The tipping points and early-warning indicators for Pine Island Glacier, West Antarctica

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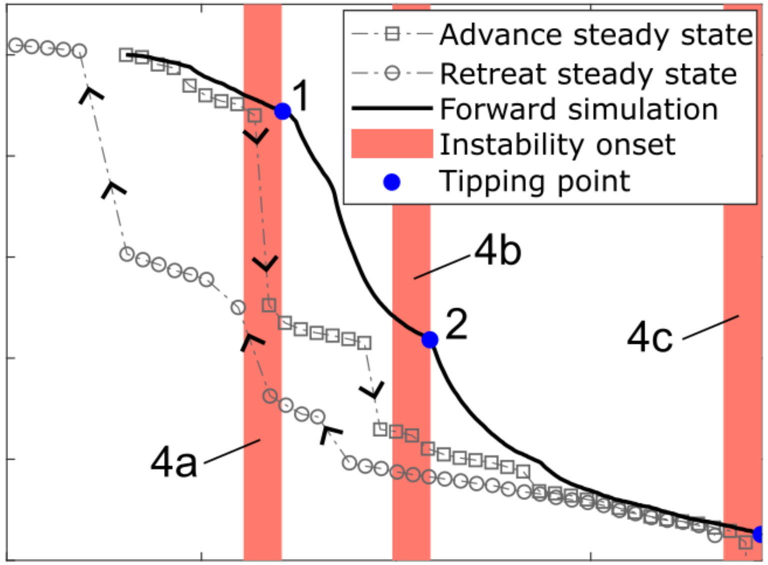

Very short summary

Read about the Marine Ice Sheet Instability

Learn about the model setup

Read about the hysteresis of Pine Island Glacier

Read about early warning indicators

Go to further aspects

References & Acknowledgements

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1 Very short summary

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What?

The potential for unstable retreat of the West Antarctic ice sheet is the largest source of uncertainty in future sea level rise projections. The so-called marine ice sheet instability could raise sea-level by more than three meters and may be initiated at Pine Island Glacier - a glacier that has added more to sea level rise than any other in recent decades.

Main finding 1

Using the state-of-the-art ice flow model Úa, we analyse the stability regime of Pine Island Glacier. We identify three distinct tipping points with the last, largest event being triggered for an ocean warming of about 1.2°C.

Main finding 2

All three tipping events can be identified using early warning indicators that detect critical slowing as a tipping point is approached.

Implications

- We here map out for the first time the hysteresis behavior of Pine Island Glacier.
- The robustness of the early warning indicators is promising for application to further cryospheric systems.

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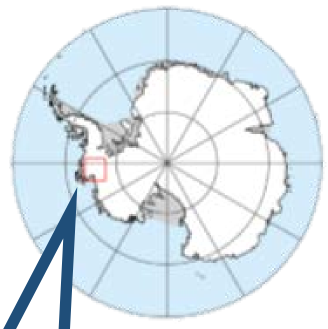
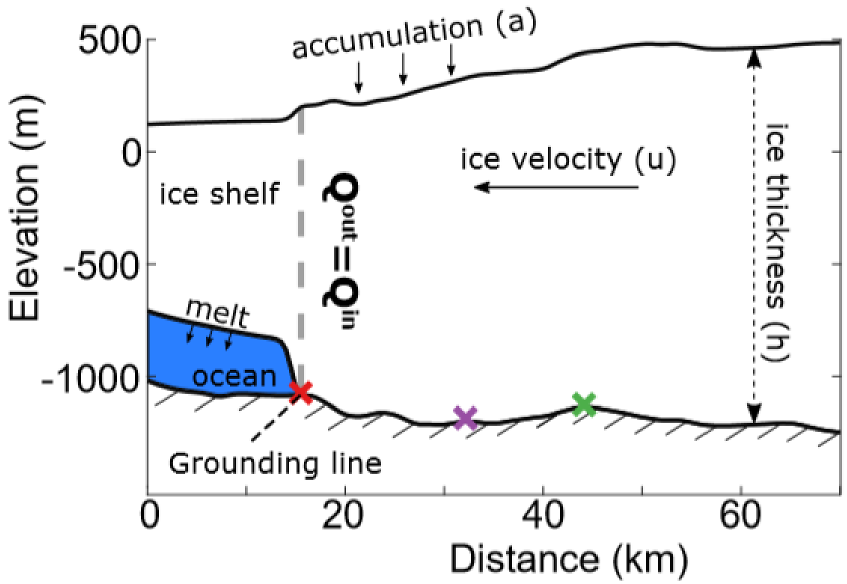
2 Marine Ice Sheet Instability (MISI)

How does the instability work?

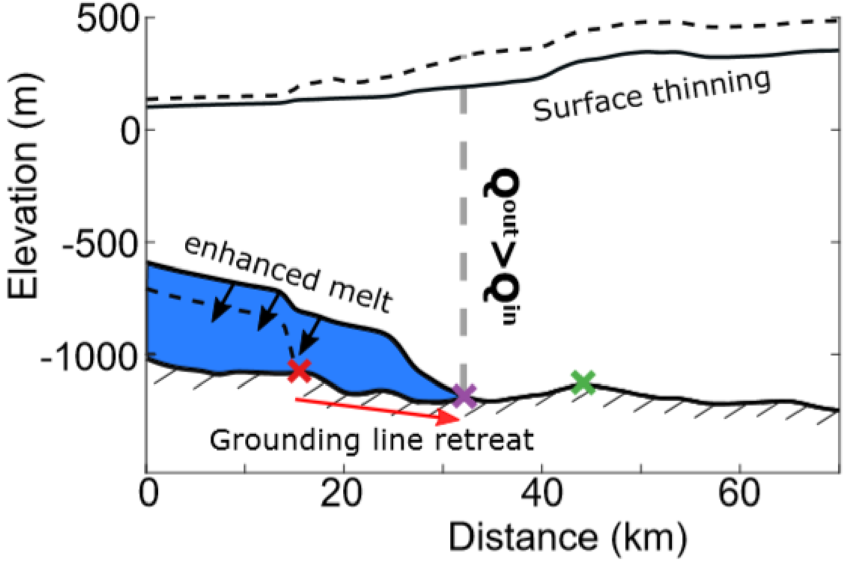


Where is Pine Island Glacier?

- Ice flows from the continent towards the ocean. At the **grounding line**, it starts to float on the ocean and forms the so-called **ice shelves**.



Lateral view of the Pine Island glacier in steady state. In the initial steady state, fluxes (Q_{in} and Q_{out}) are in balance.



Ongoing instable retreat. This causes an increase in the flux across the grounding line Q_{out}, pushing the glacier to be out of balance and leading to continued unstable retreat.

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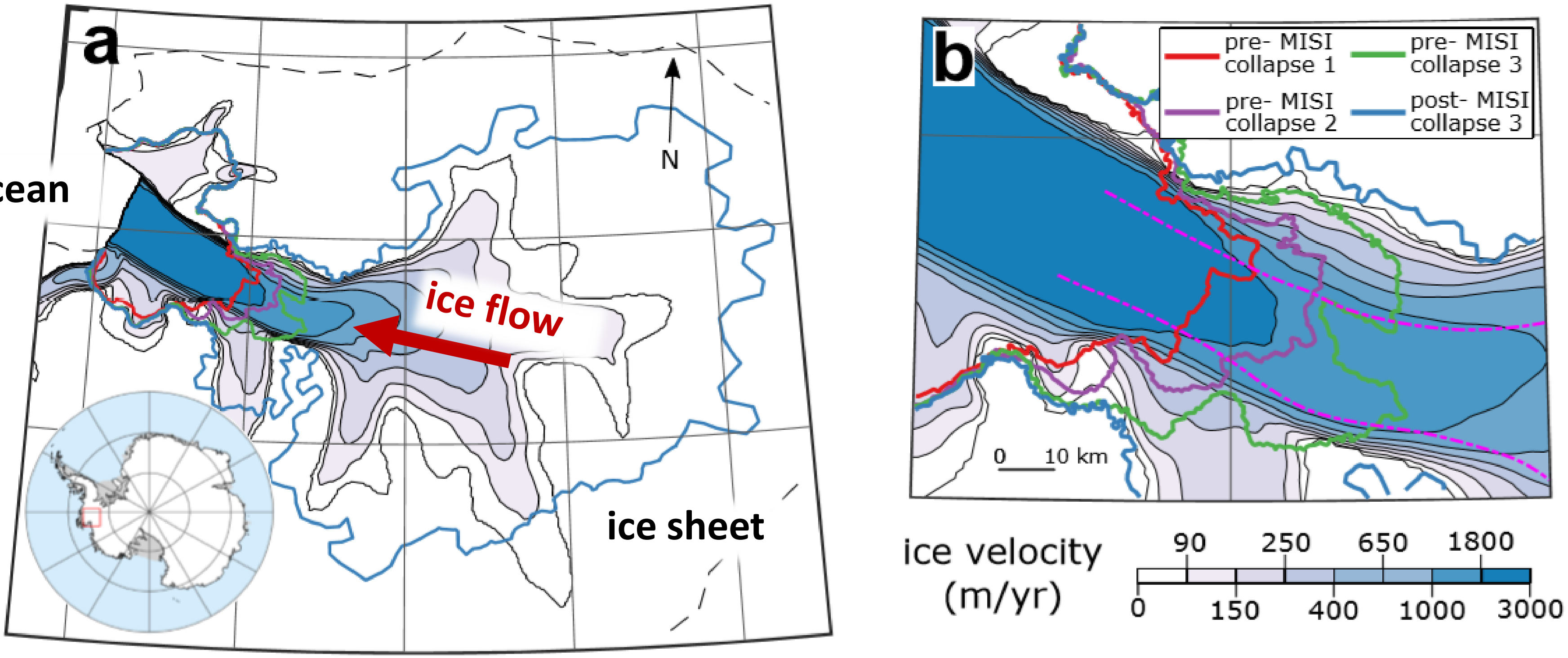
3 Model setup of Pine Island Glacier

- All simulations were done with the ice flow model Úa

More about Úa (git repository)



Three distinct tipping events for Pine Island Glacier

Marine Ice Sheet Instability events for Pine Island Glacier. Shown are (a) grounding line positions before and after the three MISI driven glacier collapses with (b) a zoom to the initial events (coloured lines). The colormap indicates initially modelled ice velocity and the model domain boundary is indicated by a dashed black contour in (a) .

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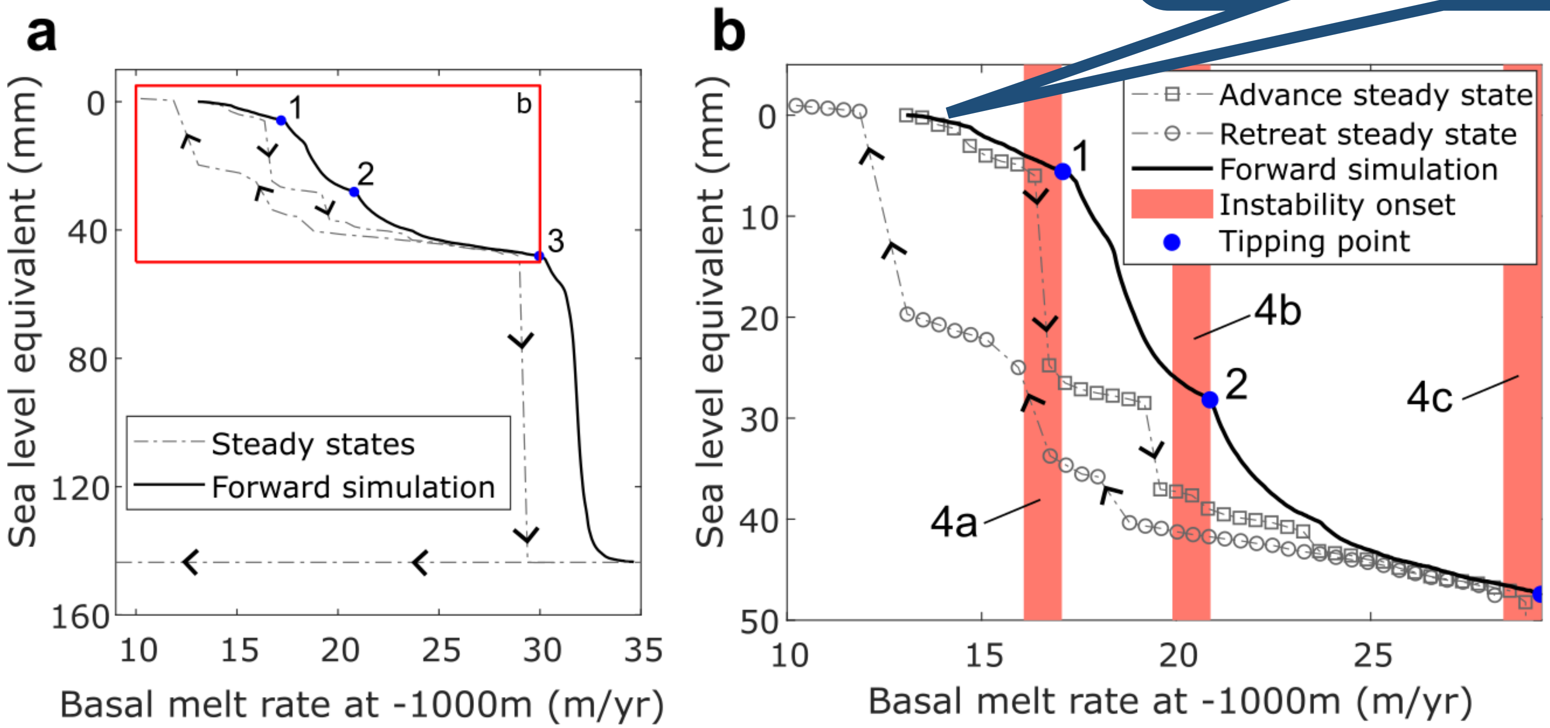
Hysteresis of Pine Island Glacier

Hysteresis loops support that PIG has three distinct tipping points.

Ocean-driven melting causes observed retreat



Panel (b) focuses on the model response before the larger tipping point (event 3) and shows the three windows in which we can anticipate the tipping with early warning indicators.

Change in system state (sea level equivalent ice volume) as a function of the control parameter (melt rate at the ice-ocean interface). The model is run forward with a slowly increasing basal melt rate (solid black line) and shows three distinct tipping points (blue dots). The steady states for a given melt rate in both an advance and retreat configuration are plotted as dashed grey lines, arrows indicate the direction of the hysteresis.

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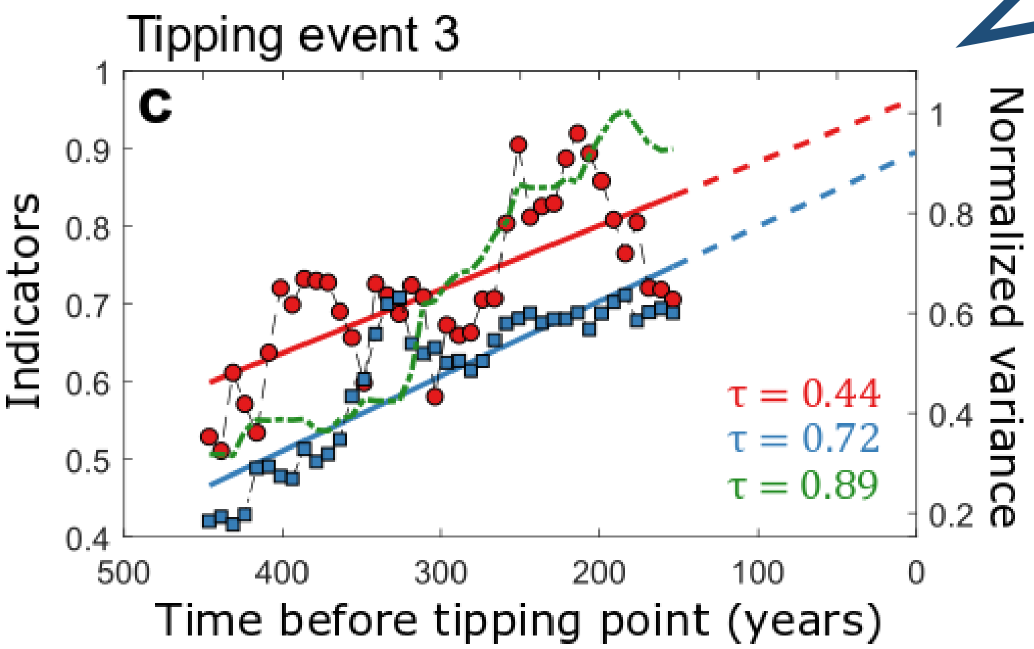
5 Early warning indicators



Indicators robustly anticipate the tipping point.

Early warning is based on the concept of **critical slowing**, i.e., the systems **response time** increases towards infinity when a tipping point is approached.

Early warning indicators

- Lag-1 autocorrelation
- Detrended fluctuation analysis
  "How close is the next system state to the previous?"
- Variance
  Shocks decay more slowly, their accumulating effect increases the variance

Early warning indicators for the marine ice sheet instability in Pine Island Glacier. Early warning indicators preceding the biggest MISI tipping event, along with the linear trend extrapolated to the point in the simulation when the tipping event occurs. Increasing trends in all indicators are shown by a positive Kendall's τ coefficient which measures the correlation between each indicator and time between -1 and 1.

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6 Further aspects in the paper

Tipping points of Pine Island Glacier

- Discussion on the difference between transient early warning indicated tipping points and the equilibrium hysteresis curve
- Details on the ocean forcing which is based on present-day observed values with imposed natural variability
- Details on the model initialization, model grid and domain

Early warning indicators

- Details on the state variable used (grounding line flux)
- Details on data preprocessing and a detailed parameter analysis
- Discussion on the sliding window length used
- Robustness test using surrogate timeseries
- Response timescales for a simplified flowline setup

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7 References & Acknowledgements

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