Stability of the Greenland Ice Sheet: from the Last Glacial Maximum to the future

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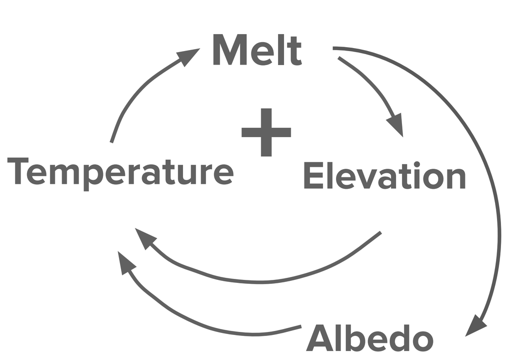
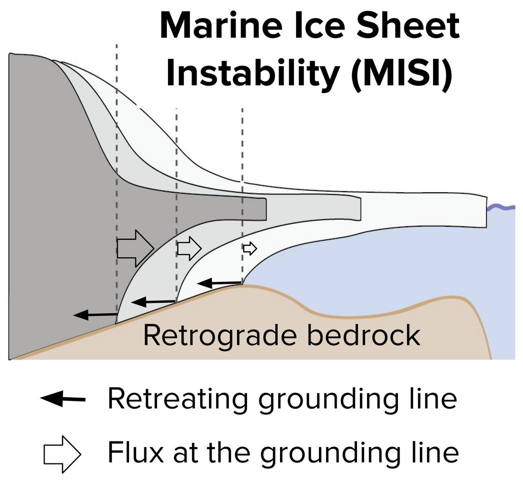
Abstract. In the coming century, the Greenland Ice Sheet (GrIS) is expected to be one of the main contributors to global sea-level rise. In addition, it is thought to be a tipping element due to the existence of positive feedbacks governing its mass balance. Previous studies have explored its stability across a range of temperatures, from present-day conditions to a global warming of 4° C, showing a threshold behavior in its response. However, the value of its critical thresholds, or tipping points, remains highly uncertain. Furthermore, the stability of the GrIS at lower temperatures has not been studied yet. Here we use the ice-sheet model Yelmo coupled with the regional moisture-energy balance model REMBO and a linear parameterization of the oceanic basal melting to obtain the bifurcation diagram of the GrIS within a range of regional summer air temperature anomalies relative to present, extending from a climate representative of the Last Glacial Maximum (-12K) to a warmer climate (+4K). We find that the hysteresis persists in almost the entire study range. We identify two critical thresholds. Consistent with previous studies, a critical threshold is found between +1.2 – +1.6 K of regional summer air temperature anomaly, associated with atmospheric feedbacks. In addition, a critical threshold is found between -10 – -9K, that is mainly driven by ocean warming causing dynamic ice loss, reflecting the role of marine ice-sheet instability in the glacial GrIS.

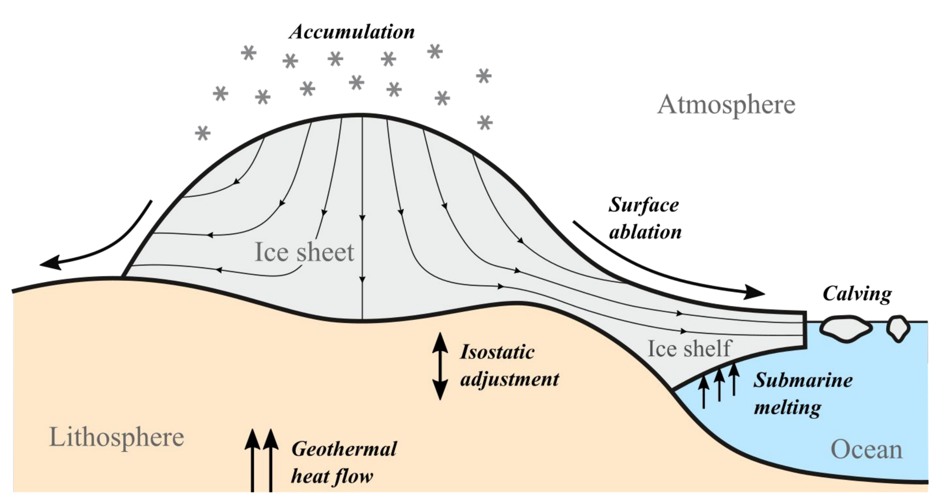
1. Main feedbacks in the ice sheets





2. Methods

An ice sheet can be considered as a very viscous fluid which flows slowly from the top to the margins.

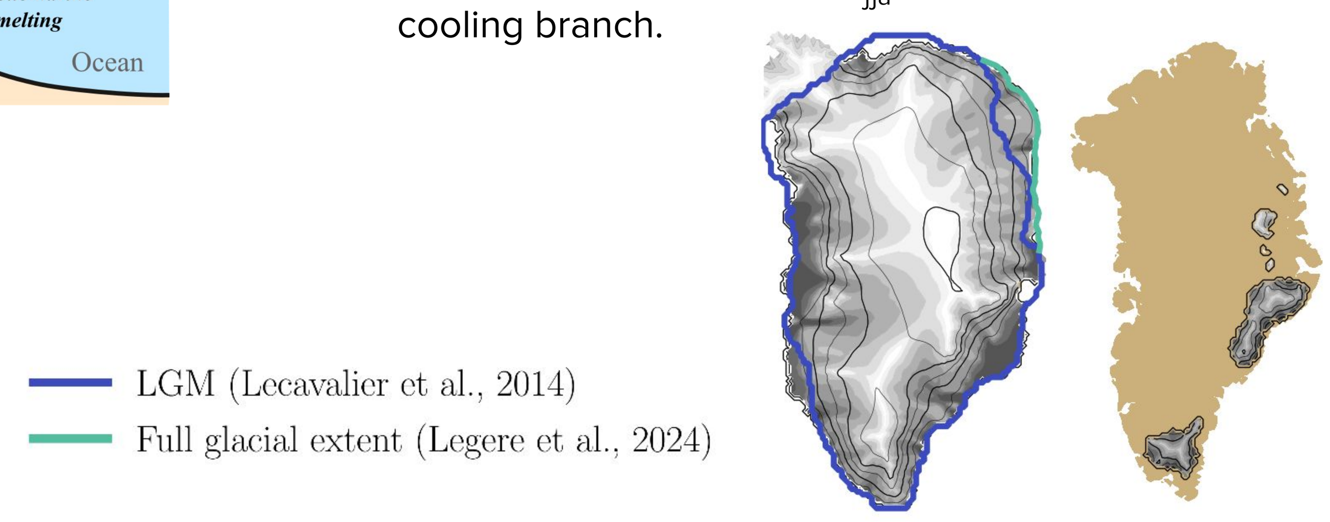


Yelmo: 3D thermomechanical ice sheet model (Robinson et al., 2020). It includes the FastIsostasy model for the isostatic adjustment (Swierczek-Jereczek et al., 2024).

REMBO: regional climate model that solves the energy and moisture balance equations (Robinson et al., 2010). It takes into account the orography of Greenland and the planetary albedo (and its seasonal changes).

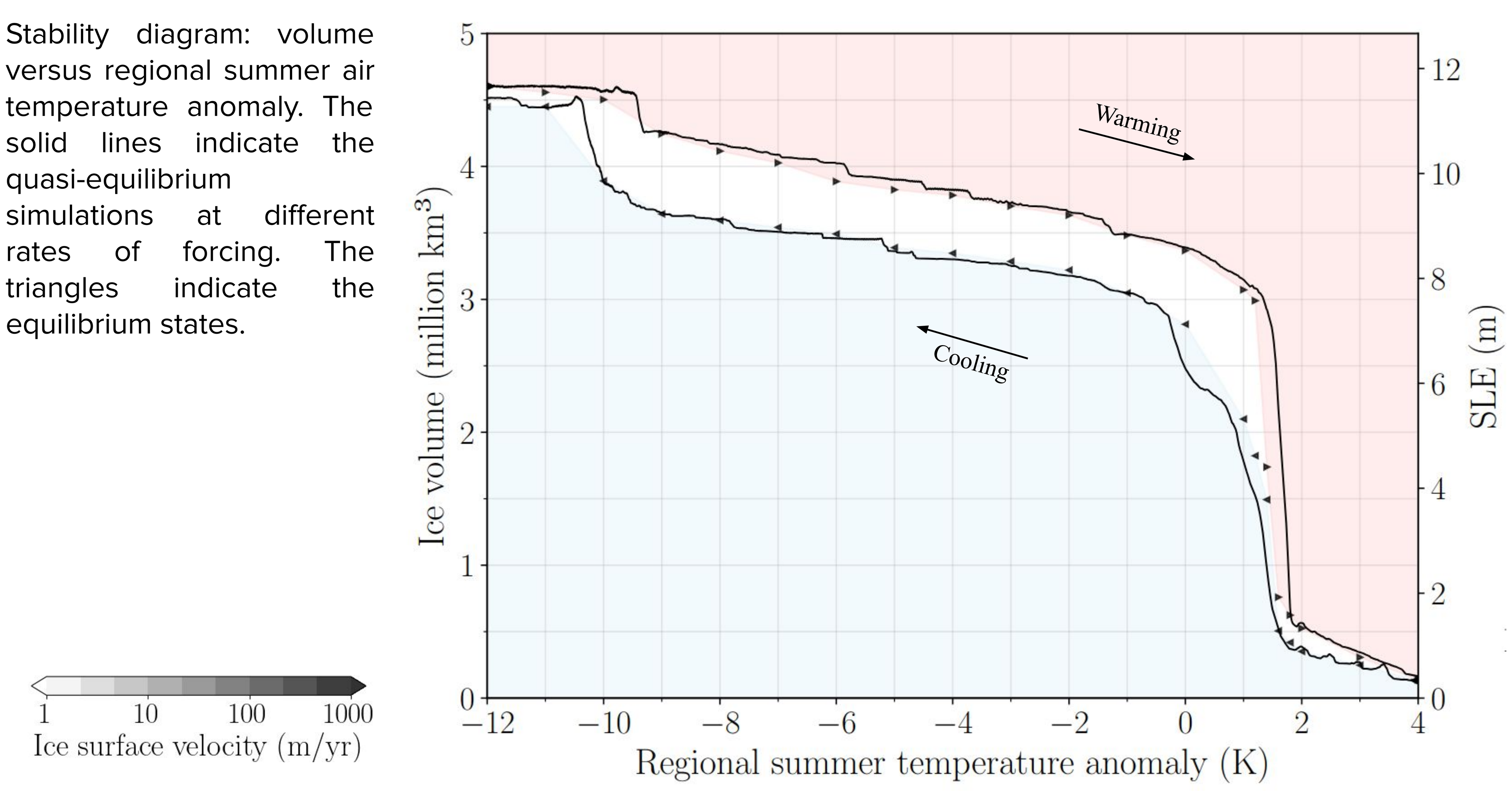
Experimental set-up: Two spin-up simulations are run at constant temperature anomalies:

- **LGM-like state** (ΔT_{jja}=-12K): initial state of the warming branch.
- **Virtually ice-free state**(ΔT_{jja}=+4K): initial state of the cooling branch.

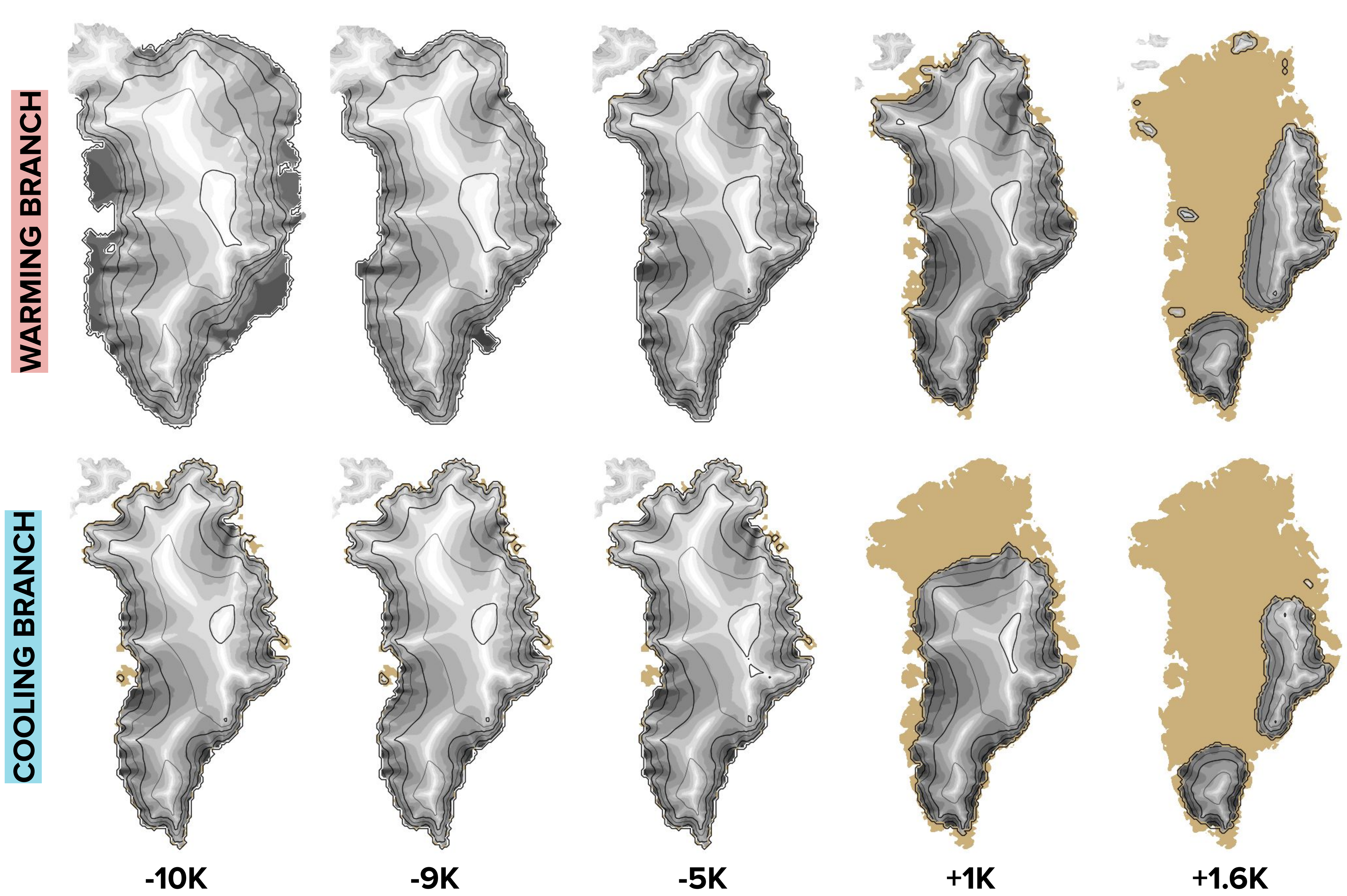


3. What are the critical thresholds of the GrIS?

Stability diagram: volume versus regional summer air temperature anomaly. The solid lines indicate the quasi-equilibrium simulations at different rates of forcing. The triangles indicate the equilibrium states.

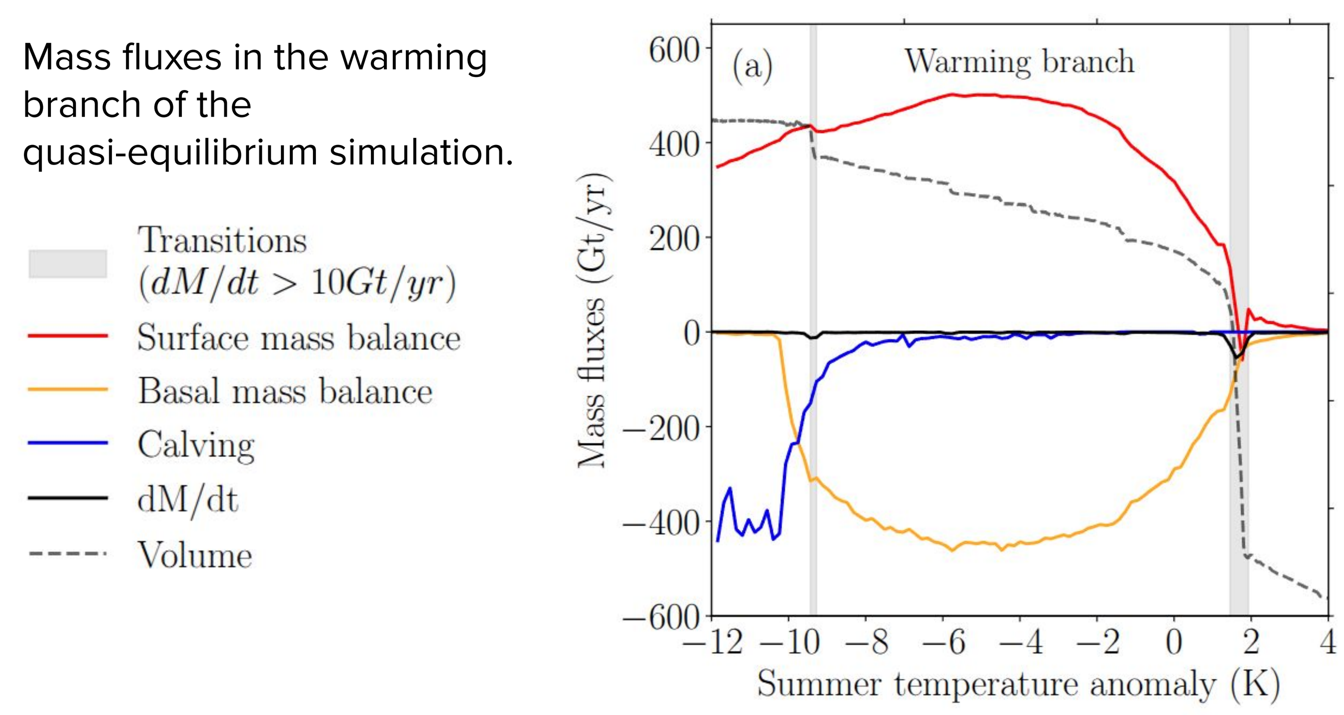


If the GrIS completely melted, sea level would rise by about 7 meters... Can you imagine what that would mean?

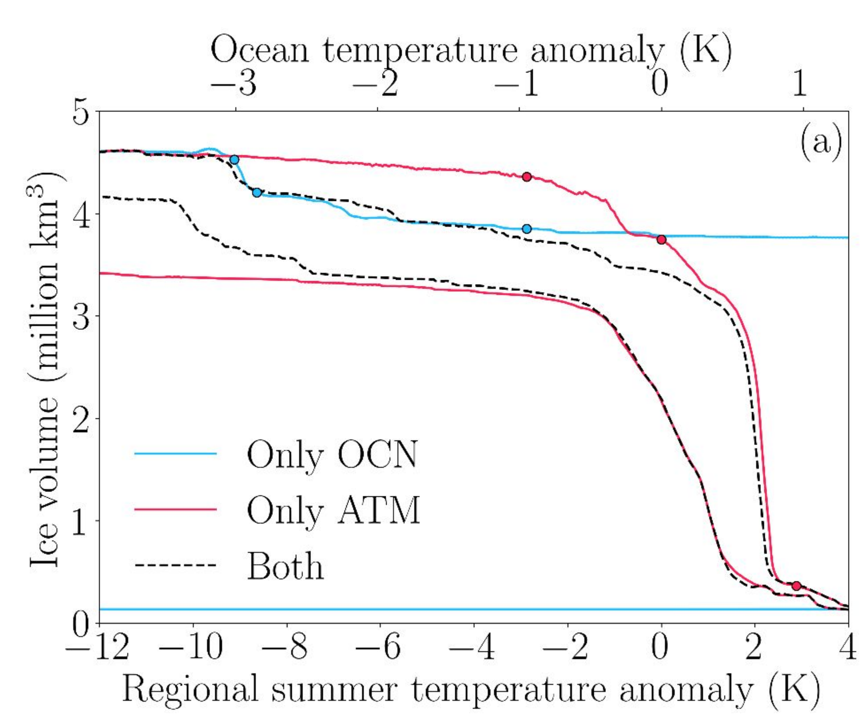


4. Forcing mechanisms: ocean and atmosphere

Mass fluxes in the warming branch of the quasi-equilibrium simulation.



Experiments separately turning off atmosphere and ocean



6. Conclusions

We obtain two bifurcation points:

First bifurcation point: between -10 to -9 K, mainly affecting the northeast. Ocean-driven ice loss dominates, especially via basal melting and MISI (Marine Ice Sheet Instability).

Second bifurcation point: between +1.2 to +1.6 K (+1.50 to +1.84 K of global mean temperature anomalies) with a continental scale impact. Ice loss is driven by atmospheric processes and feedbacks.

Ice regrowth is much slower than ice loss and requires significantly colder temperatures, illustrating multistability and strong hysteresis.

Even if the Paris Agreement is met, this limit will be surpassed in the coming decades. The rate at which the GrIS approaches this new ice-free equilibrium state will depend on the rate of warming and the time spent above this threshold.

References

Robinson, A., Calov, R., & Ganopolski, A. (2010). An efficient regional energy-moisture balance model for simulation of the Greenland Ice Sheet response to climate change. *The Cryosphere*, *4*(2), 129-144.

Robinson, A. et al. (2020). Description and validation of the ice-sheet model Yelmo (version 1.0). *Geoscientific Model Development*, 2020, 1-28.

Swierczek-Jereczek, J., et al. (2024). FastIsostasy v1. 0–a regional, accelerated 2D glacial isostatic adjustment (GIA) model accounting for the lateral variability of the solid Earth. *Geoscientific Model Development*, 17(13), 5263-5290.

Acknowledgements

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