The far reach of ice-shelf thinning in Antarctica

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The Antarctic Ice Sheet is the world's largest freshwater reservoir. Its melting has the potential to raise global sea levels by about 58 meters. The contribution from ice dynamics in Antarctica is one of the largest uncertainties in projections of future sea-level rise in a warming world. Key to this is the complex dynamics at the grounding line where the floating ice shelves are connected with the continental ice sheet. This thesis aims at deepening our understanding of the dynamic processes that drive the presently observed retreat of Antarctic grounding lines.

Interactions between the floating ice shelves and the Southern Ocean are the main reason for current mass losses from Antarctica. So far, however, a model to cover distributed sub-shelf melting in a physical and efficient way has not been available. In a first contribution to my thesis, I filled this gap by developing the Potsdam Ice-shelf Cavity mOdel (PICO) and implementing it in the Parallel Ice Sheet Model (PISM). PICO simulates the overturning circulation observed underneath Antarctic ice shelves and determines the melt rates at their base (Reese *et al.*, TC, 2018).

Although the ice shelves themselves are afloat and their melting has no direct impact on sea levels, they can have an indirect effect by exerting a backstress on adjacent ice streams. Because of this 'buttressing effect', they play a central role for the overall mass balance of the Antarctic Ice Sheet. In fact, in some regions of Antarctica the ice shelves are currently thinning. In the second study of my thesis, I show particularly far-reaching effects of ice-shelf thinning on upstream ice flow: localized thinning can instantaneously increase the flow across the surrounding grounding lines. Herein, the location of ice shelf changes is of importance. In some regions, a perturbation can accelerate ice streams located more than 900 km away. While the calving of icebergs occurs at the shelf edge and hence in areas which have minor influence on the inland flow, warm ocean waters can reach the deeper areas of the ice shelves, which I have identified as particularly critical for grounding-line flux in my work (Reese *et al.*, Nat. Clim., 2017).

With progressing global warming, melt rates underneath Antarctic ice shelves are expected to increase, thereby reducing their buttressing potential. To advance the theoretical understanding of buttressing, I examine in my third paper the complex effects that ice shelves exert on ice transport across the grounding line. I find this to be an inherently three-dimensional problem that needs to be simulated explicitly (Reese *et al.*, accepted for TC, 2018).

Ice shelves respond particularly fast and strongly to changes in the surrounding atmosphere and the ocean. Using PICO, in the fourth contribution to my thesis is shown that also over long periods of time, buttressing has a major influence on the mass balance and extent of the Antarctic grounding lines (Kingslake *et al.*, Nature, 2018). Their motion is also determined by the surface mass balance: it can advance when the ice sheet gains mass via snowfall. In a fifth contribution to my thesis, consistent lines of evidence are combined to show that snowfall increases by about 5 percent per degree of regional warming (Frieler *et al.*, Nat. Clim., 2015).

Overall, in my PhD project, I investigate these effects of increased snowfall, enhanced sub-shelf melting and reduced buttressing on Antarctica's mass balance using three methodological approaches by (1) developing the Potsdam Ice-shelf Cavity Model (PICO), which provides physically-based sub-shelf melt rates for dynamic ice-shelf and ice-sheet simulations, (2) advancing the theory of ice-shelf buttressing using diagnostic solutions of the stress balance for the present-day Antarctic Ice Sheet, and (3) analysing ice core and regional climate model data and emulating the dynamic response of the ice sheet to snowfall changes using linear response theory. My results are based on the combination of the numerically efficient, thermodynamically-coupled Parallel Ice Sheet Model (PISM) and the ice flow model Úa whose inversion capabilities allow for high-resolution simulations in close accordance with measured conditions.

All three approaches allow me to demonstrate the central role of the indirect, or 'hidden', ice-dynamic processes in determining the Antarctic sea-level contribution in the near future and on the long term.