The present day retreat of Pine Island Glacier is subject to marine ice sheet instability

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Over the last 40 years Pine Island Glacier in West Antarctica has thinned at an accelerating rate ([1]; [22]; [30]), so that it is currently the largest single contributor to sea-level rise in Antarctica [26]. In recent years, the grounding line, which separates the grounded ice sheet from the floating ice shelf, has retreated by tens of kilometres ([17]). At present, the grounding line is crossing a retrograde bedrock slope that lies well below sea level, raising the possibility that the glacier is susceptible to the marine ice sheet instability mechanism ([24]; [3]; [11]). Here, using three state-of-the-art ice flow models ([5]; [2]; [9]), we ~~calculate~~show that Pine Island Glacier's grounding line is likely engaged in an unstable 40 kilometre retreat. The associated mass loss increases substantially over the course of our simulations from the average value of 20 Gt a^{-1} observed for the 1992-2011 period [26], up to and above 100 Gt a^{-1} equivalent to 3.5–10 mm eustatic sea-level rise over the following 20 years. Mass loss remains elevated from then on, ranging from 60 to 100 Gt a^{-1}.

Currently Pine Island Glacier (PIG) is responsible for 20% of the total ice ~~loss off~~discharge from the West Antarctic Ice Sheet (WAIS) ([22]; [30]). The accelerated thinning observed since the 1980s has essentially been attributed to enhanced sub-ice shelf melting [21] induced by the recent alteration of Circumpolar Deep Water circulation [10]. This has reduced the buttressing exerted by the ice shelf, leading to the acceleration of the ice stream and the ongoing retreat of the grounding line (GL) along the glacier's trunk observed since 1992 [17]. Today the GL lies over bedrock that has a steep retrograde slope [29] (Figure 1c) raising the possibility that PIG may already be engaged in an irrevocable retreat. ~~Provided~~Assuming that ice flow is dominated

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by basal sliding and lateral variation can be ignored, grounding lines located on retrograde slopes are always unstable [24, 3], but in realistic, three-dimensional geometries lateral drag and buttressing in the ice shelf can act to prevent unstable retreat [9]. Assessing the stability of PIG therefore requires numerical models that accurately represent these additional forces. Models designed to study the evolution of PIG have been reported, though limited to flowline geometries [7] or extreme forcings [11]. Overall, the short-term behaviour of PIG is not well understood, and projections vary wildly, ranging from modest retreat to almost full collapse of the main trunk within a century [11, 7].

Here, we evaluate the potential instability of PIG and its short-term contribution to sea-level rise (SLR) using state-of-the-art ice flow models. To decide whether PIG is subject to Marine Ice Sheet Instability (MISI) at present, we must answer two questions: (i) to what extent is the dynamic response of PIG to changes in its ice shelf dictated by the bedrock topography rather than the type and amplitude of the perturbation, and, (ii) can the GL be stabilized on the retrograde slope? Confidence in the answers we propose is of course affected by the accuracy of both the physics implemented in the models that we use and our estimates of poorly constrained parameters. We addressed these questions using three different ice-flow models: the full Stokes model *Elmer/Ice* [5] and two vertically-integrated models: the hybrid (L1L2) model *BISICLES* [2] and the Shallow Shelf Approximation (SSA) model *Úa* [9]. All three models participated in the MISMIP3D inter-comparison project [19] and showed similar GL dynamics, though the SSA solution differed most (Supplementary, Section 1.2). Any model of a real glacier suffers from incomplete data sources over and above any shortcomings in model physics: we reflect this inevitable source of error to some extent by having the three models make different assumptions about ice viscosity and basal flow conditions (Supplementary, Section 3.2).

For all three models, the geometry is relaxed over 15 years to remove unphysical surface undulations induced by remaining uncertainties in the model initial conditions [6]. Surface accumulation is given by the regional atmospheric model RACMO (1980-2004 period, [28]) and sub-ice shelf melting is imposed as a piecewise linear function of ~~the lower surface elevation~~water depth with a maximum melting rate of 100 m a^{-1} below -800 m ~~depth~~, linearly decreasing to no melt above -400 m. This melt-rate parametrisation, which we will refer to as ~~*m0*~~ *control*, is in reasonable agreement with the amplitude and the enhanced melting close to the GL that are inferred from observations [4], but is clearly less sophisticated than coupling with an ocean circulation model, as for example in [8]. The resulting initialization procedure leads to good agreement with observations for the three models, with a contribution to SLR comparable to the average estimate of about 20 Gt a^{-1} over the past 20 years [26]. Afterwards, the contribution remains similar during the 50 years of the control run (Figure 2). The initial state of each model is described in more detail in the Supplementary, Section 4.2.

The recent retreat of PIG is now firmly attributed to acceleration of the glacier in response to sub-ice shelf melting. To evaluate the consequences of melting on PIG dynamics, ~~five~~four different melt-rate perturbations are tested. These are described in detail in the Supplementary Information, Section 3.3, but in brief, *m1* doubles the peak melt-rate of ~~*m0*~~ control, *m2* ~~and *m4*~~ extends the region of melting to a larger portion of the ice shelf, *m3* does both, and ~~*m5*~~ *m4* is initially the same as *m2* but is limited to the region of the present day ice shelf even if the grounding line retreats. The amplitudes of these melt-rate perturbations are plausible when compared to observational and modelling results ([4]; [20], Supplementary Information, Section 2.2). For *Elmer/Ice*, the *m1* melt-rate distribution does not alter the GL position but the remainder leads to significant retreat. *BISICLES* exhibits retreat in all ~~five~~four cases, but the response to *m1* is delayed by 20 years. Once *Elmer/Ice* and *BISICLES* have started to retreat, they behave similarly. The GL retreats by 40 km over the retrograde slope within a few years and the rate of contribution to SLR reaches a peak of almost 130 Gt a^{-1} (Figure 2), after which the rate of retreat diminishes. The associated rate of contribution to SLR also reduces after the rapid retreat but mass imbalance remains elevated, at between 60 and 120 Gt a^{-1}, i.e., 3 to 6 times higher than before the perturbation was imposed. Imbalance estimations made by *BISICLES* are generally higher than those made by *Elmer/Ice*: the GL of the former model being more prone to ~~keep~~continued retreating over gentle slopes. *BISICLES* is indeed known to react slightly faster than *Elmer/Ice* [19]; alternatively the spatial resolution of *Elmer/Ice* may be insufficient to properly model a moderate retreat rate (details in the Supplementary information, Section 4.1). We see similar patterns of retreat when we consider different perturbations, such as calving events (Supplementary information, Section 4.1), or alternative melt-rate parametrizations (Supplementary information, Section 5.2). The response to the melt-rate perturbations is different ~~with~~for *Úa* as *m1* and *m3* lead to substantial retreat, while *m2* leads to less of a response. Once retreat starts, though, the *Úa*'s GL steadily retreats and the contribution to SLR continuously increases up to 250 Gt a^{-1}, leading to a rapid collapse of the main trunk. The faster retreat computed by *Úa* might be explained by the SSA model itself [19], but also might be related to the model's parameters. For example, *Úa* computes the fluidity, A, and hence the effective viscosity, in a different way (Supplementary, Section 3.2). Viscous stresses play a vital role in the dynamics close to the GL but are much less important far from it [24], so that models with quite different ~~A~~viscosity can reproduce the observed velocity equally well, but diverge from one another as the GL retreats.

We explore the degree of irreversibility further by carrying out experiments where the melt-rate is reduced as soon as the PIG GL starts retreating ~~irrevocably~~. In each ~~of these~~experiment, the most moderate perturbation that leads to retreat (*m2* for *Elmer/Ice* and *BISICLES* and *m1* for *Úa*) is applied until the acceleration of the dynamic contribution to SLR reaches a maximum, at which point the melt-rate reverts to ~~*m0*~~*control*. For *Elmer/Ice* and *BISICLES*, this slightly impacts ice dynamics: the GL keeps retreating and the imbalance is not significantly affected when crossing the bedrock steep retrograde slope area. However, it does limit both further retreat and the imbalance that persists once the bottom of the trench is reached (see Figure 3). *Úa* behaves quite differently, with the GL returning to its original location after an initial retreat across the retrograde slope. We examine further the conditions under which a complete reversal could occur by conducting similar experiments where the melt-rate is reduced to 75, 50, 25, 10 or 5% of ~~*m0*~~ *control*. The glacier recovers its initial state in all of the *Úa* simulations, but only when the melt-rate is reduced to 10% of ~~*m0*~~ *control* or less for Elmer/Ice and 25% or less for *BISICLES*. Most importantly, none of the models produce a steady GL on the reverse slope. Further experiments along these lines are described in the Supplementary, Section 5.2.

In summary, we find that re-advance takes place because a large reduction of melt-rates lowers the bottom surface which then regains contact with elevated points on the bedrock. Grounded pinning points increase the buttressing force exerted by the ice shelf, reduce imbalance and may slow down the GL retreat add and possibly induce a readvance of the GL. Note that the presence of pinning points is not a sufficient condition for stabilizing the ice sheet; the MISI may still occur if only weak grounded pinning points have been formed (Figure 3). As the initial position of the GL before perturbation can only be regained if the melt-rate is reduced substantially and to far less than the currently observed value, reversibility of the present retreat of PIG looks unlikely.

Our study shows that for the next ~~few years~~decade the PIG GL is likely engaged in an irreversible retreat over tens of kilometres and that the dynamic contribution to SLR will remain at a significantly higher level compared to pre-retreat conditions. All three models, despite their differing physics, numerics and parameters, support the notion of MISI in PIG, and two out of three cast doubt on any possible recovery. Starting from the first years of significant imbalance increase, the variation of the mass loss between experiments after 20 years is relatively narrow with a cumulative contribution to SLR of 3.5–10 mm over this period (Figure 4). Afterwards, estimates diverge dependent on further retreat of the GL across a region of gentler slopes and stronger basal traction behind the instability zone. Once the GL has crossed the steep retrograde slope, imbalance decreases but remains between 3 and 6 times higher than the mean estimates obtained for the last 20 years (20 Gt a^{-1}, [26]).

Methods

Models and numerics. Simulations were carried out with three ice flow models. *Elmer/Ice* [5] solves the full Stokes set of equations in 3D, *BISICLES* and *Úa* are based on L1L2 [25] and SSA [16] models, respectively, and solve simplified vertically integrated equation sets that retain all but vertical shear stress terms, which are ignored in the SSA model and parametrised in the L1L2 model. *Elmer/Ice* applies a finite element method on a fixed and horizontally unstructured locally refined grid, *BISICLES* a finite volume method on a block-structured adaptive mesh and *Úa* a finite element method on a refined grid.

Inputs. *Elmer/Ice* and *BISICLES* interpolate topographic data from a 1 km mesh grid version of the ALBMAP dataset, computed using similar methods described in [13]. Temperatures were computed on a 5 km grid in [18] and do not evolve with time. Surface velocities were acquired during the last International Polar Year [23] and accumulation rates are given by regional atmospheric modeling [28]. In *Úa* the topography is constrained using [27] bedrock and surface altitude datasets and [15] ice-shelf thickness dataset, surface velocities are given by [12] and surface accumulation by [14].

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Author contributions

LF and GD designed the experiments. LF did the numerical modelling with *Elmer/Ice*, SLC with *BISICLES* and GHG with *Úa*. OG, FG and TZ contributed to the set-up of *Elmer/Ice*, AJP contributed to *BISICLES*. AMLB provided the high resolution topographic input dataset that has been used by *Elmer/Ice* and *BISICLES*. LF, GHD and SLC led the writing of the manuscript which has been improved by all authors.

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Figure 1: (a) Relaxed surface velocities plotted on the *Elmer/Ice* computational domain, the solid black line represents the relaxed GL. (b) Domain zoom-in with the bedrock elevation (in m). The 2011 GL from [17] is shown in purple, the 2009 GL from [11] is in white. (c) Geometry of PIG produced by *Elmer/Ice* along the yellow flowline shown in (a) at t=0 (dotted line) and after 50 years under melting scenario *m2* (red line). ~~The red line shows the steepest retrograde slopes where the instability is the most likely.~~

Figure 2: Results of the melting experiments for *Elmer/Ice* (left), *BISICLES* (middle) and *Úa* (right, for which *m4* is similar to *m2* and not therefore visible) for: change in grounded areas (top row) and annual contribution to SLR (middle row). *Elmer/Ice* and *BISICLES* respond to enhanced melting ~~by~~with a rapid retreat across the steep reverse slope followed by slower retreat thereafter, while *Úa* increases its rate of retreat throughout the simulations. The ~~third~~bottom row shows the bedrock altitude (m) and the initial GLs for each model (solid black line), as well as the GLs, computed during the *m2* experiment, at the beginning (solid red lines) and at the end (dashed red line) of the rapid retreat for *Elmer/Ice* and *BISICLES* (*Úa* is not shown here because of the difficulty ~~to identify those~~of identifying these two times). Corresponding times are indicated by a square and a circle respectively in the upper rows. The ~~third~~bottom row also shows the areas (shaded) separating the GL as observed in 2011 (purple line, [17]) from the relaxed model GLs, which cover 364±50 km^2, 426±50 km^2 for *Elmer/Ice*, *BISICLES*, respectively (not shown for *Úa* because of the non continuous profile of the GL). The thick grey lines in the top row indicate the same area.

Figure 3: ~~Results of the reverse experiments for *Elmer/Ice* (left), *BISICLES* (middle) and *Úa* (right)~~Retreat reversibility experiments starting from the *m2* experiment for *Elmer/Ice* (left) and *BISICLES* (middle), and from the *m3* experiment for *Úa* (right), in terms of change in grounded areas (top row) and annual contribution to SLR (middle row). The third row shows the bedrock (in m) with GLs taken at times symbolized by a square in the upper rows. The thick horizontal grey line in top row is reproduced from Figure 2 and represents the 2011 GL observed by [17]. The *Elmer/Ice r25* simulation does eventually retreat across the MISI zone (as shown in the Supplementary, Figure 14.)

Figure 4: Integrated contribution to SLR for melting experiments that produces a GL retreat. The results have been shifted to equal a null contribution at the year 2011 which is also the year of the last measured GL [17]. The corresponding offsets were estimated from the intersection between thick grey lines and changes in grounded areas from the first row in Figure 2.