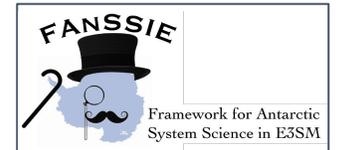
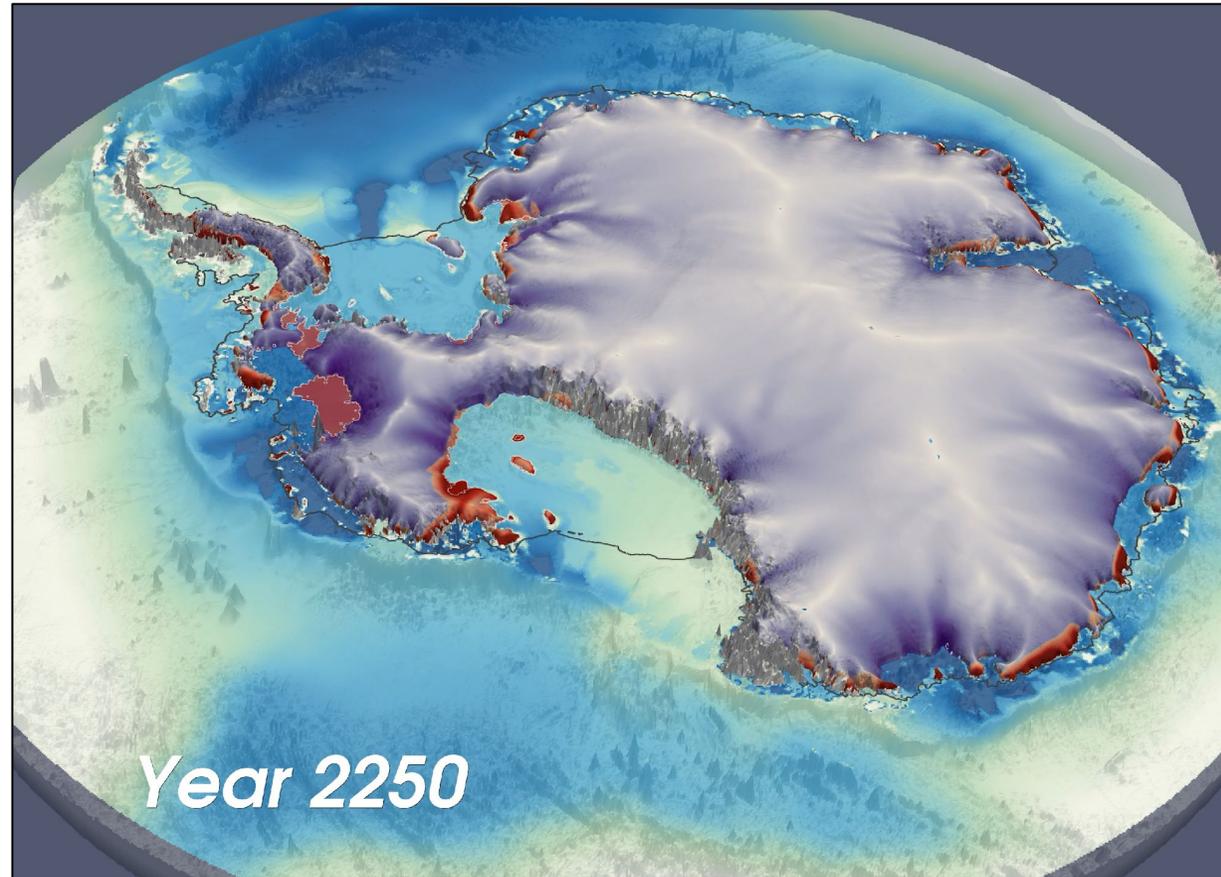


The MPAS-Albany Land Ice (MALI) Antarctic Ice Sheet configuration



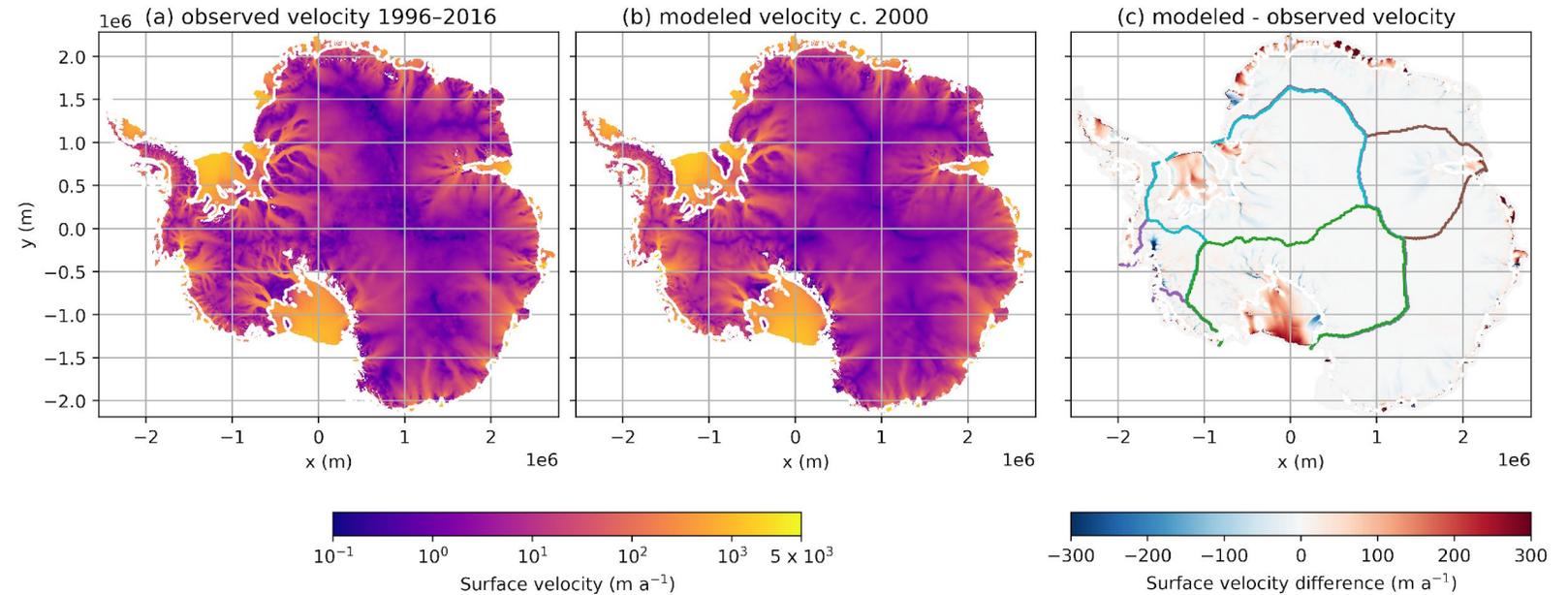
Trevor R. Hillebrand¹, Matthew J. Hoffman¹, Holly K. Han^{1,2},
Mauro Perego³, Alexander Hager¹, Andrew Nolan¹, Xylar
Asay-Davis⁴, Stephen F. Price¹, Jerry Watkins⁵, and Max
Carlson⁵

1. Los Alamos National Laboratory; 2. Jet Propulsion Laboratory; 3. Sandia National

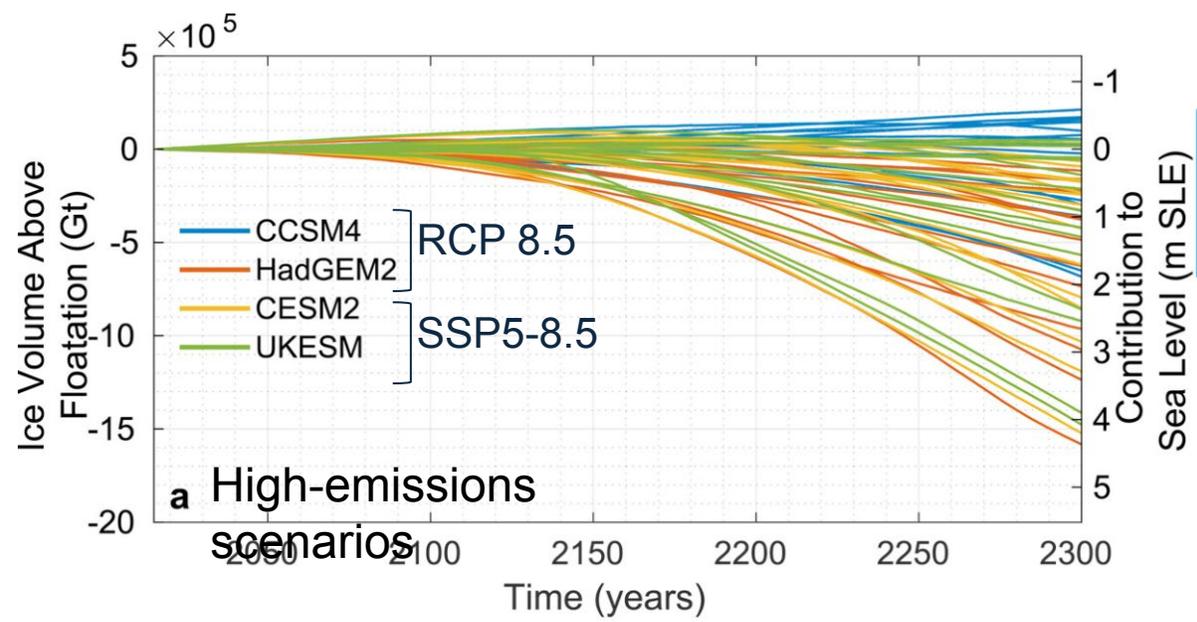
Hillebrand et al. (2025)
preprint

MALI configuration, initial condition and historical behavior

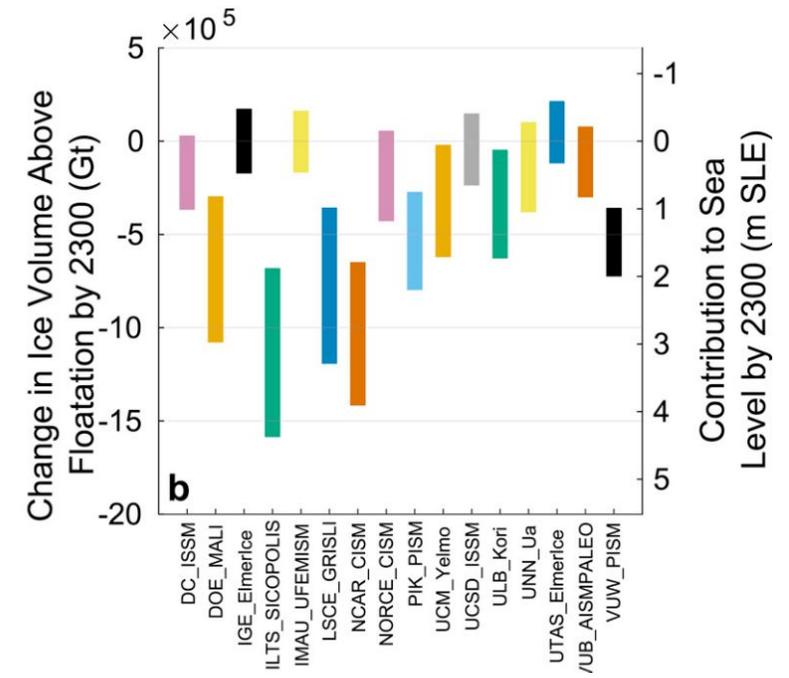
- 4–20 km variable resolution mesh; 385k cells; 5 terrain-following vertical layers
- 3D higher-order (Blatter-Pattyn) stress balance
- Thermo-mechanical coupling via temperature-based thermal solver
- Non-linear Weertman-type sliding law with exponent $q=1/5$
- Optimized basal friction and ice stiffness fields to minimize misfit to observed 1996–2016 velocities (Rignot et al., 2017)
- Non-local quadratic sub-shelf melt parameterization with mean Antarctic calibration target (Jourdain et al., 2020)
- BedMachine v2 bed topography and ice thickness
 - Ice thickness in Amundsen Sea Embayment derived from BedMap2 ice surface for more stable c. 2000 geometry.
- Historical surface mass balance from RACMO2 3p2 (van Wessem et al.



ISMIP6-Antarctica-2300 ensemble



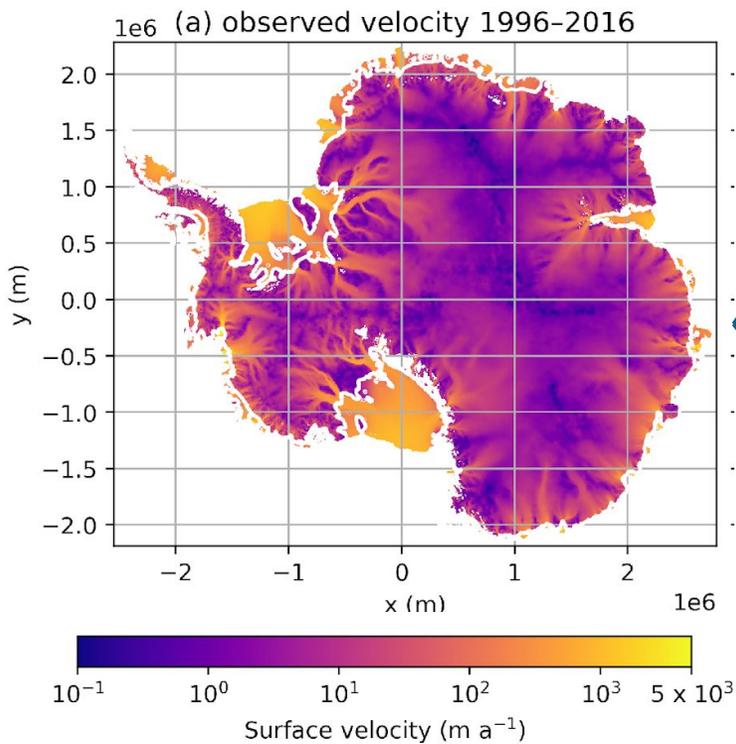
Seroussi et al. (2024)



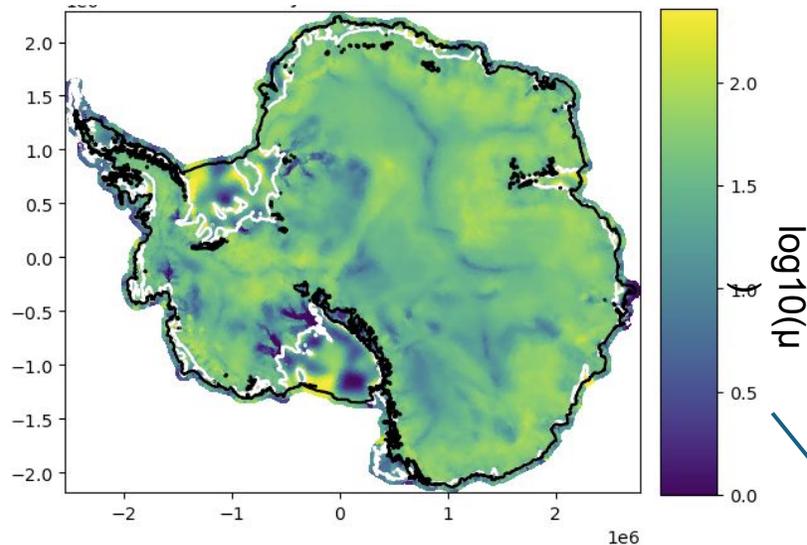
PDE-constrained optimization

Solve for friction and stiffness fields that minimize misfit to observed velocities.

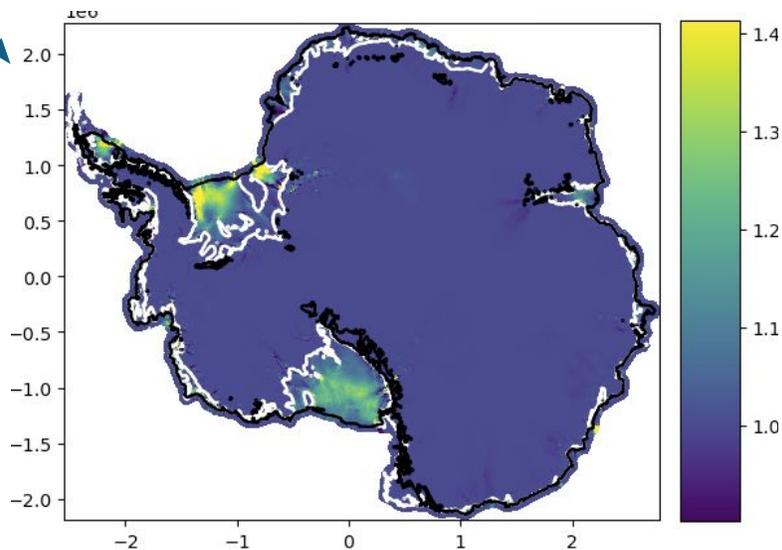
Temperature field taken from previous inversion on 8km mesh.



Weertman friction coefficient*

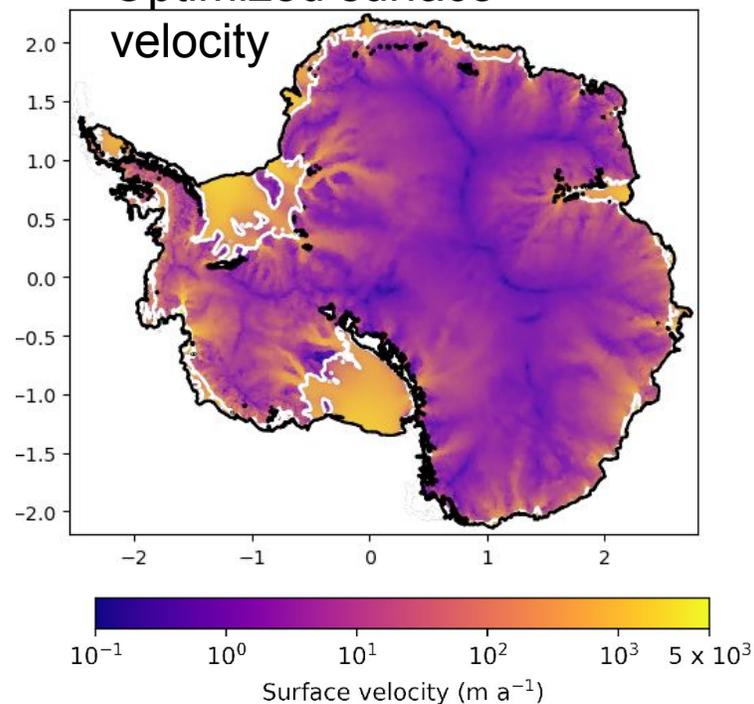


Ice stiffness

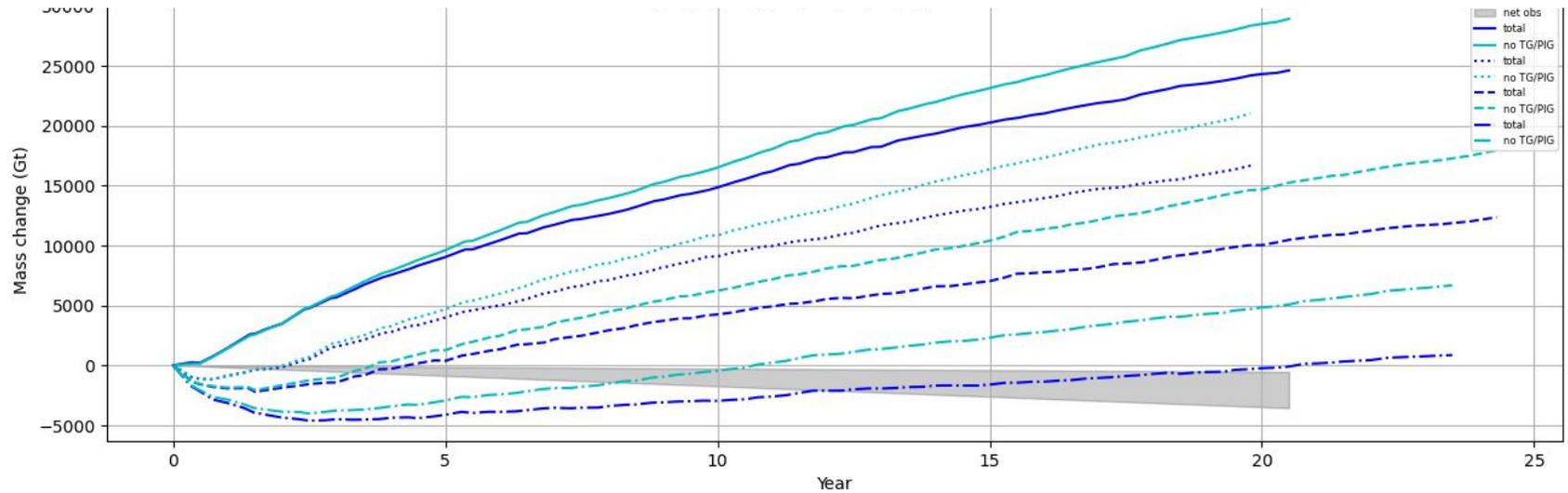
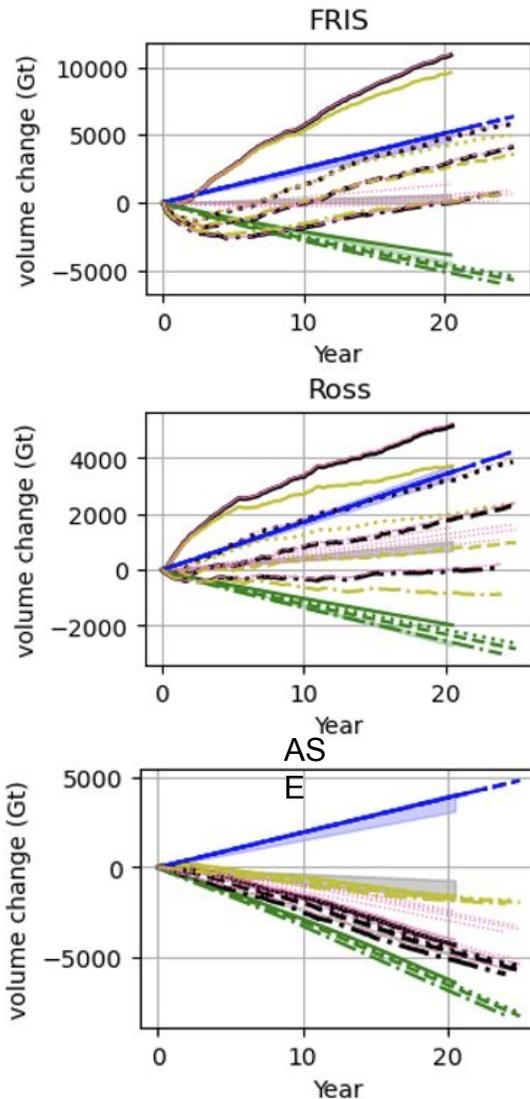


* We can recalculate friction coefficient field for different choices of friction law exponent without re-running optimization.

Optimized surface velocity



Adjusting seafloor topography within uncertainty



Solid: no drop
 dotted: 5 m drop
 dashed: 10 m drop
 dash-dot: 20 m drop

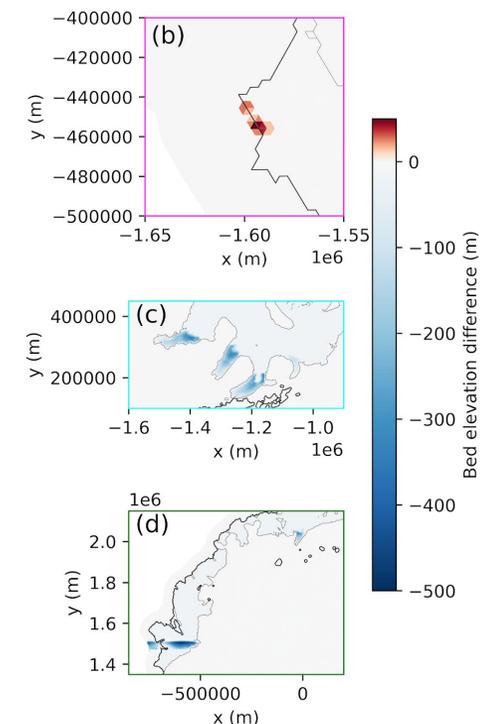
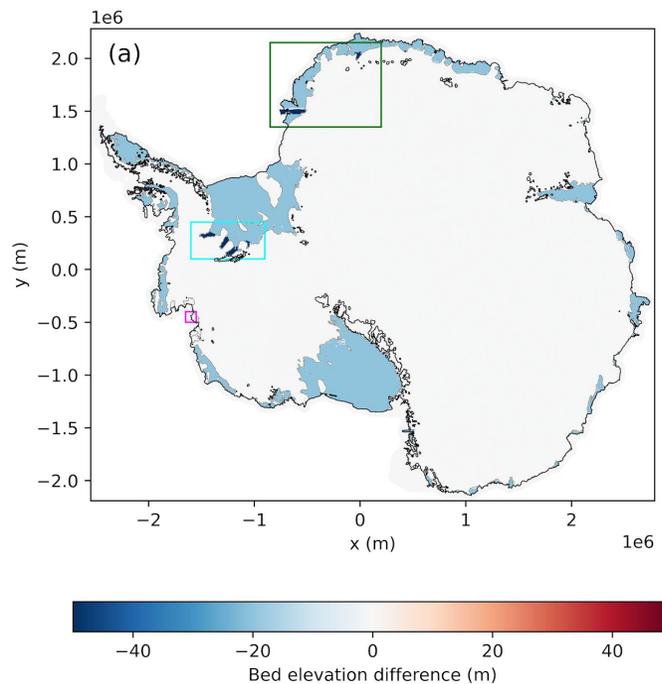
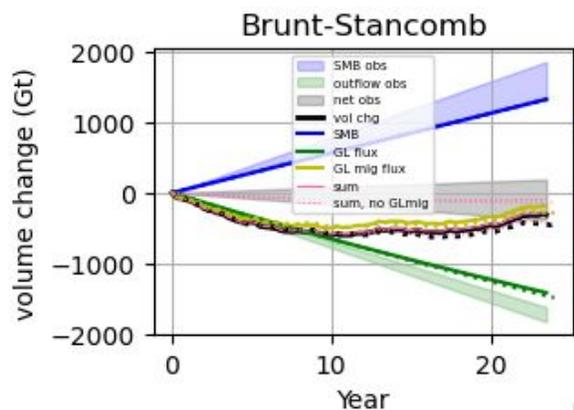
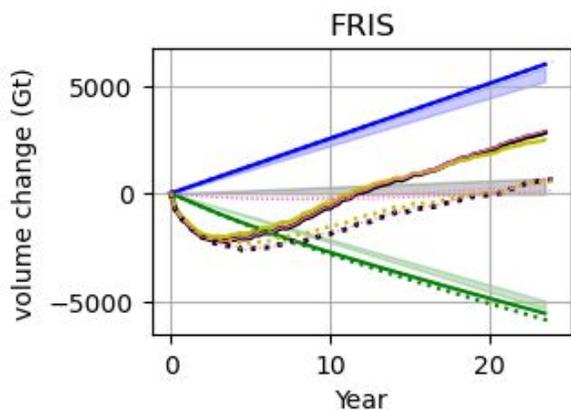
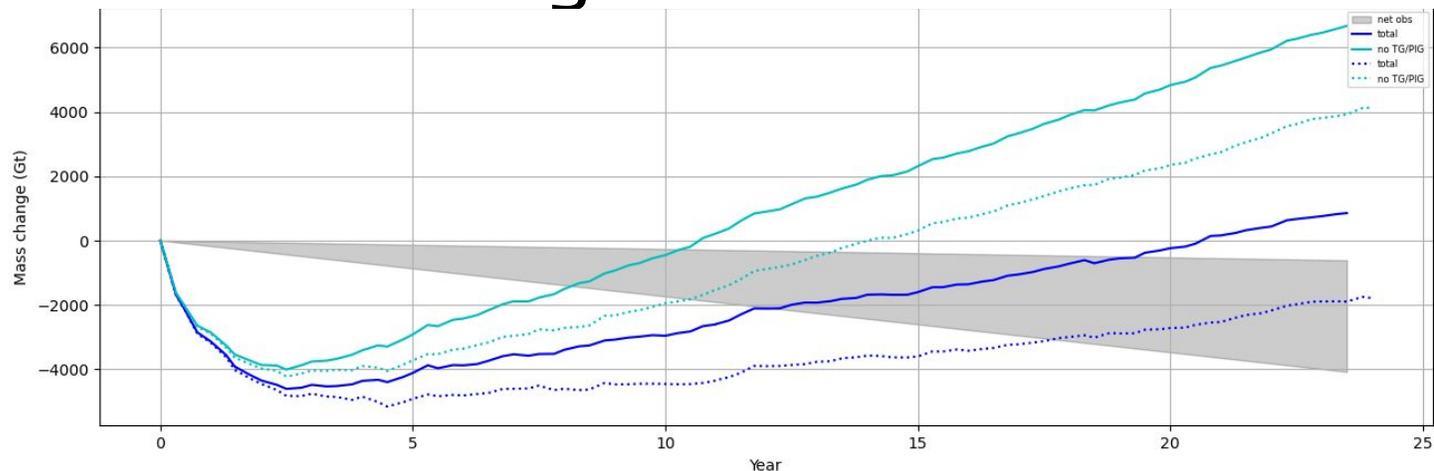
Dropping seafloor by 20m (well within BedMachine uncertainty) helps in most areas but slightly increases bias in Amundsen Sea Embayment. We therefore lowered the seafloor everywhere *except* the ASE by 20 m.

Black curves are total mass change

Grey shading is observations

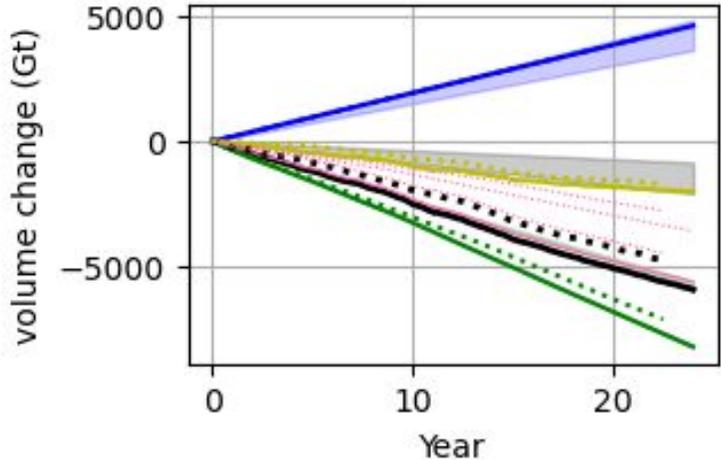
Adjustment to bed artifacts in troughs

solid: troughs not bulldozed
dotted: troughs bulldozed

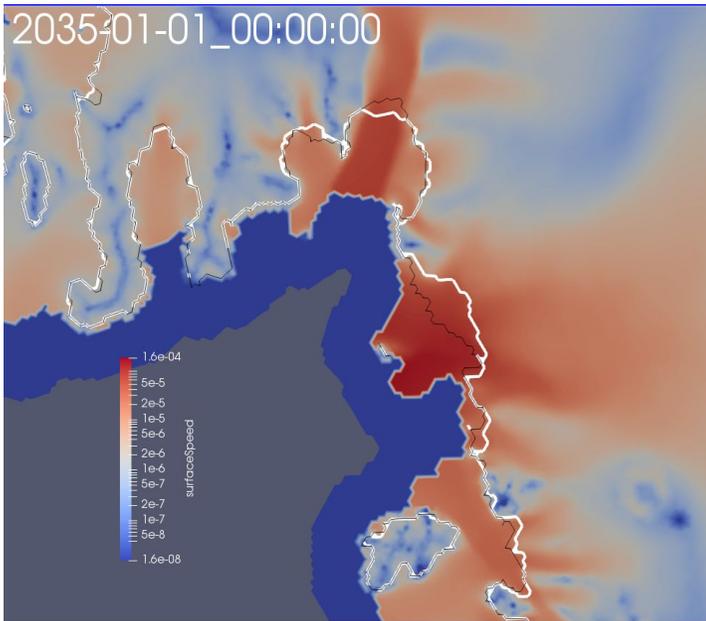


Maps of changes made to BedMachine v2 bed elevation data

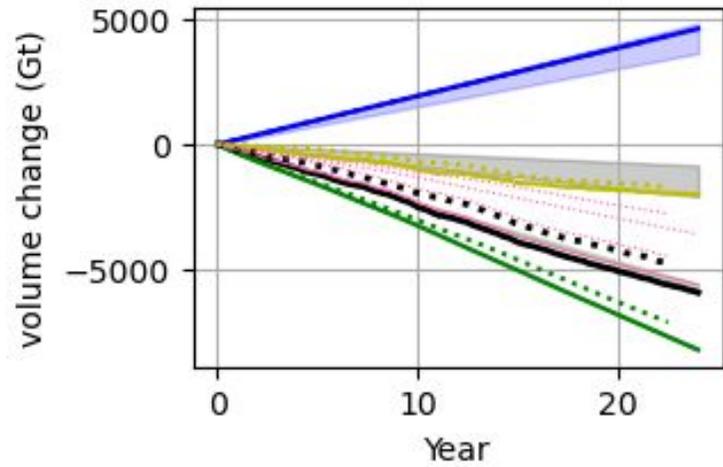
Adding Thwaites pinning point



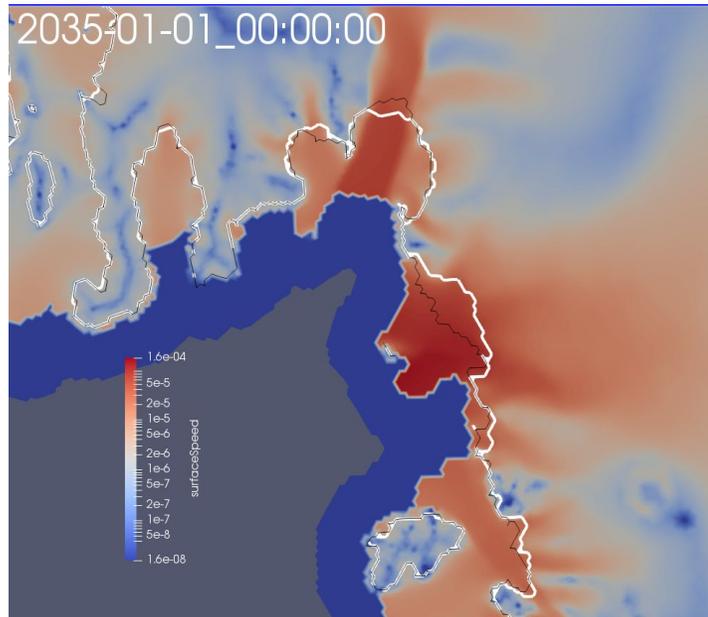
Solid: no pinning point
Dotted: with pinning point



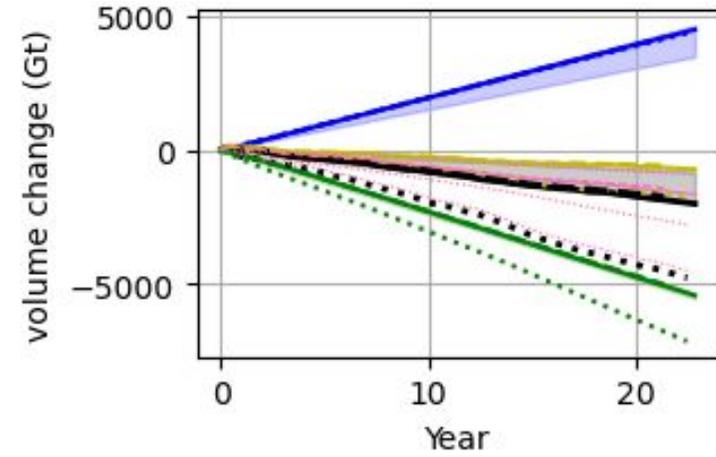
Adding Thwaites pinning point



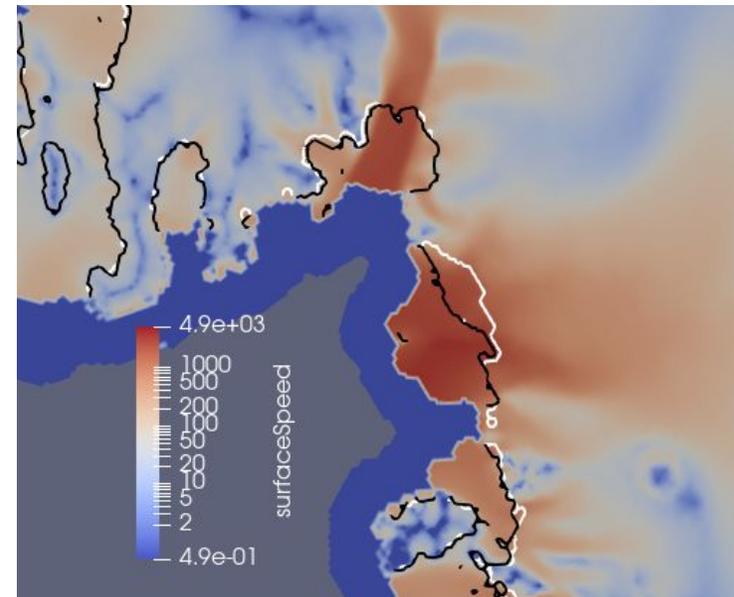
Solid: no pinning point
Dotted: with pinning point



Using BedMap2 ice surface in ASE

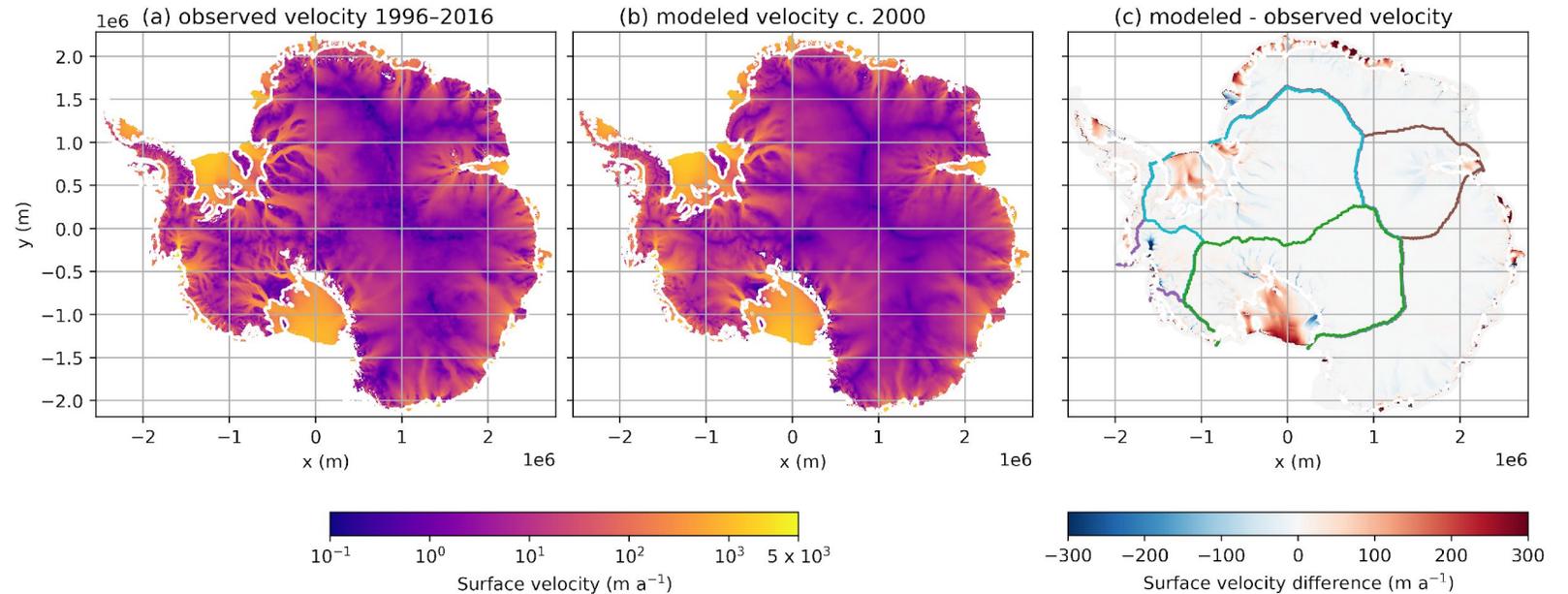


solid: new ASE geometry
dotted: old ASE geometry



Summary:

- Optimization: solve for friction and stiffness fields to match observed velocity.
- Lower bed topography beneath ice shelves by 20 m (except in ASE)
- Remove artifacts downstream of grounding line in ice-stream troughs
- Add pinning point back to Thwaites Ice Shelf
- Use BedMap2 c. 2000 surface elevations in ASE.
- 10-year relaxation run with 0 melt in ASE to remove fast transients without significant grounding-line retreat.
- Tune friction law exponent, q



Towards ISMIP7

Anticipated changes:

- 4–20km higher resolution mesh (≥ 1 or 2km)
- BedMachine v2 BedMachine v4 or BedMap3
- Velocity-constrained dH/dt-constrained initialization
- First order Higher-order advection and time stepping
- Retreat only calving von Mises or crevasse-depth law
- Weertman friction Regularized Coulomb friction
- No GIA Add coupling to global sea-level model

(likely) staying the same:

- Blatter-Pattyn velocity solver
- Temperature-based thermal solver
- Quadratic non-local sub-shelf melt
- ~linear submarine melt of grounded termini

Acknowledgements

Framework for Antarctic System Science in E3SM project
Energy Exascale Earth System Model project
Biological and Environmental Research
Advanced Scientific Computing Research
Scientific Discovery through Advanced Computing

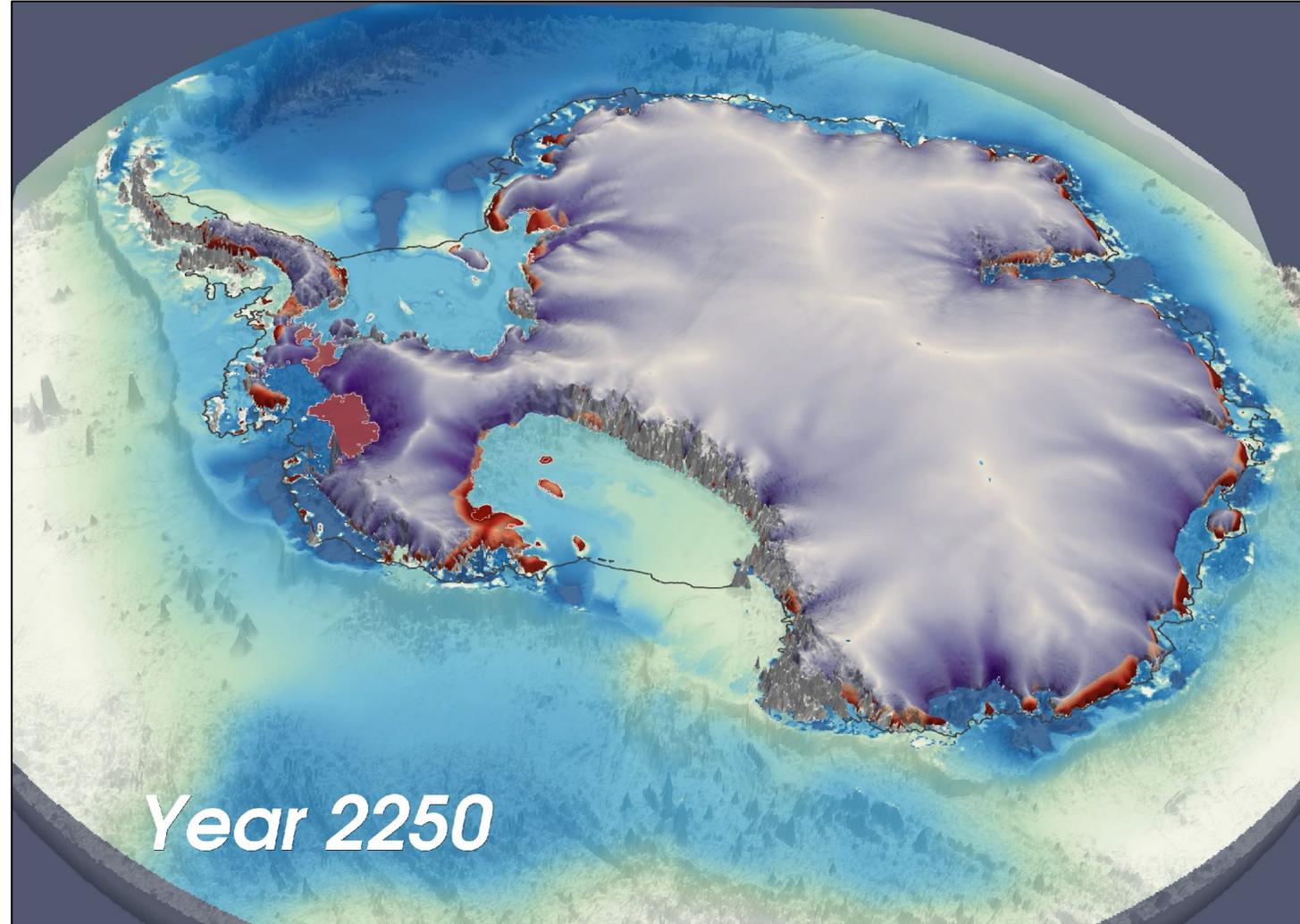
National Energy Research Scientific Computing Center, a U.S. Department of Energy Office of Science User Facility located at Lawrence Berkeley National Laboratory, operated under Contract No. DE-AC02-05CH11231 using NERSC awards ERCAP0027769, ERCAP0028051, ERCAP0032965, ERCAP0032964

Baseline ISMIP6-AIS-2300 projections from MALI

- 4–20 km variable resolution mesh with 385k cells and 5 vertical layers
- 3D Blatter-Pattyn velocity solver
- Thermo-mechanical coupling via temperature-based thermal solver
- Non-linear Weertman-type sliding law

Change in mass above
floatation (10^6 Gt)

Sea-level equivalent
(mm)



CESM2 forcing with ice-shelf
hydrofracture

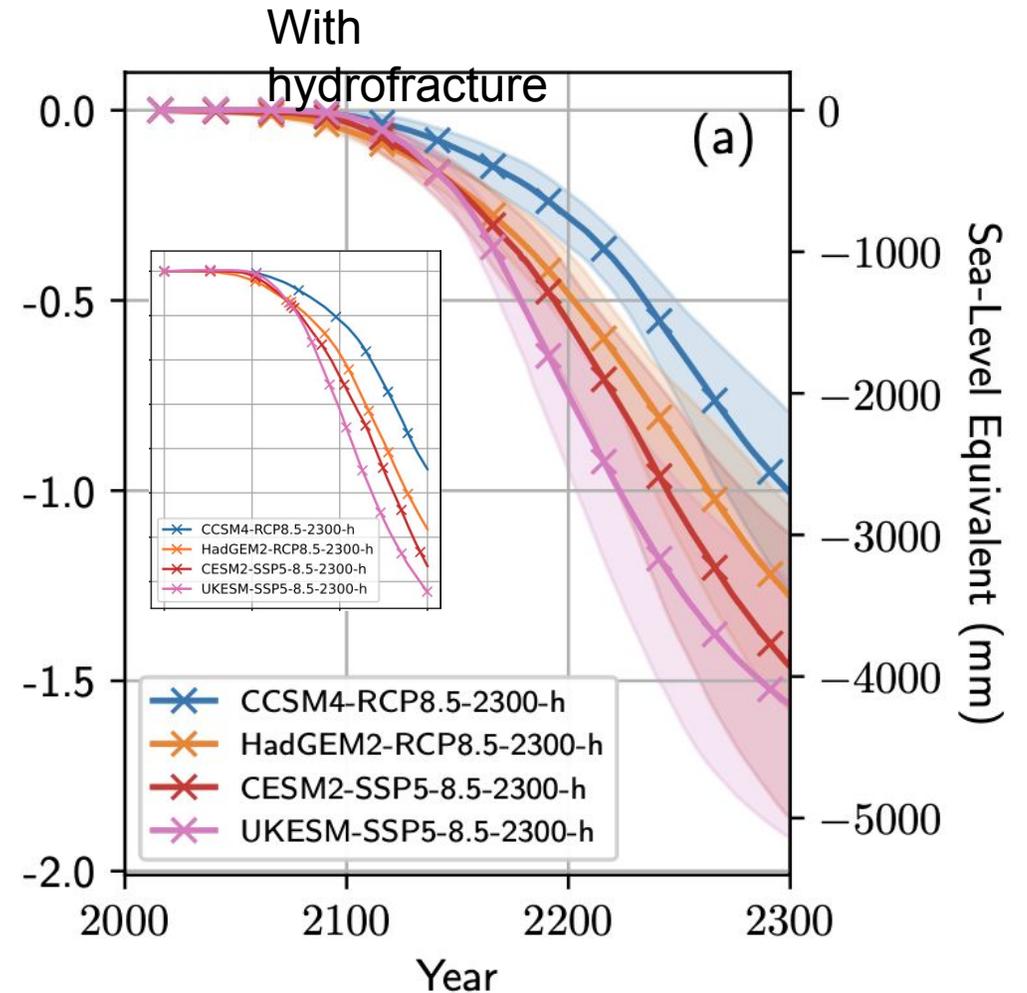
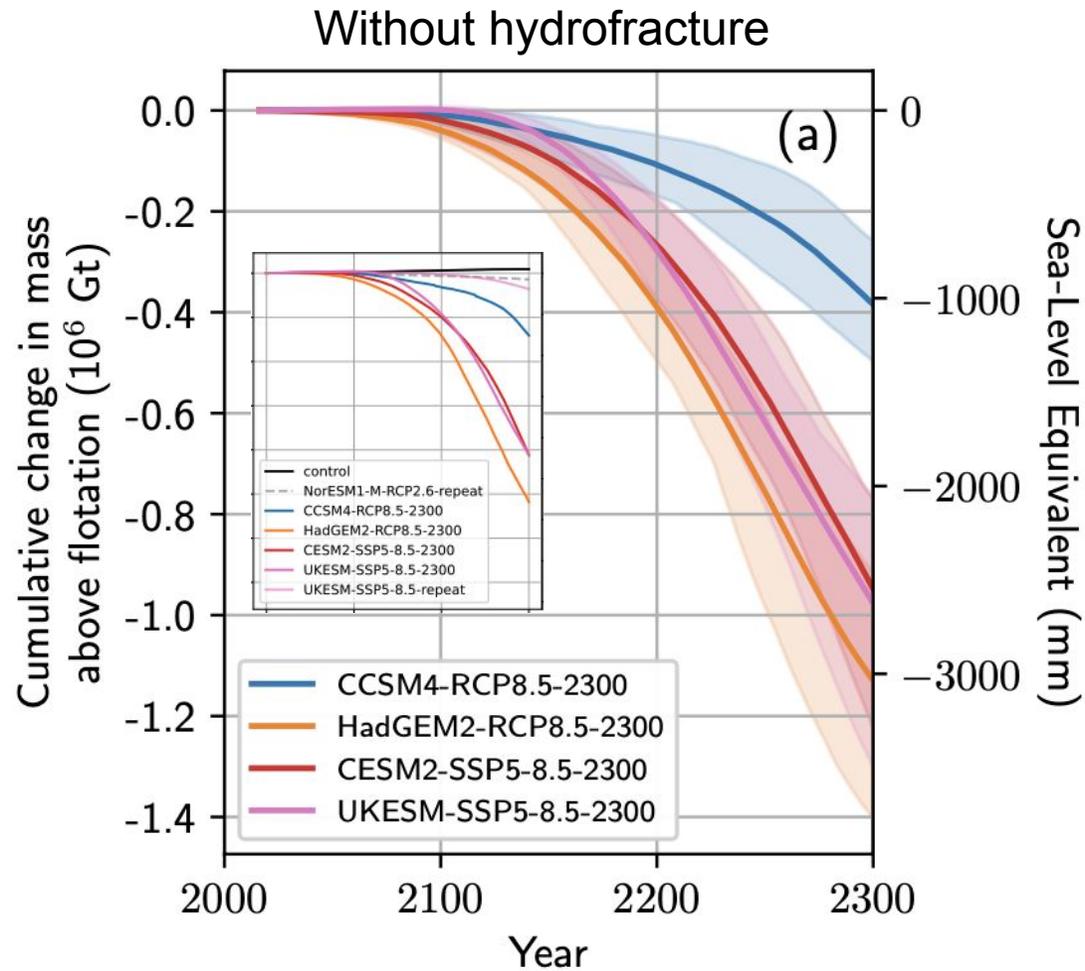
MAI ensemble design

- source of atmosphere & ocean
- sensitivity of ocean-driven basal melting
- plasticity of basal friction
- are ice shelves removed at a surface melt threshold

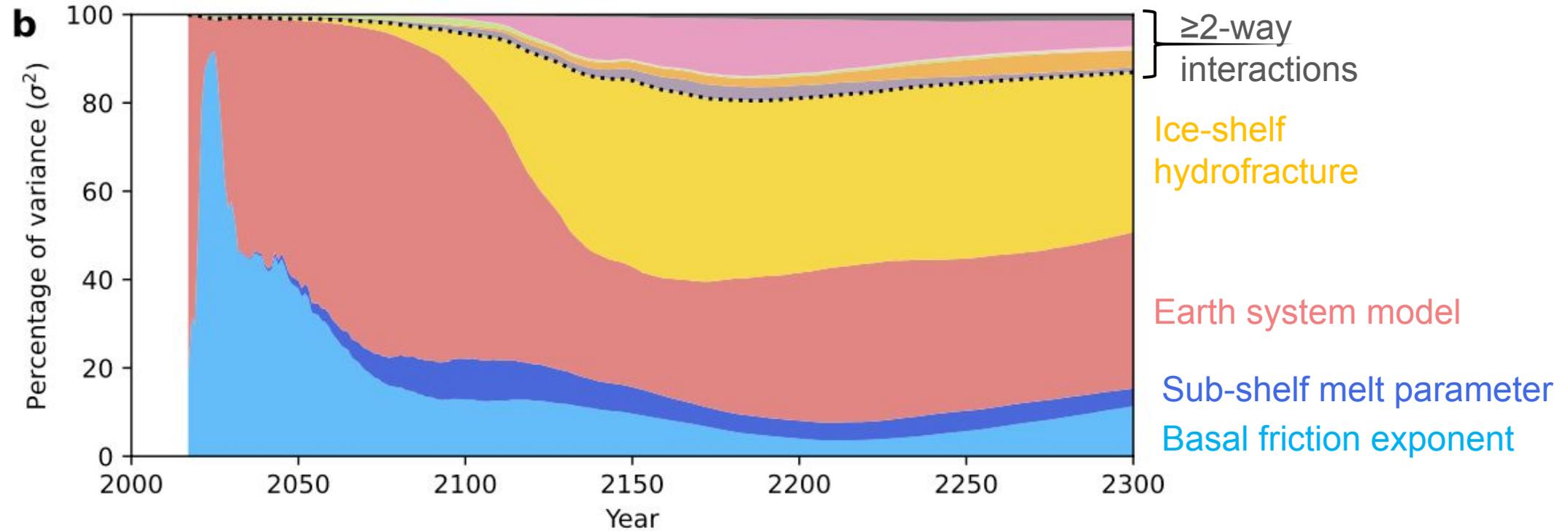
Parameter	Values
Earth System Model	CCSM4, HadGEM2, CESM2, UKESM
γ_0 (m yr ⁻¹)	9 620, 14 500, 21 000 (5 th , 50 th , 95 th percentile)
q	$\frac{1}{3}$, $\frac{1}{5}$, $\frac{1}{10}$
hydrofracture	off, on

- Full factorial experimental design with 72 simulations
- Switch to depth-integrated first-order solver (3x speedup)
- Each simulation run on 8 NVIDIA A100 GPUs (2 nodes) on Perlmutter. Average of 74 node-hrs per run.
- Plenty of processes/properties remain uninvestigated: calving, GIA, ice rheology, subglacial hydrology

MAI ensemble results

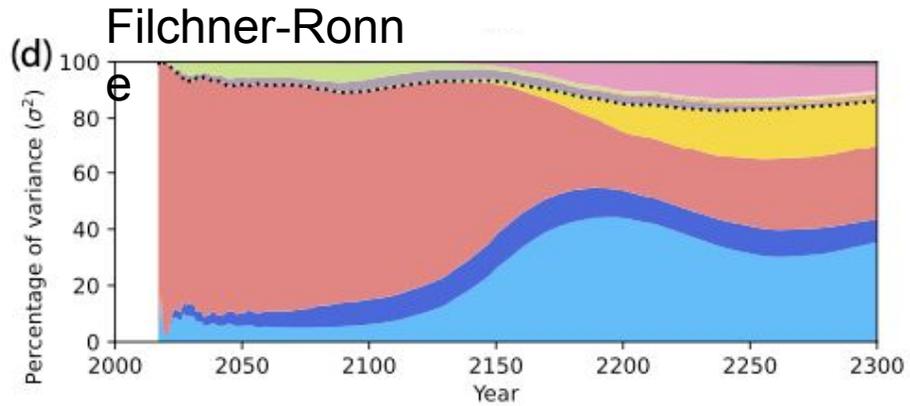


Analysis of variance: whole ice sheet

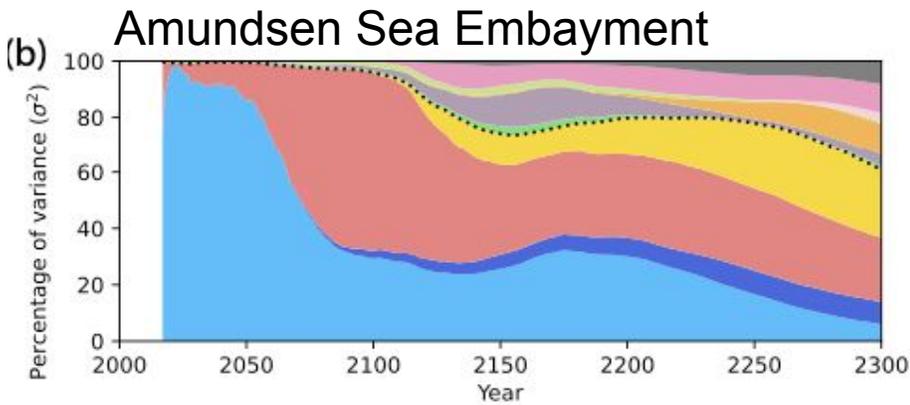


- **Hydrofracture** and **Earth system model** terms are by far the largest contributors to ensemble variance in the long term
- Influence of **basal friction exponent** important for initial decades
- **Sub-shelf melt sensitivity parameter** is never very important
- ≥ 2 -way interaction terms are mostly negligible
 - Earth system model-hydrofracture **interaction term** is the exception

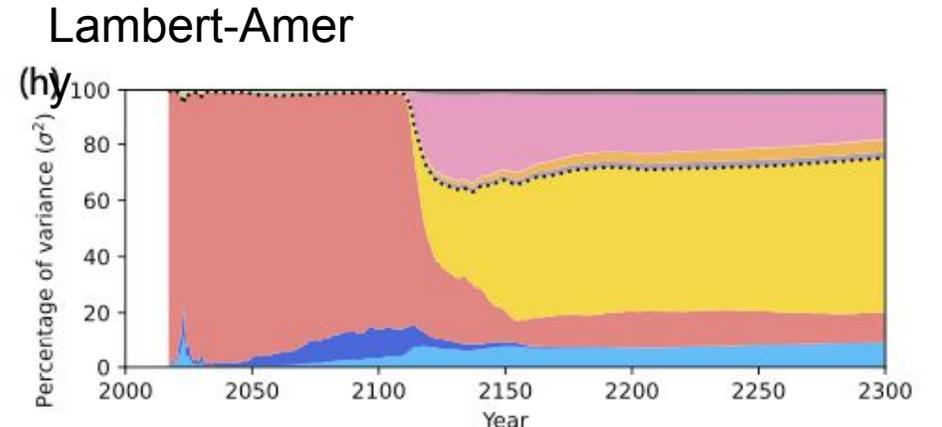
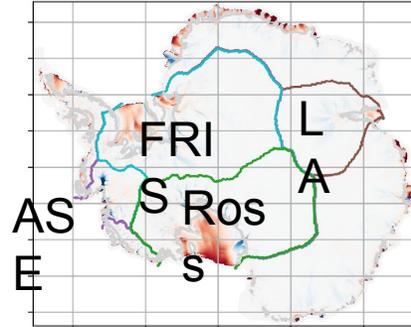
Analysis of variance: different dominant influences between regio



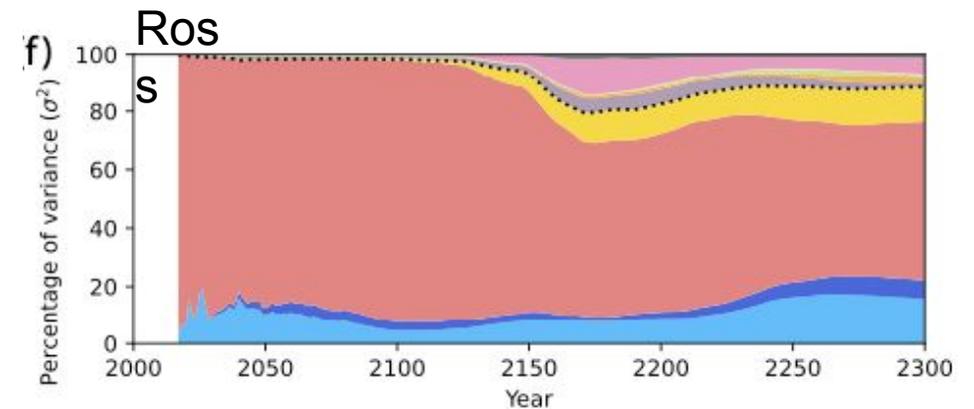
Increasing importance of basal friction exponent as hydrofracture initiates.



Basal friction exponent dominates initially, but ESM and eventually hydrofracture dominate after 2075.

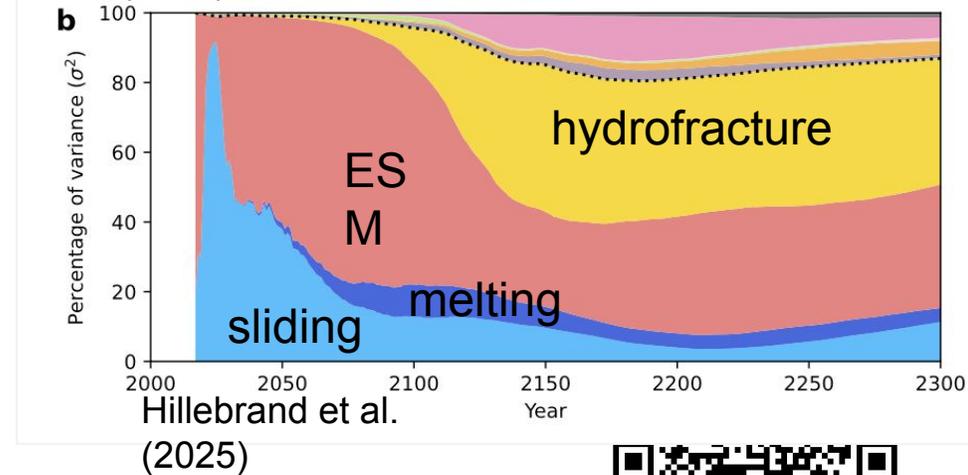
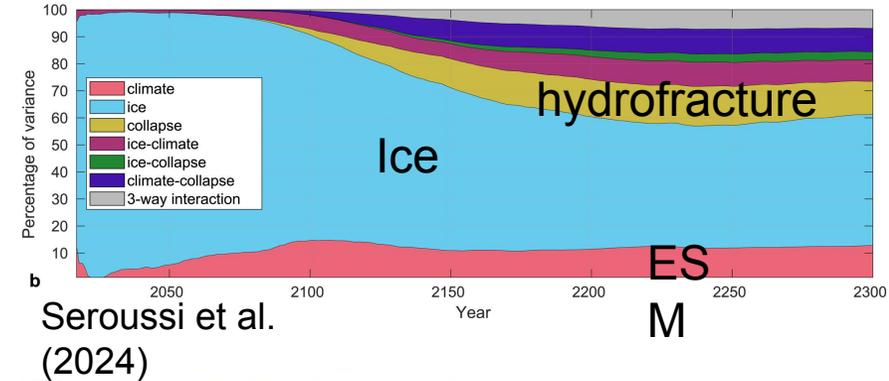


ESM dominates initially. Hydrofracture dominates after 2125.



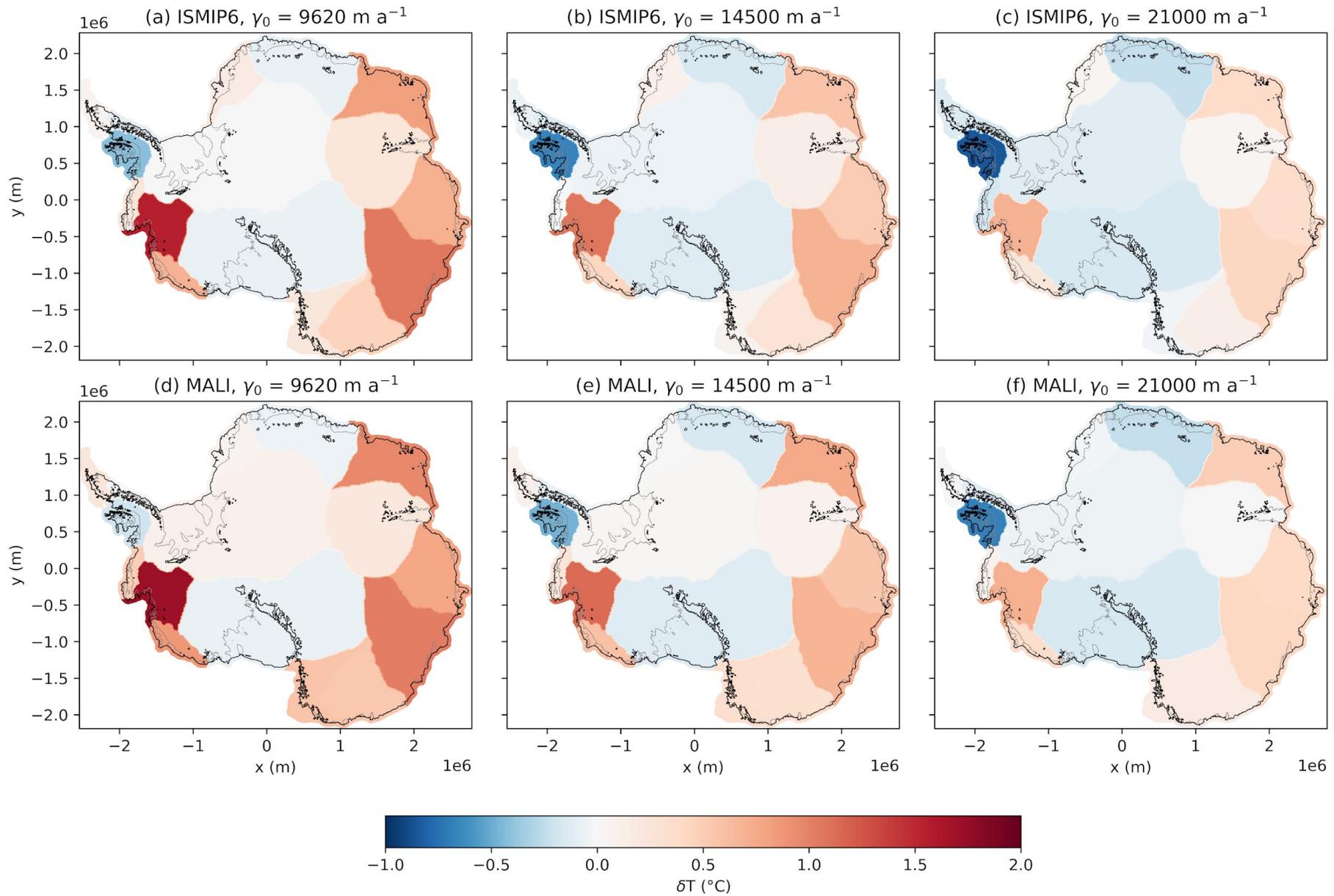
Choice of ESM forcing is always the dominant term.

- Introducing uncertainty in two key ice-sheet model parameters leads to little ice-model variance relative to choice of ESM forcing and presence of hydrofracture
- Ice-model uncertainty more likely coming from structural uncertainty and initial condition uncertainty



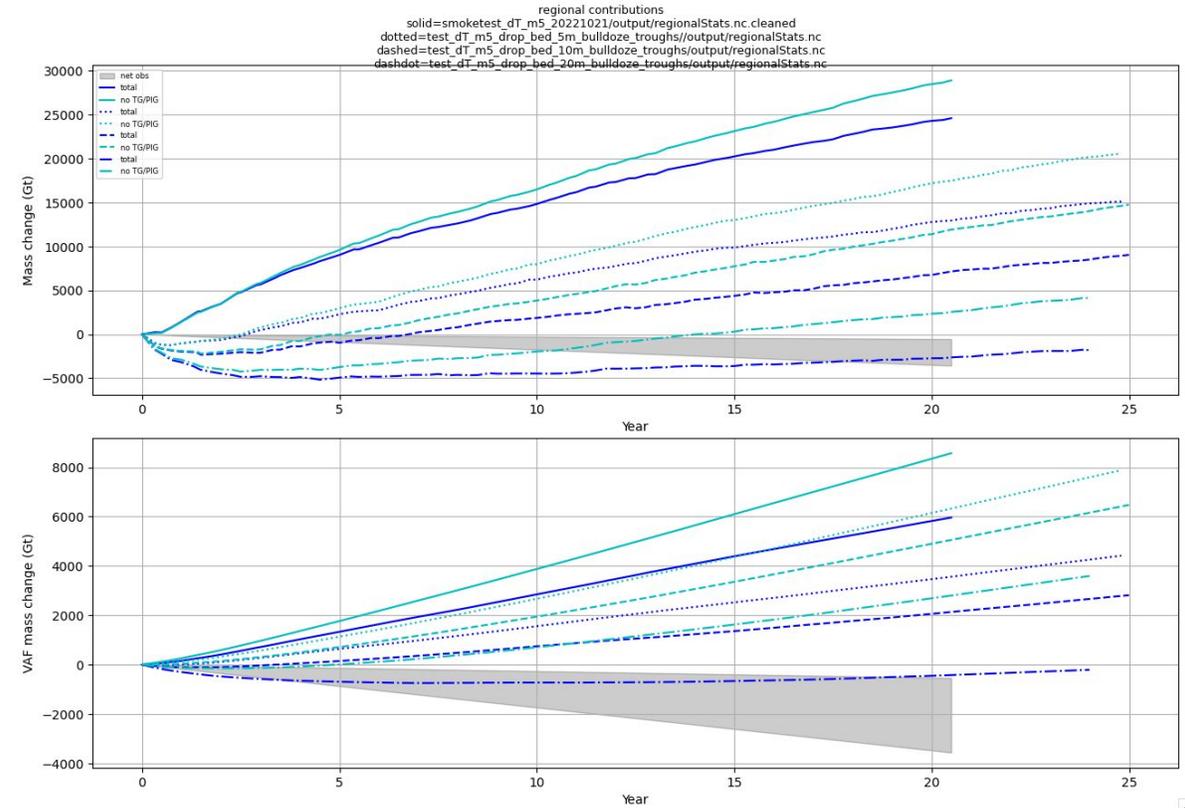
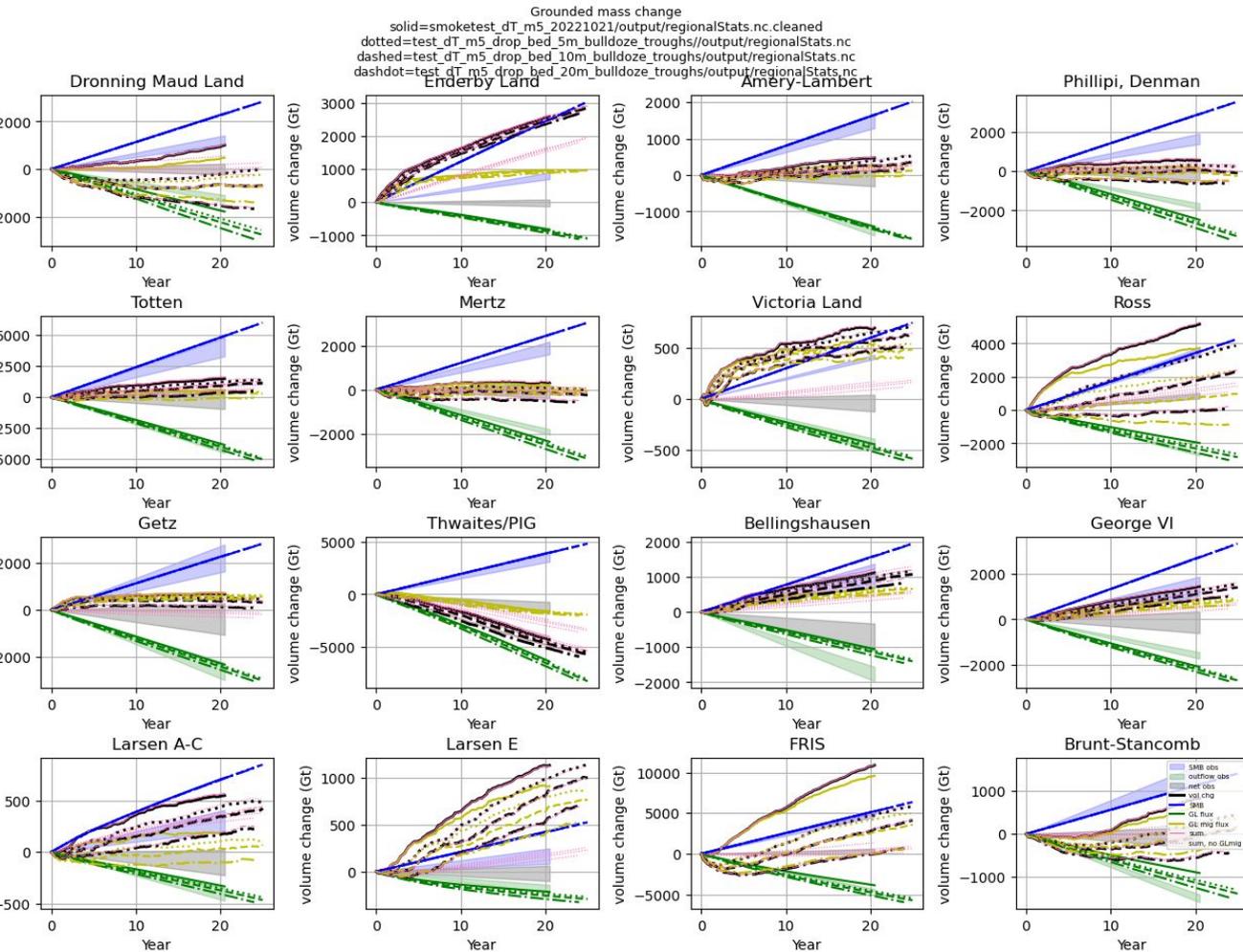
Pre-print





Recalibration of ocean thermal forcing bias correction to match Rignot et al. (2013) melt rates

comparing all dropped bed + trough bulldoze



all runs using dT changes, $q=1/5$
 solid: no bed changes
 dotted: drop 5 m, bulldoze
 dashed: drop 10m, bulldoze
 dash-dot: drop 20m, bulldoze