Rate-induced tipping of the Greenland ice sheet

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Introduction

Due to the rapid pace of anthropogenic warming, the response of components of the Earth's climate not only to the amount of warming but also to the rate at which it occurs is important to understand. This study focuses on the Greenland ice sheet (GrIS), which is experiencing a large amount of warming due to Arctic amplification. Using an ice sheet model coupled to a regional energy/moisture balance model, the long-term behaviour of the ice sheet subjected to a range of warming at different rates is studied.

Model description

Yelmo [1] is a depth-integrated viscosity approximation (DIVA) ice-sheet model run at 16km resolution. It is coupled to the diffusive regional energy-moisture balance orographic model REMBO [2]. Forcing manifests as warming of the summer sea-level temperature on the boundary of the ice sheet.

Experimental setup

We first run an adaptive quasi-equilibrium function (AQEF) to track the equilibrium state of the ice sheet as a function of forcing. We do this to locate the bifurcation point. We then run transient experiments to forcing values around the critical value at different rates as shown in Figure (1).

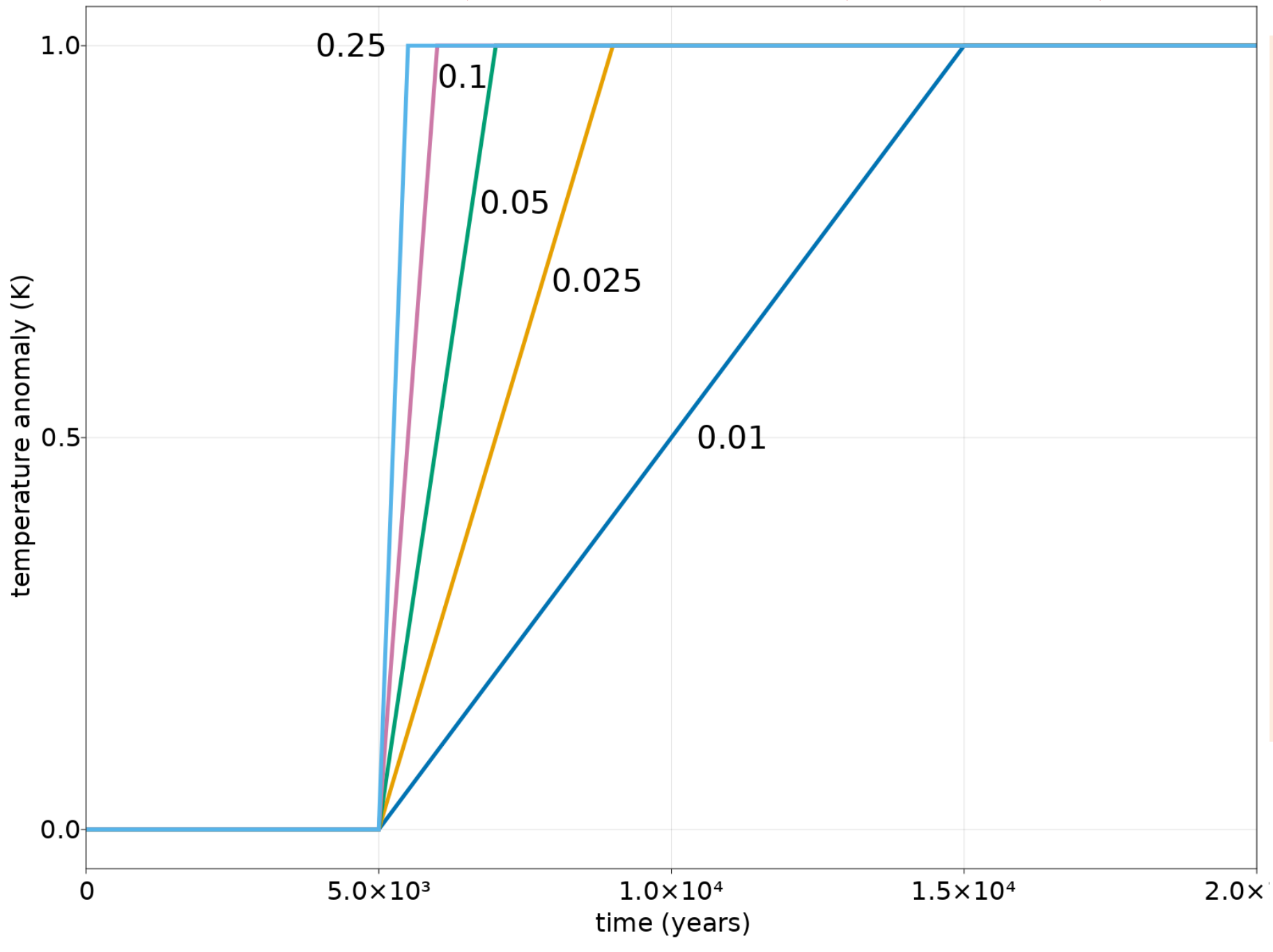

Figure (1): Example of parameter forcing for a ramping experiment.

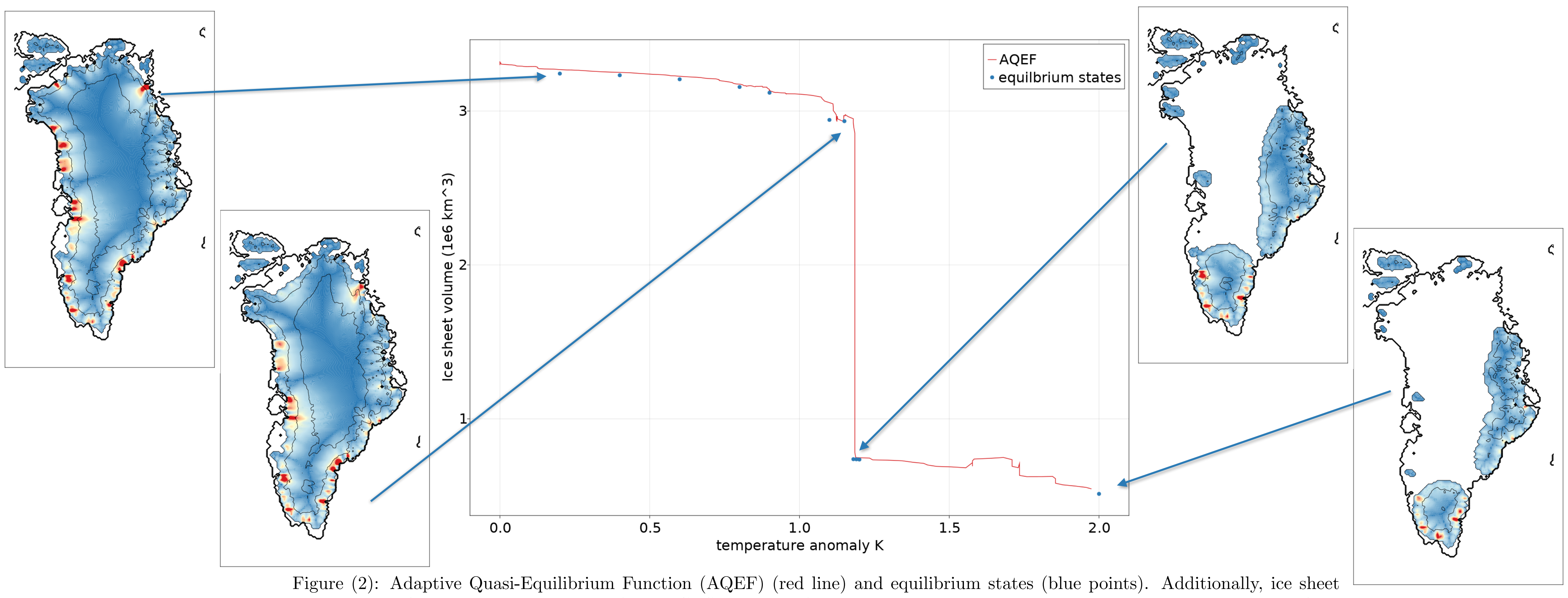

Figure (2): Adaptive Quasi-Equilibrium Function (AQEF) (red line) and equilibrium states (blue points). Additionally, ice sheet height and surface velocity contour plots for the GrIS at various forcing values. Ice sheet loss begins in the northwestern basin of the GrIS. Glaciers in the mountains in the south and east coasts remain after tipping.

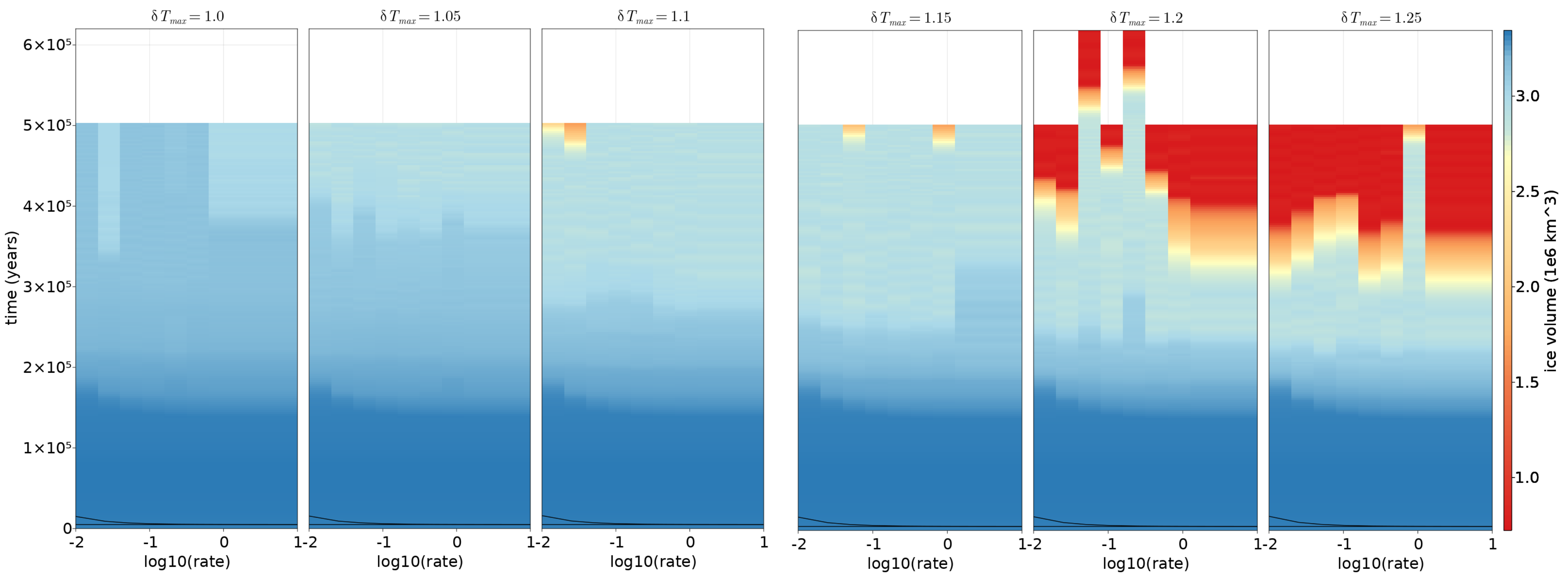

Figure (3): Results of the ramping experiments for the different forcing values (subplots) and the different rates (x-axes of the subplots). Blue indicates a surviving ice sheet, red indicates a loss of the ice sheet.

Rate-induced tipping

The GrIS may be either mostly ice-covered or ice-free due to the positive ice-albedo and elevation feedbacks. Negative feedbacks such as glacial isostatic rebound (GIA) or marine ice sheet instability can weaken the effect of the positive feedbacks, causing a bifurcation to happen at a larger forcing value than if they were absent. Rate-induced tipping (r-tipping) occurs when a system experiences a beyond-critical rate of forcing that causes it to tip before a bifurcation point is reached. In this case, the negative feedbacks respond on a longer timescale than the fast positive feedbacks and the ramping, and are weakened. Due to a lack of strong feedbacks across different time scales in the GrIS, we expect to see no r-tipping behaviour.

[1] Robinson, A. et al. Description and validation of the ice-sheet model Yelmo (version 1.0). Geosci. Model Dev. 13, 2805–2823 (2020).
[2] Robinson, A., Calov, R. & Ganopolski, A. An efficient regional energy-moisture balance model for simulation of the Greenland Ice Sheet response to climate change. The Cryosphere (2010).

Chaotic transients

While all the runs for $\delta T_{max} \geq 1.2$ K tip, they do so at different times and not monotonically with rate. This is because they are chaotic transients. Coupling a fast chaotic system such as REMBO to a slow multistable model like Yelmo produces chaotic transients. These are trajectories that have been forced past the bifurcation point, but do not tip immediately. They instead follow a 'ghost attractor' which matches that of the untipped state for an arbitrary amount of time. Thus is impossible to determine exactly whether a trajectory has reached either stable attractor after finite time.

However, they can be investigated probabilistically. Their lifetimes (tipping times) are exponentially distributed. Additionally, their average transient lifetime scales as $|f - f_c|^{-\gamma}$. Thus the closer the forcing f is to the critical f_c, the longer the average transient lifetime. Figure (5) suggests an exponential distribution as well as dependence of transient lifetime on forcing level, however there are not enough data points to make this claim with high confidence.

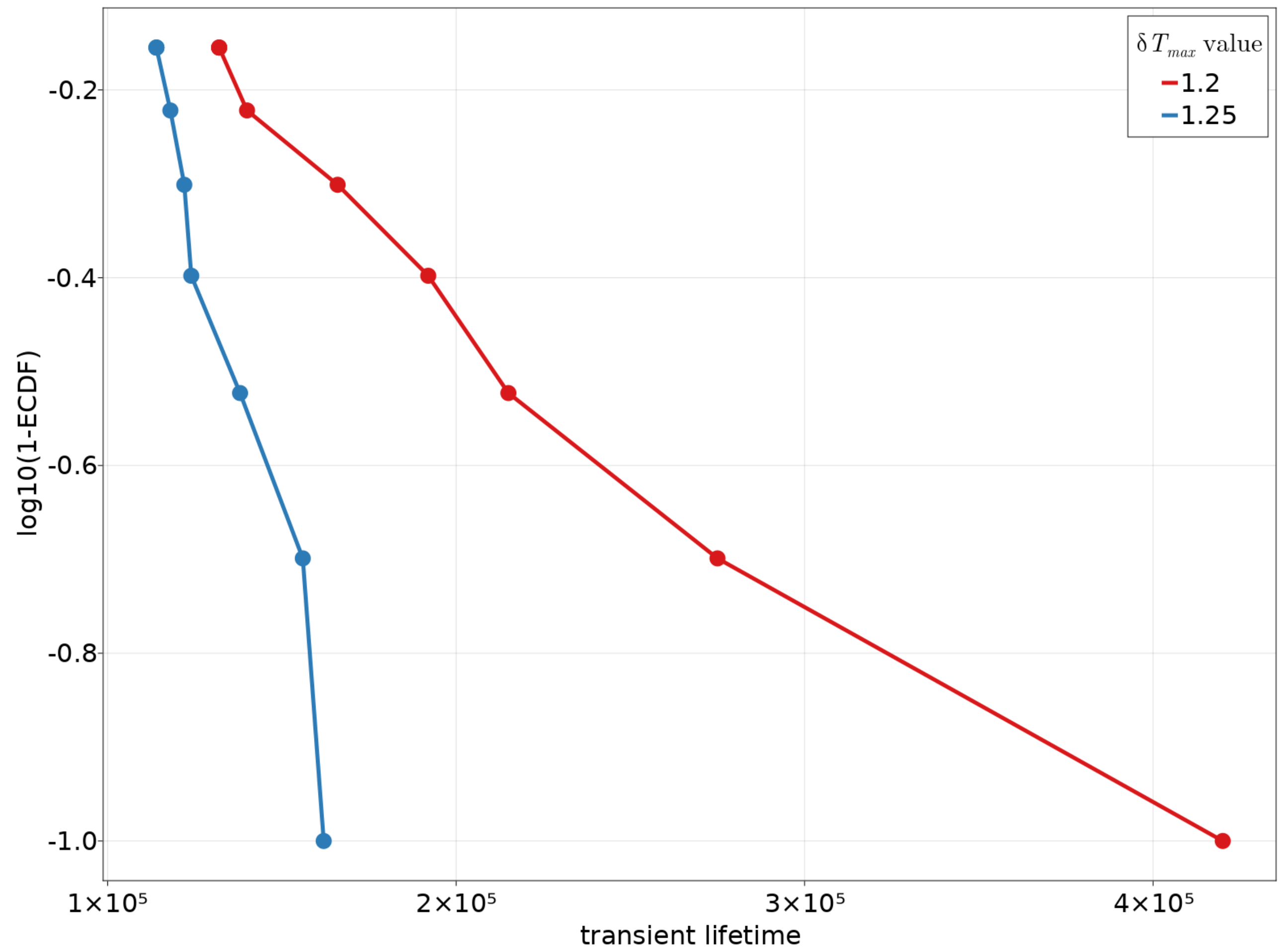

Figure (4): Logarithm of cumulative distribution of lifetimes (tipping times) of transient trajectories for $\delta T_{max} = 1.2$ (red) and $\delta T_{max} = 1.25$ (blue).

Conclusions

- Some ramping runs tip before the bifurcation point, indicating some rate-induced effects
  - However, these may be chaotic transients or due to a fractal basin boundary (future work)
- Due to the long response time of the GrIS when forced to values close to the bifurcation, tipping behaviour does not occur on timescales shorter than that of orbital forcing
  - The GrIS shows no robust r-tipping behaviour