Toward Coupled Modeling of the Antarctic Ice Sheet

William Lipscomb
National Center for Atmospheric Research

Matthew Hoffman
Los Alamos National Laboratory

Robin Smith
NCAS, University of Reading

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Outline

- Coupled ice sheets in Earth system models
  - Community Earth System Model (CESM)
  - UK Earth System Model (UKESM)
  - Energy Exascale Earth System Model (E3SM)

- Outstanding questions and modeling challenges

Ice sheets in Earth system models

For many years, **global climate models lacked dynamic ice sheets**. Ice sheets were treated as big bright rocks.

- Ice sheets were thought to be too sluggish to change on human time scales.
- Dynamic ice sheets break the assumption of fixed boundaries between land, atmosphere and ocean.

Around 2010, Earth system models (ESMs) began including processes that were missing in traditional climate models.

- Physical climate model (atmosphere, land, ocean, sea ice) + biosphere + chemistry + **ice sheets**

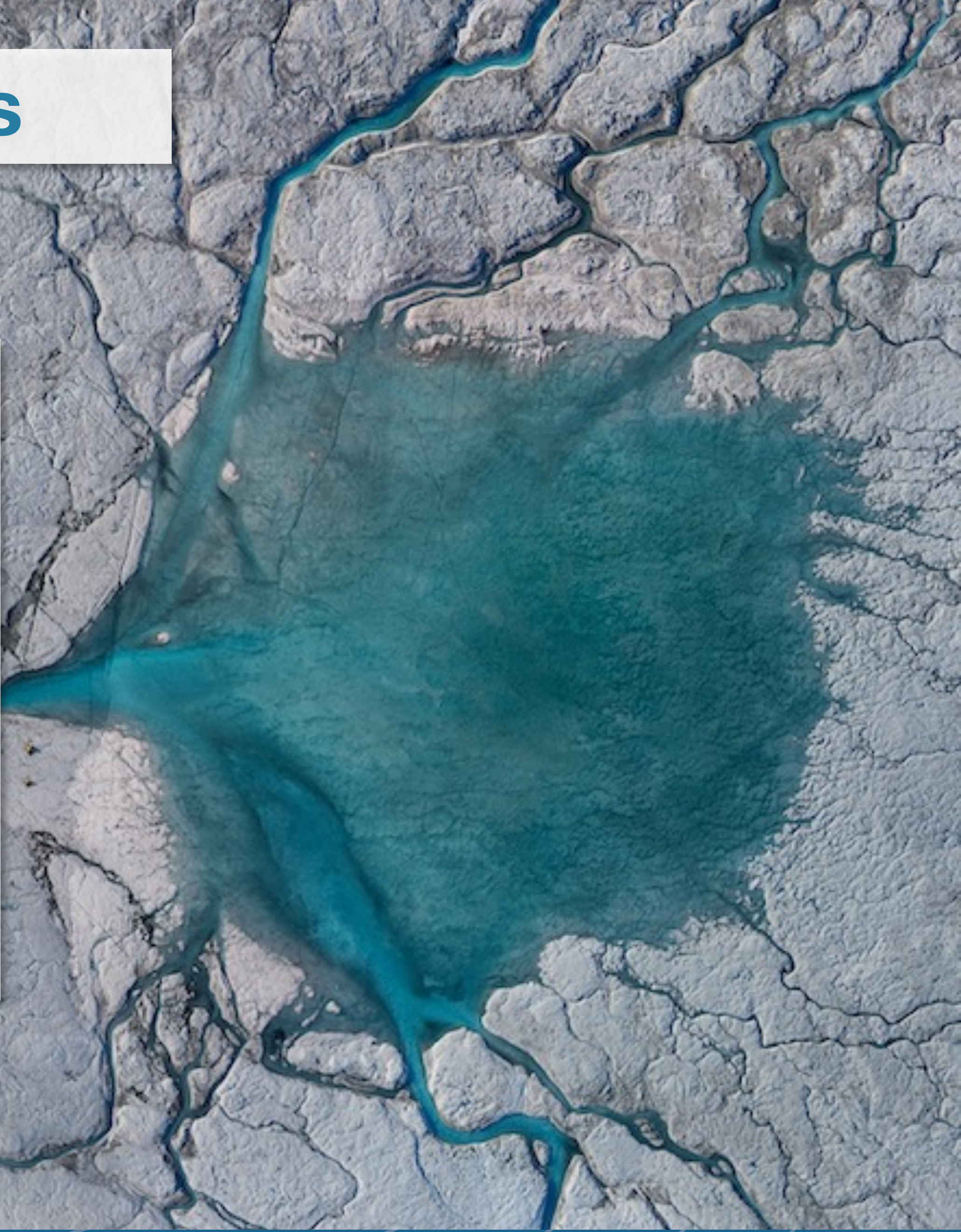


Image: Greenland ice sheet/NASA

Ice sheets in the Community Earth System Model

CESM (2010+) was one of the first complex ESMs to include dynamic ice sheets.

- The **Community Land Model (CLM)** computes the **surface mass balance** (snowfall and melting/runoff) for ice sheets, using sub-grid elevation tiles to compensate for coarse resolution (~50–100 km).
    - This approach avoids duplication of snow physics, reduces computational cost, and allows hourly coupling of the ice/snow surface to the atmosphere.
- The **coupler** remaps the surface mass balance to a finer ice sheet grid (~4 km).
- The **Community Ice Sheet Model (CISM)** computes ice flow.
    - Suite of approximate Stokes solvers (default is depth-integrated higher-order)
    - 3D ice thickness and temperature evolution
    - Parameterizations for basal sliding, iceberg calving, sub-shelf melting, etc.

Ice sheets in CESM2

CESM2 (2018+) supports **interactive coupling** between the **Greenland Ice Sheet** and the land and atmosphere.

Land -> Ice sheet

(10 classes + bare land)

- Surface mass balance
- Surface elevation
- Surface temperature

Ice sheet -> Land

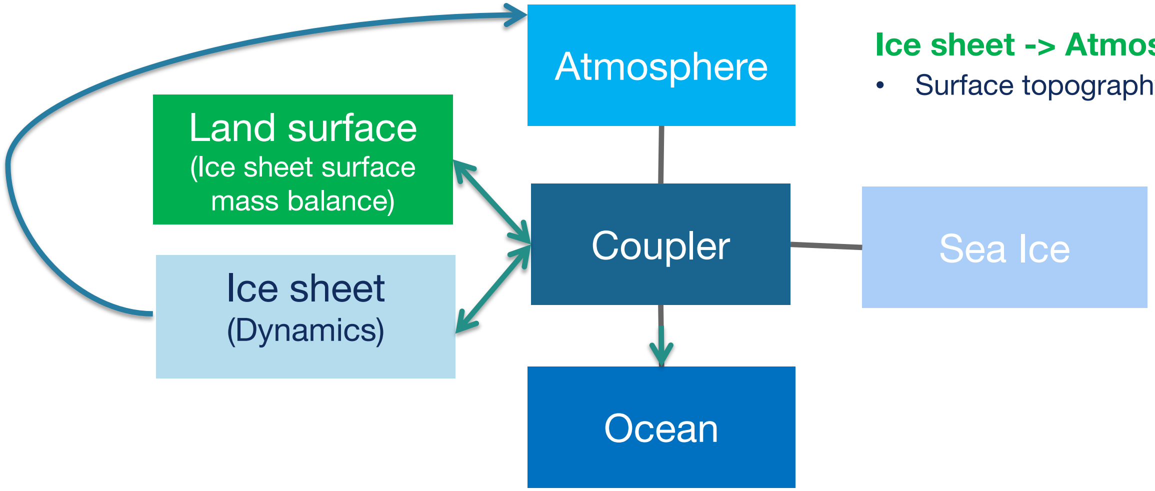
- Ice extent
- Ice surface elevation

Ice sheet -> Ocean

- Solid and liquid fluxes

Ice sheet -> Atmosphere (offline)

- Surface topography



- Ice sheets are fixed by default.
- Optionally, ice sheets and the land surface can co-evolve with **two-way coupling.**
  - The land model computes the surface mass balance (snowfall/melting) and passes it to CISM.
  - CISM returns the new ice sheet area and elevation.
  - Land types are dynamic (glacier ⇔ vegetated); important for albedo feedbacks.

Coupled Greenland Ice Sheet evolution in CESM: SSP5-8.5

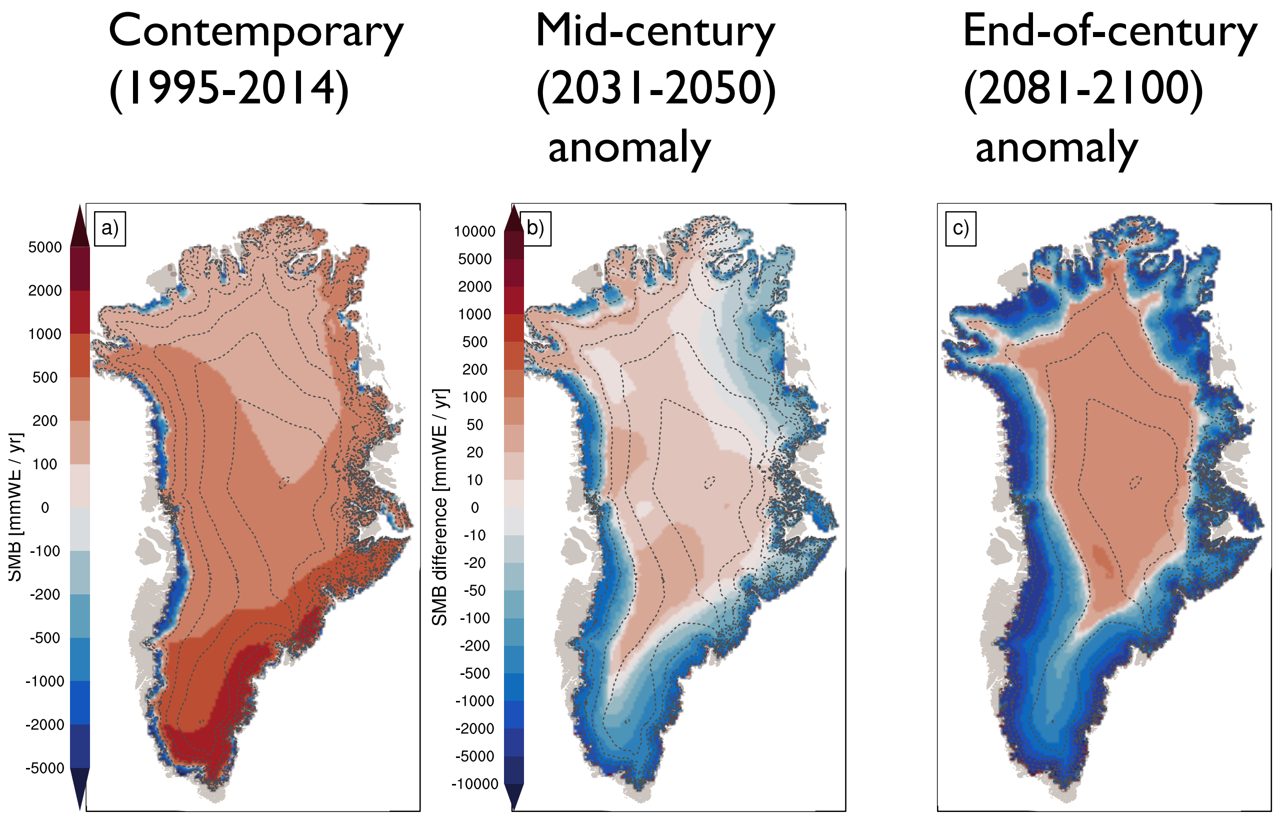
ISMIP6 runs with an **interactive GrIS:**

Climate evolution:

- Global CO_2 rises to ~**1100 ppm**
- Global surface air temperature rises by **5.4°C**

GrIS evolution:

- Ice thins near margins with increased melting
- Modest increase in interior snowfall
- **Global mean SLR of 110 mm by 2100**
- Small effect on ocean circulation, AMOC



Increased melting of the **Greenland Ice Sheet** in CESM2 (Muntjewerf et al., 2020) under the ssp5-85 warming scenario. The expanding melt region is **blue**.

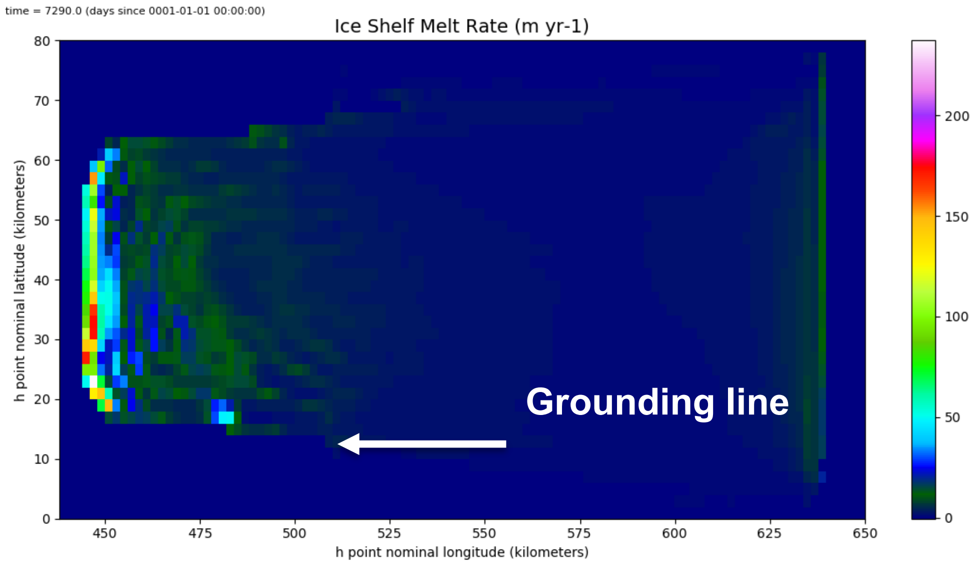
Antarctic coupling

CESM3 will support fully coupled climate – ice sheet simulations with **Greenland, Antarctica, and/or paleo ice sheets.**

- We have added support for running **Antarctica** out-of-the-box.
- We have also added support for running **multiple ice sheets** in a single simulation. This is the first out-of-the-box support for a CESM component with multiple grids, each with its own physics parameters.
- Testing is under way

The **MOM6** ocean model (replacing POP) allows ocean circulation beneath ice shelves.

- Compute sub-shelf melting based on ice draft and ocean temperate/salinity



Sub-ice-shelf melt rate (m/yr) for an idealized experiment with CISM coupled to the MOM6 ocean model (G. Marques).

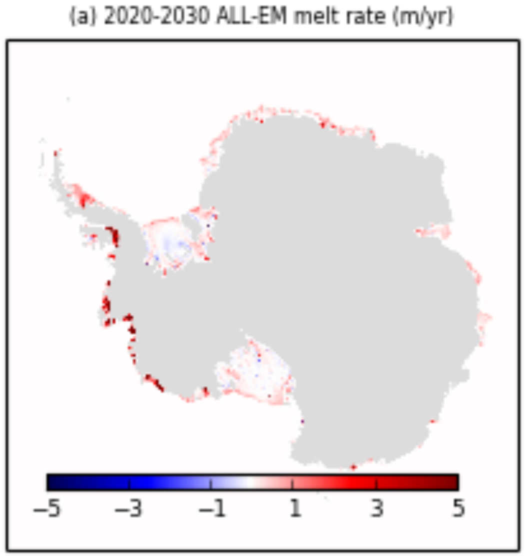
Antarctic coupling in UKESM

- First interactive coupling of a dynamic ice sheet model (both Antarctica and Greenland) to ocean and atmosphere models in an IPCC-class ESM
- Two-way coupling between the NEMO ocean model and the BISICLES ice sheet model, with sub-shelf cavities
- SSP1-1.9 and SSP5-8.5 forcing applied till 2100+
- SSP5-8.5: Warm water intrusions drive increased melting of the Ross and Filchner ice shelves
- Modest retreat of grounded ice; increased snowfall dominates the sea-level signal

References:

- Smith et al., *J. Adv. Modeling Earth Systems,* 2021, doi.org/10.1029/2021MS002520
- Siahaan et al., *The Cryosphere,* 2022, doi.org/10.5194/tc-2021-371

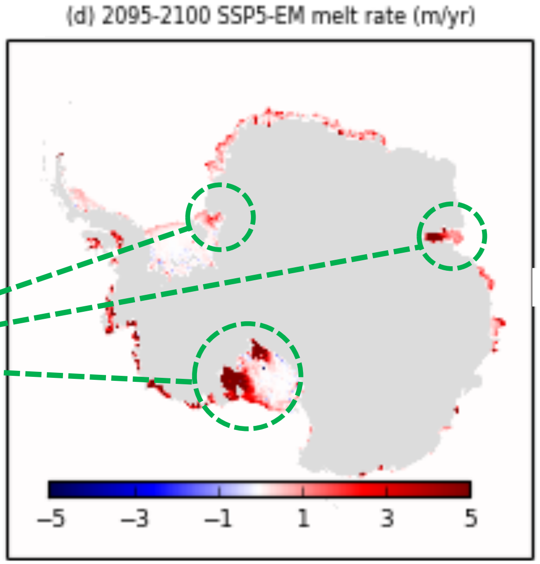
Warm water enters cold cavities



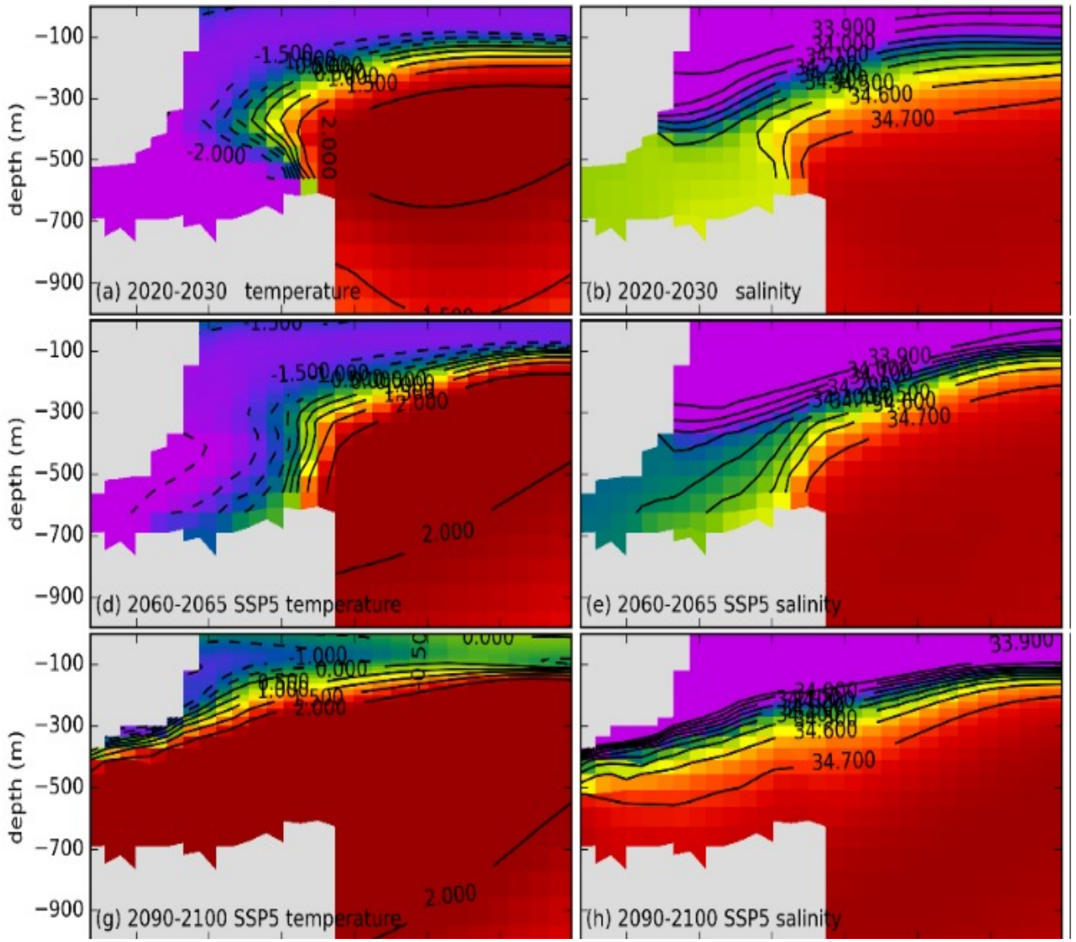
2020–2030: Melt confined to small shelves in the Amundsen and Bellingshausen regions

2095–2100: Melt extends to the Ross, Filchner, and Amery shelves

Incursions of warm water

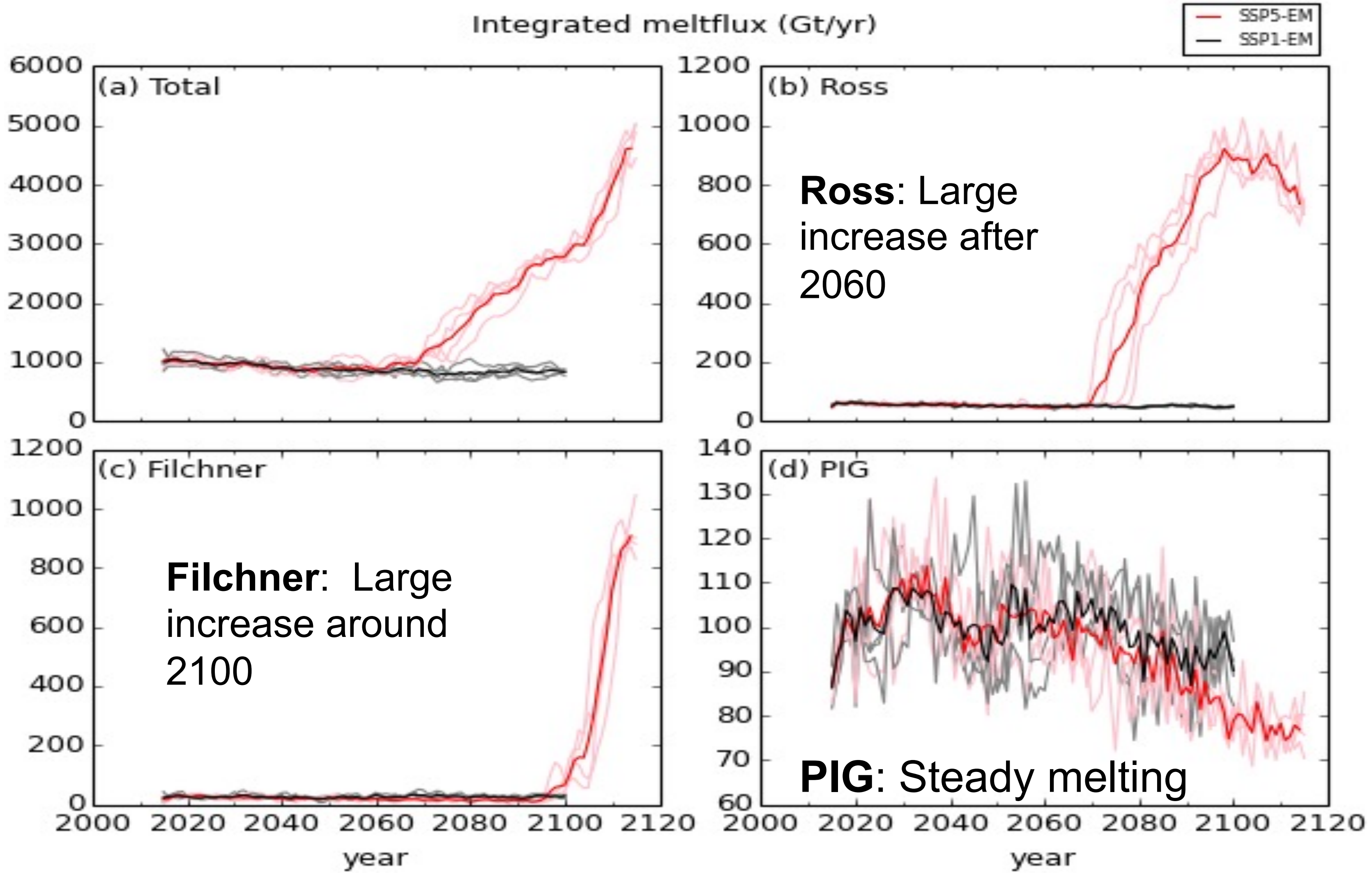


Ross warming mechanism

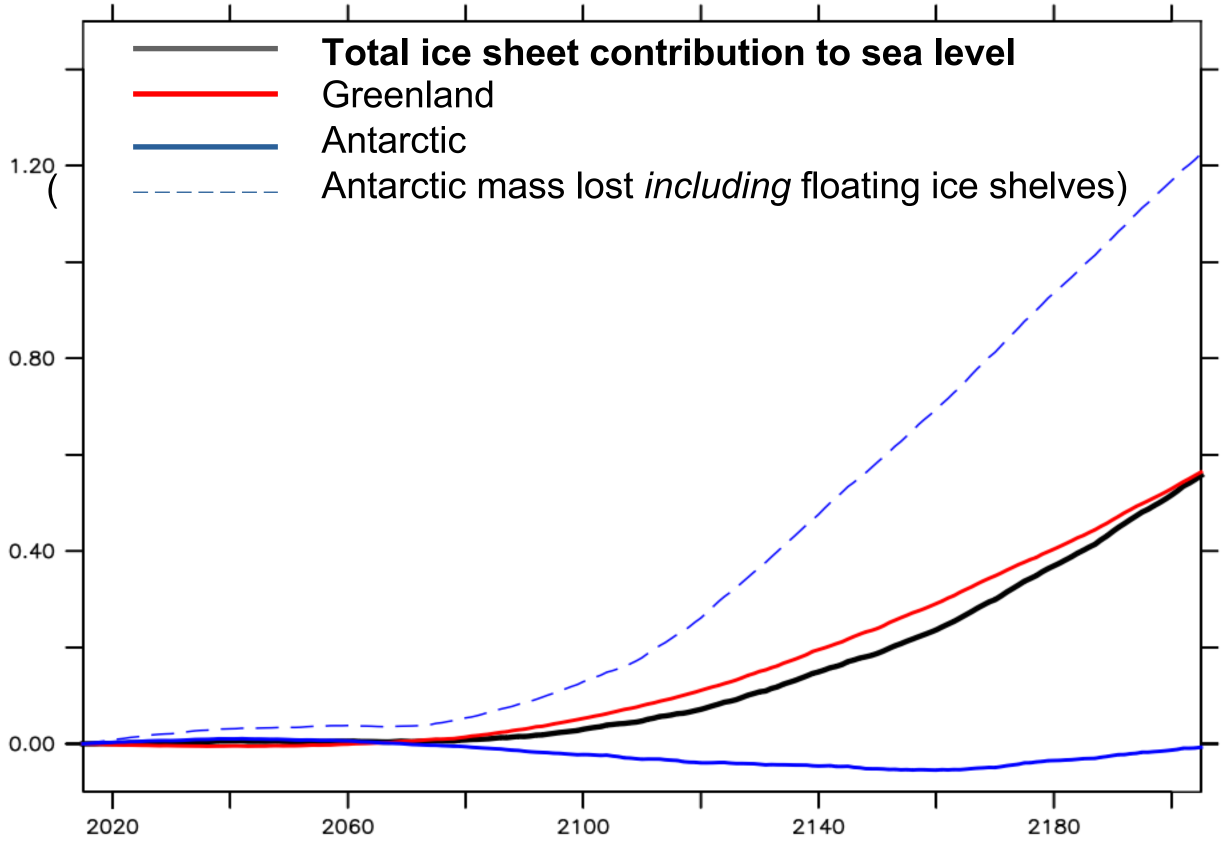


Warm water intrusions preceded by freshening and sea-ice reduction

"Projected" NEMO shelf melting

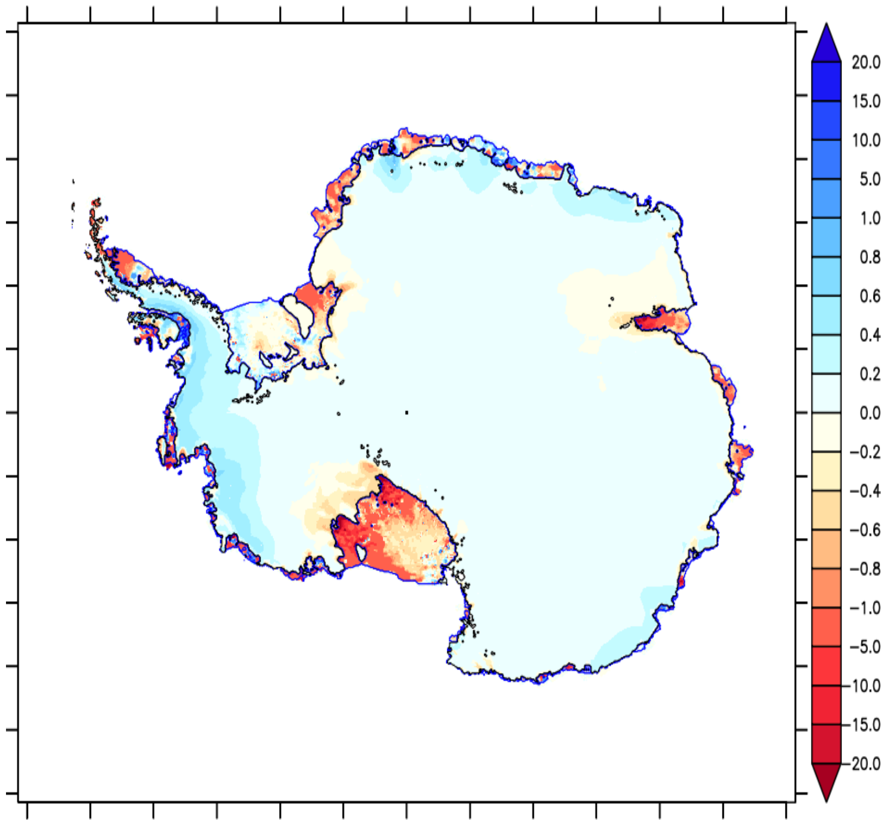


“Projected” sea-level rise



Meters of equivalent sea level rise (m) in the next two centuries, UKESM coupled simulation.

“Projected” mass balance



SSP5 surface and basal mass balance (m/yr) of the AIS in 2100

Antarctic coupling in UKESM

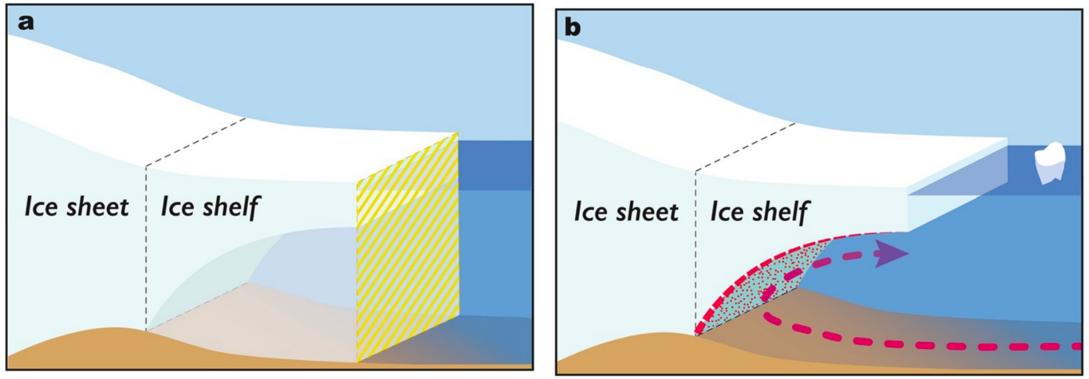
Limitations:

- Relatively coarse ocean resolution of ~1^{o}
- Ad hoc initialization; not feasible to run a multi-centennial ice–ocean spin-up with cavities
- Timing of warm water intrusions may be influenced by salinity biases
- Fixed calving front and other ice sheet model simplifications

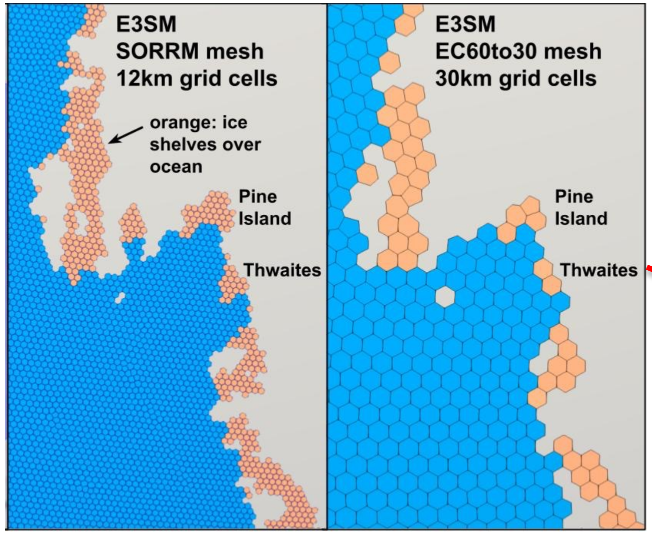
Antarctic ice-shelf cavities in E3SM

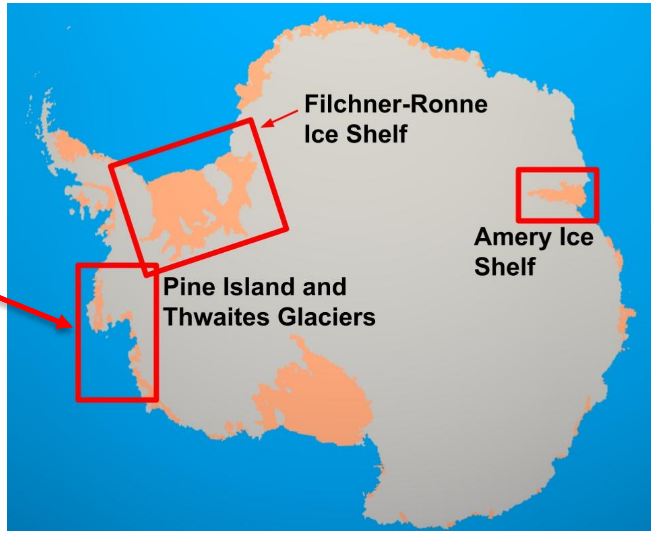
- E3SM v1.2 introduced ocean circulation within Antarctic ice-shelf cavities

- E3SM has global configurations with **30 km** or **12 km** ocean model resolution around AIS



Comeau, D. et al. (2022). The DOE E3SM v1.2 cryosphere configuration: Description and simulated Antarctic ice-shelf basal melting. *Journal of Advances in Modeling Earth Systems, 14*, e2021MS002468. https://doi.org/10.1029/2021MS002468

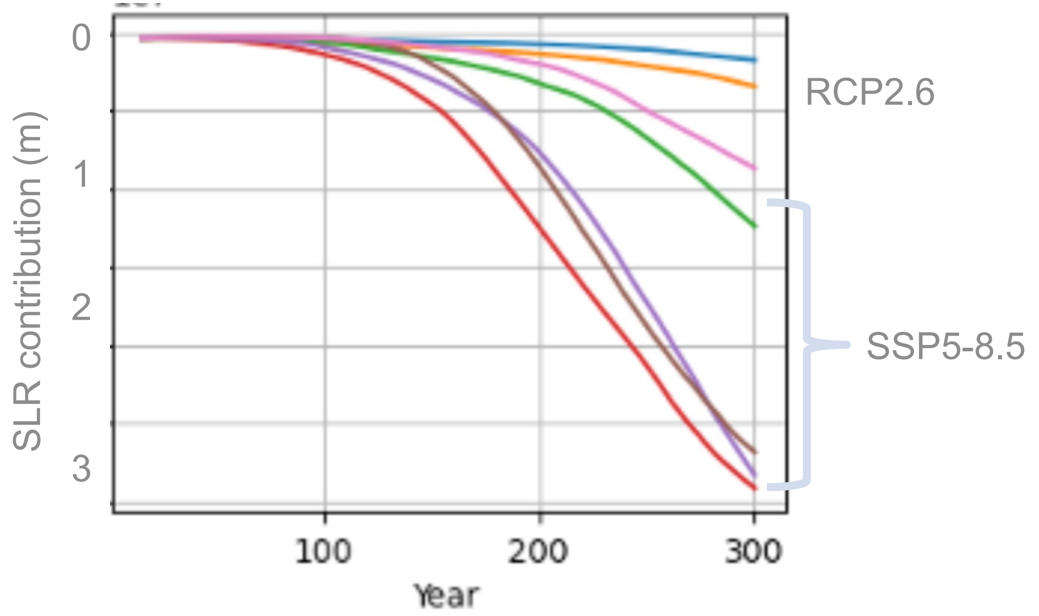


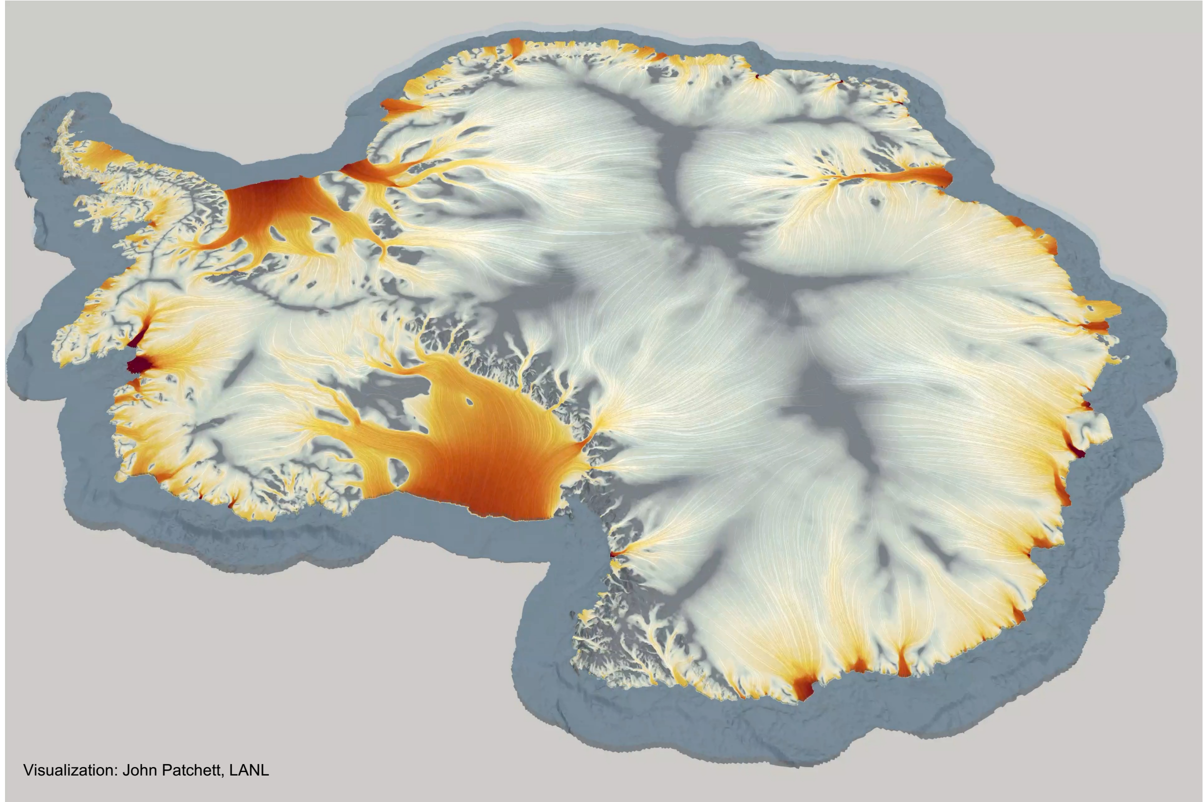


Antarctic Ice Sheet in E3SM

E3SM ice-sheet component, MALI, is a higher-order, unstructured ice-sheet model that has been applied to whole AIS at up to 2km resolution in standalone mode

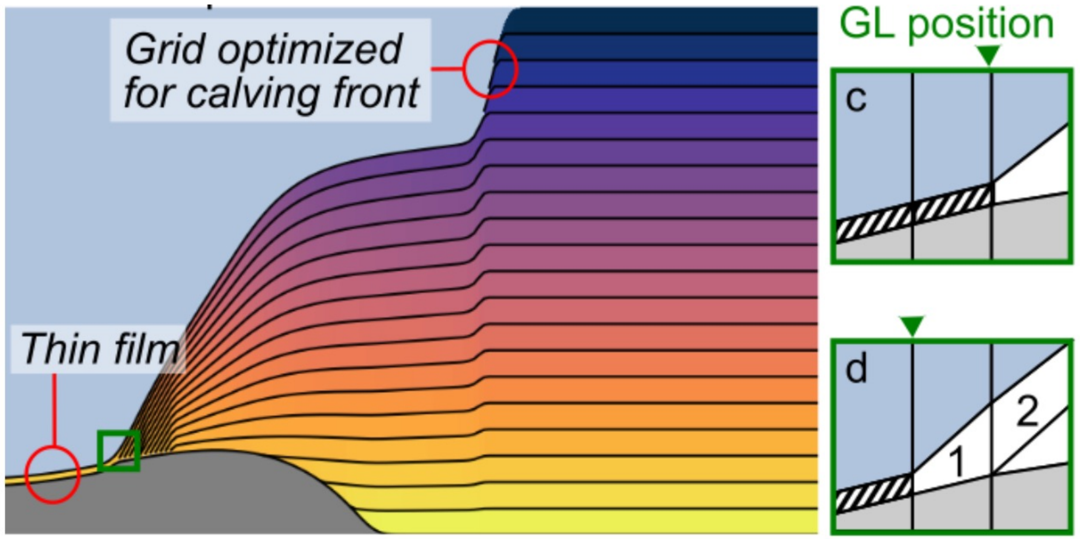
MALI contribution to ISMIP6-2300





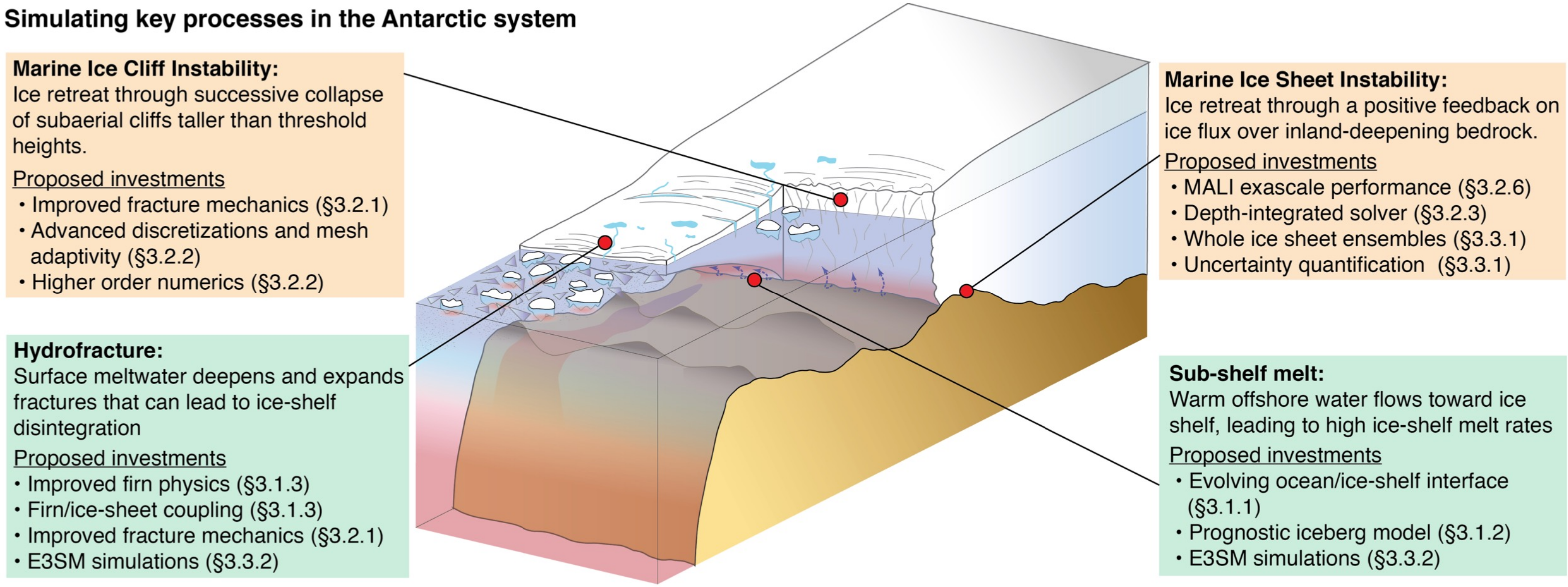
Ice sheet–ocean coupling

- MALI is coupled to E3SM ocean model:
  - mass and heat fluxes passed between ocean and ice components
  - ocean sees changing ice-shelf thickness
- Ocean model wetting and drying (grounding line evolution) still in progress.



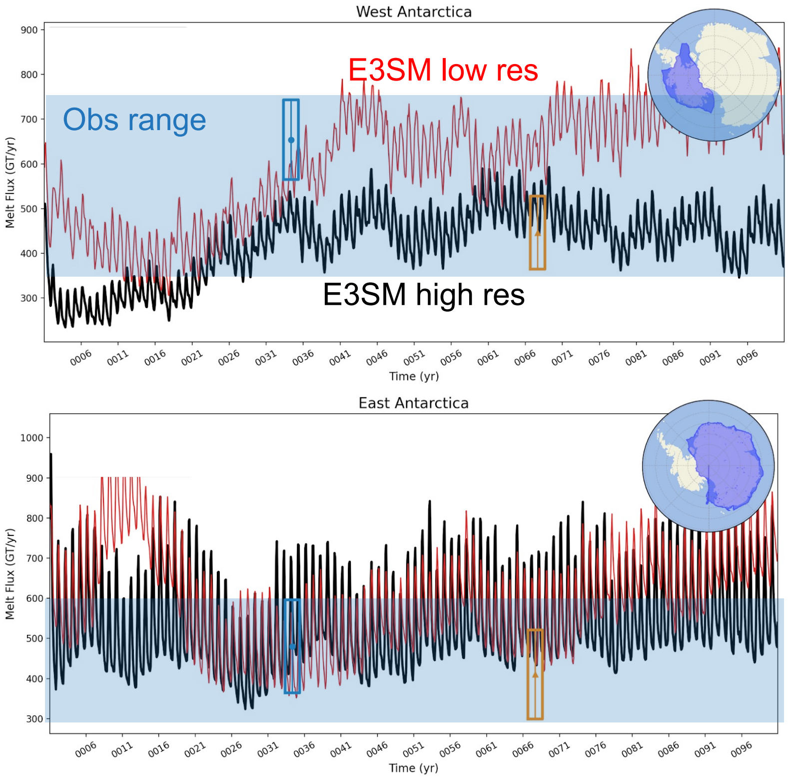
Future Work

- Complete ice/ocean coupling
- Improve fracture mechanics
- Add atmospheric-driven hydrofracture of ice shelves
- Dynamic iceberg model

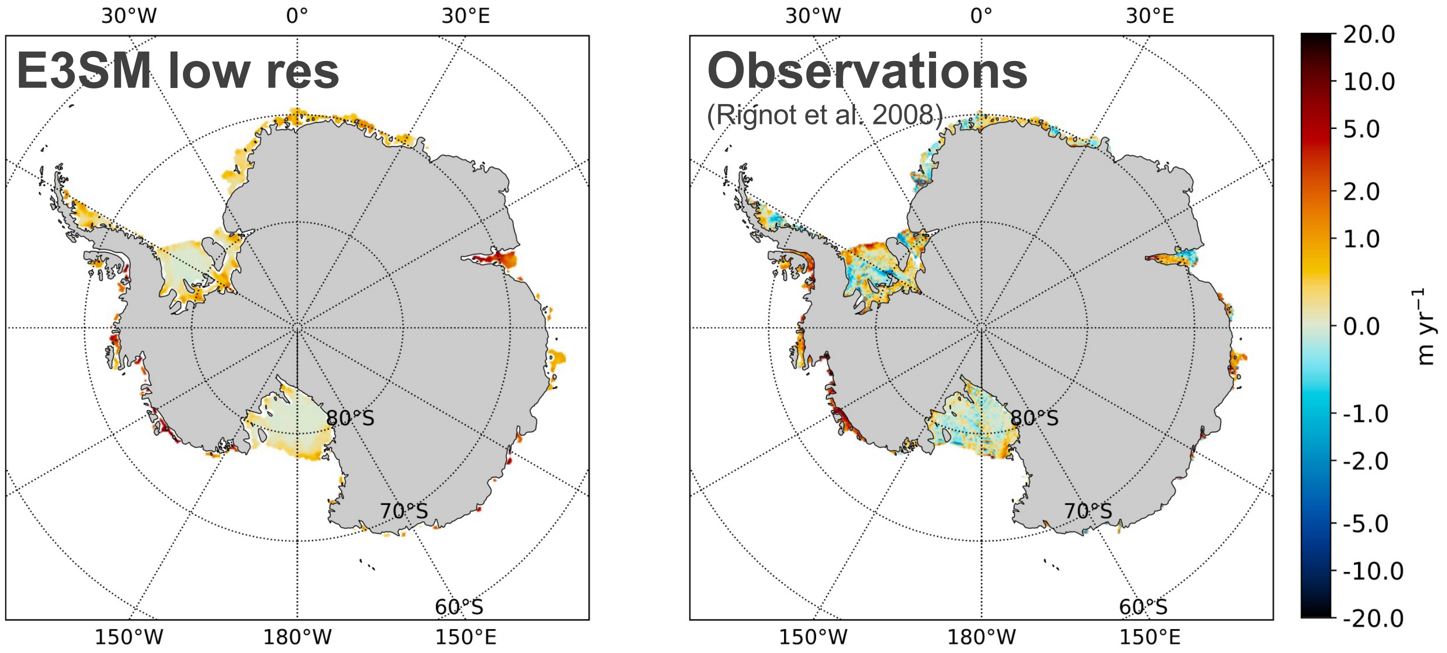


Basal melt rates

Melt flux magnitude close to observational estimates



Spatial distribution of melt rates similar to observations

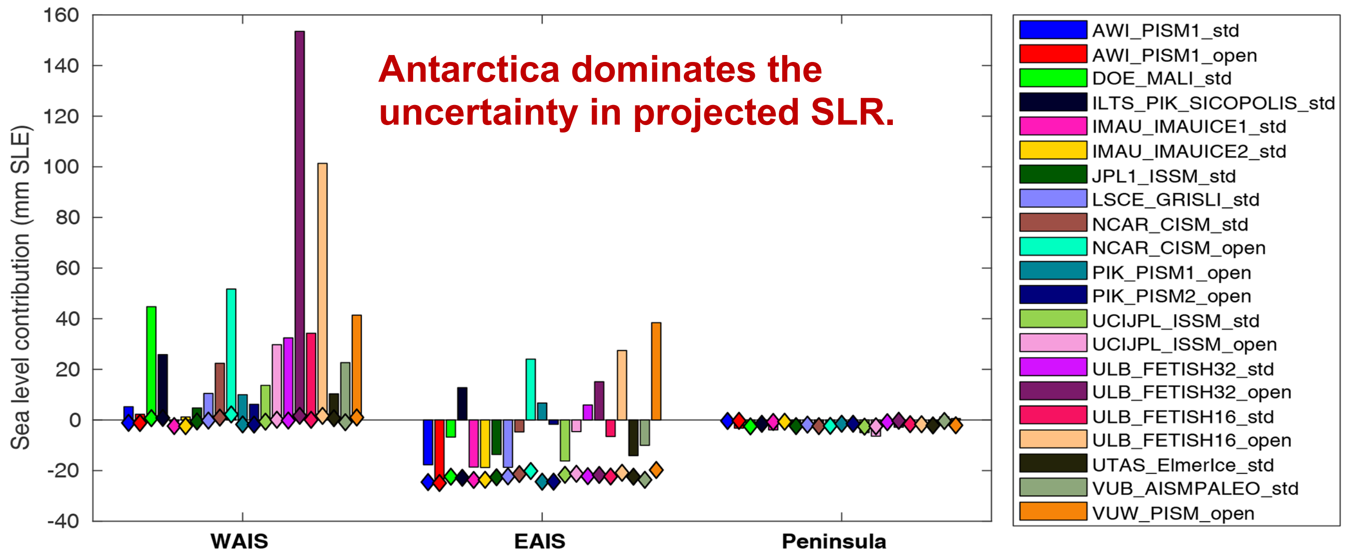


Ice sheet projections

- **IPCC AR6**: "Both the Greenland Ice Sheet (*virtually certain*) and the Antarctic Ice Sheet (*likely*) will continue to lose mass throughout this century under all considered SSP scenarios."
- SSP5-85 projections:
  - GrIS: 0.09–0.18 m
  - AIS: **0.03–0.34 m**

ISMIP6 Antarctica (Seroussi et al., 2020)

- **WAIS**: Mass loss **up to 180 mm SLE** by 2100
- **EAIS**: Mass change of **-61 to 83 mm SLE**
- Large uncertainties in **snowfall, sub-shelf melting**

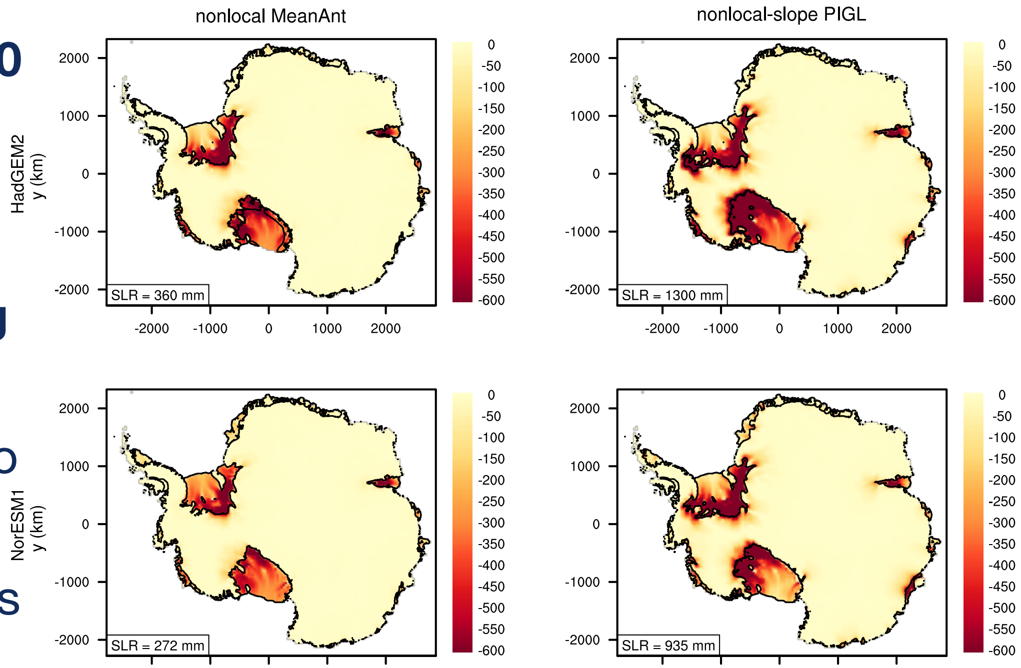


Antarctic regional sea-level contributions (mm SLE) from multiple ice sheet models under RCP 8.5 forcing

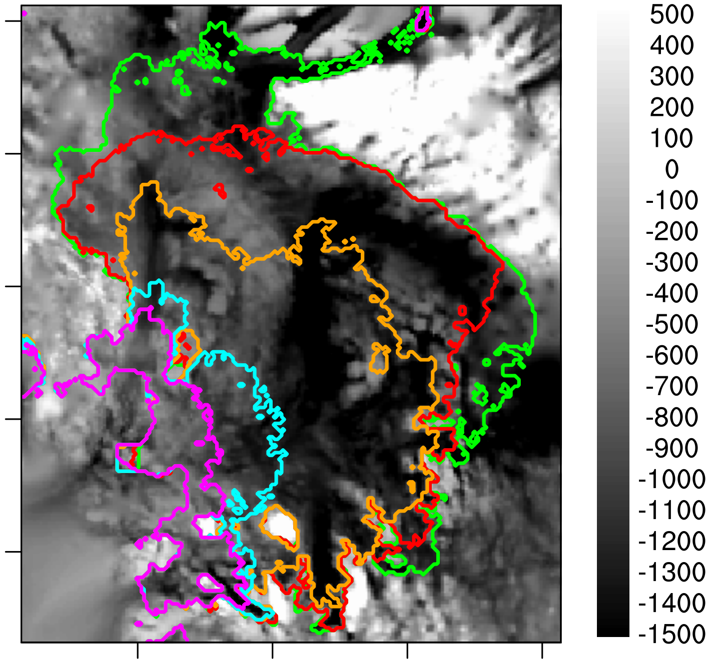
Ocean-forced Antarctic projections with CISM

Projected Antarctic retreat with late 21st century ocean forcing extended to 2500

- Ice loss of **150 mm** to **>1500 mm SLE**; mainly Ross and Filchner-Ronne basins
- Sensitive to the **basal melt scheme** and **ocean forcing**
- **Threshold behavior for Thwaites**, increasing SLR to ~3 m
- In new simulations, Thwaites collapses after 500–1000 years under **present-day forcing**.



Modeled Antarctic ice thickness change (m), 1950–2500, with two basal melt schemes and ocean forcing from two global ESMs (Lipscomb et al., 2021)



Simulated ice retreat in the Amundsen sector. Bright lines show grounding-line position at 100-year intervals from 2100.

Outstanding questions

- Under climate warming, will the Ross and Filchner-Ronne shelves transition from cold-cavity to warm-cavity?
  - If so, when? Once under way, is the retreat reversible?
- Under what conditions will Thwaites Glacier collapse?
  - Model simulations (e.g., Urruty et al. and Reese et al, 2022, TCD) suggest that the current retreat is stable, but could become unstable under continuing present-day conditions.
  - Under different climate scenarios, how quickly will we reach the point of certain collapse?

Modeling challenges

- **Process uncertainties**: Basal sliding, calving, hydrofracture, sub-shelf melting, isostatic rebound
- **Cold–warm cavity transitions** depend on **coupled small-scale processes**: mesoscale eddy transport, sea-ice brine rejection, sub-shelf freshwater mixing, etc.
  - Can we parameterize these processes accurately in global models?
  - Can we predict the timing of transitions, given that small biases affect the timing?
- How do we **initialize** a coupled ocean–sea ice–ice sheet system?