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Rate of Mass Loss Across the Instability Threshold for Thwaites Glacier Determines Rate of Mass Loss for Entire Basin

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Key Points:
- Small differences in the marine forcing rate prior to instability can generate large differences in unstable grounding line retreat of Thwaites Glacier
- Transient ice shelf thickening and grounding line advance can modify the rate of retreat after an instability is initiated
- Grounding line re-advance due to a change in marine forcing does not imply that an instability has not been initiated

Supporting Information:
- Supporting Information S1
- Movie S1
- Movie S2

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Rate of Mass Loss Across the Instability Threshold for Thwaites Glacier Determines Rate of Mass Loss for Entire Basin

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Abstract Rapid change now underway on Thwaites Glacier (TG) raises concern that a threshold for unstoppable grounding line retreat has been or is about to be crossed. We use a high-resolution ice sheet model to examine the mechanics of TG self-sustained retreat by nudging the grounding line just past the point of instability. We find that by modifying surface slope in the region of the grounding line, the rate of the forcing dictates the rate of retreat, even after the external forcing is removed. Grounding line retreats that begin faster proceed more rapidly because the shorter time interval for the grounding line to erode into the grounded ice sheet means relatively thicker ice and larger driving stress upstream of the boundary. Retreat is sensitive to short-duration re-advances associated with reduced external forcing where the bathymetry allows regrounding, even when an instability is invoked.

1. Introduction

The West Antarctic Ice Sheet (WAIS) is vulnerable to rapid mass loss due to its marine setting. Many of its outlet glaciers and ice streams terminate in floating ice shelves, the bed underneath the ice is well below sea level, and the bed deepens toward the ice sheet interior. Around the Amundsen Sea Embayment (ASE), ice shelves are small and grounding lines are close to relatively warm Circumpolar Deep Water (Pritchard et al., 2012; Scambos et al., 2017). Together, these attributes appear to make the ASE sector of the WAIS particularly vulnerable to rapid change.

The marine ice sheet instability (MISI) is a theoretical vulnerability to rapid grounding line retreat that arises from the superlinear relationship between ice thickness at, and flux through, the grounding line (Schoof, 2007; Weertman, 1974). In the simplest case, in which only stresses acting along a flow line are considered, flux must always increase as the grounding line retreats over a bed that deepens upstream (a retrograde bed). When lateral shear stresses are also important, grounding lines on retrograde beds may be conditionally stable (Gudmundsson et al., 2012). Addition of locally high bed features modifies the momentum balance and thus grounding line stability (Goldberg et al., 2009).

While expectations about MISI are theoretical and complicated by various boundary properties (Dupont & Alley, 2005; Nias et al., 2016; Parizek et al., 2013), the view that the WAIS is sensitive to small changes in environmental conditions is encouraged by observation. For example, relatively warm Circumpolar Deep Water is observed on the ASE continental shelf at the same time that glaciers in this sector are speeding up (Parizek et al., 2013; Rignot, 2008; Rignot et al., 2002; Shepherd et al., 2012; Shepherd & Wingham, 2007; Thomas et al., 2004; Wåhlin et al., 2010). Apart from waiting and watching, the only way to develop new insight into the rate and nature of ice sheet response to climate change is via experimentation with computational models (e.g., Cornford et al., 2015; Feldmann & Levermann, 2015; Joughin et al., 2014; Morlighem et al., 2010; Nias et al., 2016; Parizek et al., 2013).

We investigate the MISI in the Thwaites Glacier (TG) catchment basin of the WAIS with the objective of pushing a conditionally stable grounding line into a self-sustained retreat. Starting from an ice sheet model initialized using standard data sets (Text S2 in the supporting information) and parameterized basal melting, we nudge the grounding line by applying a slowly increasing anomalous melting rate under the floating part of the model domain. This is similar to nudging strategies used in other contexts to find abrupt dynamical changes (e.g., Ortega et al., 2017). Eventually, the anomalous marine forcing yields a disproportionately large response and when this is detected, we shut off the extra melting and track the ensuing retreat (Text S3). The

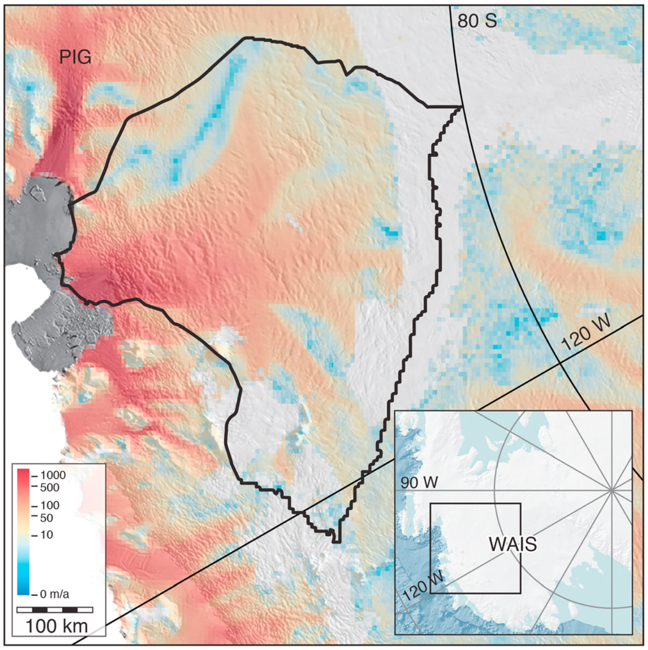

Figure 1. Model catchment boundary for TG experiments. The color map shows surface speed from Rignot et al. (2011) draped over the MOA (Haran et al., 2005).

intent of the nudging approach is to generate retreats that are driven as purely as possible by MISI mechanics, and the slow linear ramp allows us to search, gradually, for only the forcing and grounding line position necessary to initiate this type of retreat. We retain the background melting boundary condition because it was the condition associated with model steady state. Other studies have simulated "committed" retreat by perturbing a steady state field by arbitrary amounts for arbitrary durations (e.g., Feldmann & Levermann, 2015). By nudging the grounding line just beyond the point of instability, we are able to examine the mechanics of retreat in detail without other complications.

2. Methods

2.1. Ice Sheet Model

We use the vertically integrated, adaptive-mesh BISICLES (Cornford et al., 2013) model to investigate ice sheet and grounding line response to anomalous ocean forcing in the TG catchment (Text S1). The model catchment boundary is set using model-derived velocity of the whole continent (Figure 1). This ensures a boundary consistent with model solutions to the governing equations and boundary conditions. The boundary is held fixed with no-flow conditions and high basal traction coefficients outside the catchment. The fixed boundary becomes less realistic over time, but we note that where it has been observed via ice sheet internal layer geometry, the WAIS divide has recently migrated at a rate of 1 km per 100 a (Conway & Rasmussen, 2009).

Model parameters are initialized using an adjoint of the governing equations and standard boundary value data sets (Text S2; Arthern et al., 2006; Fretwell et al., 2013; Pattyn, 2010; Rignot et al., 2011). Basal traction is represented using a viscous law, and the temperature-dependent ice viscosity is modified using a scalar tuning. Once optimized, these parameters remain fixed during forward simulations. This is a common simplification, and we rationalize it via our focus on comparative studies rather than projections. The procedure also assumes steady state melting on the underside of the floating ice.

Our perturbation experiment design requires a melting field that can be manipulated in a simple, linear way. We choose to parameterize a background marine melting (MM) using two simple schemes. In one, melting is spatially uniform at a rate of -0.3 m a^{-1}. In the other, a piecewise linear function sets melt rate to vary between -0.3 and -1 m a^{-1} according to the thickness of the water column such that larger melt rates are applied to ice above a thinner water column near the grounding line than to ice over a thicker water column away from the grounding line. The function is

$$\dot{m} = f(h_w) = \begin{cases} -1 & \text{for } h_w \leq 100 \text{ m} \\ 0.005h_w - 1.5 & \text{for } 100 \text{ m} < h_w \leq 200 \text{ m} \\ 0.004h_w - 1.3 & \text{for } 200 \text{ m} < h_w \leq 250 \text{ m} \\ -0.3 & \text{for } h_w > 250 \text{ m} \end{cases}$$

in which $\dot{m}$ is the mean annual melt rate and h_w is the water column thickness. The objective is to mimic the effect of ice shelf draft (Jenkins & Doake, 1991) in a way that is easy to implement. Other similar parameterizations use linear functions of ice thickness (Cornford et al., 2013; Favier et al., 2014; Sun et al., 2014). Nias et al. (2016) apply an exponential shape determined by an expected length scale. The background melting rates are lower than present-day rates inferred from remote sensing (Paolo et al., 2015); however, present-day rates are not steady state and can vary in both magnitude and sign over any given observational interval. Equally importantly, we are interested in a model melting rate that produces a steady state model grounding line near the observed present-day grounding line position (Greene et al., 2017; Mouginot et al., 2017; Rignot et al., 2013) and this scheme accomplishes that goal (Figure S4).

The initialized model is then relaxed toward a steady state geometry for the parameterized basal melting. The relaxation runs for 100 years, and at the end of this time the model grounding line is seaward of major highs on the seafloor (Figure S4). Over the last decade of relaxation, the mean rate of change in volume flux across the TG grounding line is about 0.1%.

2.2. Model Forcing and Self-Sustained Retreat

We are interested in self-sustained retreat of the TG system rather than retreat driven by melting, and thus aim to find the smallest possible forcing that will generate a MISI transition. The grounding line is nudged by adding an anomalous marine melting (AMM) to the background MM, as a slow and steady ramp that increases at 0.05 m a^{-2}. Once the instability is detected, the anomalous melting is shut off while the background MM remains. We then monitor the self-sustained retreat of the grounding line.

While the ice sheet bed has an overall retrograde trend, it is also characterized by numerous local forward slopes and these generate spatial and temporal variations in the rate of grounding line retreat in both the forced and unforced periods of our simulations. This means that a locally large rate of retreat may not be symptomatic of the basin-wide situation and a basin-wide metric should be used to identify the MISI transition.

The transition to self-sustained retreat is found by monitoring the rate of change in total grounded ice area as the AMM increases (Text S3, Figures S1 to S3). Grounded area necessarily decreases as the grounding line retreats and prior to MISI and a small change in AMM should tend to produce a small change in grounded area. That relationship will change when the instability is invoked because the retreat is no longer simply driven by the AMM. Thus, we look for a transition to sustained, anomalously large (order of magnitude) rate of change in grounded ice area as the AMM proceeds. The comparison requires us to run the model past the point of instability. Once the transition is found, the simulation returns to that point and the AMM is stopped.

2.3. Grounding Line Retreat Experiments

Two retreat scenarios are explored, one in which the AMM is shut off as soon as the self-sustained retreat is detected and another in which the AMM continues to increase for an additional 10 years. The experiment is repeated for the variable and uniform background MM. All other parameter values remain fixed so that effects associated with ice dynamics dominate our analysis. For example, adjusting surface mass balance to account for changing surface elevation would have obscured thickness and surface slope changes associated with MISI feedback. Arranged in this way, comparisons between scenarios allow us to examine dynamics of self-sustained retreat in the TG catchment basin.

Model responses to slightly different AMM forcings are evaluated by comparing ice geometry and flow for equivalent grounding line positions in different scenarios. Pairs of model years when grounding lines are approximately co-located in space are found using a nearest neighbor algorithm along fixed curvilinear transects through the TG basin. We search for matches within 250 m of each other along a transect near the center of the basin in the first instance but expand the search to find matches along other transects when required to improve the result. Some time gaps arise when there are large transverse variations in the retreat rate but in general the approach works well.

3. Results

Grounding line retreat is initially driven purely by the AMM in our model experiment design. Melting removes ice downstream of the grounding line so its position must shift and retreat must continue as long as the anomalous forcing is applied. When the AMM is shut off, the grounding line may advance as thicker ice moving across the boundary is no longer lost to melting. Grounding line retreat stalls when the AMM is shut off before the instability is detected. For example, when the AMM is shut off at model year 170, the retreat rate slows and the ice sheet geometry relaxes toward a new shape as accumulation slowly replaces ice lost during the forced retreat (Figure S2). While some sections of the grounding line are over locally reverse slopes, the net balance of forces does not favor retreat.

The instability is first detected around year 260 when a long segment of the grounding line reaches the upstream edge of a relatively shallow “highland” region of the bed in the eastern sector of TG and crests two isolated highs in the western sector of the basin (Figure S4). The AMM at this time is 13 m a^{-1}. The transition happens at about the same grounding line position for both background MM parameterizations, but the retreats proceed differently thereafter.

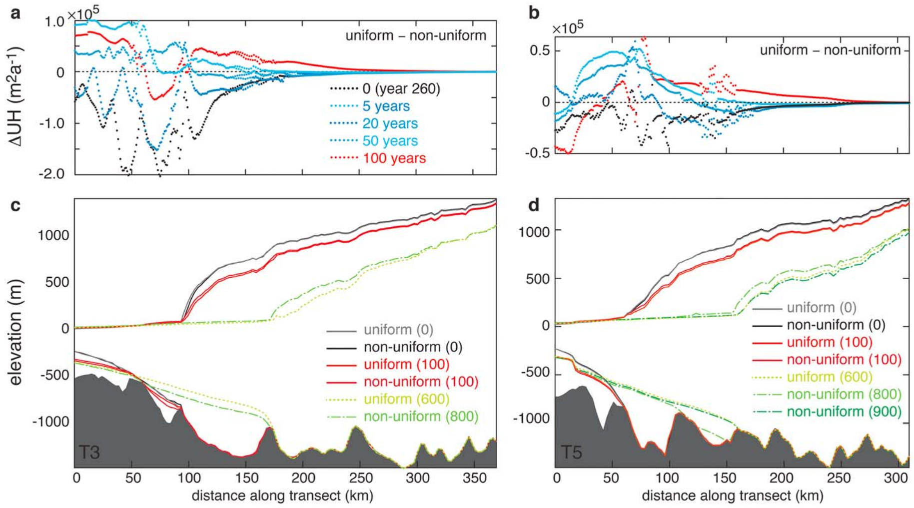

Figure 2. Model variables plotted along transects (a and c) T3 and (b and d) T5 in Figure S5. Difference in the product of speed and thickness (Figures 2a and 2b) gives an indication of the difference in mass transport between models with different background melting and the flux transition when the AMM is shut off. Noise in the calculation (around 150 km) is associated with mesh refinement. Ice sheet profiles (Figures 2c and 2d) demonstrate initial thickening of floating ice when the AMM is shut off and the larger thickening associated with larger flux (year 100). The additional time in Figure 2d (years 800 to 900) demonstrates rapid retreat when a pinning point is lost.

Grounding line retreat proceeds faster in the scenarios initiated with the slightly larger and longer anomalous forcing and more slowly in scenarios initiated with the slightly smaller and shorter forcing (Figures S3 and S5). This is the case for both background melting parameterizations; however, there are differences. The scenarios with larger basal melting near the grounding line (nonuniform MM) support larger ice flux, and when the AMM is shut off, the larger flux causes thickening and some re-grounding in the floating ice (Figure 2). This, in turn, causes flux through the ice shelf to decline. The effect is more pronounced in the central part of the TG basin, where fluxes are larger overall (Figures 2a and 2c). Rates of grounding line retreat and thus the fluxes of ice across the grounding line diverge in the case of uniform background MM while they do not in the case of nonuniform MM (Figure 3).

Self-sustained retreat involves feedback that keep driving stresses near the grounding line relatively large as the retreat proceeds (Text S4). In our experiments, retreats initiated with slightly larger and longer anomalous forcing periods are characterized by larger driving stresses and this difference, relative to fixed locations on the bed, is maintained as the various retreats proceed (Figure 4). This means that in the case of a larger push, the surface is locally steeper as the grounding line retreats past any particular region of the bed, and because the retreat proceeds more rapidly, ice thickness remains relatively larger upstream of the approaching grounding line (Figures S6 and S7). Together, these consequences of faster retreat sustain the difference in retreat rate between the slightly larger and slightly smaller forcing.

Grounding line retreat after AMM shutoff is faster in the experiments with uniform background MM (Figures 3c and 3d). Prior to initiation of the instability, these simulations have larger fluxes through the grounding line (Figure 2), and when the AMM is shut off, the larger fluxes move relatively more ice across the grounding line, generating thickening and some regrounding downstream of the grounding line. This reduces the flux rate and causes the post–shut off thickening of floating ice to persist. The effect is more apparent in some locations than others due to different bed features (Figure 2c versus Figure 2d). Without retarding effects of reduced flux through the ice shelf, the grounding line is able to continue its retreat immediately and the amplifying effects of the instability are felt more directly.

4. Discussion

The MISI is invoked when driving stresses overcome resistive stresses in a way that amplifies the initial, externally forced change in the driving stress. It is reasonable to suppose that in the specific case of TG, changes on the floating side of the grounding line would have limited effect on ice dynamics because the floating region is small and relatively unconfined, thus providing relatively little resistance to balance driving stresses (Fürst

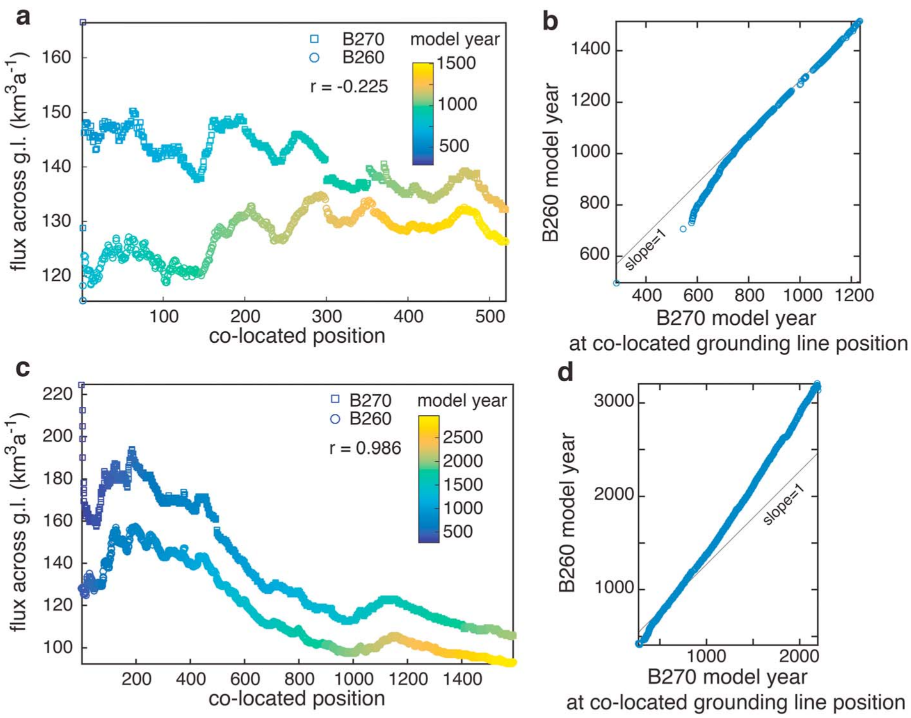

Figure 3. Flux across the grounding line for equivalent grounding line positions during retreat in the (a and b) nonuniform and (c and d) uniform background melting experiments. The co-located position axes are not linear, as indicated in Figures 3b and 3d. Color coding in Figures 3a and 3c indicates time of arrival at any particular grounding line location. In the nonuniform MM case, rates of grounding line retreat converge (Figure 3b) while in the uniform MM case, they diverge (Figure 3d). The correlation between the two series with respect to grounding line location is reported. The two experiments ran for different periods of time.

et al., 2016; MacGregor et al., 2012). Nevertheless, we find that different anomalous forcing magnitudes and spatial patterns produce different retreat scenarios.

Irrespective of ice shelf arrangement, melting and thinning on the floating side can cause steepening across the grounding line and thereby increase the driving stress, ice flux, and thinning rate across that boundary. Increased flux across the grounding line can affect the force budget by steepening the surface slope on the grounded side of the ice sheet. In our experiments, longer and slightly larger anomalous forcing produces larger driving stresses in the downstream reach of the TG catchment and thus a requirement for larger longitudinal stretching (faster flow) to balance that stress (Figure S9). This in turn drives faster thinning at the grounding line and faster retreat of that boundary. However, a more rapid retreat also limits the total amount of ice lost from the interior of the ice sheet by the time the grounding line arrives at any particular location. This is because total draw-down time is shorter for the faster retreats. This effect works to maintain larger driving stresses in the faster retreats.

Larger fluxes can also have a less intuitive effect when the anomalous marine forcing declines. Regardless of forcing magnitude, when the forcing ends, ice on the floating side must thicken. It may also reground in some places. However, because MISI has been invoked, this postforcing effect should be transient and grounding line retreat must resume. When the flux from ice sheet to ice shelf is larger, the postforcing ice-shelf thickening effect must also be larger and the transient may be longer-lived. This is what we observe in our simulations.

Bed control on the rate of change ice discharge is reflected in correlation coefficients between retreat series (Figures 3a and 3c). In the case where ice on the floating side has little effect on retreat (uniform MM; Figure 3c), the changes in flux across any region of the bed (co-located grounding line location) are similar in the faster retreating and slower retreating experiments (Pearson correlation coefficient of 0.986). Forward and reverse slopes on the bed are exerting a strong influence on the ice flux, regardless of retreat rate. In contrast to this, when effects on the floating side are relatively more important (nonuniform MM; Figure 3a), the correlation between the two series is poor.

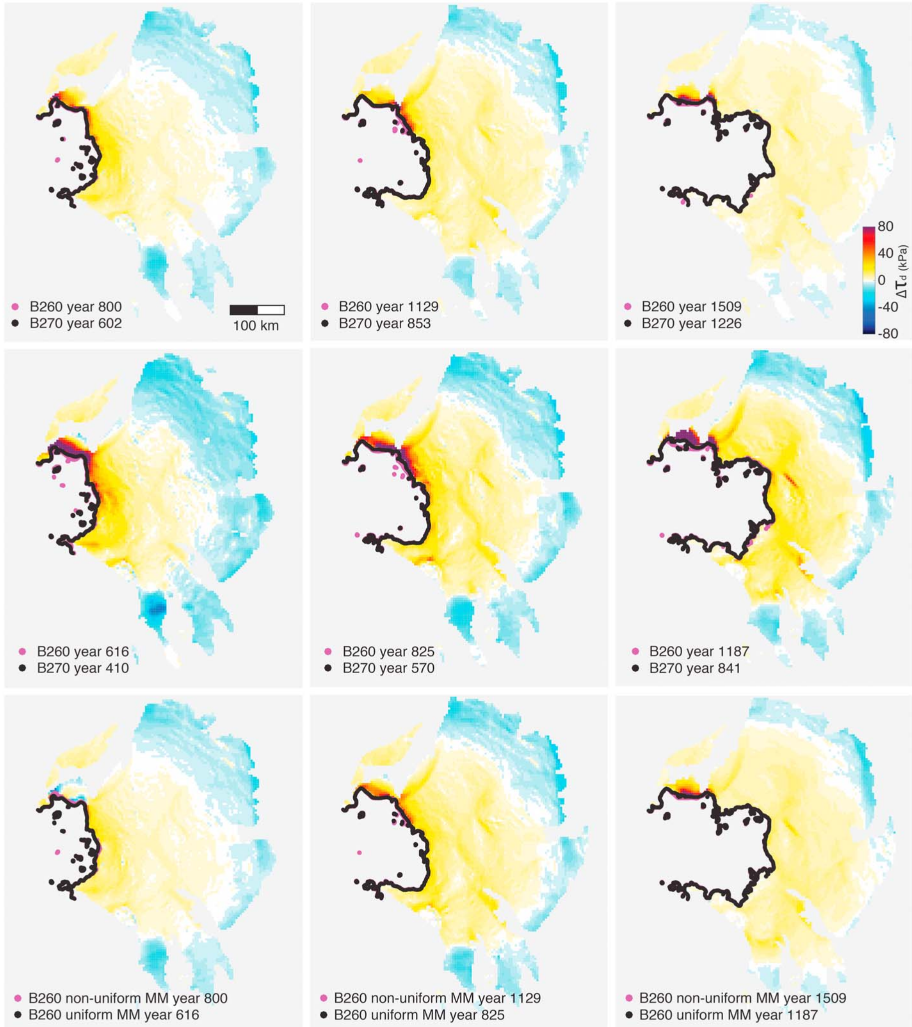

Figure 4. Driving stress difference for the same grounding line position in retreats initiated with different forcing magnitudes and proceeding with different background MM. In each panel, the slower retreat (magenta dots grounding line) is subtracted from the faster retreat. Top row is with nonuniform background MM, middle row is with spatially uniform MM, and bottom row compares the two. The comparisons are limited to regions of the model domain where ice speed is larger than 10 m a^{-1}. Ice rises appear as closed grounding line contours seaward of the main grounding line.

Sea floor shape is not the only condition for initiating the instability, and there may be many quasi-stable grounding line positions and many locations at which the transition to self-sustained retreat occurs. Other (larger) anomalous forcing rates, by increasing flux across and driving stress upstream of the grounding line, could produce the transition at locations seaward of those obtained in this study. Additionally, the transition is a bifurcation in the relationship between climate forcing and grounding line response (Schoof, 2007). While the basin-scale metric we use to search for that point is unlikely to have identified the exact time step across which it occurred, by testing possible initiation times (Figures S1 to S3), we are confident that our method finds the correct neighborhood of the transition.

Different modeling studies suggest different degrees of grounding line sensitivity to the form of the marine melting parameterization (Gladstone et al., 2017; Seroussi et al., 2017). Relatively small sensitivity might be expected in the case of TG because the ice shelf is relatively unconfined and provides limited resistance to flow across the grounding line (Fürst et al., 2016; Nias et al., 2016; Parizek et al., 2013). On this view, different melting rates more than a few ice thicknesses from the grounding line are not important to grounding line retreat. We suggest a new reason to care about the parameterization. When (if) enhanced melting declines, a forced retreat that was slower to proceed is less likely to experience transient re-advance and the associated damping effect on self-sustained retreat. A forcing that generated larger fluxes across the grounding line is more likely to experience transient thickening and re-advance, a circumstance that can slow the retreat.

Similar to other studies (Feldmann & Levermann, 2015; Seroussi et al., 2017), the ice sheet model used here assumes a linear viscous rheology for subglacial till. Parizek et al. (2013) used a flow line model to show that adopting a plastic rheology reduces vulnerability to instability by changing the distribution of basal stresses and allowing more rapid catchment-wide redistribution of mass. This tends to stabilize the system by more rapidly reducing surface slope and thus the driving stress near the grounding line. By comparison, our treatment of the bed amplifies the differences arising from different forcing magnitudes and durations.

5. Conclusions

Ice-shelf terminating glaciers on the Amundsen Sea coast appear today to be very close to a threshold past which retreat will be self-sustaining (Favier et al., 2014; Joughin et al., 2014; Rignot et al., 2014). Even if incursion of CDW onto the shelf is episodic or due to climate variability rather than a long-term trend, invoking MISI sets an inevitable course for deglaciation of West Antarctica and future sea level rise (Christianson et al., 2016; Feldmann & Levermann, 2015; Seroussi et al., 2017). However, the complicated bed shape together with transverse effects means that multiple steady state grounding line positions are possible (Goldberg et al., 2009; Schoof, 2007). Here we use a high-resolution ice sheet model to examine the three-dimensional setting of the TG transition to self-sustained retreat.

We show that the magnitude of the forcing yields different retreats and different ice flux time series. Looking upstream into the glacier catchment, we find that those differences arise from effects that determine driving stress in the grounded ice. Faster retreats yield steeper surface slopes and relatively thicker ice when the grounding line arrives at any particular location and so a retreat that begins faster proceeds faster. In the absence of competing effects, that amplification causes different retreat rates to diverge. Looking downstream, we find that transient thickening of the floating ice can suppress that divergence. A marine forcing that generates larger fluxes across the grounding line may produce transient thickening and grounding line re-advance when (if) the forcing declines. However, this does not imply that an instability has not been invoked; it simply changes the rate at which the self-sustained retreat proceeds.

All together, we show that small differences in forcing lead to large differences in retreat rate and ice discharge across the grounding line. The implication for future change is clear. If lower end future warming scenarios are possible, then the sooner anthropogenic forcing is reduced, the slower the ice sheet response, even if a self-sustaining retreat has been initiated. Retreat may be inevitable past a certain dynamical threshold, but the rate at which the retreat proceeds is not. Our results also suggest caution in how grounding line advance, should it be detected, is interpreted.

Acknowledgments
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