Antarctic ice sheet–ocean tipping points

High-resolution coupled Antarctic ice sheet and ocean projections and characterization of related tipping points and their interaction

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In Short

- coupled ocean–sea ice–ice shelf–ice sheet
- stability of Southern Ocean and Antarctic Ice Sheet
- interaction of tipping points

In the context of the H2020 project TiPACCs (Tipping Points in Antarctic Climate Components), the overall aim of this project is to assess the likelihood of large and abrupt near-future changes in the contribution of the Antarctic Ice Sheet to global sea level, caused by tipping points in the Antarctic continental shelf seas and the Antarctic Ice Sheet.

Of particular importance is the question wheather ongoing changes in our environment will be gradual and roughly proportional to external changes, or greatly amplified and sudden. Large and sudden changes might occur within systems with self-amplifying feedbacks and thus internal thresholds. Worryingly, research does suggest the existence of several tipping points within the climate system, which, once passed, may give rise to large, abrupt and possibly irreversible changes in the environment with significant societal implications.

One such potential environmental tipping point is associated with the internal dynamics of the Antarctic Ice Sheet. It is now firmly established that marine ice sheets (ice sheets resting on bed below sea level) such as the West Antarctic Ice Sheet, are susceptible to an unstable and irreversible retreat. However, currently the exact conditions under which such an unstable retreat is initiated, and specifically the resulting implications for the dynamics of the Antarctic Ice Sheet and global sea level, are unknown.

Another potential environmental tipping point relates to the state of the Antarctic continental shelf seas. Recent research suggests that these can flip from a 'cold' to a 'warm' state in response to changes in wind and sea ice conditions in a warming world, which influence the shelf water density and the stability of the Antarctic Slope Front.

Interestingly, recent research furthermore suggests a new and hitherto unexpected potential link between these two tipping points, i.e. between the thermal states of the oceans (i.e. cold or warm) and the stability regime of the Antarctic Ice Sheet. This link is due to the impact that ice shelves can have on upstream ice flow and on the dynamics of grounding line motion (Fig. 1). Broadly speaking the process is as follows: A warmer ocean increases basal melting and thinning of ice shelves. This in turn causes a reduction in ice-shelf buttressing and changes in the stability regime of the grounding lines. Hence, increased ice-shelf melting due to the Antarctic continental shelf seas flipping from cold to warm state may cause an unstable backwards migration of the grounding lines of the Antarctic Ice Sheet.

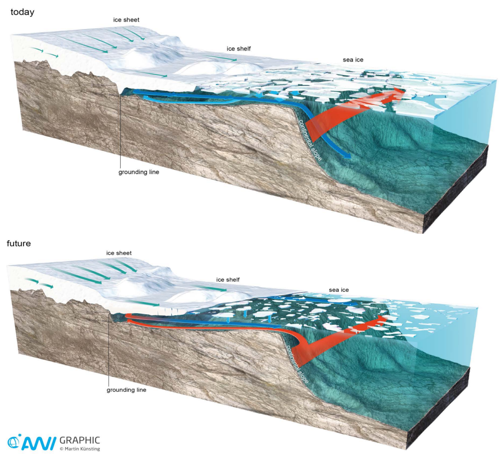

***Figure 1:** Section along the Filchner Trough illustrating the potential change in ocean circulation and the switch from a 'cold' to a 'warm' cavity with increased inflow of warm circumpolar deep water and the subsequent increased ice discharge.*

The long-term stability of the Antarctic Ice Sheet has so far only been studied in stand-alone simulations: A large-scale hysteresis analysis of the Antarctic Ice Sheet was for instance conducted by Garbe et al. (2020)[1]. With respect to ocean tipping points, studies [2,3] showed that the ocean circulation may shift from a cold cavity to a warm cavity by the end of this century in the Wedell Sea sector. In a subsequent project[4], this ocean setup was coupled to the Parallel Ice Sheet Model (PISM) in a regional setup for the Filchner-Ronne drainage basin. In the coupled model, a reduction of ice shelf thickness was found to cause an increase of grounded ice discharge equivalent to a sea-level rise of 27 mm from the Filchner-Ronne basin by 2150 in response to the regime shift.

In this project's predecessor, the coupled Weddell Sea setup was used to further investigate the factors that can lead to tipping of the ocean cavities. A suite of coupled experiments with forcings reversing to 20th century climate state were conducted. A (partially) non-reversible tipping point is found in the ocean with no self-amplified retreat of the grounding line. As a preparation for the experiments in this project, two highly resolved initial states of the Antarctic Ice Sheet model were developed in 2022. These states were forced by the historic period starting from 1850 and agree well with the observed ice loss rates and the total ice mass, respectively.

To study the interacting tipping points, we couple two state-of-the-art models, a global ocean circulation model (FESOM) that resolves the complex geometry of ice-shelf cavities and an ice flow model (PISM) simulating dynamics of the Antarctic Ice Sheet. We will determine potential feedbacks between the ocean and the ice-sheet tipping points. In particular, we will investigate whether changes in the ocean circulation and hydrography in the cavity beneath the ice shelf can further destabilize adjacent grounding lines. Furthermore, we will determine how changes in the ice-shelf cavities affect the ocean circulation, and how the dynamics of different ice basins and the ocean circulation change in fully coupled simulations compared to stand-alone model runs. We plan to do coupled simulations from 1950–2100 with realistic forcings from CMIP6 and idealized forcings to enhance the understanding of the relevant physical processes connected to the tipping of the coupled ice shelf–ocean circulation system. Since the relevant time scales of ice dynamics are longer than the centennial-scale period of the coupled simulations, we will setup the coupled model for a collapsed West Antarctic Ice Sheet. This allows us to improve our understanding of ocean circulations in cavities significantly deviating from present day geometries. With the gained knowledge, we can improve the ice sheet standalone simulations on the whole trajectory from present-day to collapsed ice sheets on a multi-millenial time-scale.

As a whole, the project will provide a better understanding of the dynamics and interaction of both tipping points and their specific impact on global sea level, and thus, contribute to improve confidence in future climate/sea level predictions.

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More Information

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[2] H.H. Hellmer, F. Kauker, R. Timmermann and T. Hattermann, *Journal of Climate* **30(12)**, 4337-4350 (2017). doi:10.1175/JCLI- D-16-0420.1

[3] R. Timmermann and S. Goeller, *Ocean Sci.* **13**, 765-776, (2017). doi:10.5194/os-2017-41

[4] R. Timmermann and T. Albrecht: Coupled ocean–ice shelf–ice sheet projections for the Weddell Sea Basin, Antarctica. *EGU General Assembly* (2020). https://meetingorganizer.copernicus.org/EGU2020/EGU2020-18743.html

Project Partners

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