Dear Editor,

We are very thankful for the reviewers' comments. We have revised the manuscript accordingly. We re-organized a couple of elements of our discussion, we added several points, we fixed typos and unclear sentences and we improved the figures. The results are essentially unchanged as well as the conclusions of the paper.

We hope you will find the paper acceptable for publication.

Respectfully,

Hongju Yu, on behalf of the co-authors

1 Response to Reviewer Stephen Cornford

Detailed below are our point-by-point responses to the comments of Reviewer Stephen Cornford. Reviewer's comments are printed in blue font followed by our responses in black.

This paper describes a set of ISSM ice sheet model simulations to the Thwaites Glacier. It plays to one of ISSMs notable strengths, namely its ability to be switched between the three suitable model types (in order of fidelity, 2d hydrostatic , 3d hydrostatic, and 3d non-hydrostatic 'full Stokes' models) for this sort of application. It shows that although the three model types result in some variation, that variation is smaller than the influence of differing treatments of friction at the ice bed interface. It also adds the general body of model results in Thwaites glacier, with projections that tend to confirm those of similar models. I think that the manuscript is in good shape, and could be published with only very minor revision.

General comments

I think the manuscript could more obviously distinguish between choice of physics and choices that affect numerical error. Two of the authors at least are very familiar with the issue of melt on partially floating cells, and I think that they have - correctly - concluded in recent work that it is a design error, rather than a straightforward choice. The text does acknowledge that the numerical error can be reduced arbitrarily, so I don't think this is a major issue.

Agreed. We re-organized our manuscript to better distinguish between choice of physics and choices that affect numerical error.

We added in the introduction that with a Weertman friction law, if we apply no melt on partially floating elements, the model is more robust to changes in mesh resolution. In contrast, it is difficult to conclude in the case of a Coulumb type friction law, as suggested in Seroussi and Morlighem (2018). See page 2, line 33 – page 3, line 2.

Specific comments (and corrections)

P1,L16 (and 19) : dischargers? An unusual word for this case. 'Outflow' or 'sink' might be a more conventional choice.

We changed 'dischargers' to 'outflow' on page 1, line 16 and 20.

P2, L13 'conditional' –> 'conditionally'

Done on page 2, line 14.

P2, L17 'we need numerical models'. I'm not sure that everyone agrees on 'need', but at any rate follow text supports the common use of numerical models rather than their proven utility.

We removed the sentence 'we need numerical models' and emphasized that several numerical studies have been conducted on Thwaites Glacier. See page 2, line 18.

P2, L24 'a transition in stress field' - I think something more specific is needed here about the type of transition, i.e from gravitational stress being balanced largely by local (in x,y) basal traction in the interior to being balanced by distant (in x,y) basal stresses via englacial viscous stresses.

We discussed in more detail the transition of stress field from being controlled by basal sliding and vertical shear on grounded ice to longitudinal stretching on floating ice. See page 2, line 25–27.

L2, L30 : Here is an example where physics and numeric could be more clearly seens as distinct.

We modified the manuscript to emphasize that we investigate the impact of both physics (stress balance model and friction law) and numerics (treatment of ice shelf melt in partially floating elements) on page 3, line 4–6.

P4, L11. Melt and Nomelt don't seem like a good choice af name to me. A lazy reader that look at the figures without reading the text, might think there was no sub-shelf melt in *the nomelt experiment. There is a Seroussi et al paper that talks about friction schemes (in hydrostatic models) that names schemes like NSEP, SEP1, and so on that are clear but don't mislead the lazy. The 'Melt' scheme sees like a melt version of SEP1 (If I recall correctly), so it could be SEMP1? And Nomelt becomes SEMP0?*

In the revision, we changed the name of our Melt and Nomelt experiment to NMP and SEM1. We added another set of experiments with a different implementation of ice shelf melt on partially floating elements named SEM2. The current naming convention follows Seroussi and Morlighem (2018).

L21: You should comment on the different behaviour of non-linear rules in the literature, it is especially important in the Joughin 2010 Pine Island Glacier paper, and others have commented too.

This is a good point. Previous studies have shown that the use of non-linear friction laws will help the signals in grounding line region propagate faster upstream and will lead to more grounding line retreat and mass loss. We added this discussion on page 4, line 29–31.

L23 'ensemble' –> 'combination' ?

Done on page 5, line 10.

L29 Dirichlett condition - I think here you have modelled only part of the catchment, so that you need observations rather than setting divide conditions $u \cdot n = 0$ etc. You just need to say why this is OK (because there is very little flux leaving the region along those boundaries)

We modeled the whole drainage basin of Thwaites Glacier. At the inflow boundary, we impose the observed velocity and we make sure that the velocity is tangential to the model domain ($u \cdot n = 0$) so that the ice flux across the boundary is zero. We modified the manuscript to make this clear on page 5, line 14–16.

P6, L9 '8 layers'. This seems a common choice for full stokes, but is it enough? How do you know?

Eight layers is about the maximum vertical layers we can have to ensure a high horizontal resolution near the grounding line and to keep the model numerically affordable. The vertical layers are denser at the base so that the region closer to bed is better resolved. We have run the MISMIP3d and MISMIP+ experiments before to find that 8 layers produces results in good agreement with models using more vertical layers. See page 6, line 18–page 7, line 2.

L11 'conduct an inversion of' –> 'solve a typical inverse problem to estimate'

Done on page 7, line 4.

L14 'relax the model' –> 'relax the geometry'?

Done on page 7, line 9.

Fig 3 : Odd units in the top row. Why the $\hat{}(-\frac{1}{2})$*?*

Apologies, the unit was wrong. The figure showed the square root of the basal friction coefficient. We updated Fig. 3 to show the basal friction coefficient with the correct unit.

P11, L6: This paragraph is about mathematical issues o not a numerical issue, since it would occur even in (no-existent but still imaginable) analytic solutions. I think this whole subsection needs a rewrite; it mixes up physics, mathematics, and computation performance, sometimes within a paragraph e.g L14

Agreed. We re-organized this subsection to make the discussion clearer. We changed 'numerical' to 'mathematical' and we separated the discussion into physics, mathematics and computational performance.

P. L20; This is a numerical issue, but is preceded by a choice of physics (SSA/HO/FS) then is followed by a choice of physics (friction rule). Perhaps re-order?

Agreed. We re-ordered our discussion. Now we discuss the impact of stress balance model first, followed by the friction law, and then the implementation of ice shelf melt.

P12, L1 'friction is reduced with the Budd friction law' : Because $C_w = C_b N$ *in the first instance, so your* C_b *has to be much lower inland where* N *is large in the initial state. That might work out differently if our knowledge of* N *was poor (e.g due to hydrology)*

In the revision, we noted that our knowledge of N was poor and may lead to estimation errors in the interior. See page 12, line 28–29.

L10. Though the extra parameter, f in Tsai 2015 is O(1) rather than being able to take on any value.

Yes, the parameter f is an O(1) parameter and is often taken as 0.5. However, the exact value of f may vary for different glaciers and different parts of the same glacier. An inversion of f within a certain range could provide a better match to our observations, but we think that this is beyond the scope of our study.

L27: 'TG is retrograde' - and, the channel widens too.

Done on page 14, line 3.

2 Response to Reviewer Lionel Favier

General comments

This study from Yu and his colleagues aims at simulating the future of Thwaites Glacier in West Antarctica, over the next century. They use the ISSM ice-sheet model in its full-Stokes (FS), Shallow Shelf Approximation (SSA) and Higher Order (HO) versions, applying two kinds of basal friction laws (either based on effective pressure, using the Budd law, or not, using the linear Weertman law), two different grounding line parameterizations and various sub-shelf melting depth-dependent functions. This represents 12 familys of simulations, each of which forced by 8 different melt parameterizations.

Almost all the simulations show a similar retreating pattern, which I think is consistent, that the soon future Thwaites Glacier will be much thinner and that its grounding line will be much farther inland, especially its Eastern part. The Thwaites Glacier has been the focus of quite a lot of attention during the last couple of years, but I think this study adds novelty in this field of research. The results are in line with past studies, such as (Joughin et al., 2014).

The paper reads quite well, which is a pleasure, and is mostly well organised, which is even more a pleasure. A significant number of simulations was ran and I dont think it has been easy to organise the results this way.

I have two or three main concerns about the paper, which are not to be considered as major, but to which I would like the authors to respond. This consists other simulations and a point to add to the discussion.

As you say, your 80_1000 melt scenario is representative of a cold year melt scenario, and was calibrated to match ice/ocean coupled simulations from (Seroussi et al., 2017). What I am concerned about here is the fact, which was also a conclusion from the (Seroussi et al., 2017) paper, that this type of sub-shelf parameterization leads to higher ice mass loss, compared to the coupled model. Thus, I would recommend to run another set of simulations in which the melt would be halved (for instance, could be a 40_1000 scenario), or at least significantly decreased so your study would consider the fact that the ice-sheet response to this type of parameterization is overestimated.

In response to your comment, we performed a new set of simulations with our model under a 40_1000 ice shelf melt scenario, with a total of 16 simulations, to establish a lower limit. The results show less retreat and less mass loss compared to the higher melt scenarios, but the reduction is not large. We modified Fig. 2, Fig. 5 and our discussion accordingly to include these new experiments.

My second concern is the proximity of the Pine Island Glacier (PIG) nearby. In all the simulations, the West part that is retreating is touching the PIG drainage basin, and I wonder the implications related to the change in boundary conditions. The (Brondex et al., 2018) paper now in TCD seems to show a prior retreat from a nearby PIG tributary, of which the floating part eventually links to the floating part of TG. I would like this point to be included somewhere in the discussion.

This is a good point. There is a subglacial trough between the second and third eastern subglacial ridges that are discussed in the manuscript. If the grounding line of TG were to retreat into these regions (in the SEM experiments with high melt), it would connect with the grounding line of Pine Island Glacier and the two drainage basins would merge. To investigate the impact of this merge on the flow field and mass loss, we would need to run simulations of the entire Amundsen Sea Embayment, as in Brondex et al. (2018), but this is beyond the scope of our study. We noted this comment in the discussion on page 13, line 29–33.

Finally, a number of grounding line discretizations have been explored by your team ((Seroussi et al., 2014), (Seroussi and Morlighem, 2018)). If I understood well you used the so-called NMP in the (Seroussi and Morlighem, 2018) paper, in which you don't apply melt to partially floating elements and the so-called SEM1 discretization in which you also apply melt to the element in which lies the grounding line, but in proportion to the floating area of this element. I would be in favor of running another set of simulations considering the SEM2 grounding line discretization (or the SEM1 if I was wrong and misunderstood the fact that you used the SEM2...), since I don't think one can discard one parameterization or another on the basis of ideal simulations only (Seroussi and Morlighem, 2018). I don't think this is a big deal for you to do so.

In the original manuscript, we used the SEM1 implementation of melt for partially floating elements. In response to your comment, we performed another set of experiments for our SSA and HO experiments with the SEM2 implementation. The results are similar compared to SEM1, which is consistent with the findings in Seroussi and Morlighem (2018). For FS, every vertex in the mesh is masked by either 1 (grounded) or -1 (floating) and the actual grounding line position within the partially floating elements is not known, so it does not make sense to run FS with the SEM2 implementation. In total, we added another 28 simulations. We updated Fig. 4, Fig. 5 and our discussion accordingly.

The rest of my review is a series of specific comments.

Specific comments

Page 2, l25 to l28: Here, I understand that the ice mass loss is more sensitive to the use of different friction laws, or melt treatment close to the grounding line, but only when the *stress balance is approximated (HO or SSA) but not when full-Stokes is used? I dont think this is what you wanted to say, since you have an impact of friction laws onto full Stokes modelling as well. Could you rephrase or explain.*

We re-wrote the sentence to make it clear that ice mass loss is sensitive to the friction law and the melt treatment, regardless of what stress balance model we use. See page 2, line 30–31.

Page 2, l33: In regards to the simplicity of your melt parameterization, the use of the word "realistic" is far from being fair. Could you rephrase.

We removed the word "realistic" and rephrased the sentence. See page 3, line 6–7.

Page 3, Fig.1: For consistency and clarity of the figure, in a) could you add the other grounding lines. For b) could you do the same and also add the front of all the glaciers.

We added the grounding line position for all glaciers in both a) and b) of Fig. 1. We also added the name of glaciers in a) and the ice front positions in b).

Page 3, l9: Could you add those sensitivity tests as a Supplementary figure.

We added a figure showing the sensitivity experiment with the thermal regime in the appendix as Fig. A1a.

Page 4, l6 to l11: Here, you should refer to (Seroussi et al., 2014) and (Seroussi and Morlighem, 2018) and mention the discretizations name that you used as defined in those two papers. This would clarify if you used SEM1 or SEM2 grounding line discretization, which is not completely clear to me.

Agreed. As noted above, we added 28 simulations with the SEM2 ice shelf melt implementation.

Page 4, l19: For clarity, could you define the effective pressure.

We added the definition of the effective pressure at page 4, line 25.

Page 5, l5: Could you refer to my first main comment above.

As mentioned in the response to the first main comment, we added 16 new simulations with a 40_1000 ice shelf melt scenario to establish a lower limit case of warm water intrusion.

Page 6, l14: I wouldnt only blame the datasets for this change in velocities after inversion. I would say that the model is not perfect as well, and that the model parameters can induce part of those initial changes (Gillet-Chaulet et al., 2012). Could you rephrase.

We noted that the large velocity change at the beginning of transient simulations is also due to the inversion itself since it cannot fully account for the mismatch between model and observation. See page 7, line 6–8.

Page 6, l30: Here, I would like a little explanation about why is the ice stiffer at the grounding line, or softer much higher up inland (different stress regimes, this is discussed in (Ma et al., 2010).

The ice is stiffer at the grounding line due to the advection of colder ice from upstream, the change of stress regimes and the removal of warmer, softer ice at the bottom of the ice shelf. The ice is softer at the junction between the eastern ice shelf and the main trunk because of marginal softening. In the relaxation process, ice thickness changes. In the following inversion process, ice would become stiffer in the region where ice thickness increases (the grounding line region in our case). See page 7, line 24–26.

Page 6, Fig. 3: Could you draw the grounding line position in those maps.

We added the grounding line position in every panel of Fig. 3.

Page 10, Fig. 5: For clarity reasons, I would be in favor of using different maximums for the vertical axis so one could distinguish the differences within each type of friction law and implementations of the ice-shelf melt (like VAFmax=40 for the two Budds and VAFmax=25 for the other Budds)

We changed the scale for the vertical axis in Fig. 5. Now each type of ice shelf melt implementation has one maximum value along the y-axis.

Page 11, l31: Could you add those results in a supplementary figure.

We added a figure showing the results of our sensitivity tests on mesh resolution with different ice shelf melt implementation in the appendix as Fig. A1b.

Page 12, l10: There is a law that you didn't discussed, the so-called Schoof law that is used in (Brondex et al., 2018) and (Brondex et al., 2017). I would strongly recommend it to appear in the paper as it has strong physical basis.

Agreed. We included both the Schoof's law and Tsai's law in our discussion by introducing their main characteristics and recent numerical results. See page 12, line 30–34.

Page 12, l18: I would like to see those ridges you talk about shown in the figures (for instance Fig. 1)

We added four gray boxes in Fig. 1b to show the positions of the four subglacial ridges (three in the east and one in the west).

Page 13, l16 to l21: your sub-shelf melting is a major limitation of your study, not just one limitation. For instance, the difference in grounding line position between the coupled model and parameterized simulations in the study from (Seroussi et al., 2017) is significant. Could you discuss and insist a bit more on that point please. Also, I would recommend to add another set of simulations with even less melt in order to compensate for the overestimation of mass loss related to this type of parameterizations (see my comment at the top).

We modified our manuscript to emphasize that our melt rate parameterization is over simplified and that a coupled ice-ocean model would be necessary to simulate TG more realistically. See page 14, line 26–33. We did add a new set of experiments with low melt in the manuscript, as discussed above.

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Retreat of Thwaites Glacier, West Antarctica, over the next 100 years using various ice flow models, ice shelf melt scenarios and basal friction laws

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Abstract. Thwaites Glacier (TG), West Antarctica, experiences rapid, potentially irreversible grounding line retreat and mass loss in response to enhanced ice shelf melting. ~~Several numerical models of TG have been developed recently, showing~~ Results from recent numerical models suggest a large spread ~~in~~ on the evolution of the glacier in the coming decades to a century. It is ~~, however, not clear how different~~ therefore important to investigate how different approximations of the ice stress balance, parameterizations of basal friction, and ice shelf melt ~~or different approximations in ice stress balance~~ parameterizations may affect projections. Here, we simulate the evolution of TG using ~~different ice shelf melt, basal friction laws and ice~~ ice sheet models of varying levels of complexity~~to quantify the effect of these model configurations on the results~~, different basal friction laws and ice shelf melt to quantify their effect on the projections. We find that the grounding line retreat and its sensitivity to ~~ocean forcing~~ ice shelf melt is enhanced when a full-Stokes model is used, a Budd friction is used, and ice shelf melt is applied on partially floating elements~~, and a Budd friction is used~~. Initial conditions also impact the model results. Yet, all simulations suggest a rapid, sustained retreat of the glacier along the same preferred pathway. The ~~highest~~ fastest retreat rate occurs on the eastern side of the glacier and the ~~lowest rate on~~ slowest retreat occurs across a subglacial ridge on the western side. All the simulations indicate that TG will undergo an accelerated retreat once ~~it~~ the glacier retreats past the western subglacial ridge. Combining ~~the results~~all the simulations, we find ~~the uncertainty~~ that the uncertainty of the projections is small in the first 30 years, with a cumulative contribution to sea level rise of 5 mm, similar to the current rate. After 30 years, the ~~mass loss~~ contribution to seal level depends on the model configurations, with ~~a~~ differences up to 300% ~~difference~~ over the next 100 years, ranging from 14 to 42 mm.

1 Introduction

Thwaites Glacier (TG), located in the Amundsen Sea Embayment (ASE) sector of West Antarctica, is one of the largest ~~ice dischargers in Antarctica, with a~~ outflow of ice in Antarctica. It has the potential to raise global mean sea level by ~~59 cm, and~~ 0.6 m and it is one of the largest contributors to the mass loss from Antarctica (Holt et al., 2006; Mouginot et al., 2014). With a maximum speed over 4,000 m/yr and a width of ~~nearly~~ 120 km (Fig. 1a), the glacier discharged 126 Gt of ice into the ocean in 2014 (Mouginot et al., 2014), ~~nearly~~ or three times as much as Jakobshavn Isbrae, the largest ~~discharger~~ outflow of ice in Greenland (Howat et al., 2011). Over the past decade, the rate of mass loss of TG has increased from 28 Gt/yr in 2006 to 50 Gt/yr in 2014 (Medley et al., 2014; Mouginot et al., 2014; Rignot, 2008). The grounding line of TG has retreated by 14 km from 1992 to 2011 along ~~its fast flowing~~ the fast-flowing main trunk (Rignot et al., 2014). The surface has thinned at a rate of ~~about~~ 4 m/yr near the grounding line and more than 1 m/yr ~~about~~ up to 100 km inland (Pritchard et al., 2009). The rate of change in mass loss increased from 2.7 Gt/yr^2 in 1978-2014 to 3.2 Gt/yr^2 in 1992-2014, and 5.6 Gt/yr^2 in 2002-2014 (Mouginot et al., 2014). If these rates of acceleration in mass loss were to maintain over the coming decades, they would raise global sea level by, respectively, 41, 48 and 81 mm by 2100.

The rapid mass loss and grounding line retreat of TG have been attributed to an increase in ice shelf melt rate induced by warmer ocean conditions (Rignot, 2001; Joughin et al., 2014; Seroussi et al., 2017). The strengthening of westerlies around the Antarctic continent over the past decades has ~~caused~~ forced more warm, salty Circumpolar Deep Water (CDW) to intrude onto the continental shelf, flow along troughs in the sea floor, reach the sub-ice-shelf cavities and glacier grounding lines, and melt them from below (Schneider and Steig, 2008; Spence et al., 2014; Dutrieux et al., 2014; Li et al., 2015; Scambos et al., 2017). An increase in ice shelf melt rate thins the ice shelves ~~,~~ and reduces the buttressing they provide to the grounded ice, ~~and~~ which triggers glacier speed up, ~~yielding further thinning and retreat of the glaciers~~ thins the glacier and leads to further retreat (Schoof, 2007; Goldberg et al., 2009).

For a marine-terminating glacier, bed topography ~~also~~ plays a crucial role in controlling the grounding line stability. According to the marine ice sheet instability (MISI) theory, in 2D, a grounding line position is stable when sitting on a prograde bed, i.e., a bed elevation that increases in the inland direction, and unstable when sitting on a retrograde bed (Weertman, 1974). In 3D, glaciers on retrograde bed are ~~conditional~~ conditionally stable due to the buttressing from ice shelves and lateral drag (Gudmundsson et al., 2012). The grounding line of the central trunk of TG is currently sitting on a subglacial ridge on the western part of the glacier. Upstream of the ridge, the bed is mostly retrograde until the ice divide (Fig. 1b), which indicates limited stability to changes (Hughes, 1981; Rignot et al., 2014; Joughin et al., 2014).

~~To assess the future of TG , we need numerical models. Based on prior studies ,~~ Many studies have investigated the evolution of TG with numerical ice sheet models. All of these studies conclude that TG will experience continuous and rapid retreat, ~~however,~~ but the timing and extent of the ~~projected retreat varies~~ retreat vary significantly between models (Parizek et al., 2013; Joughin et al., 2014; Feldmann and Levermann, 2015; Seroussi et al., 2017; Rignot et al., 2014; Cornford et al., 2015). One important factor explaining the differences between the models is that they employ different model configurations and ocean ~~forcings, so~~ thermal forcings, hence it is not clear which model best captures the future behavior of TG. To simulate the evolution of TG, it is important to model the grounding line migration accurately. The grounding line position is key to the stability of marine-terminating glaciers, but it is difficult to model numerically because ~~the sharp transition~~ of the transition in stress regime from grounded ice to floating ice ~~involves a transition in stress field~~ (Vieli and Payne, 2005; Nowicki and Wingham, 2008; Favier et al., 2012). Upstream of the grounding line, ice flow is mostly controlled by basal sliding and vertical shear stress. Downstream of the grounding line, ice flow is mostly controlled by longitudinal stretching and lateral shear. A full-Stokes (FS) model is required in this transition region to ~~capture the complete~~ fully capture the ice physics (Durand et al., 2009; Morlighem et al., 2010). Most prior ice sheet models applied to TG, however, used simplified physics (Seroussi et al., 2017; Joughin et al., 2014). ~~In that context, the~~

Apart from the stress balance model, the choice of friction law and the treatment of ice shelf melt near the grounding line ~~and the choice of the friction law may~~ may also have a significant impact on the rate of grounding line retreat and glacier mass loss ~~(Seroussi et al., 2014; Golledge et al., 2015; Arthern and Williams, 2017; Brondex et al., 2017).~~ (Seroussi et al., 2014; Golledge et al., 201 Brondex et al. (2017) showed that a Weertman type friction law systematically produces less retreat than a Coulomb type friction law, which produces less retreat than a Budd type friction law. Seroussi and Morlighem (2018) found that if a Weertman type friction law is used, a model with no ice shelf melt applied on partially floating elements is more robust to mesh resolution than a model that applies ice shelf melt on partially floating elements, for which a fine resolution is necessary to correctly capture the retreat. If a Coulomb type friction law is used, however, it is unclear which approach is more robust.

In this study, we simulate the dynamics and evolution of TG ~~for~~ over the next 100 years using the Ice Sheet System Model (ISSM) (Larour et al., 2012). To investigate the impact of different ~~configurations, we apply~~ physical approximations and numerical implementations, we employ three different stress balance models (FS~~and two approximations~~, Higher-Order and Shelfy-Stream Approximation), two ~~treatments~~ friction laws and three implementations of ice shelf melt near the grounding line~~, and two friction laws. For each of these twelve~~ . With a total of sixteen models, we employ ~~six~~ seven different ice shelf melt scenarios parameterized to match prior ocean model results and satellite observations ~~and to encompass a realistic regime of~~ to encompass ice shelf melt ranging from cold conditions with ~~low~~ limited access of CDW to the glacier to warm conditions with enhanced access of CDW to the glacier. We compare the results from the different ~~models~~ simulations and conclude on the range of evolution of TG over the coming century~~based on the model results~~.

2 Data and methods

2.1 Data

We conduct numerical simulations of the ice flow of TG over its entire drainage basin (Fig. 1). We use BEDMAP-2 data for ice surface elevation and ice shelf draft elevation (Fretwell et al., 2013), ~~the~~ a bed elevation from mass conservation on grounded ice (Morlighem et al., 2011, 2013) and ~~the~~ a sea floor bathymetry from a gravity inversion ~~beneath floating ice~~ (Millan et al., 2017). We use the surface temperature field from the regional atmospheric climate model RACMO2.3 (Lenaerts and van den Broeke, 2012) and the geothermal heat flux from Shapiro and Ritzwoller (2004) to compute the steady state ~~temperature field~~ thermal regime of TG (Seroussi et al., 2017). Previous studies have shown that the uncertainty in the thermal regime does not have a major impact on the evolution of ~~glaciers within~~ the glaciers over a time scale of one century (Seroussi et al., 2013). ~~We performed some~~ Here, we performed sensitivity tests (~~not shown here)and the model volume was~~ Fig.A1a), showing that the ice volume remains within 3% of the original run at the end of the simulations if we change the ice thermal regime. We therefore keep the thermal regime constant~~here~~. The surface mass balance is from RACMO 2.3 (Lenaerts and van den Broeke, 2012). The initial ice surface velocity (Fig. 1a) is derived from interferometric synthetic aperture radar data for the year ~~2008~~ 2007–2008 (Rignot et al., 2011b).

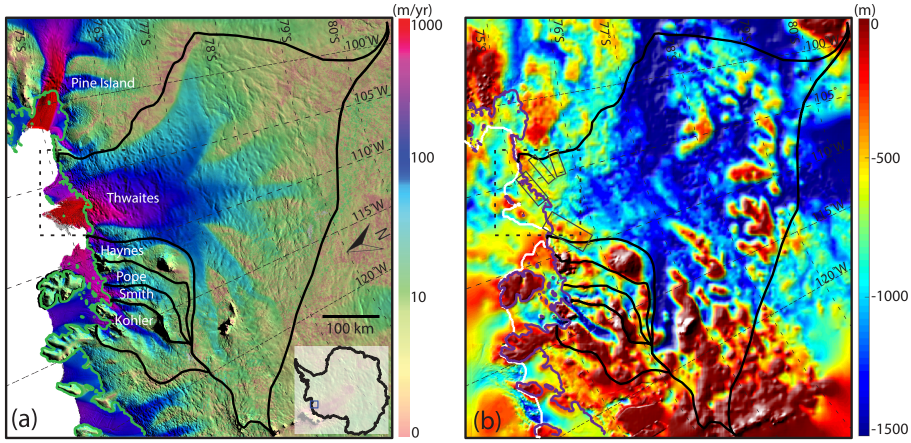

Figure 1. (a) Surface velocity of Thwaites Glacier, West Antarctica, derived from satellite radar interferometry (Rignot et al., 2011b). (b) Bed elevation of Thwaites Glacier and surrounding sea floor (Morlighem et al., 2011; Millan et al., 2017). The green line in (a) and ~~red~~ purple line in (b) are the grounding line positions of all the glaciers in ~~2011~~ the region (Rignot et al., 2011a). The black ~~contour is~~ contours are the boundaries of the drainage ~~basin~~basins. The white line in b) is the ice front position. The black dashed box in (a) is the region shown in Fig 4. The gray boxes in (b) denote four subglacial ridges near the current grounding line of TG.

2.2 Ice flow models

Stress balance models. To solve the stress balance ~~of ice flow without approximationin the stress field~~equations without approximation, we use a full-Stokes (FS) model. ~~In addition, we~~ We also use two widely-used simplified models: 1) the Higher Order (HO) model, which assumes that the horizontal gradient of the vertical velocity and the bridging effect are negligible (Blatter, 1995; Pattyn, 2003); and 2) the Shelfy-Stream Approximation (SSA) model, which is a 2D depth-averaged model, with the additional assumption that vertical shear is negligible (Morland, 1987; MacAyeal, 1989). The criterion for grounding line migration differs among ~~these~~ the models. In FS, the grounding line migration is treated as a contact problem. The grounding line retreats if the normal stress at the base of the ice is smaller than the water pressure at the base. Conversely, the grounding line advances if the ice bottom tries to extend below the bed (Durand et al., 2009; Yu et al., 2017). In ~~contrast, in~~ HO and SSA, the grounding line position is computed solely ~~from~~ based on hydrostatic equilibrium (Seroussi et al., 2014).

~~During the simulation, the position of the grounding line lies within the elements of the mesh. Numerical models implement ice shelf melt in these partially floating elements differently. Some models apply melt in proportion to the floating area fraction of each element, while some models only apply melt to fully floating elements. In our simulations, we quantify the difference between these two types of implementations by running both of them. We refer these two sets of experiments as Melt and Nomelt in the remainder of this paper.~~

Friction laws. We employ and compare two different friction laws. The first one is a Weertman friction law (Weertman, 1957):

$$\boldsymbol{\tau_b} = -C_w|\boldsymbol{v}_b|^{m-1}\boldsymbol{v}_b \quad (1)$$

where $\boldsymbol{\tau_b}$ is the basal drag, $\boldsymbol{v}_b$ is basal velocity and C_w is the friction coefficient. The second one is a Budd friction law (Budd et al., 1979):

$$\boldsymbol{\tau_b} = -C_bN|\boldsymbol{v}_b|^{m-1}\boldsymbol{v}_b$$

$$\boldsymbol{\tau_b} = -C_bN|\boldsymbol{v}_b|^{m-1}\boldsymbol{v}_b \quad (2)$$

$$N = \rho_i gH + \rho_w gb \quad (3)$$

where N is the effective pressure at the ice baseand , C_b is the friction coefficient, ρ_i and ρ_w are the density of ice and water, respectively, g is the gravitational acceleration, H is the ice thickness and b is the ice bottom elevation. Weertman (1957) proposed an exponent of $m = 1/3$. Here, we use a linearized version with $m = 1$ to focus on the impact of the effective pressure. However, The use of non-linear friction lawscould lead to different model behaviors. These , however, leads to faster and further inland propagation of changes in the grounding line region and tends to increase overall retreat and mass loss (Joughin et al., 2010a; Ritz et al., 2015; Gillet-Chaulet et al., 2016). We refer to these two sets of experiments are referred to as Weertman and Budd experiments.

The ensemble **Ice shelf melt treatment near grounding line.** During the simulation, the grounding line position lies within mesh elements. Numerical models implement ice shelf melt in these partially floating elements differently. Some models apply melt in proportion to the floating area fraction of each element, while others only apply melt to fully floating elements. In our simulations, we use three types of implementations, named NMP, SEM1, and SEM2, following Seroussi and Morlighem (2018) to quantify their impact on the rate of retreat. In the NMP experiments, no melt is applied to partially floating elements. In SEM1, melt is applied to the partially floating elements in proportion to their fraction of floating area. In SEM2, the melt is applied only on the floating part of the element. For FS, only NMP and SEM1 are run because the grounding line position is not derived from hydrostatic equilibrium (i.e. using a subelement scheme) and the grounding line therefore does not retreat continuously.

The combination of stress balance models, basal friction laws and ice shelf melt implementations , and friction laws lead to 12 leads to 16 different sets of experimentssimulations.

Boundary conditions. The boundary conditions are the same for in all experiments apart from the friction law. A stress free surface is applied at the ice-atmosphere interface. At the ice-ocean interface, water pressure is applied. Along the other boundaries of the model domain, Dirichlet conditions are applied to ensure that ice velocity equals the observed velocity and the direction of ice velocity is tangential to the boundary. The calving front position is kept constant throughout our simulations~~.~~, i.e. the ice shelf front is not retreating and an ice shelf is always present.

2.3 Ice shelf melt scenarios

To simulate the response of TG to enhanced ice shelf melting, we run the model with ~~six~~ seven different ice shelf melt scenarios (Fig. 2). In all scenarios, the ice shelf melt rate is parameterized as a function of ice shelf basal elevation and is set to ~~0~~ zero above 150 m depth. In the first scenario, the ice shelf melt rate linearly increases to a maximum of 80 m/yr at 1000 m depth. Below 1000 m depth, the ice shelf melt rate is kept constant at 80 m/yr. This scenario originates from ~~simulations using~~ the coupled ISSM/MITgcm ice-ocean model for year 1992 (Seroussi et al., 2017). Year 1992 was a cold year with a low ice shelf melt rate in ASE compared to the average melt rate over the past 30 years (Schodlok et al., 2012), which makes this scenario representative of ~~relatively~~ cold ocean conditions. ~~With~~ Using this parameterization, the mass loss from ice shelf melt for TG is 73.7 Gt/yr at the beginning of the simulation~~. This value is~~ , close to the estimated ice shelf melt of 69 Gt/yr from Depoorter et al. (2013) and 24% less than the 97.5 Gt/yr for the years 2003-2008 in Rignot et al. (2013) .

In the other ~~five~~ six scenarios, we change the maximum ice shelf melt rate and the depth ~~where~~ at which the maximum melt occurs. To constrain the range of ice shelf melt rates, we calculate the ice shelf melt rate with mass conservation as in (Rignot et al., 2013) using the 2008 velocity, ice shelf thickness from BEDMAP-2, and the bathymetry of ASE to find a maximum ice shelf melt rate ~~at~~ of 125 m/yr, or 50% larger than the ~~first~~ 1992 scenario. In 2007, which was a warm year, the nearby Pine Island Glacier experienced ∼50 % more melt compared to 1992 (Schodlok et al., 2012). Therefore, in the second scenario, we increase the maximum ice shelf melt rate by 50 % to 120 m/yr to represent warm ocean conditions. Jacobs et al. (2012) showed that in 2007, the thermal forcing, which is the difference between the *in-situ* ocean temperature and the *in-situ* freezing point of seawater, exceeded +4°C at the ice front of TG, which implied almost undiluted CDW. This indicates that the potential ~~of further~~ increase in ice shelf melt rate is limited unless CDW outside the continental shelf would also warm up. Therefore, in the third scenario, we ~~choose to~~ increase the maximum ice shelf melt rate by another 40 m/yr to 160 m/yr to represent ~~extreme warmth~~near maximum ocean thermal forcing. We also vary the depth at which the ice shelf melt rate reaches its maximum. Ocean observations show that the bottom of the thermocline has been relatively constant at 700 m depth in the past two decades ~~in ASE~~ (Dutrieux et al., 2014). Accordingly, we run three additional ice shelf melt scenarios with the maximum ice shelf melt rate (80 m/yr, 120 m/yr, 160 m/yr) occurs below 700 m instead of 1000 m (Fig. 2). Seroussi et al. (2017) showed that it takes more time for warm water to intrude into newly ungrounded cavity with a coupled ice-ocean model. Their results indicate that the melt rate close to the grounding line could be reduced to 40 m/yr as it retreats inland. Therefore, we add a 7th experiment, Exp. 40_1000, to represent near minimal thermal forcing.

~~Overall~~In total, we run ~~a total of 72 simulations(6~~ 112 simulations: 7 ice shelf melt scenarios ~~by 12 models)~~for 16 models. We name our simulations from the combination of ~~their~~ ice shelf melt scenario, stress balance equation, ice shelf melt treatment, and friction law. For instance, Exp. 80_1000_FS_~~Nomelt_Budd~~Budd_NMP represents the experiment conducted with a maximum of 80 m/yr ice shelf melt rate below 1000 m depth, FS stress balance model, ice shelf melt only applied to fully floating elements, and a Budd friction law.

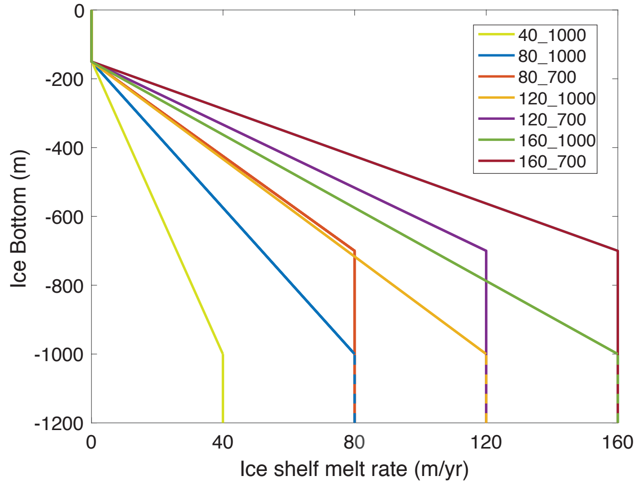

Figure 2. Ice shelf melt rate parameterization of for the six seven ocean thermal forcing scenarios.

2.4 Initial model setup

The mesh is constructed using an anisotropic metric based on ice surface velocity and distance to the grounding line , and comprises over the entire drainage basin of TG. The horizontal mesh spacing is 300 m in the grounding line region, progressively increasing to 10 km in the interior of the ice sheet. Vertically, the domain is divided into 8 vertical layers that are denser at the bottom. This is the maximum number of layers that we can have to ensure a high horizontal resolution and to keep the model numerically affordable. We validated the number of layers by running the MISMIP3d and MISMIP+ experiments and found that the results did not change significantly when using 8 or more layers and were in agreement with other models (Pattyn et al., 2013; Asay-Davis et al., 2016). In total, our mesh includes 561,799 triangular prismatic elements.

In order to To relax the model while maintaining a good fit with surface observations, we adopt the following procedure. We first conduct an inversion of solve an inverse problem to estimate the basal friction coefficient over the grounded ice and of the ice viscosity parameter over the floating ice to best match the modeled surface velocity with the observed surface velocity (Morlighem et al., 2010). After the inversion, we find a rapid change in ice velocity of a few 100 m/yr at the grounding line in transient simulationsdue to inconsistencies between datasets (Seroussi et al., 2011). We attribute this adjustment to the fact that the datasets are not consistent and the inversion does not produce an exact fit of the observed velocity (Seroussi et al., 2011; Gillet-Chaulet et al., 2012). To avoid this problem, we run the model for 0.5 yr to relax the model and perform a second geometry and then perform a new inversion. We repeat this procedure 4 times until we reach a stable solutionconfiguration. After these iterative steps, the modeled velocity is consistent with remains within 50 m/yr of the observations at the beginning of transient simulations , within 50 m/yr (Fig. 3). Note that the inversions We note that the inversion for ice viscosity parameter and basal friction are conducted independently for the three ice flow models so that each model has its own, self-consistent initial set up. The inversions are conducted with using the Weertman friction law. For the

Budd friction law, the friction coefficient is computed directly through $C_b = C_w/N$ to ensure the same initial basal conditions for the two sets of experiments.

FS is more sensitive to mesh resolution than HO and SSA~~and~~ , hence requires a higher mesh resolution in the interior than other models ~~in order~~ to converge. To avoid the computational cost of a high resolution FS modeling over the entire drainage basin, we use a tiling method to apply FS within 150 km of the grounding line and HO in the interior (Seroussi et al., 2012). In this manner, we insure that the FS model is computationally efficient, the results are reliable, and the regions where the grounding line retreats are effectively modeled using FS.

3 Results

Inversion. The inversion results are shown in Fig. 3. The pattern of basal friction is the same ~~for~~ in all models, with high friction near the ice divide and low friction in the deep basin. SSA needs a smaller friction coefficient than HO and FS to match the observed velocity because of the neglected vertical shear. The inferred ice viscosity parameter over floating ice is also similar for the three models~~with stiff ice~~ . Stiff ice is found near the grounding line ~~and soft ice~~ due to the advection of cold ice from upstream, the change of stress regime, and the removal of warmer and softer ice by ice shelf melt. Soft ice is found at the junction between the eastern ice shelf and the main trunk~~.~~ , resulting from marginal softening (Larour, 2005; Khazendar et al., 2009; Ma et al., 2010). During the relaxation period, the ice adjusts to become stiffer at the regions where ice thickness increases, in the grounding line region in our case. After the inversion, the mismatch between modeled and observed surface velocity is small, ~~i.e.~~ within 200 m/yr in the fast moving region and ~~within~~ 30 m/yr for HO and SSA in the interior. For FS, the difference is large in the interior, ~~about~~ up to 100 m/yr due to the tiling method, but this difference has limited impact on our results ~~since~~ because it takes place far from the grounding line region (>100 km) ~~and the changes in that region~~ where changes are relatively small.

Grounding line retreat and mass loss. In transient simulations, the results display a consistent, general pattern of retreat, with different ~~magnitude~~ magnitudes of mass loss and rates of grounding line retreat. Overall, the grounding line retreats faster on the eastern side of the glacier and tends to remain more stable on the western side. A sustained mass loss is obtained for all simulations.

The evolution of the grounding line positions for all ~~12~~ 16 models with the ~~lowest (~~80_1000 ~~) and highest ice shelf melt (~~and 160_700 ~~)~~ melt rate scenarios are shown in Fig. 4. The grounding line retreat shows distinct features on the eastern and western sides due to bed topography ~~.~~ (Fig. 1b). On the eastern side, the grounding line retreats continuously in all experiments for 30-65 km. The main difference among the simulations is whether and when the grounding line retreats ~~over~~ past the subglacial ridge 35 km upstream of its present location. On the western side, the grounding line is stable with only small retreat in all cases except for the ~~Melt experiments in~~ SEM experiments with high ice shelf melt~~scenarios. However, once~~ . Once the grounding line starts to retreat in the west, however, it retreats rapidly at more than 1 km/yr. The changes in grounded area are consistent

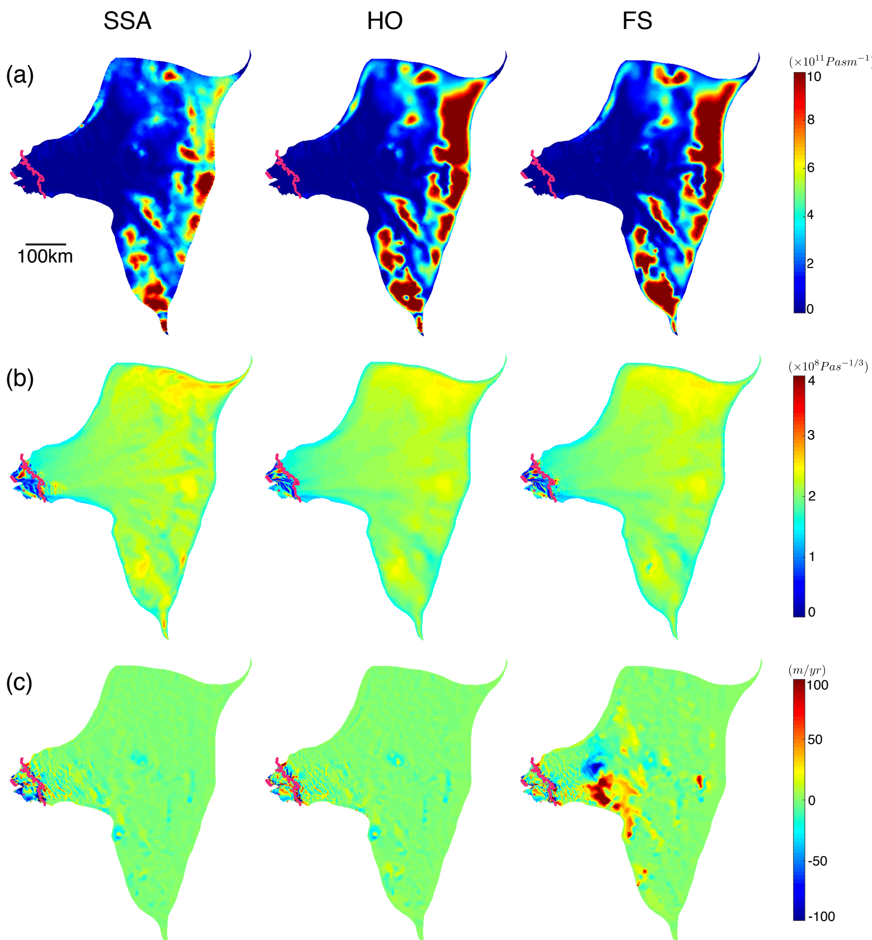

Figure 3. Inversion results. a) Basal friction coefficient inferred for SSA (left column), HO (middle column) and FS (right column) models. b) Depth-average ice viscosity parameter for the three models, combined with thermal model output over grounded ice and inversion results over floating ice. c) Difference between modeled and observed surface velocity for the three models. The pink lines in each panel are grounding line positions.

with the rate of grounding line migration (Fig. 5), i.e., ~~limited change~~ we project slow changes when the grounding line sits on a subglacial ridge and faster ~~change~~ changes when the grounding line retreats along the retrograde or flat part of the bed.

The mass loss is significant and rapid in all simulations (Fig. 5). The loss in volume above flotation (VAF) is ~~closer to linear than grounded area loss due to~~ almost linear compared to the loss in grounded area because of the relatively constant thinning rate in the interior. Combining all simulations, the VAF loss is equivalent to a ~~15–42~~ contribution of 14–42 mm global mean sea level (GMSL) rise in 100 years.

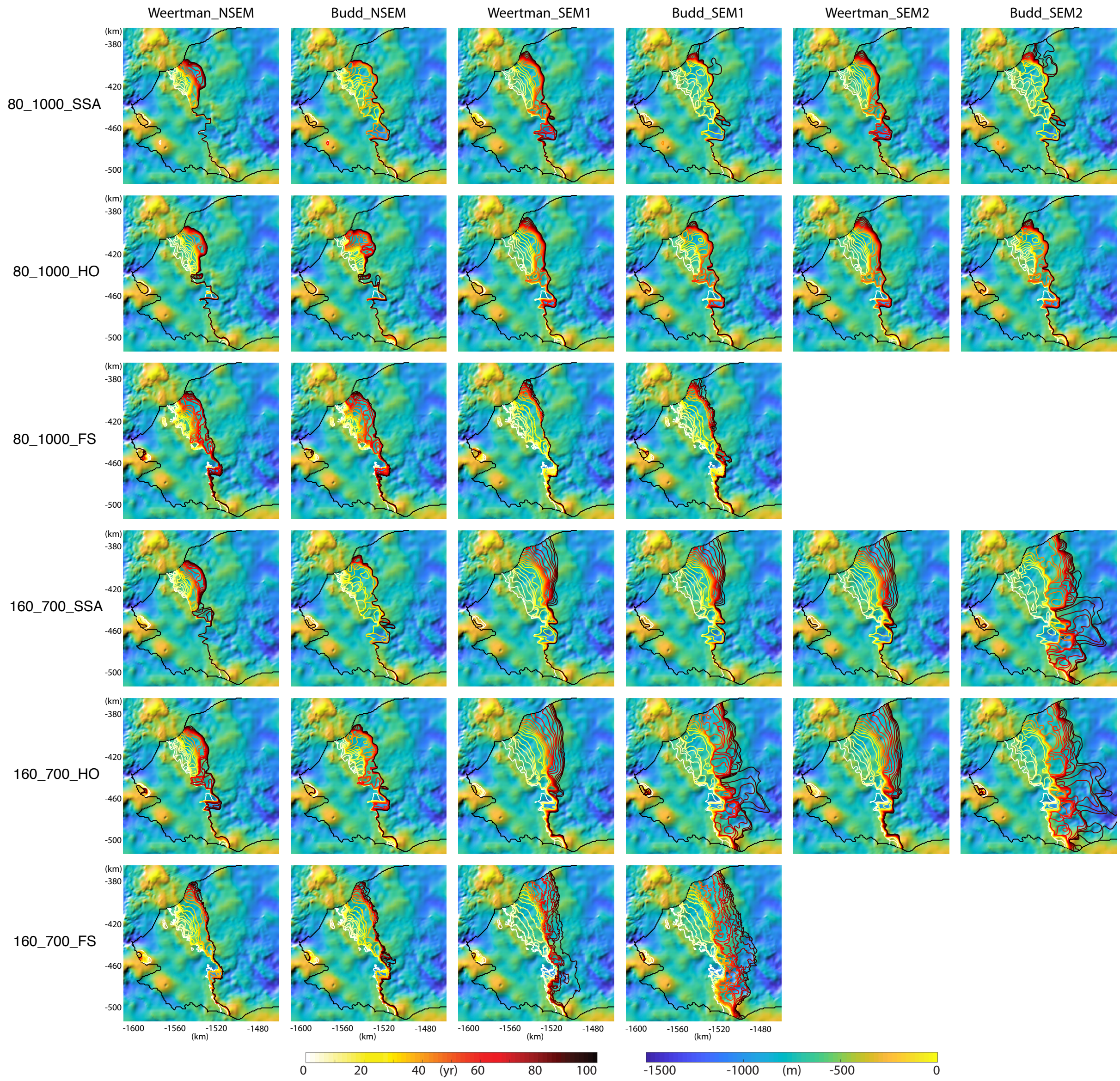

Figure 4. Grounding line evolution of ~~all 12~~ Thwaites Glacier, West Antarctica from 16 models with the ~~two end members~~ 80_1000 and 160_700 ice shelf melt scenarios, overlaid on the bed elevation map~~of Thwaites Glacier, West Antarctica~~. Each panel ~~represents~~ is one simulation. Within each panel, the grounding line positions are plotted every 5 years.

Differences among simulations. The response of TG to ~~ocean melting differs when using~~ ice shelf melt differs with different stress balance models, ice shelf melt implementations and friction laws. Among the three stress balance models, FS shows consistently more grounding line retreat than HO and SSA, except in the ~~Melt_Weertman~~Weertman_SEM1 experiments, where HO retreats the most. In the ~~Nomelt and Melt_Budd~~ Budd_NMP and Budd_SEM1 experiments, FS produces 5-40% more grounded area loss than HO and SSA. In the ~~Melt_Weertman~~Weertman_SEM1 experiments, FS has 10% less retreat than HO and 15% more than SSA. In the ~~VAF loss perspective~~SEM2 experiments, HO displays 10-20% more retreat than SSA. In terms of VAF loss, the three models are closer to each other. SSA shows more VAF loss in the Budd experiments, while FS shows more VAF loss in the Weertman experiments. The overall differences between these simulations are within 20%.

The ~~grounding line retreat rate is significantly reduced in the Nomelt experiments compared to the Melt experiments. The total grounded area loss is reduced by 35-65% and the VAF loss is reduced by 15-40%. The~~ choice of friction law ~~also~~ has a significant impact on the results. The Budd friction law produces more grounding line retreat (10-50%) and more VAF loss (15-90%) than the Weertman friction law. The Budd experiments also display a higher sensitivity to ocean thermal forcing than the Weertman experiments. The grounding line retreat rate is significantly reduced in the NMP experiments compared to the SEM experiments. The total grounded area loss is reduced by 35-65% and the VAF loss is reduced by 15-40% with the NMP experiments.

Different ice shelf melt scenarios have significant impact on the behavior of TG. ~~A~~ On one hand, a higher ice shelf melt rate always leads to more retreat. ~~However~~On the other hand, the sensitivity to changes in ice shelf melt rate varies among the models. The ~~Melt~~ SEM experiments with FS or HO and Budd friction law are more sensitive to ocean thermal forcing than the ~~Nomelt~~ NMP experiments with SSA and Weertman friction law. Between the SEM1 and SEM2 experiments, however, the differences are limited and typically within 5%, except for the 160_700_Budd experiments. This result is consistent with previous studies on idealized geometry (Seroussi and Morlighem, 2018).

4 Discussion

Impact of the stress balance models. In our simulations, the stress balance models produce different results ~~for several reasons. First, the model physics are different.~~ due to both physical and mathematical reasons. With the inclusion of vertical shear and bridging effects in the stress field, the ice viscosity in FS is lowered, which leads to a larger acceleration as the grounding line retreats. In the MISMIP3D experiments, ~~for example,~~ using the same initial setting, the modeled ice velocity of FS is faster than HO by 0-5%, and HO is faster than SSA by another 0-5% (Pattyn et al., 2013). Second, the grounding line positions are computed differently. For HO and SSA, ~~it is computed through~~ the grounding line is computed from hydrostatic equilibrium, which compares the bottom water pressure with the overburden ice pressure. For FS, the bottom water pressure is compared with the normal stress at the base, which deviates from the overburden ice pressure by a few percent. In the grounding line region, and in particular, in the bending zone of the glacier, ice is pushed below hydrostatic equilibrium because of the bending moment of ice as it ~~tries to reach hydrostatic equilibrium in the ocean water~~ adjusts to hydrostatic equilibrium (Rignot, 2001; Yu et al., 2017). As a result of this non-hydrostatic condition, the vertical velocity is high downstream of the grounding line, which produces high vertical shear that decreases the normal stress at the base. Moreover, the horizontal stretching of ice is large in the grounding line region, which reduces the normal stress at the ice base (van der Veen and Whillans, 1989; Pattyn et al., 2013).

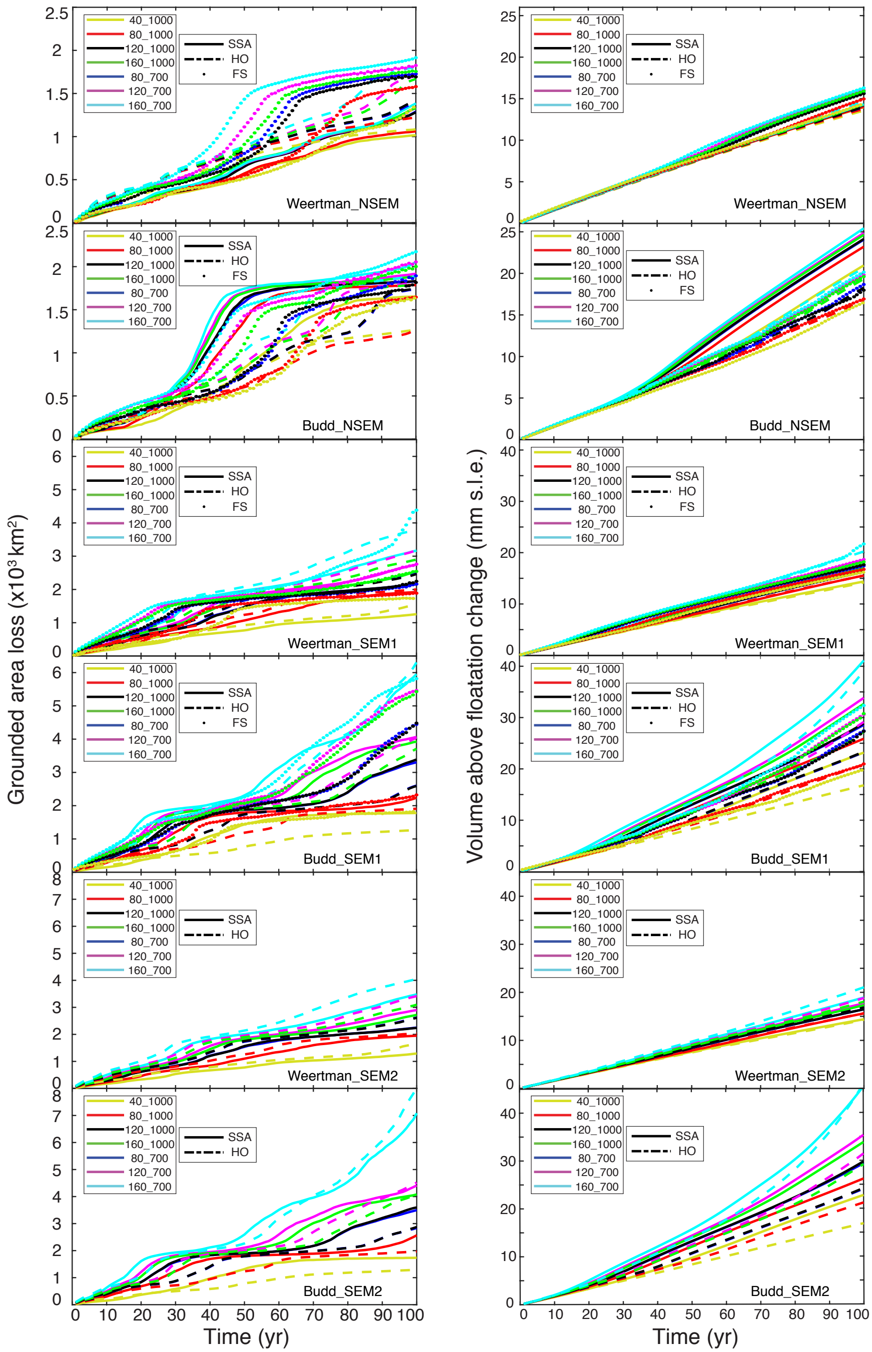

Figure 5. Grounded area loss (left column) and volume above flotation (VAF) loss (right column) of Thwaites Glacier, West Antarctica for the ~~72~~ 112 experiments over the next 100 ~~year simulation~~years.

~~Numerical issues also contribute to the differences between the models. We conduct inversions~~ In terms of mathematical implementation, the inversions are conducted separately for each model ~~separately~~ to make sure that they best fit the observations. Hence, the initial conditions are slightly different for each model, which sets them up on different trajectories. In transient simulations, small differences in initial conditions ~~may~~ accumulate with time and ~~lead to further~~ may lead to significant differences in the model outcomes. Here, SSA has a higher rate of VAF loss than grounded area loss ~~with respected~~ compared to HO and FS ~~. This is~~ due to the higher thinning rate in the interior~~simulated by SSA~~. This sensitivity to the initial conditions indicates that we need better constraints for the inversion process. For instance, ~~we should~~ it would be useful to infer the basal friction coefficient and ice viscosity parameter ~~using a~~ from a time series of observed velocities, as in Goldberg et al. (2015), rather than from a single velocity map.

In summary, the FS model ~~has~~ includes more complex physics ~~compared to HO and SSA and~~ and leads to faster grounding line retreat, especially over subglacial ridges, compared to SSA or HO models. The difference between FS and simplified models ~~depends on~~ varies with the bed topography. Meanwhile, initial conditions are also critical to consider when comparing model results.

The limitation of FS is mostly computational. FS is 10 times slower than HO and 100 times slower than SSA. In our results, ~~however,~~ we find that the impact of ~~different stress balance models~~ choosing stress balance model is smaller than the impact of choosing ice shelf melt treatment and friction law. ~~Meanwhile, initial conditions are also critical to consider when comparing model results.~~

~~Our results also show that if we apply ice shelf melt in the partially floating elements, the results change significantly, which is consistent with previous studies (Golledge et al., 2015; Arthern and Williams, 2017). Theoretically, these two methods should have the same results if the mesh resolution is small enough. However, this is not achieved with our 300 m resolution and may therefore be difficult to achieve numerically. For the partially floating elements, it is expected that some ice shelf melt would occur in the floating portion, so not applying any ice shelf melt might underestimate the mass loss. In the newly ungrounded cavity, the ice shelf melt rate may not be as high as the previously floating area due to its limited access to warm water. The removal of ice at the base in partially floating elements may also lead to unrealistic thinning upstream of the grounding line due to the implementation of the mass transport equation. Therefore, the model may overestimate mass loss if ice shelf melt is applied in the partially floating elements. We also conducted the same simulation with coarser and finer mesh resolutions with SSA and the Nomelt experiments are showing less sensitivity to mesh resolutions than the Melt experiments.~~

Impact of the friction laws. The introduction of an effective pressure term in the Budd friction law produces more retreat and mass loss compared to the Weertman experiments. With the Budd friction law, the basal drag is reduced when the ice is thinning, which in turn accelerates ~~further~~ the retreat and thinning, forming a positive feedback. In our results, the difference between Weertman and Budd experiments is larger in VAF loss than grounded area loss due to the ~~changes~~ differences in the interior. Once the friction is reduced with the Budd friction law, ice thinning increases and propagates inland to produce more VAF loss than ~~with the Weertman experiments~~in the Weertman case. This result indicates that the difference in grounding line retreat between these two sets of experiments diverges with time as the upstream thinning ~~signal~~ evolves.

The underlying assumption for the Budd friction law is the existence of a subglacial drainage system. Previous studies have revealed that such systems exist in West Antarctica and are connected to the ocean (Gray et al., 2005; Fricker et al., 2007; Le Brocq et al., 2013). Therefore, it might be more reasonable to use a Budd friction law in the grounding line region of TG. However, in the interior of the ice sheet, such drainage system may not be presentand our current knowledge of the effective pressure is poor and it is not clear if such a drainage system is present. In that case, the use of a Budd friction law could overestimate the total mass loss. Recently,

Several new friction laws have been proposed recently. Schoof (2005) derived a friction law by inducing an upper bound for basal drag that is determined by bed slope. Tsai et al. (2015) proposed a friction law that incorporates both a Weertman friction law and a Coulomb friction lawincludes both the Weertman and the Coulomb friction regimes. Both of these laws incorporate the Weertman and the Coulomb friction laws, which might work for both the grounding line and the interior regions. This method requires two sets of basal friction coefficients, which is difficult to infer in a real glacier and remains beyond the scope of this study. Numerical simulations have shown that these friction laws produce grounding line retreat that lie within the Weertman friction and the Budd friction laws (Brondex et al., 2017, 2018). At this point, it is still unclear which friction law should be employed in ice sheet models.

Impact of the ice shelf melt treatment near grounding line. Our results show that if we apply ice shelf melt over the floating area of partially floating elements (SEM1 & SEM2), the retreat changes significantly, which is consistent with previous studies (Golledge et al., 2015; Arthern and Williams, 2017). Theoretically, the three methods should produce the same result if the mesh resolution is fine enough. Yet, this is not achieved with our 300 m resolution mesh. For the partially floating elements, it is expected that some ice shelf melt would occur on the floating part of partially floating elements, so not applying any ice shelf melt might underestimate the mass loss. In the newly ungrounded cavity, the ice shelf melt rate may not be as high as the previously floating area due to its limited access to warm water. The removal of ice at the base in partially floating elements may also lead to unrealistic thinning upstream of the grounding line due to the implementation of the mass transport equation. Therefore, the model may overestimate mass loss if ice shelf melt is applied in partially floating elements. We have conducted the same experiments with coarser (1000 m) and finer (200 m) mesh resolutions to assess the impact of mesh resolution and the treatment of ice shelf melt in partially floating elements. We find that, similar to previous studies on simplified test cases (Seroussi and Morlighem, 2018), the NMP experiments are showing less sensitivity to mesh resolutions than the SEM1 and SEM2 experiments (Fig.A1b).

Impact of bed topography and ocean forcing. Despite the differences between these models, the overall results are similaras , i.e., the glacier retreats along essentially the same preferred paths. The major difference between the models is on the time it takes for each model to overcome ridges in bed topography along the pathway of the retreat. In all simulations, TG experiences grounding line retreat and mass loss over the entire period, which is consistent with previous studies (Joughin et al., 2014; Feldmann and Levermann, 2015; Seroussi et al., 2017). The retreat rate is highly dependent on bed topography . (Fig. 1b). On the eastern side, there are three subglacial ridges that provide temporary stability to the glacier. The current grounding line position is on the retrograde side of the first ridge on the east. The second ridge is 35 km upstream. In the ~~Nomelt~~ NMP experiments, the grounding line positions ~~are still sitting~~ will remain on this ridge after 100 years. In the ~~Melt~~ SEM experiments, all simulations except the 40_1000 and 80_1000 ones have their grounding ~~line~~ lines retreat over this ridge, with the timing varying from 55 to 90 years. The third ridge is another 25 km upstream. None of our simulations show grounding line retreats over this ridge within ~~one~~ the next century. The slope of the third ridge is similar to the second ridge. We therefore expect this ridge to have a similar stabilizing effect as the second ridge.

There is a subglacial trough between the second and third ridge that connects Pine Island Glacier (PIG) and TG. If the grounding line of TG retreats into this region (SEM experiments with high melt), the grounding line of TG will connect with the grounding line of PIG, and the two drainage basins will merge into one. The flow of ice could be significantly impacted if this merge takes place. In this study, we did not account for this scenario as it would require simulating the entire ASE (Brondex et al., 2018).

The subglacial ridge that has the strongest stabilizing effect is the western subglacial ridge where the grounding line is currently ~~sitting on~~anchored. In the ~~Nomelt~~ NMP experiments, the grounding lines are stable in the west. In the ~~Melt_Weertman~~Weertman_SEM experiments, only the FS model with the highest ice shelf melt rate has its grounding line retreat over the ridge at year 95. In the ~~Melt_Budd~~Budd_SEM experiments, the grounding line retreats over this ridge for the three high ice shelf melt scenarios (160_700, 160_1000, 120_700). Further upstream, the bed slope of TG is retrograde until the ice divide and the subglacial channel widens inland. Once the grounding line retreats ~~over~~ past the western ridge, ~~it is not clear how the retreat of the grounding line could~~ our model results do not suggest that the retreat can be stopped.

The impact of ocean thermal forcing is most significant in the ~~Melt_Budd~~Budd_SEM experiments and is ~~relatively~~ small in the ~~Nomelt~~ NMP experiments. The difference is due to the grounding line retreat rate~~in these experiments~~. In the ~~scenario~~ scenarios where the grounding line is constantly retreating, a higher ice shelf melt rate will remove ice in the newly ungrounded area more rapidly and reduces the buttressing force on the inland ice faster, which leads to further retreat. If the grounding line position is relatively stable, however, a higher ice shelf melt rate will only act over floating ice and has no impact over grounded ice. The removal of ice ~~is limitedin this region as~~ becomes limited, the ice bottom ~~evolves to~~ reaches a steady shape and the reduction ~~of buttressing becomes limited~~in buttressing is minimal.

In our simulations, the effect of changing the depth of maximum melt from 1000 m to 700 m is similar to increasing the maximum ice shelf melt rate by 50% (80_700 ~~v. s.~~ vs. 120_1000 and 120_700 ~~v. s.~~ vs. 160_1000). This is because the bed elevation between the current grounding line and the upstream subglacial ridges is between 800 and 500 m~~depth~~, which makes the melt rate at this depth particularly important. If warm ocean water intrudes at 700 m depth, as observed on Pine Island Glacier, or above, the retreat of TG will be more rapid, even without increasing the maximum ice shelf melt rate. Indeed, the bathymetry in Millan et al. (2017) suggests that the main points of entry of CDW into the sub-ice-shelf cavities of TG have a maximum depth of 700 m.

Contribution to global sea level rise. The contribution to global sea level rise revealed by our simulations spread ~~a large range~~ from 14 to 42 mm in the next 100 years. However, in the first 30 years, all models ~~suggests~~ suggest a global sea level rise of

5 mm, or 0.18 mm/yr. This rate is consistent with the satellite observations of 0.14 mm/yr in ~~2014, which kept increasing in the past decades.~~ 2014. Previous modeling studies ~~also have~~ had similar estimations, ranging from 0.15 mm/yr to 0.25 mm/yr (Joughin et al., 2010b; Cornford et al., 2015; Seroussi et al., 2017). After 30 years, the retreat of TG ~~would continue, whether the~~ will continue. The acceleration in retreat rate will ~~accelerate is highly~~ dependent on the numerical model used and a longer time record of observations ~~are~~ is needed to know which model best reproduce the observational period.

Limitations of the model study. One major limitation of this model study is the ice shelf melt rate parameterization. ~~It would be preferable to apply~~ We estimate the ice shelf melt rate ~~calculated using a coupled~~ from observations and try to cover both cold and warm scenarios. In reality, the melt rate could have large spatial and temporal variability, especially as the grounding line retreats. These variabilities are likely to affect the evolution of TG. Coupled ice-ocean ~~model, i. e. with a time-dependent cavity (Seroussi et al., 2017; Cornford et al., 2015). Coupled~~ models indicate that warm ocean water has more limited access to newly formed cavities as ~~ice~~ the ice sheet retreats (De Rydt and Gudmundsson, 2016; Seroussi et al., 2017). This lower efficiency of ice shelf melt will lower the contribution of TG to sea level rise in the 21st century. It is therefore best to apply an ice shelf melt rate calculated from a coupled ice-ocean model, i.e. with a time-dependent cavity, to obtain a more realistic projection of the evolution of TG (De Rydt and Gudmundsson, 2016; Seroussi et al., 2017; Cornford et al., 2015).

~~Similarly, ice~~ Another limitation is that the ice shelf front migration is not included in our simulations. We assume that the ice shelf front position of TG remains fixed~~so that~~ , i.e., all ice passing the ~~present day ice front immediately calves~~ ice shelf front calves immediately. Densely distributed crevasses along the ice shelf of TG, however, make the ice shelf conducive to rapid calving (Yu et al., 2017). Once the ice shelf is removed, the grounding line will retreat into deeper regions, and the probability of calving increases according to the marine ice-cliff instability theory (Pollard et al., 2015; Wise et al., 2017). Crevassing and calving will therefore reduce ice shelf buttressing ~~drastically~~ and accelerate ice ~~flow further, which means that~~ speed, i.e., our simulations underestimate the potential mass loss of TG (MacGregor et al., 2012). On Pine Island Glacier, calving has increased in frequency and its ice front is now 35 km farther inland on the eastern side than in the 1940's (MacGregor et al., 2012; Jeong et al., 2016). On TG, the floating ice tongue in the center trunk has retreated by 26 km from 1973 to 2009 (MacGregor et al., 2012). The eastern ice shelf has been thinning and retreating, which means that the ice shelf ~~may disintegrate~~ could be disintegrating in the coming decades.

5 Conclusions

We simulate the response of Thwaites Glacier, West Antarctica to varying model configurations and ice shelf melt scenarios. We find that the stress balance approximations, the friction law, the treatment of ice shelf melt near the grounding line, ~~the friction law,~~ and the ice shelf melt rate parameterization all affect the retreat of TG significantly. Different model configurations affect the results mainly through the timing for the grounding line to retreat past subglacial ridges; different ice shelf melt rates mainly affect the retreat rate when the grounding line is retreating along retrograde portions of the bed. Despite the differences, however, all models follow similar trajectories and concur to indicate that TG will continue to retreat at a rapid rate over the next century, under both cold and warm ocean water scenarios. The retreat is controlled by the bed topography. Subglacial ridges on the eastern side will ~~only~~ moderately delay the retreat, whereas the western ridge provides the most stability for the glacier, for at least the next several decades. Once the grounding line retreats past the western subglacial ridge, our simulations suggest that there will be no further stabilization of the glacier and the retreat will become unstoppable ~~over~~ for the next 100 years. Our simulations project a 5 mm global mean sea level ~~contributions~~ contribution from TG in the next 30 years, and 14-42 mm in the next 100 years.

Code and data availability. The ice flow model ISSM can be found and downloaded at https://issm.jpl.nasa.gov/ (Larour et al., 2012). The input data can be found and downloaded at http://faculty.sites.uci.edu/erignot/data/

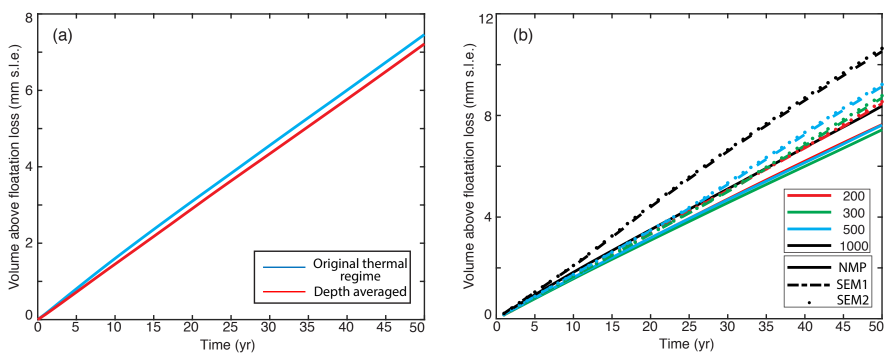

Figure A1. Volume above flotation loss in two sensitivity experiments a) Exp. 160_1000_HO_Weertman_NMP with original thermal regime and its depth average. b) Exp. 160_1000_SSA_Weertman with different ice shelf melt implementations and mesh resolutions.

Competing interests. The authors declare that there is no conflict of interest.

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