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Key Points:
- Model simulations confirm that the present climate can drive a slow but sustained sea level contribution from West Antarctica
- Additional submarine melting in newly formed ocean cavities, at rates similar to those observed, can provide a positive feedback to retreat
- For sufficiently intense submarine melting the simulated retreat can accelerate over time, even without ice shelf or ice cliff collapse

Supporting Information:
- Supporting Information S1
- Movie S1

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The sensitivity of West Antarctica to the submarine melting feedback

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Abstract We use an ice sheet model with realistic initial conditions to forecast how the Amundsen Sea sector of West Antarctica responds to recently observed rates of submarine melting. In these simulations, we isolate the effects of a positive feedback, driven by submarine melt in new ocean cavities flooded during retreat, by allowing the present climate, calving front and melting beneath existing ice shelves to persist over the 21st century. Even without additional forcing from changes in climate, ice shelf collapse, or ice cliff collapse, the model predicts slow, sustained retreat of West Antarctica, driven by the marine ice sheet instability and current levels of ocean-driven melting. When observed rates of melting are included in new subglacial ocean cavities, the simulated sea level contribution increases, and for sufficiently intense melting it accelerates over time. Conditional Bayesian probabilities for sea level contributions can be derived but will require improved predictions of ocean heat delivery.

1. Introduction

Recent observations have revealed intense melting in new subglacial ocean cavities that flood as thinning Antarctic ice goes afloat [*Khazendar et al.*, 2016]. Here we use an advanced ice sheet model [*Goldberg*, 2011] to forecast how the 21st century sea level contribution from the Amundsen Sea sector of West Antarctica depends upon this submarine melting. The model simulates velocities at all depths through the ice sheet and begins from realistic initial conditions that include the full-depth flow field beneath the surface, derived from data assimilation [*Arthern et al.*, 2015].

The West Antarctic Ice Sheet is a marine ice sheet. It is grounded on rock and sediment below sea level and attached at the grounding line to ice shelves that float on the ocean. The floating ice shelves are fed by snow accumulation and by flow of ice from the grounded ice sheet. They lose ice by calving icebergs from their seaward margins and by submarine melting from their base into the ocean [*Rignot et al.*, 2013; *Depoorter et al.*, 2013].

Any imbalance between the snow that accumulates on the grounded ice sheet and the ice that flows across the grounding line produces a contribution to sea level rise. For glaciers resting on terrain below sea level that deepens toward the interior [*Rignot et al.*, 2014], previous work has suggested retreat into deeper water can accelerate subsequent losses [*Weertman*, 1974; *Schoof*, 2007a; *Joughin et al.*, 2014], potentially causing an irreversible and societally significant increase in sea level [*Bamber et al.*, 2009; *Church et al.*, 2013; *Feldmann and Levermann*, 2015].

Determining the probability that any particular sea level contribution will be realized presently requires input from expert judgment [*Bamber and Aspinall*, 2013; *Ritz et al.*, 2015] or simplified models that do not fully resolve the details of ice flow [*Ritz et al.*, 2015; *DeConto and Pollard*, 2016]. Previous simulations have shown that the predicted flow of ice across the grounding line depends sensitively on the resolution and mechanical approximations employed in models [*Schoof*, 2007a; *Cornford et al.*, 2015; *Pattyn et al.*, 2013]. To robustly assess the future behavior of West Antarctica, it is important to derive predictions using a variety of techniques.

The model used in this study [*Goldberg*, 2011; *Arthern et al.*, 2015] has a more complete representation of englacial stresses and velocities than earlier simulations of this sector [*Joughin et al.*, 2010; *Cornford et al.*, 2015]. The simulations build on previous work [*Kamb and Echelmeyer*, 1986; *Blatter*, 1995; *Pattyn*, 2002; *Bueler and Brown*, 2009; *Schoof and Hindmarsh*, 2010; *Joughin et al.*, 2010; *Favier et al.*, 2014; *Joughin et al.*, 2014; *Cornford et al.*, 2015; *Feldmann and Levermann*, 2015; *Ritz et al.*, 2015; *Golledge et al.*, 2015; *DeConto and Pollard*, 2016], with notable differences in model resolution, model formulation, inverse methods and other methodology that are outlined in section 2 and the supporting information.

Feedbacks from bed topography, basal drag, ice shelf buttressing, and melting are interrelated, but it is illuminating to consider their effects separately. As well as the marine ice sheet instability considered by *Weertman* [1974] and *Schoof* [2007a], two other important feedbacks can modify the response of the ice sheet. One is a negative feedback, wherein retreat forms larger ice shelves that provide more buttressing, restraining the delivery of ice to the ocean [*Gudmundsson et al.*, 2012]. A competing positive feedback is that larger ice shelves allow more melt within the subglacial ocean cavities that flood as the thinning Antarctic ice goes afloat. This melt can thin the ice shelves and lessen their capacity to provide the negative butressing feedback. This may promote and accelerate the retreat, but only if the combined effects of the positive feedbacks outweigh the negative buttressing feedback. Here we seek to clarify the circumstances under which this can occur and to establish whether positive or negative feedbacks are likely to dominate for typically observed rates of submarine melt in new ocean cavities.

2. Methods

We use a wavelet-based, adaptive-grid, vertically integrated ice sheet model (WAVI) to simulate the consequences of oceanographic melt for the sector of the Antarctic Ice Sheet that drains into the Amundsen sea.

The WAVI model, described in a previous paper [*Arthern et al.*, 2015], simulates the flow of grounded and floating ice. For melt beneath floating ice shelves to affect global sea level, the thinning of the floating ice must propagate inland, across the grounding line that separates grounded and floating ice. The model resolves the mechanical stresses and mass fluxes needed to simulate this process. A wavelet-based adaptive grid is used to accelerate the calculations [*Vasilyev and Kevlahan*, 2005; *Arthern et al.*, 2015].

Simulations were performed at model resolutions of 2 or 3 km. To adequately represent grounding line migration at this resolution, we implemented a subgrid parametrization of basal drag and driving stress near the grounding line [e.g., *Pattyn et al.*, 2006; *Gladstone et al.*, 2012; *Seroussi et al.*, 2014]. To allow comparison of the grounding line dynamics in our model with other models, we performed MISMIP3D and MISMIP+ experiments [*Pattyn et al.*, 2013; *Asay-Davis et al.*, 2015] (see the supporting information). These and other tests described in the supporting information indicate weak sensitivity to model resolution, without requiring a flux parametrization of the type used by lower resolution models [*Schoof*, 2007a; *Ritz et al.*, 2015; *DeConto and Pollard*, 2016].

Modeled retreat rates can be sensitive to how melting is applied at the grounding line [*Parizek et al.*, 2013; *Golledge et al.*, 2015]. We implemented a subgrid melting parametrization and performed two sets of simulations, either applying melt to partially grounded cells in proportion to their floating area fraction or restricting all submarine melting to fully floating cells. This produces faster or slower retreat respectively, and we show both sets of results.

Starting from an initial state that represents conditions in 2008 [*Fretwell et al.*, 2013; *Pritchard et al.*, 2009; *Arthern et al.*, 2006; *Le Brocq et al.*, 2010; *Rignot et al.*, 2011], we run the model forward in time for 100 years. Basal topography is from Bedmap2 [*Fretwell et al.*, 2013]. Englacial temperatures are fixed throughout the simulations [*Pattyn*, 2010]. We apply surface mass balance from *Arthern et al.* [2006].

The melt rate beneath the new ice shelves is prescribed as a parameter M that we vary over the full range of values recently observed [*Khazendar et al.*, 2016]. To isolate the effect of melting within new ocean cavities, temperatures and surface mass balance are held constant throughout the simulations and the calving front is fixed at the present location. On existing ice shelves melt rates are fixed at present-day values using the spatially variable melt rates that are needed to reproduce the observed rate of thinning [*Pritchard et al.*, 2012], a similar approach to previous studies [*Joughin et al.*, 2014; *Cornford et al.*, 2015].

Melting is stopped for any ice that goes aground. We also stop melt for ice less than 50 m in thickness to reflect the observation that high melt rates are not sustained on thin ice shelves in the region [*Rignot et al.*, 2013]. Retaining ice shelves at this minimum thickness up to the present calving front would likely provide more backstress than melange produced by disintegrating ice shelves or tidewater glaciers, so this represents a conservative assumption that slows the retreat. We examine the sensitivity to reducing the minimum thickness in the supporting information. To include the buttressing effect of unresolved ice rises [*Berger et al.*, 2016], we allowed our inversion for basal drag to produce nonzero values on floating ice, where this is needed to match the observed surface velocities. Later we consider the consequences of removing drag from these unresolved ice rises, to simulate what would happen if some proportion of them went afloat.

Fixing all climatic variables except M at present-day values does not capture expected variability over the 21st Century but shows the impact of varying the intensity of melting in new submarine cavities under the present climate, providing a systematic investigation of the submarine melt feedback. Three considerations support this approach. First, the anticipated warming of the Southern Ocean may be delayed by upwelling of older waters [*Armour et al.*, 2016], so that persistence of present melt rates on existing ice shelves can be considered a reasonable approximation for the 21st century. Second, ocean models currently show little skill at predicting the timing of wind-driven changes in the Southern Ocean and Amundsen Sea [*Hellmer et al.*, 2012; *Heuz et al.*, 2013; *Cornford et al.*, 2015; *DeConto and Pollard*, 2016]. Again, this lack of demonstrated skill favors a persistence based approach. Third, this simplified setup provides clarity as to the potential consequences of warmer ocean water entering the new cavities because all differences between the simulations can be attributed to the rate of submarine melting in new cavities, not some other aspect of the forcing.

The simulations of the 21st century start from a realistic initial state defined using data assimilation methods [*Arthern et al.*, 2015]. They show how the contribution to sea level varies as a function of the prescribed melt rate M when other quantities are held fixed. The simulated loss of grounded ice is separated into two components: one from melting that is already occurring beneath existing ice shelves, with no submarine melting feedback, and another from melting within the subglacial ocean cavities that flood as the grounding line retreats. We attribute this additional component of the sea level contribution to the submarine melting feedback.

3. Results

We ran the model with five different melt rates in new cavities: $M = [0, 10, 20, 50, 100]$ m a^{-1}. All are within the range of values observed in this sector of Antarctica [*Khazendar et al.*, 2016]. Middle and lower panels of Figure 1 show the ice sheet geometry after 100 years of simulation for three different melt rates: (middle left, lower left) $M = 0$ m a^{-1}; (middle middle, lower middle) $M = 20$ m a^{-1}; (middle right, lower right) $M = 100$ m a^{-1}. For the middle panels no melting was applied to partially grounded cells. For lower panels melting was applied in proportion to the floating area fraction. An animated version of this figure showing the retreat is included in the supplementary material. Figure 2 shows (a) the rate of sea level contribution $\dot{S}(t; M)$ at time t since the start of the simulation for the five different prescribed melt rates M and (b) the cumulative contribution $S(t; M)$ to sea level from these simulations.

When melting is restricted to fully floating cells, retreat rates are generally lower than when melt is also applied to partially grounded cells. For $M = [0, 10, 20, 50, 100]$ m a^{-1}, the sea level contributions over the century are, respectively, [8, 8, 8, 14, 29] mm when melt is restricted to fully floating cells and [10, 16, 26, 91, 339] mm when melt is applied to partially grounded cells.

The simulation with $M = 0$ m a^{-1} exhibits sustained retreat, contributing about 10 mm to sea level rise over the 21st Century. Extending this simulation to 400 years, the retreat continues, contributing 22.5 mm to sea level without reaching a stable configuration. This suggests the ice sheet is not presently in a stable equilibrium with recent climate forcing nor within 400 years of reaching one. This supports the argument that a sustained retreat of this sector of Antarctica may already be underway [*Joughin et al.*, 2014]. For $M = 0$ m a^{-1}, the retreat does not accelerate but slows over time, perhaps because increased buttressing compensates for retreat into deeper water [*Gudmundsson et al.*, 2012].

In general, the sea level contribution is an increasing, nonlinear function of the melt rate M imposed in new cavities. For simulations with melt restricted to fully floating cells there is low sensitivity to increasing melt rates M in new subglacial cavities until $M = 50$ m a^{-1}, beyond which the simulated sea level contribution triggered by melting in the new cavities accelerates over time. When melting of partially grounded cells is included, the sea level contribution accelerates for melt rates as low as 10 m a^{-1}. In both cases, the simulations reveal a threshold value of M beyond which the sea level contribution accelerates over time. For larger melt rates, retreat into the deeper subglacial terrain of West Antarctica and the lengthening of the grounding line seen in Figure 1 are important feedbacks that promotes more rapid loss of grounded ice.

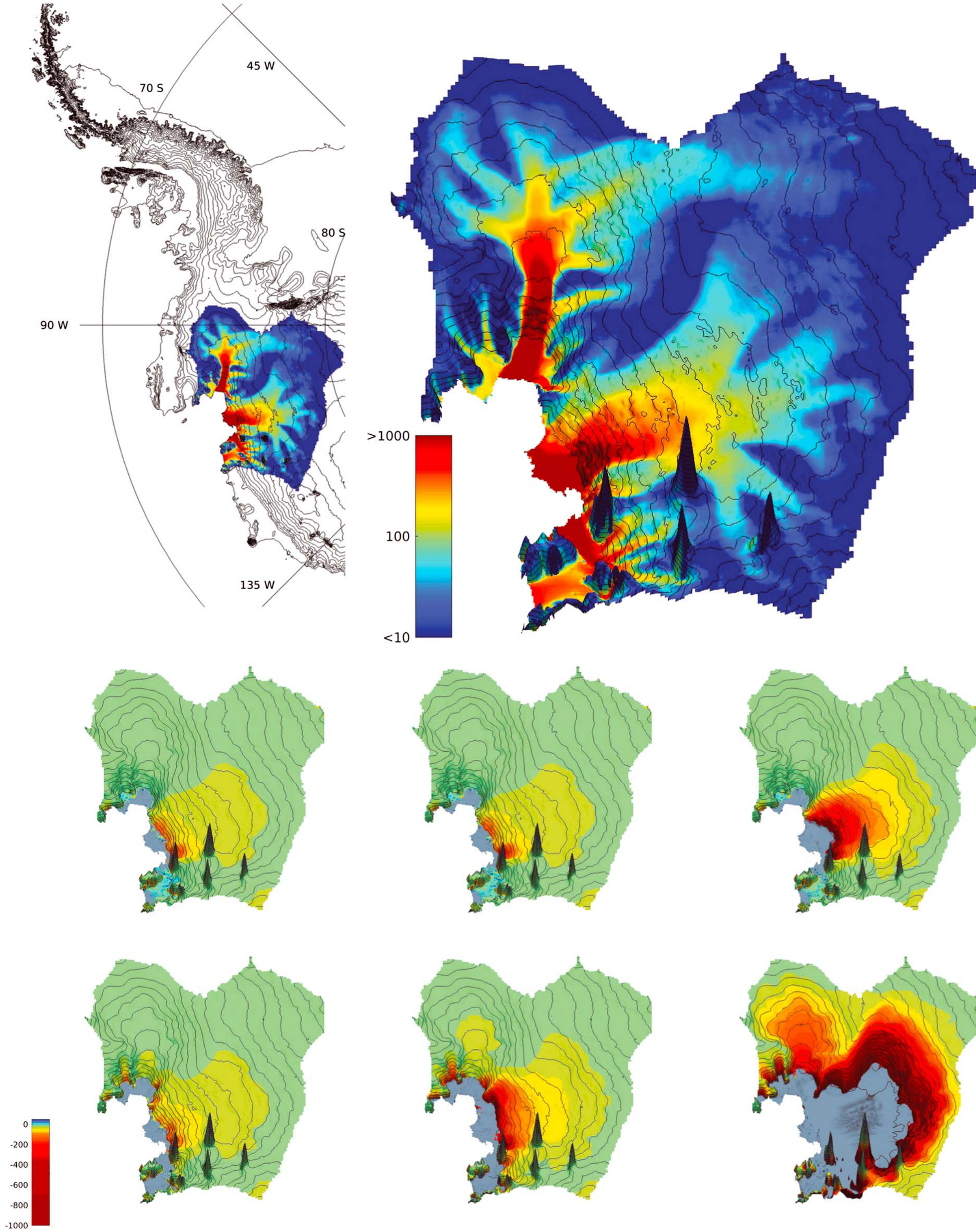

Figure 1. (top row) Model domain and initial state from data assimilation. Elevation contours are at 200 m intervals. Colors show surface velocities (m a^{-1}). (middle row) Simulated ice sheet geometry after 100 years of simulation for different prescribed melt rates M applied in new ocean cavities but not to partially grounded cells (colors show cumulative change in elevation (m) and floating ice shelves are shaded gray): $M = 0$ m a^{-1} (middle left); $M = 20$ m a^{-1} (middle middle); and $M = 100$ m a^{-1} (middle right); (bottom row) Same as for Figure 1 (middle row) but with melting applied in proportion to floating area fraction for partially grounded cells. The vertical scale is exaggerated in isometric views: steeply sloping conical features show mountains and rock outcrops.

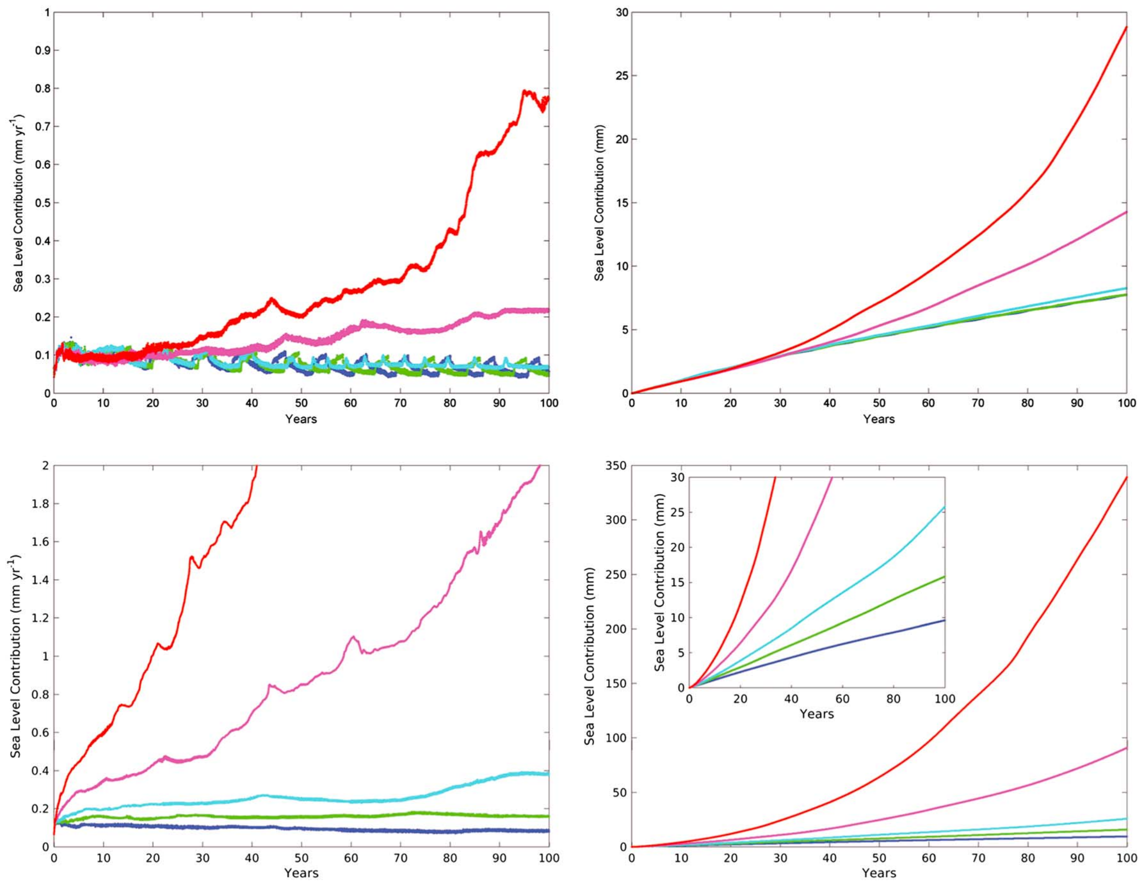

Figure 2. (top left) Simulated values for the rate of sea level contribution $\dot{S}(t;M)$ at time t, for different prescribed melt rates M applied in new ocean cavities but not to partially grounded cells: (blue) $M = 0$ m a^{-1}; (green) $M = 10$ m a^{-1}; (cyan) $M = 20$ m a^{-1}; (magenta) $M = 50$ m a^{-1}; (red) $M = 100$ m a^{-1}. (top right) Simulated values for the cumulative contribution to sea level $S(t;M)$ up to time t, with the same values of M represented by the same colors. (bottom row) Same as for Figure 2 (top row) but with melting applied in proportion to floating area fraction for partially grounded cells. The inset figure shows an expanded vertical scale.

Figure 3 (top left) shows Bayesian probabilities $p(S > S^*)$ of exceeding a particular sea level contribution S^* at time t. These probabilities are conditional on the applied forcing, so they apply if the calving front, surface mass balance, and other climate-related parameters remain fixed. They were derived using an exponential prior for M with mean $\bar{M} = 16$ m a^{-1}, which is comparable to observations of submarine melt rates beneath nearby ice shelves [*Rignot et al.*, 2013; *Depoorter et al.*, 2013]. This prior assigns probabilities of exceeding melt rates M = [0, 10, 20, 50, 100] m a^{-1} of, respectively, [1, 0.54, 0.29, 0.044, 0.0019]. For more details of the prior distribution see the supporting information [also *Jaynes*, 2003; *Arthern*, 2015]. Given the current planetary energy imbalance and projected heat uptake by the oceans [*Church et al.*, 2013], melt may increase in the future. Figure 3 (top right) shows probabilities for an exponential prior with mean $\bar{M} = 32$ m a^{-1}, similar to the average of observed values in regions where warm water incursion has occurred [*Khazendar et al.*, 2016]. This test shows that doubling the expected melt rate $\bar{M}$ would cause a particular probability for exceeding any given sea level contribution to occur earlier in time. This inverse relationship follows from results shown in Figure S5. Figure 3 (bottom row) shows results for the same two values of average melt rate, but corresponding to immediate floatation of all unresolved ice rises at the start of the simulation. Again, this causes any particular probability for exceeding any given sea level contribution to be exceeded earlier in time.

Because of the wider spread of melt rate values applied in our sensitivity experiment, and other differences in experimental design, it does not seem surprising that we obtain a wider spread than other studies of the Amundsen Sea sector forced by melt perturbations, for example, 0 to 50 mm [*Cornford et al.*, 2015] and 0 to 18 mm [*Feldmann and Levermann*, 2015]. We simulated the full spread of observed melt rates, but the prior probabilities that we assign consider values $M > 50$ m a^{-1} unlikely. Until future melt rates and the timing of ice rise floatation can be better constrained, the probabilities of Figure 3 remain provisional. In supporting

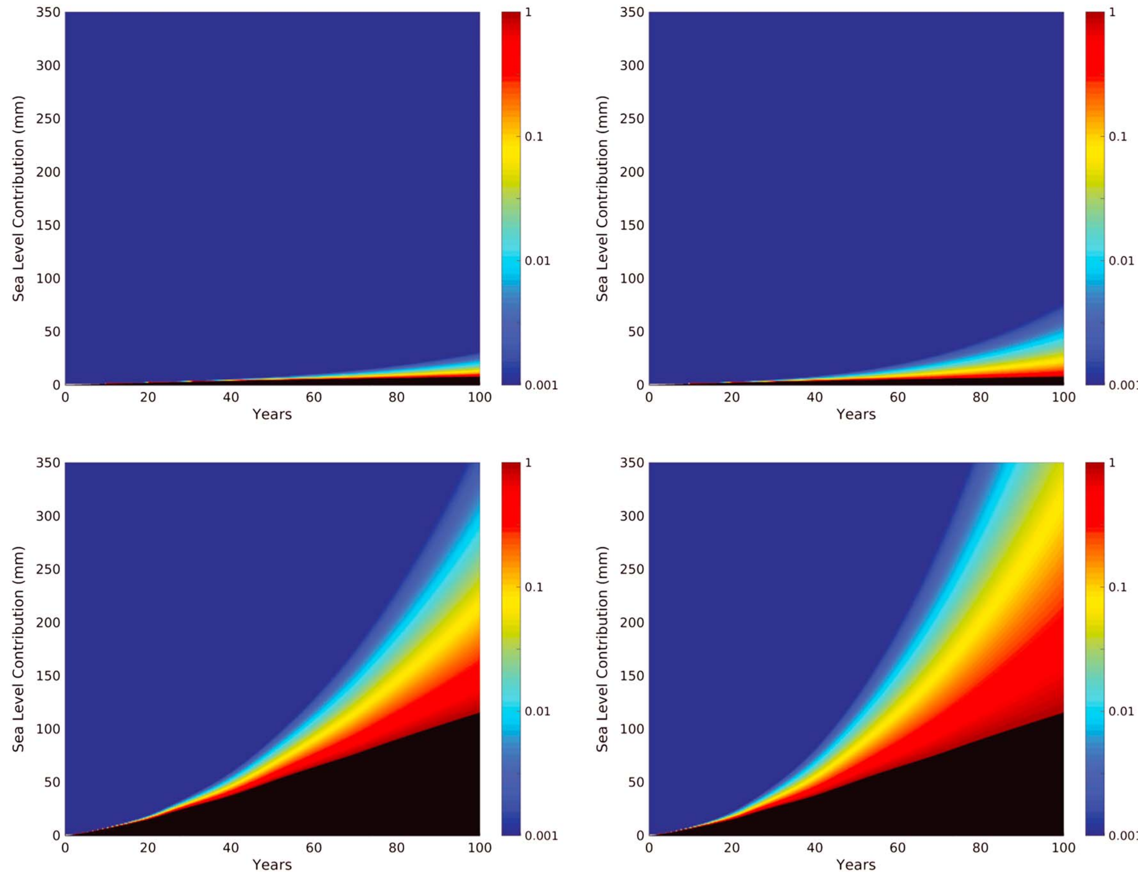

Figure 3. Conditional probability of exceeding a specified sea level contribution at different times if no melt is applied to partially grounded cells and the calving front, surface mass balance and other climate-related parameters remain fixed. The prior distribution for submarine melt rate in new ocean cavities is an exponential distribution with mean $\bar{M}$. Probabilities are shown, conditional on four different assumptions: (top left) $\bar{M} = 16$ m a^{-1}, no floatation of unresolved ice rises; (top right) $\bar{M} = 32$ m a^{-1}, no floatation of unresolved ice rises; (bottom left) $\bar{M} = 16$ m a^{-1}, immediate floatation of unresolved ice rises; and (bottom right) $\bar{M} = 32$ m a^{-1}, immediate floatation of unresolved ice rises. Contributions shown in black would require melt rates to decrease, basal drag coefficients to increase, or surface mass balance to increase.

information Figure S6, we show that applying melting to partially grounded cells can also change the probabilities by more than an order of magnitude relative to those shown in Figure 3.

The results are sensitive to whether melting is applied or not within partially grounded cells. Despite weak dependence on grid size, this may indicate failure to adequately resolve interactions between melting and basal drag close to the grounding line. If so, this is a noteworthy source of uncertainty. We expect at least some melting close to the grounding line, so not applying melt for partially grounded cells seems likely to underestimate the retreat rate, especially as melting near the grounding line can be effective at driving retreat [*Walker et al.*, 2008]. Conversely, applying melt to partially grounded cells may promote retreat that should not occur, since it allows submarine melt to drive floatation and loss of basal drag [*Golledge et al.*, 2015].

Physically, some interaction between melting and basal drag may be expected [*Parizek et al.*, 2013]. Retreat rates may prove to be sensitive to whether oceanic melting can thin the ice upstream of discrete pinning points that support basal drag, allowing them to go afloat. Sediment cores collected beneath Pine Island ice shelf indicate that this is a viable mechanism for loss of basal drag and acceleration of retreat [*Smith et al.*, 2017]. For now, the degree to which this mechanism applies at the subgrid scale remains uncertain, so it is not clear how much melting, if any, should be applied to the partially grounded cells. Theory to homogenize basal drag and submarine melting over a grounding zone with isolated pinning points would be useful, as would direct observations of submarine melt and basal shear close to the grounding line.

Reliable probabilistic forecasts will need additional information about the influential processes identified in our simulations and more consideration of the effects of spatial variations in submarine melting

[*Walker et al.*, 2008; *Gagliardini et al.*, 2010]. We did not include glacial isostatic adjustment or gravitational feedbacks. Under our conservative forcing we have not included climatic variations, changes to the calving front [*Fürst et al.*, 2016], changes to basal drag caused by altered subglacial hydrology, or hydrofracture and ice cliff failure [*DeConto and Pollard*, 2016]. These processes all merit further investigation.

The behavior seen in the simulations is characteristic of tipping elements in the Earth system [*Lenton et al.*, 2008] but indicates that accelerating loss of ice from West Antarctica is not driven purely by the mechanical marine ice sheet instability considered by *Weertman* [1974] and *Schoof* [2007b]. The retreat accelerates only if melting within new cavities exceeds some threshold, so that positive feedbacks outweigh negative feedbacks. In our simulations melting does not trigger an instability in a previously stable ice sheet, but it lessens the negative feedback produced by buttressing as the ice sheet retreats. Melt in excess of the threshold restores the marine ice sheet instability that is inherent in the system but would otherwise be masked by buttressing. This produces more retreat, more floatation, and yet more melt. Over time, the nonlinearity of this response can significantly increase the rate of sea level rise.

Loss of grounded ice increases monotonically with the melt rate M for all values considered here. This suggests that retreat is limited by supply of heat from the ocean, not some timescale inherent to ice dynamics. This highlights the importance of simulating accurately the timing of heat delivery from the ocean to the ice sheet over the 21st Century [*Hellmer et al.*, 2012; *Armour et al.*, 2016]. Observations or modeling that constrain melt rates will be extremely valuable in assessing the risk of sea level rise over the 21st century.

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