Land Ice Modeling in CESM

Annual CESM Tutorial

William Lipscomb and the CESM Land Ice Working Group

NCAR

12 AUGUST 2022

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

Outline

- Background on land ice and sea level rise
- Ice sheets in the Community Earth System Model (CESM)
- CESM contributions to CMIP6
- Recent research and future plans

Thanks to: Sarah Bradley, Tessa Gorte, Adam Herrington, Jan Lenaerts, Gunter Leguy, Marcus Lofverstrom, Gustavo Marques, Laura Muntjewerf, Bette Otto-Bliesner, Michele Petrini, Bill Sacks, Aleah Sommers, Kate Thayer-Calder, Mariana Vertenstein, Miren Vizcaíno, and other members of the CESM Land Ice Working Group

Causes of global sea level rise (SLR)

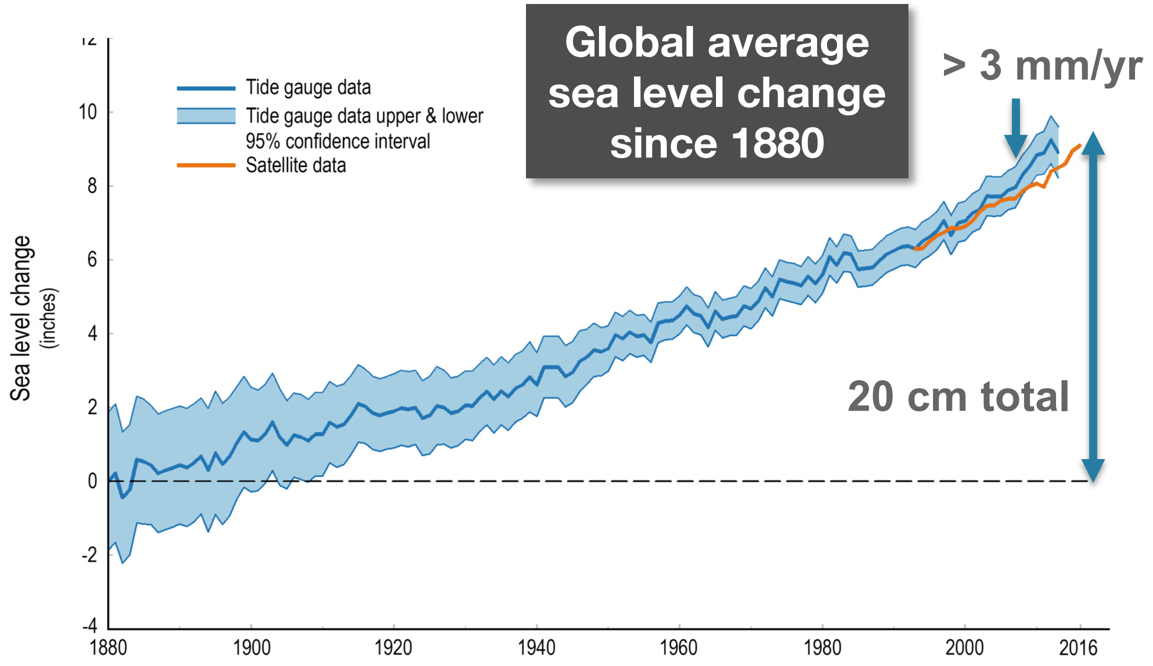
Most 20th century sea-level rise was caused by **ocean thermal expansion** and **melting of mountain glaciers.**

The **Greenland and Antarctic ice sheets** began losing mass around 1990 and account for about 35% of recent sea level rise (> 1 Gt/day).

Global mean sea level has risen by about 20 cm since the late 1800s. The rate of SLR has accelerated to about **3.7 mm/yr**.

Estimated sea level rise	**1901-1990** (mm/yr)	**2006-2018** (mm/yr)
Thermal expansion	0.36	1.39
Glaciers (outside Greenland & Antarctica)	0.58	0.62
Greenland	0.33	0.91
Antarctica	~0	0.53

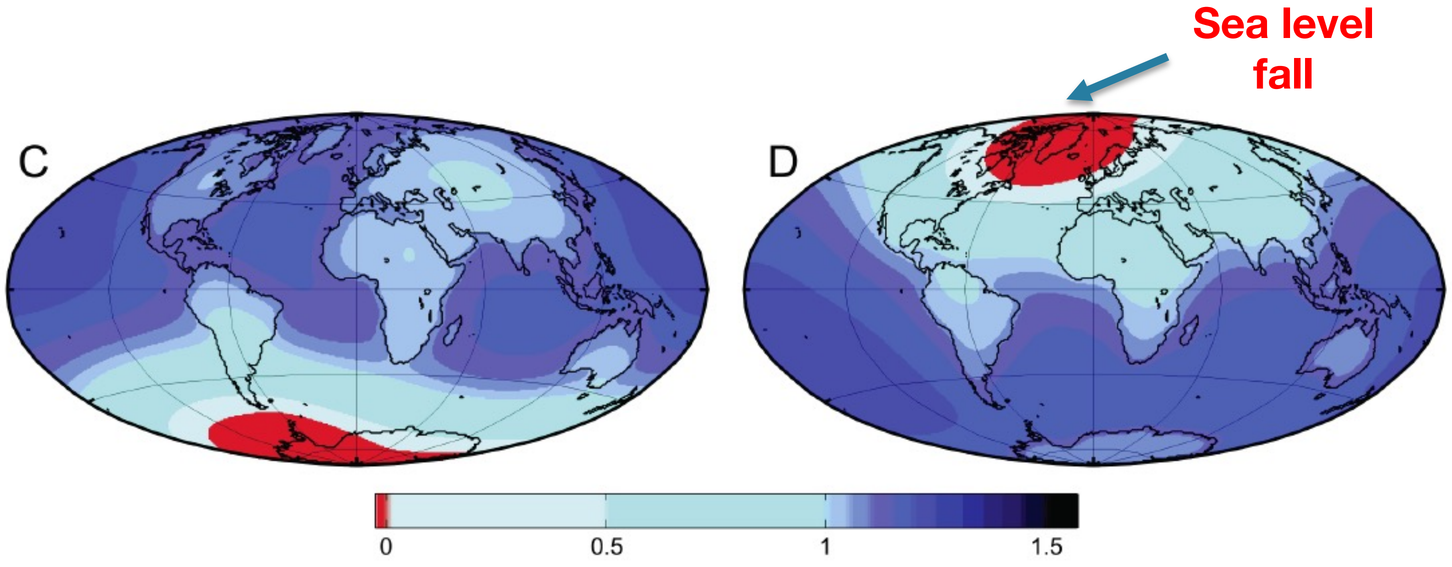
Estimates from IPCC AR6, Table 9.5



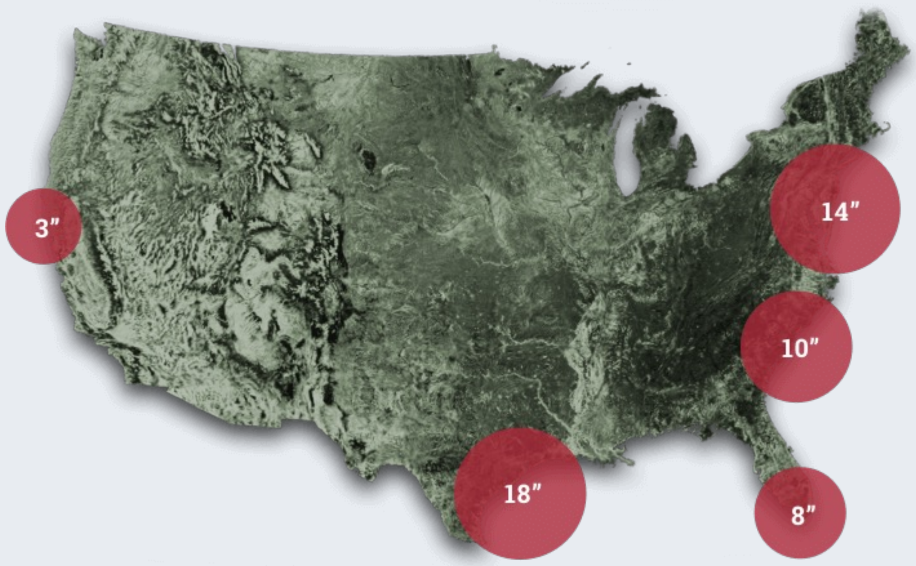
Regional sea-level variations

Sea level rise varies regionally because of **land subsidence, glacial rebound, ocean circulation changes** and changes in **ice sheet self-gravity**.

- With weaker self-gravity, water moves away from shrinking ice sheets and piles up elsewhere.



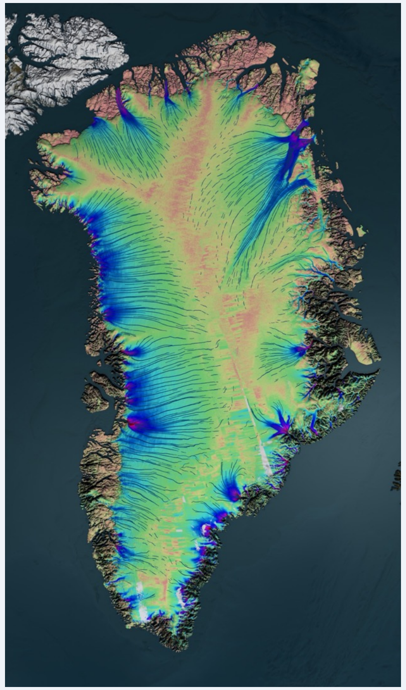
Relative sea-level change from retreat of the West Antarctic Ice Sheet (left) and Greenland Ice Sheet (right) (Mitrovica et al. 2011).



Inches of sea level rise in U.S. coastal regions since 1950.
Source: sealevelrise.org

Greenland Ice Sheet

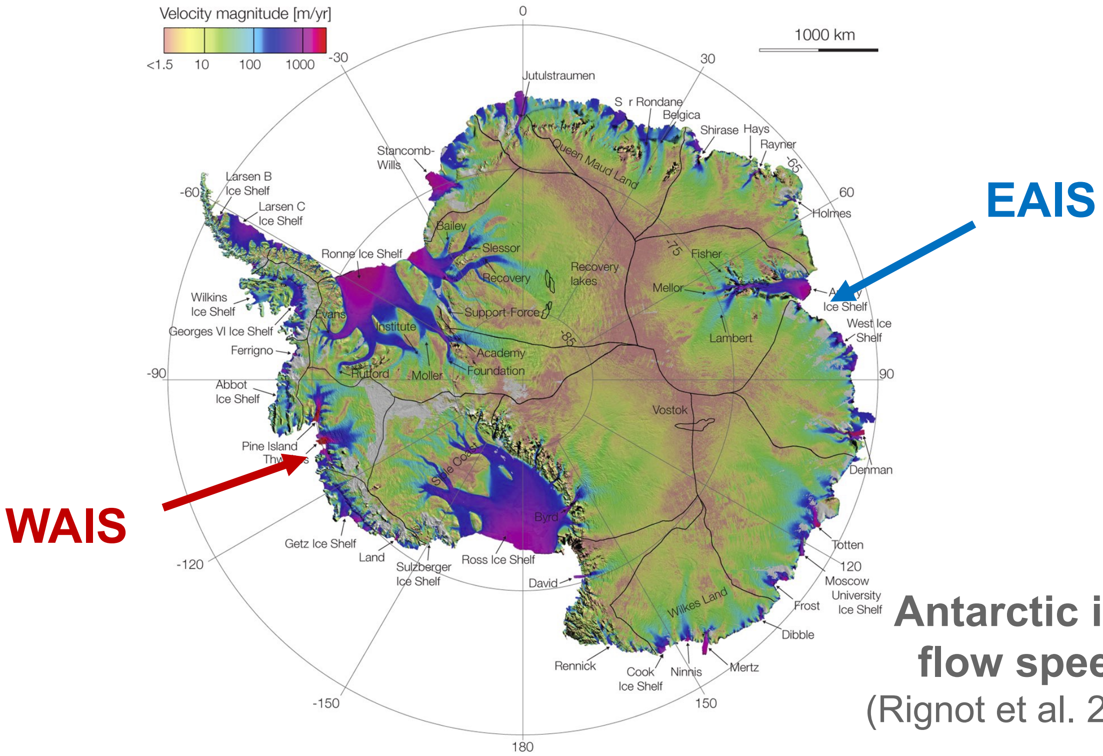
- **7 m** sea level equivalent
- **Snowfall** balanced by **surface runoff** and **iceberg calving**
- Mass loss of **230 Gt/year**, 2006–2018



Greenland ice flow speed
NASA/Goddard Space Flight Center Scientific Visualization Studio

Antarctic Ice Sheet

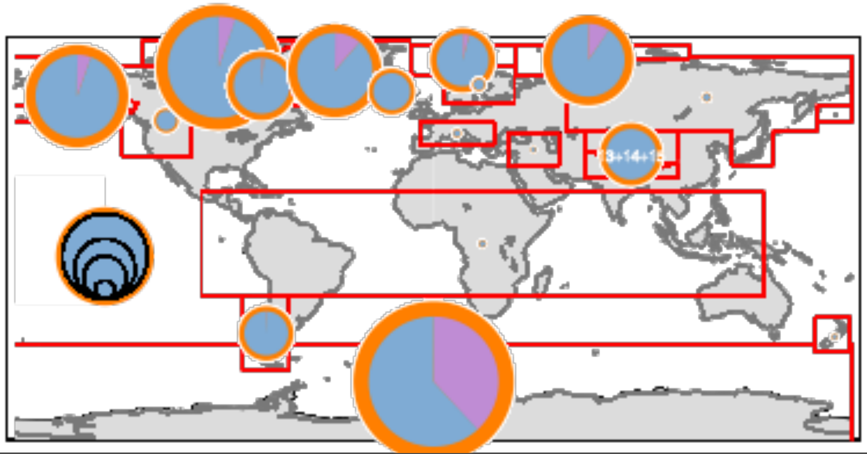
- **58 m** sea level equivalent (**5 m** in West Antarctica)
- **Snowfall** balanced by calving and melting from **floating ice shelves**, with little surface melting
- Mass loss of **130 Gt/year**, 2006-2018



Antarctic ice flow speed
(Rignot et al. 2011)

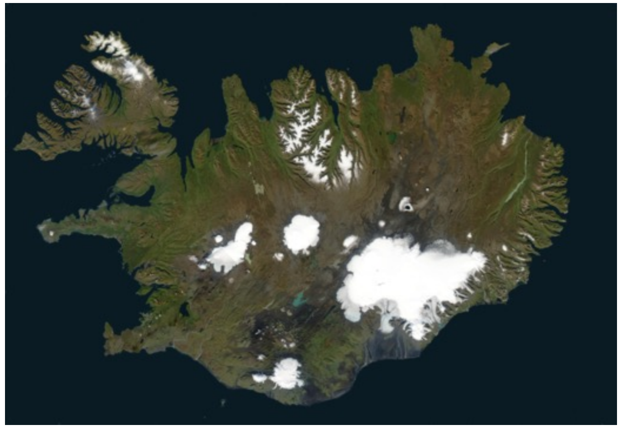
Mountain glaciers

- Glaciers outside the two ice sheets contain about **0.4 m** sea level equivalent.
    - Most glacier volume is in the Arctic (Canadian and Russian Arctic, Greenland periphery, Alaska), the Antarctic periphery, and High Mountain Asia
- The volume is small compared to ice sheets, but the relative rate of loss is large: about **230 Gt/yr**, 2006–2018.
- Besides raising sea level, glacier melting can endanger **water supplies** and trigger **outburst flooding**.



Regional glacier volume (Farinotti et al. 2019)

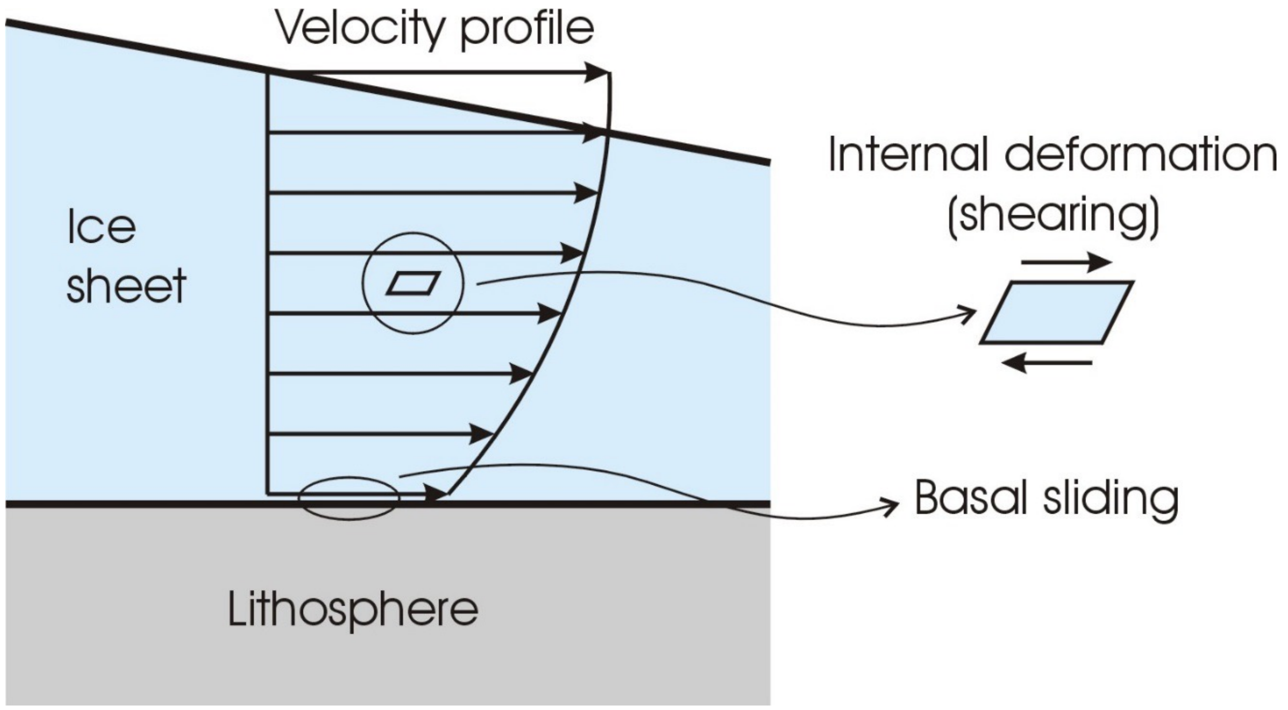
Mer de Glace, French Alps
Photo by Eduard Spelterini, 1909



Iceland with Vatnajokull ice cap

How glaciers move

- **Glaciers flow downhill** under the force of gravity.
- Ice deforms like a very **viscous fluid**. Warmer ice is softer and flows faster.
- When there is water at the bed, glaciers can **slide** at speeds up to several km/year.



- Slowly deforming ice that is frozen at the bed is described by the **shallow ice approximation**.
- Ice that is sliding with little vertical shear is described by the **shallow shelf approximation**.
- General ice flow is described by the **Stokes equations** or **higher-order approximations**.

How ice sheets gain and lose mass

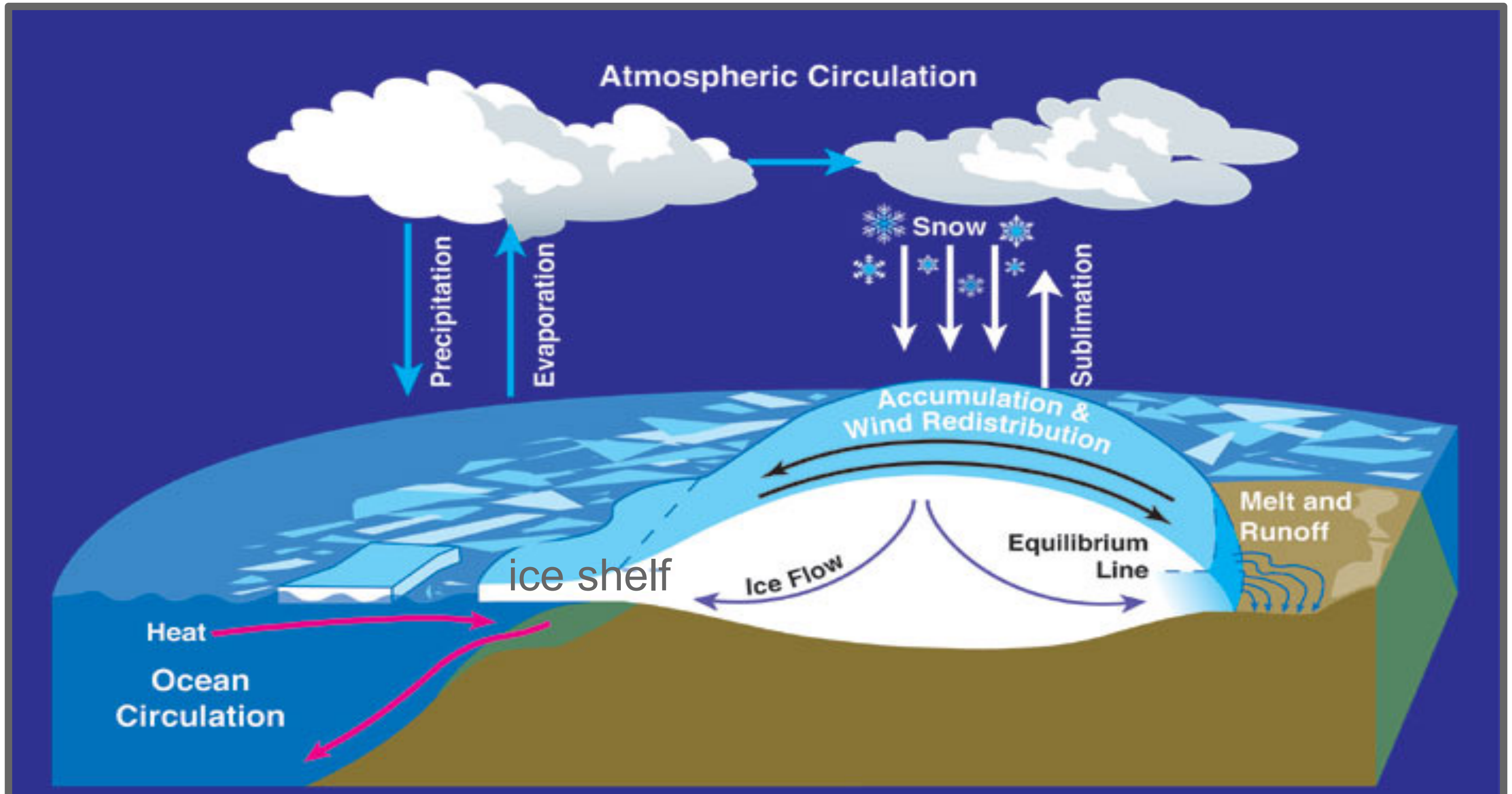


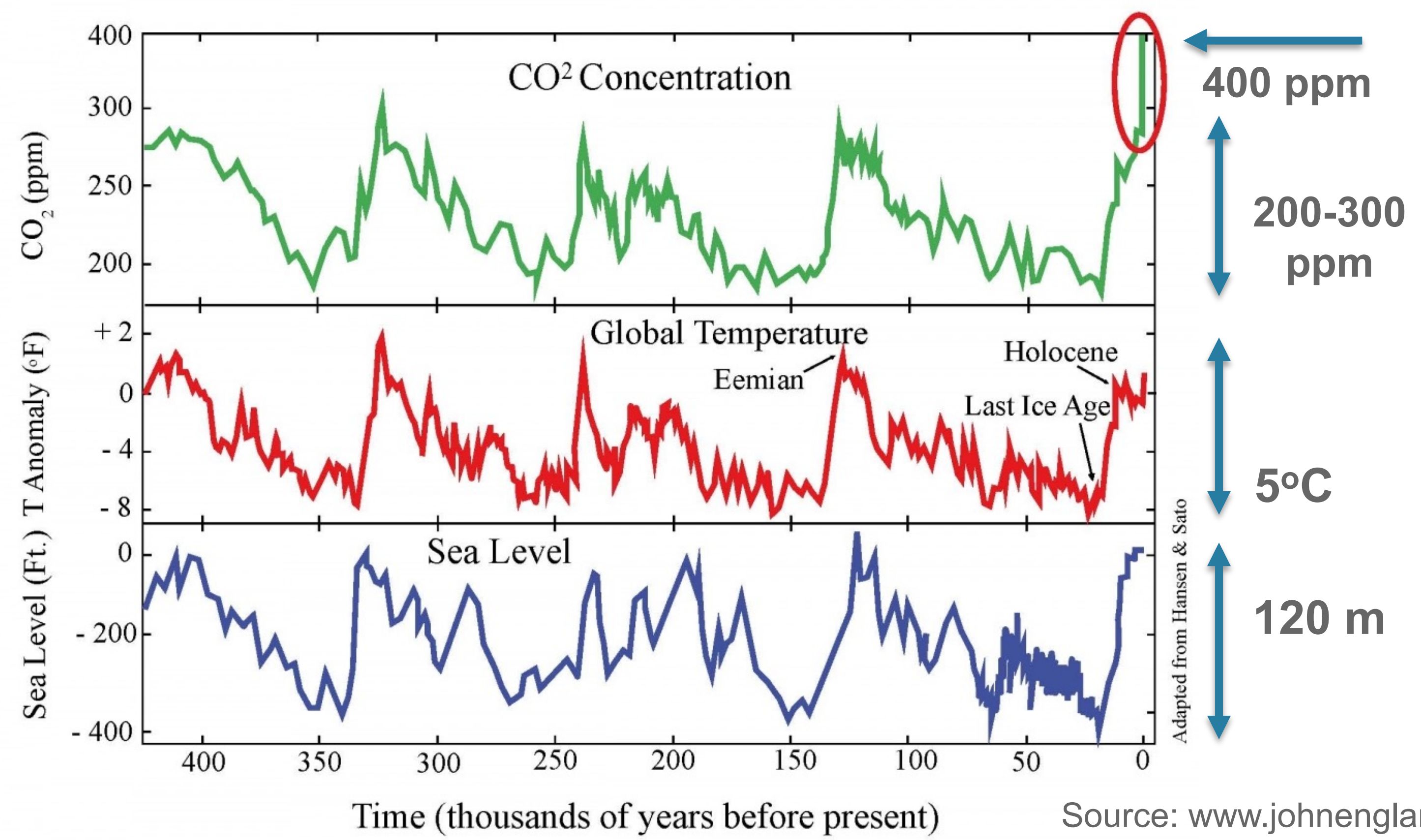
Image source: http://www.nasa.gov/images/content/53743main_atmos_circ.jpg

Mass Balance: Change in ice sheet mass = mass in – mass out

Sea level change! Snowfall melting, calving

Carbon dioxide, temperature, and sea level

- **Sea level** is closely linked to global average **temperature** and **CO_2 concentration**.
- In past climates, temperature co-evolved with CO_2. Now CO_2 is the main driver.
- Ice sheets tend to **build up slowly** and **melt quickly**.

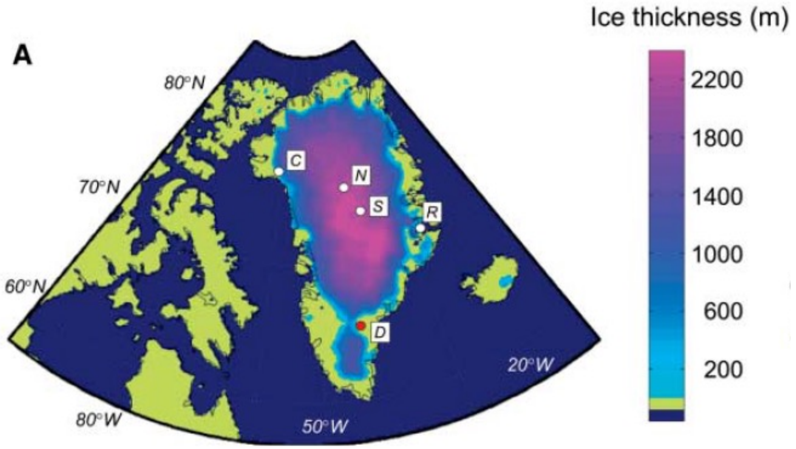


Source: www.johnenglander.net

Ice sheets in warm climates

Last Interglacial (125,000 years ago)

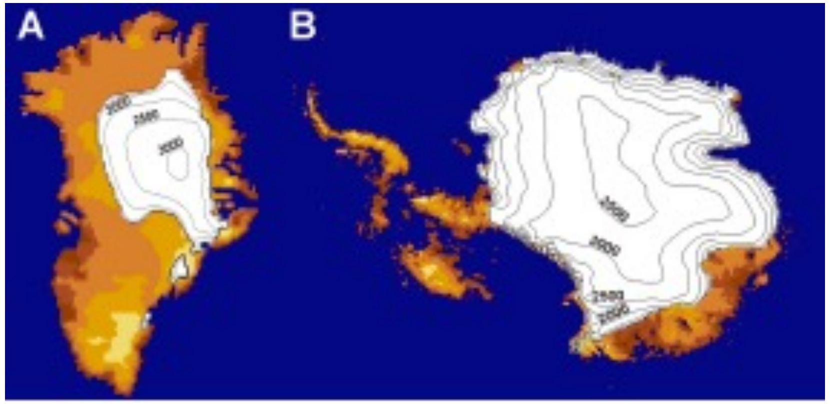
- Warming **1-2°C**, CO_2 = **280 ppm**
- Global sea level **6–9 m higher** than now
- About 2–4 m from Greenland, > 2 m from Antarctica



Modeled Greenland ice thickness for the Last Interglacial (Otto-Bliesner et al. 2006)

Pliocene (3 million years ago)

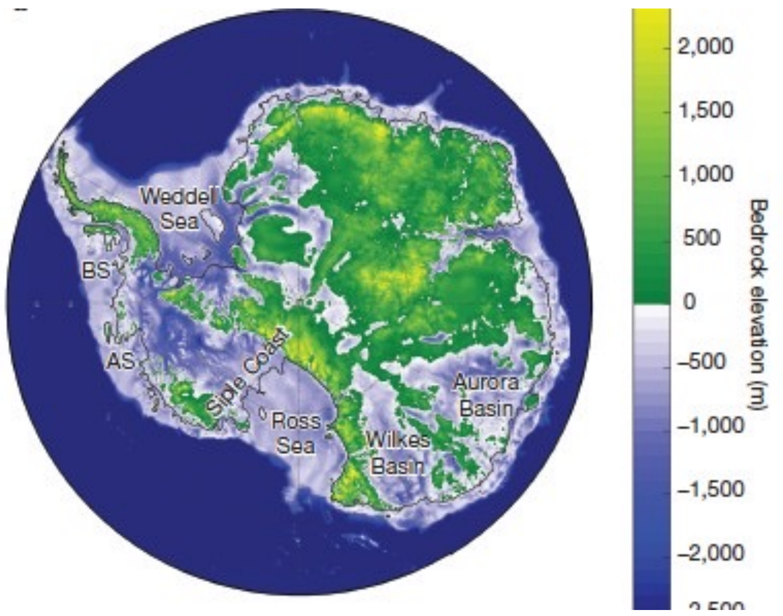
- Warming **2-3°C**, CO_2 = **400 ppm**
- Global sea level **5–20 m higher** than now
- Up to 7 m from Greenland, 5 m from West Antarctica, and possibly retreat from East Antarctica



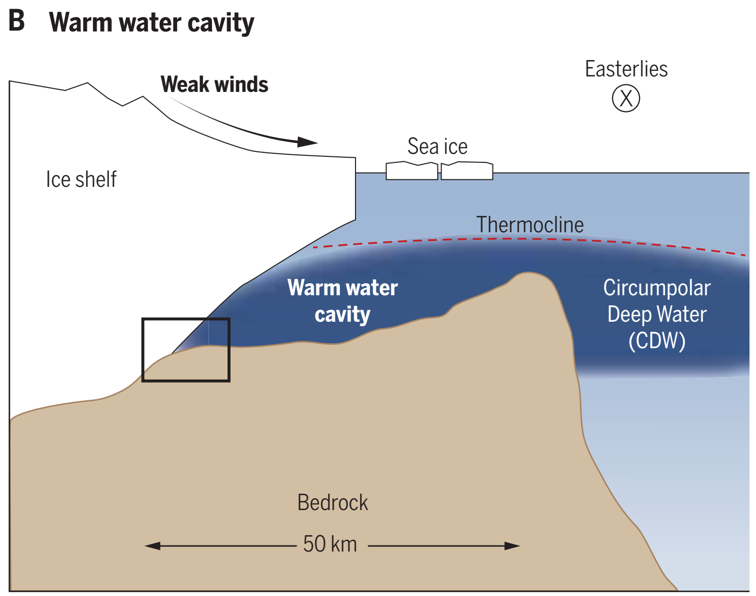
Pliocene ice sheet reconstructions (Haywood et al. 2010)

Antarctic ice sheet instability

- Much of the Antarctic ice sheet is **grounded below sea level**
- This ice is vulnerable to intrusions of warm Circumpolar Deep Water, especially in the Amundsen Sea region (Thwaites and Pine Island Glaciers).
- Ice sheets on reverse-sloping sea beds may be subject to the **Marine Ice Sheet Instability**.



Antarctic basal topography
Global Warming Art Project

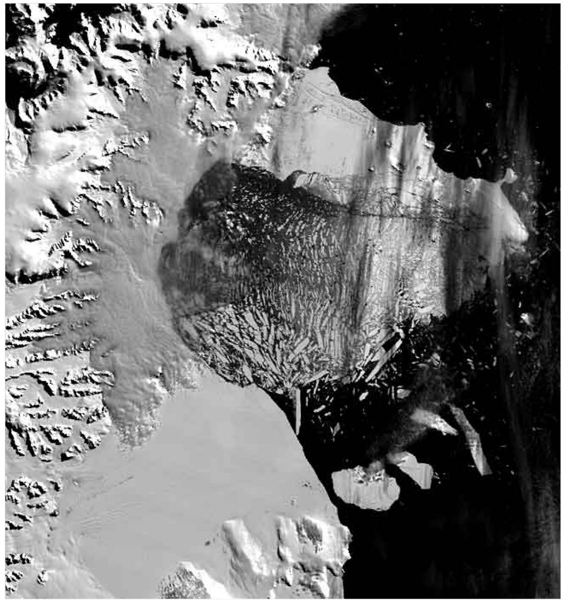


Schematic of a warm sub-ice-shelf cavity (Holland et al. 2020)

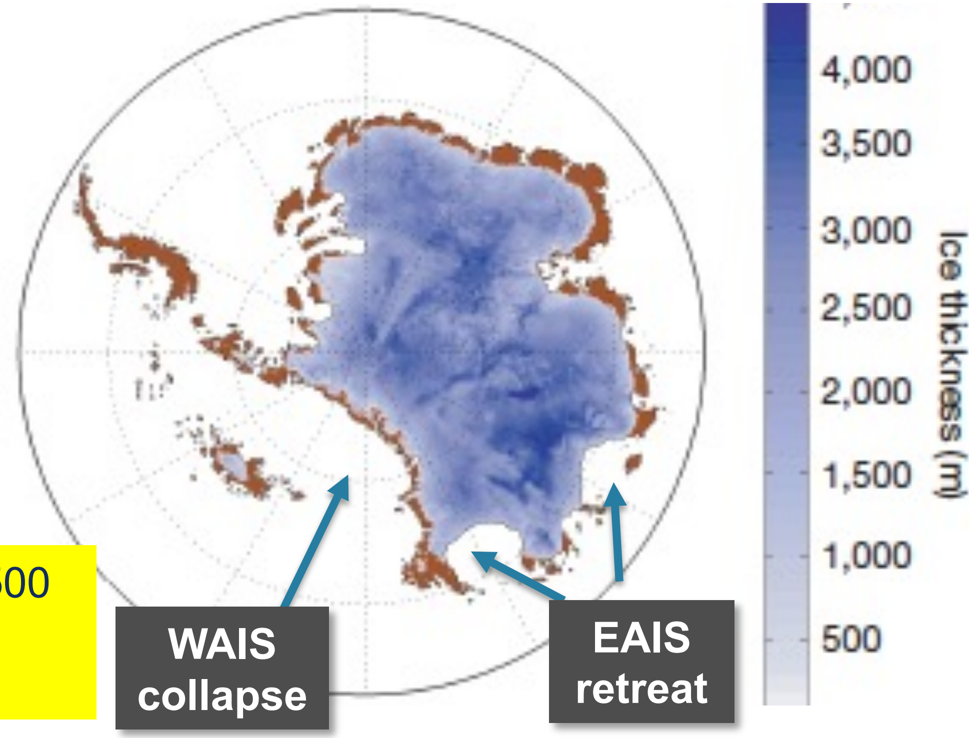
Abrupt Antarctic ice sheet retreat?

DeConto & Pollard (2016) proposed mechanisms for fast collapse of Antarctic marine ice:

- **Hydrofracture** leading to ice shelf collapse, followed by **marine ice cliff instability (MICI)** leading to fast retreat of grounded ice (0.8 m SLR by 2100, 12 m by 2500)
- But MICI is poorly constrained and has not been observed on a large scale



Abrupt collapse of the **Larsen B ice shelf** due to hydrofracture, March 2002 (courtesy of Ted Scambos)



Projected AIS retreat by 2500 under high emissions, DeConto & Pollard (2016)

Ice sheets in Earth system models

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

Why not ice sheets?

- Before recent observations, 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.

- Climate model = atmosphere, land, ocean, sea ice (linked by a coupler)
- Earth system model = climate model + biosphere + chemistry + ice sheets + …

Image: Greenland ice sheet/NASA

Ice sheets in the Community Earth System Model (CESM)

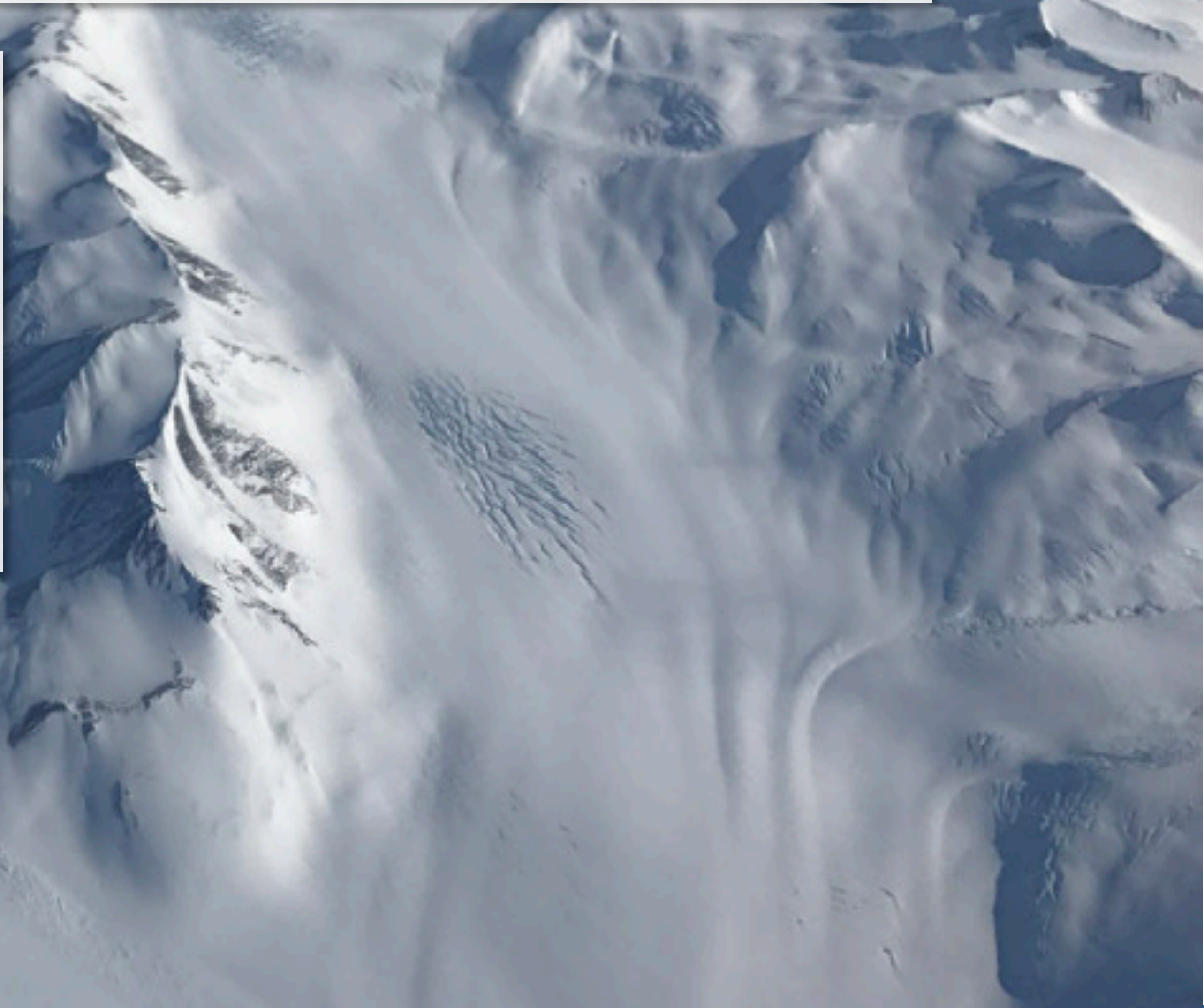
CESM1 (2010+) was one of the first complex ESMs to include ice sheets.

Division of labor:

- The **Community Land Model (CLM)** computes the **surface mass balance** (snowfall and surface melting) for ice sheets, using subgrid elevation tiles to make up for coarse resolution (~50–100 km).
- The **coupler** remaps the surface mass balance to a finer ice sheet grid (~5 km).
- The **Community Ice Sheet Model (CISM)** computes ice flow.

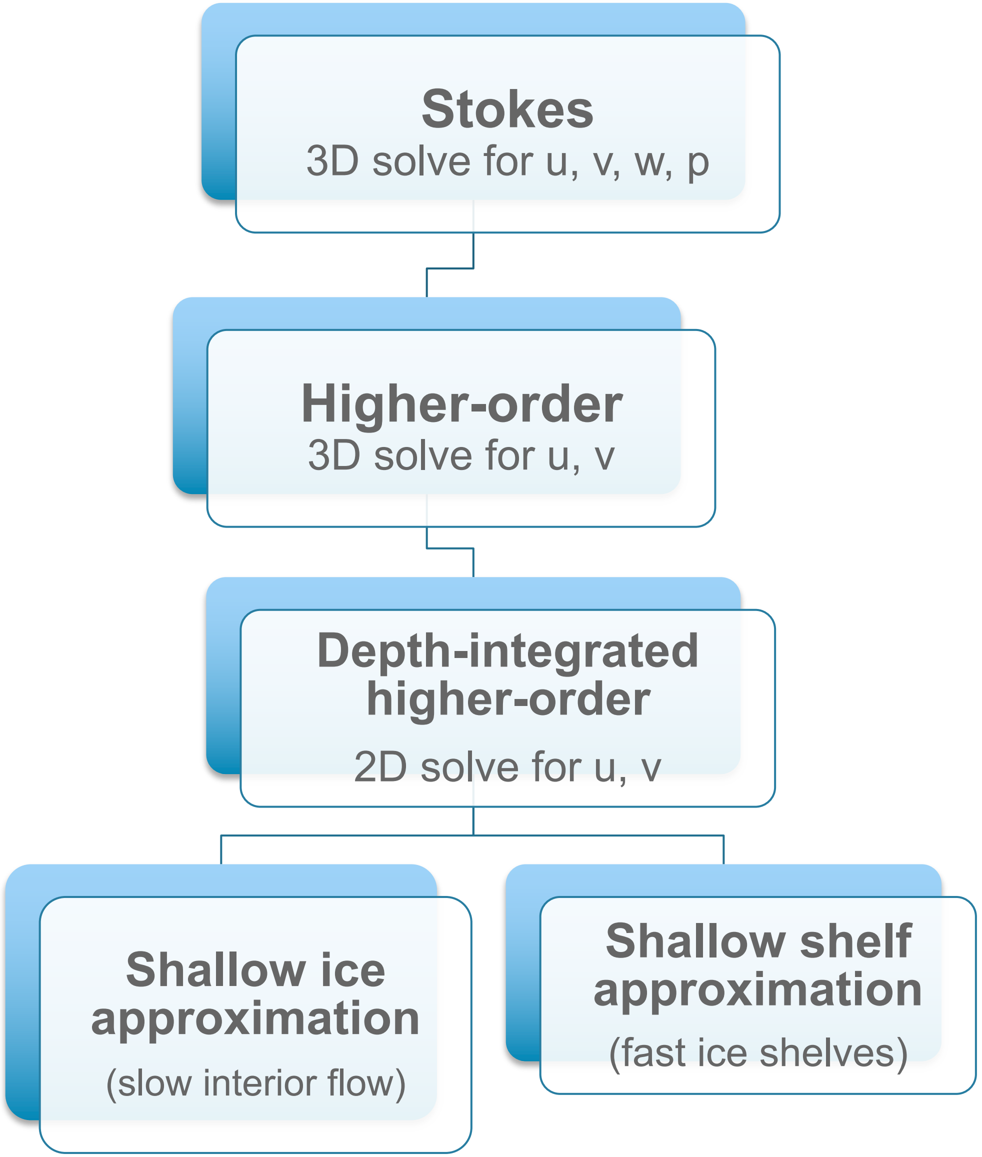
Simplifying assumptions:

- **Shallow-ice dynamics** (not accurate for ice streams and ice shelves), Greenland only
- **One-way coupling**: Ice sheet changes do not affect other model components



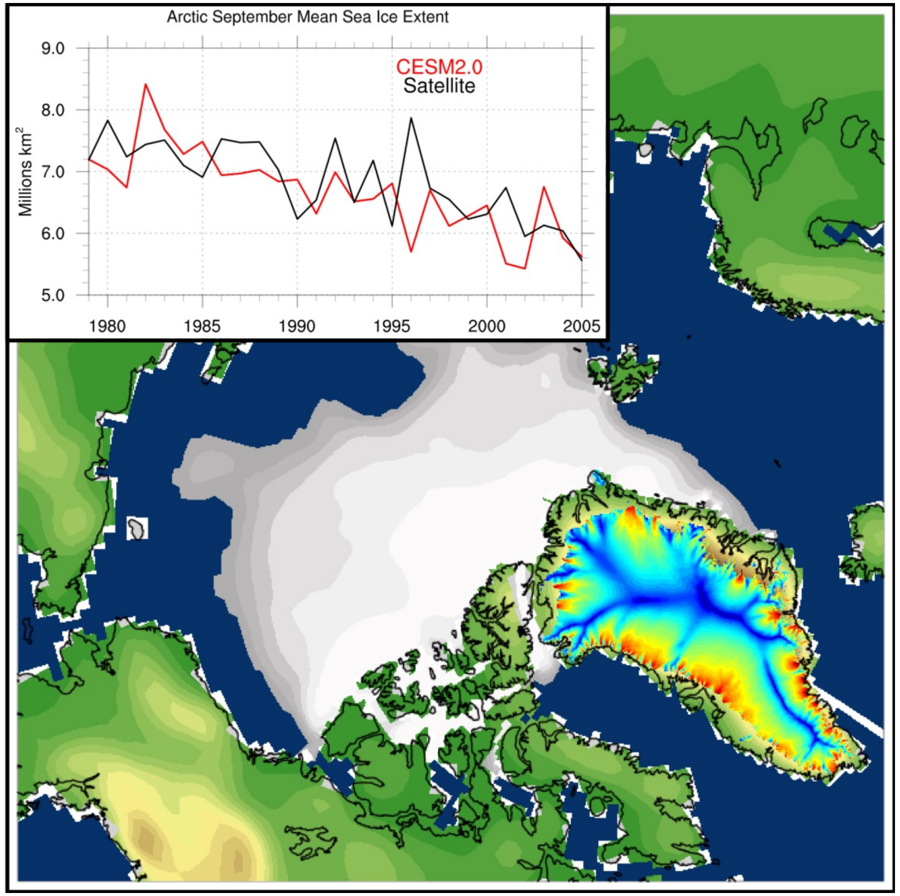
Goals for CESM2

- **Realistic ice sheet dynamics** (higher-order ice-flow model) valid for flow over the entire ice sheet
- **Two-way coupling**: Changes in ice sheet elevation and extent can feed back on the climate



Hierarchy of ice sheet velocity solvers

Ice sheets in CESM2



CESM2 supports **interactive coupling** between the **Greenland Ice Sheet** and the land and atmosphere.

- By default, ice sheets are fixed.
- 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.

CESM2 also includes **improved physics for snow and firn** (the transitional layer between snow and ice).

Ice sheets in CESM2

Land -> Ice sheet

(10 classes + bare land)

- Surface mass balance
- Surface elevation
- Surface temperature

Ice sheet -> Land

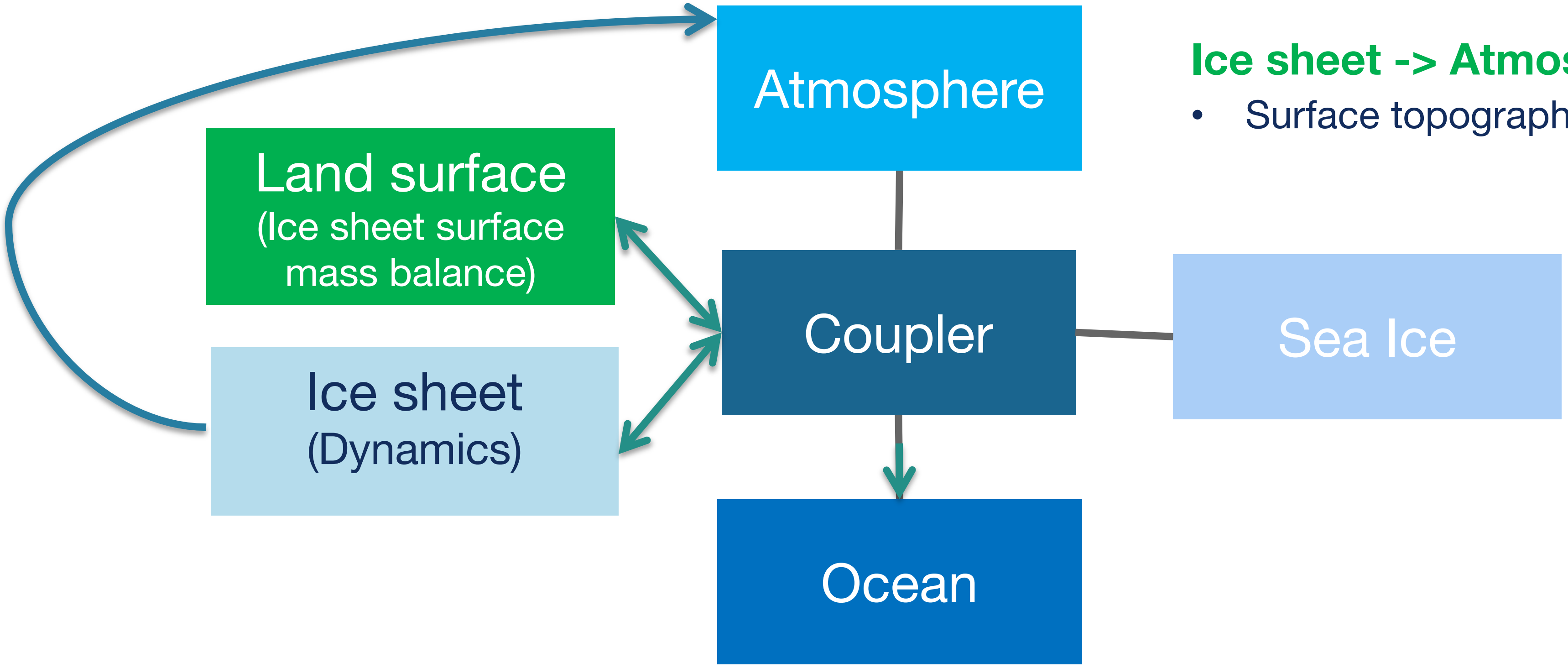
- Ice extent
- Ice surface elevation

Ice sheet -> Ocean

- Solid and liquid fluxes

Ice sheet -> Atmosphere (offline)

- Surface topography

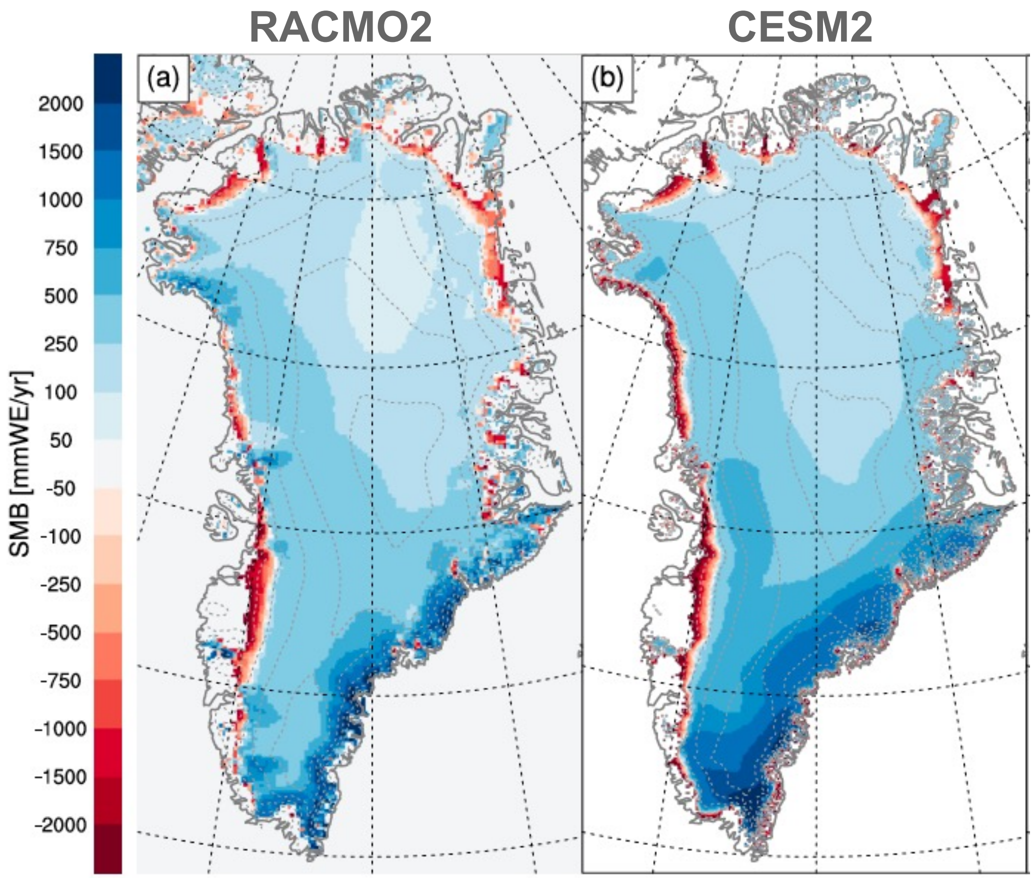


Greenland surface mass balance in CESM2

The surface climate of ice sheets has improved compared to CESM1:

- More realistic **refreezing and firn**
- Improved **surface winds**
- Better **polar cloud forcing**
- Still have **too much snowfall** in southern Greenland

The Greenland surface mass balance in CESM2 compares well with **regional Arctic models** that are run at ~5 times higher resolution (~10–20 km).



Courtesy of Leo van Kampenhout.

Greenland surface mass balance (mm/yr).
Left: RACMO regional model. *Right:* CESM2.
Blue = accumulation, **red = ablation**.

Ice Sheet Model Intercomparison Project for CMIP6

CMIP is the Climate Model Intercomparison Project

ISMIP6 is the first CMIP project focused on ice sheets:

- Analyze ice-sheet-relevant results from standard climate models (fixed ice sheets)
- **Standalone ice sheet experiments for Greenland and Antarctica,** using atmosphere and ocean forcing derived from CMIP models, to estimate future sea level rise
- **Coupled climate – ice sheet experiments** to explore feedbacks

Coupled Greenland Ice Sheet evolution in CESM-CISM

First published ISMIP6 runs with an **interactive Greenland ice sheet**:

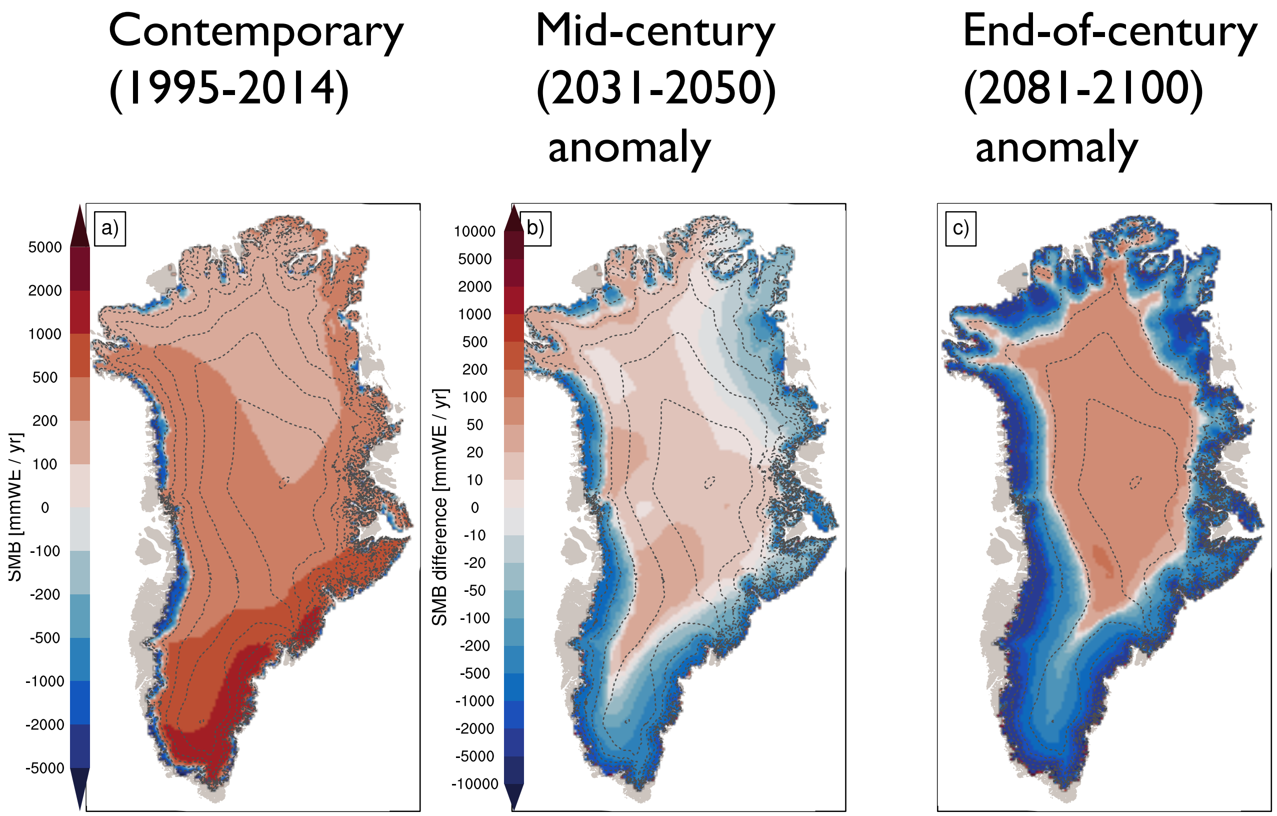
1) Dynamic ice sheet margin in land model
2) Ice calving fluxes to ocean model
3) Evolving atmosphere topography

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**



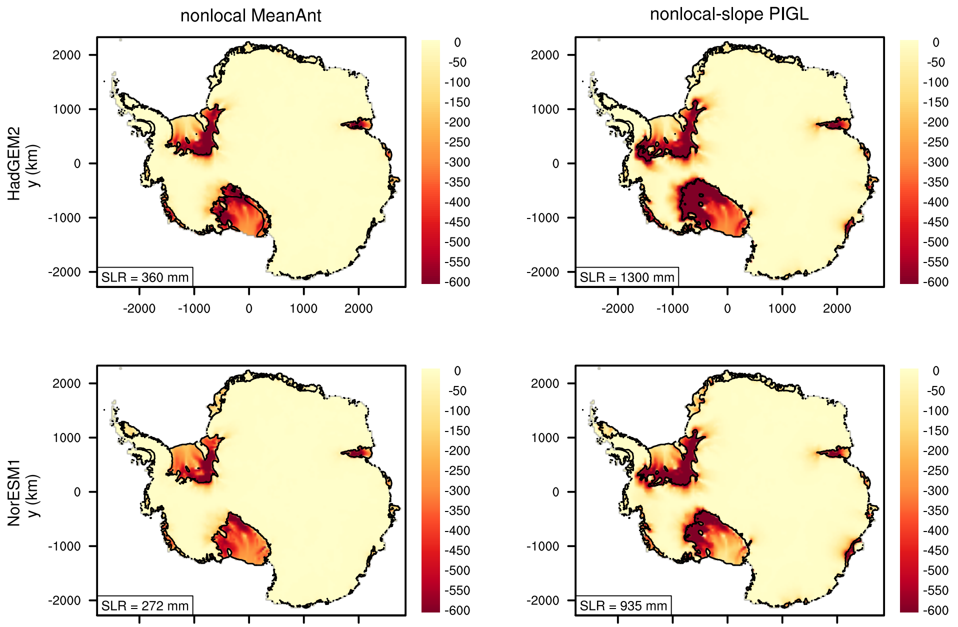
Increased melting of the **Greenland Ice Sheet** in CESM2 (Muntjewerf et al., 2020) under the ssp5-85 warming scenario. The expanding melt region is **blue**.

Ocean-forced Antarctic projections with CISM

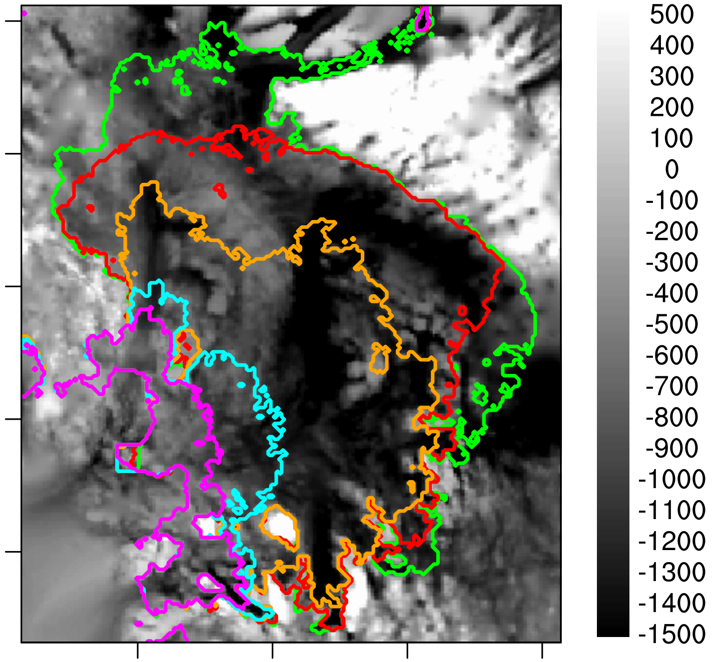
Question: Could ocean warming projected for 2100 drive irreversible retreat of the **West Antarctic Ice Sheet**?

Results:

- Ice loss of **150 mm** to **>1500 mm SLE**; mainly Ross and Filchner-Ronne basins
- High sensitivity to the **basal melt parameterization** and **ocean forcing**
- **Threshold behavior in Amundsen sector**, increasing SLR to ~3 m



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.

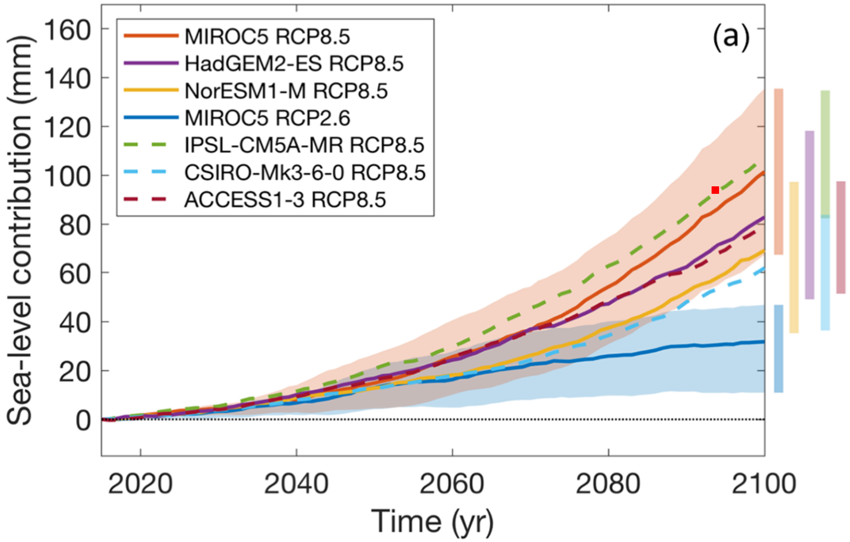
ISMIP6 ice sheet projections

Greenland (Goelzer et al. 2020)

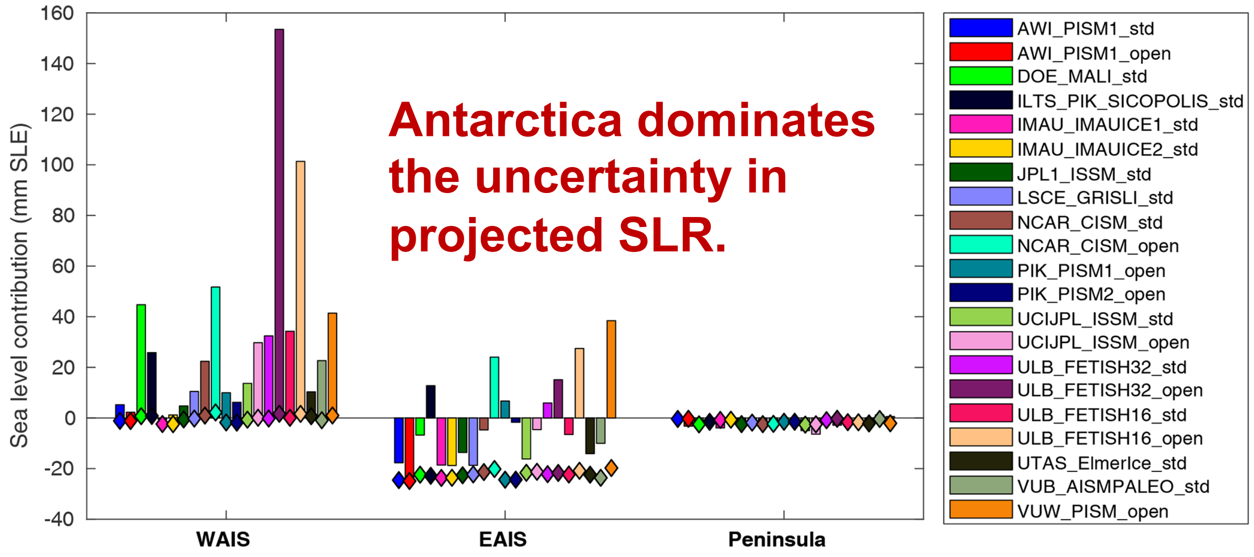
- SLR by 2100: **32 ± 17 mm** (RCP2.6), **90 ± 50 mm** (RCP 8.5), mainly from **increased surface melting**. Good agreement across models.

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, ice-shelf melting**



Greenland ensemble mean sea-level projections



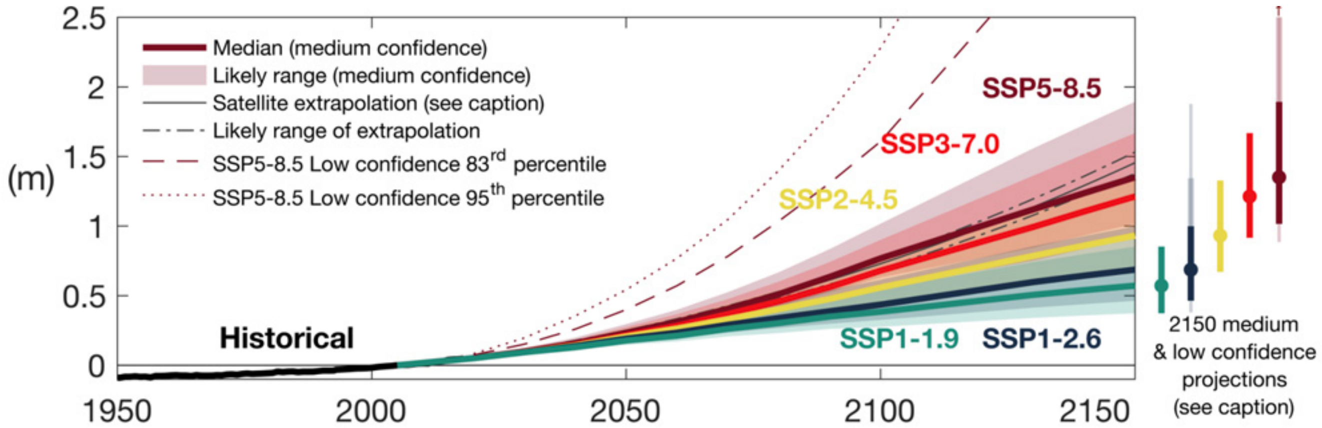
Antarctic regional sea-level contributions (mm SLE) from multiple ice sheet models under RCP 8.5 forcing

IPCC AR6 sea level projections

Chapter 9: Ocean, cryosphere, and sea level

- "It is ***virtually certain*** that global mean sea level will continue to rise through 2100" (and beyond).
- "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.").
- "These ***likely*** range projections do not include those ice-sheet-related processes that are characterized by **deep uncertainty**."
  - Unknowns: **marine ice cliff instability** and **sub-ice-shelf melting**

Projected global mean sea level rise



AR6: Likely SLR by 2100

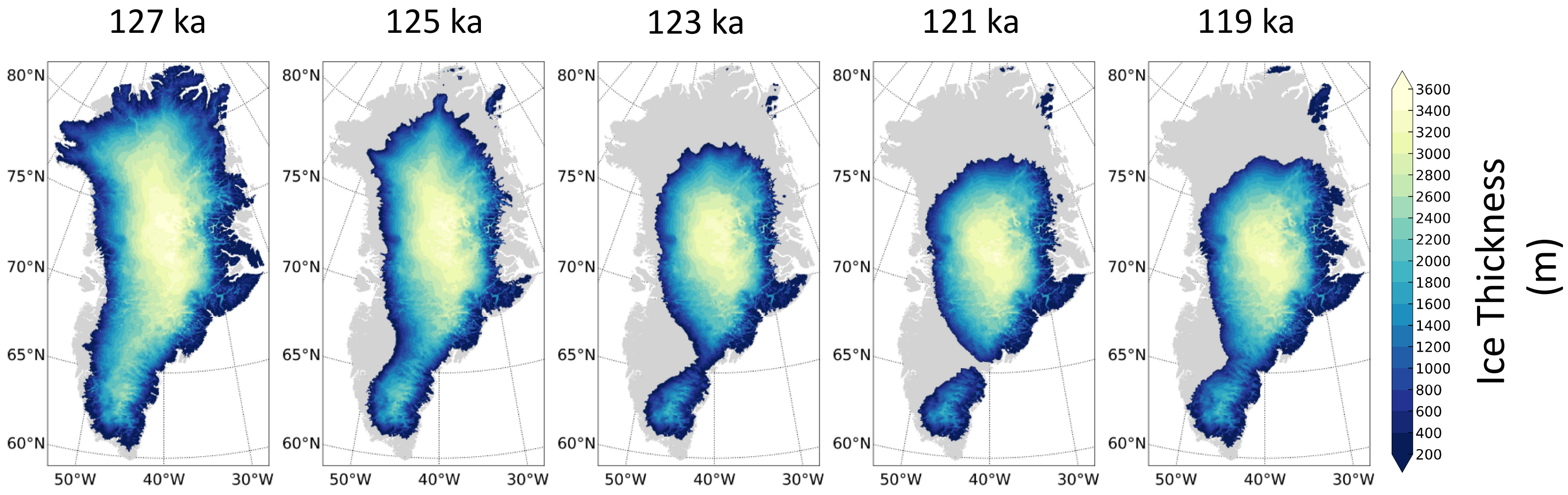
- **28 to 55 cm** for low emissions (ssp1-19)
- **63 to 102 cm** for high emissions (ssp5-85)

Since AR5 we have learned more about all components of sea level rise, but not enough to quantify the risk of **Antarctic ice sheet collapse**.

Coupled Greenland simulations of the Last Interglacial

CESM-CISM simulations of the **Last Interglacial**, 127–119 ka, with an interactive Greenland ice sheet

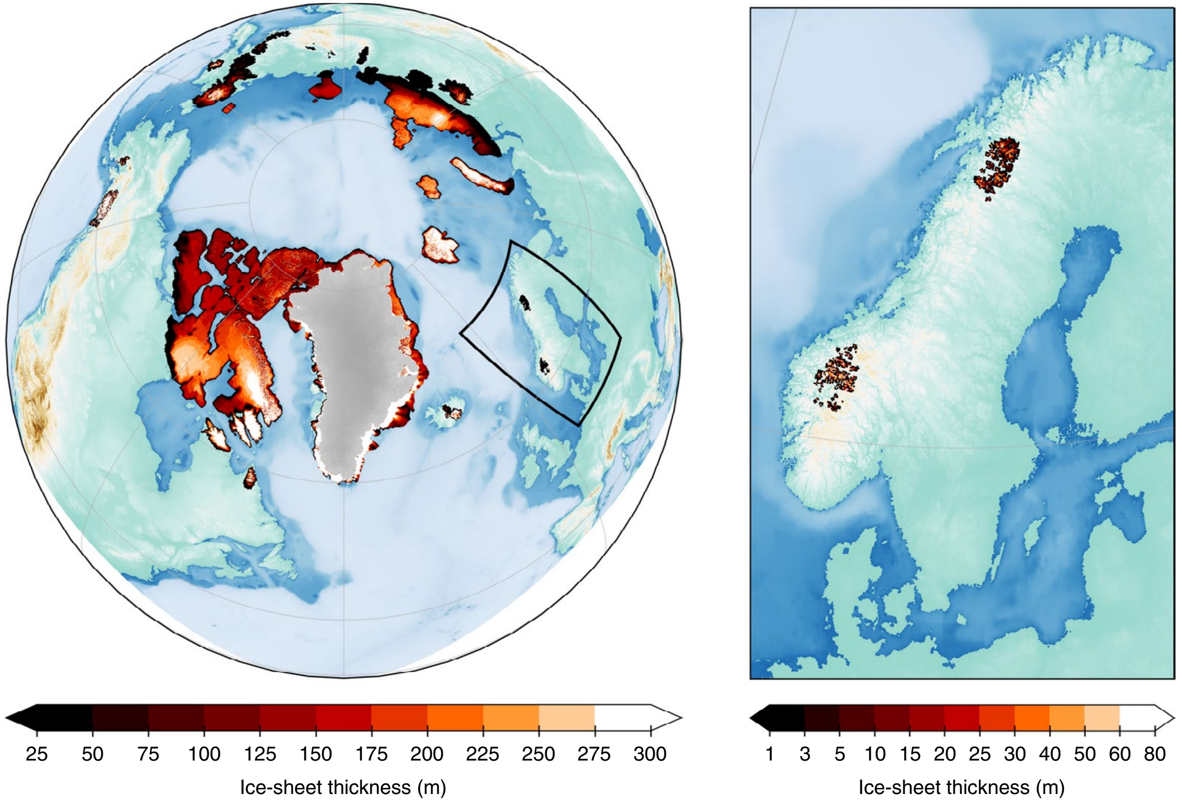
- The Greenland Ice Sheet shrinks from **8.3 m SLE** at 127 ka to **4.2 m SLE** at 122 ka, then slowly recovers.
- Interactive **vegetation** warms the climate and enhances the retreat.



Evolution of ice thickness (m) for the Greenland Ice sheet from 127 to 119 ka in a coupled CESM-CISM simulation, with vegetation updated every 500 CISM years.

Sommers et al. (2022)

Ocean gateways and ice sheet expansion

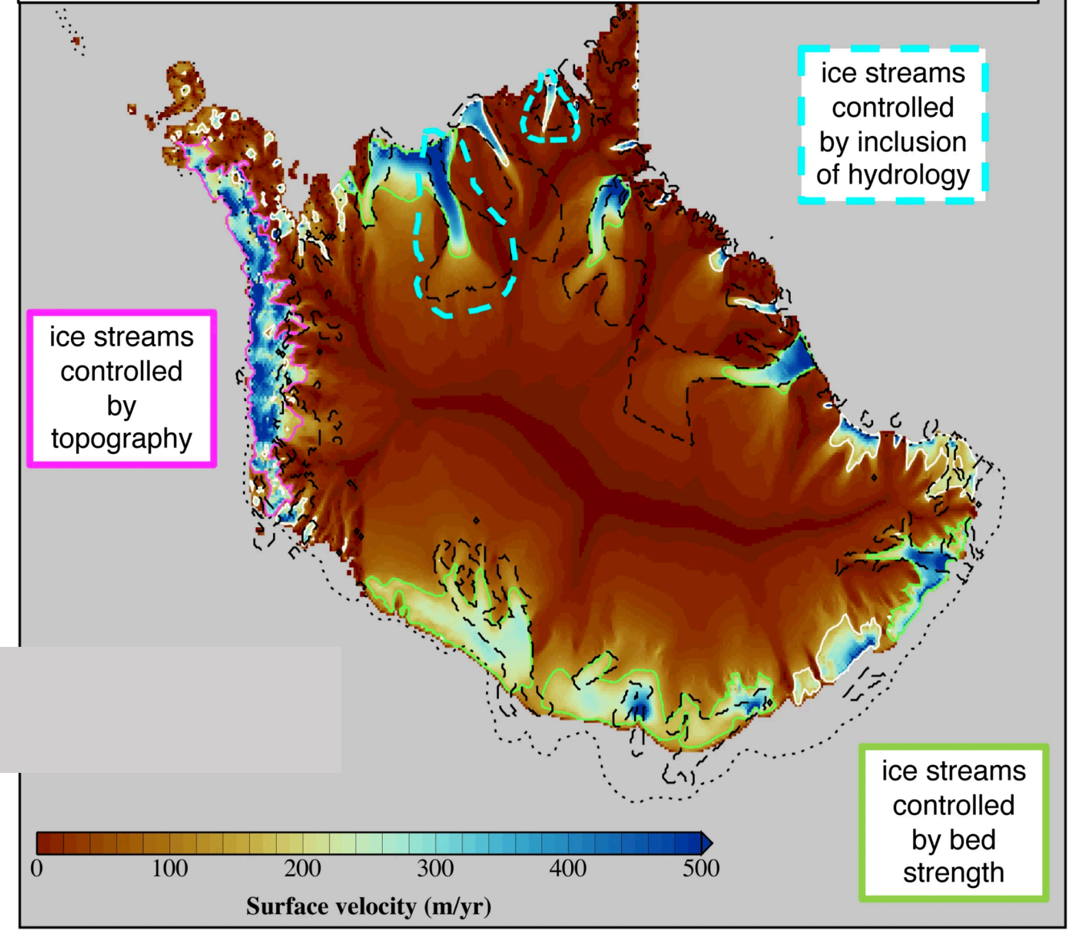


Lofverstrom et al. (2022)

- Simulated **Northern Hemisphere ice sheet inception** at 116 ka using coupled CESM–CISM.
- Proximity to the warm North Atlantic initially precludes ice growth in Scandinavia.
- A growing North American ice sheet **closes ocean gateways** in the Canadian Arctic Archipelago (left).
- **Freshwater is diverted** east of Greenland. North Atlantic freshening leads to sea ice expansion, cooling, and **Scandinavian ice growth** (right).

Paleo ice sheet simulations with CISM

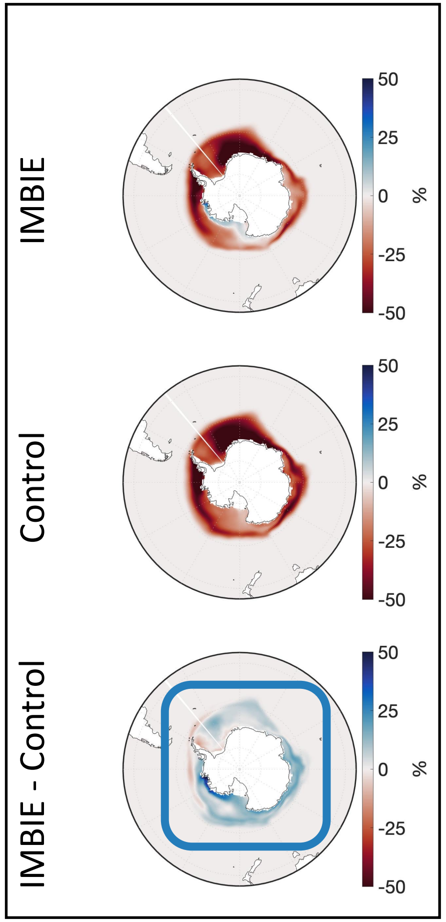
Surface velocity (m/yr) at 21ka BP from a simulation including hydrology and bed properties. Dashed black contour highlights location of known ice streams (*Margold et al., 2018; Eyles et al., 2018*) and the dotted black contour initial ice extent. Regions of fast flow (> 150 m/yr) are marked by the pink and green contours.



- CESM and CISM are being applied to the North American Ice Sheet complex at the time of the **Last Glacial Maximum**, 21 ka.
- CISM generates ice streams in good agreement with the paleoclimate record, as a result of **subglacial hydrology** (Arctic margin), **steep bed topography** (Pacific margin), and **weak basal till** (southern margin).
- These runs use offline coupling, but CESM-CISM is now enabled for **multiple coupled ice sheets**, including Antarctica.

Courtesy of Sarah Bradley

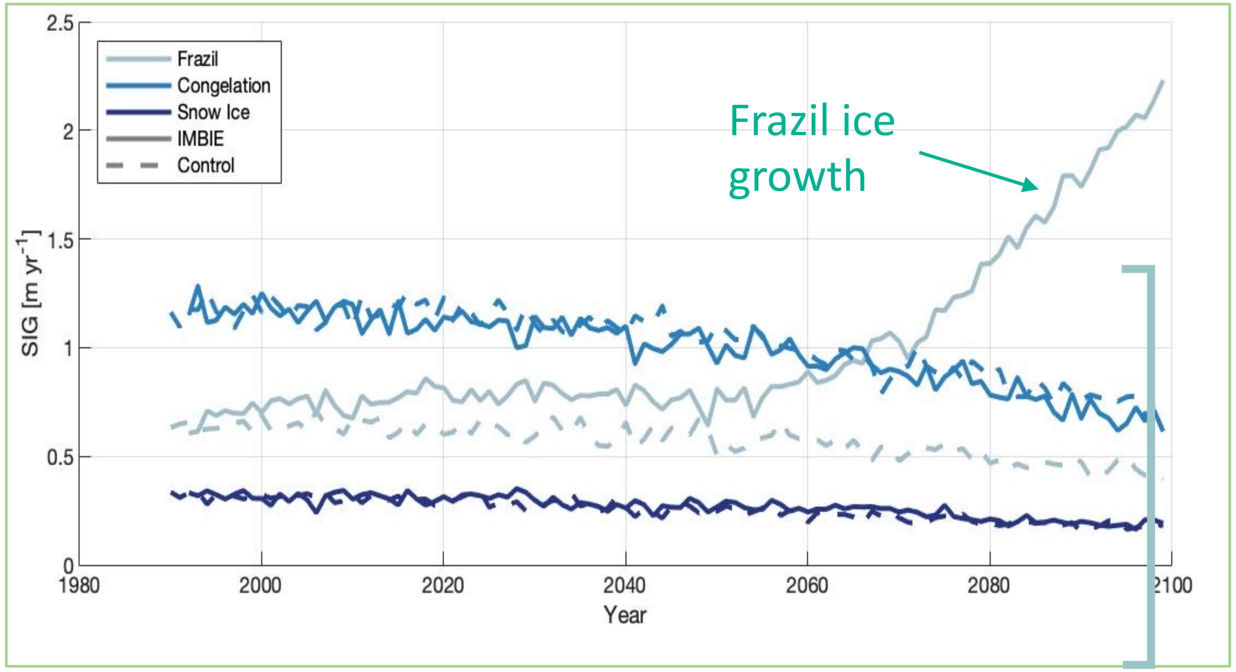
Impacts of Antarctic freshwater input to the Southern Ocean



Sea ice fraction, difference between end and beginning of century

Increased AIS freshwater (from high AIS melt scenarios) drives significantly more Southern Ocean sea ice, largely driven by **frazil ice growth**.

Sea ice growth (m/yr)

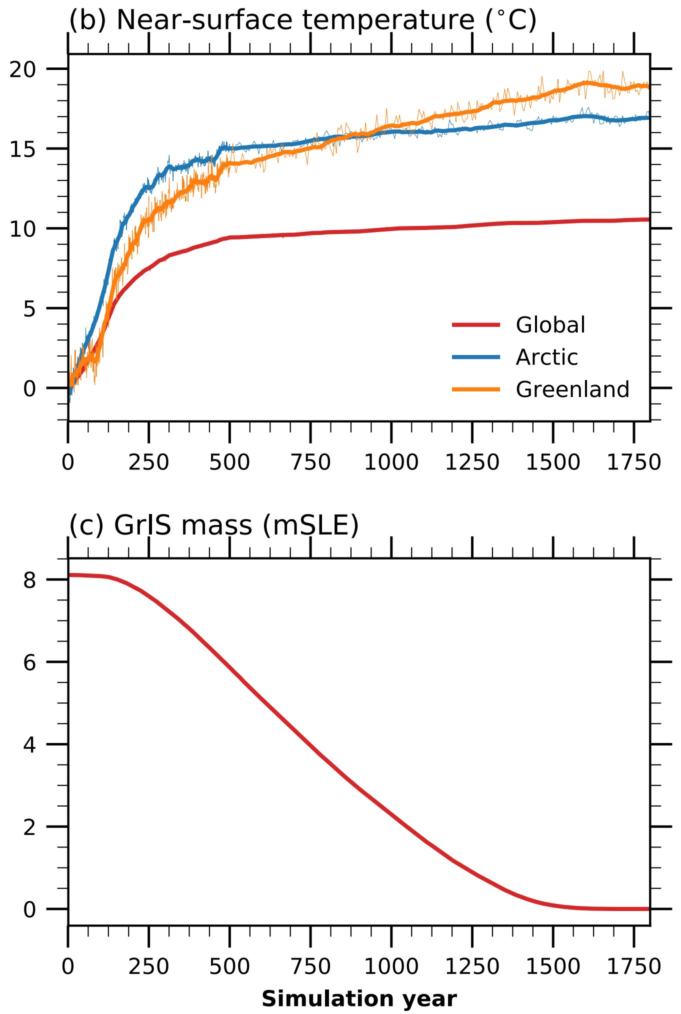


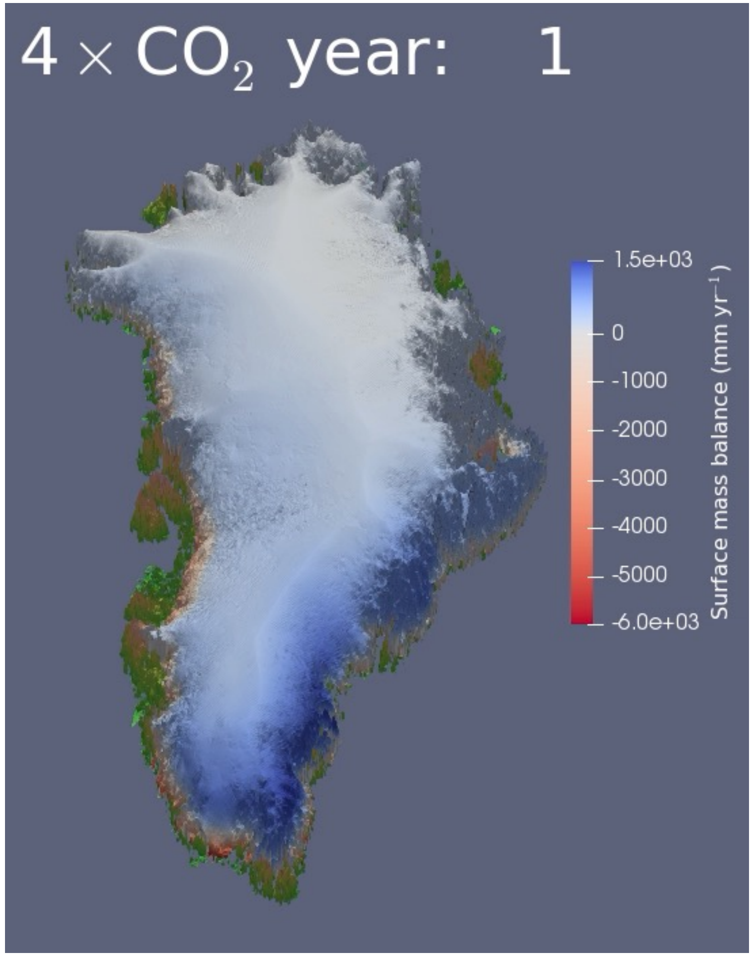
Courtesy of Tessa Gorte

What is driving the difference in sea ice?

- In addition to being fresher, the surface ocean is also cooler. The cooler, fresher surface ocean is trapping more warm water at depth.
- Also, there is a reduction of the AMOC weakening signal.

Simulations of complete Greenland Ice Sheet melting with CESM2-CISM2 under high emissions



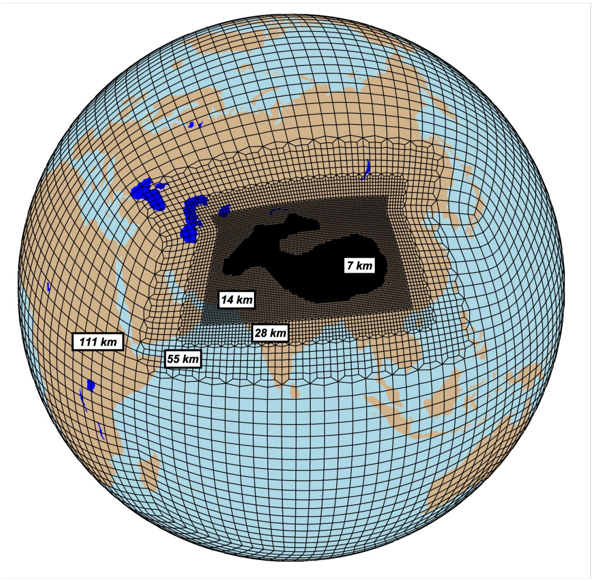


- Total deglaciation in **<1700 years** under 4xCO_2
- Fastest margin retreat in the Southwest, then the North
- Melt acceleration from albedo feedback and increased sensible and latent heat fluxes
- Feedback from glacial isostatic adjustment is modest because of the fast deglaciation

Simulating mountain glaciers with CESM and CISM

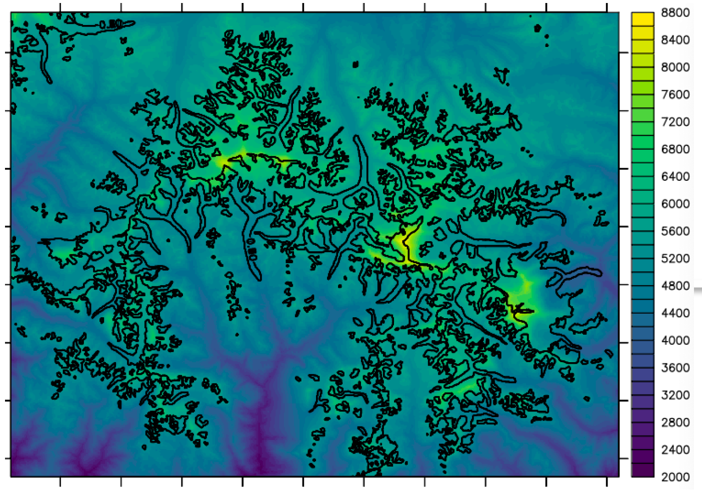
We have run 20-year simulations of glacier surface mass balance using a **variable-resolution atmosphere grid refined to 7 km over High Mountain Asia** (Wijngaard et al., in prep)

Using CISM, we will carry out **3D, fully dynamic, high-resolution (100 m) simulations** of thousands of glaciers in the Himalayas and other regions (Minallah et al., in prep)

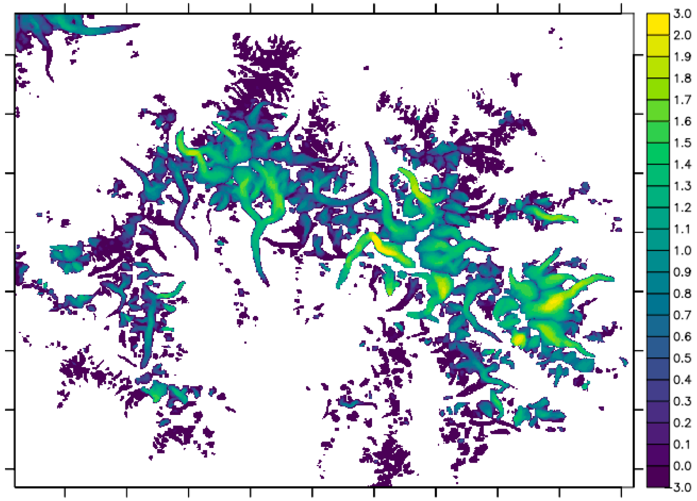


Variable-resolution CAM grid focused on High Mountain Asia (A. Herrington)

CISM glacier simulations in the Nepal Everest region



Initial surface elevation and glacier outlines

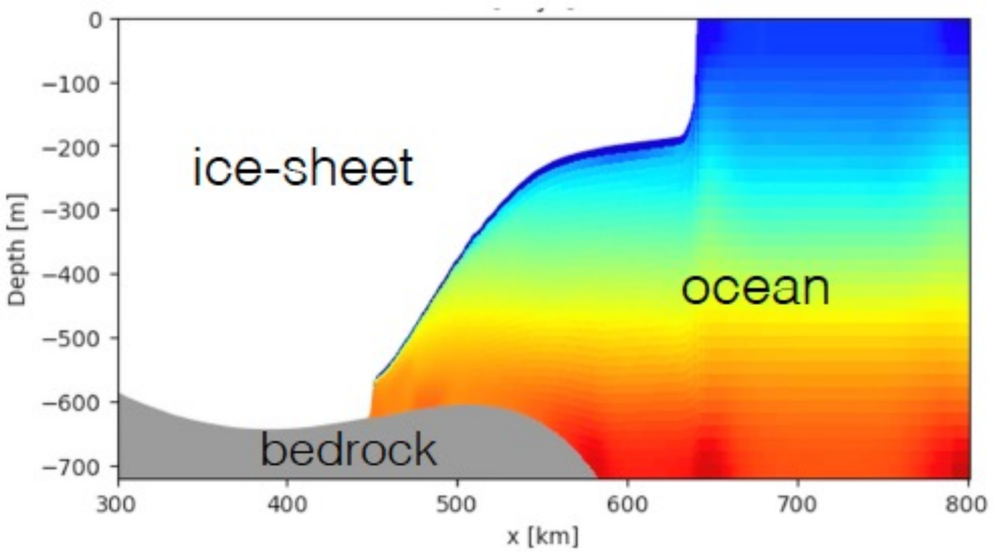


Simulated surface ice speed (m/yr, log scale)

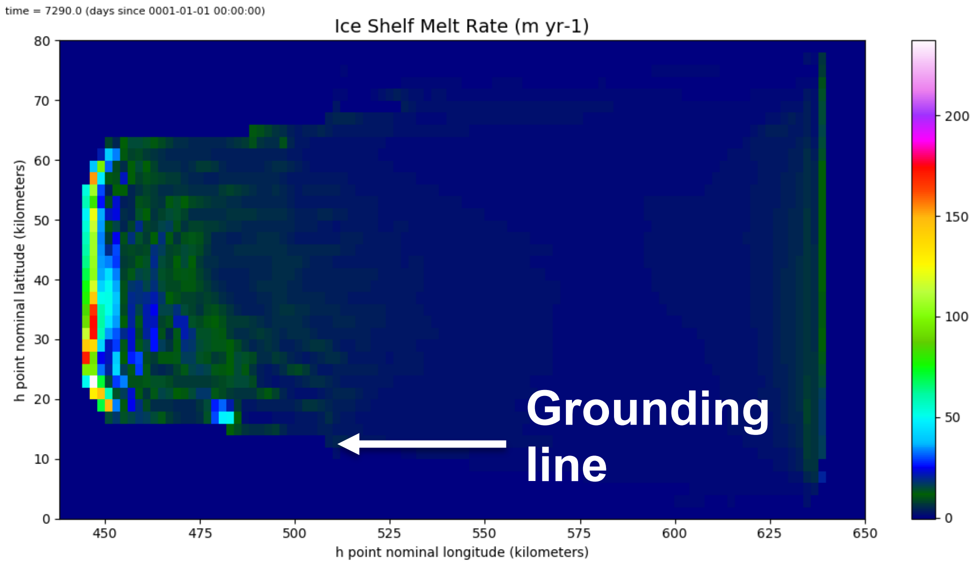
Antarctic coupling

Until now, CESM has supported interactive coupling only with the Greenland Ice Sheet.

- We are adding support for Antarctic ice sheet coupling and running multiple ice sheets in a single simulation, including paleo ice sheets.
- The MOM6 ocean model (replacing POP) allows ocean circulation beneath ice shelves.



Schematic of sub-ice-shelf cavity



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

Plans for CISM3

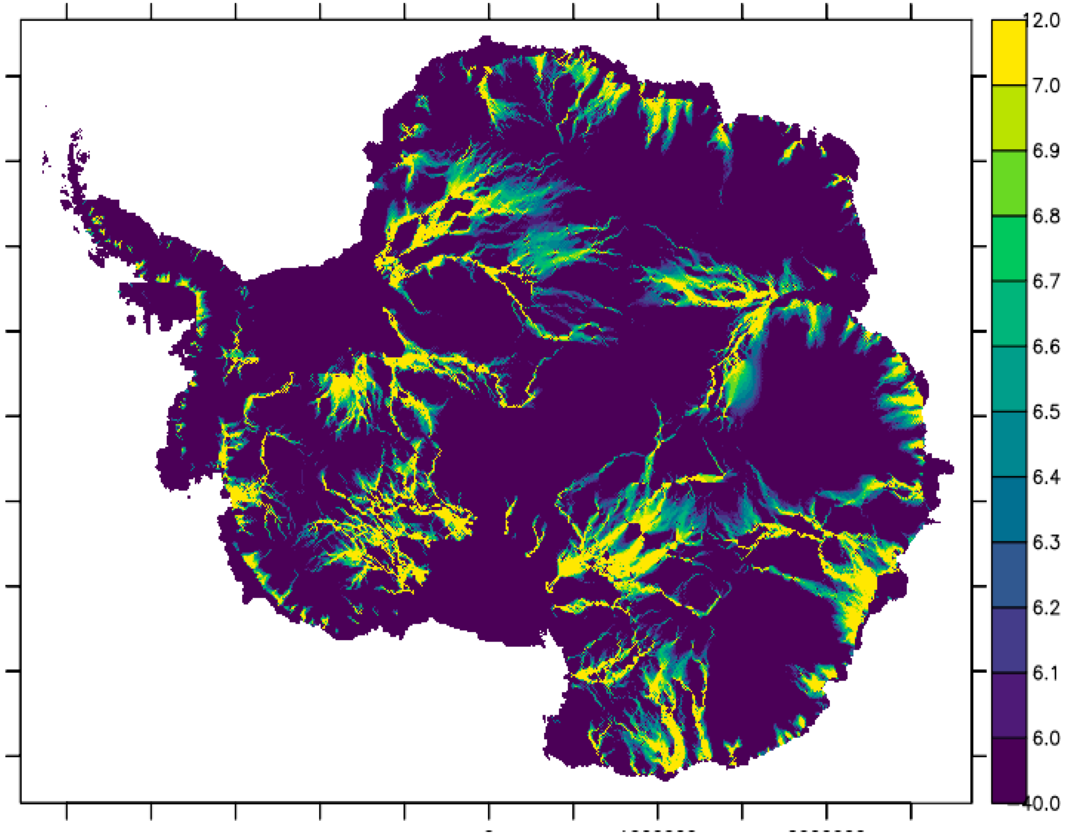
CESM3 will support fully coupled climate – ice sheet simulations with **Greenland, Antarctica, and/or paleo ice sheets**.

- Until now, CESM-CISM has supported only a single ice sheet. The only out-of-the-box ice sheet has been Greenland.
- 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. (Thanks to Bill Sacks and Mariana Vertenstein for software development.)

We also plan to use CISM and CESM for studies of **mountain glacier retreat** and regional water security (e.g., GlacierMIP).

CISM development

- **Subglacial hydrology model**
- Better models of **iceberg calving** and **sub-ice-shelf melting**
- **Hydrofracture and cliff collapse**
- **Mountain glaciers**
- **Solid Earth and sea level model** (glacial rebound, ice sheet self gravity)
- **Water isotopes**



Basal water flux (log scale) for the Antarctic Ice Sheet in a steady-state subglacial water model.

Modeling summary

- For ice sheets, CESM2 and CISM2 include major scientific and software advances compared to earlier models.
- These advances are enabling first-of-a-kind coupled simulations of ice sheets in past and future climates.
- Coupling of ice sheets to the land and atmosphere is fairly mature, but ocean–ice sheet coupling is just beginning.
- Uncertainty in sea-level projections continues to be dominated by Antarctica.

Science summary

- Sea level rise by 2100 probably will not be much greater than 1 meter.
- With global average warming of **> 2^{o}C**, long-term sea level rise of **5 m or more** is likely (based on past climates).
- Once critical thresholds are reached, ice sheet retreat in some regions may be **irreversible**.

Contact information

Land Ice Working Group website:
https://www.cesm.ucar.edu/working_groups/Land+Ice/

Co-chairs:

- Bill Lipscomb, NCAR, Lipscomb@ucar.edu
- Miren Vizcaino, TU Delft, M.Vizcaino@tudelft.nl

Liaisons:

- Gunter Leguy, NCAR, gunterl@ucar.edu
- Kate Thayer-Calder, NCAR, katec@ucar.edu

Please join us for our winter meeting in 2023.