Forcing Earth's sea level: instabilities and linear responses

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Sustained sea-level rise caused by global warming poses a challenge to coastal areas worldwide. Improved sea-level projections are necessary to estimate future impacts, assess mitigation options and guide adaptation measures. Despite significant improvements in cryospheric modeling, uncertainty remains high along the causal chain from greenhouse emissions to sea-level rise.

This is particularly true for the future ice discharge from Antarctica. Difficulties arise, for example, because two possibly intertwined instabilities exert major influence on the part of the Antarctic ice that is grounded below sea level. First, the oceanic slope front around Antarctica shields warm waters from the ice sheet, but recent simulations have shown that it can erode abruptly under future climate change. Secondly, the ice sheet itself can retreat in a self-sustained manner through the marine ice-sheet instability. The future Antarctic sea-level contribution depends on how global warming forces these two instabilities and how they will interact.

In my thesis, I have examined future sea-level rise with a number of different methods and focus herein particularly on the role of the Antarctic ice sheet under future warming.

[1] I demonstrate the existence of an ice instability in the vast glacial body of East Antarctica in dynamic ice-sheet simulations with the Parallel Ice sheet Model (PISM). Within the Wilkes basin a large ice mass is prone to retreat if a small coastal part of the ice sheet is removed, that I termed “ice plug”. The irreversible retreat occurs on a millennial time scale.

[2] Whether ice instabilities dominate the sea level contribution on shorter time scales is less clear. In ocean simulations, a slope-front breakdown leads to strong warming below the Filchner-Ronne ice shelf (FRIS), the second largest ice shelf of Antarctica. Based on PISM simulations I show that the sea-level relevant ice loss of the FRIS glaciers follows quasi-linearly the additional ice-shelf melt for strong ocean warming. Thus, the capacity of the ocean to provide heat to the ice dominates over local ice instabilities here.

[3] The outlet glaciers of the Greenland ice sheet have accelerated during the past two decades while adjacent ocean waters have significantly warmed. The warming has been linked to changes in the North Atlantic subpolar gyre circulation. In simulations with an intermediate complexity climate model I show that an ocean density related threshold in the gyre circulation can be the reason for high ocean variability, relating Greenland ice mass loss to an ocean instability.

[4+5] We develop two approaches that enable a probabilistic assessment of future sea level rise while incorporating the knowledge gained from process-based modeling. First, we apply linear response functions to generalize the response of a set of ice-sheet models to uniform basal melting below Antarctic ice shelves and convolve the response functions with global climate projections. We find that the probability distributions of ice discharge have high positive skew, indicating the risk for high mass losses even without the full inclusion of potential instabilities in this linear approach. Secondly, I introduce a semi-empirical approach based on pursuit curves that constrains the individual contributions to sea level rise by past observations and their long term sensitivity. While the pursuit curve sea level projections are generally consistent with IPCC AR5, both the response function and the pursuit curve approach yield sea-level estimates from Antarctica higher than IPCC , underlining the increasingly important role of the ice-sheet.

[6] To assess the response of regional climate system components such as the ice sheets, global temperature change needs to be translated to local forcing. The use of computationally expensive climate models is not always feasible for such a translation, especially in probabilistic frameworks. We introduce a new approach to down-scale global to regional climate change that allows for the formal error treatment in climate model ensembles. Scaling coefficients are derived from the CMIP3 model ensemble for several world regions.

[7] Finally, in an exploratory work, we test if sea-level rise can be delayed by the large-scale addition of sea water on Antarctica's ice-sheet surface. We find that ice has to be stored at least 700 km from the coast to ensure the delay of sea level rise for a millennium or longer.