Modeling the Greenland ice sheet englacial stratigraphy

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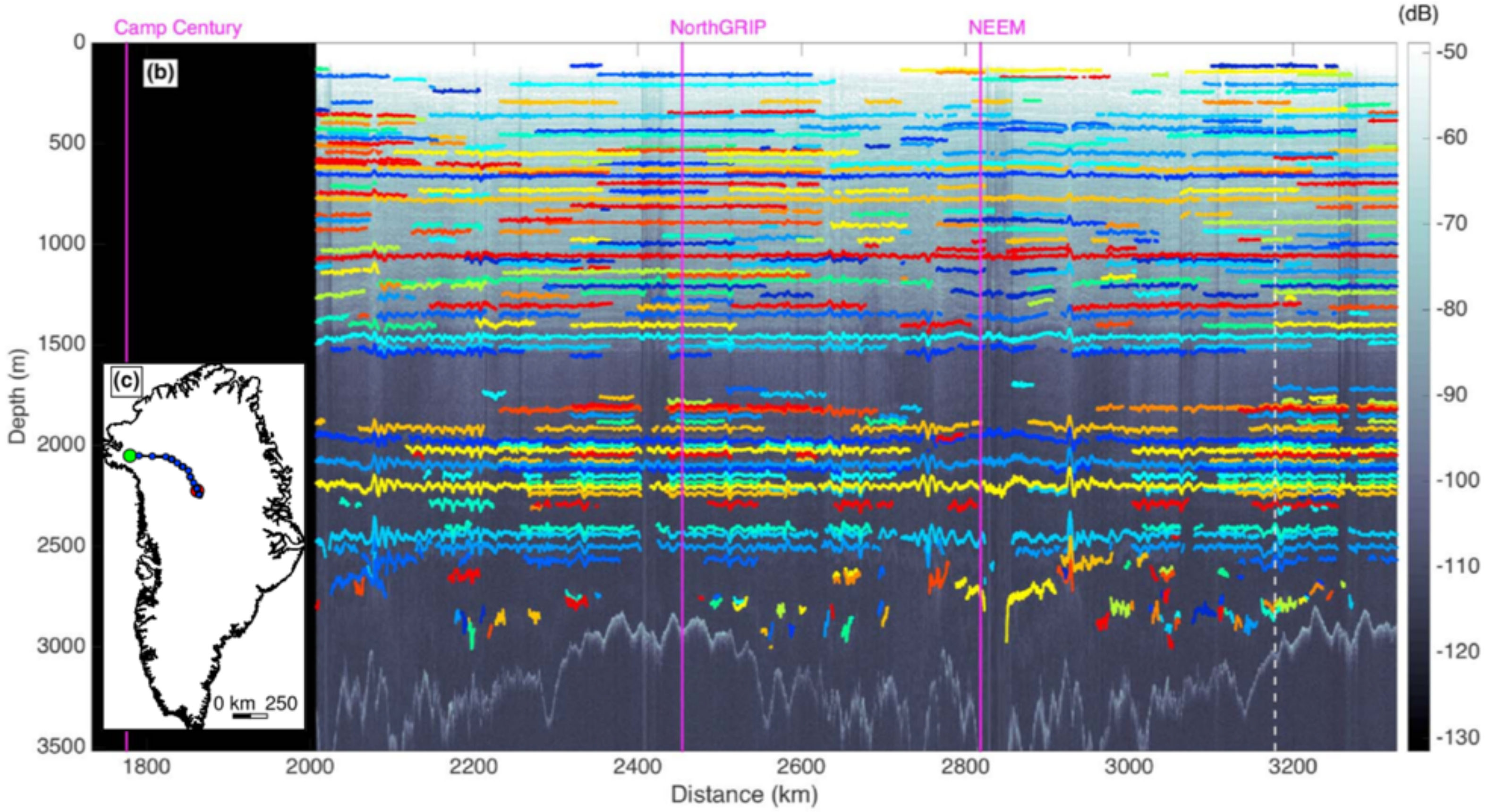
What is the englacial stratigraphy?

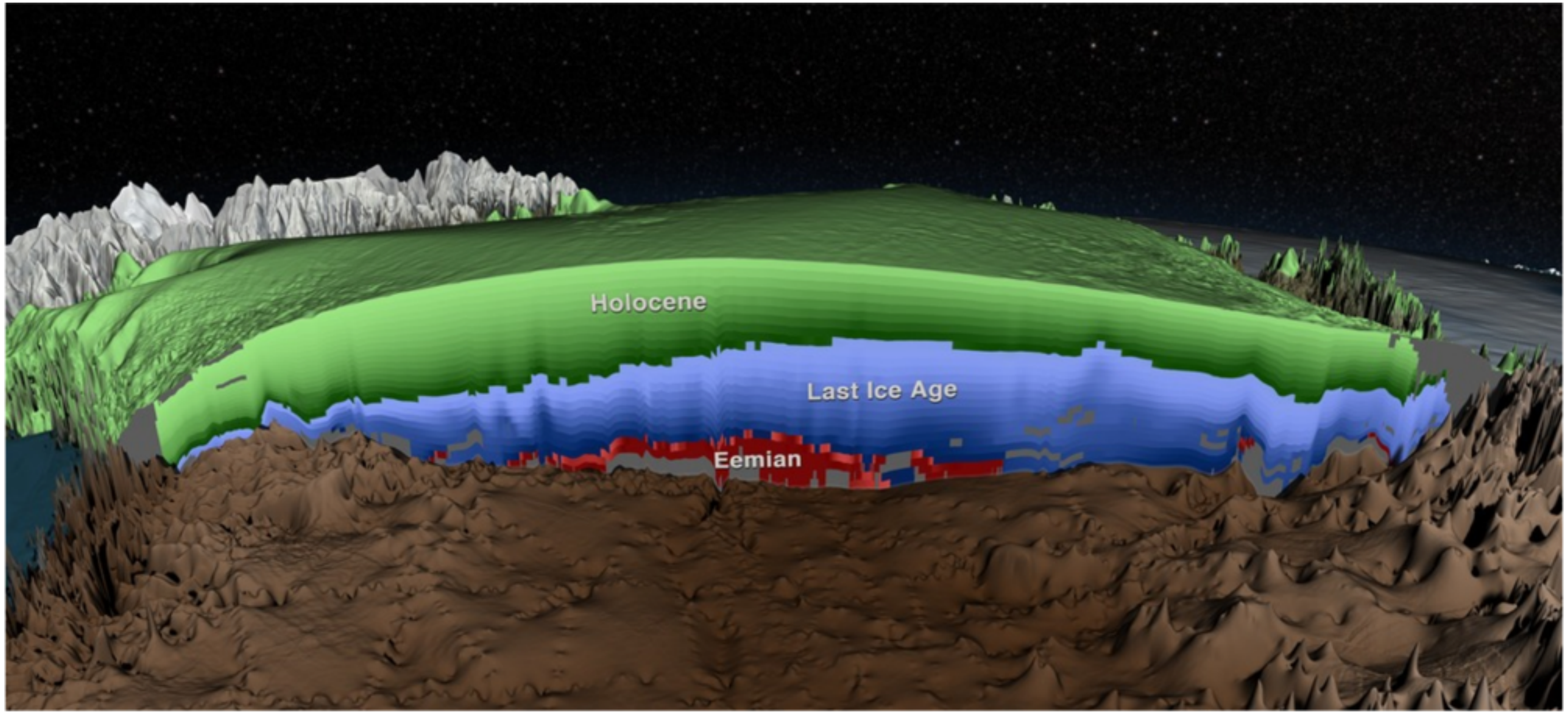
- The ice sheet is built up by the accumulation of ice layers year by year.
- Each layer therefore represents a specific age (isochronal layers).



MacGregor et al., 2015

What is the englacial stratigraphy?

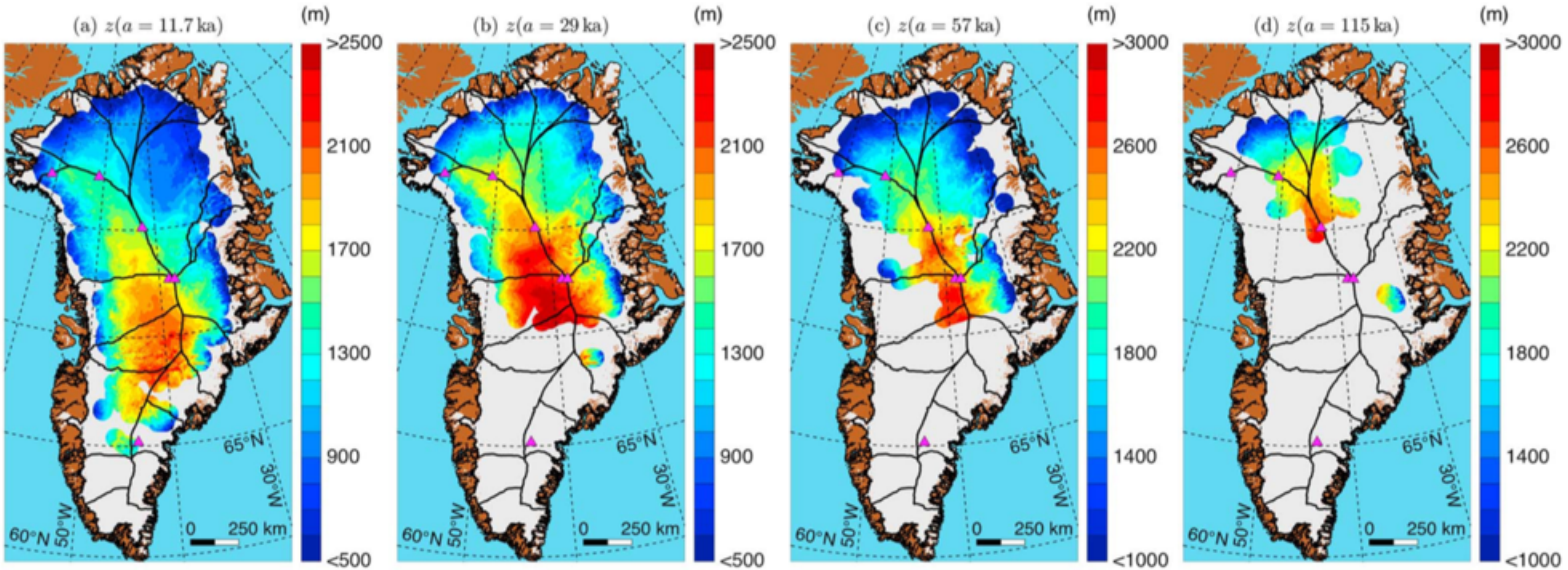
- Combined with precise age estimates from the ice cores, a 3D map of isochrones has been produced for the Greenland ice sheet.



MacGregor et al., 2015; NASA

Why simulate isochrones?

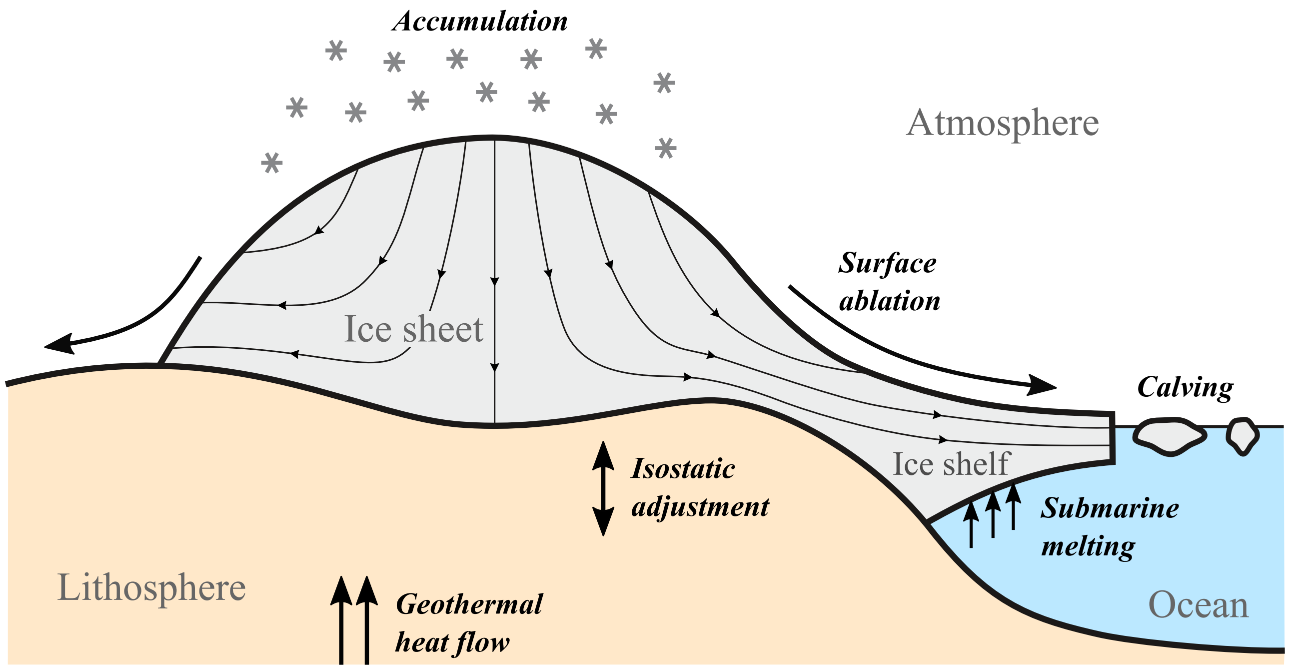
- Isochronal distribution is determined solely by ice dynamics, with no direct dependence on other variables.
- Could provide a powerful constraint on ice-sheet models!

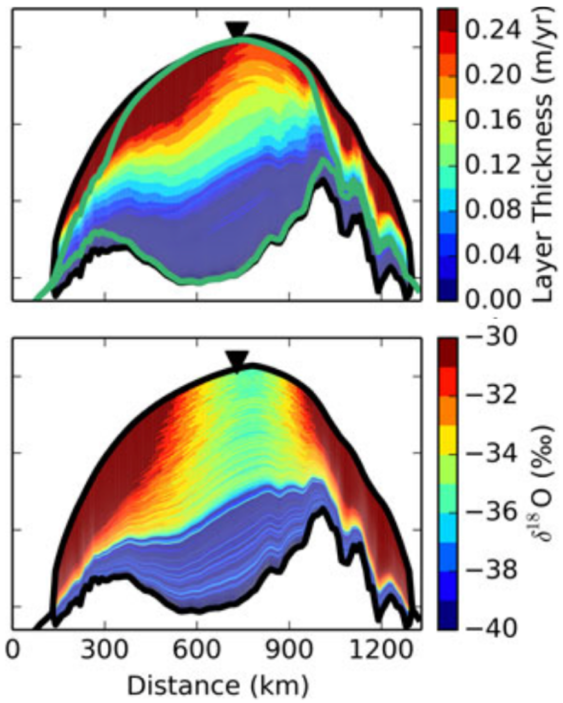


MacGregor et al., 2015

Yelmo + Pancakes

- Yelmo is an open-source ice-sheet model designed for long timescale and ensemble simulations. It includes an Eulerian age-tracing scheme.
- Additional modules used to treat external processes (GIA, climatic forcing, oceanic melt).
- Isochronal model (codename: Pancakes) is an innovative ice-layer tracing model coupled to Yelmo.

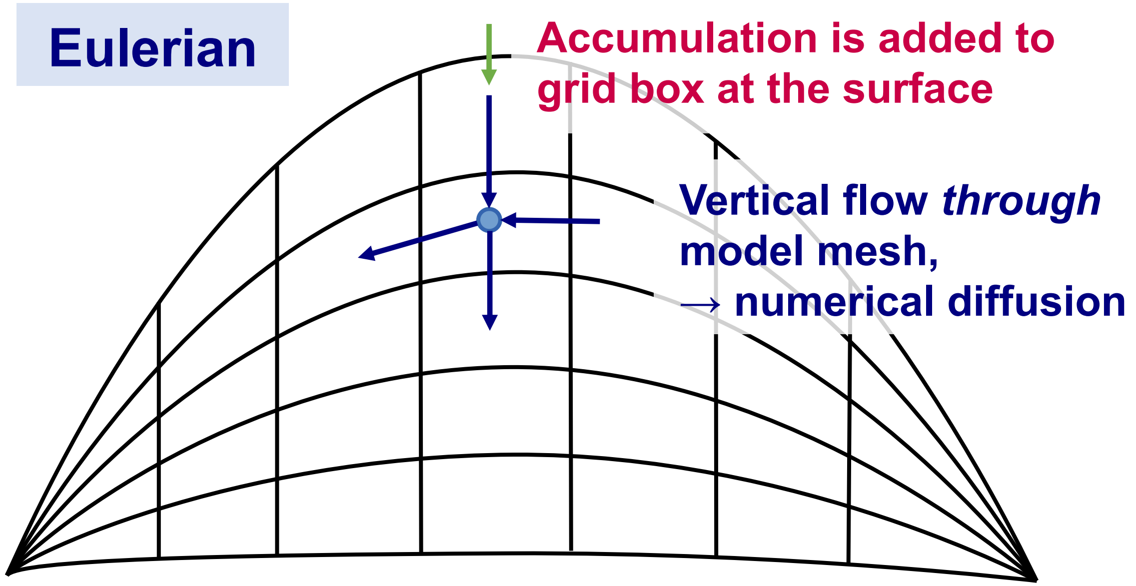


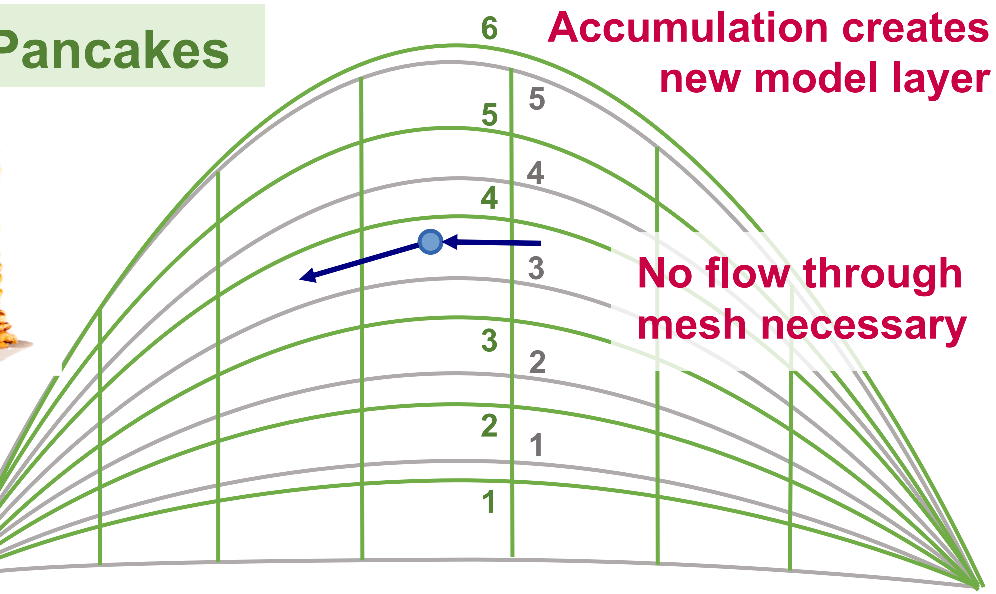


Robinson et al., 2020; Born, 2016; Born and Robinson, in prep.

Modeling isochrones = modeling ice layers

- Isochronal model explicitly models age layers in the vertical direction.
- Inputs (obtained from Yelmo):
  - ice thickness
  - 3D horizontal velocity field
  - mass fluxes at the ice surface and the bed
- Layer resolution used here is 200 yrs.





Experimental design

- Transient ice-sheet simulations from 160 kyr ago to present day, 32 km resolution.

- Index method used to obtain transient climatic forcing from PMIP3 LGM snapshots and present-day climatology:

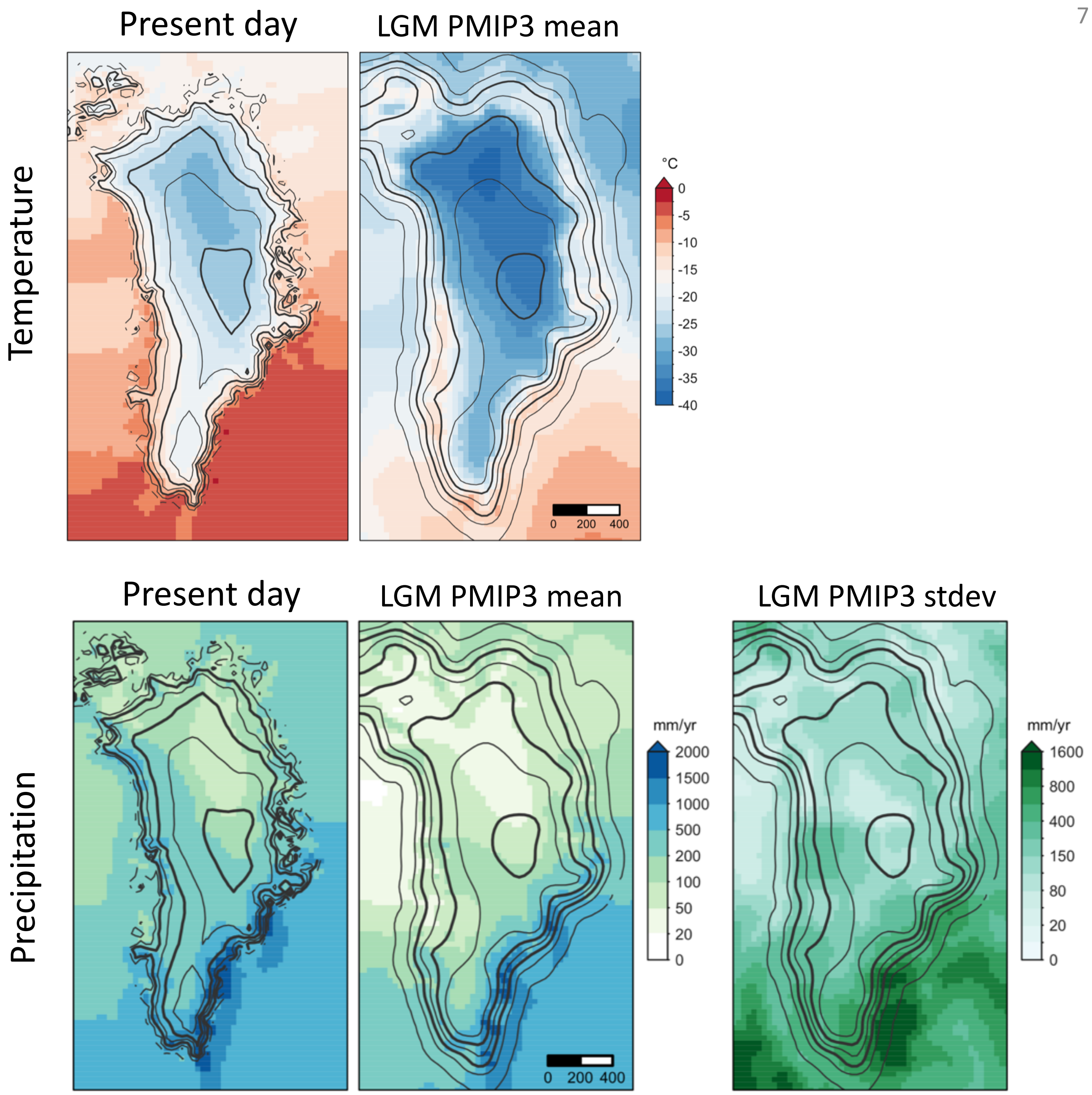
$$T = T_{\rm pd} + \alpha_c \left(T_{\rm lgm} - T_{\rm pre}\right)$$

- LGM precipitation field is perturbed via standard deviation to assess impact on isochrones:

$$P_{\rm LGM} = \bar{P}_{\rm LGM} + f_{\rm LGM}\sigma_P$$

- Mid-Holocene precipitation is also perturbed via another index with a free parameter $\Delta P_{\rm HOL}$.

$$P = P_{\rm pd}\left(\alpha_c\left[\frac{P_{\rm lgm}}{P_{\rm pre}} - 1\right] + 1\right) + \alpha_p \Delta P_{\rm hol}$$



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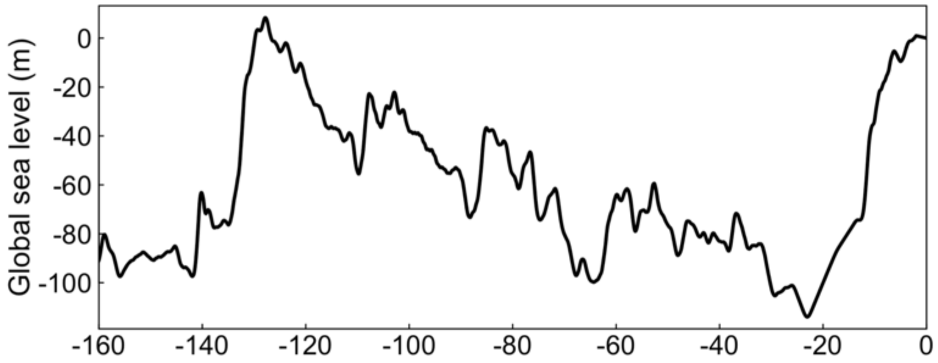
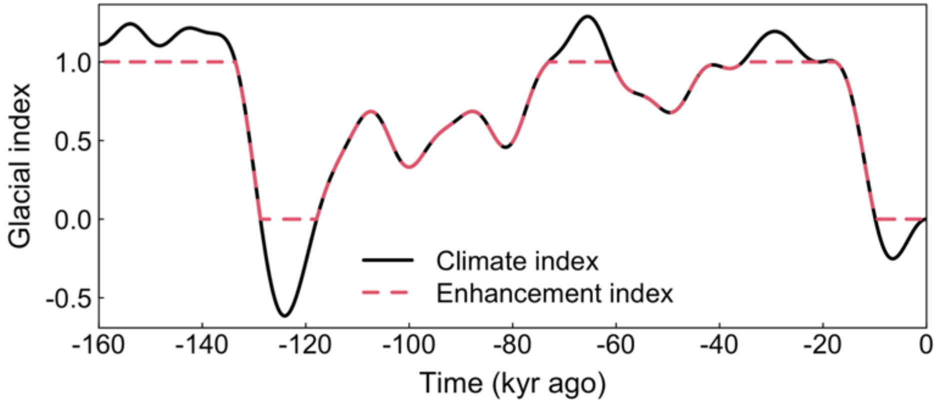
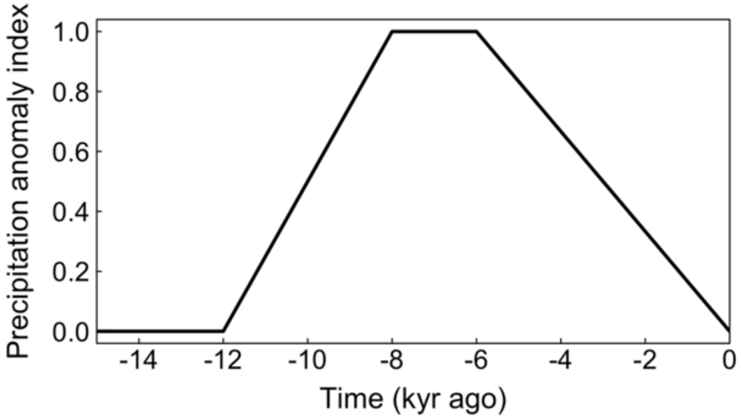
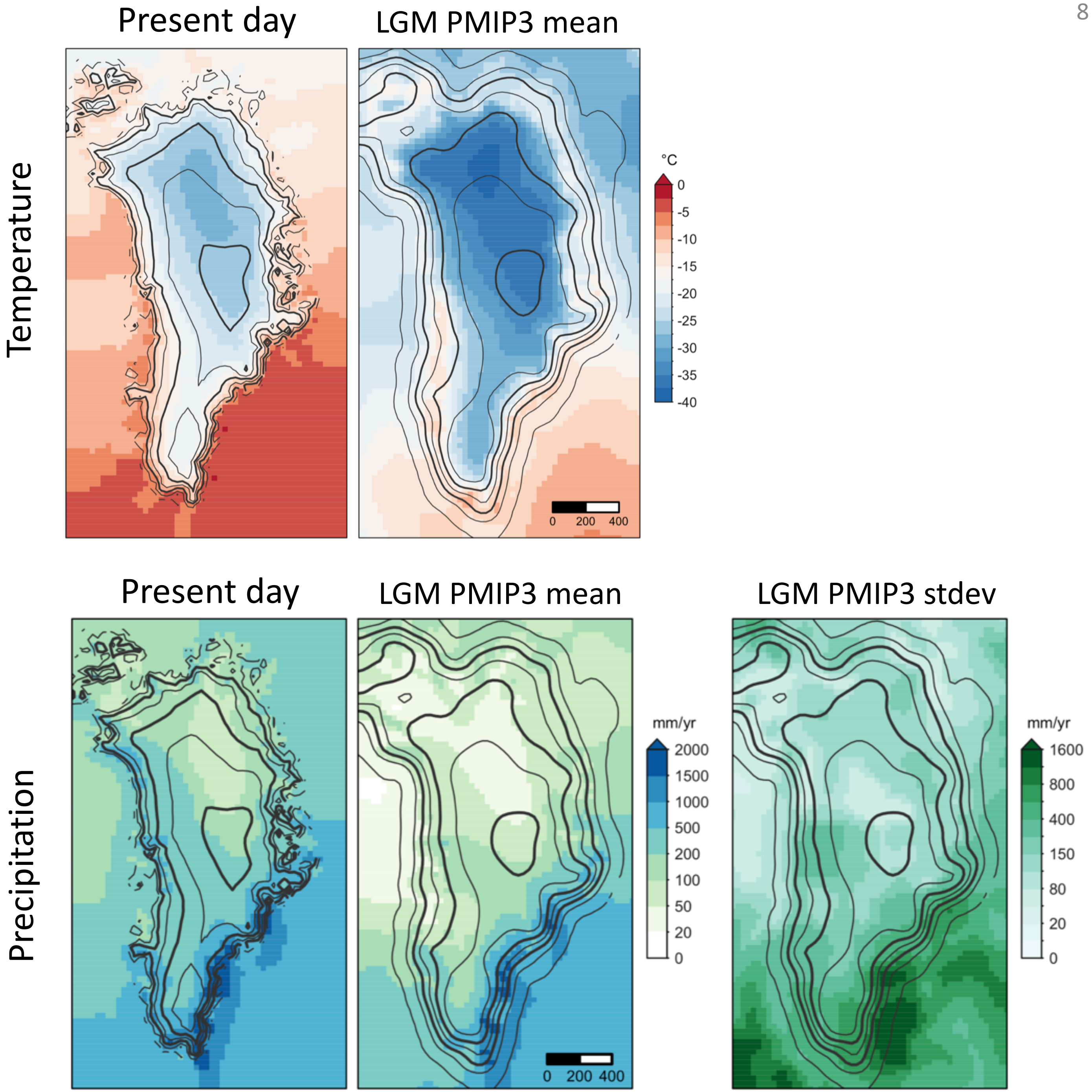








Enhancement factor treated as a tracer

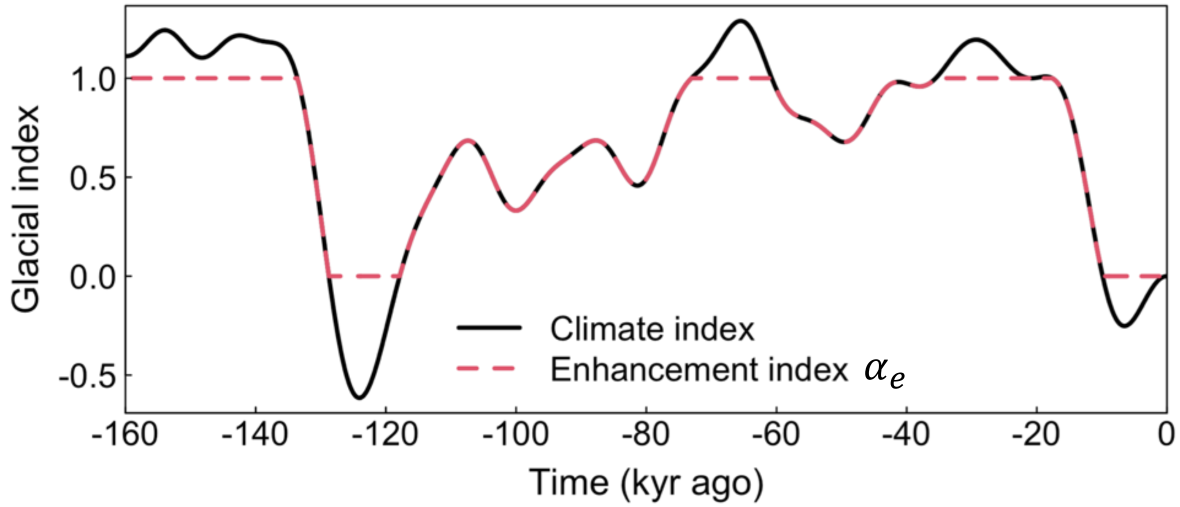
$$E = E_{\mathrm{ref}} \cdot E_t$$

E_{ref} changes instantaneously depending on the flow regime (shear or streaming):

$$E_{\mathrm{ref}} = f_z E_{\mathrm{shr}} + (1 - f_z) E_{\mathrm{strm}}$$

Tracer field advected through the ice sheet, with surface value prescribed following index method:

$$E_t(z = z_s) = \alpha_e E_{\mathrm{glac}} + (1 - \alpha_e) E_{\mathrm{int}}$$



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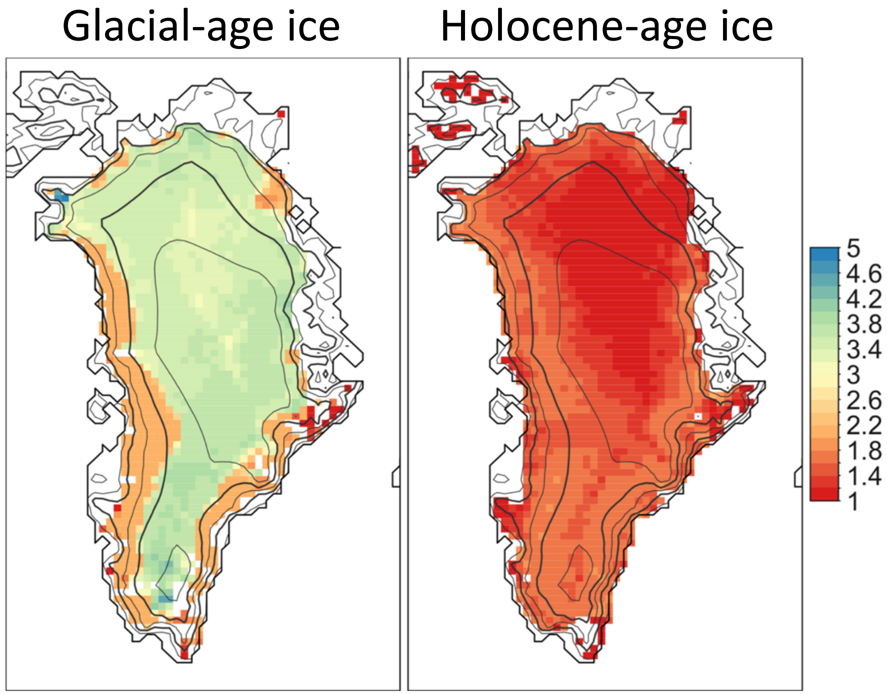


Friction tuning

Spin up

Optimize c_b in a steady-state present-day simulation.

Perturb model parameters for large paleo ensemble.

Run 20 kyr to near-equilibrium with LGM boundary conditions.

Basal friction tuning

Run transient simulation from LGM to present-day.

Improve c_b as a function of ice-thickness error at present day.

10x

Operational simulation

Run transient simulation from 160 kyr ago to present day with paleo-optimized c_b.

Friction law

$$\beta = \frac{c_b}{u_0} N_{\mathrm{eff}} = \frac{c_b}{u_0} (\rho g H)$$

$$u_0 = 100 \text{ m/a}; c_b \in (0,1)$$

Optimization strategy

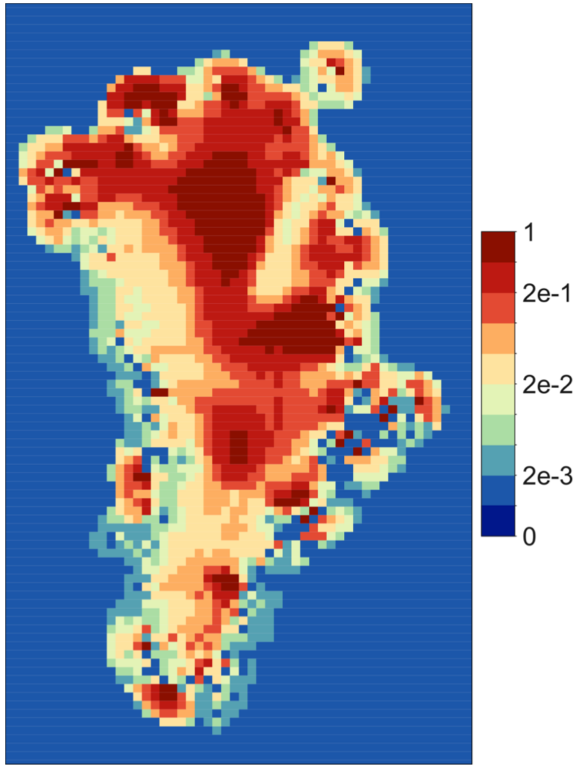
$$c_b^{n+1} = c_b \, 10^{-\epsilon} \qquad \epsilon = \frac{H - H_{obs}}{1000} \in (-1.5, 1.5)$$

Note: ϵ is calculated upstream of the optimization point.

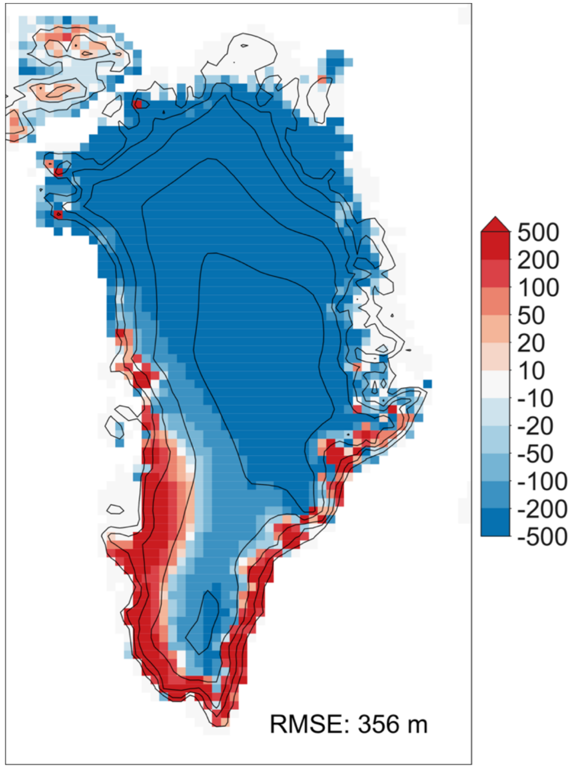
Friction tuning

After 1 iteration…

Basal friction, c_f

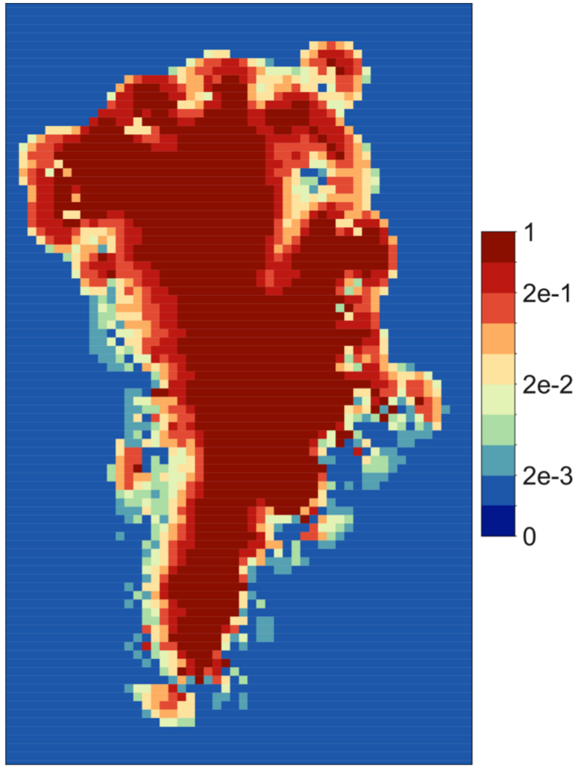


Ice thickness error (m)



After 10 iterations…

Basal friction, c_f



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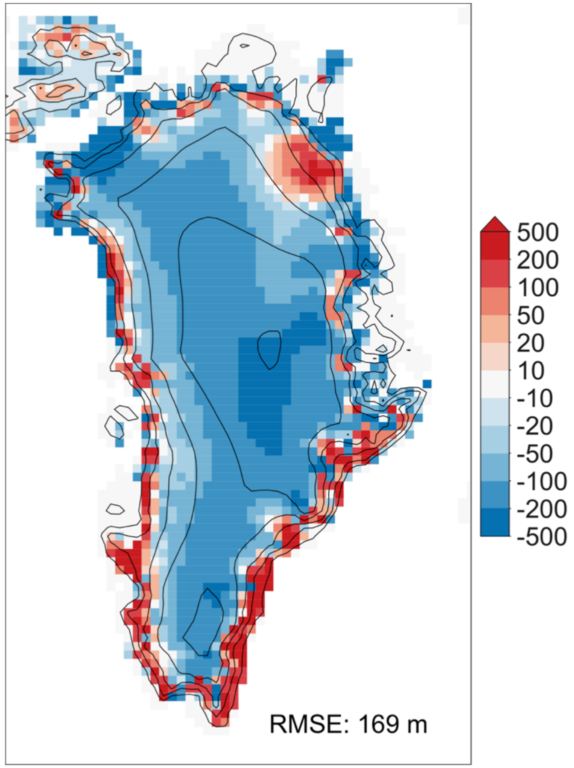

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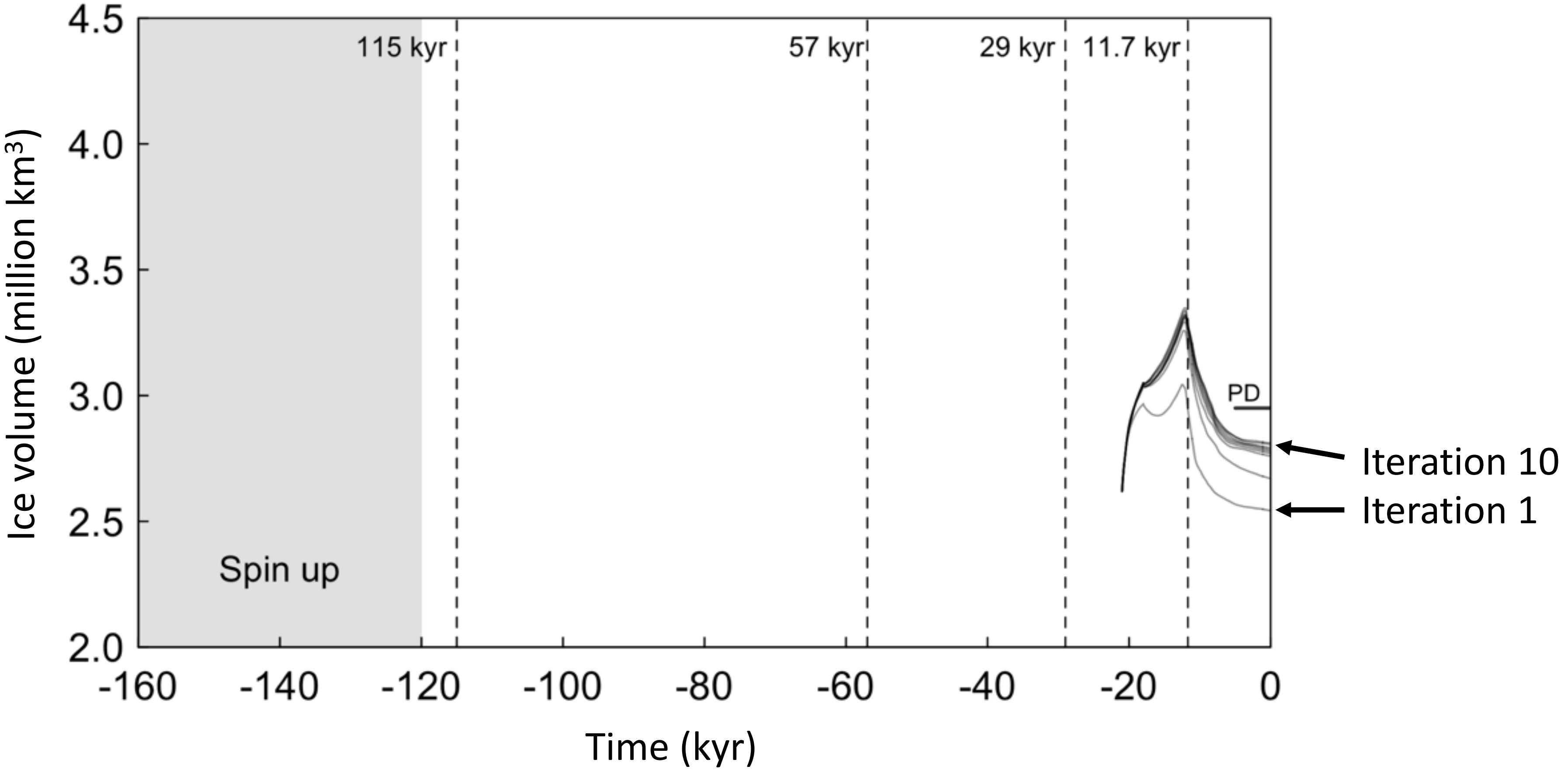
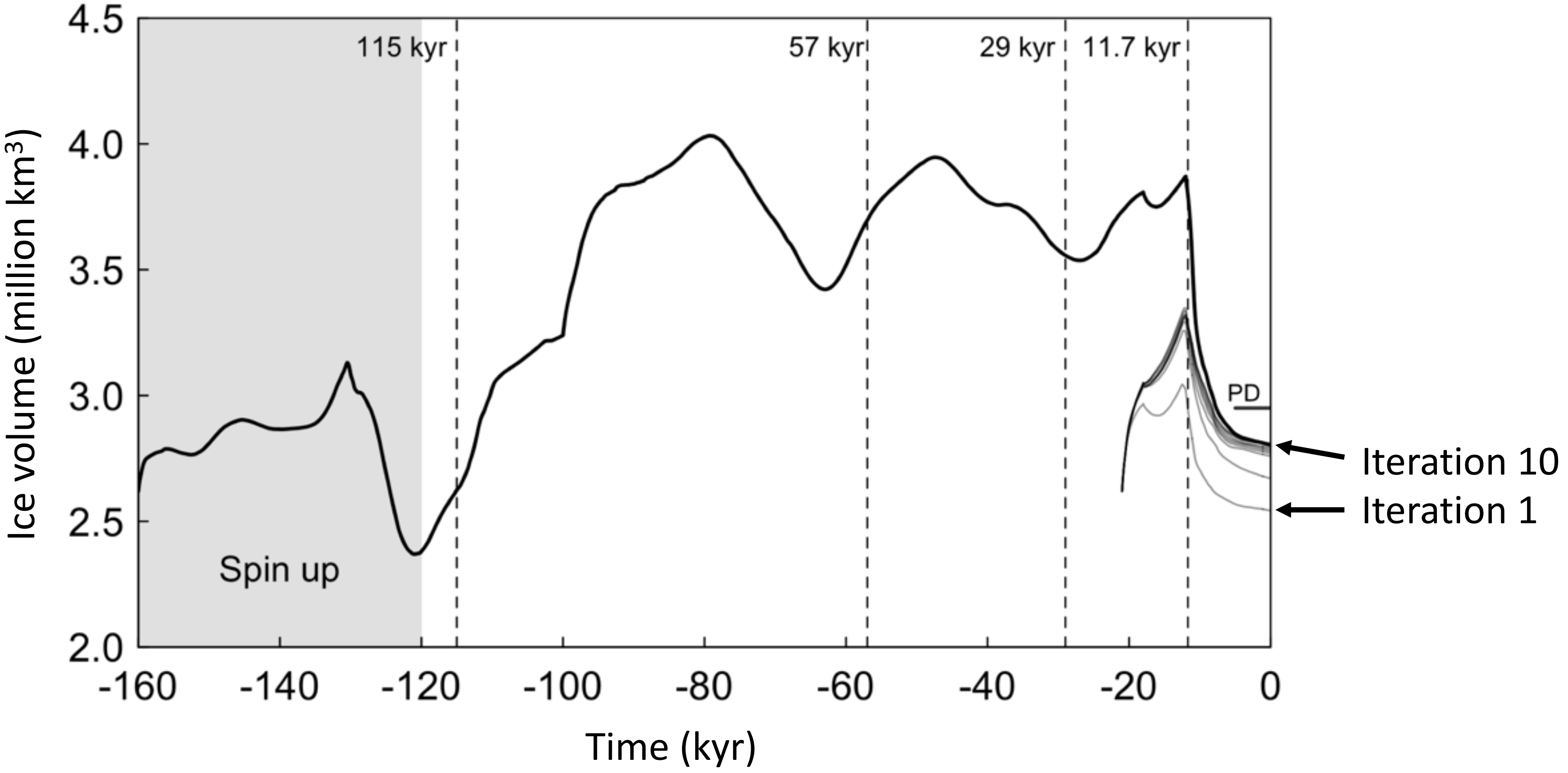


- c_b solution converges (does not improve) within ~10 iterations.

Transient simulations



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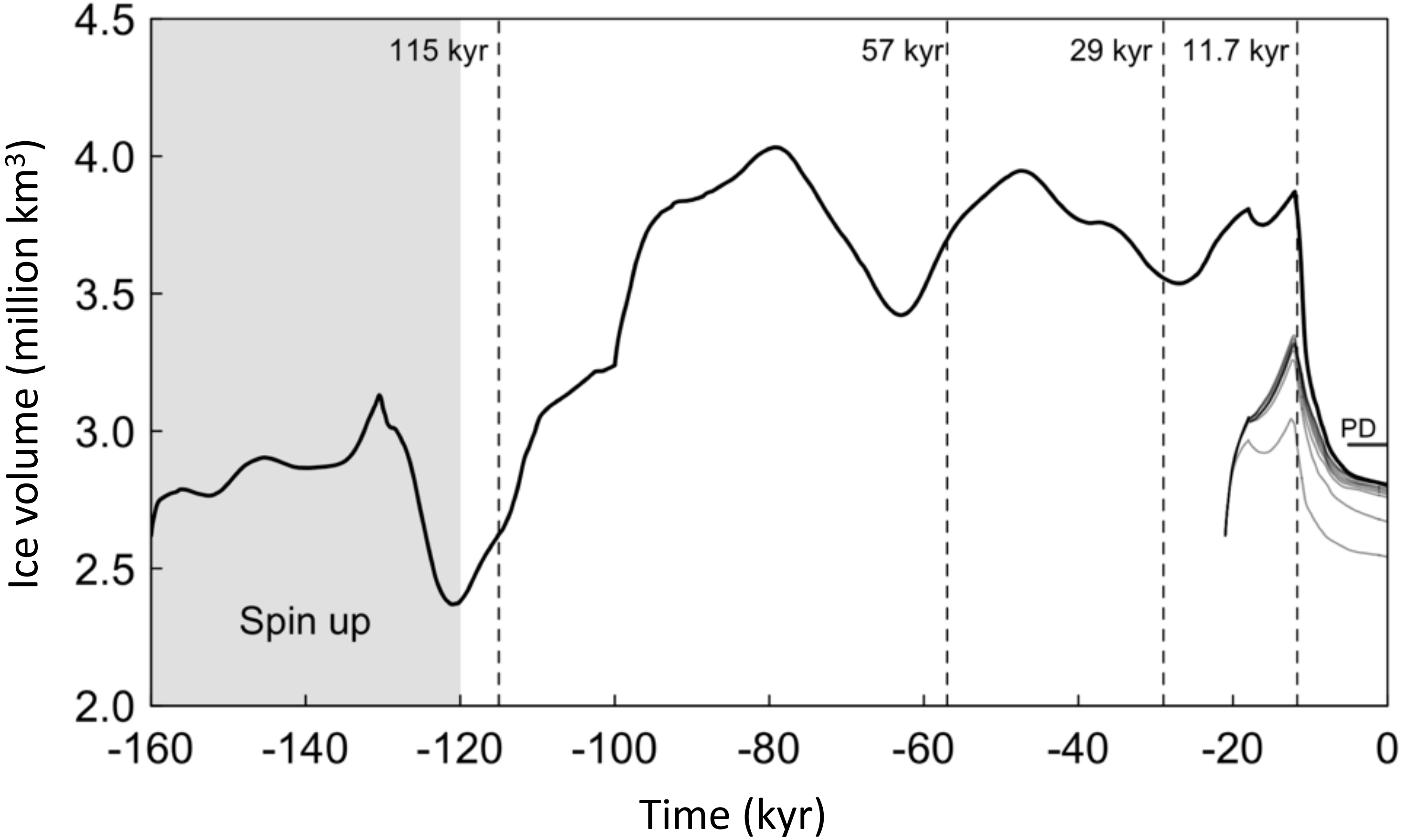

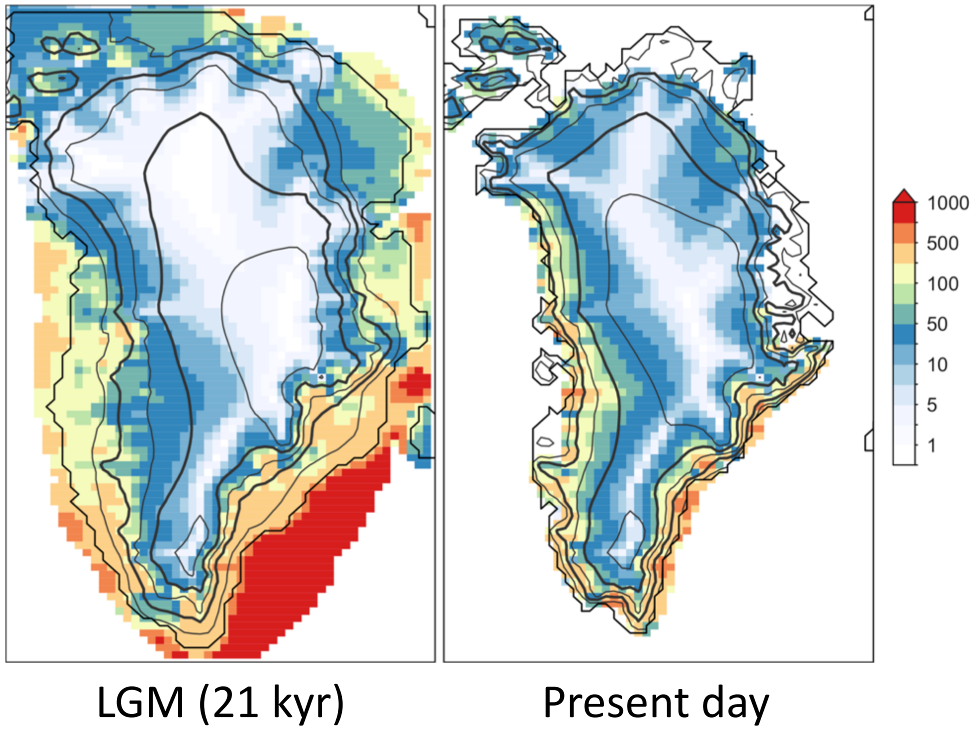

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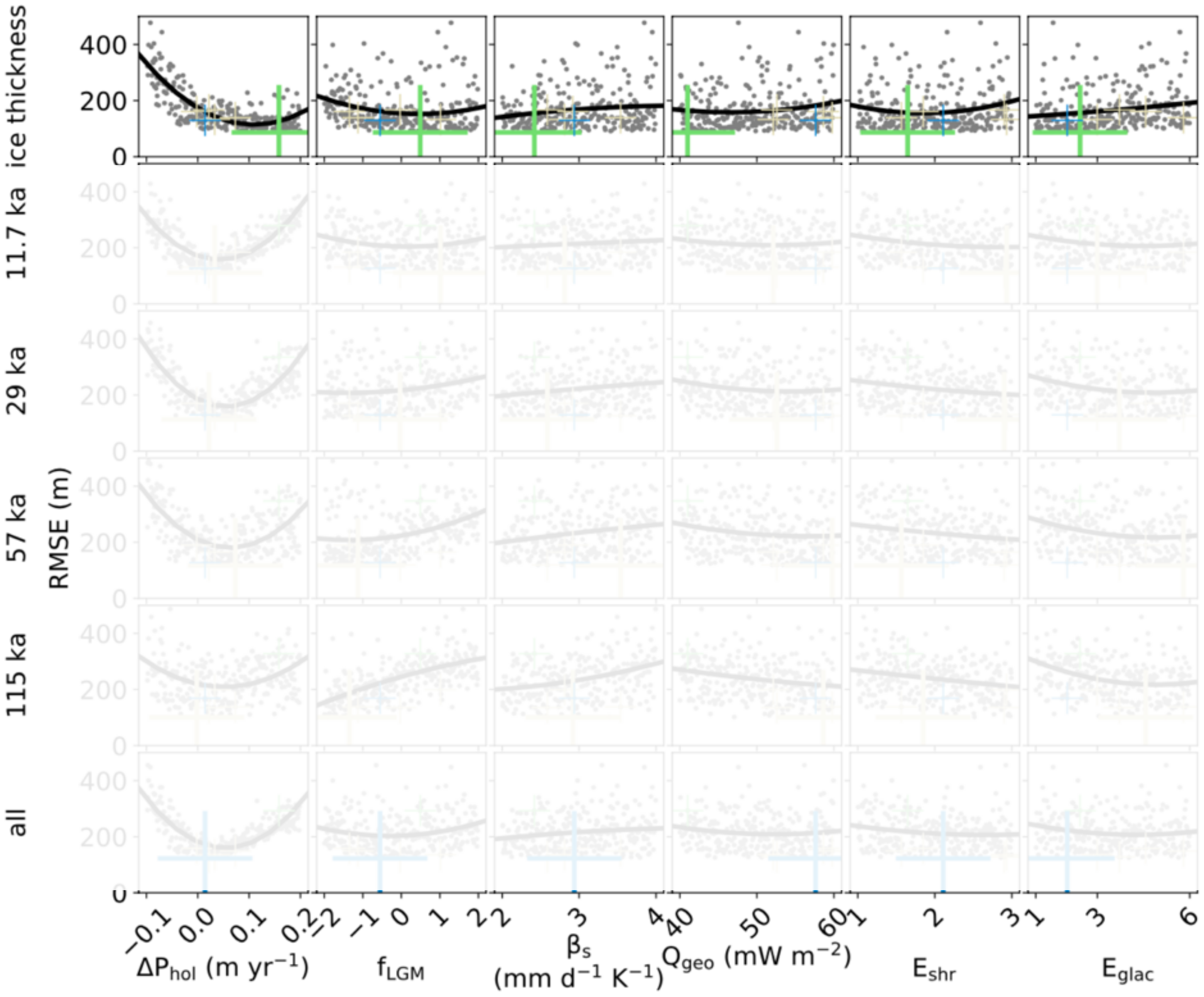
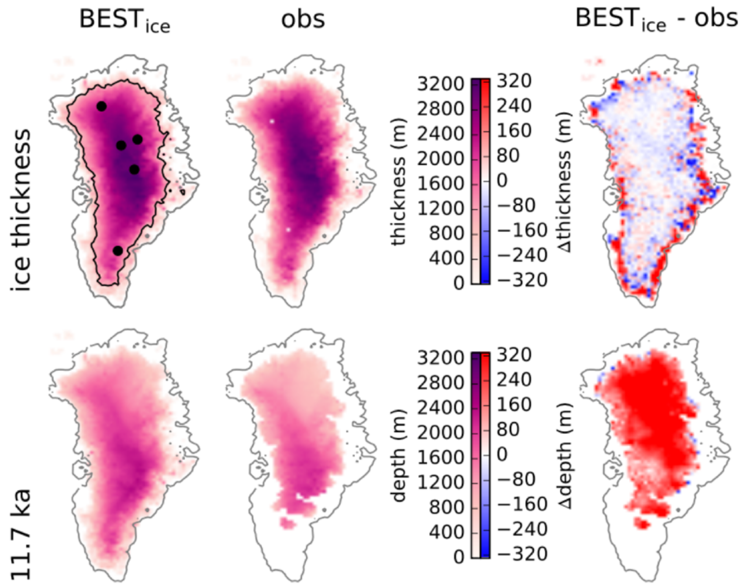
Ensemble results

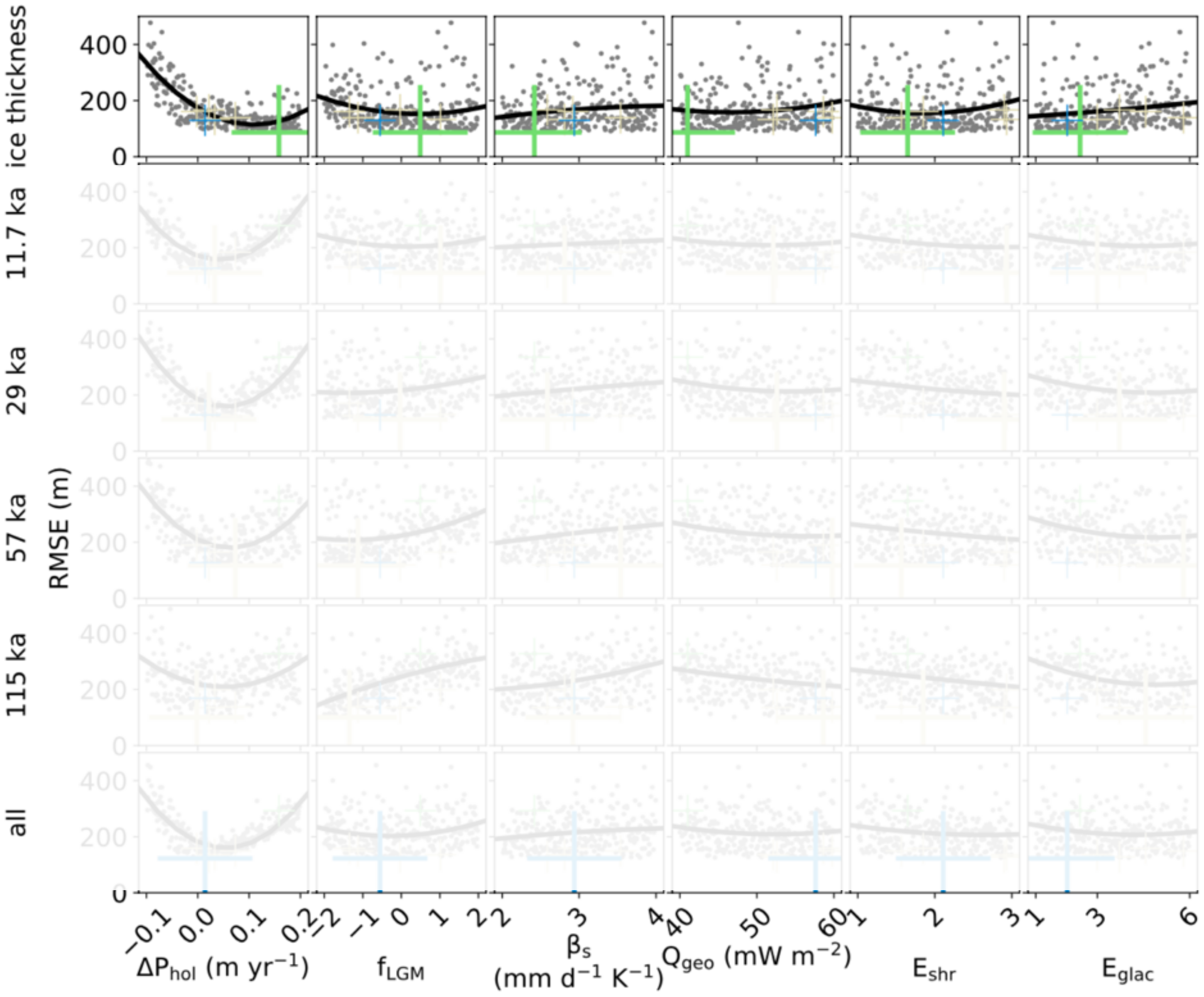
- A nice optimal simulation can be found when PD ice thickness is only constraint (green cross, top row).



Ensemble results

- A nice optimal simulation can be found when PD ice thickness is only constraint (green cross, top row).
- This simulation does poorly in simulating the 11.7 kyr (and all) isochronal layers!

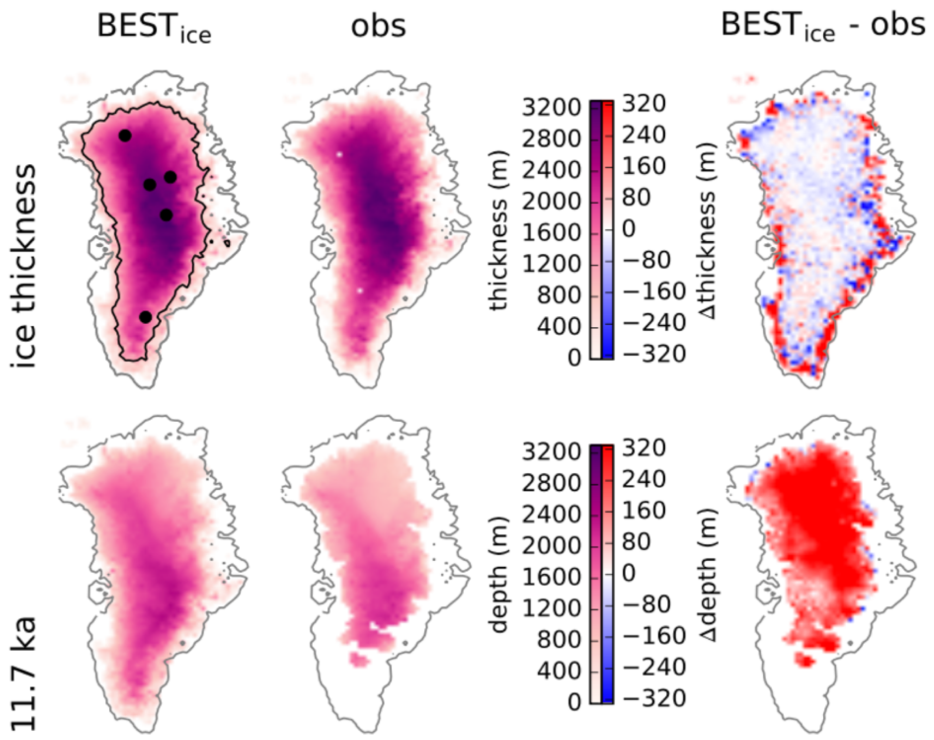


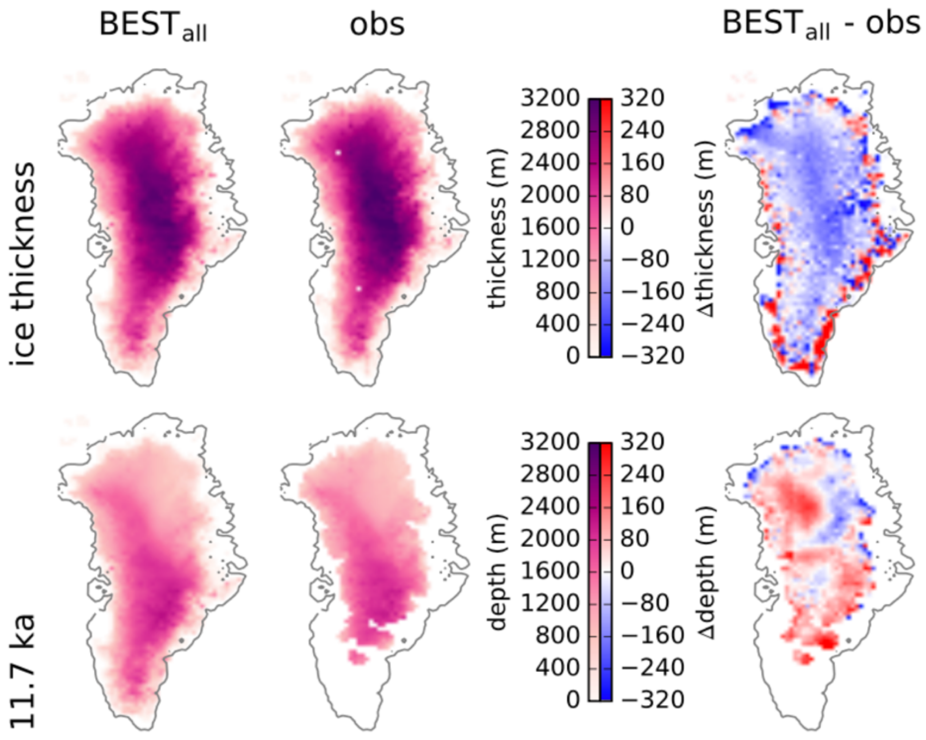


Ensemble results

Optimizing for ice thickness leads to great performance at the expense of isochronal layer errors.

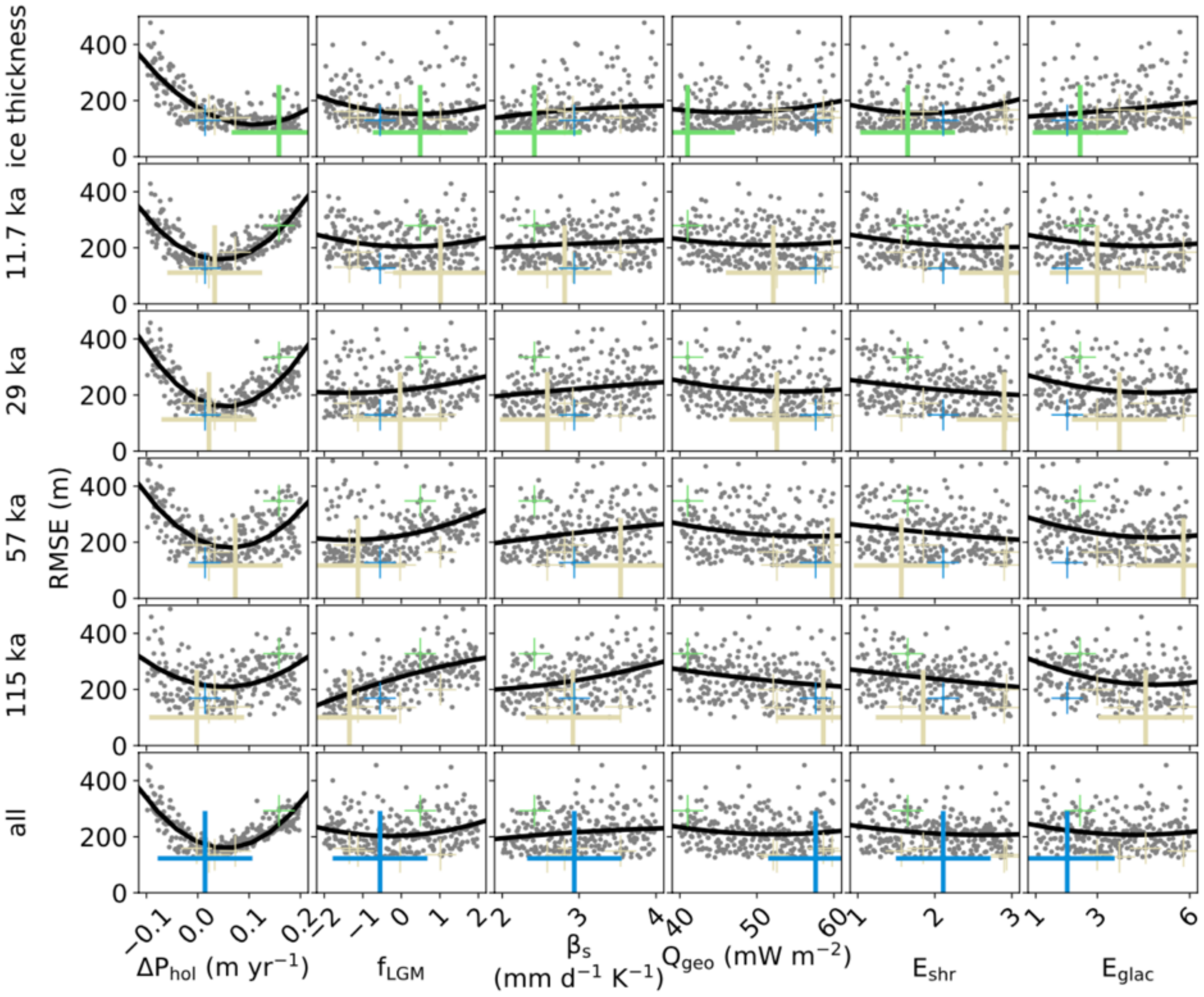
Best match to all constraints gives slightly poorer performance for ice thickness, for better performance overall.





Ensemble results

- A nice optimal simulation can be found when PD ice thickness is only constraint (green cross, top row).
- This simulation does poorly in simulating the 11.7 kyr (and all) isochronal layers!
- Isochronal layers provide additional information about model-parameter performance.
- Precipitation during the Holocene influences all isochronal depths significantly – LGM precipitation influences older isochrones.



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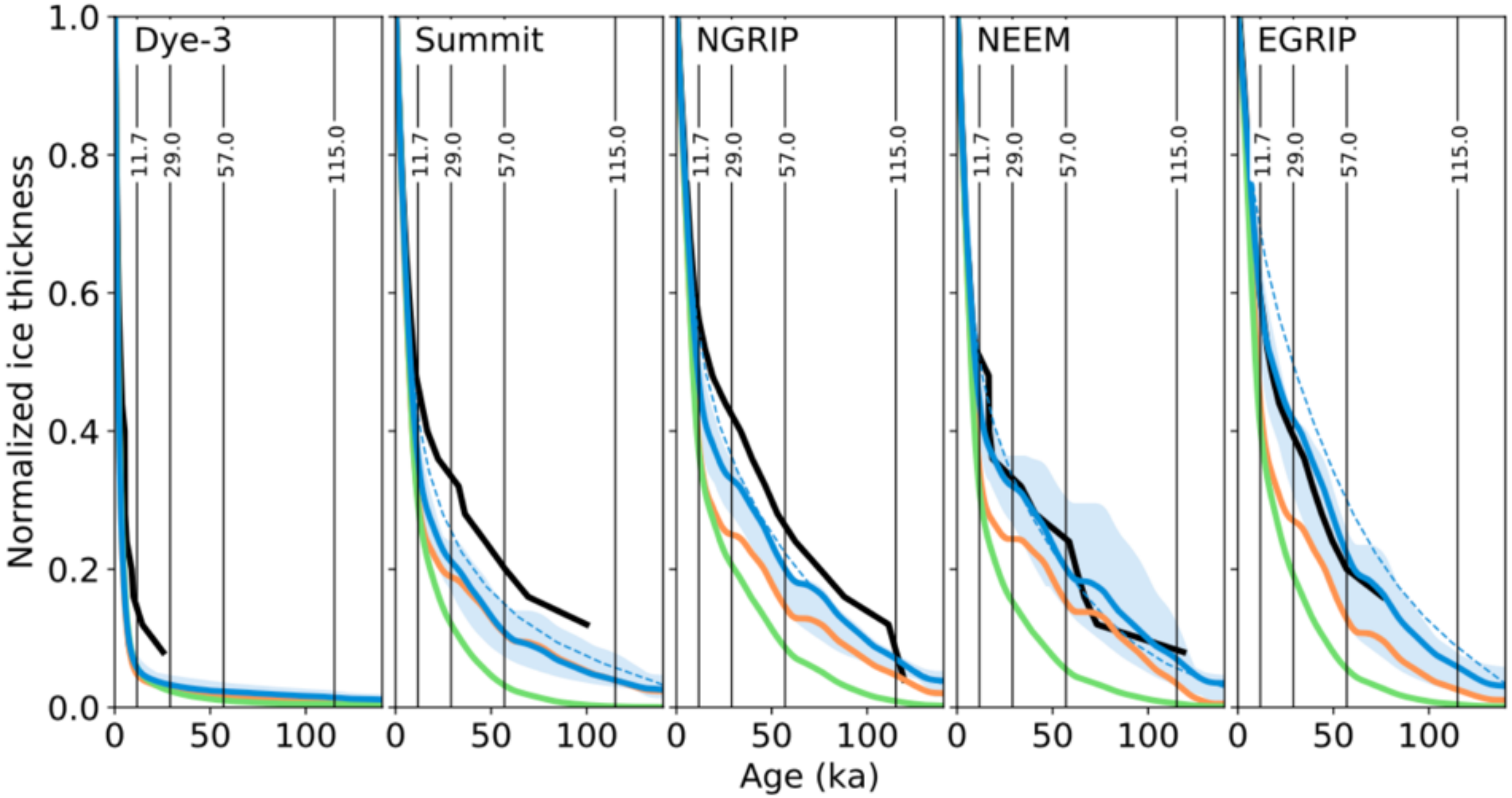
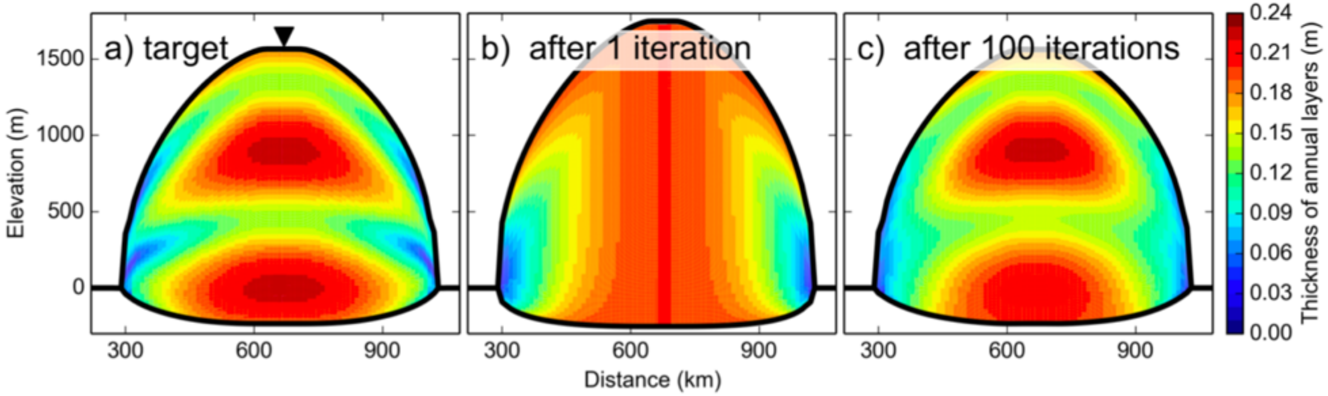


- Simulation optimized to match ice thickness and isochronal layer depths [**blue line**] does a pretty good job of capturing the age-depth profile at individual ice cores.
- Only optimizing for ice thickness [**green line**] shows a much poorer match.
- Additionally, simulating the isochrones with an Eulerian tracer model [**orange line**] shows deficiencies compared to the layer-tracing scheme, though it is better than nothing.

Conclusions and outlook

- Isochronal layers do provide valuable information for constraining simulations – but the devil is in the details!
- Using Eulerian tracer methods leads to biases in the age distribution in the ice sheet, but it can be a useful first-order check.
- Precipitation is a critical input and important to do well – inverse modeling may help here:



Born et al., in prep.