

Tipping points: nonlinearity and hysteresis in ice sheets

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One of the central concerns in ice sheet dynamics, and in the wider field of climate dynamics, is the possibility of abrupt changes. In ice sheet dynamics, such abrupt changes could be surges in ice streams with major impacts on decadal to centennial time scales. A more subtle type of abrupt change occurs when a bifurcation or 'tipping point' is reached. For instance, given enough atmospheric warming, the Greenland ice sheet may reach a point of no return past which the ice sheet is doomed to melt completely if the warming trend is not quickly reversed. This is a type of abrupt change that does not manifest itself instantly, as it could still take many centuries for the ice sheet to decay completely and observations may not initially reveal whether a tipping point has been reached; nonetheless, reaching the climatic tipping point is an abrupt change in the sense that the ice sheet goes from being long-term viable to being destined to disappear.

Tipping points of this type thus represent a change in long-term behaviour, rather than a dramatic short-term effect. From the modeller's perspective, they represent changes in the steady-state configuration of the ice sheet. Importantly, the change in steady-state configuration is also non-reversible: if the climatic tipping point for Greenland were reached and enough time had passed for the ice to melt, then reversing atmospheric warming to just below the tipping point would not make the ice sheet reappear. Instead, much more significant cooling would be required to make the ice sheet re-form, and the ice sheet can undergo hysteresis under climatic forcing.

In this presentation, I focus on the fundamental processes that underly the main tipping points that occur in ice sheet dynamics. For a largely continental ice sheet with significant ablation zones, like Greenland, hysteresis can occur under temperature changes as described above. This is the case because the ice sheet generates its own topography, and the elevated surface in its centre will lead to net snowfall there even at relatively high temperatures. Take the ice sheet away, the exposed land surface has a much lower elevation and may not receive net snowfall, and hence melting the ice sheet is an irreversible process. For a marine ice sheet like West Antarctica, hysteresis need not be driven by temperature changes but may occur due to sea level forcings. To explain this, I will explain how the mass balance of a marine ice sheet is controlled by ice sheet-ice shelf mechanisms, and how in two-dimensional geometries, steady states are controlled by a combination of climatic factors, ice rheology, sliding behaviour, and bed geometry.

Short-term variability, for instance due to cyclic behaviour in ice streams or changing environmental forcings, and observational uncertainty can make it difficult to determine observationally whether a given ice sheet is close to a steady state or not, and therefore whether it has passed a tipping point or not, or if it is approaching one. Can modelling help here? Up to a point, but it is unlikely that models will provide a completely conclusive answer soon, and policy makers will have to leave with significant uncertainty for the time being. The basic hysteresis mechanisms I describe are based on simple models, and I will describe some of the future advances that will improve them, but in keeping with the theme of this session, I will also delve into some that I suspect ice sheet models will not be able to do for the foreseeable, both in terms of spatial and temporal resolution and due to lack of sufficiently long observational time series.