Rate-Induced Tipping of the West-Antarctic Ice Sheet

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Abstract

The retreat of the West-Antarctic Ice Sheet (WAIS) represents one of the largest sources of potential future sea-level rise, as large-scale ice loss may be abrupt due to an underlying bifurcation. Here we assess the potential for rate-induced tipping of the WAIS by stressing the discrepancies between ice-sheet responses to quasi-equilibrium and transient forcings. It appears that the higher the rate of forcing, the lower the warming needed for a collapse. In particular, we show that warming rates of intermediate-emission scenarios already lead to a collapse of the WAIS for levels of warming that are 10% lower than the bifurcation point.

Introduction

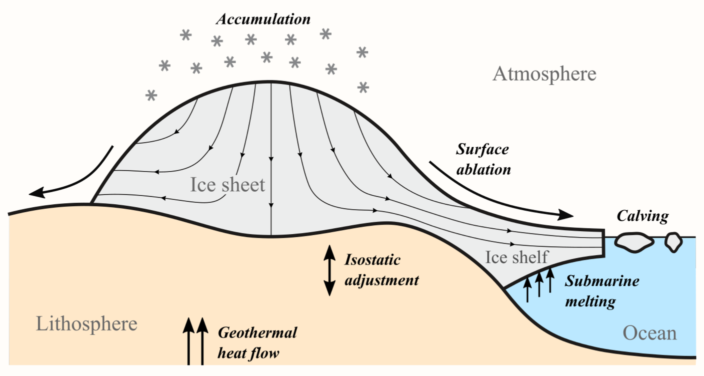

Figure 1: Representation of the mass balance of an ice sheet [1].

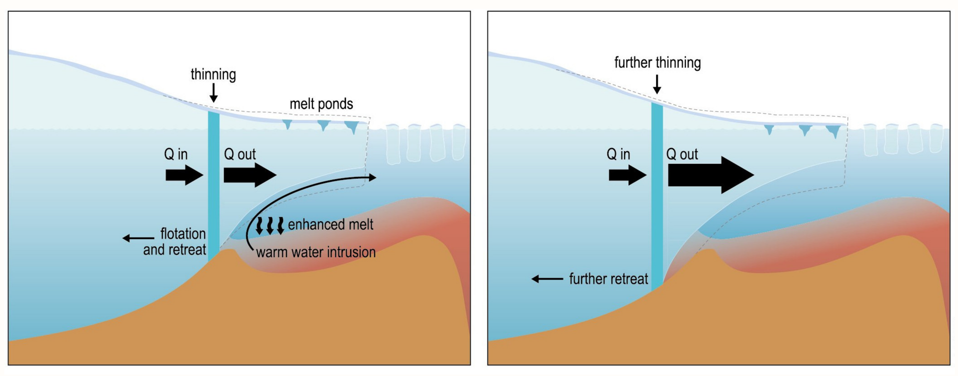

Figure 2: Representation of the Marine Ice-Sheet Instability (MISI), a feedback that could destabilise the WAIS [2].

Nonlinear dynamic systems can undergo tipping without crossing a bifurcation point as a consequence of large forcing rates. This phenomenon called rate-induced tipping (R-tipping) is here studied for the WAIS by using Yelmo [3], a state-of-the-art, 3D, ice-sheet model with thermomechanical coupling.

Result and discussions

Bifurcation of the WAIS The equilibrium behaviour of the WAIS retreat is assessed by using the mean regional oceanic and atmospheric temperature anomalies as forcing parameters ΔT_{ocn}, ΔT_{ocn}. To enforce quasi-equilibrium, we employ an adaptive technique that increases the forcing of the system only when the rate of ice-loss is below a predefined threshold. The resulting time series displayed in Figure 3 show that, at $\Delta T_{atm} = 2.8\,\mathrm{K}$, retreat is self-reinforcing, hinting to a bifurcation. The tipping proceeds at a rate of $0.6\,\mathrm{m\,SLE\,kyr^{-1}}$ and with a magnitude of about $3\,\mathrm{mSLE}$. Its onset coincides with a sharp increase in the magnitude of basal mass balance (BMB), likely to be the manifestation of MISI that is not sufficiently compensated by the surface mass balance (SMB). As displayed in Figure 4, the collapse originates from an enhanced ice flow in the Amundsen embayment, leading to a large retreat of the grounding line. This region displays the largest rate of observed ice loss in recent history [4] as well as a retrograde bedrock and relatively small ice shelves. This results in little buttressing and low resilience.

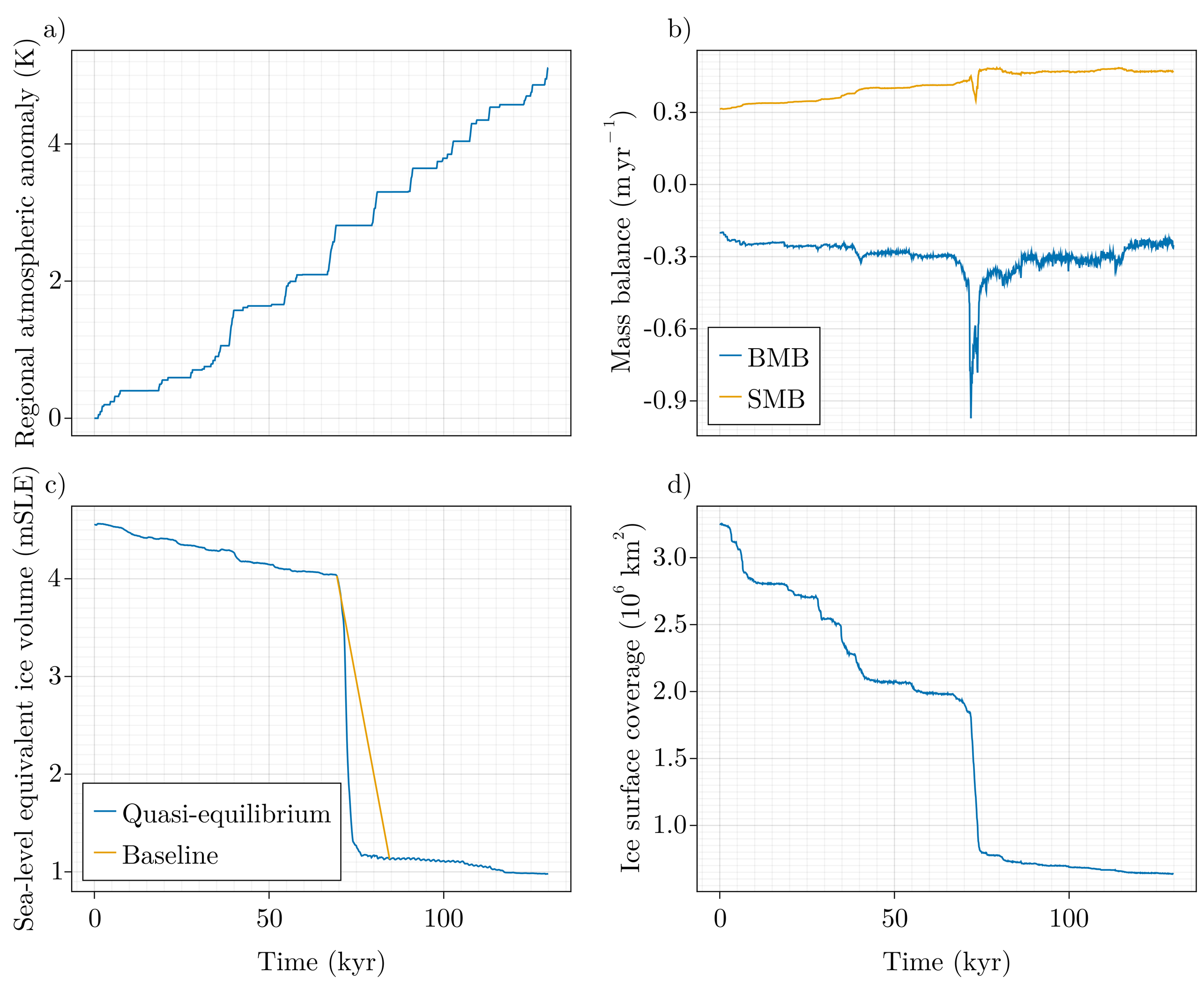

Figure 3: Time series of the WAIS forcing, mass balance, ice-volume and ice surface for the quasi-equilibrium experiment. For comparison, the 1979-2017 average rate melting is derived from [4] and used as baseline.

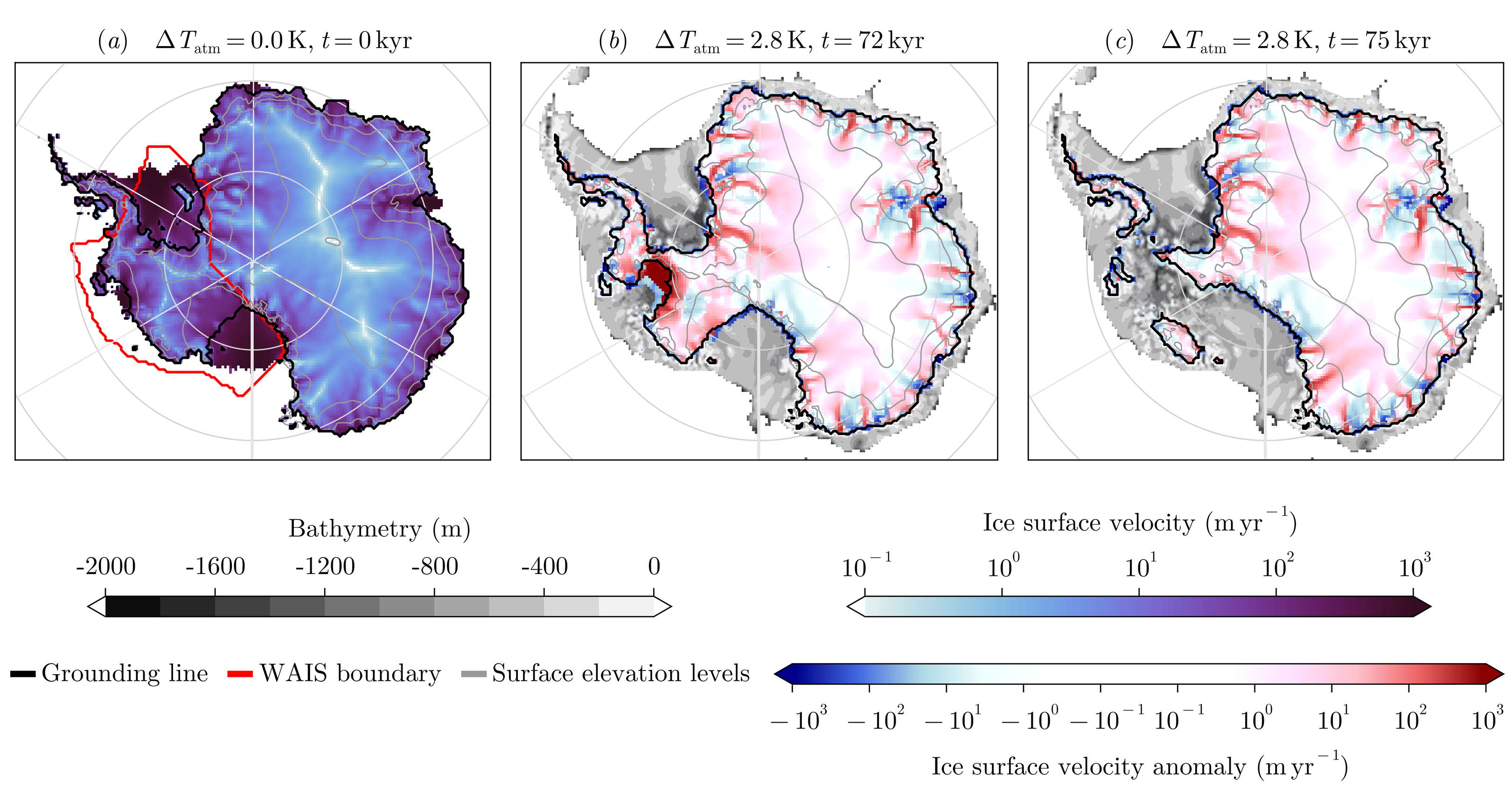

Figure 4: WAIS evolution over quasi-equilibrium experiment: (a) computed surface velocities of the WAIS at present-day conditions (control), (b-c) velocity anomalies with respect to the control run.

R-tipping of the WAIS To assess the effect of rate on the tipping process, we use idealised forcing experiments comprising three phases. First, constant forcing with zero anomaly is applied until $5\,\mathrm{kyr}$. Second, the anomaly is ramped up with a chosen rate of warming. Third, the anomaly is kept constant at a temperature, hereafter called the maximal regional warming. The rate of warming and the maximal regional warming are degrees of freedom that are used to generate an ensemble of forcing profiles. The maximal regional warming is linearly sampled from ca. 80 to 100% of the bifurcation point. The slope is sampled logarithmically on $[0.1, 5]\,\mathrm{K\,century^{-1}}$, thus encompassing quasi-equilibrium scenarios as well as the upper limit of the SSP scenarios as defined until 2100. The corresponding ensemble results can be viewed in Figure 5.

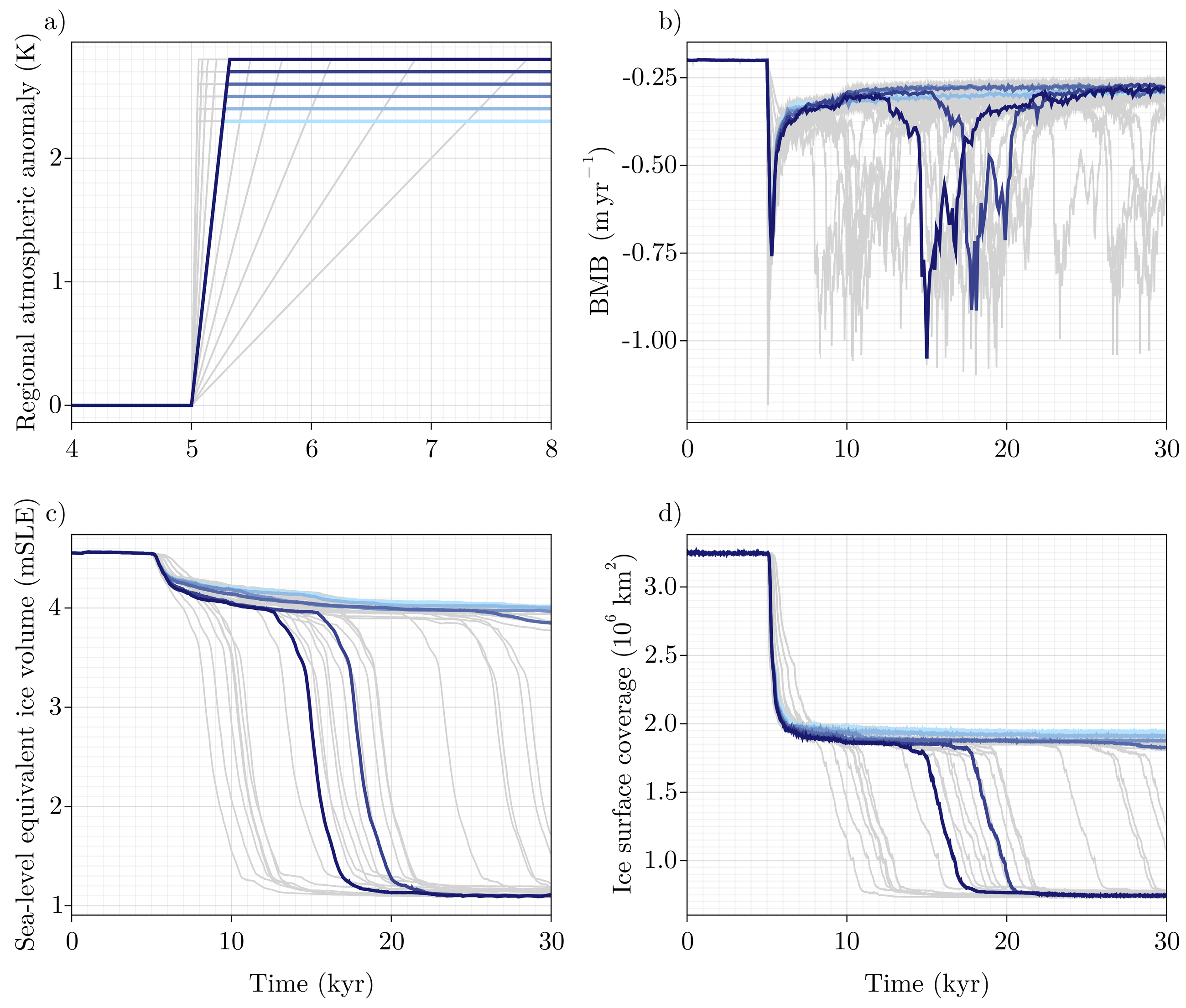

Figure 5: Time series of the WAIS forcing, mass balance, ice-volume and ice surface for the ramp ensemble. Highlighted curves correspond to various levels of maximal regional forcing for a fixed ramp slope.

To investigate the combined dependency on the maximal regional warming and its slope, the final WAIS volume is represented in the forcing parameter-space, as depicted in Figure 6. Here, the separation between tipped and non-tipped experiments is a curve representing the smallest maximal regional warming needed to make the system tip at a given rate. It will further be called the forcing separatrix (FS), as an analogy within the forcing space to the concept of separatrix, a boundary separating two regimes of a differential equation in the state-space. The main result of the present study is that the FS corresponds to a monotonously decreasing function of the ramp slope, meaning that increasing the rate of forcing lowers the minimal forcing level needed to make the system tip.

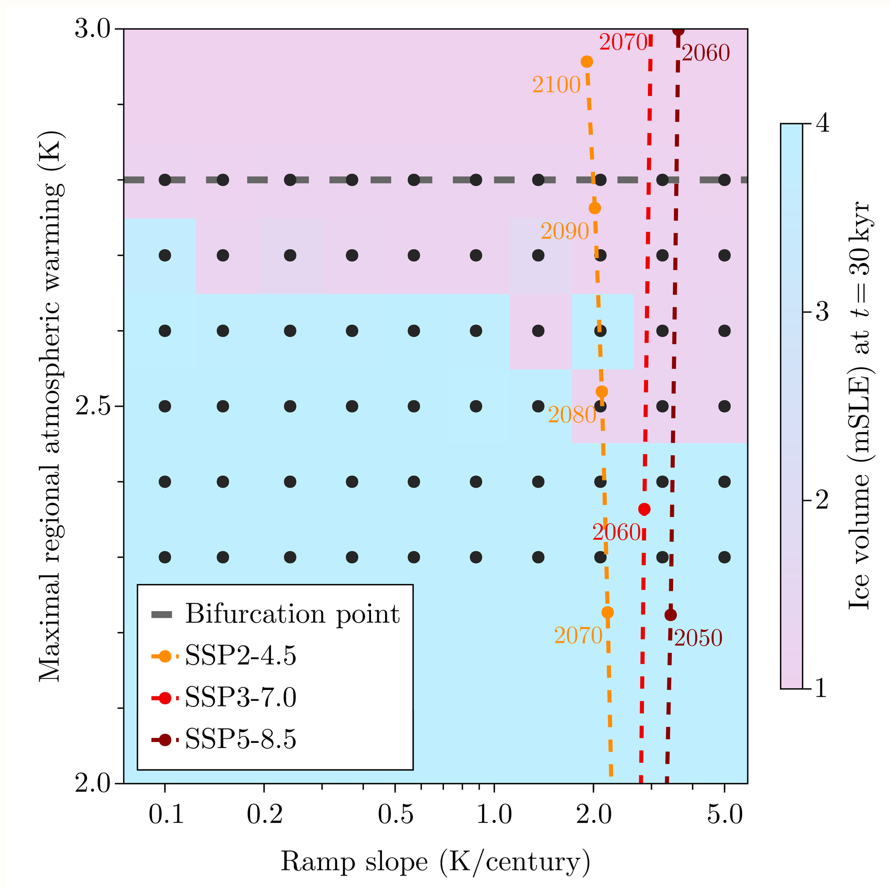

Figure 6: R-tipping pattern of the ramp ensemble. Each dot represents an experiment in the ramp-parameter space.

In particular for slopes larger than $2\,\mathrm{K\,century^{-1}}$, this effect leads to an effective threshold as little as 90% of the previously assessed bifurcation point. To put this effective lowering into the perspective of projected anthropogenic greenhouse-gas emissions, the level and the rate of warming over Antarctica are computed for the SSP2-4.5, SSP4-7.0 and SSP5-8.5 scenarios. It appears in Figure 6 that they all classify in the high-rate portion of the diagram, where the effective threshold has decreased the most. According to the present set of experiments, they lead to overshooting of the FS of the WAIS within the second half of the 21st century.

Conclusions and outlook

The present study stresses that the effect of rate can lead to tipping for levels of regional warming that are upto 10% lower than the bifurcation point of the WAIS. The physical explanation of this effect, as well as similar invesigations on other tipping elements represent crucial work left for future investigation.
Overshooting a critical threshold might not lead to tipping if the forcing is reduced rapidly enough. Recent studies [5, 6] have confirmed this intuition. Studying such scenarios to prevent the WAIS from tipping is left for future work.

References

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