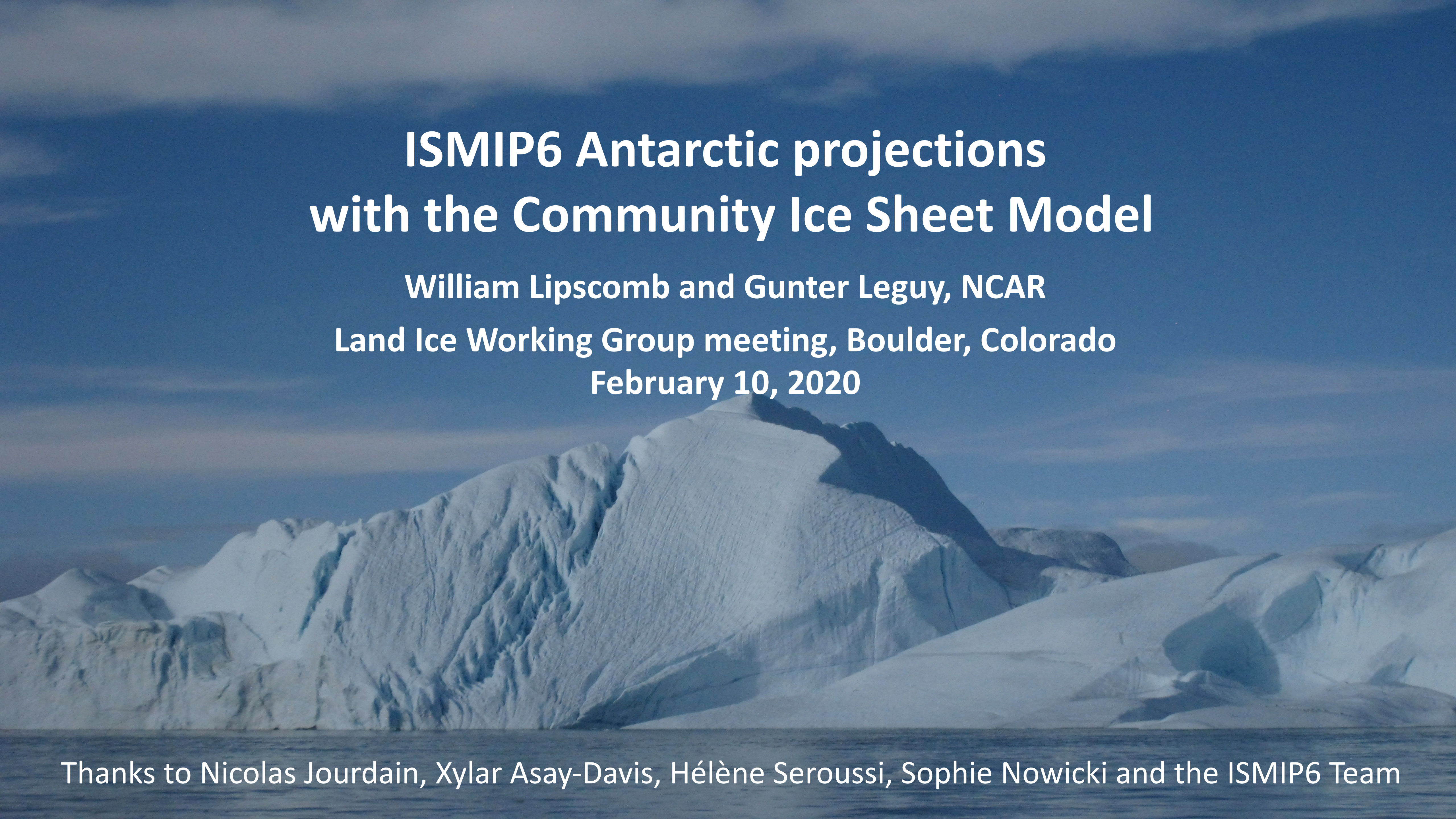

ISMIP6 Antarctic projections with the Community Ice Sheet Model

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Land Ice Working Group meeting, Boulder, Colorado
February 10, 2020

Thanks to Nicolas Jourdain, Xylar Asay-Davis, Hélène Seroussi, Sophie Nowicki and the ISMIP6 Team

ISMIP6 ice sheet projections

- Standalone ice sheet model experiments for Greenland and Antarctica
  - Goal: Provide 21st century sea level projections to inform IPCC AR6
  - Initialize the ice sheet to a modern state, then run through the 21st century with forcing derived from CMIP climate models
  - Run multiple experiments to sample uncertainty in models and forcing
- Antarctic experiment protocols:
  - 12 core experiments, many optional experiments
  - 6 climate models (CCSM4, MIROC, NorESM,…), low and high emission scenarios (RCP/SSP 2.6/8.5), 3 levels of basal melt sensitivity (low, medium, high), and different basal melt parameterizations (standard and open)

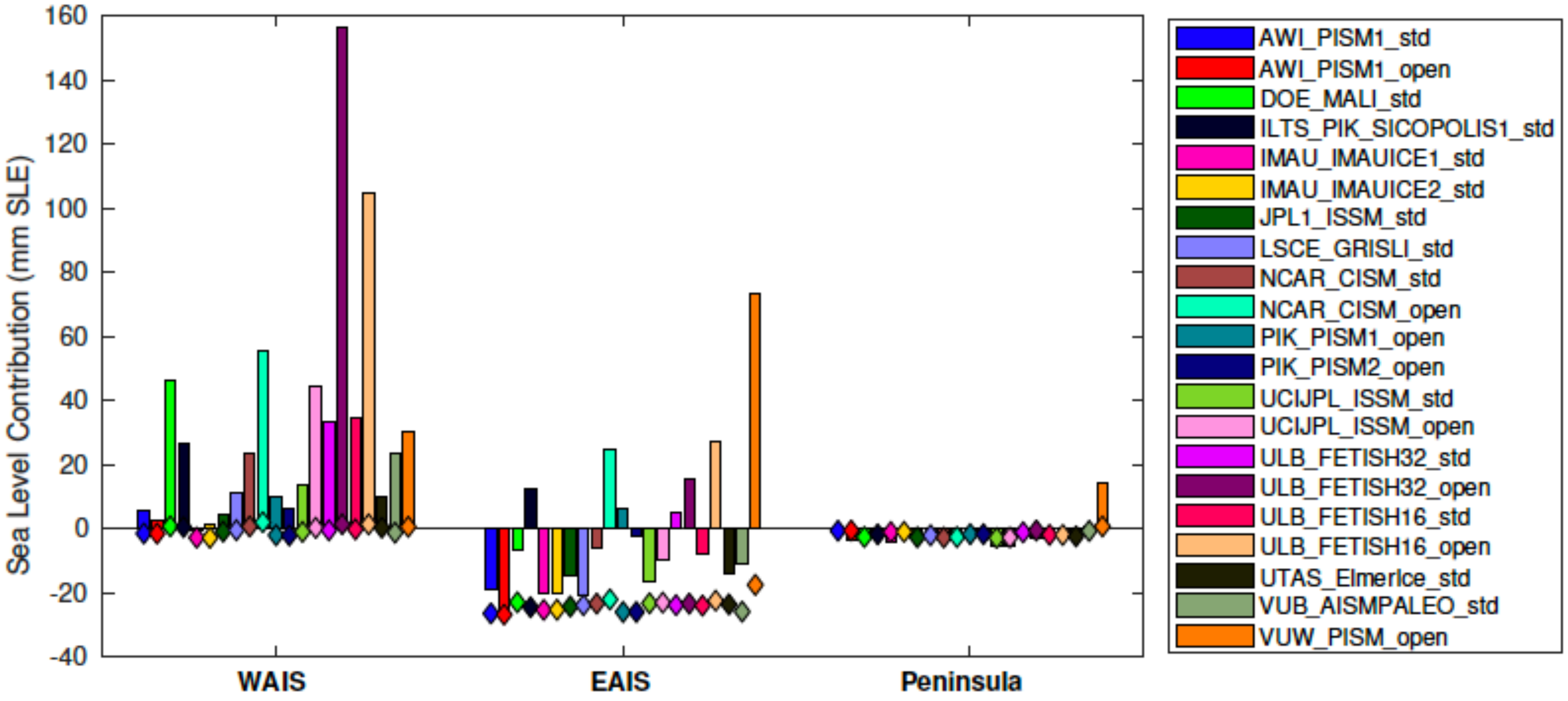
ISMIP6 = Ice Sheet Model Intercomparison Project for CMIP6

http://www.climate-cryosphere.org/wiki/index.php?title=ISMIP6_wiki_page

ISMIP6 Antarctic results

Seroussi et al. (*The Cryosphere*, in review):

- Submissions from 15 ice sheet modeling groups; focus on 2015–2100
- Atmosphere-driven mass gain in East Antarctica (increased snowfall)
- Widely varying ocean-driven mass loss in West Antarctica



Regional change in ice volume above flotation (mm SLE) during 2015–2100 from 21 ice sheet model simulations under medium forcing from the NorESM-1 RCP8.5 scenario, relative to a control scenario (Seroussi et al., in review). Diamonds show SMB changes.

Antarctic sensitivity study

Hypothesis:

- Ocean warming that is projected to occur before 2100 under high-emission scenarios could drive long-term retreat of the West Antarctic Ice Sheet, with substantial sea level rise after 2100.

Method:

- Using the ISMIP6 framework and a single model (the Community Ice Sheet Model), determine the range of multi-century (500-year) Antarctic ice sheet retreat under a variety of basal melting schemes and ocean-only forcing scenarios.
- Atmospheric forcing (increased SMB) is not included—not because it is unimportant but because it is better constrained than ocean forcing.

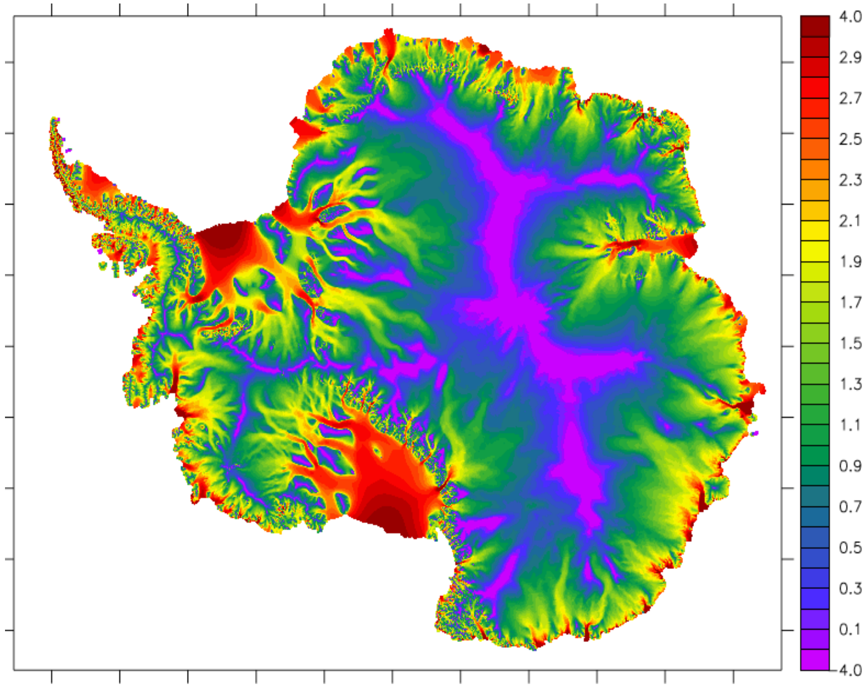
Limitations:

- Uncertainties in ocean bathymetry and future forcing, highly parameterized basal melt rates, lack of ice sheet–ocean coupling, etc.

Community Ice Sheet Model (CISM)

CISM version 2.1

- Released in 2018 with CESM 2.0 (see Lipscomb et al. 2019)
- Participated in initMIP-Greenland (Goelzer et al. 2018) and, initMIP-Antarctica (Seroussi et al. 2019) prior to ISMIP6
- For Antarctic spin-up:
  - 4 km uniform grid, bed topography from BedMachine (Morlighem et al., 2019)
  - Depth-integrated higher-order solver (Goldberg, 2011)
  - Basal sliding law based on Schoof (2005)
  - No-advance calving law
  - Grounding-line parameterizations for basal shear stress and basal melt rate
  - No “fast” physics (e.g., hydrofracture and cliff failure)
  - **Sub-ice-shelf melting based on ISMIP6**



CISM2.1: Simulated surface speed (m/yr, log scale) for the Antarctic ice sheet from a spin-up for initMIP-Antarctica

ISMIP6 standard basal melt parameterizations

Standard experiments use a **nonlocal quadratic parameterization** suggested by Favier et al. (2019) based on comparison with a coupled ice–ocean model:

$$m(x,y) = \gamma_0 \times \left(\frac{\rho_{sw} c_{pw}}{\rho_i L_f}\right) \times \left[TF(x,y,z_{\mathrm{draft}}) + \delta T_{\mathrm{basin}}\right] \times \left|\langle TF_{\mathrm{draft} \in \mathrm{basin}} \rangle + \delta T_{\mathrm{basin}}\right|$$

m = basal melt rate

$TF(x,y,z_{\mathrm{draft}})$ = thermal forcing at ice−ocean interface

$\langle TF \rangle$ = basin mean thermal forcing

γ_0 = empirical melt coefficient

$\delta T_{\mathrm{basin}}$ = basin−dependent temperature correction (16 basins)

- **Thermal forcing** (TF) from observations (Jourdain et al., *TC*, in review) is extrapolated into sub-shelf cavities, and then interpolated to the ice shelf base at runtime.
- Empirical coefficients are tuned to match basin-mean melt estimated from observations.
- There is also a **local parameterization** in which $m(x,y) \sim |TF(x,y,z_{\mathrm{draft}}) + \delta T_{\mathrm{basin}}|^2$

Slope-based basal melt parameterization

Open experiments use the same thermal forcing data, but can use any basal melt scheme.

For CISM, we modify the standard melt scheme to **focus melting near the grounding line**:

$$m(x,y) = \gamma_0 \times \left(\frac{\rho_{sw} c_{pw}}{\rho_i L_f}\right) \times [TF(x,y,z_{\mathrm{draft}}) + \delta T_{\mathrm{basin}}] \times |\langle TF_{\mathrm{draft} \in \mathrm{basin}} \rangle + \delta T_{\mathrm{basin}}|$$

$$\boldsymbol{m'(x,y) = m(x,y) \times sin(\theta)}$$

θ is the angle of the ice shelf base with the horizontal

γ_0 is recalibrated to match Antarctic-mean melt rates

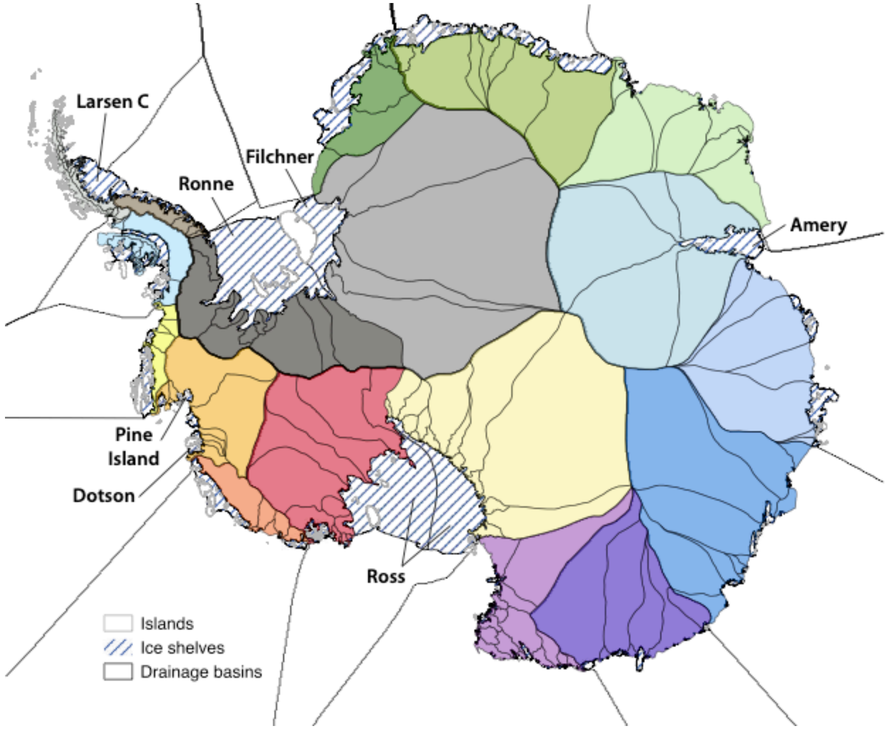
- Favier et al. (2019) noted that melt rates from the standard scheme tend to be too large near the calving front and too small near the grounding line.
- Jenkins et al. (2018) suggested that the rate of entrainment of warm ambient water into the sub-shelf boundary current is proportional to $\sin(\theta)$.

CISM spin-up with inversion

Goal: Obtain an ice sheet in steady state with modern forcing (SMB from RACMO, thermal forcing from ISMIP6 climatology), with ice extent and thickness close to observed values.

Procedure: Spin up the model for 20 ky, nudging toward the observed thickness (similar to Pollard & DeConto 2012).

- Adjust basal friction parameters beneath grounded ice (one value per grid cell)
- Adjust the thermal forcing coefficient δT in each of 16 basins (one value per basin)
- Six spin-ups: one for each of *three parameterizations* and *two calibrations* (see Jourdain et al., in review):
  - Parameterizations: **Local, nonlocal, nonlocal-slope**
  - Calibrations: **Mean-Antarctic** (lower γ_0) and **PIGL** (greater γ_0 for high melt near Pine Island grounding line)

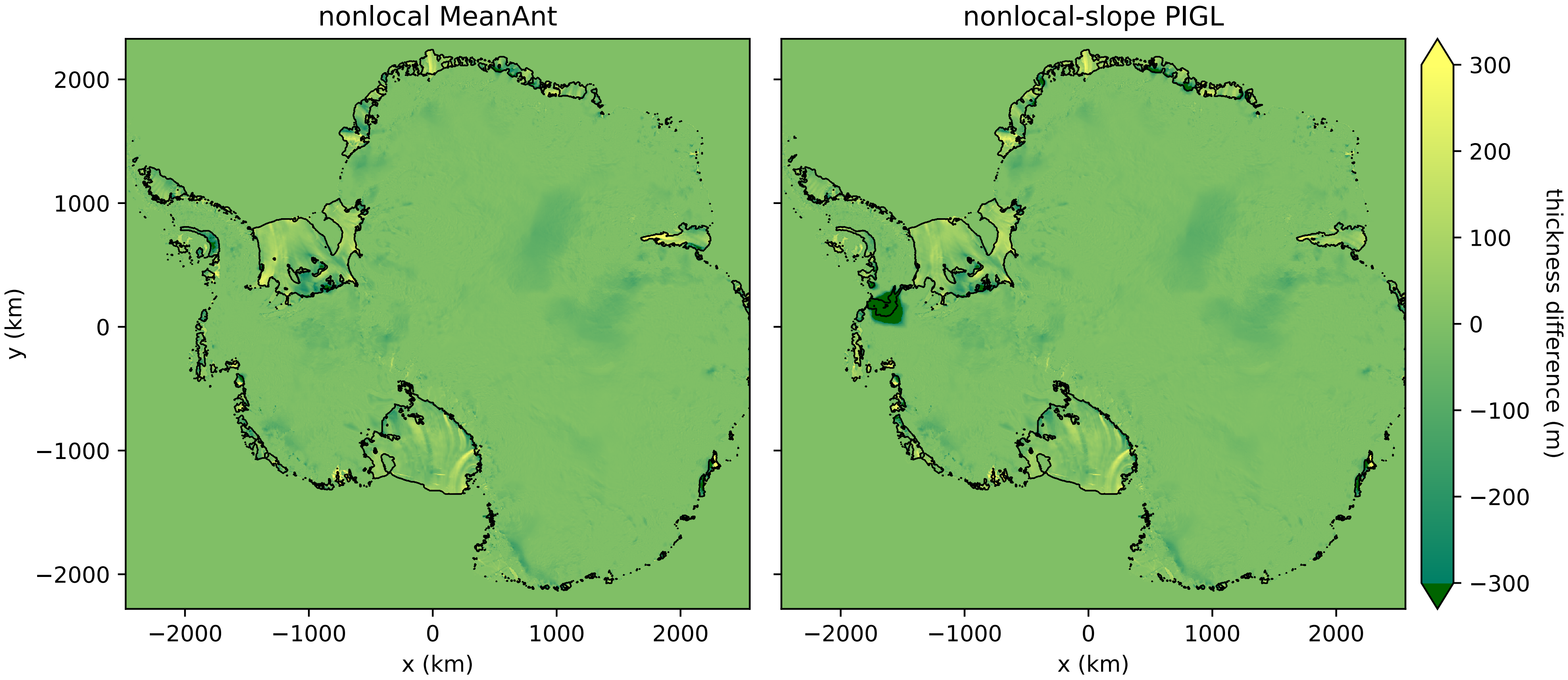


Antarctic drainage basins as defined by Mouginot et al. (2017) and Rignot et al. (2019). Figure from Jourdain et al. (*TC*, in review).

Spin-up results

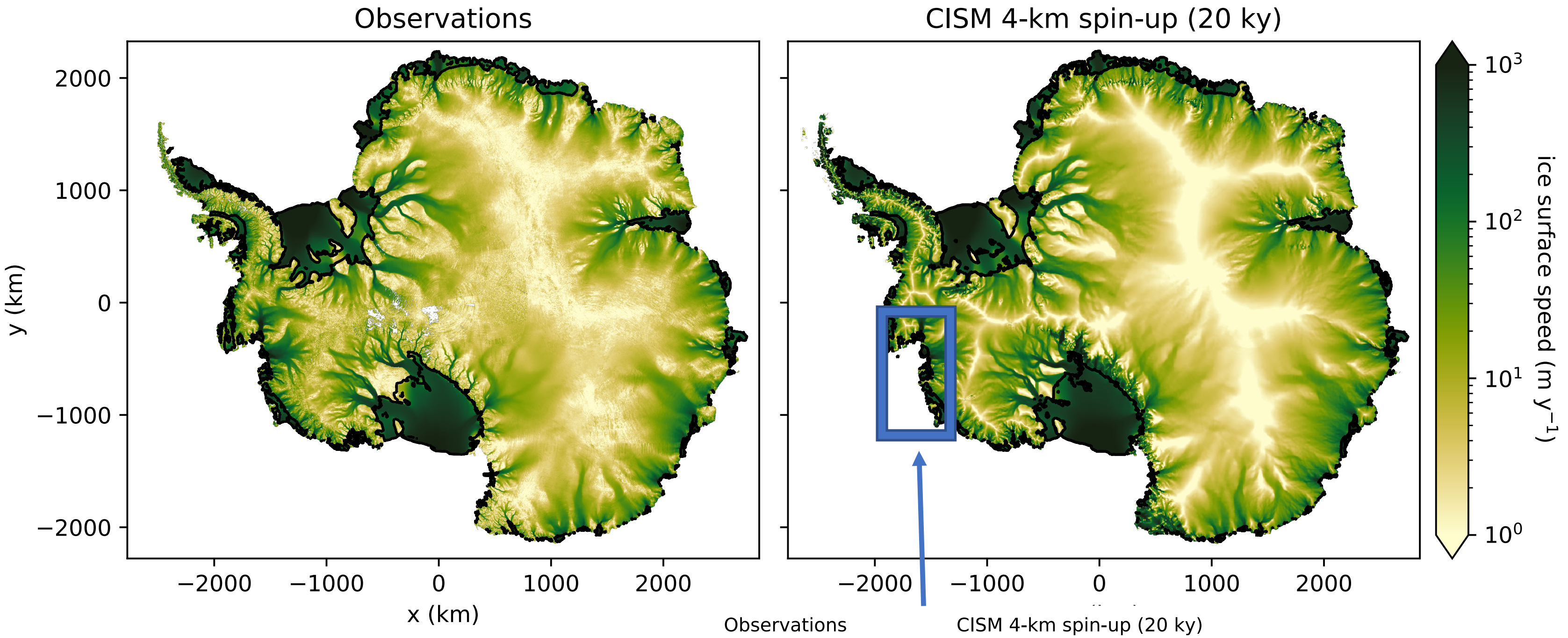
- Good agreement with observed ice thickness over most of the grounded ice sheet
- Some grounding lines are too far advanced (e.g., Pine Island) or retreated (e.g., eastern Thwaites), with associated thickness biases.
- Spun-up state (including biases) is fairly consistent across melt parameterizations and calibrations.

Modeled minus observed ice thickness (m) at the end of two 20 ky CISM spin-ups at 4-km resolution: (left) nonlocal-MeanAnt and (right) nonlocal-slope-PIGL. Black contours show the extent of floating ice shelves.

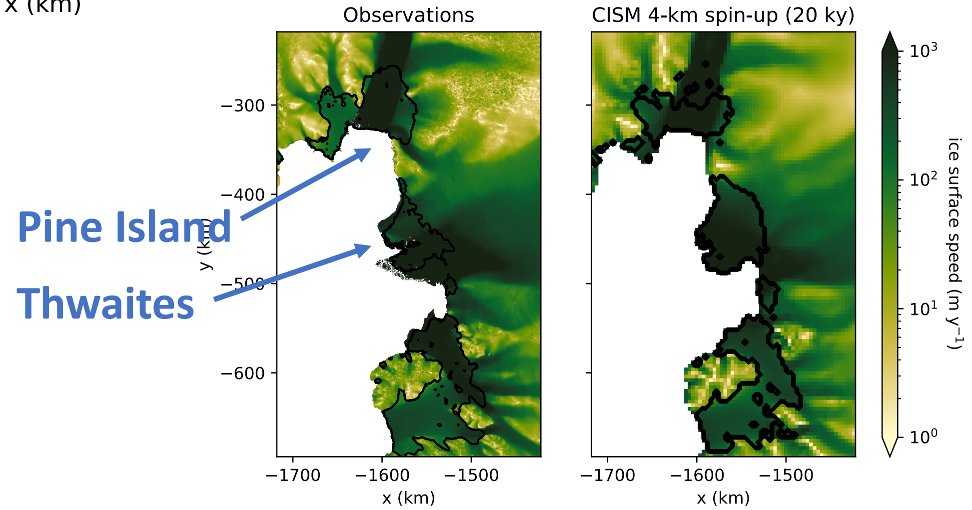


Spin-up results

- Good agreement with observed surface ice speeds
- Some local errors: e.g., the east–west gradient in Thwaites flow is too weak



Surface ice speed (m/y, log scale) from (left) observations (Rignot et al., 2011) and (right) a 20 ky CISM spin-up (4-km grid, nonlocal-MeanAnt melt scheme).
Top: Antarctic ice sheet.
Bottom: Amundsen Sea Embayment.

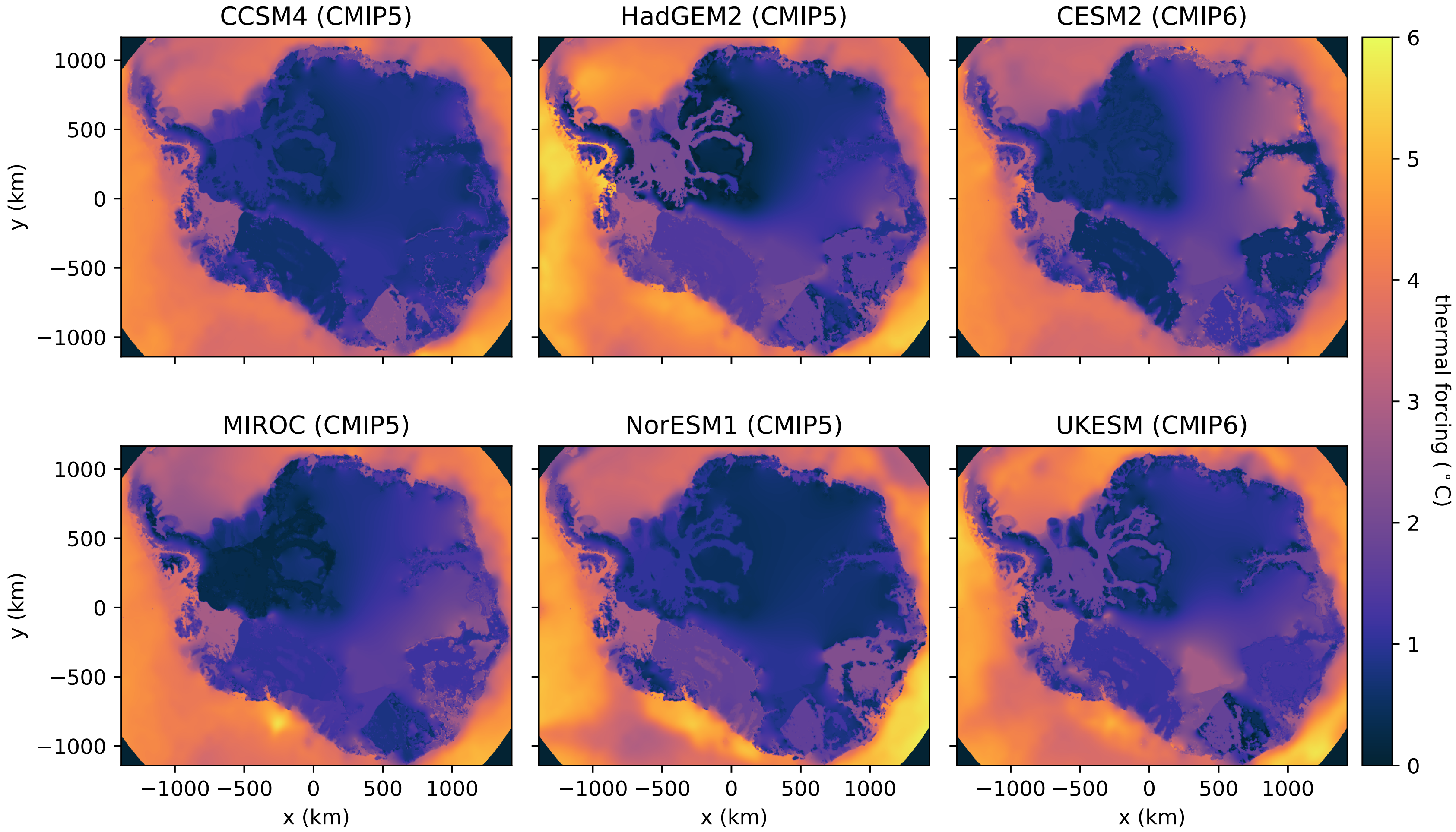


Pine Island

Thwaites

Ocean forcing experiments

From each spin-up, run 500-year experiments with ocean thermal forcing from 6 Earth system models (4 from CMIP5, RCP8.5; 2 from CMIP6, ssp5-85). After 2100, cycle repeatedly through 2081–2100.



Ocean thermal forcing (◦C) at z = −510 m, averaged over 2081–2100, for the four CMIP5 models and two CMIP6 models used in ocean-forced Antarctic projection experiments.

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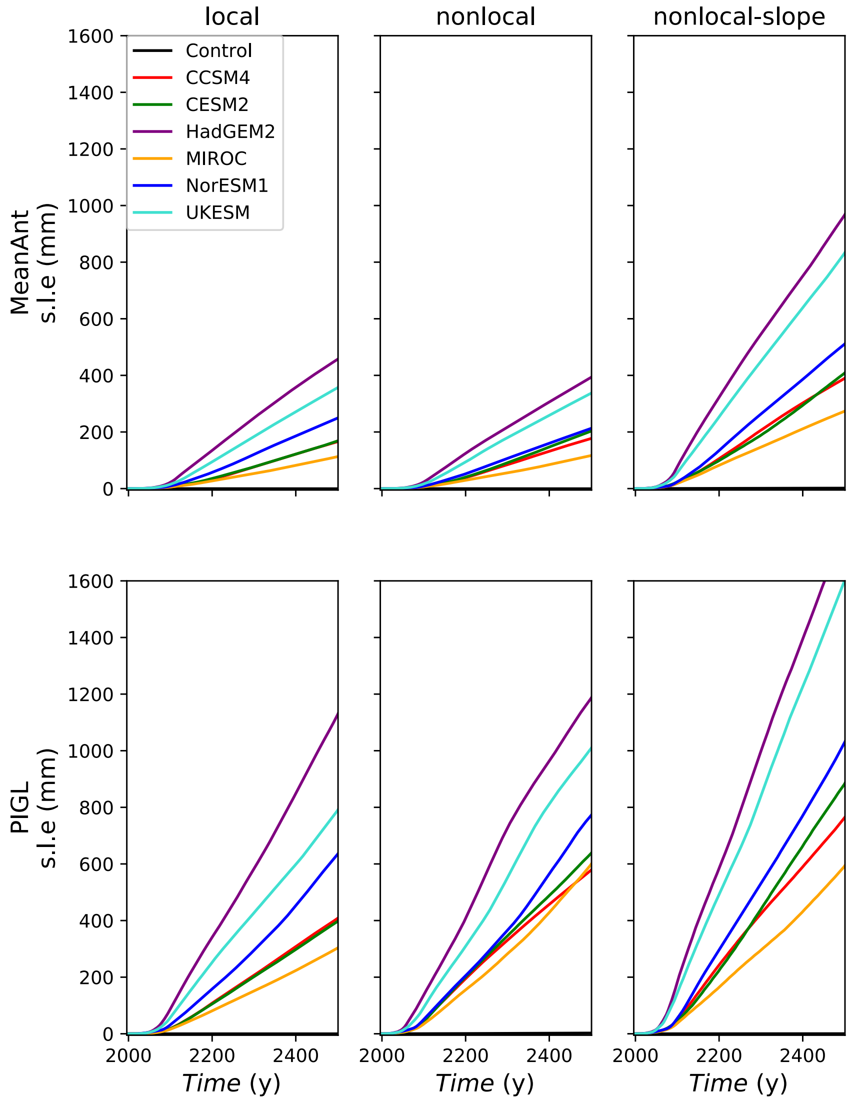
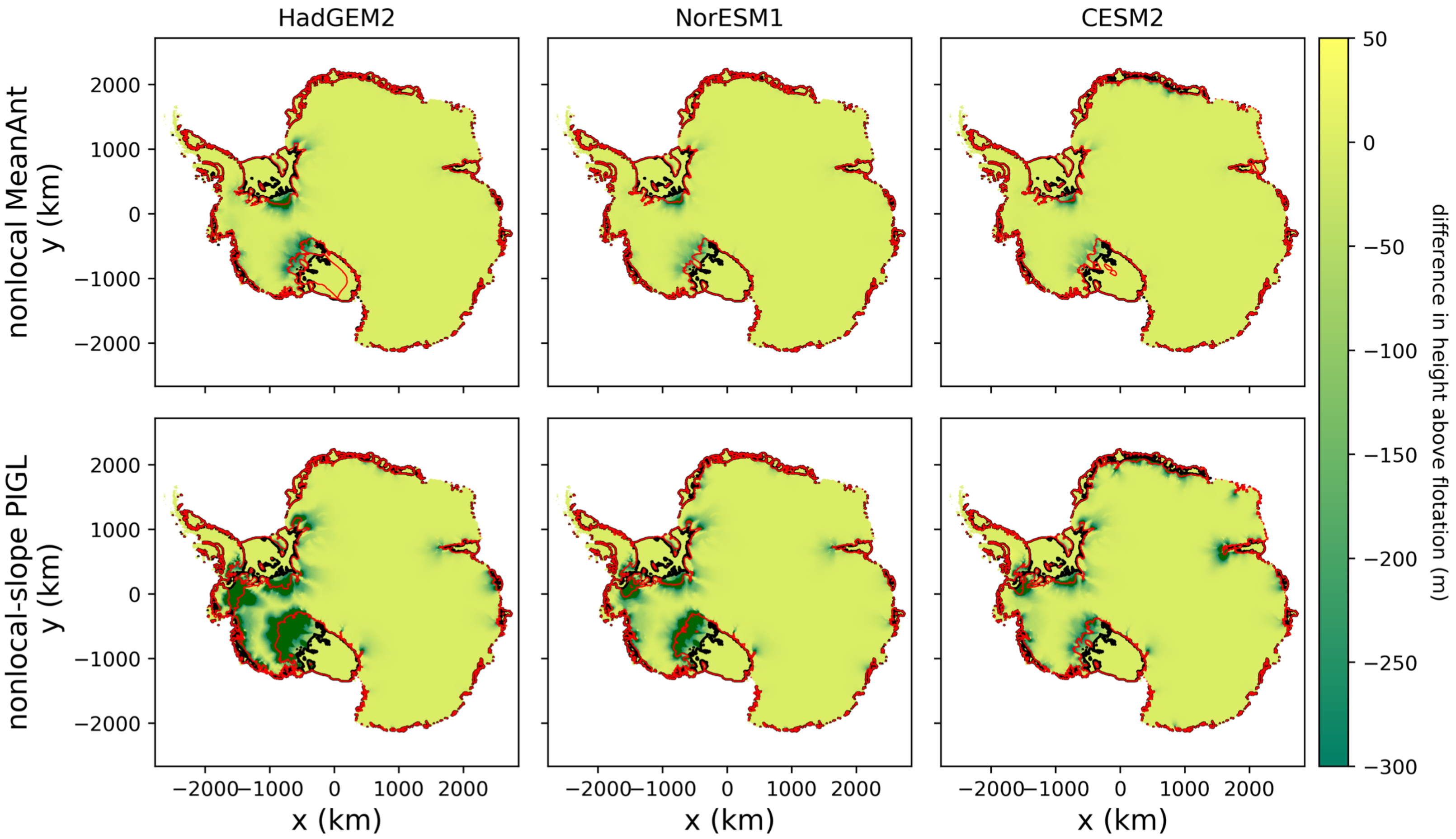
Results: Sea level contribution

- The figure shows the sea-level contribution over 500 years from 36 experiments (6 forcing scenarios for each of 6 basal melt schemes).
- Sea-level rise starts slowly, then accelerates after 2100, with no leveling off by 2500.
- Cumulative SLR ranges from ~0.1 m to 1.8 m, depending on the melt scheme and forcing.
- Melt scheme sensitivity:
  - More SLR for nonlocal-slope (right column) than for standard local and nonlocal.
  - More SLR for PIGL (bottom row) than MeanAnt
- Ocean forcing sensitivity
  - Greatest SLR for HadGEM2, followed by UKESM, NorESM1, CESM2/CCSM4, and MIROC



Results: Ice sheet thinning

- Most loss of ice thickness above flotation is in three West Antarctic basins: Filchner-Ronne, Ross (Siple Coast), and Amundsen Sea (especially Thwaites). All are prone to marine ice-sheet instability (MISI).
- Consistent with earlier results (e.g., Cornford et al. (2015); Pollard & DeConto (2016); Larour et al. (2019))



Change in ice thickness above flotation (m) during 500-year experiments for two basal melt schemes: nonlocal MeanAnt (top row) and nonlocal-slope PIGL (bottom row). Results are shown for ocean forcing from three ESMs: HadGEM2 (left), NorESM1 (center), and CESM2 (right).

Conclusions

- Using CISM, we obtained a stable Antarctic spun-up state, in good agreement with observed thickness and velocity, by inverting for basal parameters.
- In 500-year experiments, most of the sea-level rise takes place after 2100.
- Most retreat takes place in West Antarctic basins prone to marine ice-sheet instability.
- The locations and magnitude of mass loss (~10 cm to nearly 2 m SLE) are sensitive to the melt parameterization and calibration and to the ocean forcing.
- Caveats:
  - The model spin-up procedure may delay the onset of retreat.
  - At 4 km resolution, grounding lines may be under-resolved.
  - Basal melt is parameterized and is missing important physics, including ocean coupling.

Future work

Near-term:

- Improve the initial state of key glaciers (e.g., Thwaites grounding line is too far retreated).
- Extend the forcing experiments to 1000 years.
- Repeat the experiments at 2-km grid resolution.

Long-term:

- Develop more realistic basal melt schemes, validated with high-resolution, coupled ice–ocean models.
  - Parameterizations with more detailed physics (e.g., bed topography, Coriolis)
  - Reduced-physics ocean models
  - Statistical emulators
- Implement ice sheet–ocean coupling in Earth system models.
  - First step in CESM: Force CISM with thermal forcing derived from POP or MOM6.

Extra slides

ISMIP6 projections

- **Spin up** the ice sheet model to a modern state (c. 1990)
- **Control run** to 2100
- **Historical run**, 1995 – 2014
- **Projection runs**, 2015 – 2100
  - Anomalies of surface mass balance and surface temperature from CMIP5 GCMs
  - Thermal forcing (TF) from observed ocean climatology plus GCM anomalies
    - Convert thermal forcing to sub-ice-shelf melt rates

deltaT basin corrections

- This figure shows values of the thermal forcing correction in each of 16 basins for each of 6 spin-ups.
- In most basins, the corrections are modest, < 1° in either direction.
- But note large negative corrections for the Amundsen Sea basin, especially for the **PIGL** runs.