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## Geophysical Research Letters

### Instantaneous Antarctic ice-sheet mass loss driven by thinning ice shelves

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#### Key Points:

- **First continent-wide assessment of the impact of observed changes in ice-shelf thickness on the mass loss of the Antarctic Ice Sheet**
- **Process-based predictions of changes in ice flow are in good agreement with observed spatial patterns of ice loss**
- **Changes in ice-shelf thickness are having a substantial and instantaneous impact on ongoing mass loss of the Antarctic ice sheet**

#### Abstract

Recent observations show that the rate at which the Antarctic Ice Sheet (AIS) is contributing to sea level rise is increasing. Increasing ice-ocean heat exchange has the potential to induce substantial mass loss through the melting of its ice shelves. Lack of data and limitations in modelling, however, have made it challenging to quantify the importance of ocean-induced changes in ice-shelf thickness as a driver for ongoing mass loss. Here, we use a numerical ice-sheet model in combination with satellite observations of ice-shelf thinning from 1994 to 2017 to quantify instantaneous changes in ice flow across all AIS grounding lines, resulting from changes in ice-shelf buttressing alone. Our process-based predictions are in good agreement with observed spatial

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**patterns of ice loss, providing support for the notion that a significant portion of the current ice loss of the AIS is ocean driven and caused by a reduction in ice-shelf buttressing.**

## **Plain Language Summary**

The Antarctic Ice Sheet is currently losing mass but the causes for the mass loss remain unclear. It has been suggested that reduction in the thickness of the floating ice shelves that surround the ice sheet, for example due to ocean warming or changes in ocean circulation, may be responsible for some of the observed ice loss. However, this hypothesis has remained untested. Here we use a state-of-the-art numerical ice-flow model to calculate the direct mass loss due to observed changes in ice shelves between 1994 and 2017. We find that the magnitude and spatial variability of modelled changes are in good agreement with observations, suggesting that thinning ice shelves have driven a substantial portion of the recent ice-loss of the Antarctic ice sheet. The process we consider (ice-shelf buttressing) relates to changes in forces within the ice alone and is therefore effectively instantaneous (i.e. only limited by the speed of stress transition within the ice). Besides providing a possible explanation for a large part of the ongoing mass loss, this finding also shows that we are not protected against the impact of the Antarctic Ice Sheet on global sea levels by a long response time.

## **1 Introduction**

Antarctica is fringed by floating ice shelves that form where the grounded ice sheet meets the ocean. Recent numerical and theoretical work has stressed the importance of ice shelves in controlling Antarctica's ice discharge across its grounding lines (GLs), the boundary between grounded and floating ice (Haseloff & Sergienko, 2018; Pegler, 2018), through a process known as "buttressing". Thinning of ice shelves through excess melting can reduce the buttressing they provide to upstream flow (Fig. 1), leading to increased grounded-ice discharge into the oceans, with consequent rise in global sea level (Fürst et al., 2016). Reduction in ice-shelf buttressing has a near instantaneous effect on ice flow (limited only by the speed of elastic-wave propagation in ice). This implies that this process can result in rapid changes in grounded-ice flux in response to ocean-induced ice-shelf thinning, however, to date this effect has not been quantified in the context of current Antarctic Ice Sheet loss.

Previous work has demonstrated a correlation between locations where ice shelves are thinning and grounding-lines retreating, and regions where deep warm water can access the sub-ice-shelf cavities, and suggested that observed retreat and mass loss may be due to ocean forcing (Cook et al., 2016; Pritchard et al., 2012). However, correlation between potential ocean thermal forcing and observed ice loss and retreat is not evidence for ocean-induced melt being a driver for the ongoing mass loss. While warm ocean waters are likely to cause high rates of ice-shelf melting (Jenkins et al., 2016), high basal melt rates do not imply high rates of ice-shelf thinning, because in some regions high melt rates are required to maintain the steady state. Similarly, high rates of thinning do not indicate high rates of basal melt as significant vertical strain can be attributed to increased ice-flux divergence. Furthermore, changes in ice-shelf thickness do not necessarily cause changes in upstream flow; e.g., an unconfined ice shelf has no mechanical influence on GL flux (Sanderson, 1979; Schoof, 2007). It is therefore incorrect to conclude that the mere presence of warm oceans implies thinning of ice shelves, or that thinning of ice shelves necessarily leads to enhanced flow across grounding lines. Any attribution of changes in GL flux due to ice-shelf thinning requires a

quantification of the impact of observed thinning on upstream flow. The impact can be divided into the instantaneous mechanical impact due to changes in ice-shelf buttressing, and the subsequent transient flow response involving changes in geometry and mass redistribution. Here we provide the first quantitative estimate of the *instantaneous* impact of *observed* ice-shelf thickness changes on upstream ice flow due to loss of ice-shelf buttressing for the Antarctic ice sheet.

Changes in ice-shelf buttressing affect horizontal spreading rates upstream of the GLs (Fig. 1). How far upstream such perturbations are transmitted depends both on the mechanical properties of the bed and ice stream geometry, but generally scales with the ice-stream width (Gudmundsson, 2003). Across the GLs of the Antarctic Ice Sheet, ice discharge is also affected by ice thickness and mechanical bed properties (Pegler, 2017; Schoof, 2007). The resulting change in ice flux at the GL is the result of an intricate interplay between several opposing processes, and is dependent on the geometrical and mechanical conditions on both sides of the GL. Thinning of a confined ice shelf generally causes a reduction in buttressing along the GL and, therefore, an increase in ice-shelf flow speed, but also reduces the local spreading rate of ice shelves causing a decrease in flow speed. Thus, the resulting changes in ice-shelf flow arise through two different physical processes acting in opposite directions. This complexity in flow response to changes in ice-shelf thickness implies that, while the mechanical principle of ice-shelf buttressing is well understood (Fürst et al., 2016; Reese et al., 2018; De Rydt et al., 2015; Williams et al., 2012), predicting the immediate impact of changes in ice-shelf geometry on ice flow requires bespoke process-based modelling efforts (Minchew et al., 2018).

Calculating changes in ice flux across GLs has proven to be a challenging modelling task requiring high spatial resolution (on the order of one ice thickness) in the vicinity of GLs (Pattyn et al., 2012; Seroussi et al., 2014). Modelling the changes in ice-shelf buttressing and the resulting influence on grounding-line flux for a large region, such as the AIS, involves simultaneous inversion for parameters related to both ice rheology and the mechanical properties of the bed. This requires the availability of surface velocity data covering the whole AIS, as well as spatially comprehensive data of ice-shelf thinning over all major ice shelves. Recent advances in numerical modelling and improved coverage of surface velocity data (Gardner et al., 2018) across the AIS have, however, now made large-scale data assimilation of observed velocities possible (Cornford et al., 2015; Pattyn et al., 2017). Combined with robust estimation of ice-shelf buttressing and its impact on ice flow (Arthern et al., 2015; Cornford et al., 2013; Reese et al., 2018), direct measurements of ice-shelf thickness change (Paolo et al., 2015) now allows us to quantify the instantaneous impact of observed ice-shelf thinning on the ice-sheet mass loss due to changes in buttressing, using well-established glacier-mechanical principles.

## 2 Observations

Satellite altimetry observations since 1994 have shown that all of Antarctica's ice shelves are thinning, likely in response to enhanced basal melting (Pritchard et al., 2012; Paolo et al., 2015). An 18-year pan-Antarctic satellite record of changes in ice-shelf thickness showed that the volume loss of the ice shelves is increasing, mostly dominated by changes in West Antarctica (Paolo et al., 2015). This thickness change data set was obtained by combining observations from three European Space Agency (ESA) satellite radar altimetry missions (ERS-1, ERS-2 and Envisat) resulting in a highly-resolved (spatial and temporal resolutions of ~30 km and ~3 months, respectively) record of thickness for all Antarctic ice-shelf areas north of 81.5°S for the period 1994–2012 (Paolo et al., 2016). In addition, we also use a more recent (2010–2017) record incorporating the CryoSat-2 radar altimeter (Paolo et al., 2018; Adusumilli et al., 2018). The CryoSat-2 data set provides full data

coverage over all ice shelves. Figs S8 and S11 in supporting information (SI) show the resulting two ice-thickness perturbations.

### 3 Methodology

We used data assimilation techniques to determine optimal model parameters related to basal conditions (basal slipperiness,  $C$ ) and ice rheology (rate factor,  $A$ ), from continent-wide measurements of ice velocities (Gardner et al., 2018) (Figs. 4 and 5 in SI). We invert for both  $A$  and  $C$  simultaneously using Tikhonov regularization on both amplitude and slope. The regularisation parameters were determined from an L-curve analysis. The same methodology using the same numerical model has been implemented in several recent publications (Hill et al., 2018; Reese et al., 2018; Rosier & Gudmundsson, 2018). The optimised model, which closely reproduced observed velocities over the AIS (Fig. 1 in SI), provided our ‘reference’ model of the ice-sheet flow. We then perturbed the ice-thickness distribution of our reference model with measured changes (Paolo et al., 2015), and recalculated ice velocities. The difference between the two velocity distributions provided an estimate of the mechanical impact of observed ice-shelf thinning on the ice-sheet flow.

We chose to only make modifications in ice-shelf thickness over the sections of our computational domain that were considered ‘fully floating’. That is, we only applied a thickness perturbation to a given node of the finite-element computational mesh if all the nodes of all neighbouring elements were also afloat (Figs. 2 and 3 in SI). Therefore, in our diagnostic experiments the surface slopes (and ‘driving stresses’) across GLs are unaffected. We also conducted experiments modifying thickness over all floating nodes (including ‘partially floating’ elements), and found the overall spatial pattern of mass loss and gain to be similar. Because we only made modifications to ice thicknesses over the floating parts, GL positions remained unchanged (Seroussi et al., 2014).

We applied a perturbation in ice-shelf thicknesses corresponding to the 18-year ERS-1/ERS-2/Envisat observational period 1994–2012 (Fig. 8 in SI), and obtained a predicted pattern of changes in ice flow and ice flux across the entire Antarctic GL due to ice-shelf thinning (Fig. 2 and 3). We also calculated instantaneous changes in velocity and ice fluxes using data from CryoSat-2 covering the period 2010–2017 (Figs 11 and 12 in SI). Using the 2010–2017 data resulted in a similar overall pattern of buttressing-related mass loss as the 1994–2012 data, demonstrating that our results are robust with respect to errors in thickness change. We estimated the effect of changes in ice-shelf buttressing on ice fluxes across the GL (Fig 2 and Fig 12 in SI, coloured circles, and Fig 12 in SI), within each Antarctic drainage basin (Zwally et al., 2012). We also tested the impact of different model parameters on our results (see SI). The calculated spatial pattern of mass loss is insensitive to any model assumptions affecting (similarly) different model runs. In addition, our data assimilation approach ensures that calculated velocities were always in good agreement with measurements, independent of some model parameters (SI).

We tested the sensitivity of calculated GL flux response to different magnitudes of changes in ice-shelf thickness using different scaling factors. We found that GL fluxes scaled almost linearly with the magnitude of the changes (Fig 10 in SI). Hence, applying one year of average thickness changes instead of eighteen (as in Fig. 2), caused an almost directly proportional change in calculated flux response (i.e. a reduction by a factor of  $\sim 18$ ). Again, while the magnitudes of calculated flux perturbation for each catchment basin (see Fig 7 in SI for definition of catchment basins) changed with the magnitude of the applied thickness change, the relative spatial pattern was unaffected. This means that the calculated spatial pattern of ice loss (Fig. 2) is a robust feature of our modelling approach and can be considered a ‘fingerprint’ of mass loss due to recent changes in ice-shelf buttressing. We stress that observations of ice-shelf velocities and horizontal divergence, as well as

estimates and modelling of ice-shelf surface mass balance show that the recent thickness changes over ice-shelves are almost entirely due to ocean-induced melt (Jenkins et al., 2018; Turner et al., 2017).

#### **4 Discussion**

Our modelled spatial pattern of mass loss (Fig. 2) is consistent with observations (e.g. Gardner et al., 2018; Nerem et al., 2018; Rignot et al., 2019; Shepherd, 2018). While temporally-coincident estimates of changes in grounding-line fluxes over the period 1994–2012 are not available for all ice streams, available coincident observations (Rignot et al., 2019) have the same general spatial pattern (as in Fig. 2). Large changes in modelled GL flux are almost exclusively concentrated along the West Antarctic Ice Sheet (WAIS) margin, and are especially pronounced across the drainage basins of the Amundsen and the Bellingshausen Seas (Fig. 3), with significantly smaller ice losses taking place over the East Antarctic Ice Sheet (Fig. 2). Relative to changes over the WAIS, modelled changes across all ice streams flowing into Filchner-Ronne and Ross Ice shelves are small. Where long-term observations of velocity changes over smaller ice shelves are available, these are also in good agreement with our modelling results; e.g., on Brunt Ice Shelf modelled velocities increase while flux across the GL remains almost unchanged, which is consistent with observations (Gudmundsson et al., 2017).

Our modelled estimates of changes in GL ice fluxes are due to changes in ice-shelf buttressing alone. In reality, we expect various transient flow effects to play a role, and we caution against expecting a perfect numerical agreement between modelled and observed changes in ice flow. While exact quantification of the impact of processes not included in our modelling approach is not possible, we surmise that our estimates of changes in ice flow may be biased low, for three reasons: (i) We only apply thickness changes downstream of the GLs. Hence, we do not include an additional response from changes in driving stress across GLs. We performed numerical experiments where thinning was applied over all floating ice, and found this to increase the magnitude of response but not to affect the spatial patterns; (ii) The thinning rates estimated from satellite radar altimetry are underestimates of the actual thinning rate, as they exclude data next to the GLs (< 3 km) where some of the largest changes are taking place (e.g. Pine Island Glacier and Thwaites); this is due to the large footprint (km scale) of satellite radar altimeters and concerns about potential biases from ice-shelf flexural effects. Furthermore, the 1994–2012 data are only available north of 81.5°S (the satellites' orbit limit), which excludes a substantial portion of the Ross Ice Shelf. For the 1994–2012 period, we set thinning rates south of this limit to zero; (iii) We estimated thickness-change trends with a regression method that constrains the magnitude of the trend in the presence of high variance (i.e. noise) (Paolo et al., 2016), meaning that our thinning rates are conservative estimates.

#### **5 Conclusions**

Predicting the near-future (decadal-to-centennial scale) global impacts of the Antarctic Ice Sheet requires identifying and understanding the drivers of current changes (Jenkins et al., 2016). Using a process-based modelling approach forced by observations of ice shelf thickness, we have shown that the pattern of observed changes in the flow of the grounded WAIS is consistent with a direct and instantaneous mechanical response to recent ice-shelf thinning. Other explanations previously put forward to explain ongoing mass loss in WAIS include the possibility that part of the ice sheet is currently undergoing an unstable and irreversible retreat driven by an internal instability mechanism (Favier et al., 2014). Although we do not discount this possibility, our findings lessen the need to invoke a mechanism of self-sustained retreat to explain current rates of mass loss, and support the notion that increased ice discharge is related to external climate drivers (Mengel et al., 2015). Our

results have important implications for assessing future mass loss from the Antarctic Ice Sheet and resulting sea-level rise: thinning of ice shelves is now significantly affecting discharge of ice into the oceans; because this process is almost instantaneous, we are not protected against the impact of the Antarctic Ice Sheet on global sea levels by a long response time.

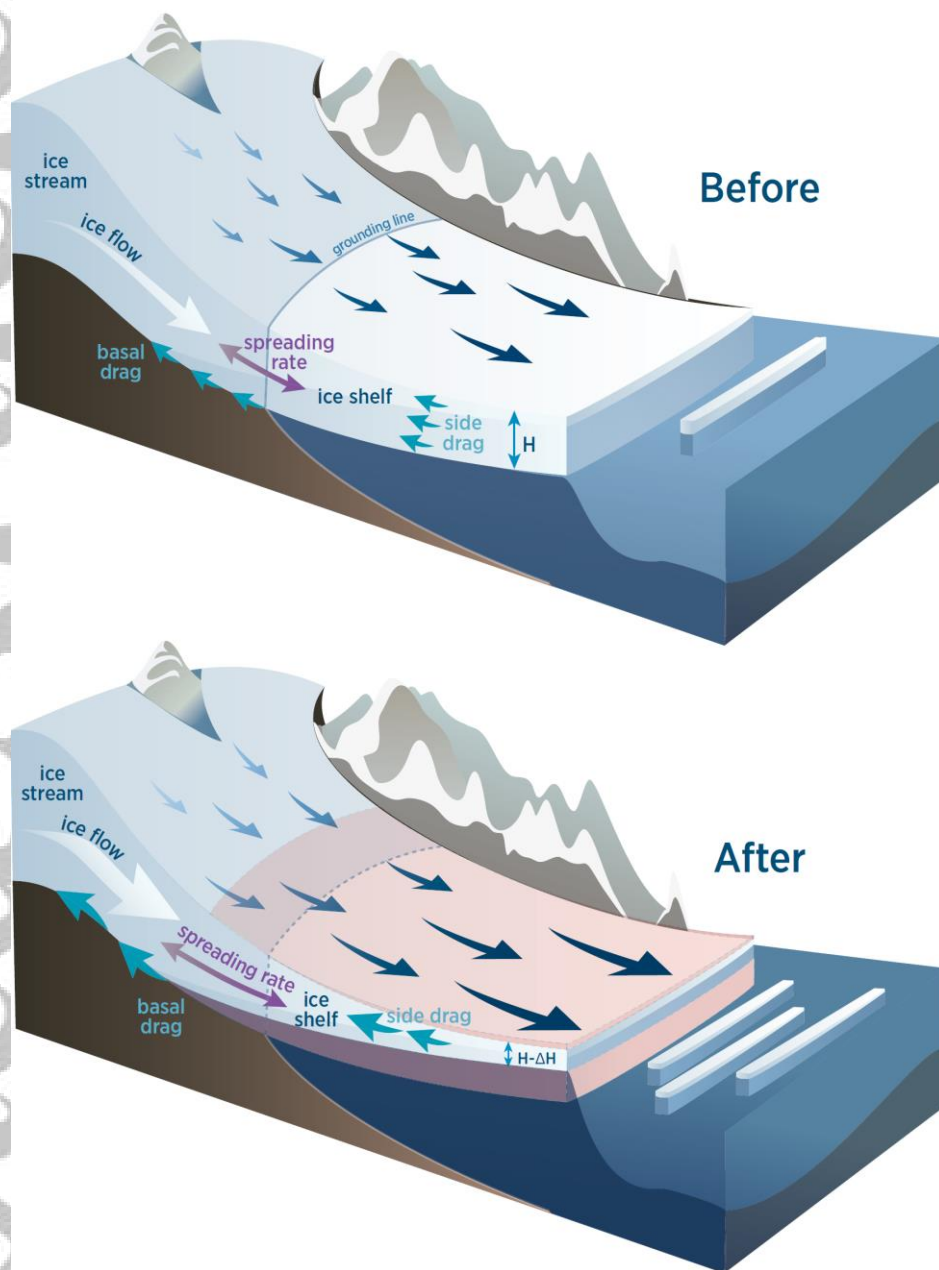
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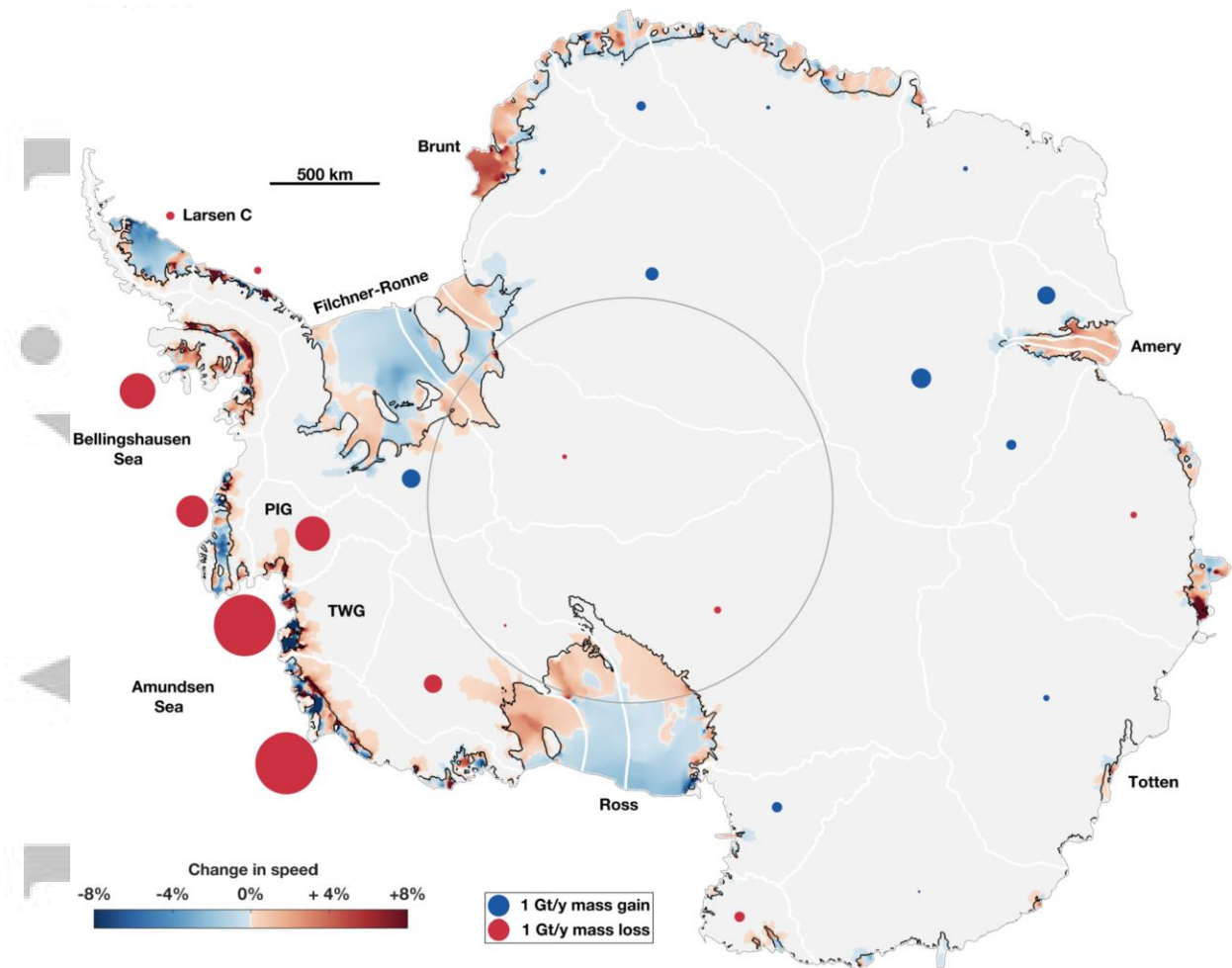
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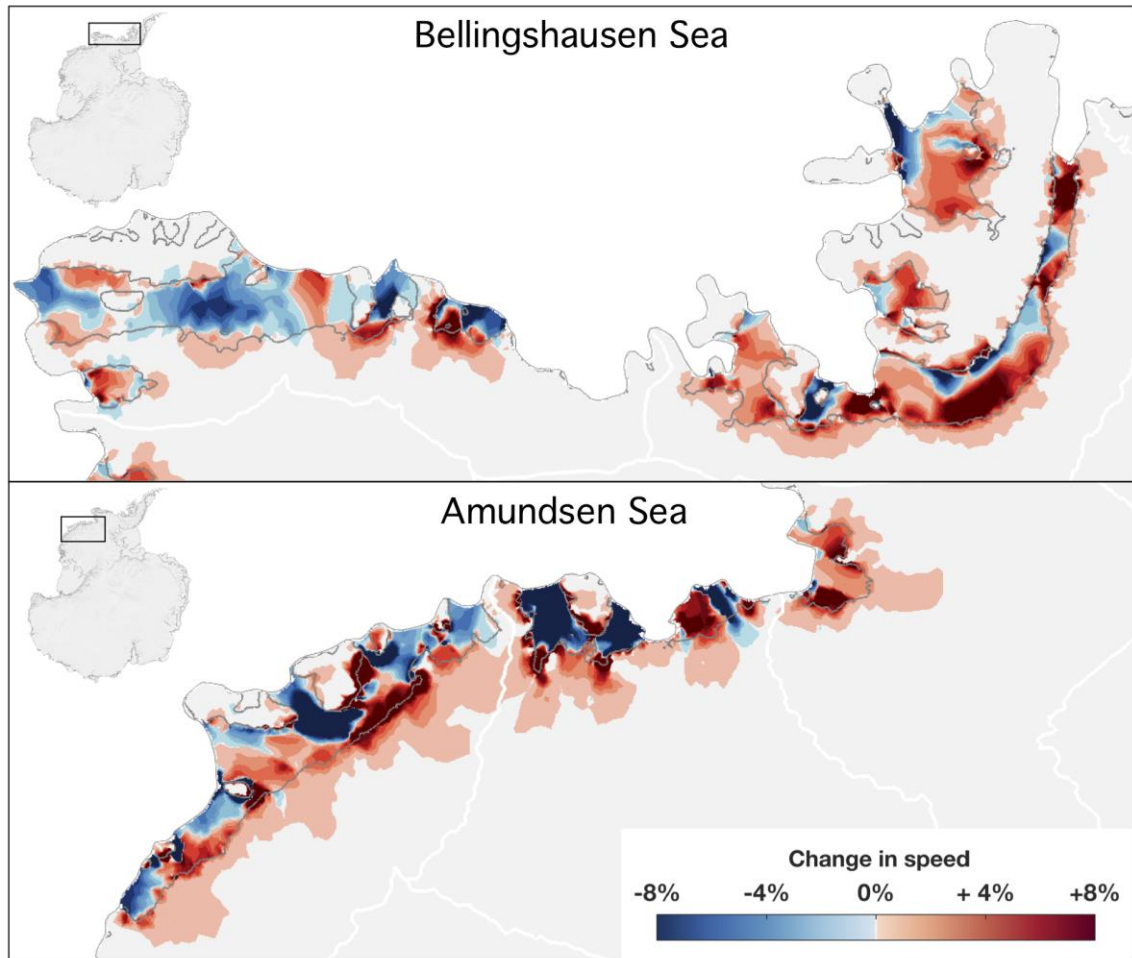
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**Fig. 1: Ice shelf buttressing and grounding line flux.** Confined ice shelves restrain the flow of upstream glaciers. Thinning of ice shelves increases the longitudinal stress and with it the spreading rate at the grounding line (GL). This effect transmits some distance upstream, and the net results is an increase in GL ice-flux. (a) Ice-shelf thickness ( $H$ ) and ice flow prior to onset of ice-shelf thinning. (b) Onset of ice-shelf thinning (thickness loss in red) reduces buttressing and increases both longitudinal spreading and ice flux across the GL, speeding up glacier discharge into the ocean.



**Fig. 2: Instantaneous changes in ice velocities and grounding-line fluxes due to ice-shelf thinning (1994–2012).** The coloured field shows modelled percentage changes in speed due to observed ice-self thinning. The red and blue circles indicate increases and decreases, respectively, in grounding-line fluxes, integrated over all the grounding lines of a corresponding catchment basin. The outlines of the drainage basins show as white lines. The black circle is the 81.5°S latitude, south of which no data on ice thickness changes are available. The colour scale is adjusted so that areas where speed changes by less than 1% are masked. Grounding lines show in black and the outlines of the numerical computational domain in grey. The abbreviations PIG and TWG, stand for Pine Island Glacier and Thwaites Glacier, respectively. Values were calculated using a basal sliding stress exponent  $m=3$ .



**Fig. 3: Instantaneous changes in ice velocities due to ice-shelf thinning along the West Antarctic margin.** The panels show a detailed view of modelled changes in ice flow due to loss of ice-shelf buttressing alone. Large increases in velocity are concentrated along the grounding lines of rapidly thinning ice shelves, increasing ice discharge, with the changes propagating upstream far inland (100-km scale). The overall pattern of changes in grounded-ice flow is consistent with current observations of rapid mass loss across the catchment basins in West Antarctica.