GL positions located on the retrograde slope without having to add any lateral stress.*

We have added modified this sentence to include the reference to Brondex (2017) here. It now reads: "More recent analysis has shown that stable grounding line configurations may be possible on retrograde sloping bedrock when the buttressing of floating ice shelves and 3D geometry of the system is included (Katz and Worster, 2010; Gudmundsson et al., 2012; Gudmundsson, 2013) or in some configurations where the basal friction coefficient is tuned spatially (Brondex et al. 2017)."

*P2 L6-7: I have the feeling that the two sentences about the need for a very fine mesh resolution at the GL are redundant.*

We have combined these sentences to read as " These models require very fine mesh resolution due to the sharp change in sheer stress across the grounding line (Vieli et al. 2005, Gladstone et al. 2010, Cornford et al. 2013, Leguy et al. 2014, Gladstone et al. 2017).

*P2 L12: "do not cause such strong mesh resolution dependency and do not suffer from the same mesh resolution issues as Weertman type relations" → here too I think that the information is redundant. In addition I would suggest to cite the work of Leguy and others (2014).*

"and do not suffer from the same mesh resolution issues as Weertman type relations" has been deleted.

*P2 L22: "even leading to a partial recovery from MISI" → it is not clear what is meant by "partial recovery" here,i.e. is it the grounding line stabilizing on the retrograde slope ? Or advancing back to its initial position ?*

I think in this context a "partial recovery" simply means the grounding line advancing again after a period of retreat. It doesn't have to advance to its initial (pre-retreat) position in order to constitute a "partial recovery". We have modified this sentence to "even leading to a partial recovery from MISI with the grounding line advancing again after a period of retreat."

*P3 L11: I think there is a mistake in Eq. (3): it should be a n instead of the m for the exponent of the parameter C . Otherwise, you need to define the parameter m for this equation (but it is defined for Eq. (5) as  $m = 1/n$  , whereas it should be n for Eq. (3)).*

This was a mistake, and Equation 3 is now corrected using n for the exponent of  $C_{\max}$ .

*P3 L11 and L19: the way you use the parameter  $A_S$  in Eq. (3) is not consistent with the way you use it in Eq. (5). Indeed, a dimensional analysis of Eq. (3) reveals that in this equation  $A_S$  should be given in  $\text{myr}^{-1} \text{Pa}^{-n}$  (which does not correspond to the unit you give in Table 1 of Appendix B) while it should be given in  $\text{Pam}^{-1/n} \text{yr}^{-1/n}$  in Eq. (5). The mistake probably comes from the fact that your Eq. (5) is not equivalent to Eq. (13) of Gagliardini*

and others (2007): they have  $u_b = A_S \tau_b$  (in this case  $A_S$  ought to be called a sliding parameter as an increase of  $A_S$  is  $1/n$  associated to an increase of  $u_b$ ) while you have  $\tau_b = A_S u_b$  (in this case,  $A_S$  should be called a friction coefficient as an increase of  $A_S$  induces an increase of  $\tau_b$ ). I would suggest that you read again Gagliardini and others (2007) and rewrite properly all these equations. It could also be worth it to justify the fact that you decided to take  $q = 1$  in Eq. (4), or at least to explain what is the role of this parameter. You also need to be clearer on the terminology "sliding parameter/coefficient" and "friction parameter/coefficient": most of the time the notation  $A_S$  is used for a sliding coefficient while in Eq. (5) you need a friction coefficient. More broadly speaking, I would rather speak about "friction law" instead of "sliding law" (or "sliding relation") when  $\tau_b$  is given as a function of other parameters.

We agree with the review that the notation and language used originally to describe the sliding relations and parameters was inconsistent and has caused confusion. We have decided to follow Brondex et al. (2017) using  $C_{W,S,B}$  to differentiate between the friction coefficients in the different sliding relations. We have chosen to use "sliding relation" consistently in the manuscript.

*P3 L24: once again, the expression that you give for  $K$  does not correspond to the original one of Gagliardini and others (2010). In particular, I don't really understand why  $i$  appears in your expression. In addition, in the current state of your manuscript it is impossible for the reader to understand how this parametrisation of lateral drag is included in the global stress balance, which is not straightforward as we are considering a 1HD ice sheet.*

The lateral drag formula as it originally appears in our paper is consistent with that given in the Elmer/ice online documentation detailing its implementation in the model code and notes that as it appears there  $K$  is equal to  $K/\rho_{ice}$ . To avoid confusion, we will use the equation for  $K$  as it appears in the supplementary material of Gagliardini et. al. (2010). We have also added further text and an equation to describe how this alters the total stress balance of the system, describing how the force contributes to the stress balance. This section now reads:

"A buttressing-like force due to friction along glacier side walls is included through by adding a body force into the force balance using a parameterisation relating lateral resistance to the rheological parameters of the ice and a ice shelf embayment width described by [3]. The body force is given by:  $\mathbf{f} = -K|\mathbf{u}|^{m_{lr}-1}\mathbf{u}$

where  $m_{lr} = 1/n$  is the lateral resistance exponent where the lateral resistance parameter with  $n$  the usual Glen's law parameter. The resistance parameter  $K$  is given by:  $K = \frac{(n+1)^{1/n}}{W^{\frac{n+1}{n}}(2A)^{1/n}}$  with  $A$  the fluidity parameter of the ice.  $W$  is a parameter corresponding to a channel half-width which we use to modify the lateral drag during the experiment from being initially high (i.e. low  $W$ ) and then decreased by changing to a high value of  $W$  as a means of forcing the glacier to retreat."

*P4 L16: "resulting in a total spinup time of 25000 years" → It seems to me that this is not consistent with the description of the spinup procedure given in*

*the previous lines: 16600 years of spinup with 1 m yr<sup>-1</sup> of top surface accumulation followed by, at least, 10000 years of spinup with 0.3 m yr<sup>-1</sup> of top surface accumulation as you say that: "We determine that the spinup has finished and the ice sheet has reached a steady state when there has been no change in the grounding line position, and the mesh velocity, determining the change in the top and bottom free surfaces, remains less than 0.001 m yr<sup>-1</sup> over 10000 years"* Thank you for pointing out this error, the correct procedure was 10000 years at 1 m yr<sup>-1</sup> and then 0.3 m yr<sup>-1</sup> held thereafter for 25000 years total. This is now corrected in the text.

*P4 L19: "an" → typo*  
Corrected "an" → "and".

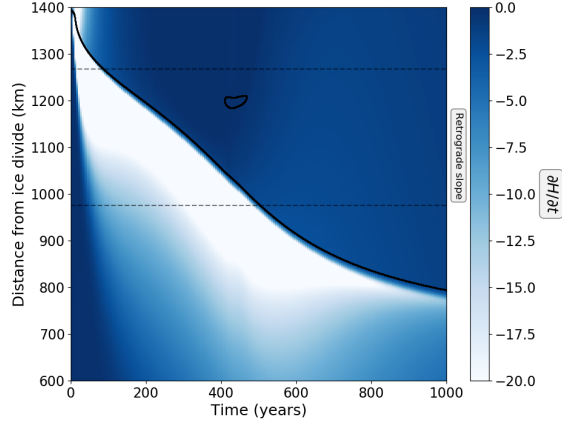
*P4 L26: as already said, the way you choose the Weertman law friction (or sliding ?) parameter is not clear to me.*

We have amended the text in the paper to clarify this: "Recently, [2] showed that far from the grounding line, (i.e. for large values of height above flotation) the Weertman and Cavitation sliding relations give an approximately equivalent relationship between basal velocity  $u_b$  and basal shear stress  $\tau_b$ . For this study we chose a Weertman friction coefficient such that the Weertman and Cavitation relations give similar values of  $\tau_b$  far from the grounding line (with high height above flotation) and that would also result in the initial position of the grounding line being within a few km for both sets of experiments."

*P4 L28: you have also run simulations for  $W = 400$  km and  $W = 500$  km based on Fig. 3.*  
This is now explicitly stated in the text.

*P5 L11-18: in my opinion, it would make more sense to have this part in the discussion section. In addition, I think that the point discussed here could be better illustrated by a plot of the thickness rates of change  $\partial H/\partial t$  as a function of  $x$  at different times following buttressing release.*

Since the text is describing what is seen in the plots it refers to, we are happy to leave this in the results section with further discussion about the differences seen between the sliding laws left to the discussion. The thickness rate plot is an interesting idea that we have investigated at your suggestion. While it definitely shows some changes in the thinning rate around the regrounding event, the change in velocity across the grounding line shows this much more clearly. We include the plot (focussing on the regrounding event region and time with the colour scale cropping out larger negative values to see detail). It shows that the thinning increases across the ice shelf after the regrounding event has passed but does not illustrate the temporary slowing in ice velocity across the grounding line in the way that Figure 1c does. In addition, in response to a further comment about Fig. 1c, we have added some discussion about it as detailed below for P6 Fig1.



*P5 L23-26: as already said, this result might be highly sensitive to the value attributed to the  $C$  parameter in Eq.(2). Therefore, I would suggest to run similar simulations with higher values of this parameter.*

We agree that the results might be sensitive to the value of  $C$ . However, the results may be sensitive to many inputs, including different forcings and geometries. A study of all of them would be interesting but also a much larger undertaking than can be incorporated into revisions of the current paper.

*P6 Fig1: I think you never refer to Fig. 1c in the text, therefore I wonder if it is really relevant to have it here.*

Fig. 1c (and it's counterpart in Fig 3b) is to show the reduction in the ice velocity across the grounding line at the same time that the regrounding occurs. In two-column format these plots are designed to be stacked vertically and the slowdown in the velocity is more pronounced. The paragraph that previously at P6L19 in which Fig1b is discussed now includes discussion of Fig.1c. "The position of the flux gate in Figure 1b (1200km from the ice divide) is chosen as it is located where the regrounding occurs. The flux reaches a maximum as the grounding line approaches the inland end of the retrograde bedrock region, and decreases as the grounding line migrates up the prograde slope. Similarly, we see a reduction in the sliding speed of the ice across the grounding line as shown in Figure 1c. For the cases where dynamic regrounding occurs we see a temporary reduction in the flux and sliding speed, but this reduction is not sufficient to stabilise retreat." We have added further explanation of the velocity plots in the discussion in relation to the qualitative differences seen in the results between the two sliding relations used: "The plots of sliding velocity across the grounding line in Figures 1(c) and 3(b) also point to differences resulting from the choice of sliding relation used. After the initial adjustment in response to the change in buttressing the peak grounding line ice velocity corresponds to the time when the grounding line position changes from lying on reverse bedrock to the positive slope. For the Cavitation sliding case we also see a small dip in velocity when the regrounding occurs. As previously stated we have chosen a Weertman friction coefficient such that both relations give similar basal drag inland (high height above floatation). In the Weertman case the friction must increase towards



the grounding line position (because the ice velocity has increased while the in the Cavitation sliding case, the friction must to decrease due to the effective pressure dependence. This results in the Weertman sliding case showing higher basal friction and slower velocities compared to the Cavitation sliding case.”

*P6 L5: "Fig. 3a" I think you mean Fig. 4a*  
Yes, this is now corrected to refer to Fig. 4a.

*P7 L6 and P8 L1: "but we cannot rule out the possibility that such behaviour could stabilise a retreating ice sheet for certain geometries." → This is a too strong statement considering the results that are presented in your manuscript for which the transient regrounding obtained with the Schoof law for  $W = 350$  km and  $W = 375$  km are far from preventing the GL to retreat over the retrograde slope.*

While it may be unlikely that this type of dynamic regrounding can fundamentally stabilise an ice sheet, such a possibility cannot be completely ruled out, because there are a lot of competing processes and feedbacks that could kick in. We have altered this sentence now to: "The current study demonstrates temporary regrounding, associated with a small drop in ice flow velocities. Whether or not this kind of dynamic regrounding could occur on larger spatial or temporal scales, or even stabilise a marine ice sheet, cannot be inferred from the current study."

*P8 L9: "ice shelf ice shelf" → typo*  
Corrected.

*P8 L13: "force balance" → In my opinion, "stress distribution" or "stress state" would be more appropriate*  
We have changed "force balance" to "stress state" as per the reviewers request.

*P8 L20: "transition zone" → I don't agree with the use you make of the term "transition zone" in this case. In line with Pattyn and others (2006), I understand the "transition zone" as being the narrow region right upstream the GL over which  $\tau_b$  progressively vanishes. By construction, the Weertman law with a uniform friction coefficient leads to a discontinuity of  $\tau_b$  at the GL which is equivalent to say that the length of the transition zone is reduced to 0. There cannot be any "transition zone" within the ice shelf - as you seem to suggest - as  $\tau_b = 0$  wherever ice is floating.*

To clarify our meaning here, we have changed this existing wording: "For the case of Weertman sliding, the instantaneous decay of basal shear stress from its maximum value to zero as the grounding line is crossed (Figure 4) causes the transition zone to extend into the ice shelf several km (typically around 20km in our experiments) causing the concave and rapidly thinning ice shelf in this region." to the following: "For the case of Weertman sliding, the basal shear stress drops from its maximum value to zero as the grounding line is crossed (Figure 4). The high basal shear stress right up to the grounding line is balanced by a correspondingly high driving stress, with maximum surface slope occurring at the grounding line. Thus instead of a transition zone upstream

of the grounding line, a geometrically concave region with very high spatial gradients in driving stress and flow speed extends downstream into the ice shelf (typically around 20km in our experiments) before a more typical shelf regime is attained.”

*P9 L5: this result was already highlighted in Tsai and others (2015), Gladstone and others (2017) and Brondex and others (2017) (the Budd law being investigated in the two latter), and therefore a citation of these studies would be welcome here.*

Yes, our results are consistent with these results and citations have been added. The final line of this paragraph now reads: ”This difference in ice shelf profile is a direct result of dependence on effective pressure at the bed and is likely to be present also for other sliding relations featuring such a dependence, as has been shown in (e.g. Tsai 2015, Gladstone 2017, Brondex 2017)”

*P10 L5-6: ”in which regrounding of an ice shelf after retreat has stabilised may occur through bedrock uplift after ice unloading” → I don’t understand the meaning of this sentence, is there a problem with it ?*

The text has been corrected to read ”in which regrounding of an ice shelf after grounding line retreat may occur through bedrock uplift after ice unloading.”

*P10 L7: to me, it is not very clear to what timescale you refer. Is it the duration of the regrounding ?*

The duration of regrounding following this overshoot process can be more or less permanent, so the timescale here refers to the whole process from the onset of retreat to when the regrounding occurs and is of order hundreds of years or thousands of years. To clarify we have changed ”timescale for dynamic regrounding” to ”timescale for dynamic regrounding in the current study”, because timescales may well be different for different systems and would likely depend on bedrock geometry.

*P11 L13: ”For each channel width” This formulation is misleading as the cases  $W = 250$  km ,  $W = 375$  km and  $W = 450$  km do not seem to be tested in your sensitivity analysis.*

Text now explicitly states ”For values of  $W=300$ km,  $350$ km and  $400$ km”

*P11 L14: ”We conclude that the effects shown here are not dependent on the mesh resolution” here too the formulation is misleading: if I am correct (based on Fig. 6), the 2 km mesh spacing case shows no regrounding at all even for  $W = 350$  km so it is not correct to state that your results are not dependent on the mesh resolution.*

By this we mean that we are confident that we have enough resolution to show that the effect is not simply an artefact of mesh resolution, showing that the results for the two finer resolutions using 1km and 500m mesh spacings are consistent. To clarify we have altered the text to read : ”We conclude that, for resolutions of 1km or finer, the effects shown here are not dependent on the mesh resolution”

*P12 L3: "Previous studies into the mesh resolution" → I am not a native english speaker but this formulation sounds odd to me"*

*P3P12 L4: e.g. (Durand et al., 2009)" → (e.g. Durand et al., 2009)*

We have corrected this sentence for clarity to: "Previous studies of mesh resolution dependence of the grounding line position and evolution using Weertman sliding, e.g. Durand (2009), have demonstrated convergence of the grounding line position."

*P13: you need to correct the friction law parameters after having rewritten the equations of P3. In addition, m should be 1/3 and not 3.*

The equations on P3 and the parameters have been corrected accordingly in this table.

## References

- [1] G. Durand, O. Gagliardini, B. de Fleurian, T. Zwinger, and E. Le Meur. Marine ice sheet dynamics: Hysteresis and neutral equilibrium. *Journal of Geophysical Research*, 114(F3):F03009, aug 2009.
- [2] Julien Brondex, Olivier Gagliardini, Fabien Gillet-Chaulet, and Gaël Durand. Sensitivity of grounding line dynamics to the choice of the friction law. *J. Glaciol.*, 63(241):854–866, oct 2017.
- [3] O. Gagliardini, G. Durand, T. Zwinger, R. C. A. Hindmarsh, and E. Le Meur. Coupling of ice-shelf melting and buttressing is a key process in ice-sheets dynamics. *Geophysical Research Letters*, 37(14):n/a–n/a, jul 2010.

# Simulated dynamic regrounding during marine ice sheet retreat

Lenneke M. Jong<sup>1,2,4</sup>, Rupert M. Gladstone<sup>1,3</sup>, Benjamin K. Galton-Fenzi<sup>1,4</sup>, and Matt A. King<sup>5</sup>

<sup>1</sup>Antarctic Climate & Ecosystems Cooperative Research Centre, University of Tasmania, Private Bag 80, Hobart, Tasmania 7001, Australia

<sup>2</sup>Institute for Marine and Antarctic Studies, University of Tasmania, Private Bag 129, Hobart, Tasmania 7001, Australia

<sup>3</sup>Arctic Centre, University of Lapland, P.O. Box 122, 96101, Rovaniemi, Finland

<sup>4</sup>Australian Antarctic Division, Channel Highway, Kingston, Tasmania 7050, Australia

<sup>5</sup>School of Land and Food, University of Tasmania, Hobart 7001, Australia

*Correspondence to:* L. M. Jong (lenneke.jong@utas.edu.au)

## Abstract.

Marine terminating ice sheets are of interest due to their potential instability, making them vulnerable to rapid retreat. Modelling the evolution of glaciers and ice streams in such regions is key to understanding their possible contribution to sea level rise. The friction caused by the sliding of ice over bedrock, and the resultant shear stress, are important factors in determining the velocity of sliding ice. Many models use simple power-law expressions for the relationship between the basal shear stress and ice velocity or introduce an effective pressure dependence into the sliding relation in an ad hoc. manner. Sliding relations based on water-filled sub-glacial cavities are more physically motivated, with the overburden pressure of the ice included. Here we show that using a cavitation based sliding relation allows for the temporary regrounding of an ice shelf at a point downstream of the main grounding line of a marine ice sheet undergoing retreat across a retrograde bedrock slope. This suggests that the choice of sliding relation is especially important when modelling grounding line behaviour of regions where potential ice rises and pinning points are present and regrounding could occur.

## 1 Introduction

Marine ice sheets, which are grounded below sea level, have been identified as having the potential to contribute significantly to future sea level rise through the rapid loss of ice under changing climate conditions. When grounded on a retrograde sloping bedrock (i.e. sloping downwards towards the interior of the continent) it has been suggested (Mercer, 1978; Weertman, 1974) that the positive relationship between ice thickness and ice flux leads to a positive feedback in which rapid retreat of the grounding line may occur, termed “marine ice sheet instability” (MISI). MISI theory predicts that the grounding line of a glacier cannot stabilise on a retrograde bedrock slope. Thus, if a glacier retreats onto a region with such a bedrock geometry it will continue retreating rapidly at least until reaching a prograde slope, potentially discharging large amounts of previously grounded ice into the ocean. Large regions of the Antarctic ice sheet, particularly in West Antarctica, are grounded below sea level with retrograde sloping bedrock (Fretwell et al., 2013) and thus may be susceptible to MISI. [Modelling of the dynamics of marine ice sheets have been investigated widely -see Pattyn et al. \(2017\) for with Pattyn et al. \(2017\) providing a recent review of the field, and development in modelling their dynamics. They](#) have been the subject of recent model intercomparison

projects such as MISMIP (Pattyn et al., 2012), MISMIP3d (Pattyn et al., 2013) and MISMIP+ (Asay-Davis et al., 2016) ~~and when focusing on retreating glaciers~~ looking at idealised systems. Retreating glaciers showing a geometry making them susceptible to MISI, such as Pine Island Glacier, have been also been a particular focus (Gladstone et al., 2012; Joughin et al., 2010; Favier et al., 2014). More recent analysis has shown that stable grounding line configurations may be possible on retrograde sloping bedrock when the buttressing of floating ice shelves and 3D geometry of the system is included (Katz and Worster, 2010; Gudmundsson et al., 2012; Gudmundsson, 2013) or in some configurations where the basal friction coefficient is tuned spatially Brondex et al. (2017).

Many ice sheet models use a power-law relationship between the basal shear stress and sliding velocity, such that of Weertman (1957). These models require very fine mesh resolution ~~in the vicinity of the grounding line~~ (Vieli and Payne, 2005; Gladstone et al., 2007). ~~The due to the sharp change in shear stress across the grounding line leads to difficulties in achieving a convergent result without very fine mesh resolution~~ (Gladstone et al., 2017) (Vieli and Payne, 2005; Gladstone et al., 2010; Cornford et al., 2013; Leguy et al., 2015). Other relations have been investigated which take into account the effective pressure of the ice at its base either determined empirically such as that of Budd et al. (1984), or by including in the presence of water-filled cavities (Schoof, 2005). Sliding relations in ice sheet models which include an effective pressure dependence, such as ~~that those of Schoof and Budd which~~ implemented in Elmer/Ice (Gagliardini et al., 2007) (Gagliardini et al., 2007; Gladstone et al., 2017; Brondex et al., 2017), provide a theoretically based treatment of basal friction, do not cause such strong mesh resolution dependency and ~~do not suffer from the same mesh resolution issues as Weertman type relations and~~ satisfy Iken's bound (Iken, 1981). Recently Tsai et al. (2015) explored the effect of using a modification to the power-law basal sliding with Coulomb friction used close to the grounding line on the stability and profiles of marine ice sheets.

The underlying geometry of the bedrock is an important control in the stability of marine ice sheets. The role of ice rises and pinning points (Favier et al., 2012; Favier and Pattyn, 2015; Fürst et al., 2016) in affecting buttressing forces and stabilisation of the grounding line has been investigated in numerical modelling efforts, as has the role of glacial isostatic adjustment (Gomez et al., 2012). Recent ensemble simulations of Antarctic Ice Sheet deglaciation since the last glacial maximum (Kingslake et al., 2017) have demonstrated that regrounding of pinning points in large ice shelves due to glacial uplift after a period of retreat can cause a stabilisation and readvance of the grounding line. Thus regrounding can be important to large scale marine ice sheet dynamics, even leading to a partial recovery from MISI with the grounding line advancing again after a period of retreat.

In this study, we further investigate the impact of the sliding law on glacier trajectory in an idealised 2D flowline model, showing that dynamic regrounding on a retrograde bedrock slope can occur when a sliding relation with a dependency on the effective pressure at the base of the ice is used.

## 2 Methods

### 2.1 Model description

In this study we use a finite element model Elmer/Ice (Gagliardini et al., 2013) to solve the full Stokes equations for a viscous fluid. A rheology following Glen's law is used, with the temperature held constant through the whole of the ice sheet at -15 C.

We use a two-dimensional flowline geometry with the bedrock shape the same as that used in a recent model intercomparison project (Pattyn et al., 2012), featuring a section of retrograde slope, described by

$$B(x) = 729 - 2184.8 \left( \frac{x}{750\text{km}} \right) + 1031.72 \left( \frac{x}{750\text{km}} \right)^4 - 151.72 \left( \frac{x}{750\text{km}} \right)^6, \quad (1)$$

5 where  $x$  is distance from the inland boundary and  $B$  is bedrock elevation relative to sea level.

The grounding line position is solved in the model through a contact problem, taking into account the geometry of the lower surface with respect to the bedrock, the effective pressure at the base of the grounded ice and the buoyancy of the ice in contact with the ocean.

We use a basal sliding relation that is based on the theory of sliding with cavitation (Schoof, 2005) and has been implemented in Elmer/Ice (Gagliardini et al., 2007). The basal friction is related to the sliding velocity by

$$\frac{\tau_b}{N} = C_{\max} \left( \frac{\chi}{1 + \alpha \chi^q} \right)^{1/n} \quad (2)$$

where  $\tau_b$  is the basal shear stress,  $u_b$  the basal ice sliding velocity

$$\chi = \frac{u_b}{C^m N^n A_s} \frac{u_b}{C_{\max}^n N^n C_S} \quad (3)$$

and

$$15 \quad \alpha = \frac{(q-1)^{q-1}}{q^q}. \quad (4)$$

$A_s C_S$  is the sliding parameter in the absence of cavitation,  $n$  Glen's law exponent,  $C_{\max}$  the maximal value of  $\tau_b \tau_b / N$  bounded by the maximum slope of the bedrock and  $q \geq 1$  the exponent controlling the post-peak decrease. The effective pressure  $N$  is calculated based on the assumption of full connectivity between the subglacial hydrologic system and the ocean. This sliding relation is henceforth referred to as the ‘‘cavitation sliding relation’’.

20 The other sliding relation used in this study, is that a non-linear Weertman-type, Weertman type friction law, of the form:

$$\tau_b = A_s \cdot u_b^{m-1} \cdot u_b C_w u_b^m \quad (5)$$

where  $m$  in this case is  $1/n$ ,  $\tau_b$  and  $u_b$  the basal shear stress and ice velocity respectively and  $A_s C_w$  is a constant sliding friction coefficient. This sliding relation is henceforth referred to as the ‘‘Weertman sliding relation’’.

25 ~~Buttressing is included~~ A buttressing-like force due to friction along glacier side walls is included through by adding a body force into the force balance using a parameterisation of lateral drag by (Gagliardini et al., 2010) relating lateral resistance to the rheological parameters of the ice and a ice shelf embayment width described by Gagliardini et al. (2010). The body force is given by:

$$\mathbf{f} = -K |\mathbf{u}|^{m_{lr}-1} \mathbf{u} \quad (6)$$

where  $m_{lr} = 1/n$  is the lateral resistance exponent where the lateral resistance parameter with  $n$  the usual Glen's law parameter. The resistance parameter  $K$  is given by:

$$K = \eta \frac{(n+1)^{\frac{1}{n}}}{(\rho_{ice} W^{1+\frac{1}{n}})} \frac{(n+1)^{1/n}}{W^{\frac{n+1}{n}} (2A)^{1/n}} \quad (7)$$

with  $\eta$  the effective viscosity of the ice,  $\rho_{ice}$  the density,  $A$  the fluidity parameter of the ice and  $n = 1/m$ .  $W$  is a parameter corresponding to a channel width-half-width which we use to modify the lateral drag from high to low in order to force during the experiment from being initially high (i.e. low  $W$ ) and then decreased by changing to a high value of  $W$  as a means of forcing the glacier to retreat.

The experiments presented here used a horizontally uniform mesh resolution with a 500m element size for simulations using the cavitation sliding relation, and 250m element size for simulations using the Weertman sliding relation. Tests were carried out at coarser resolutions to test for resolution dependence (see Appendix A for details and B for model parameter values). The mesh is extruded in the vertical direction to 20 equally spaced layers in all simulations.

## 2.2 Experimental Description

The retreat experiments examine the behaviour of an ice sheet retreating across a section of retrograde slope when using the cavitation sliding relation, which incorporates a dependency of basal shear stress on effective pressure at the base of the ice. We begin with a 2D ice sheet grown from a uniform initial thickness of 100m. During the initial 5000 years of spinup the parameterised buttressing is set to zero. The buttressing is then linearly increased from zero to an effective channel width-half-width of 100km over the next 5000 years, resulting in a high buttressing force. The model is then continued until the grounding line position rests on the seaward side of the bedrock overdeepening (at approximately 1400km from the ice divide). During this initial spinup period the top surface accumulation rate is set to  $1\text{m yr}^{-1}$ , to reduce the total run time for the spinup. After ~~16600~~ 10000 years the accumulation rate is then decreased to  $0.3\text{m yr}^{-1}$  and held at this value while the ice sheet stabilises and remains at this value throughout the retreat experiments. We determine that the spinup has finished and the ice sheet has reached a steady state when there has been no change in the grounding line position, and the mesh velocity, determining the change in the top and bottom free surfaces, remains less than  $0.001\text{m yr}^{-1}$  over 10000 years, resulting in a total spinup time of 25000 years.

We run a series of experiments where we trigger retreat of the glacier through a reduction in the buttressing force by linearly increasing the channel width-half-width parameter over 10 years to reduce the buttressing force, using values of  $W$  equal to 250km, 300km, 350km, 375km, 400km and 450km. An infinitely wide channel corresponds to the case of no lateral drag and the values of  $W$  used in the experiments should be considered as simply providing a range of values for buttressing. Simulations are then run for 2500 years, with 0.1 year timesteps with no further forcing change applied after the initial buttressing adjustment.

We carry out a similar retreat experiment using the Weertman sliding relation (equation 5). In this experiment we again spin up the ice sheet, initially for 5000 years with no buttressing and accumulation of  $1\text{m yr}^{-1}$ , increasing the buttressing with

$W = 100\text{km}$  linearly over 5000 years. The accumulation rate is then reduced to  $0.3\text{m yr}^{-1}$  and the model is left to evolve for a further 10000 years until the top and bottom free surfaces show minimal change, resulting in a total spinup time of 20000 years. ~~We chose a spatially uniform value for the Weertman sliding friction coefficient to match the value of basal shear stress observed in the cavitation sliding relation experiments at maximum values of ice velocity and height. Again, we-~~

- 5 Recently, Brondex et al. (2017) showed that far from the grounding line, (i.e. for large values of height above flotation) the Weertman and Cavitation sliding relations give an approximately equivalent relationship between basal velocity  $u_b$  and basal shear stress  $\tau_b$ . For this study we chose a Weertman friction coefficient such that the Weertman and Cavitation relations give similar values of  $\tau_b$ , far from the grounding line (with high height above flotation) and that would also result in the initial position of the grounding line being within a few km for both sets of experiments.
- 10 ~~To trigger a retreat of the grounding line by reducing the buttressing, we again reduce the buttressing by~~ increasing  $W$  from 100km to values equal to 350km linearly over, 400km and 500km linearly over a period of 10 years and then continuing to let the simulation run without further forcing. A timestep of 0.5 years was used throughout the ~~run~~experiment.

### 3 Results

#### 3.1 Cavitation sliding

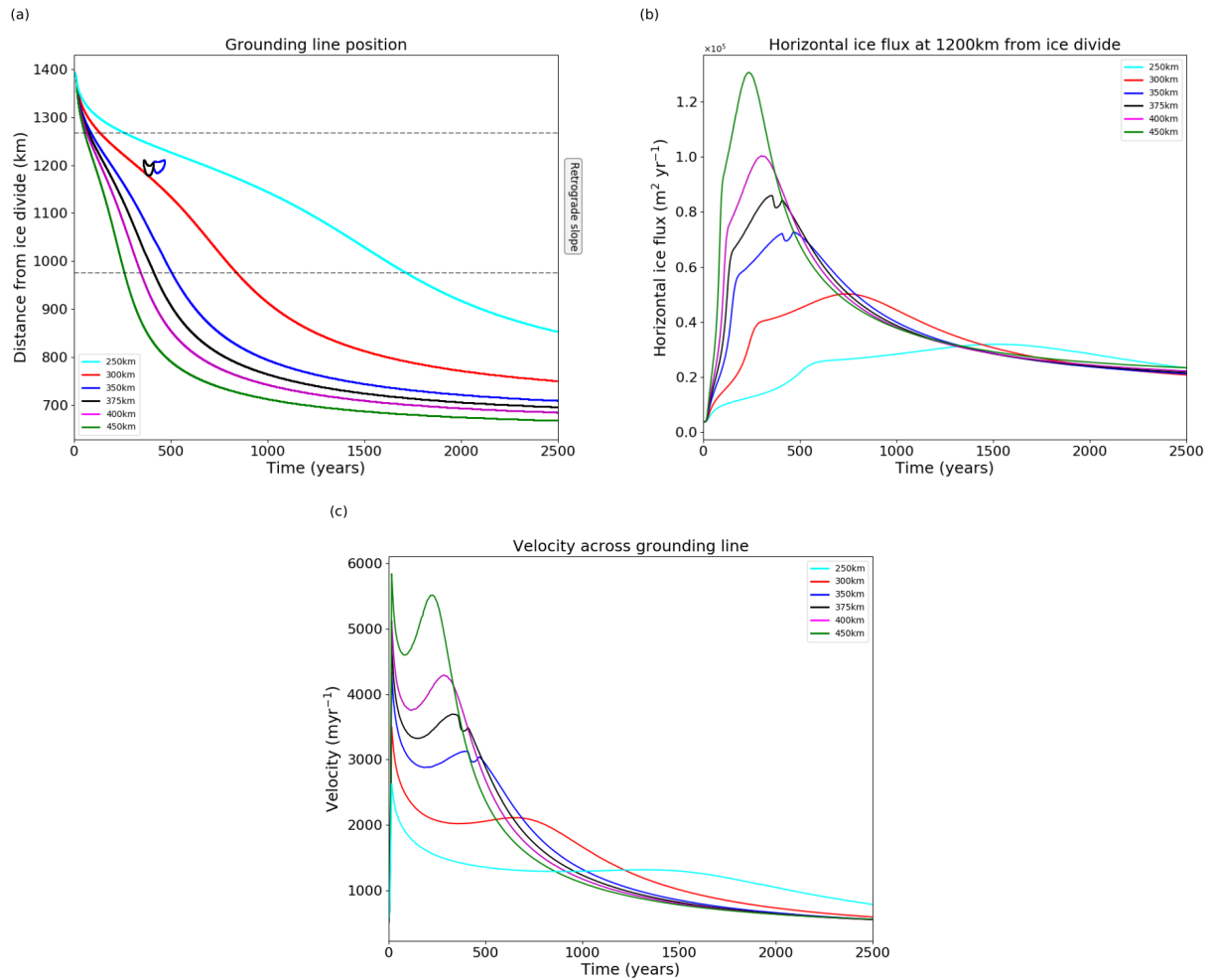
- 15 The position of the grounding line is tracked over time during the channel ~~width~~half-width increase and through the continuation of the model run (Figure 1a). In most simulations using the cavitation sliding relation the grounding line has retreated across the retrograde slope within the first 1000 years, and by 2500 years grounding lines and surface slopes are stabilising. The simulations with higher buttressing (i.e. a smaller forcing perturbation relative to the pre-retreat state) take longer to retreat and stabilise.

- 20 The simulations with  $W = 350, 375\text{km}$  feature a temporary regrounding of the ice shelf during retreat on the retrograde bedrock. The temporary regrounding occurs approximately 200km downstream of the original (henceforth “upstream”) grounding line. The upstream grounding line continues retreat during regrounding of the shelf.

- This regrounding is likely caused by the downstream advection of thicker interior ice, which is mobilised by the buttressing reduction. In general, dynamic thinning of the ice shelf due to reduced buttressing competes with thickening due to downstream advection of thicker interior ice to give either a net thinning or thickening in the shelf. For simulations with parameterised channel ~~width~~half-width  $W \geq 400\text{km}$  the peak ice discharge comes early (approximately 300 years, see also Figure 1b) and dynamic thinning is sufficient to prevent regrounding. For simulations with ~~parameterised channel width~~ $W \leq 300\text{km}$  a sharp peak in discharge is not seen (Figure 1b), and downstream advection of thicker ice is slow, too slow to overcome dynamic thinning in the shelf. Thus the simulations with  $W = 350, 375\text{km}$  represent a key region of input space in which regrounding
- 30 may occur. We refer to this as “dynamic regrounding” to distinguish it from regrounding due to bedrock uplift (described in Section 1).

The position of the flux gate in Figure 1b (1200km from the ice divide) is chosen as it is located where the regrounding occurs. The flux reaches a maximum as the grounding line approaches the inland end of the retrograde bedrock region, and

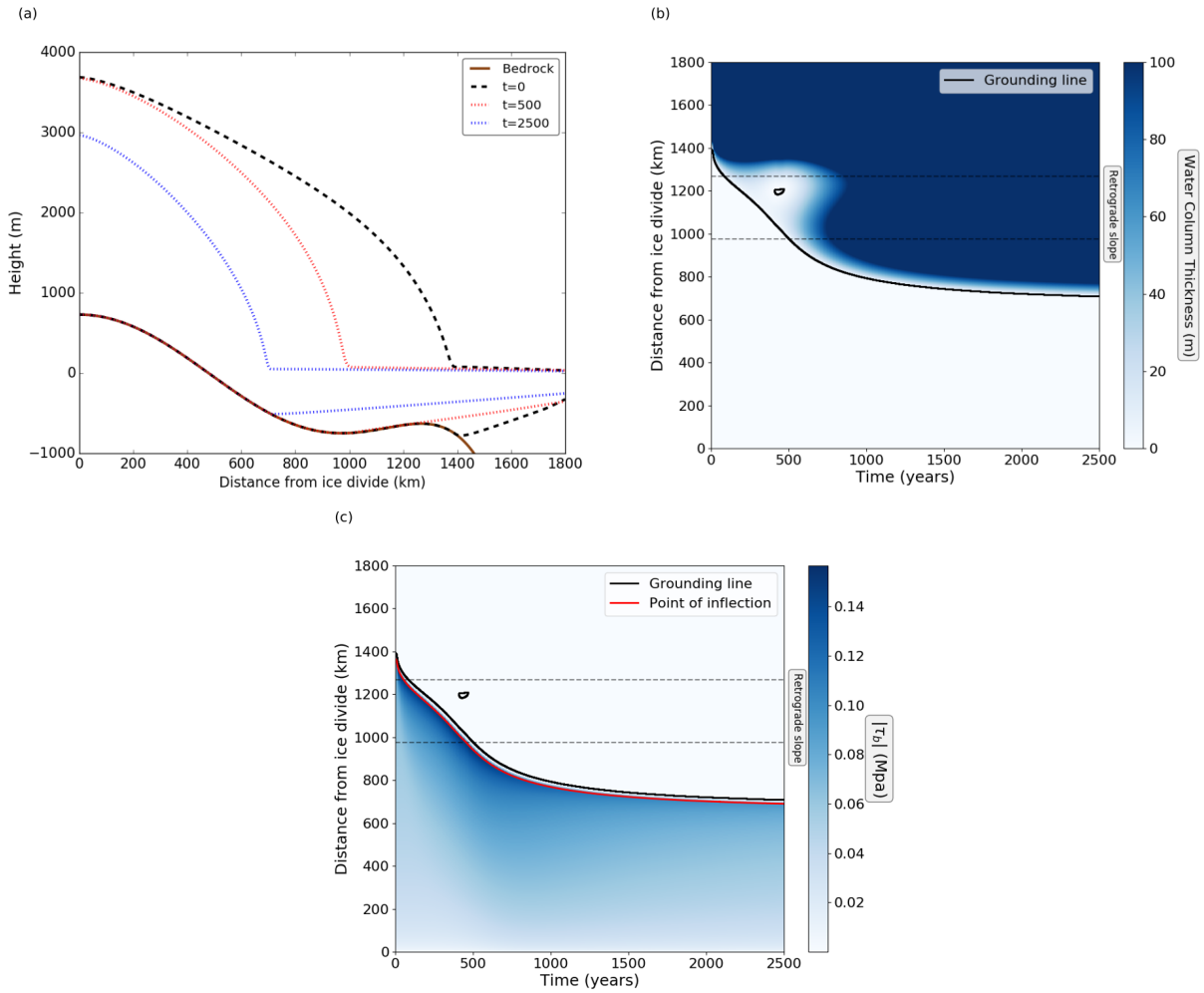




**Figure 1.** Retreat experiments using the cavitation sliding relation. (a) Evolution of grounding line position over time for a range of parameterised channel widths half-widths. Dashed lines indicate the extent of the retrograde bedrock. (b) Total flux of ice in the horizontal direction across a line 1200km from the ice divide. (c) Sliding speed across the grounding line.

decreases as the grounding line migrates up the prograde slope. Similarly, we see a reduction in the sliding speed of the ice across the grounding line as shown in Figure 1c. For the cases where dynamic regrounding occurs we see a temporary reduction in the flux and sliding speed, but this reduction is not sufficient to stabilise retreat.

Figure 2 presents a more detailed analysis of retreat and dynamic regrounding for  $W = 350\text{km}$ . It can be seen that the slope of the lower surface of the ice shelf is similar to the retrograde bedrock slope, and this corresponds to a very shallow water column under the shelf. The implication is that only a very small amount of thickening is needed to cause regrounding. The shallow water column is common to all retreat simulations with the cavitation sliding relation (not shown).



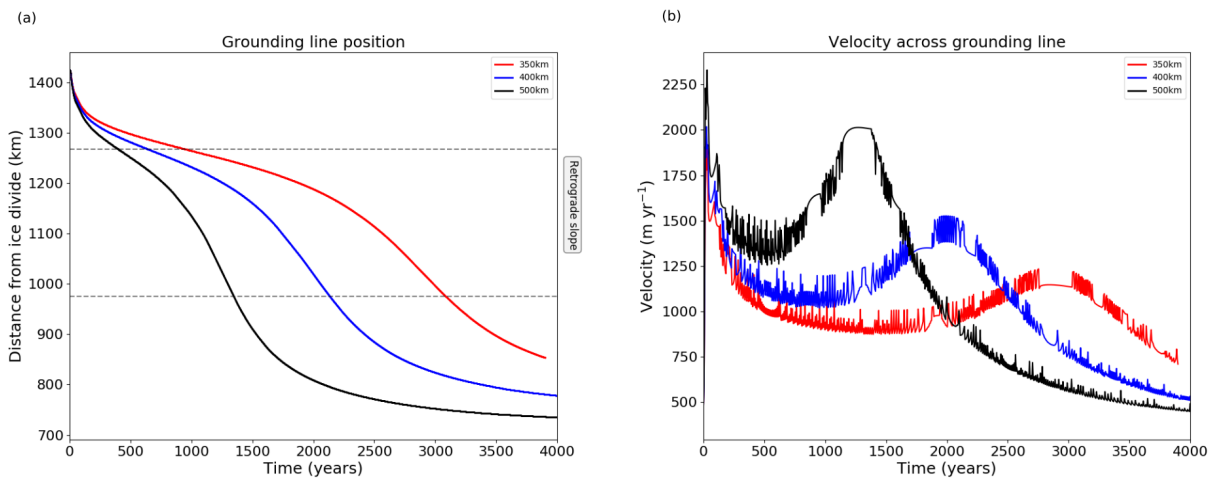
**Figure 2.** Retreat experiment details with the cavitation sliding relation and  $W = 350\text{km}$ . (a) Ice sheet profiles during retreat. Bedrock profile is also shown. (b) Evolution of the water column thickness during retreat. (c) Evolution of the basal shear stress.

Figure 2c shows basal shear stress, the point of inflection, and the grounding line. The point of inflection is with respect to the upper surface height of the ice sheet, and indicates the switch from a convex ice sheet surface (inland, which includes most of the grounded ice) to concave. It is identified here through calculation of the maximum gradient of the upper surface. Figure 2c shows that the point of inflection corresponds to the maximum in basal shear stress. Downstream of this line basal shear stress drops rapidly to zero, due to the dependence on effective pressure at the bed,  $N$ , in the cavitation sliding relation (equation 2). The grounding line is persistently a few tens of km downstream of the point of inflection. The implications of the point of inflection and basal shear stress pattern for transition zones and ice sheet profiles with different sliding relations will

be discussed further in Section 4. Basal shear stress is also very low under the regrounding region, again due to the dependence on  $N$ .

### 3.2 Weertman sliding

In experiments where the Weertman sliding law is used we see no temporary regrounding of the ice sheet. The ice shelf develops a thinner profile than with the cavitation sliding relation and a markedly different shape, as shown in Fig. 34a. A strongly concave shape is evident immediately downstream of the grounding line, in contrast to the more linear ice shelf profile when using the cavitation sliding relation. As a result of this difference, water column thickness is much larger during retreat than for the cavitation sliding relation.

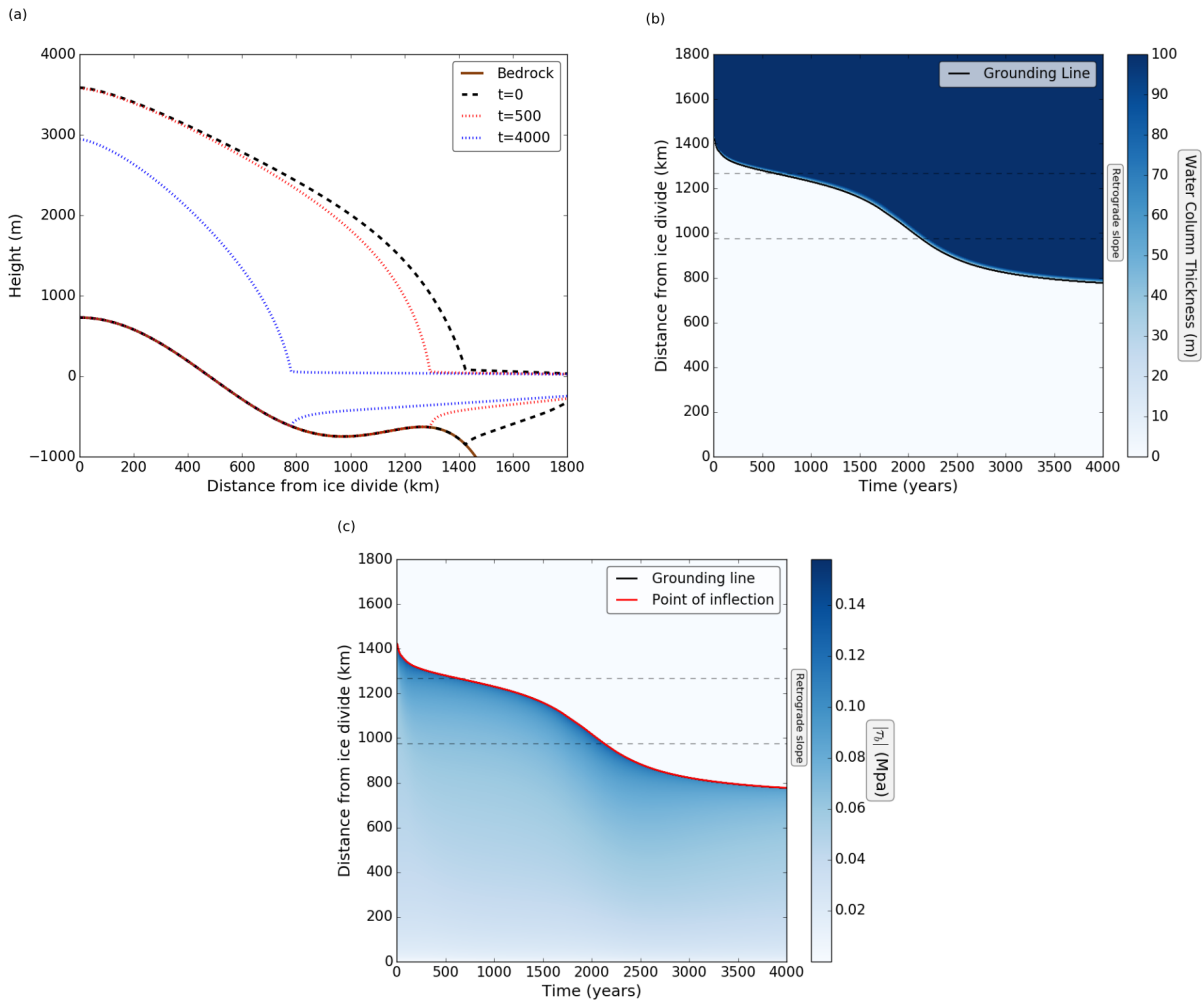


**Figure 3.** Evolution of (a) grounding line position and (b) cross-grounding line sliding speed for a range of parameterised channel widths half-widths using the Weertman sliding relation.

In Fig. 3(b) we see high frequency changes in velocity which is likely Each jump in velocity probably corresponds to grounding line movement between neighbouring elements. Ungrounding of an element significantly reduces the basal friction, allowing speedup. This does not happen with the Cavitation sliding law (Fig. 1(c)) because the dependence on effective pressure means that the basal shear stress is in any case close to zero for elements that are newly ungrounded.

## 4 Discussion

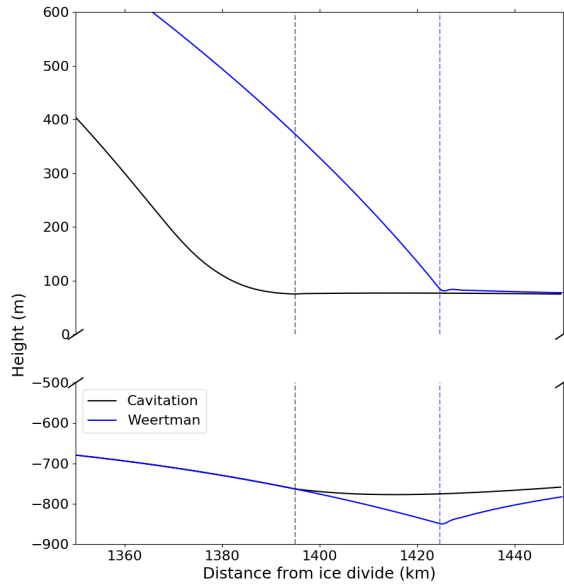
Retreat simulations in the current study have demonstrated that regrounding of an ice shelf may occur under certain conditions during the rapid, unstable retreat of a marine ice sheet. In our simulations, this regrounding has a modest negative impact on the rate of mass loss from the grounded ice sheet, but we cannot rule out the possibility that such behaviour could stabilise a retreating ice sheet for certain geometries. The current study demonstrates temporary regrounding, associated with a small drop



**Figure 4.** Retreat experiment details with the Weertman sliding relation and  $W = 400\text{km}$ . (a) Ice sheet profiles during retreat. Bedrock profile is also shown. (b) Evolution of the water column thickness during retreat. (c) Evolution of the basal shear stress. Note that the point of inflection and grounding line position are co-located.

in ice flow velocities. Whether or not this kind of dynamic regrounding could occur on larger spatial or temporal scales, or even stabilise a marine ice sheet, cannot be inferred from the current study. The regrounding occurs as thick, previously grounded ice is advected downstream toward a bedrock rise in response to reduced buttressing.

While a thorough investigation into conditions for regrounding to occur is beyond the scope of the current study, it does provide insight into possible conditions when regrounding may occur. The geometry of the ice sheet is clearly important, as advection of thicker ice is required to cause regrounding. This may be more complicated in three dimensions - flow convergence may itself provide thickening in response to grounded ice speed up. Bedrock geometry is also important - the retrograde slope



**Figure 5.** Detail of ice sheet profiles at  $t=0$  for both cavitation sliding and Weertman sliding. Dashed vertical lines indicate the position of the grounding line.

is a key feature of the current setup and it is unlikely that regrounding could occur without an overdeepening. We suggest that a higher (closer to sea level) bedrock maximum and steeper retrograde slope are both likely conducive to regrounding. Choice of sliding relation is also important. The strongly concave lower surface of the ice shelf ~~ice shelf~~ just downstream from the grounding line in the case of Weertman sliding increases the water column depth under the ice shelf and reduces the likelihood of regrounding. High sub-shelf melt rates may also cause a concave lower surface profile, reducing the likelihood of regrounding.

Impact of sliding law merits further consideration. The ~~force-balance-stress state~~ in the ice sheet changes from the grounded region to the floating ice shelf over what is typically termed a “transition zone” (Pattyn et al., 2006; Schoof, 2007a). Grounded ice typically features high gravitational driving stress and high basal shear stress, especially for the high surface gradients and high velocities as the transition zone is approached. The floating ice shelf features smaller magnitude forces with the parameterised buttressing approximately balancing longitudinal stress, and driving stress being close to zero. In the absence of buttressing the ice shelf thickness would be almost constant through most of its length (Schoof, 2007b). For the case of Weertman sliding, the ~~instantaneous decay of~~ basal shear stress ~~drops~~ from its maximum value to zero as the grounding line is crossed (Figure 3) ~~causes the transition zone to extend into the iceshelf several km~~. The high basal shear stress right up to the grounding line is balanced by a correspondingly high driving stress, with maximum surface slope occurring at the

grounding line. Thus instead of a transition zone upstream of the grounding line, a geometrically concave region with very high spatial gradients in driving stress and flow speed extends downstream into the ice shelf (typically around 20km in our experiments) ~~causing the concave and rapidly thinning ice shelf in this region before a more typical shelf regime is attained.~~"

5 For the cavitation sliding relation, the rapid decay of basal shear stress to zero in the vicinity of the point of inflection in surface slope (Figure 2) leads to a grounded transition zone with the concave ice thickness occurring upstream of the grounding line and resulting in a thicker, more linear, ice shelf. Figure 5 shows example ice sheet/shelf geometries over the transition zone for both sliding relations. This difference in ice shelf profile is a direct result of dependence on effective pressure at the bed and is likely to be present also for other sliding relations featuring such a dependence, as has been shown in (e.g. Budd et al. (1984) (Tsai et al., 2015; Gladstone et al., 2017; Brondex et al., 2017))

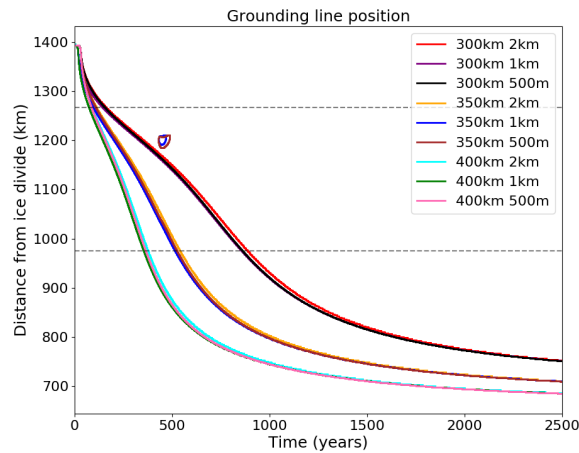
10 The plots of sliding velocity across the grounding line in figures 1(c) and 3(b) also point to differences resulting from the choice of sliding relation used. After the initial adjustment in response to the change in buttressing the peak grounding line ice velocity corresponds to the time when the grounding line position changes from lying on retrograde to prograde bedrock slope. For the Cavitation sliding case we also see a small dip in velocity when the regrounding occurs. As previously stated we have chosen a Weertman friction coefficient such that both relations give similar basal drag inland (high height above floatation).  
15 In the Weertman case the friction must increase towards the grounding line position (because the ice velocity has increased) while the in the Cavitation sliding case, the friction must to decrease due to the effective pressure dependence. This results in the Weertman sliding case showing higher basal friction and slower velocities compared to the Cavitation sliding case.

The contrasting ice shelf profiles for the two sliding relations in the current study could indicate a means for validation of the choice of sliding relation through comparison against observed ice shelf profiles. Ideally, observed profiles for simulations with  
20 low ice shelf basal melting and low buttressing would be used, as both of these factors could impact on the ice shelf geometry.

The dynamic regrounding in the current study has some similarity to the regrounding that occurs following the overshoot mechanism presented by Kingslake et al. (2017), in which regrounding of an ice shelf after ~~retreat has stabilised~~ grounding line retreat may occur through bedrock uplift after ice unloading. Both regrounding mechanisms impose a reduction in ice discharge, though the overshoot regrounding is lasting and the dynamic regrounding in the current simulations is transient. The  
25 suggested timescale for overshoot regrounding is an order of magnitude greater than the timescale for dynamic regrounding in the current study, but these timescales are also controlled by the size of the system, the ice flow speeds, and potentially ice and bedrock geometry. In the case of overshoot regrounding the timescale is also strongly dependent on mantle viscosity. It may be possible that for some bedrock configurations, and in the case of low mantle viscosity, dynamic regrounding could sufficiently retard ice sheet retreat to prevent overshoot and allow a post-retreat steady state to be reached more quickly.

## 30 **5 Conclusions**

Flowline ice sheet simulations carried out in the current study demonstrate that regrounding on a retrograde bedrock slope can occur during marine ice sheet retreat. It is not yet clear under what conditions this regrounding, combined with isostatic rebound, could counter retreat and stabilise the ice sheet.



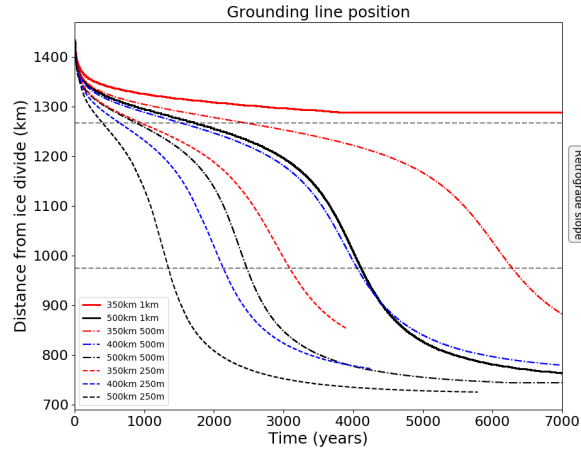
**Figure 6.** Grounding line retreat for the mesh resolution dependence experiments using the cavitation sliding relation. Buttressing parameters of 300km, 350km and 400km are used with 2km, 1km and 500m uniform element size in the horizontal.

The current study also demonstrates that use of a sliding relation in which basal shear stress is dependent on effective pressure at bed impacts on transition zone location and on ice shelf thickness profiles immediately downstream of the grounding line. This dependence implies that regrounding is less likely to occur when a Weertman sliding relation is used, and could provide a means for validating choice of sliding relation through comparison with observed ice shelf profiles.

## 5 Appendix A: Mesh Resolution Dependence

A number of experiments were run at different mesh resolutions demonstrating convergent behaviour. Identical retreat experiments were performed using the cavitation sliding relation on uniform meshes with 2km, 1km and 500m grid spacing. Runtime is considerably longer for the finest mesh resolution. The results, shown in Fig. 6, demonstrate that the regrounding behaviour is present and almost identical in both the 1km and 500m mesh spacing cases. For ~~each channel width values of  $W=300\text{km}$ ,  $350\text{km}$  and  $400\text{km}$~~ , the final position of the grounding line is the same for all mesh resolutions. We conclude that the effects shown here are not dependent on the mesh resolution and a finer resolution is not required to get convergent behaviour of the grounding line.

Similar experiments were performed using the Weertman sliding relation on uniform meshes with 1km, 500m and 250m grid spacing. In this case, while the end position of the grounding line appears to converge, the transient behaviour of the grounding line is not consistent between the grid sizes, with the finest mesh resulting in the fastest retreat of the grounding line across the retrograde slope. The concave geometry of the lower surface of the ice shelf is consistent across the mesh resolution experiments. Previous studies into the mesh resolution dependence of the grounding line [position and evolution](#) using Weertman sliding, [eg. Durand et al. \(2009\)](#), have demonstrated convergence of the grounding line position, ~~eg. (Durand et al., 2009)~~.



**Figure 7.** Grounding line retreat for the mesh resolution dependence experiments using the Weertman sliding relation. Buttressing parameters of 350km, 400km and 500km are used with 1km,500m and 250m uniform element size in the horizontal.

## Appendix B: Model Parameters

Parameter	Value	Unit	Description
$n$	3		Glen's law exponent
$T$	-15	$^{\circ}\text{C}$	ice temperature
$\rho_i$	910	$\text{kg m}^{-3}$	density of ice
$\rho_w$	1000	$\text{kg m}^{-3}$	density of water
$g$	-9.8	$\text{m s}^{-2}$	Gravitational acceleration
$a$	0.3	$\text{m yr}^{-1}$	Accumulation rate
$C_{\text{max}}$	0.1		Cavitation <del>friction law sliding</del> maximum value
$q$	1		Cavitation <del>friction law sliding</del> post peak exponent
$n$	<u>3</u>		<u>Glen's law Exponent</u>
$m$	<u>1/3</u>		Power <del>Law-law</del> exponent ( $m=n=\text{Glen's Exponent}/n$ )
$A$	$3 \times 10^{-25}$	$\text{s}^{-1} \text{Pa}^{-3}$	<del>Fluidity</del> <u>Glen's law</u> parameter
$A_s$ (Cavitation) $C_s$	$4.1613 \times 10^5$	<del><math>\text{Pa m}^{-1/3} \text{a}^{1/3}</math></del> <u><math>\text{Pa m}^{-1/3} \text{s}^{1/3}</math></u>	Cavitation <del>friction law sliding</del> parameter
$u_{t0}$	0.01	$\text{m yr}^{-1}$	Cavitation <del>friction law sliding</del> linear velocity
$A_s$ (Weertman) $C_w$	$3.812 \times 10^6$	<del><math>\text{Pa m}^{-1/3} \text{a}^{1/3}</math></del> <u><math>\text{Pa m}^{-1/3} \text{s}^{1/3}</math></u>	Weertman sliding parameter

**Table 1.** Values of model parameters used



*Acknowledgements.* The authors would like to thank Thomas Zwinger for technical help with the simulations. Rupert Gladstone is funded by the Academy of Finland, grant number 286587. This research was undertaken with the assistance of resources from the National Computational Infrastructure (NCI), which is supported by the Australian Government. This work was supported in part by the Australian Government's Cooperative Research Centres Program through the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC).

5 This research was supported under Australian Research Council's Special Research Initiative for Antarctic Gateway Partnership (Project ID SR140300001).

## References

- Asay-Davis, X. S., Cornford, S. L., Durand, G., Galton-Fenzi, B. K., Gladstone, R. M., Hilmar Gudmundsson, G., Hattermann, T., Holland, D. M., Holland, D., Holland, P. R., Martin, D. F., Mathiot, P., Pattyn, F., and Seroussi, H.: Experimental design for three interrelated marine ice sheet and ocean model intercomparison projects: MISMIP v. 3 (MISMIP +), ISOMIP v. 2 (ISOMIP +) and MISOMIP v. 1 (MISOMIP1), *Geoscientific Model Development*, doi:10.5194/gmd-9-2471-2016, 2016.
- 5 Brondex, J., Gagliardini, O., Gillet-Chaulet, F., and Durand, G.: Sensitivity of grounding line dynamics to the choice of the friction law, *J. Glaciol.*, 63, 854–866, doi:10.1017/jog.2017.51, <https://www.cambridge.org/core/product/identifier/S002214301700051X/type/journal{ }article>, 2017.
- Budd, W. F., Janssen, D., and Smith, I. N.: A three-dimensional time-dependent model of the West Antarctic ice sheet, *Annals of Glaciology*, 10 5, <http://adsabs.harvard.edu/abs/1984AnGla...5...29B>, 1984.
- Cornford, S. L., Martin, D. F., Graves, D. T., Ranken, D. F., Le Brocq, A. M., Gladstone, R. M., Payne, A. J., Ng, E. G., and Lipscomb, W. H.: Adaptive mesh, finite volume modeling of marine ice sheets, *Journal of Computational Physics*, 232, 529–549, doi:10.1016/j.jcp.2012.08.037, 2013.
- Durand, G., Gagliardini, O., Zwinger, T., Le Meur, E., and Hindmarsh, R. C.: Full Stokes modeling of marine ice sheets: influence of the 15 grid size, *Annals of Glaciology*, pp. 109–114, doi:10.3189/172756409789624283, 2009.
- Favier, L. and Pattyn, F.: Antarctic ice rise formation, evolution, and stability, *Geophysical Research Letters*, 42, 4456–4463, doi:10.1002/2015GL064195, 2015.
- Favier, L., Gagliardini, O., Durand, G., and Zwinger, T.: A three-dimensional full Stokes model of the grounding line dynamics: effect of a pinning point beneath the ice shelf, *The Cryosphere*, 6, 101–112, doi:10.5194/tc-6-101-2012, 2012.
- 20 Favier, L., Durand, G., Cornford, S. L., Gudmundsson, G. H., Gagliardini, O., Gillet-Chaulet, F., Zwinger, T., Payne, A. J., and Le Brocq, A. M.: Retreat of Pine Island Glacier controlled by marine ice-sheet instability, *Nature Climate Change*, 4, 117–121, doi:10.1038/nclimate2094, 2014.
- Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., Bianchi, C., Bingham, R. G., Blankenship, D. D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A. J., Corr, H. F. J., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, 25 S., Gim, Y., Gogineni, P., Griggs, J. A., Hindmarsh, R. C. A., Holmlund, P., Holt, J. W., Jacobel, R. W., Jenkins, A., Jokat, W., Jordan, T., King, E. C., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K. A., Leitchenkov, G., Leuschen, C., Luyendyk, B. P., Matsuoka, K., Mougintot, J., Nitsche, F. O., Nogi, Y., Nost, O. A., Popov, S. V., Rignot, E., Rippin, D. M., Rivera, A., Roberts, J., Ross, N., Siegert, M. J., Smith, A. M., Steinhage, D., Studinger, M., Sun, B., Tinto, B. K., Welch, B. C., Wilson, D., Young, D. A., Xiangbin, C., and Zirizzotti, A.: Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, *The Cryosphere*, 7, 375–393, doi:10.5194/tc-7-375-2013, 30 2013.
- Fürst, J. J., Durand, G., Gillet-Chaulet, F., Tavaré, L., Rankl, M., Braun, M., and Gagliardini, O.: The safety band of Antarctic ice shelves, *Nature Climate Change*, 6, 479–482, doi:10.1038/nclimate2912, 2016.
- Gagliardini, O., Cohen, D., Råback, P., and Zwinger, T.: Finite-element modeling of subglacial cavities and related friction law, *Journal of Geophysical Research*, 112, F02 027, doi:10.1029/2006JF000576, 2007.
- 35 Gagliardini, O., Durand, G., Zwinger, T., Hindmarsh, R. C. A., and Le Meur, E.: Coupling of ice-shelf melting and buttressing is a key process in ice-sheets dynamics, *Geophysical Research Letters*, 37, n/a–n/a, doi:10.1029/2010GL043334, 2010.

- Gagliardini, O., Zwinger, T., Gillet-Chaulet, F., Durand, G., Favier, L., de Fleurian, B., Greve, R., Malinen, M., Martín, C., Råback, P., Ruokolainen, J., Sacchettini, M., Schäfer, M., Seddik, H., and Thies, J.: Capabilities and performance of Elmer/Ice, a new-generation ice sheet model, *Geoscientific Model Development*, 6, 1299–1318, doi:10.5194/gmd-6-1299-2013, 2013.
- Gladstone, R. M., Lee, V., Vieli, A., and Payne, A. J.: Grounding line migration in an adaptive mesh ice sheet model, *Journal of Geophysical Research: Earth Surface*, 115, doi:10.1029/2009JF001615, 2010.
- Gladstone, R. M., Lee, V., Rougier, J., Payne, A. J., Hellmer, H., Le Brocq, A., Shepherd, A., Edwards, T. L., Gregory, J., and Cornford, S. L.: Calibrated prediction of Pine Island Glacier retreat during the 21st and 22nd centuries with a coupled flowline model, *Earth and Planetary Science Letters*, 333–334, 191–199, doi:10.1016/j.epsl.2012.04.022, 2012.
- Gladstone, R. M., Warner, R. C., Galton-Fenzi, B. K., Gagliardini, O., Zwinger, T., and Greve, R.: Marine ice sheet model performance depends on basal sliding physics and sub-shelf melting, *The Cryosphere*, 11, 319–329, doi:10.5194/tc-11-319-2017, <https://www.the-cryosphere.net/11/319/2017/>, 2017.
- Gomez, N., Pollard, D., Mitrovica, J. X., Huybers, P., and Clark, P. U.: Evolution of a coupled marine ice sheet-sea level model, *Journal of Geophysical Research: Earth Surface*, 117, n/a–n/a, doi:10.1029/2011JF002128, <http://doi.wiley.com/10.1029/2011JF002128>, 2012.
- Gudmundsson, G. H.: Ice-shelf buttressing and the stability of marine ice sheets, *The Cryosphere*, 7, 647–655, doi:10.5194/tc-7-647-2013, 2013.
- Gudmundsson, G. H., Krug, J., Durand, G., Favier, L., and Gagliardini, O.: The stability of grounding lines on retrograde slopes, *The Cryosphere*, 6, 1497–1505, doi:10.5194/tc-6-1497-2012, 2012.
- Iken, A.: The effect of the subglacial water pressure on the sliding velocity of a glacier in an idealized numerical model., *Journal of Glaciology*, 27, 407–421, 1981.
- Joughin, I., Smith, B. E., and Holland, D. M.: Sensitivity of 21st century sea level to ocean-induced thinning of Pine Island Glacier, Antarctica, *Geophys. Res. Lett.*, 37, 1–5, doi:10.1029/2010GL044819, 2010.
- Katz, R. F. and Worster, M. G.: Stability of ice-sheet grounding lines, *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 466, 2010.
- Kingslake, J., Scherer, R., Albrecht, T., Coenen, J., Powell, R., Reese, R., Stansell, N., Tulaczyk, S., and Whitehouse, P.: Extensive Holocene ice sheet grounding line retreat and uplift-driven readvance in West Antarctica, In preparation, 2017.
- Leguy, G. R., Asay-Davis, X. S., and Lipscomb, W. H.: Parameterization of basal friction near grounding lines in a one-dimensional ice sheet model, *Cryosphere*, 8, 1239–1259, doi:10.5194/tc-8-1239-2014, 2014.
- Mercer, J. H.: West Antarctic ice sheet and CO<sub>2</sub> greenhouse effect: a threat of disaster, *Nature*, 271, 321–325, doi:10.1038/271321a0, <http://www.nature.com/doi/10.1038/271321a0>, 1978.
- Pattyn, F., Huyghe, A., De Brabander, S., and De Smedt, B.: Role of transition zones in marine ice sheet dynamics, *Journal of Geophysical Research*, 111, F02 004, doi:10.1029/2005JF000394, 2006.
- Pattyn, F., Schoof, C., Perichon, L., Hindmarsh, R. C. a., Bueler, E., De Fleurian, B., Durand, G., Gagliardini, O., Gladstone, R., Goldberg, D., Gudmundsson, G. H., Huybrechts, P., Lee, V., Nick, F. M., Payne, a. J., Pollard, D., Rybak, O., Saito, F., and Vieli, a.: Results of the marine ice sheet model intercomparison project, MISMIP, *Cryosphere*, 6, 573–588, doi:10.5194/tc-6-573-2012, 2012.
- Pattyn, F., Perichon, L., Durand, G., Favier, L., Gagliardini, O., Hindmarsh, R. C., Zwinger, T., Albrecht, T., Cornford, S., Docquier, D., Fürst, J. J., Goldberg, D., Gudmundsson, G. H., Humbert, A., Hütten, M., Huybrechts, P., Jouvét, G., Kleiner, T., Larour, E., Martin, D., Morlighem, M., Payne, A. J., Pollard, D., Rückamp, M., Rybak, O., Seroussi, H., Thoma, M., and Wilkens, N.: Grounding-line

- migration in plan-view marine ice-sheet models: results of the ice2sea MISMIP3d intercomparison, *Journal of Glaciology*, 59, 410–422, doi:10.3189/2013JoG12J129, 2013.
- Pattyn, F., Favier, L., Sun, S., and Durand, G.: Progress in Numerical Modeling of Antarctic Ice-Sheet Dynamics, *Curr. Clim. Chang. Reports*, 3, 174–184, doi:10.1007/s40641-017-0069-7, <http://link.springer.com/10.1007/s40641-017-0069-7>, 2017.
- 5 Schoof, C.: The effect of cavitation on glacier sliding, *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 461, 609–627, doi:10.1098/rspa.2004.1350, 2005.
- Schoof, C.: Ice sheet grounding line dynamics: Steady states, stability, and hysteresis, *Journal of Geophysical Research: Earth Surface*, 112, 1–19, doi:10.1029/2006JF000664, 2007a.
- Schoof, C.: Marine ice-sheet dynamics. Part 1. The case of rapid sliding, *Journal of Fluid Mechanics*, 573, 27, doi:10.1017/S0022112006003570, 2007b.
- 10 Tsai, V. C., Stewart, A. L., and Thompson, A. F.: Marine ice-sheet profiles and stability under Coulomb basal conditions, *Journal of Glaciology*, 61, doi:10.3189/2015JoG14J221, 2015.
- Vieli, A. and Payne, A. J.: Assessing the ability of numerical ice sheet models to simulate grounding line migration, *Journal of Geophysical Research: Earth Surface*, 110, doi:10.1029/2004JF000202, 2005.
- 15 Weertman, J.: On the sliding of glaciers, *Journal of Glaciology*, 3, 33–38, doi:10.1007/978-94-015-8705-1\_19, 1957.
- Weertman, J.: Stability of the junction of an ice sheet and an ice shelf, *Journal of Glaciology*, 13, 3–11, 1974.