Stability of the West Antarctic Ice Sheet: From the concept of similitude to dynamic modeling

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Abstract

Future sea-level rise represents an increasing challenge for the world's coastal ecosystems and societies. Climate change mitigation targets and long-term adaptation strategies of coastal protection rely on accurate projections of sea-level rise which in the future might be dominated by the contribution of the ice sheets on Greenland and Antarctica. Possible instabilities of the Antarctic Ice Sheet that in total have the potential to raise global sea level by more than 20 m represent the largest uncertainty in future sea-level projections. In particular the West Antarctic Ice Sheet is prone to the so-called marine ice-sheet instability as suggested by observations. However, the long-term response of the ice sheet to both the recently observed local destabilization and projected future climatic perturbation is unclear. The time scales on which potential instabilities would, if triggered, unfold are uncertain.

Here I apply two approaches to obtain further insight into the future evolution of a potential West Antarctic instability: Firstly, numerical modeling with the ice sheet model PISM allows to analyze ice-sheet evolution based on dynamic simulations. Secondly, the principle of similitude enables an analytic investigation of the (time-)scaling behavior of ice sheets.

Confident statements about ice-sheet stability based on numerical simulations in particular require the underlying model to realistically represent grounding-line dynamics. Combining different numerical improvements of the treatment of the grounding line in PISM, I demonstrate in a set of benchmark experiments that the model is capable of simulating grounding-line dynamics similar to a model that is solving the full Stokes equation, also on medium resolution (Feldmann et al., JoG, 2014).

The currently observed rapid retreat of the ice in the Amundsen Sea sector of West Antarctica points to a destabilization of the region triggered by enhanced basal ice-shelf melting. I show, for the first time, in ice-dynamic simulations that on the long term a destabilization of this relatively small region leads to the development of a large-scale instability, causing the complete collapse of the marine part of the West Antarctic Ice Sheet (Feldmann & Levermann, PNAS, 2015).

Similar to the present-day situation of the ice shelves in the Amundsen Sea sector, the Filchner-Ronne Ice Shelf of West Antarctica might be subject to strong oceanic forcing in the future. My simulations of that region reveal that the response of the regional ice discharge to ocean warming is approximately linear and thus large-scale instability in this region is unlikely (Mengel, Feldmann & Levermann, Nature CC, 2015).

The marine ice-sheet instability is generally assumed to be triggered locally by oceanic forcing and ice-sheet drainage basins are often considered to be largely isolated from each other. I demonstrate in conceptual simulations that a marine ice-sheet instability can also be triggered from inland direction through the interaction of connected drainage basins (Feldmann & Levermann, TC, 2015). Using an

idealized model setup, the time scale of basin interaction and the scaling behavior of ice-sheet geometry is investigated in a phenomenological analysis.

Time scales of marine ice-sheet instability are poorly constrained by available paleodata and estimates of the speed of possible future Antarctic instabilities are uncertain. Also in my dynamic simulations, the time scale of the evolution of the instability is not necessarily well represented. I introduce the concept of similitude to ice-sheet dynamics for a fundamental investigation of the (time-)scaling behavior of ice sheets (Feldmann & Levermann, submitted, 2015). Scaling laws are obtained from a dimensional analysis of the governing equations. In particular, they allow to examine the ice-sheet response time dependent on changes in geometry and other physical properties without the application of numerical modeling.

Besides the regions of the West Antarctic Ice Sheet that here are investigated with numerical modeling there are a number of other potentially unstable regions in both West and East Antarctica. The application of state-of-the-art ice-sheet models to each of these Antarctic basins on a regional scale is not feasible to date. Assuming the similitude principle, I use the aforementioned scaling laws in combination with present-day observations to give a first estimate of the response times of several circum-Antarctic outlets after potential destabilization (Levermann & Feldmann, submitted, 2015). It is found that Thwaites Glacier, which is assumed to have been destabilized during recent decades, is the outlet glacier with the shortest response time in Antarctica.