ABSTRACT

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The thermal memory of the Antarctic Ice Sheet

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MOTIVATION

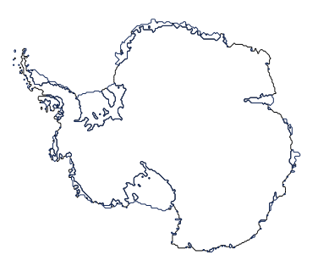
- The Antarctic Ice Sheet (AIS) keeps a **thermal memory** of the past **glacial-interglacial climate** because surface temperature anomalies propagate slowly to the base. This inherited **thermal structure impacts**:
  - (i) current **ice dynamics** (e.g., ice rheology, deformation rates, subglacial conditions, basal sliding)
  - (ii) **basal melting**, which is also critical to identify sites that could have preserved **old ice** at the base.
- **Recent work** on the thermal state of the AIS (Raspoet & Pattyn, 2025; hereafter RP25) investigated uncertainties in boundary conditions and model approximations, but considered a **thermal steady state**, thereby neglecting the legacy of glacial-interglacial climate changes.

→ Here, we force the **thermomechanical ice-sheet model** Kori-ULB with **transient paleoclimate reconstructions** spanning the last interglacial (LIG) to the present day (PD), to quantify the influence of paleoclimatic changes on the **thermal state** and **basal melting** of the AIS.

METHODS

① ICE-SHEET MODEL INITIALISATION

TRANSIENT INVERSE RUN
PRESENT-DAY CONDITIONS
THERMAL STEADY STATE



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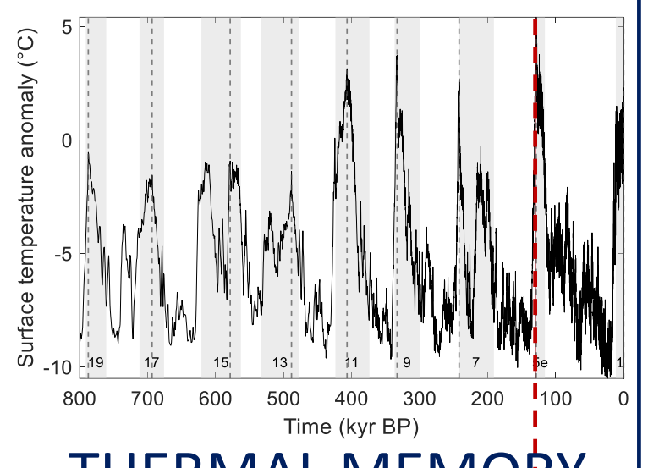
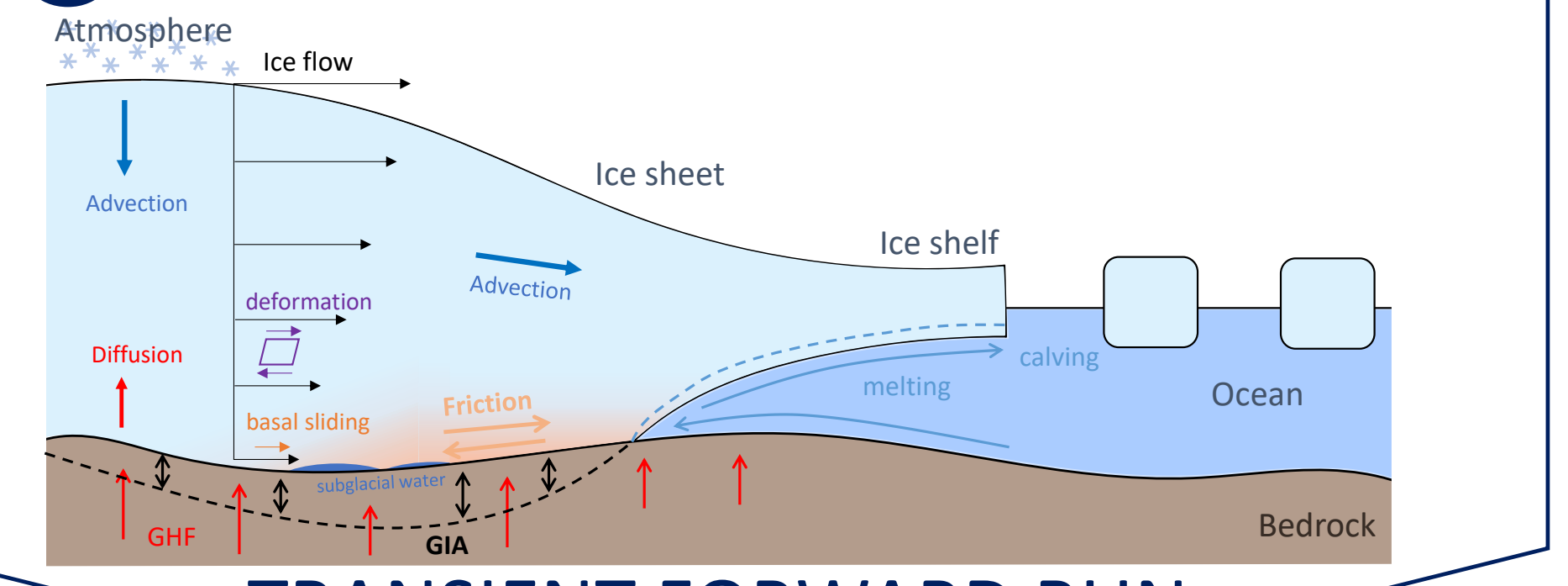


THERMAL MEMORY
FIXED GEOMETRY

③ FORCING THE ICE-SHEET MODEL



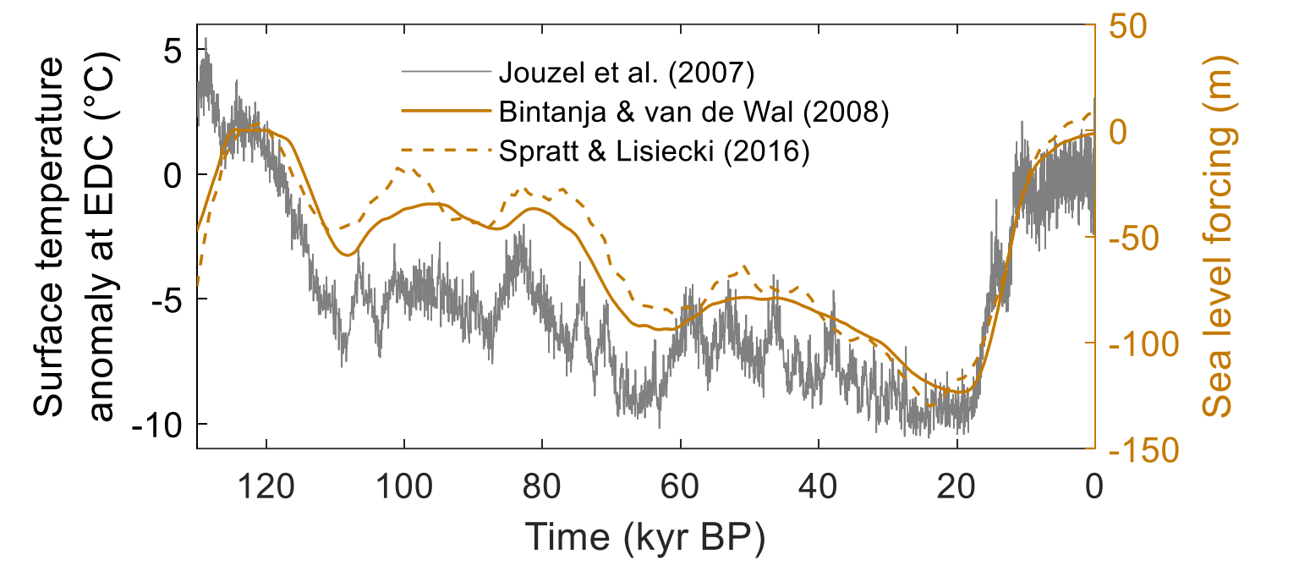
TRANSIENT FORWARD RUN

② RECONSTRUCTION OF TRANSIENT PALEOCLIMATE FORCINGS

OPTION 1: SIMPLE CLIMATE FORCING

Forcing with surface temperature anomalies derived from the EPICA DOME C record.

Subsequent scaling of other fields with parametrisations during model run (correction for elevation changes, surface mass balance components, ocean temperatures, etc.).



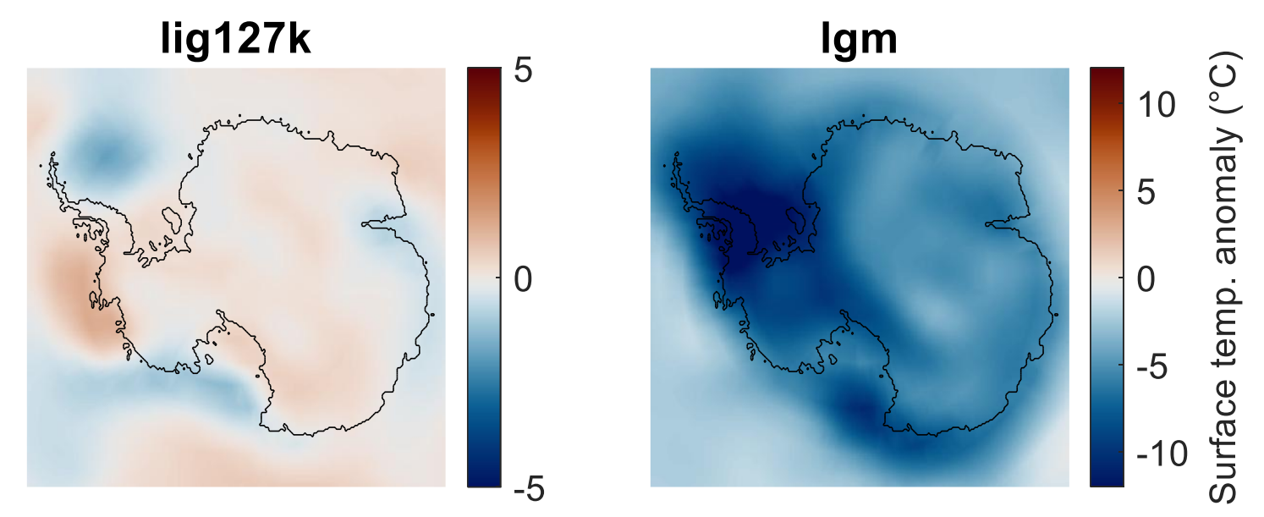
	SIMPLE FORCING	CLIMATE INDEX
+	Simple and easy to implement	Anomalies that vary in space and time
−	Spatially uniform background changes	Uncertainty from the GCM outputs

OPTION 2: CLIMATE INDEX APPROACH

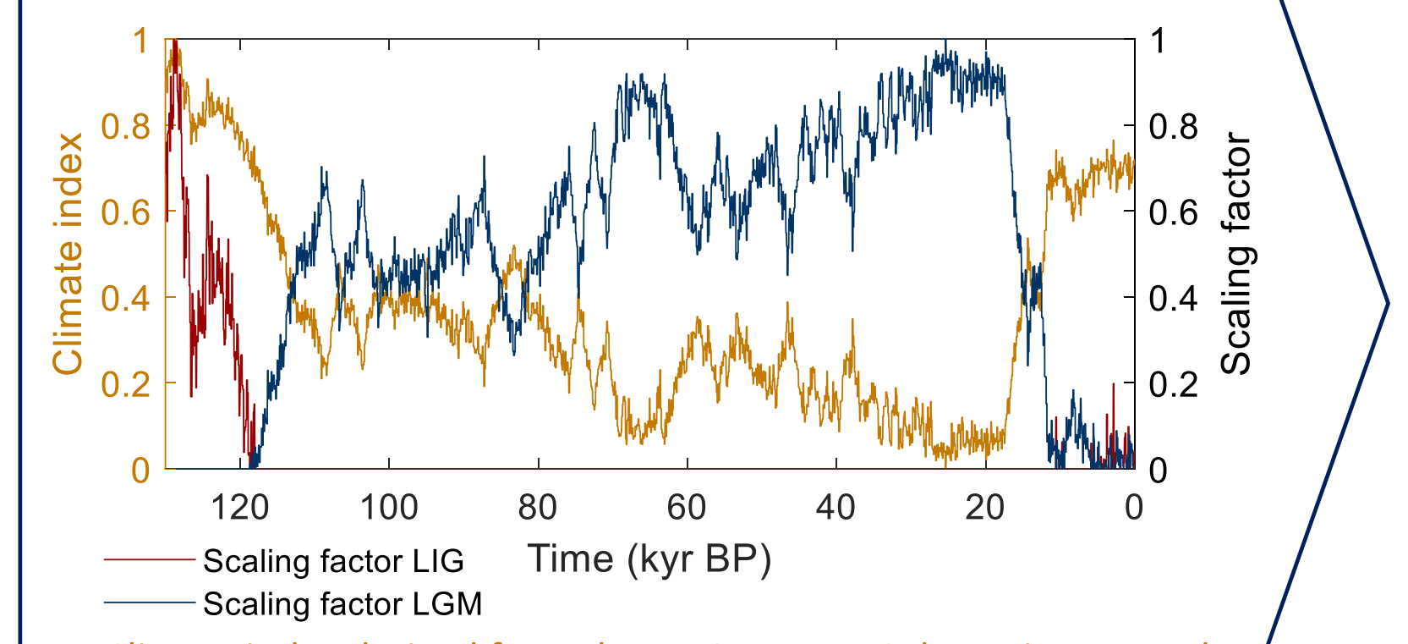
Reconstruction of transient climate snapshots (atmosphere & ocean) – method of Sutter et al. (2019)

CLIMATE ANOMALIES AT KEY TIME SLICES

We use time slices from the Global Climate Model (GCM) MIROC-ES2L for *lig127k* and *lgm* (PMIP4 experiments)

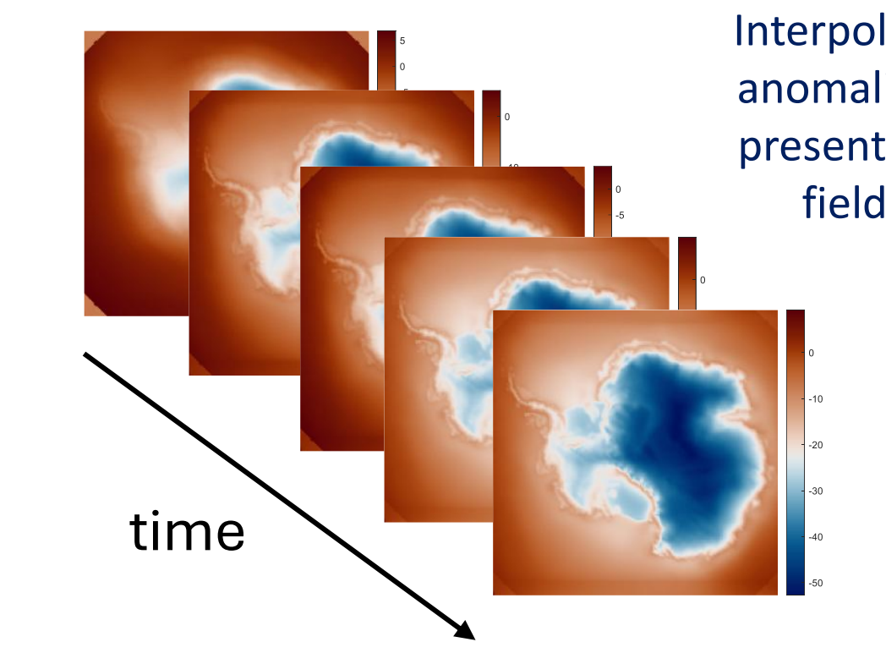


INTERPOLATION WITH A CLIMATE INDEX



Climate index derived from the EPICA Dome C deuterium record

TRANSIENT CLIMATE FORCING

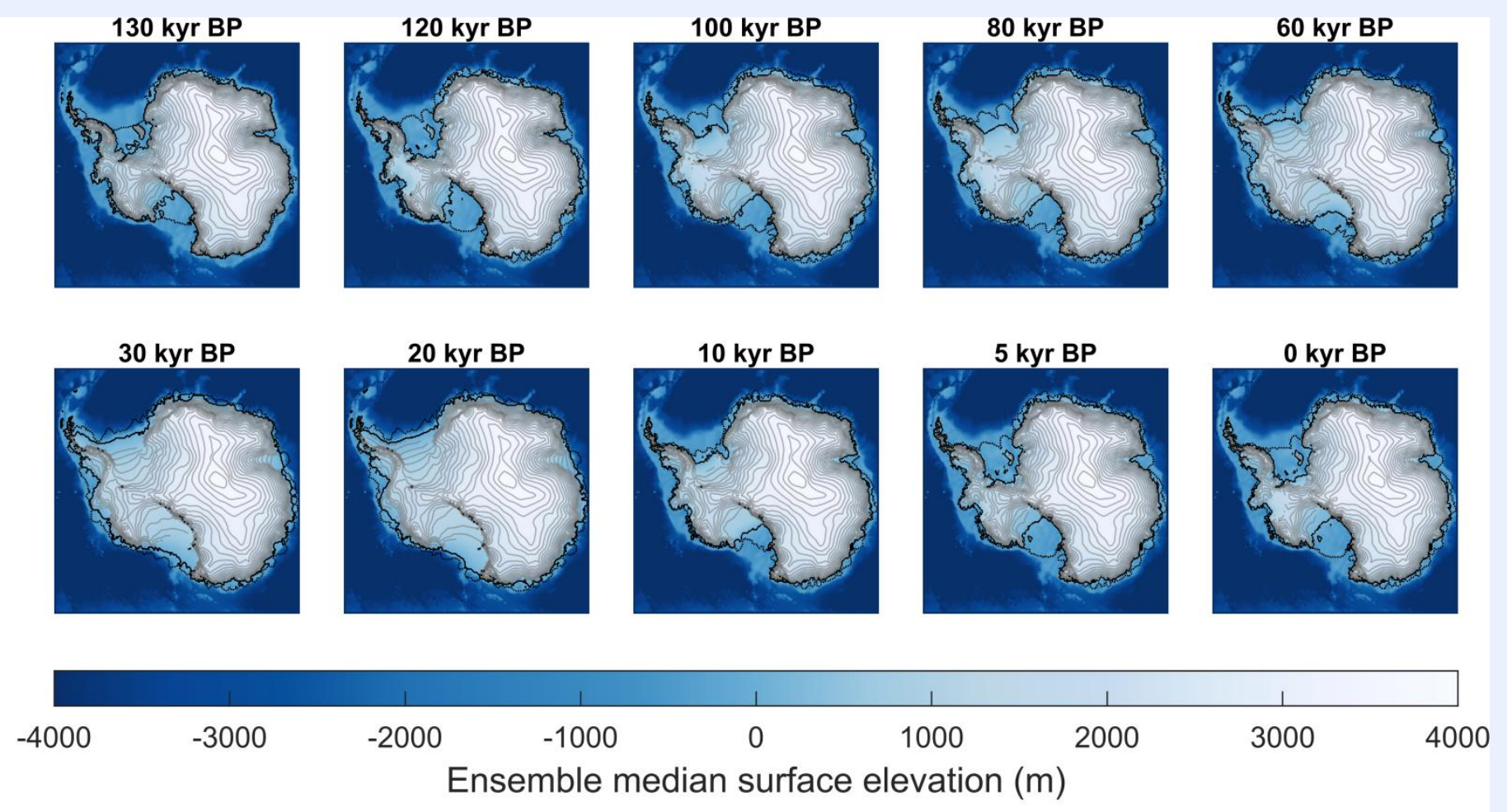


Interpolated anomalies + present-day fields

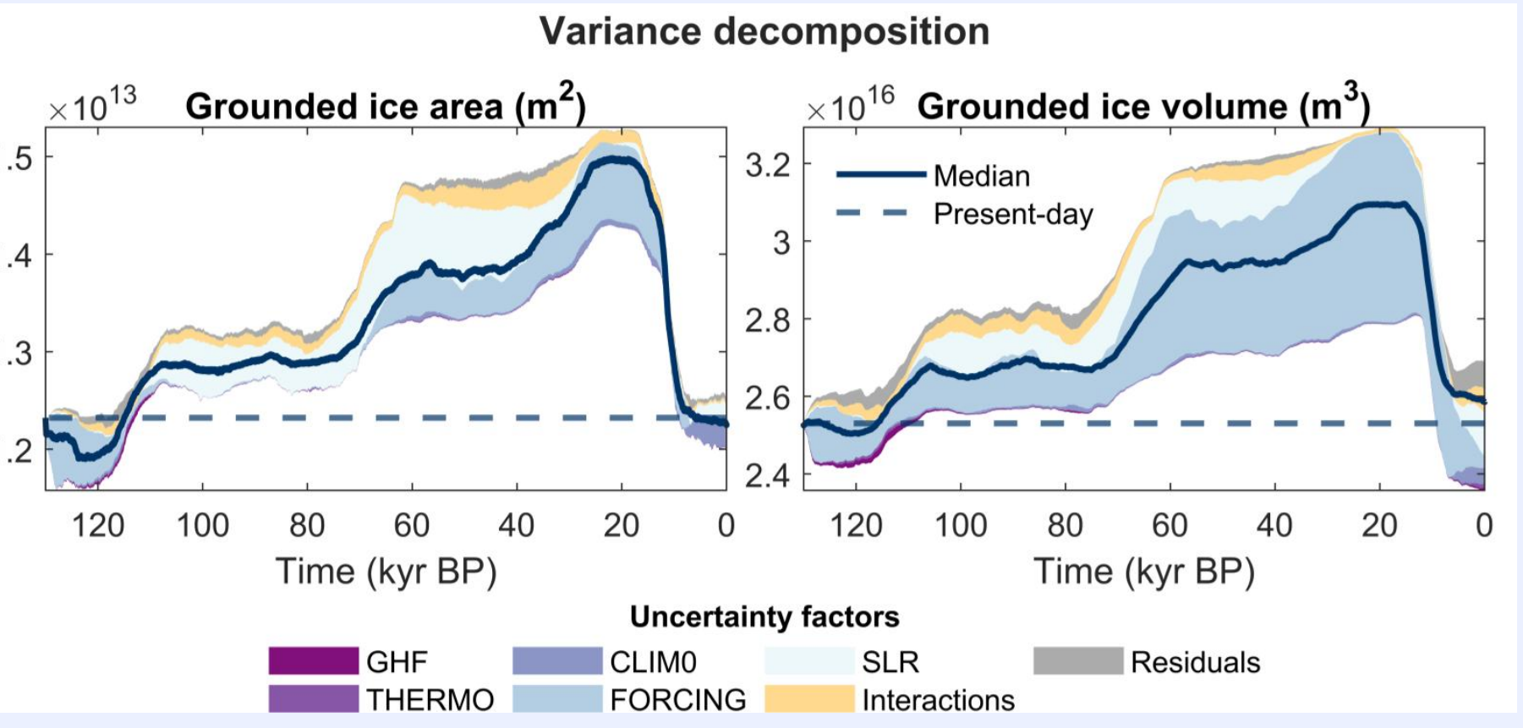
RESULTS

INFLUENCE ON THE ICE GEOMETRY

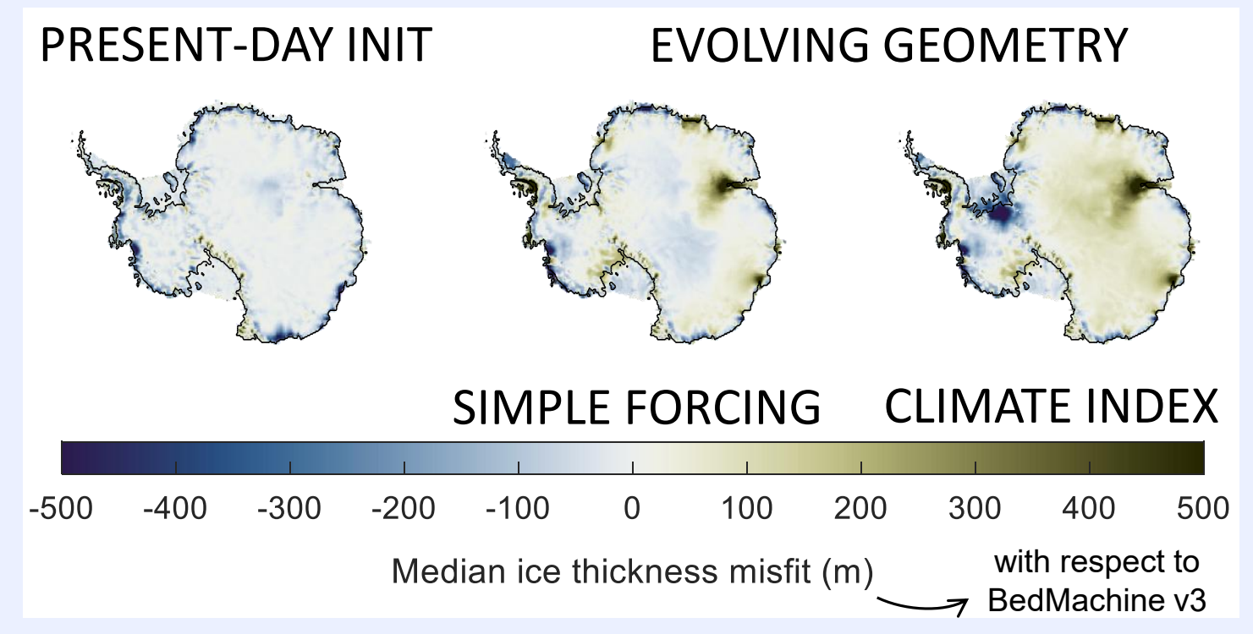
- The model satisfactorily reproduces the evolution of the ice-sheet geometry during the last glacial cycle.



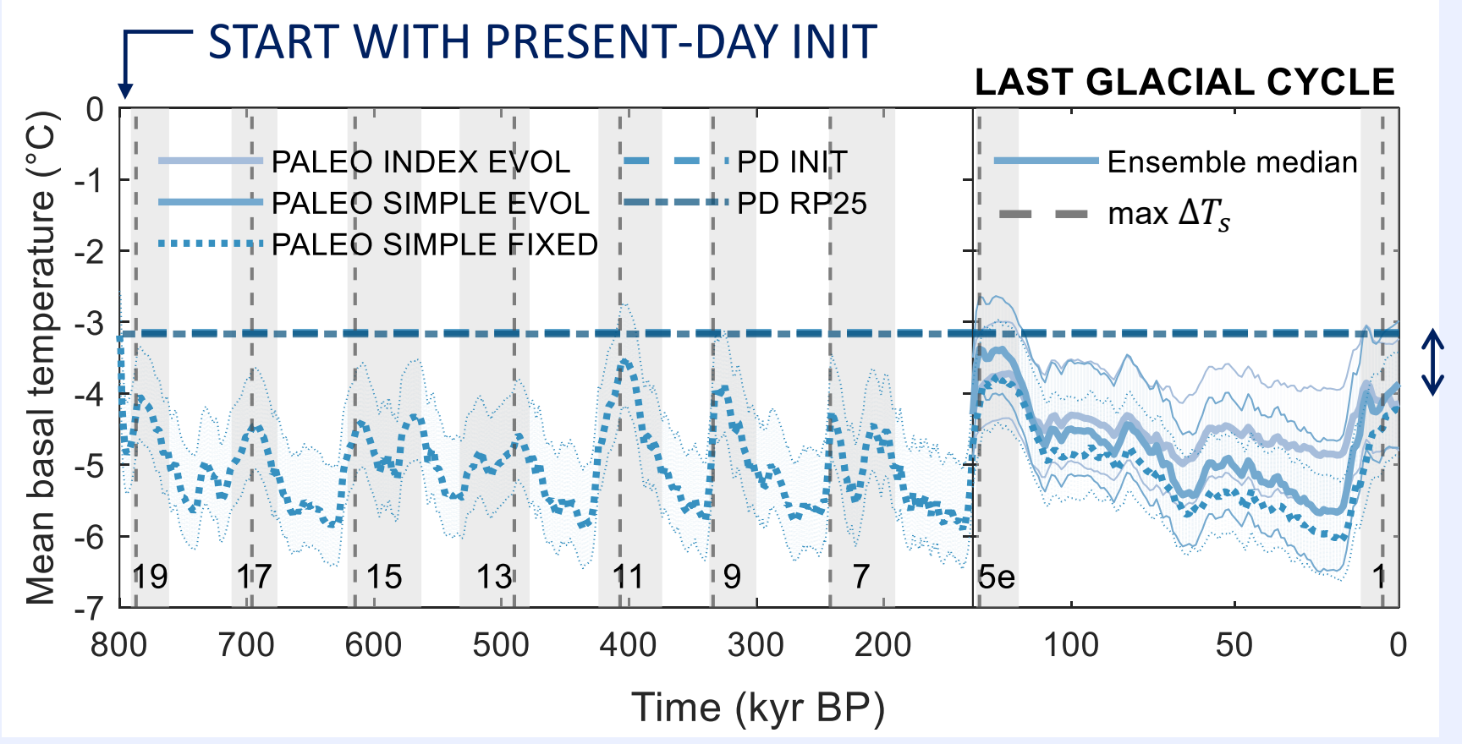
- The principal source of uncertainty pertains to climate forcing (especially the SMB).



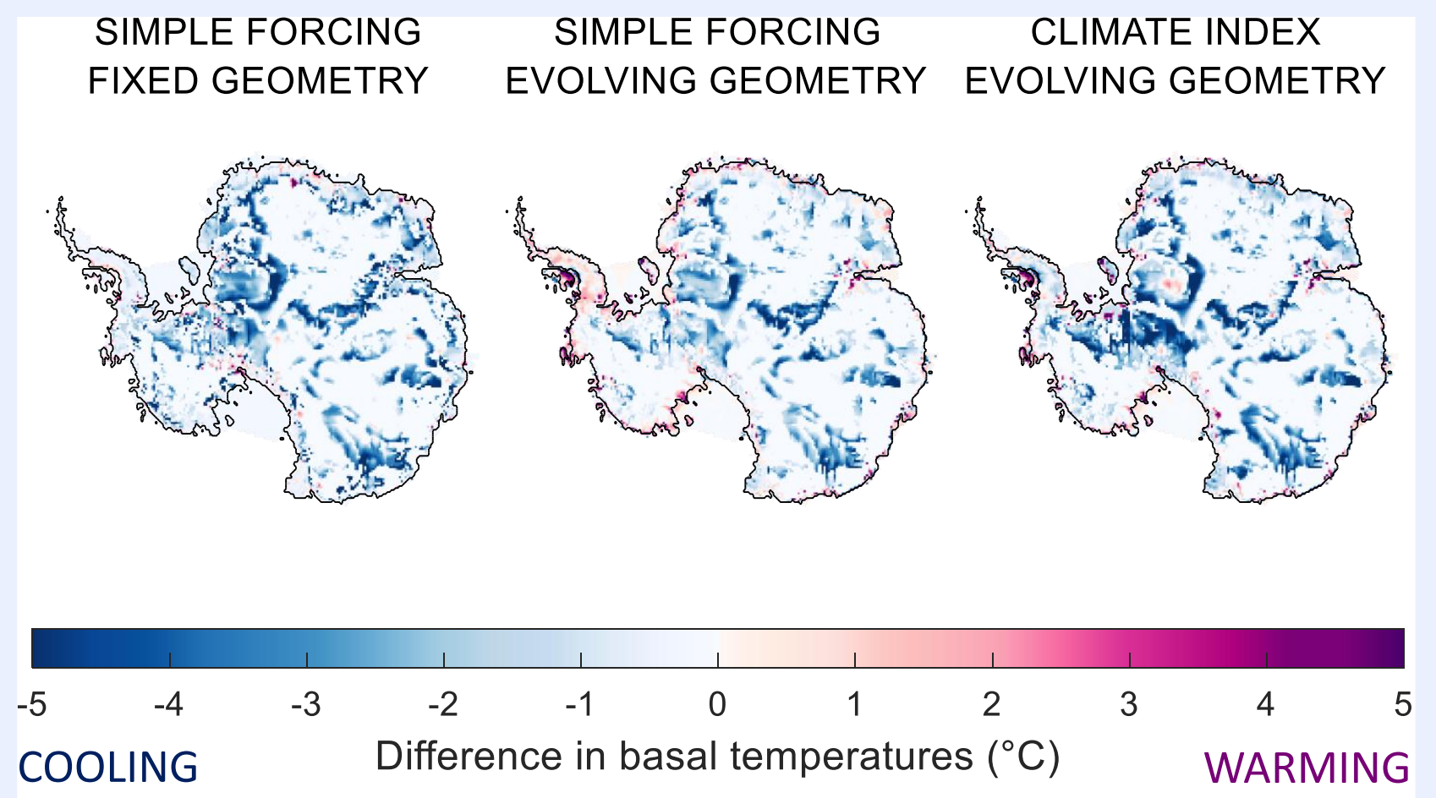
- Nevertheless, the modelled ice geometry at the end of the paleo simulations can diverge significantly from the observed one.

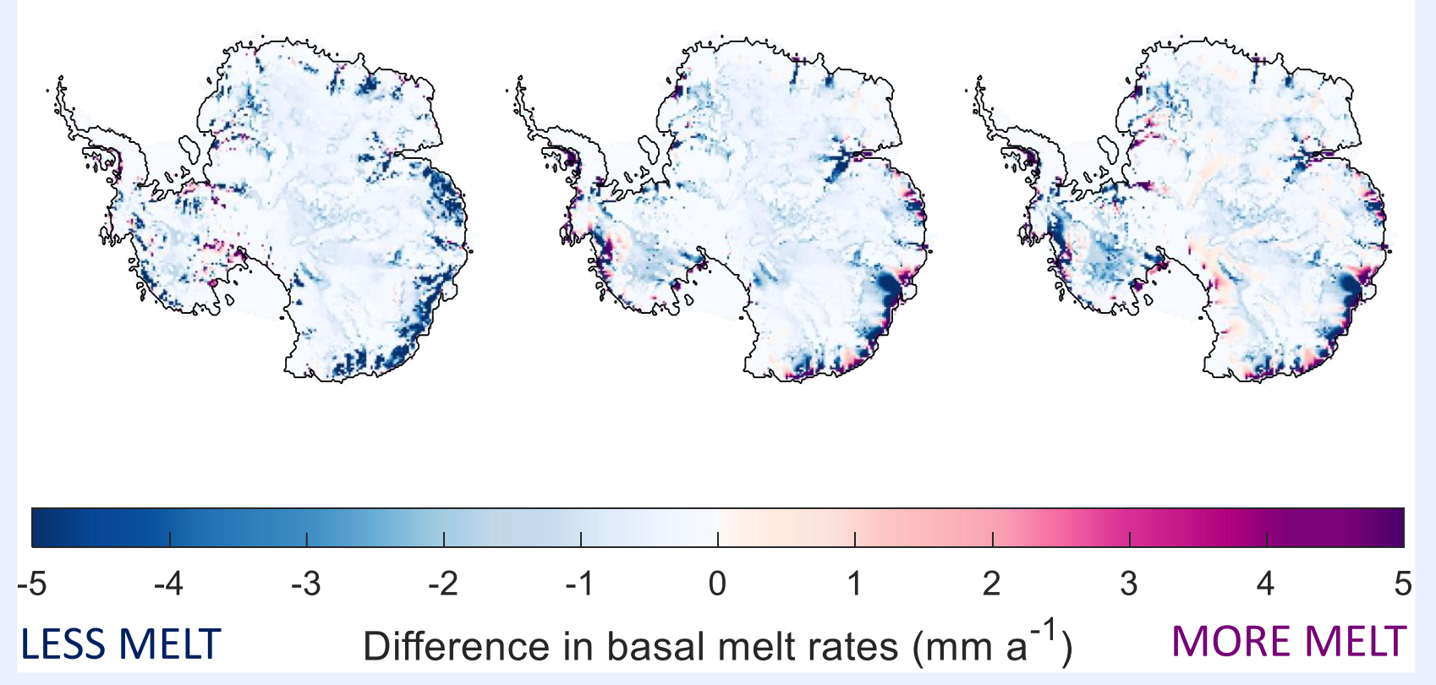


COOLING EFFECT OF PAST CLIMATE CHANGES ON ENGLACIAL AND BASAL TEMPERATURES



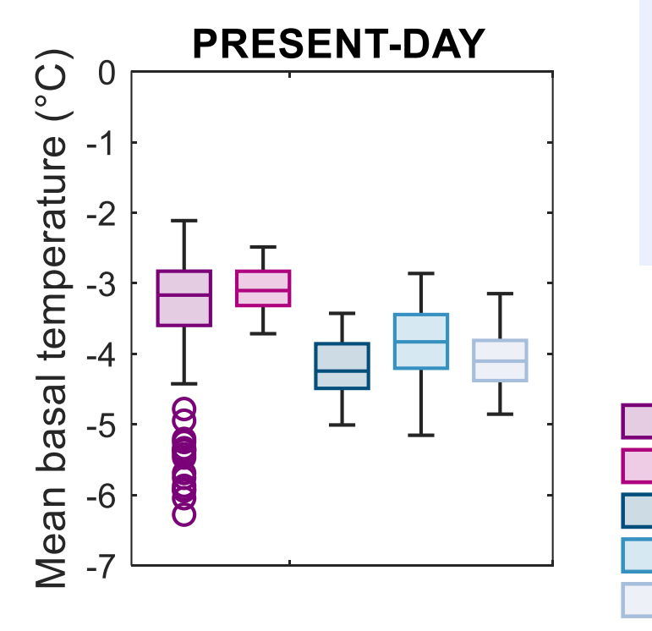
Overall, an average PD cooling of ~1°C occurs after paleo spin-up simulations compared to the thermal steady state. However, changes in basal temperatures are spatially heterogeneous, with regions experiencing more intense cooling > -5°C.



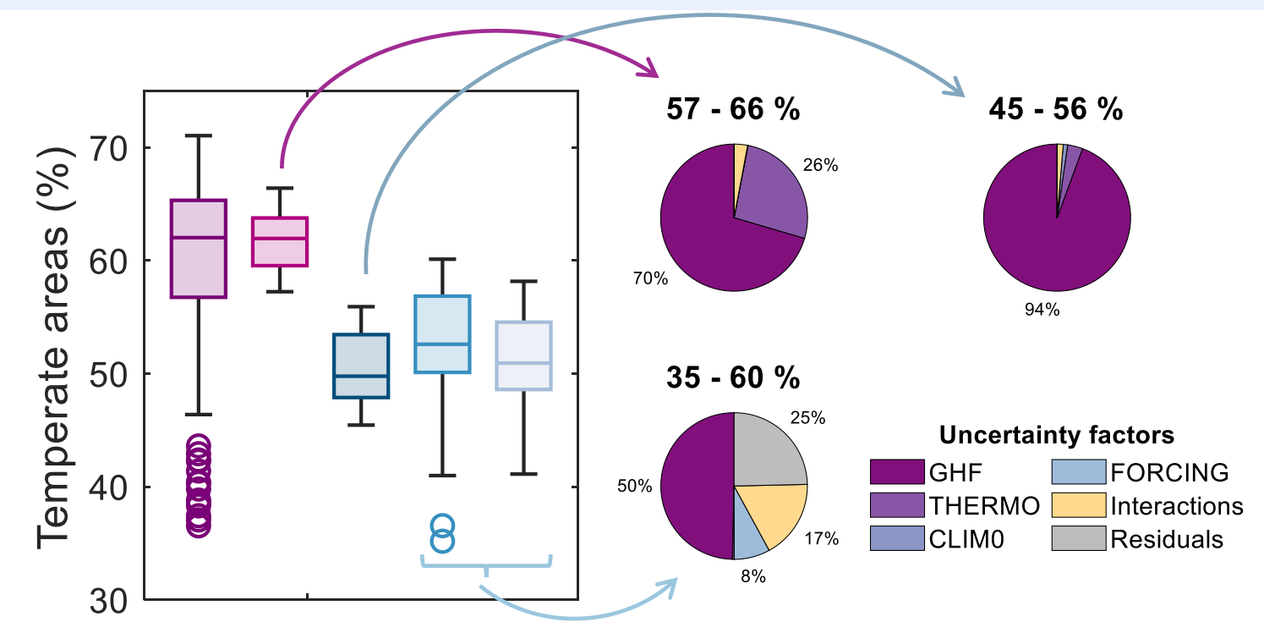


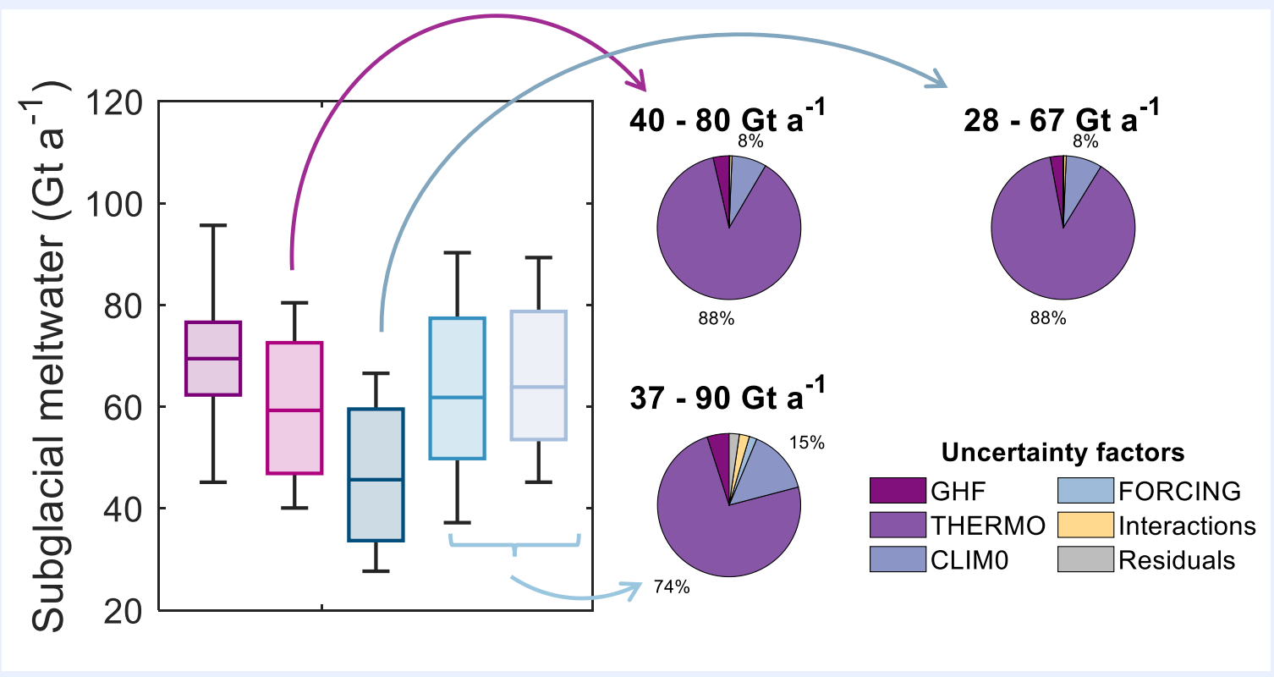
→ Similar cooling pattern inland of East Antarctica for all approaches

How does thermal memory compare with other sources of uncertainty?

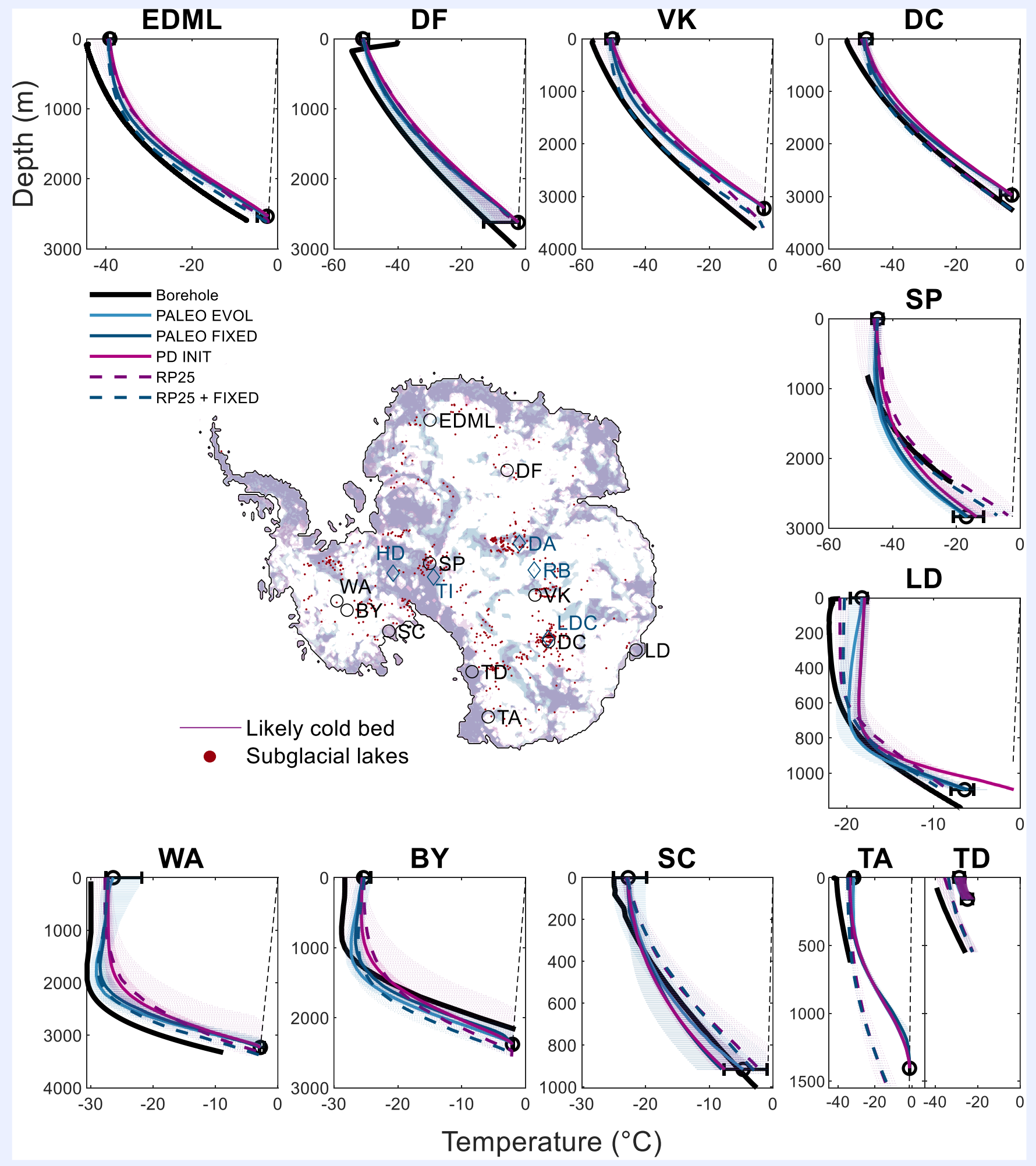


In terms of cold/temperate bed distributions, the largest source of uncertainty comes from GHF (explains ~70% of the variance at thermal steady state, similarly to RP25). Accounting for the past climate history increases the likelihood of present-day cold basal conditions by 6-22%.

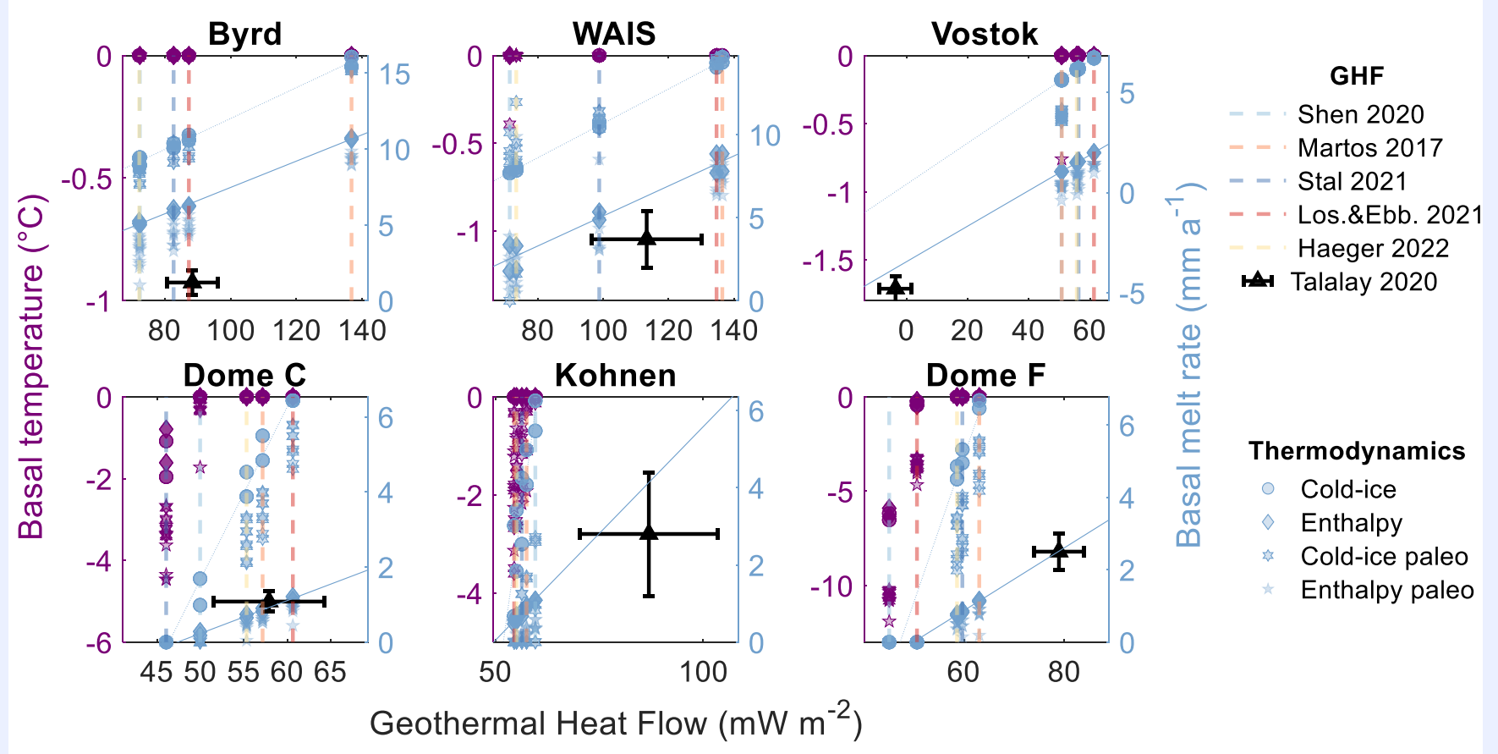




In terms of subglacial meltwater production, the largest source of uncertainty pertains to the thermodynamic model* (which explains ~88% of the variance at thermal steady state). Paleo simulations exhibit either a decrease (fixed geometry) or an increase (evolving geometry) in present-day basal meltwater production. *enthalpy vs cold-ice temperature models



Modelled temperature profiles align well with borehole measurements, especially when accounting for transient thermal effects. However, geothermal heat flow can deviate significantly from borehole-inferred values (Talalay et al., 2020), impacting the modelled basal melt rates.



SUMMARY

- We forced a thermomechanical ice-sheet model with transient paleoclimate reconstructions spanning the last glacial cycle.
- The history of past climate changes leaves an imprint on the current thermal state of the AIS: influence on subglacial conditions and englacial structure.
- Transient thermal effects are spatially heterogeneous: some regions experience significant cooling while others are close to thermal steady state (∝ ↓ advection).
- Misfits between the modelled and "observed" ice thickness can be substantial in fast-flowing regions after transient paleo simulations.
- Paleo spin-up simulations with a fixed geometry capture most of the transient thermal effects while keeping a present-day geometry close to the observed one & allowing for faster spin-ups.

NEXT STEPS

- Explore ice-sheet model, parametric, resolution, and forcing uncertainty.
- Test other paleo spin-up procedures (e.g., transient inversion, constant paleoclimate)
- Compare model results with observational constraints (e.g., The RAISED, 2014; AntIce2, Lecavalier et al., 2023) & other modelling studies.
- What are the implications for future projections of the AIS and the investigations of potential old ice sites?

REFERENCES & ACKNOWLEDGEMENTS

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References. The surface temperature forcing was reconstructed from the EPICA Dome C ice core (Jouzel et al., 2007; doi:10.1126/science.1141038) and/or the climate model MIROC-ES2L (O'ishi et al., 2019; Ohgaito et al., 2019; downloaded from https://metagrid.esgf-west.org/search) with the climate index method (Sutter et al., 2019, doi: 10.5194/tc-13-2023-2019). The sea level forcing comes from Bintanja & van de Wal (2008; doi: 10.1038/nature07158) and Spratt & Lisiecki (2016; doi: 10.25921/rd66-5820). The GIA was computed using the ELRA model from Coulon et al. (2021; doi: 10.1029/2020JF006003) with Earth's structure from van Calcar et al. (2026; doi: 10.5194/tc-20-757-2026). The ice thermodynamics were calculated following Raspoet & Pattyn (2025; doi: 10.1017/jog.2025.10087). GHF data were due to Martos et al. (2017), Shen et al. (2020), Stal et al. (2021) and Lösing & Ebbing (2021). Subshelf melt rates were calculated with the PICO model (Reese et al., 2018; doi: 10.5194/tc-12-1969-2018). Calving was determined using the parametrisation of Pollard et al. (2015; doi:10.1016/j.epsl.2014.12.035). The observed ice-sheet geometry is taken from BedMachine v3 (Morlighem et al., 2022; doi: 10.5067/FPSU0V1MWUB6). Borehole measurements of temperature profiles are from Lecavalier et al. (2023; doi: 10.5194/essd-15-3573-2023), subglacial lakes are from Livingstone et al. (2022; doi:10.1038/s43017-021-00246-9), borehole-derived GHF are from Talalay et al. (2020; doi: 10.5194/tc-14-4021-2020). **Disclaimer**: the provided list of references is not exhaustive. Detailed information about the Kori-ULB ice-sheet model can be found in the reference manual, which is available along with the code at: https://github.com/FrankPat/Kori-ULB.