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that is currently provided by a prominent seabed ridge. Recently published research has shown that PIIS may exhibit a strong melting response to calving, with melting close to the PIG grounding line always increasing with ice front retreat. Here, we describe this research and, additionally, place the results in a glaciological context by comparing melt-induced and ice-dynamical changes in the ice shelf thinning rate immediately following calving. We find that PIIS is expected to experience rapid acceleration in response to further retreat. However, the mean instantaneous thinning response is set predominantly by melting, with further ice front retreat expected to lead to enhanced thinning, with potentially serious consequences for ice shelf stability.

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The ice dynamic and melting response of Pine Island Ice Shelf to calving

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ABSTRACT. Sea level rise contributions from Pine Island Glacier are strongly modulated by the backstress that its floating extension – Pine Island Ice Shelf (PIIS) – exerts on the adjoining grounded ice. The front of PIIS has recently retreated significantly via calving, and satellite and theoretical analyses have suggested further retreat is inevitable. As well as inducing an instantaneous ice-dynamic response that is expected to result in acceleration, retreat of the PIIS front may result in increased ocean melting, by relaxing the topographic barrier to warm ocean water that is currently provided by a prominent seabed ridge. Recently published research has shown that PIIS may exhibit a strong melting response to calving, with melting close to the PIG grounding line always increasing with ice front retreat. Here, we describe this research and, additionally, place the results in a glaciological context by comparing melt-induced and ice-dynamical changes in the ice shelf thinning rate immediately following calving. We find that PIIS is expected to experience rapid acceleration in response to further retreat. However, the mean instantaneous thinning response is set predominantly by melting, with further ice front retreat expected to lead to enhanced thinning, with potentially serious consequences for ice shelf stability.

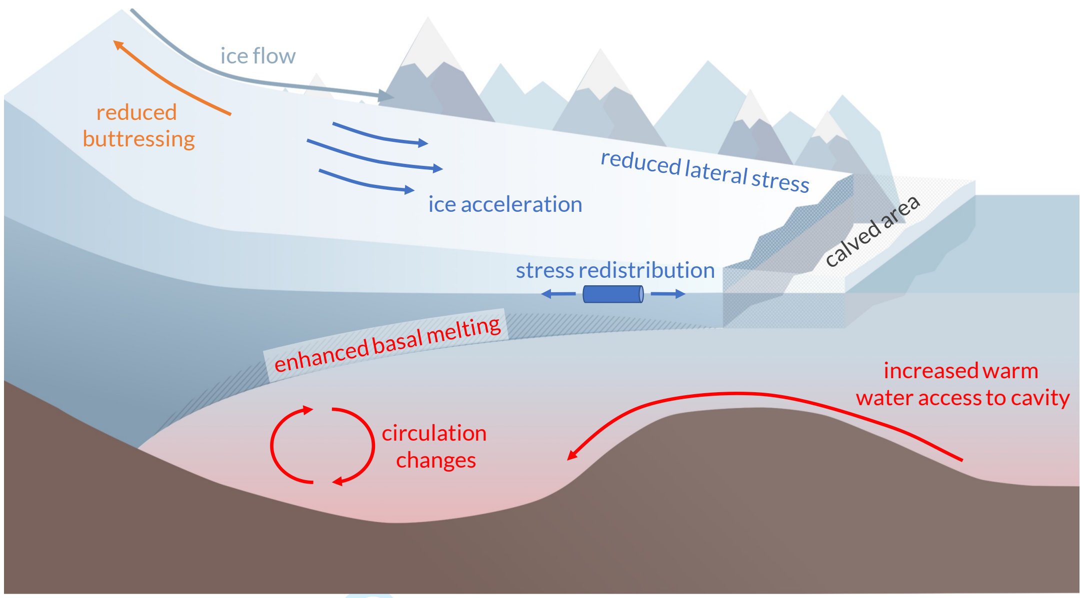

Fig. 1. Which process occur in the instantaneous response of PIIS to ice front retreat? Red and blue labels indicate ocean and ice-dynamic processes which might result from ice front retreat, respectively.

Ice sheets mainly contribute to sea level rise via increases in ice flow from their grounded parts into their floating ice shelves, across their grounding lines. Flow of ice across the grounding lines of, and thus sea level rise contributions from, ice sheets are often strongly modulated by their ice shelves via the backstress they exert on the grounded ice (Gudmundsson and others, 2019). This backstress, often referred to as buttressing, is the result of several processes, such as contact with ice margins and ice rises, confinement in valleys, and stresses within the bulk of the ice shelf.

How important a particular ice shelf is for buttressing of the adjoining grounded ice depends on the specific glacier characteristics. Pine Island Glacier (PIG) in West Antarctica, which is currently Antarctica's largest contributor to sea level rise (IMBIE, 2018), is an example of a glacier whose flow is strongly influenced by its ice shelf. PIG has accelerated significantly over the satellite era: in 2013, its trunk was flowing approximately twice as fast (approximately 4 km/yr) as in the mid-1970s (approximately 2 km/yr) (Mouginot and others, 2014); many studies have implicated melt-driven thinning of its ice shelf, and the resulting loss of buttressing, in this acceleration (Favier and others, 2014; Joughin and others, 2010, for example), while recent research has suggested that reductions in buttressing that resulted from large scale calving events also played an important role (De Rydt and others, 2021). However, the large (approximately 12%) speed-up of PIIS in 2020 is thought to have been caused entirely by the ice-dynamic response to reduced ice shelf buttressing following an ice front retreat of approximately 19 km that occurred

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in early 2020 (Joughin and others, 2021), and melt driven thinning did not play a role.

In addition to significant recent retreat, further ice front retreat of PIIS appears highly likely: the recent calving of PIIS was coincident with a recent rapid increase in ice shelf damage (Lhermitte and others, 2020), which is thought to have preconditioned the shelf for further calving. Furthermore, loss of buttressing as a result of ice front retreat may also promote further calving via a damage-calving feedback loop (Sun and others, 2017) in which ice front retreat reduces buttressing, leading to ice acceleration, enhanced shear stresses, increased ice damage and ultimately further calving.

In addition to an ice dynamic response, there may be changes to melt rates on PIIS following ice front retreat. This is because the topographic blocking by the combination of a seabed ridge beneath PIIS and the ice shelf itself reduces the amount of relatively warm water that is able to reach a cavity inshore of the ridge, restricting the amount of melting that can take place (Dutrieux and others, 2014; De Rydt and others, 2014). Ice front retreat might be expected to relax this topographic barrier and thus change melt rates on PIIS.

To investigate the possibility of a PIIS melt response to calving, we performed numerical experiments in which we explicitly resolved the ocean cavity circulation and ice shelf melting using the Massachusetts Institute of Technology General Circulation Model (Marshall and others, 1997) in a geometry accurately resembling Pine Island Glacier (see Bradley and others (2022a) for a full model description). We performed six experiments in total, each featuring a different ice front position (figure 2a). (We fixed the grounding line position and ice thickness in sections of shelf not removed in each experiment.) By comparing melt rates between experiments with different ice front positions, we gain insight into the melt response to calving. We found that (Bradley and others, 2022a), while the maps of melt rate display complex patterns of change upon ice front retreat (figure 2b), the melt rate close to the grounding line of PIIS increases monotonically with retreat (figure 2c): i.e. assuming that nothing else about the geometry changes, ice front retreat always enhances melting. This increase in melting is the result of both an increase in the amount, and temperature, of relatively warm water crossing the seabed ridge, as well as changes in the ice shelf cavity circulation as ice front retreat proceeds (figure 1).

As mentioned, ice front retreat induces an instantaneous ice dynamic response, in addition to the melt response, as the ice sheet adjusts mechanically to the loss of a section of its restraining ice shelf. To facilitate a comparison between the melt and ice dynamic responses to calving, we consider conservation

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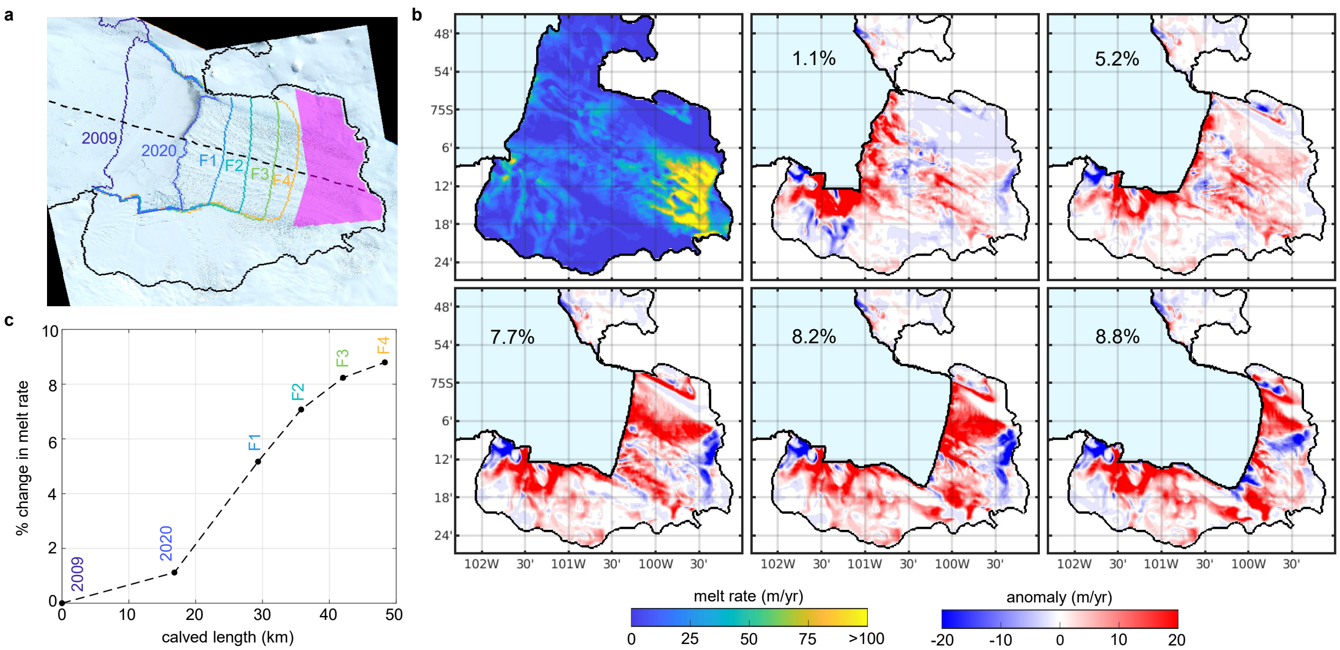

Fig. 2. (a) Ice front positions used in experiments designed to assess the melt response of the Pine Island Ice Shelf to calving. Each experiment corresponds to a different ice front position: labelled purple and blue ice fronts correspond to the 2009 and 2020 ice front positions, respectively, and the curves labelled F1–F4 correspond to possible future ice front positions. The solid black line indicates the location of the 2009 grounding line from Joughin and others (2010). The dashed line roughly indicates the centreline of the cavity, along which the calved length – the difference between the ice front in the respective experiments and the 2009 ice front – is measured. The shaded pink 'inner cavity' region indicates the section of the ice shelf close to the grounding line over which the mean melt rate values used to generate (c) are calculated. The background image is a Sentinel 2 mosaic from November 2020 (ESA, 2020). (b) Simulated melt rate in the 2009 Pine Island geometry (first panel) and cumulative (i.e. measured to the first panel) melt rate anomalies (other panels). Numbers indicate the percentage enhancement in mean melt rate over that in the 2009 geometry in the inner cavity region. (c) Percentage enhancement in melt rate as a function of calved length measured relative to the 2009 geometry. Values correspond to those shown as labels in (b).

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of mass, which requires the following to hold:

$$\frac{\partial h}{\partial t} + \nabla.(h\mathbf{u}) = -\dot{m}. \tag{1}$$

Here h is the ice thickness, $\mathbf{u}$ the depth-averaged ice velocity, $\dot{m}$ the basal melt rate (where positive indicates melting), and we have neglected surface accumulation, which is typically small in comparison with ice shelf melting on PIIS (Van den Broeke and others, 2011, for example).

The melt response enters equation (1) explicitly via the right-hand side, while the ice dynamic response enters via the second term on the left-hand side: changes in buttressing following ice front retreat affect the ice shelf velocity $\mathbf{u}$ and thus flux divergence $\nabla.(h\mathbf{u})$. Thus, the instantaneous ice-dynamic and melt responses to ice front retreat may be compared by considering their effects on the thinning rate (first term on the left-hand side of equation (1)).

To assess the instantaneous ice-dynamic response of PIIS under the calving scenarios described above, we use the ice sheet model Úa (Gudmundsson, 2022), with setup as described by De Rydt and others (2021), to determine the PIG ice velocity with the ice front positions shown in figure 2a. Comparing the ice velocity and flux divergence in these simulations gives an indication of the ice-dynamic response to calving, and thus, by comparing with the ocean simulations described above, an indication of the relative importance of ice-dynamic and melt responses to calving.

In figures 3a and e we respectively show the modelled ice velocity of PIG using the 2009 ice front, and the modelled ice velocity anomalies as the ice front is retreated (relative to the 2009 ice front configuration), i.e. the ice velocity response to ice front retreat. We see that further ice front retreat of PIIS is expected to induce significant acceleration. This increase is in velocity approximately linear in the length of the section of ice front removed (figure 3i). We predict an approximately 115 m/yr ice speed-up for every 5 km length of ice shelf removed, which is the current yearly ice front retreat rate of PIIS (Joughin and others, 2021); for reference, the mean (predominantly melt-driven) speed-up of PIIS between 1970 and 2010 was approximately 40 m/yr^2 (Mouginot and others, 2014), i.e. future ice front retreat is expected to lead to a significant increase in PIG acceleration.

In figure 3b–d we show, respectively, the negative melt rate, negative flux divergence, and effective thinning rate (sum of the negative melt rate and negative flux divergence, see equation (1)) in the experiment with the 2009 ice front, alongside the anomalies of these quantities in the calved scenarios (f–h). The large ice velocity response to ice front retreat is also borne out in the maps of flux divergence response,

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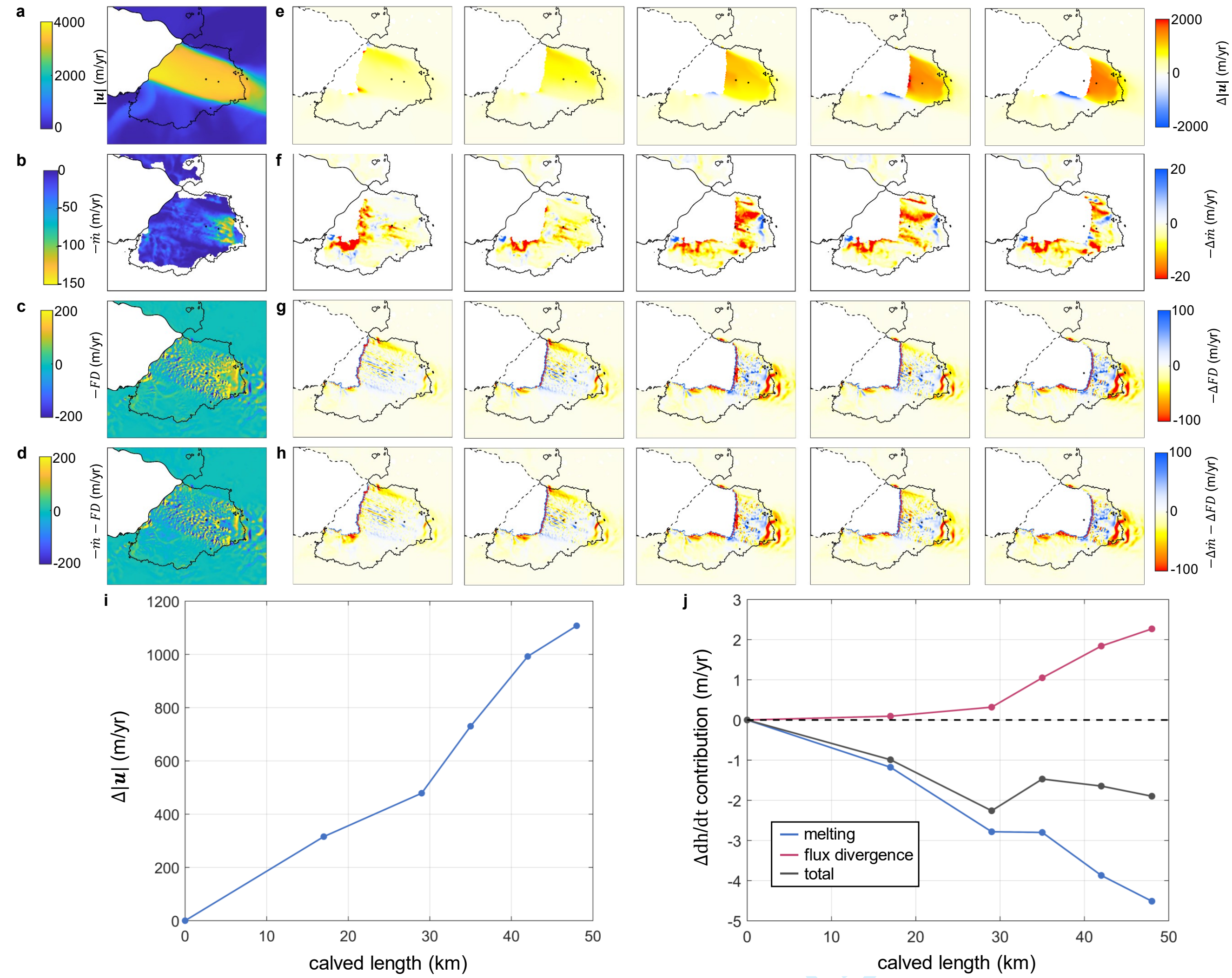

Fig. 3. Comparison of the instantaneous ice-dynamic and melt response to PIIS calving. (a) modelled PIG ice velocity and (e) velocity perturbations when sections of the ice front are removed. (b)–(d) Basal melt rate $\dot{m}$, negative flux divergence $-FD = -\nabla.(h\mathbf{u})$, and thinning rate $\dot{m} - \nabla.(h\mathbf{u})$ (i.e. the sum of (b) and (c)), alongside (f–h) perturbations in these quantities when sections of the ice front are removed. Note the different colorbar limits in (f) and (g–h). (i) Mean velocity perturbation measured over the inner cavity region (pink box in figure 1a), relative to the experiment with the ice front in the 2009 configuration. (j) As in (i) but for the melt, flux divergence and total perturbations (the total is the sum of melt and flux divergence perturbations). Note that the slight discrepancy between the melt rate data presented here and that shown in figure 3c is because a slightly different grounding line is used here (the grounding line here is from 2016 (De Rydt and others, 2021), whereas the experiments shown in figure 2 use a 2009 grounding line (Joughin and others, 2010)).

which are, in many places, an order of magnitude larger than the corresponding melt response (noting the different limits on the colour bars in f and g–h). Equivalently, the patterns of thinning rate perturbations (figure 3h) are highly similar to the patterns of flux divergence perturbations (figure 3g). Although the patterns of flux divergence perturbations are highly variable, featuring regions of large positive and negative anomalies, the mean flux divergence response in the inner cavity region (the pink box in figure 2a) is positive and increasing (figure 3j), indicating that flux divergence changes following ice front retreat always promote shelf thickening (positive $\mathrm{d}h/\mathrm{d}t$), which is consistent with the picture of increased ice advection into the shelf associated with increased ice velocity. However, we see that the positive flux divergence response contribution is outweighed by the negative melting response contribution to the thinning rate response (figure 3j): i.e. our simulations suggest that the instantaneous response to calving is always *further thinning*. This highlights the crucial role that changes in melting following ice front retreat might play: without a change in melting following ice front retreat, the instantaneous response would promote regrowth; however, as a result of the changes in melting, we expect further ice shelf thinning following ice front retreat.

Due to the geometric feedbacks of melting and ice-velocity shown above, investigating the post-instantaneous response of PIIS to ice front retreat in detail requires the use of a coupled ice-ocean-calving model. However, such models are not yet available: coupled ice-ocean modelling is in its infancy (Asay-Davis and others, 2017), with most projections still relying on parametrizations of ice shelf melting (Bradley and others, 2022b). In addition, coupled ice-calving modelling is a nascent field (Todd and others, 2018, for example), and, to the authors' knowledge, there are no extant coupled ice-ocean-calving models. The potential imminence of PIIS's decline, and understanding the implications of such, should provide significant, urgent motivation to the modelling community to develop such models. Additionally, numerical models rely on observations to determine unknown parameters, such as those related to ice fracture toughness (an essential component in models of ice shelf fracture and calving) and ocean bathymetry (to constrain ocean geometric feedbacks); thus, accurate projections of the future of ice sheets in a changing climate naturally requires a strong observational record.

Although the analysis included in this paper does not permit us to make quantitative predictions of the transient evolution of PIIS following calving, we can speculate on the longer term implications of the response to ice front retreat described here. Firstly, we have shown that the instantaneous response to ice front retreat is further ice shelf thinning. Since enhanced ice shelf thinning promotes further calving (Liu

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and others, 2015, for example), there is the potential for a retreat-melting feedback loop in which ice front retreat enhances melting, which in turn promotes enhanced calving and thus ice front retreat, potentially encouraging collapse of the PIIS. Ice shelf collapse might additionally be expedited by a retreat-damage feedback loop: the simulated ice acceleration that accompanies ice front retreat might enhance ice shelf damage (Sun and others, 2017, for example) and thus precondition the shelf for further calving and ice front retreat (Lhermitte and others, 2020, for example). Finally, ice acceleration would be expected to be accompanied by thinning, which has the potential to alter the cavity geometry and influence the melt rate. In particular, thinning that further increases the gap between the seabed ridge and ice shelf would be expected to result in an increase in the flux of relatively warm water across the seabed ridge and thus increase melt rates close to the PIIS grounding line (De Rydt and others, 2014; Bradley and others, 2022a).

The recent acceleration and retreat of Pine Island Glacier is alarming, and the possibility of the collapse of its restraining ice shelf now appears more likely than ever before. We have shown that future ice shelf front retreat is expected to lead to significant acceleration of the adjoining grounded ice, which might additionally promote further calving via a damage-acceleration-calving feedback loop. The acceleration of the grounded ice may be exacerbated by an increase in ice shelf melting in response to ice front retreat, with this melt response promoting further thinning and thus possibly further calving. An extreme acceleration of the Pine Island Glacier, as suggested by our simulations, would undoubtedly have significant consequences for the future of, and thus sea level rise contributions from, the entire West Antarctic Ice Sheet, which operates as a connected system of glaciers together holding approximately 3.3 m of sea level rise equivalent of ice. Given the possibility of significant near-future acceleration of Pine Island, a research priority must therefore be to better understand the response of the entire West Antarctic Ice Sheet to abrupt acceleration of its constituent glaciers. More generally, such acceleration and possible collapse represents an extreme scenario with far-reaching consequences; the implications of such high consequence events warrants a significant research effort, particularly as their likelihood is expected to increase in a warming world.

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