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BJERKNES CENTRE for Climate Research

Topographically constrained tipping point for complete Greenland Ice Sheet melt

In review for The Cryosphere

M. Petrini, M. Scherrenberg, L. Muntjewerf, M. Vizcaino, R. Sellevold, G. Leguy, W. Lipscomb, H. Goelzer

CESM Land Ice Working Group meeting

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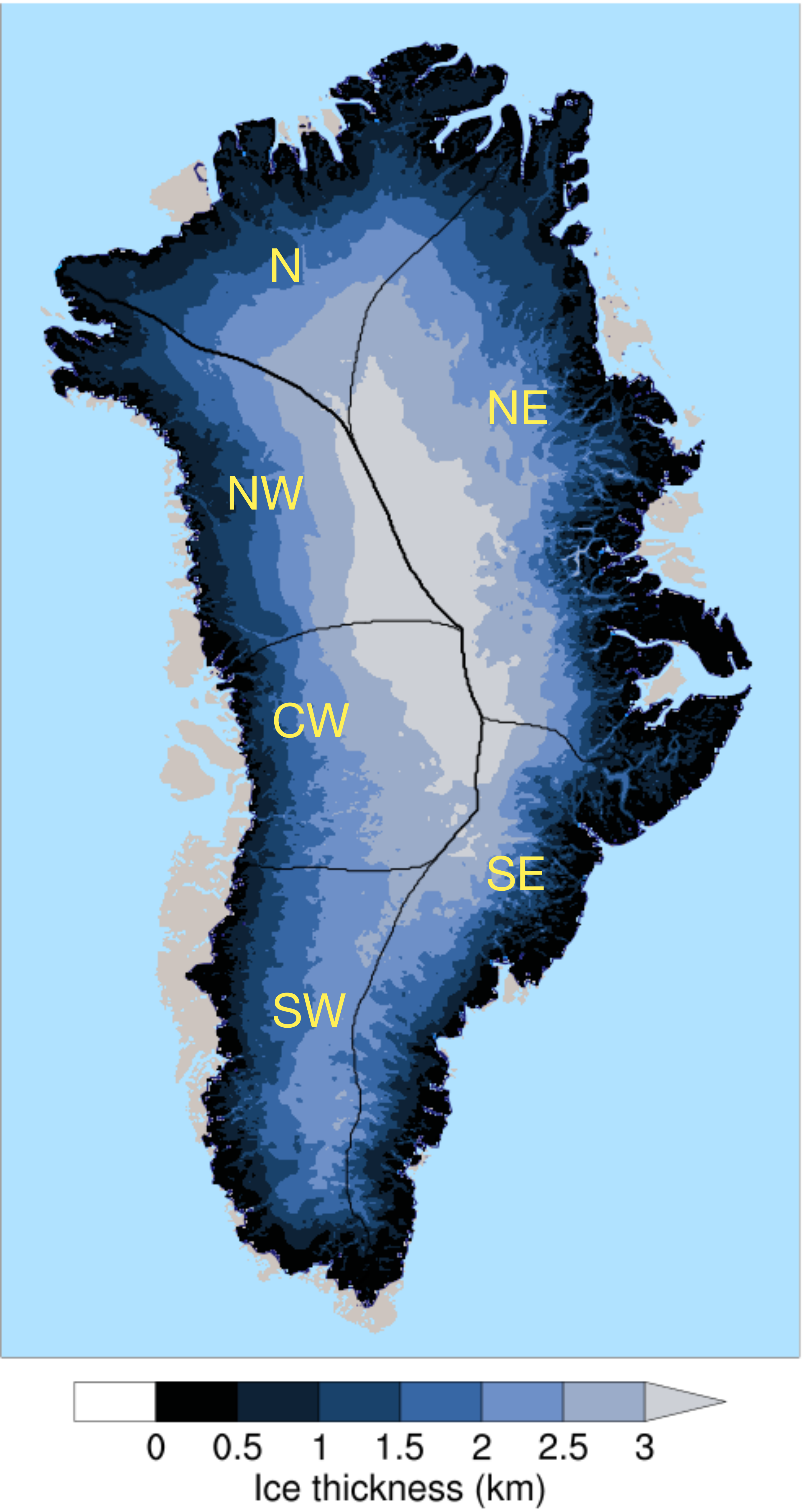
Intro:
what we are interested in
and what we know?

Aim of the study and previous results



Long-term evolution and stability of the Greenland Ice Sheet:

- Identify SMB thresholds for GrIS complete melt;
- Existence of tipping point for the GrIS (thresholds for significant change);
- Processes controlling thresholds, patterns and timescales for GrIS melt;

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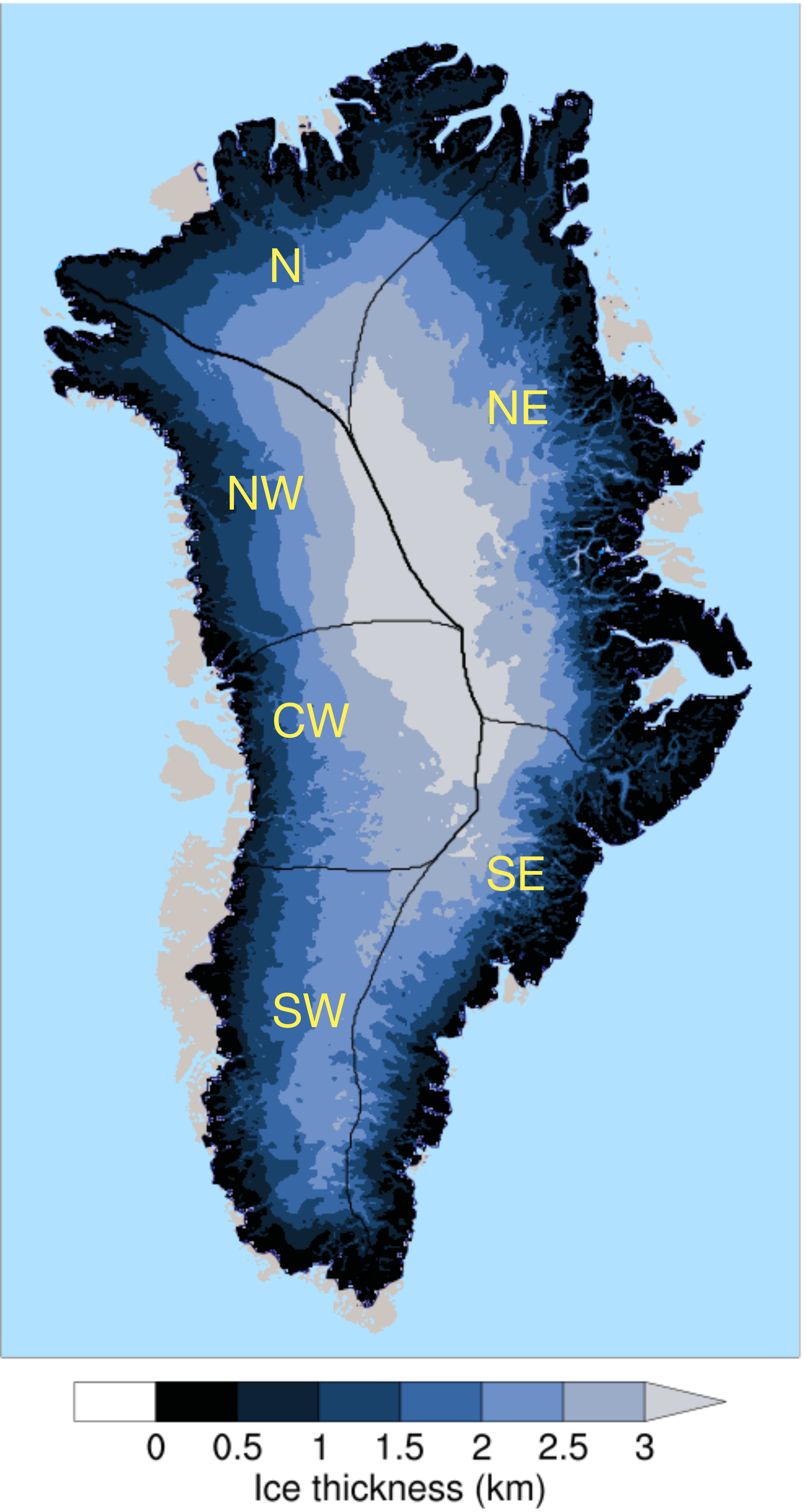

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What we know:

- *Robinson et al. 2012*: sharp threshold behaviour for GrIS complete melt;
- *Gregory et al. 2020*: wide range of equilibrium states;
- GMT thresholds for GrIS full deglaciation between 2.2-3.2 K;
- GMT threshold was likely not passed during the Eemian (GrIS loss < 4 m SLE);

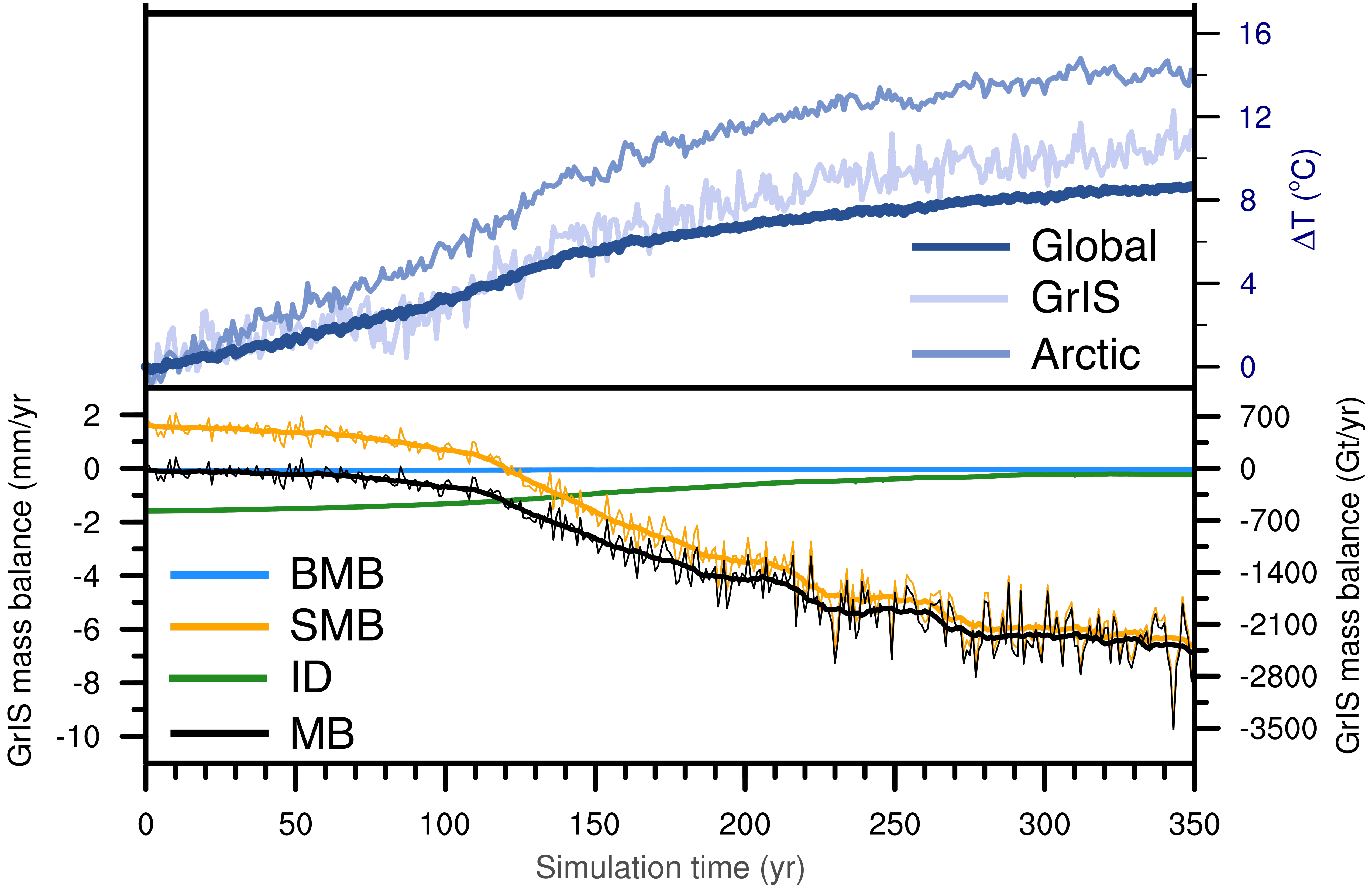
Methods: multiple Elevation Classes SMB forcing

Starting point: fully coupled CESM/CISM 1pct-CO_2 run

JAMES | Journal of Advances in Modeling Earth Systems

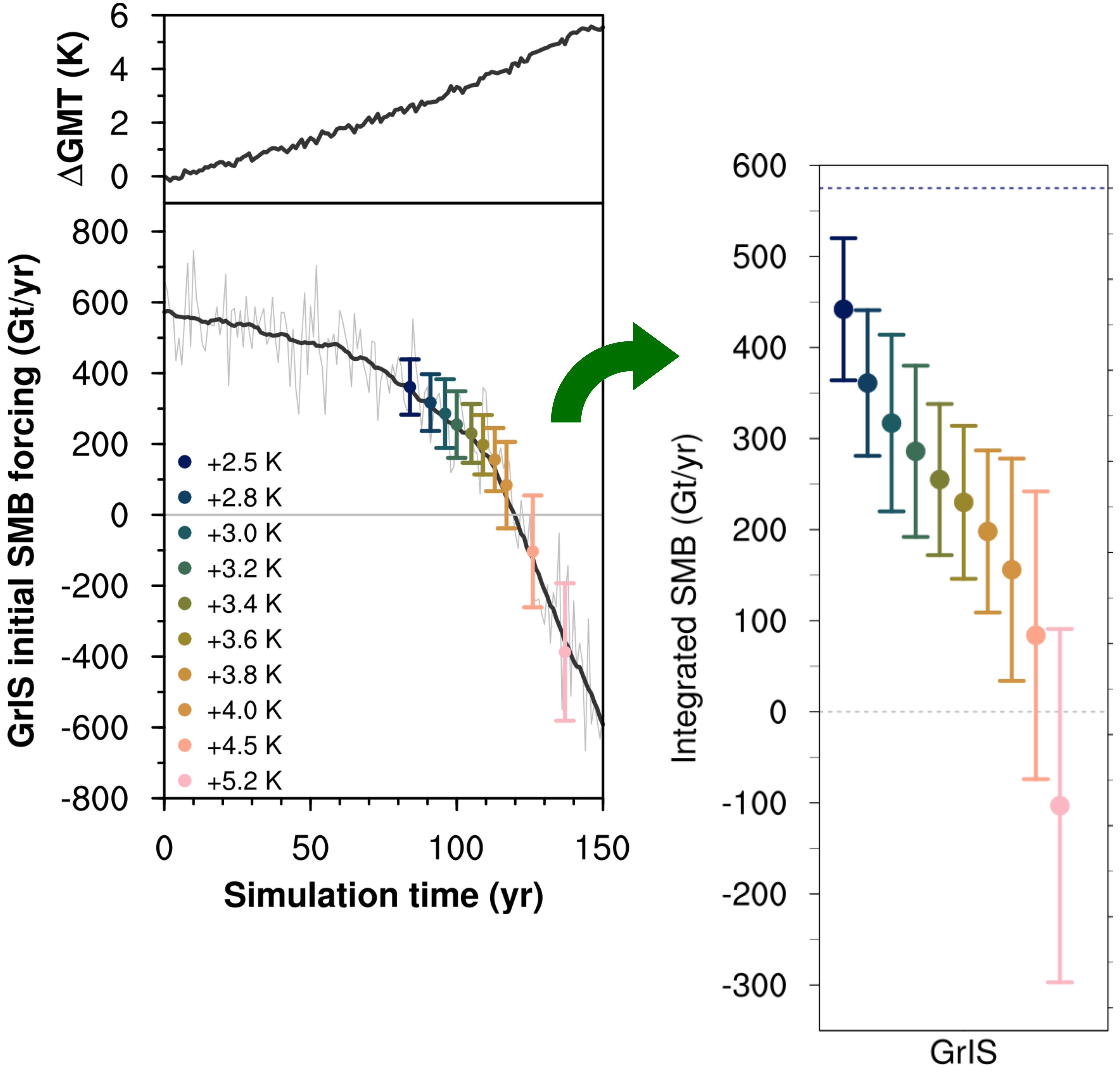
Accelerated Greenland Ice Sheet Mass Loss Under High Greenhouse Gas Forcing as Simulated by the Coupled CESM2.1-CISM2.1

Laura Muntjewerf[1], Raymond Sellevold[1], Miren Vizcaino[1], Carolina Ernani da Silva[1], Michele Petrini[1], Katherine Thayer-Calder[2], Meike D. W. Scherrenberg[1], Sarah L. Bradley[3], Caroline A. Katsman[4], Jeremy Fyke[5], William H. Lipscomb[2], Marcus Lofverstrom[6], and William J. Sacks[2]



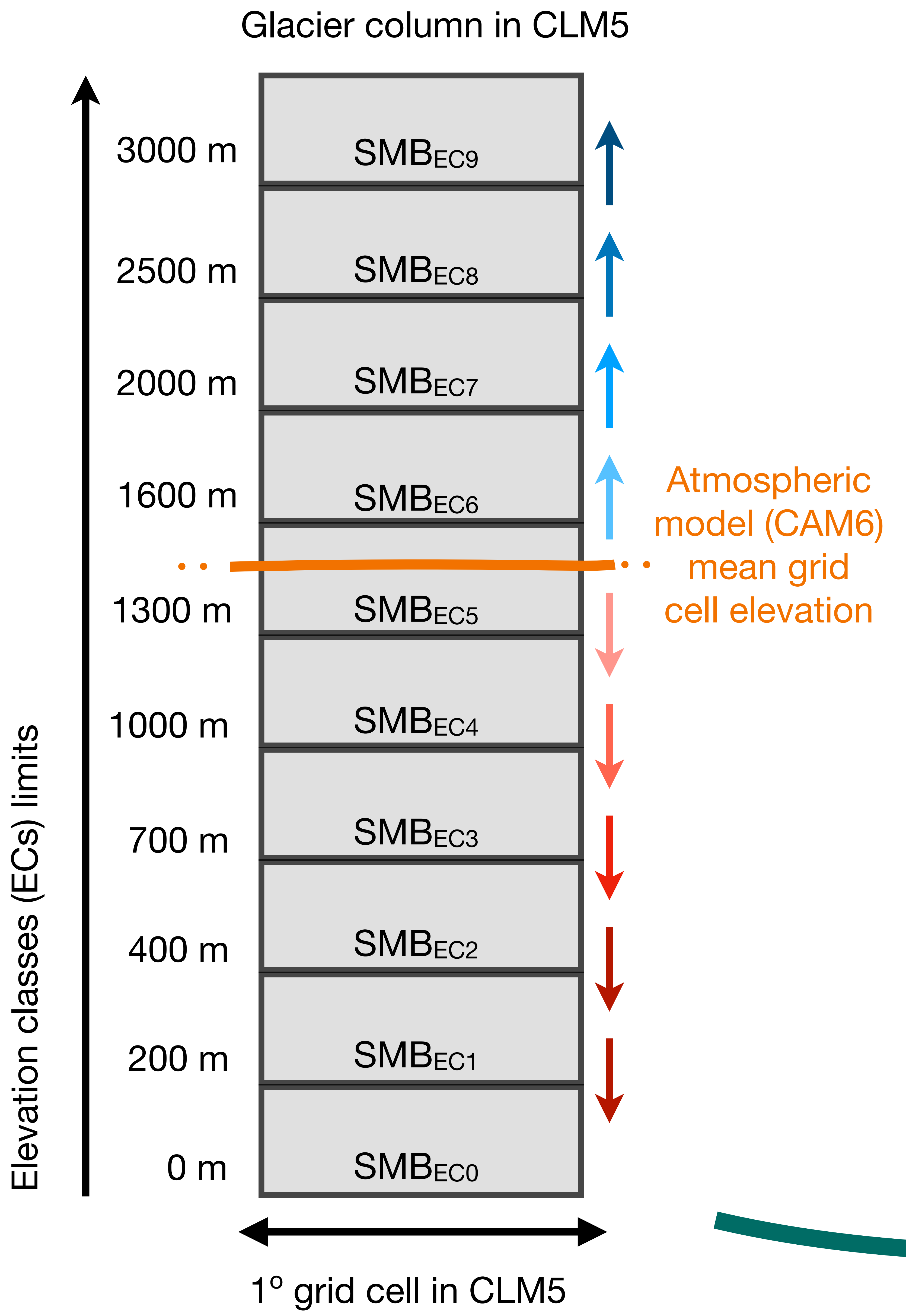
- New CESM capability: coupling with CISM, **advanced SMB calculation and downscaling**;
- Fully coupled global climate and GrIS simulation under high CO_2 forcing (Muntjewerf et al. 2020);
- CO_2 increases by 1% until reaching 4x pre-ind.;

Selection of different levels of (transient) SMB forcing



- New CESM capability: coupling with CISM, advanced SMB calculation and downscaling ;
- Fully coupled global climate and GrIS simulation Under high CO_2 forcing (Muntjewerf et al. 2020);
- CO_2 increases by 1% until reaching 4x pre-ind.;
- From this run, we select multiple time intervals corresponding to **different levels of SMB/GMT**;
- Each time interval contains **a climatology of SMB forcing <u>at multiple Elevation Classes</u>**;
- Each SMB interval used to force CISM, cycling forcing until GrIS equilibrium or deglaciation;
- Multiple Elevation Classes SMB forcing: how does it work and why it is important?

Elevation-dependent SMB: multiple elevation classes

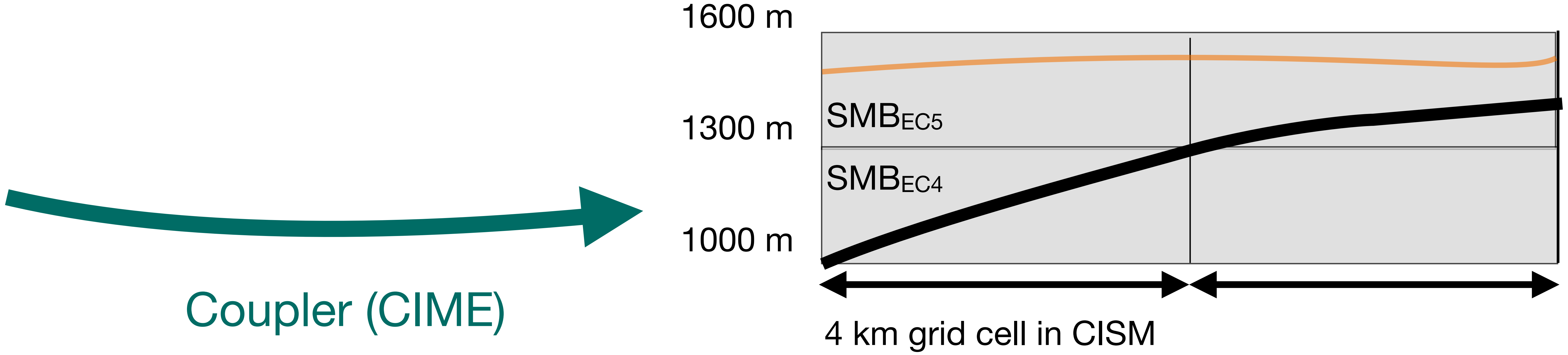


SMB calculation in CESM:

- CLM5: Surface air temp. downscaled to 10 ECs (lapse rate 6 K/km);
- CLM5: for each EC, surface-energy-balance scheme for SMB,
  SMB = snowfall + refreezing - snow_melt - ice_melt - sublimation;
- annual mean SMB at each EC saved in *coupler history files*;

CISM runs in this study:

- Forced with coupler history files from coupled 4xCO_2 run;
- SMB downscaled based on CISM surface topography;
- Account for SMB changes due to surface topography changes;

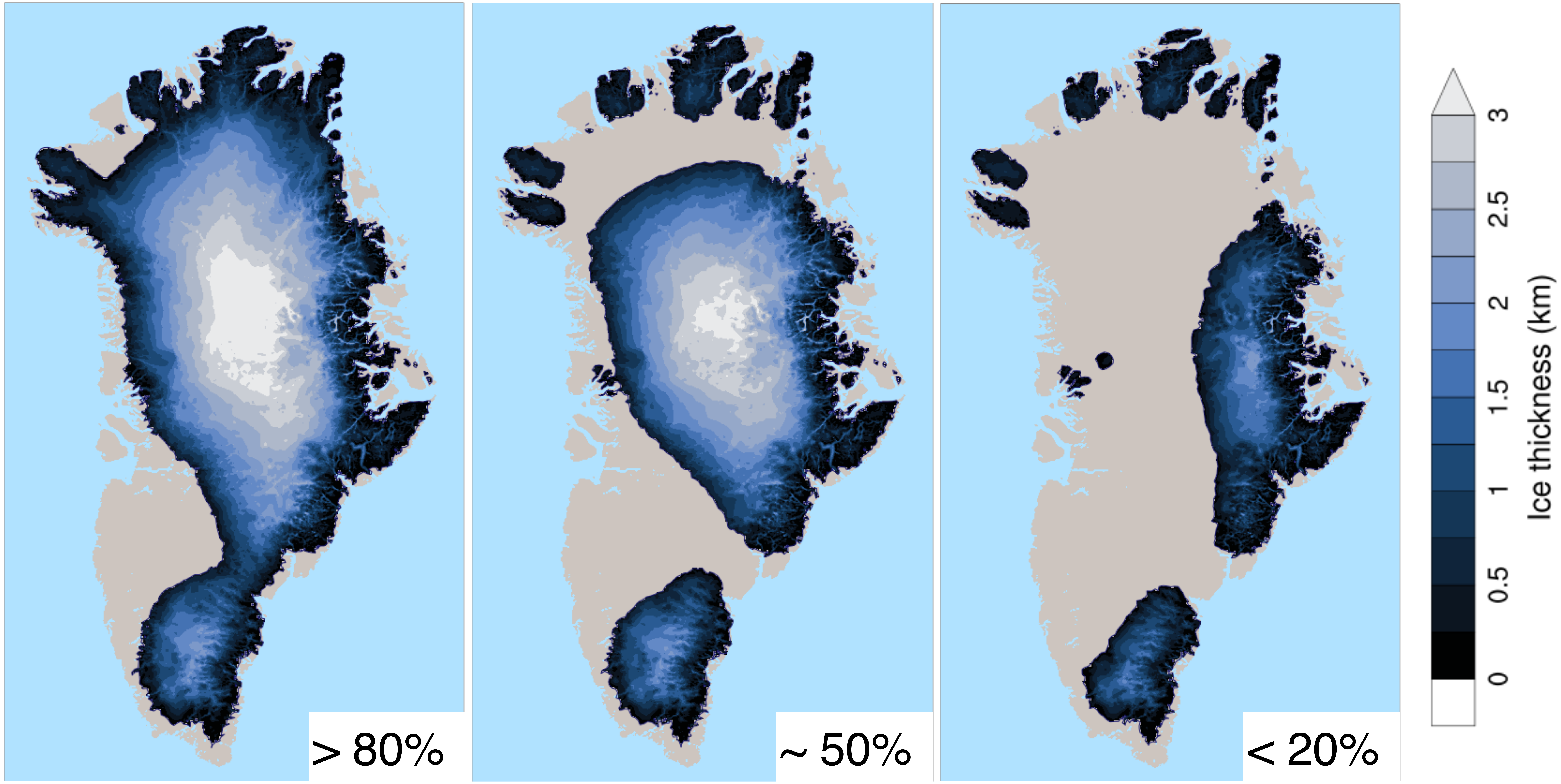


Results #1: SMB threshold, non-linearity & driving processes

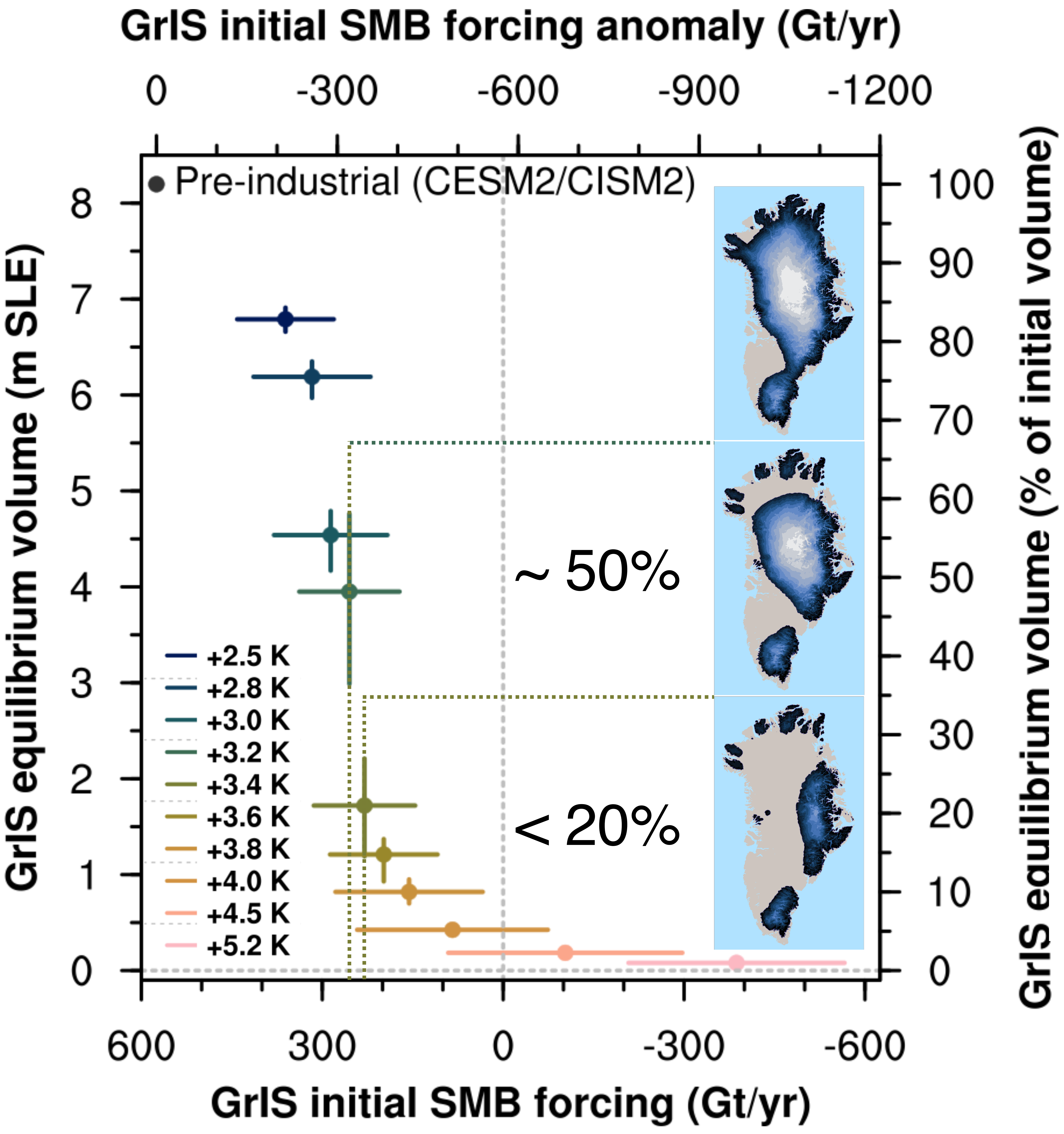
Positive (>0) SMB threshold for GrIS deglaciation

- Three main final GrIS states for close initial SMB forcing levels:

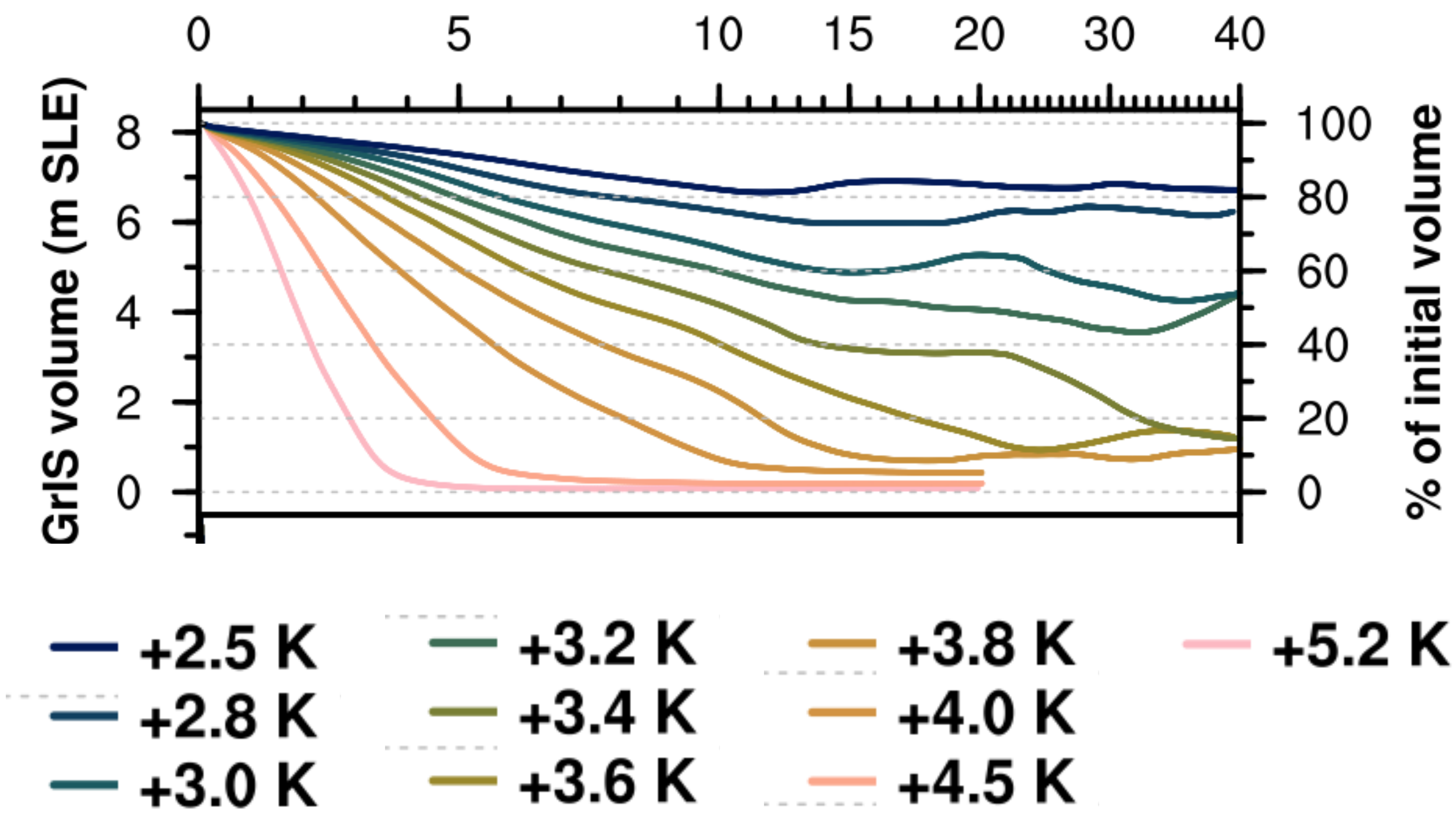
  (1) **> 80%** (SMB > 317±97 Gt/yr), (2) **~ 50%** (SMB 286±94 - 255±83 Gt/yr), (3) **< 20%** (SMB < 230±84 Gt/yr);



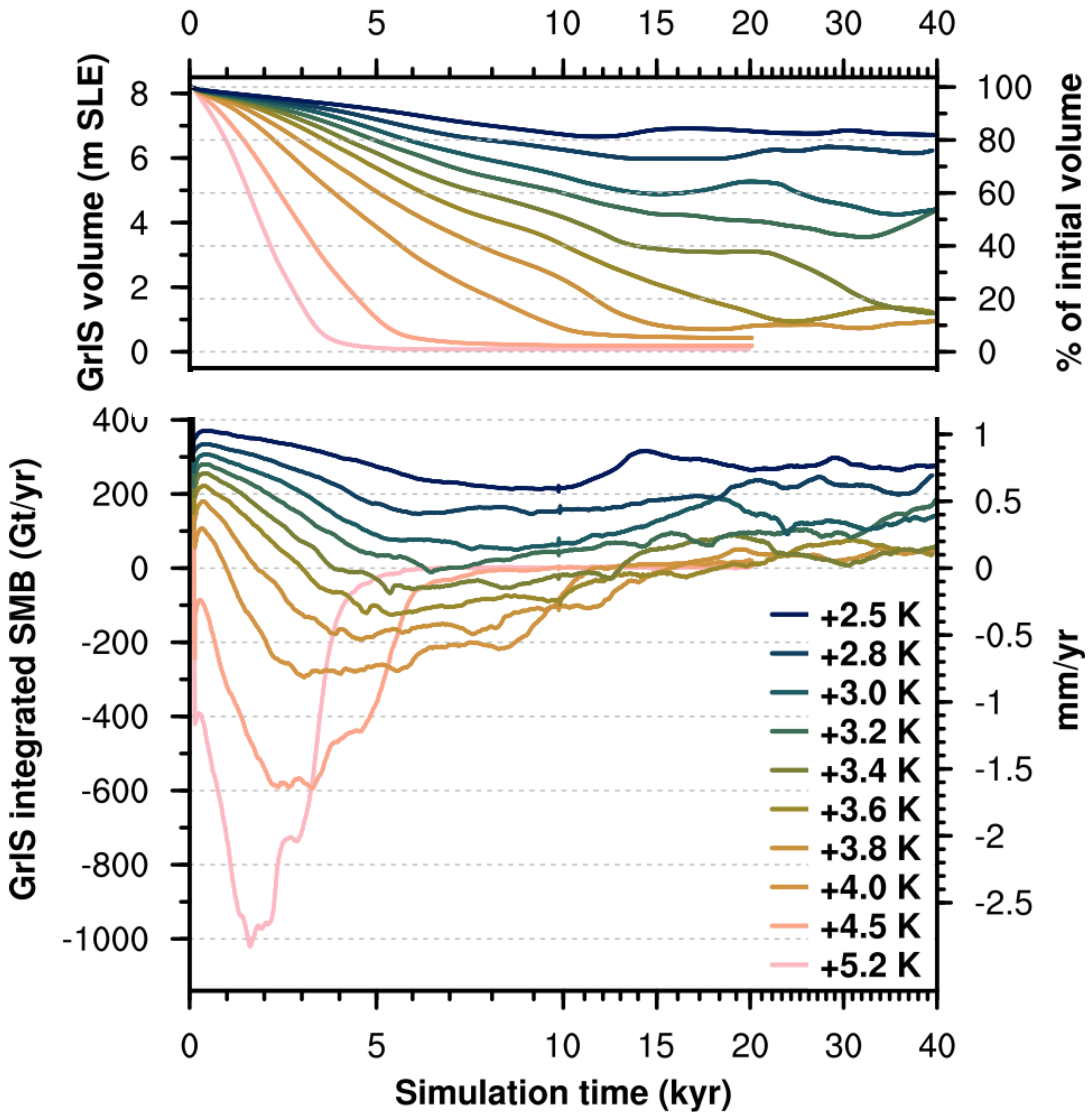
Highly non-linear GrIS response to sustained warming



- For small change in SMB forcing, strongly nonlinear GrIS response): tipping point behaviour!
- SMB threshold for GrIS deglaciation is positive, 60% decrease from pre-industrial SMB;
- Tipping run: +3.4 K (transient) warming than pre-ind.



SMB-height feedback: not only a positive feedback!



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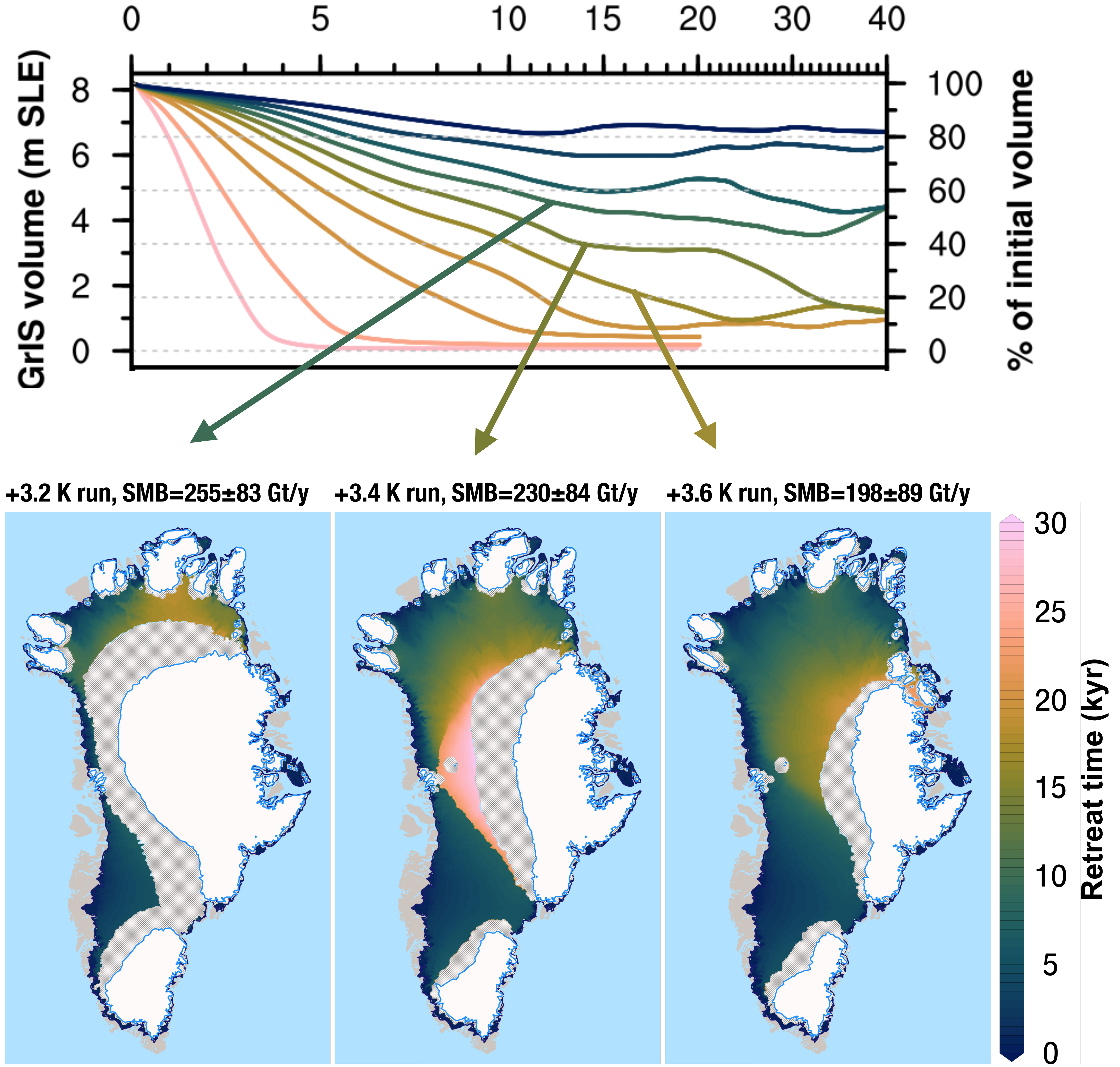

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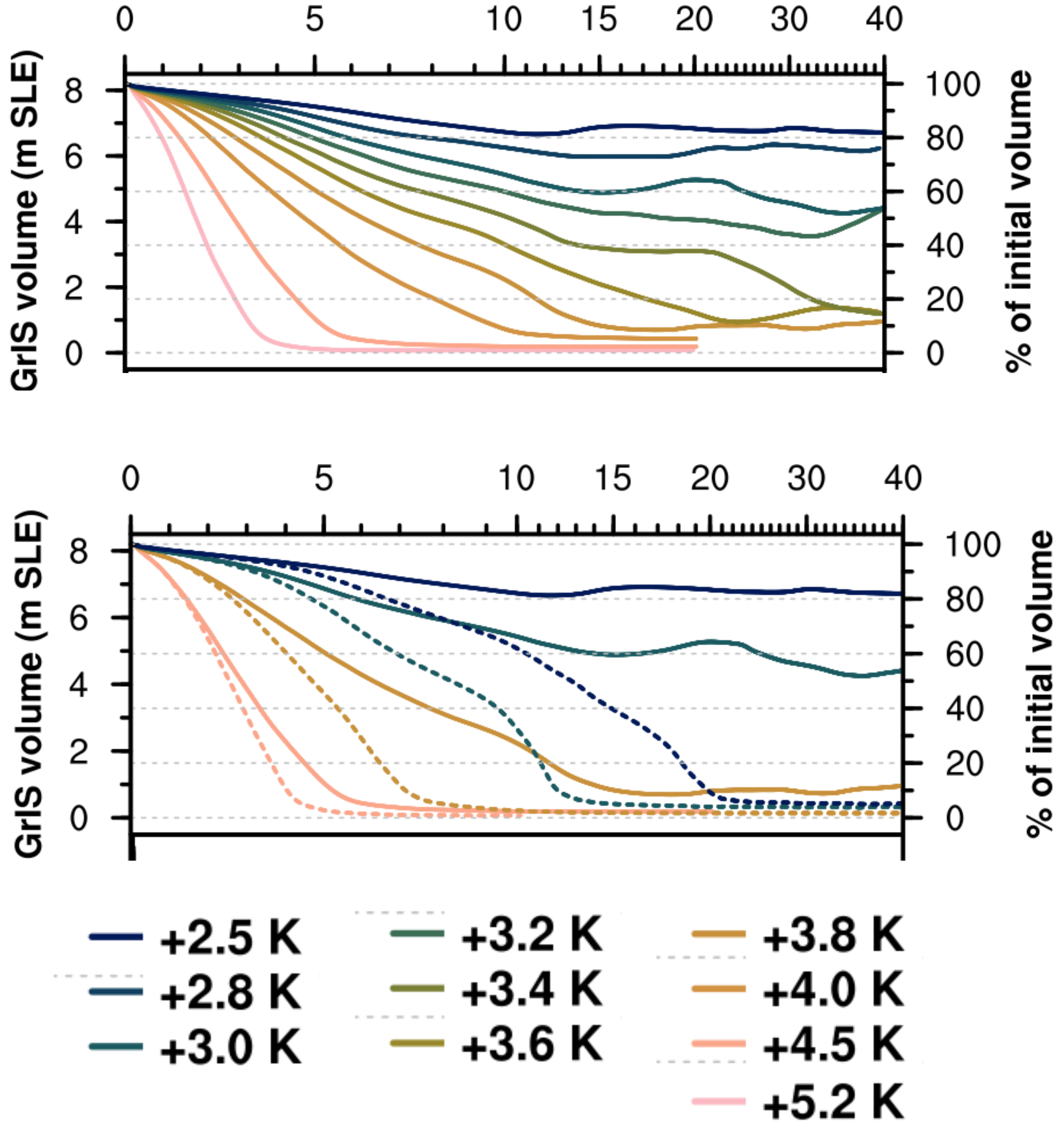
- SMB threshold for GrIS deglaciation is positive, 60% decrease from pre-industrial SMB;
- While initial SMB forcing >0, GrIS deglaciation when SMB becomes and remains negative!
- Close to SMB threshold, GrIS does not reach equilibrium: quasi-periodic oscillations!
- SMB-height feedback responds to ice thinning (surface melt) and bedrock uplift (GIA)!

Impact of GIA on the GrIS response



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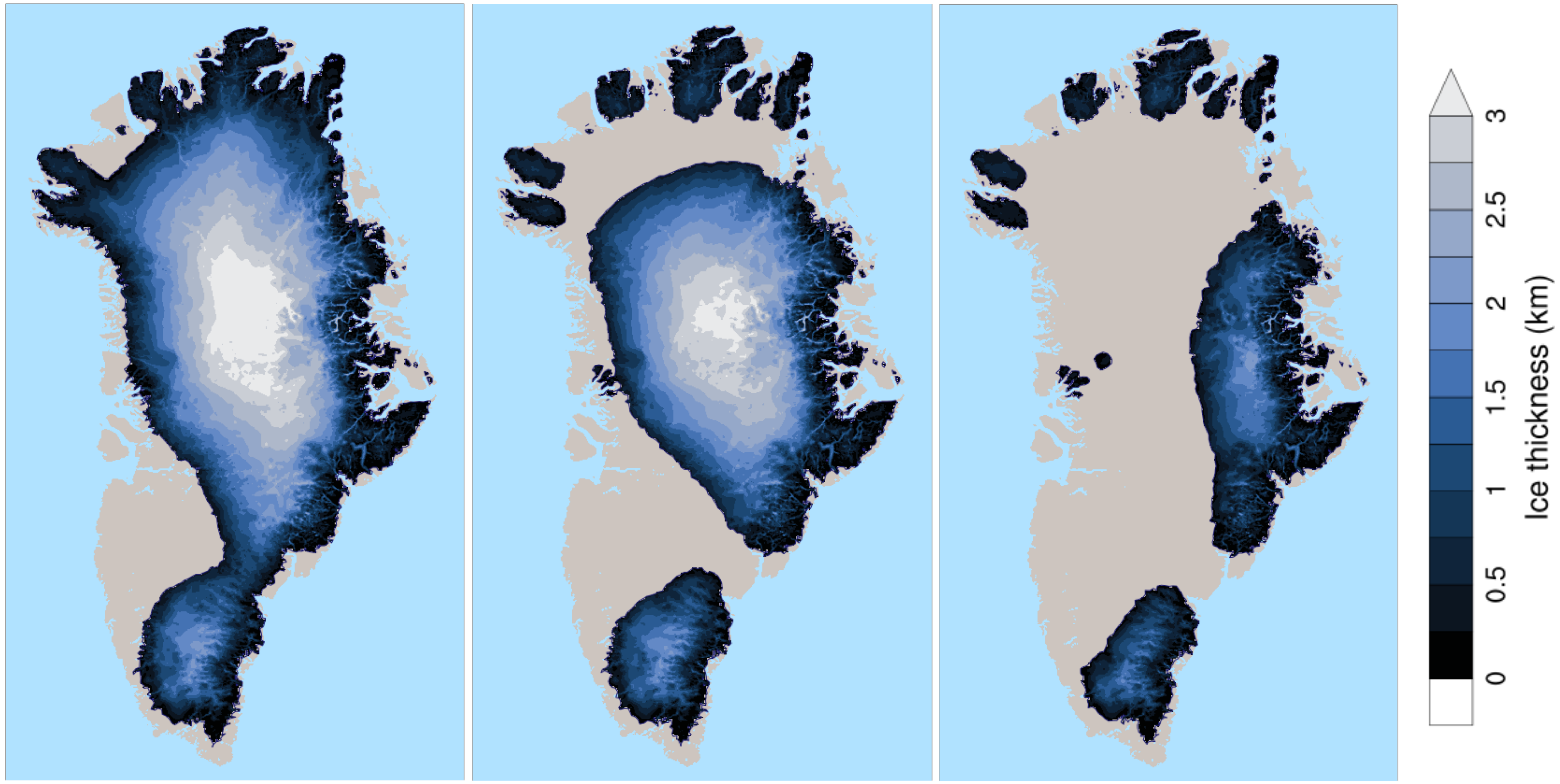
- Close to SMB threshold, GrIS does not reach equilibrium: quasi-periodic oscillations!
- SMB-height feedback responds to ice thinning (surface melt) and bedrock uplift (GIA)!
- If GIA not included, GrIS deglaciation for much lower SMB and GMT threshold!

Results #2:
Topographic control on the SMB threshold

GrIS retreat patterns



- >80% volume: retreat limited to south-western margin;
- ~50% volume: retreat at south-western and northern margins, central-western margin stays close to the coast;
- <20% volume: ice remaining only at the eastern margin, isolated ice caps in the south and north;
- How does the transition 50% —> 20% volume occur?

GrIS evolution ‘before’ tipping

+3.2 K run, year 0

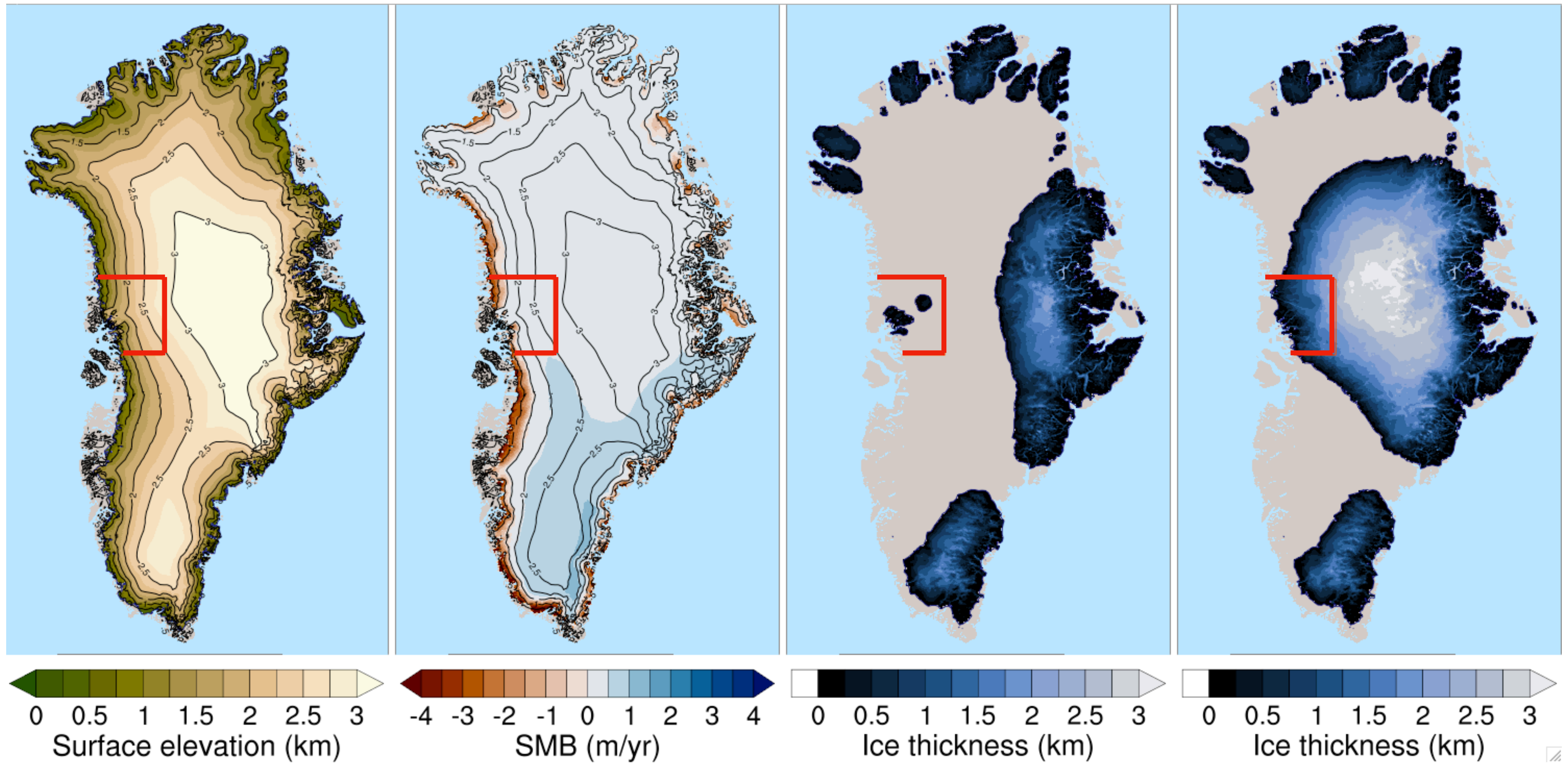
- +3.2 K run (50% volume): central-western margin close to the coast, connecting again after re-advance;
- Highlighted region in the central west: high bedrock topography and SMB;

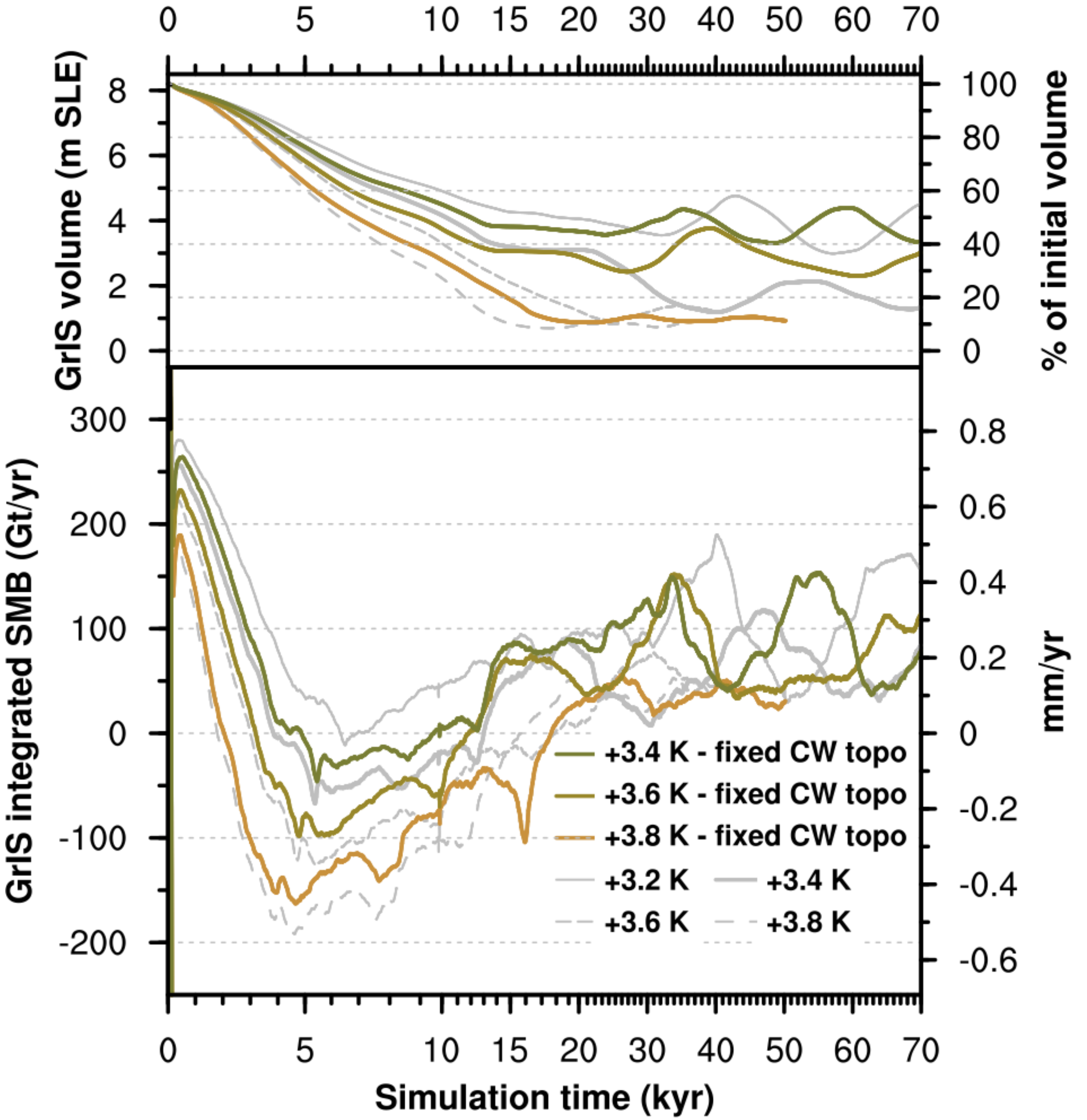
GrIS evolution ‘after’ tipping

+3.4 K run, year 0

- +3.4 K run (~20% volume): after 20 kyrs, central-western margin not able to re-advance to the coast: tipping point is passed, runaway retreat towards east (higher forcing: same pattern, shorter timescales).
- **GrIS behaviour at central western margin: a predictor for long-term, substantial ice loss?**

Topographic control on the SMB threshold



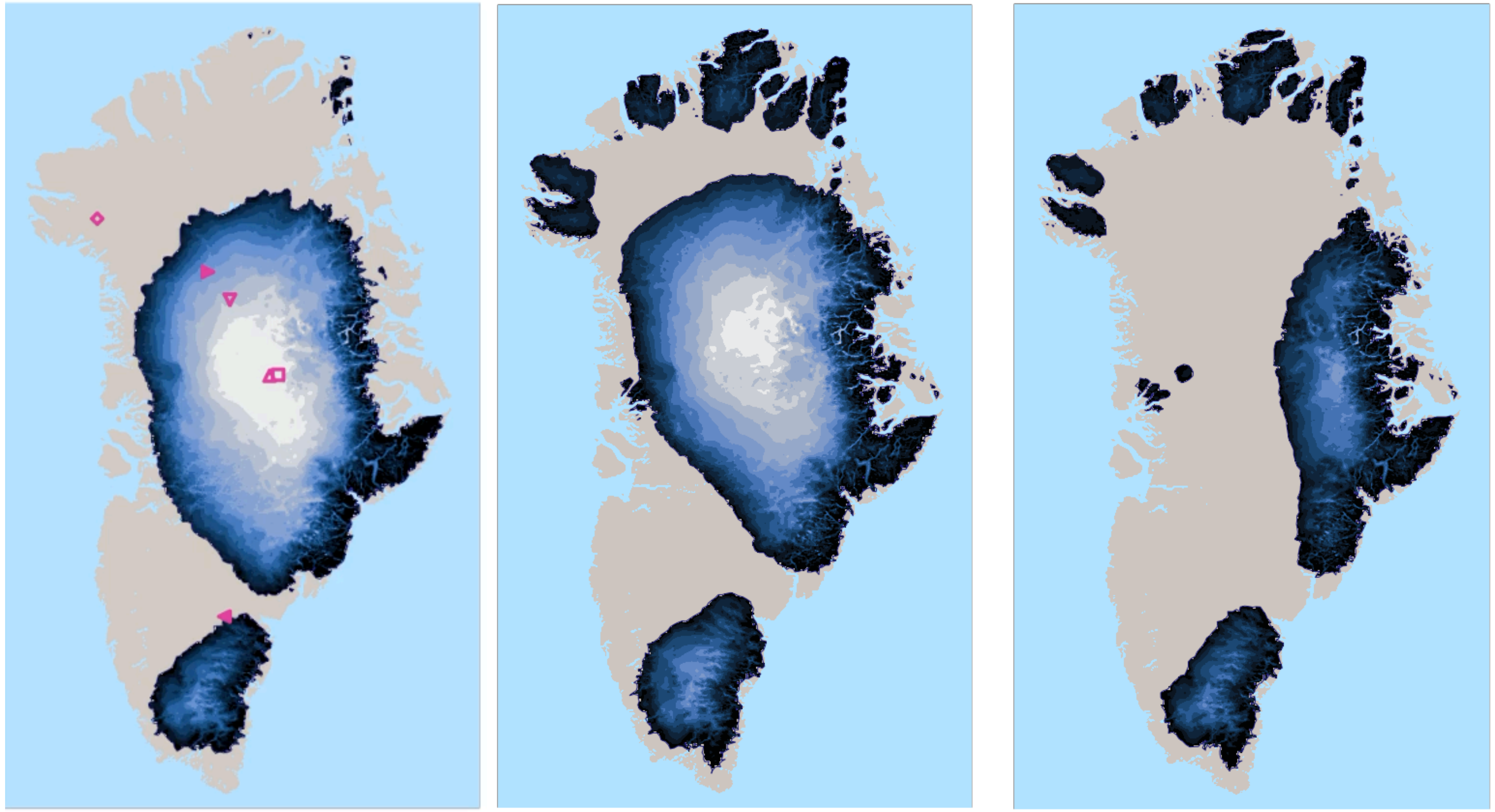


- We repeat 'tipping run' (+3.4 K) inhibiting SMB-height feedback in the red region (right panel);
- 'Tipping run' does not tip anymore: local change (central-western margin), larger-scale effect;
- Also in the +3.6 K ~40% volume remaining;

Paleo analogue: GrIS during the Last Interglacial

Fully coupled, transient CESM/CISM run of the global climate and GrIS during the Last Interglacial (Sommers et al. 2021)

Eemian run, 122 ky BP | +3.2 K run | +3.4 K run



- GrIS minimum volume around 122 kyrs BP: similar, ‘pre-tipping’ ice sheet configuration;
- Might be worth exploring potential tipping points across the Last Interglacial?

Conclusions

What?

Existence of a **SMB threshold for GrIS complete melt**, **processes controlling this threshold**, and associated **GrIS tipping point behaviour** (*small change in SMB forcing —> strongly nonlinear response*);

How?

CISM simulations forced with different levels of SMB, previously calculated at **multiple Elevation Classes** in a fully coupled CESM/CISM simulation of the global climate and GrIS *(Muntjewerf et al. 2020)*;

Key take-home messages:

- **Positive SMB threshold** for complete GrIS melt: **230±84 Gt/yr** (60% decrease from pre-ind. value);
- **Highly non-linear response**: competing effect of surface melt and GIA (SMB-height feedback);
- **Topographic control**: GrIS tipping when its CW margin unpins from coastal region with high elevation;

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Thank you for the attention!

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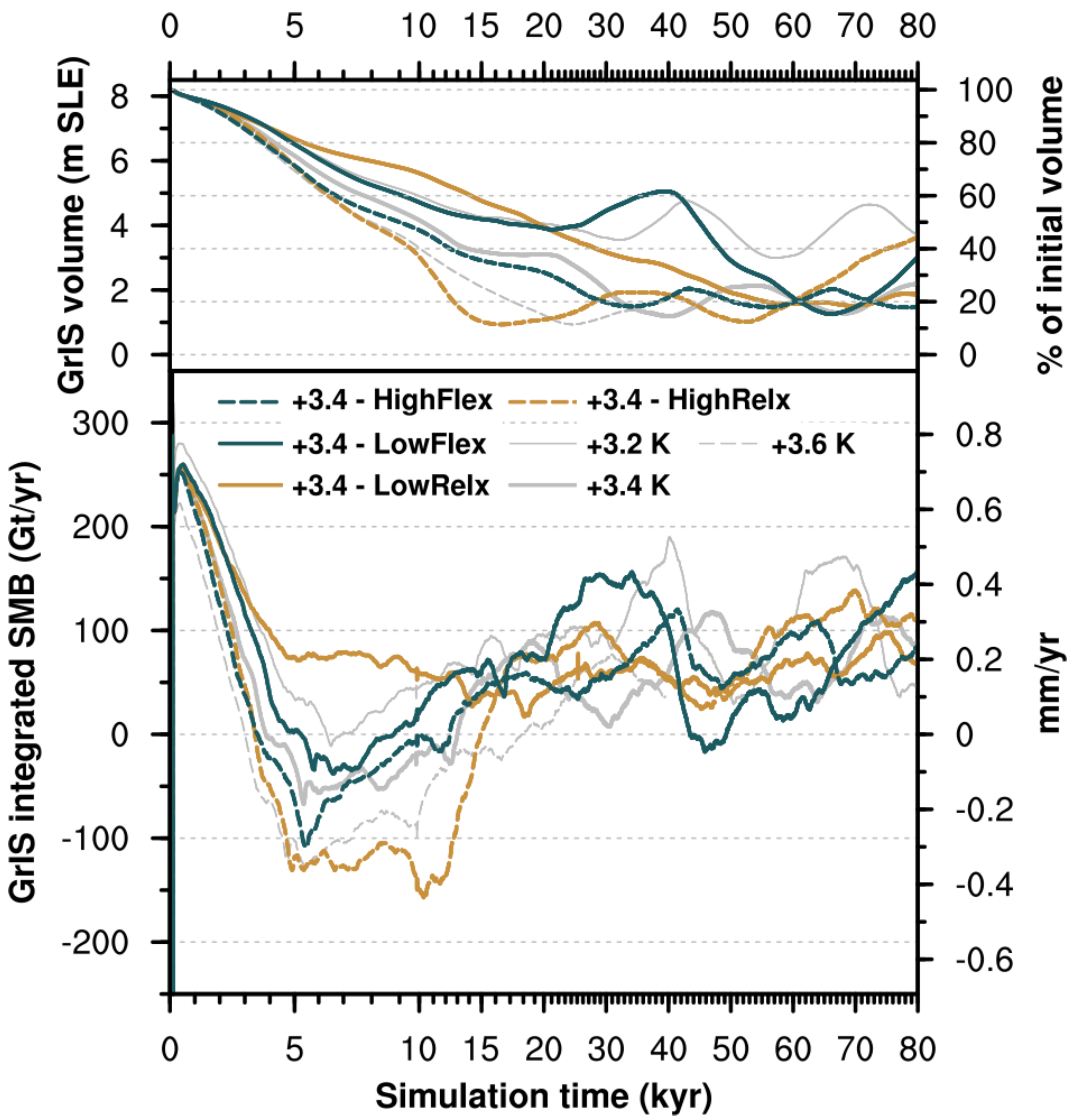
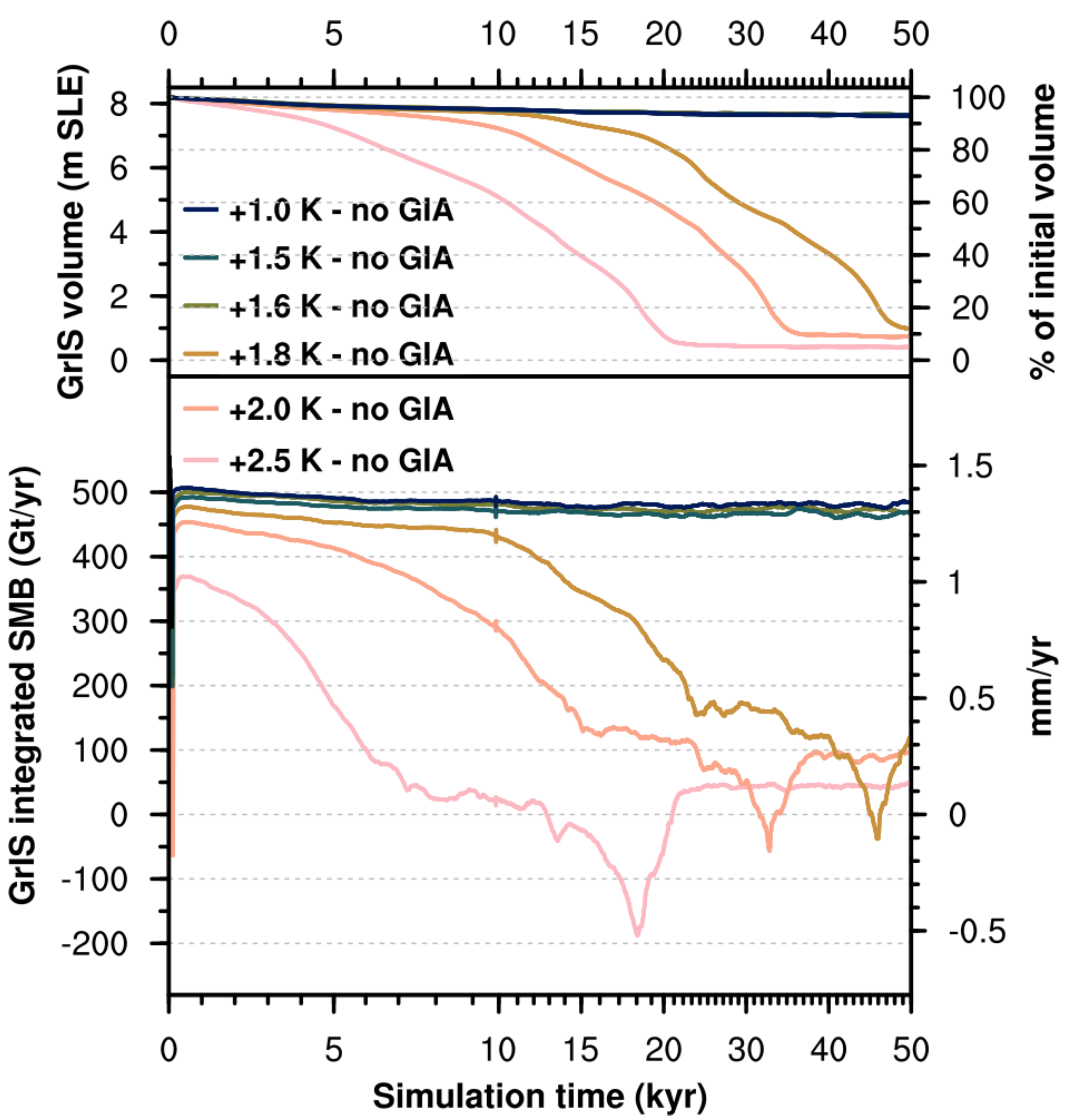


GrIS volume (m SLE)
% of initial volume
GrIS integrated SMB (Gt/yr)
mm/yr
Simulation time (kyr)
+3.4 - HighFlex
+3.4 - HighRelx
+3.4 - LowFlex
+3.2 K
+3.6 K
+3.4 - LowRelx
+3.4 K
0
5
10
15
20
30
40
50
60
70
80
8
6
4
2
0
100
80
60
40
20
0
300
200
100
0
-100
-200
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6



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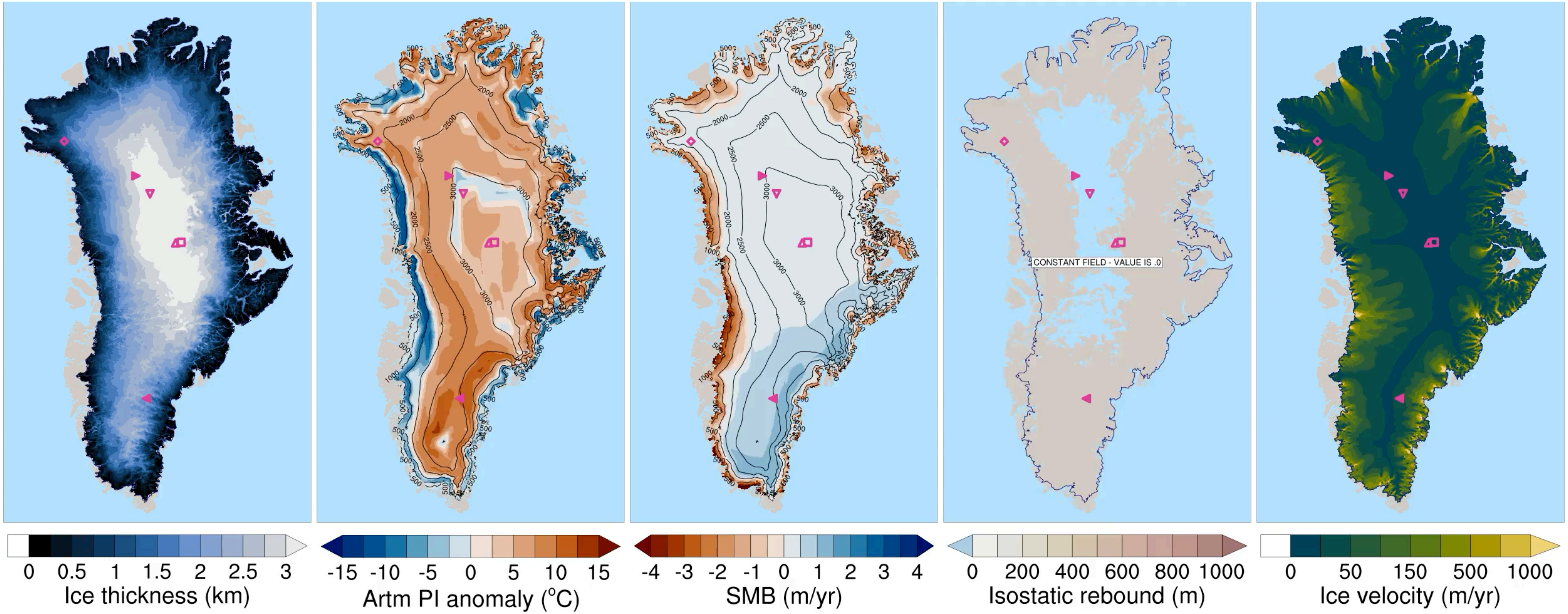
127.00 ky BP


CONSTANT FIELD - VALUE IS .0
0 0.5 1 1.5 2 2.5 3
Ice thickness (km)
-15 -10 -5 0 5 10 15
Artm PI anomaly (°C)
-4 -3 -2 -1 0 1 2 3 4
SMB (m/yr)
0 200 400 600 800 1000
Isostatic rebound (m)
0 50 150 500 1000
Ice velocity (m/yr)