Land Ice Modeling in CESM

Annual CESM Tutorial

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NCAR

NSF

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Outline

Part 1: Land ice and sea level

Part 2: Ice Sheets in CESM

Part 3: Research highlights

Part 4: Recent and ongoing research

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Outline

Part 1: Land ice and sea level

land ice

Snow => Ice => flow

Causes of global sea level rise (SLR)

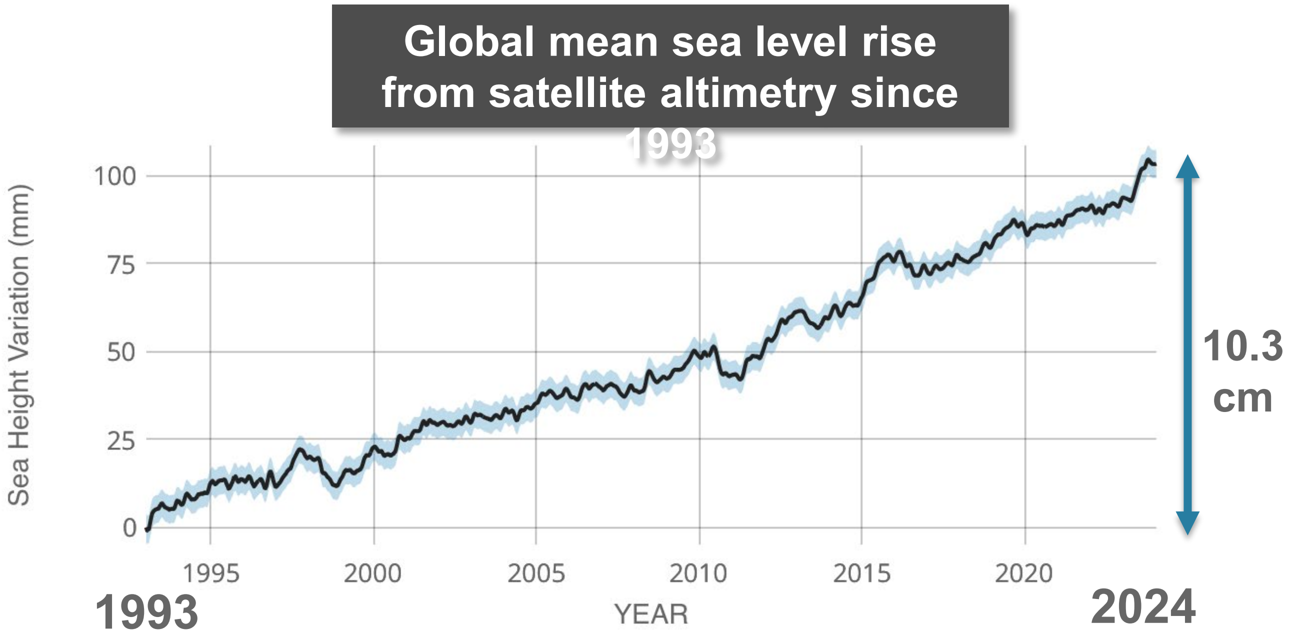
Most 20th century sea-level rise was caused by **ocean thermal expansion** and **mountain glacier melting**.

The **Greenland and Antarctic ice sheets** began losing mass around 1990 and now account for about 40% of sea level rise.

Global mean sea level has risen by about 21 cm since 1900. Since 1993 the rate of SLR has increased from about 2 mm/yr to **4 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

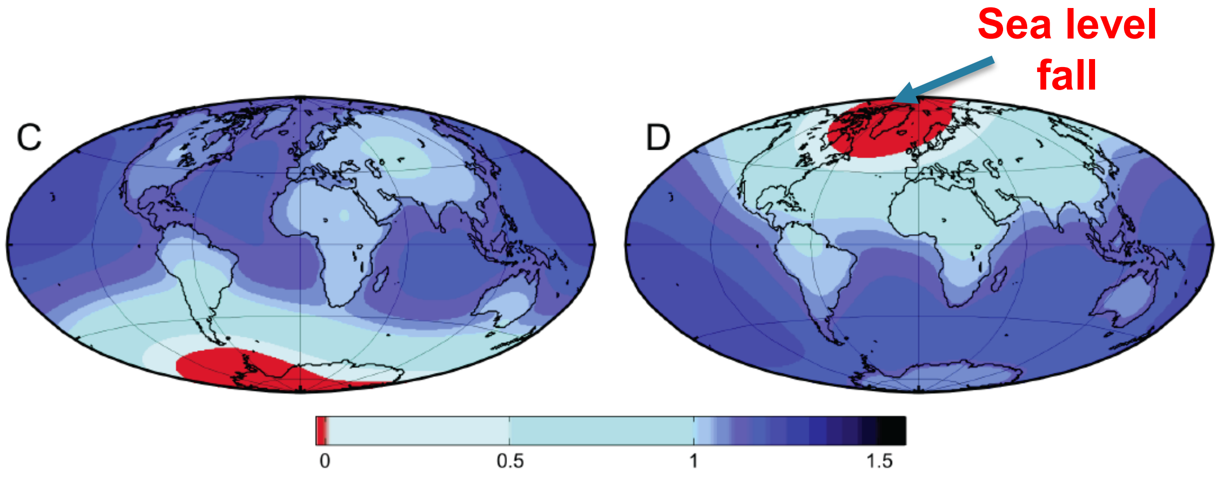


Credit: NASA GSFC/PO.DAAC

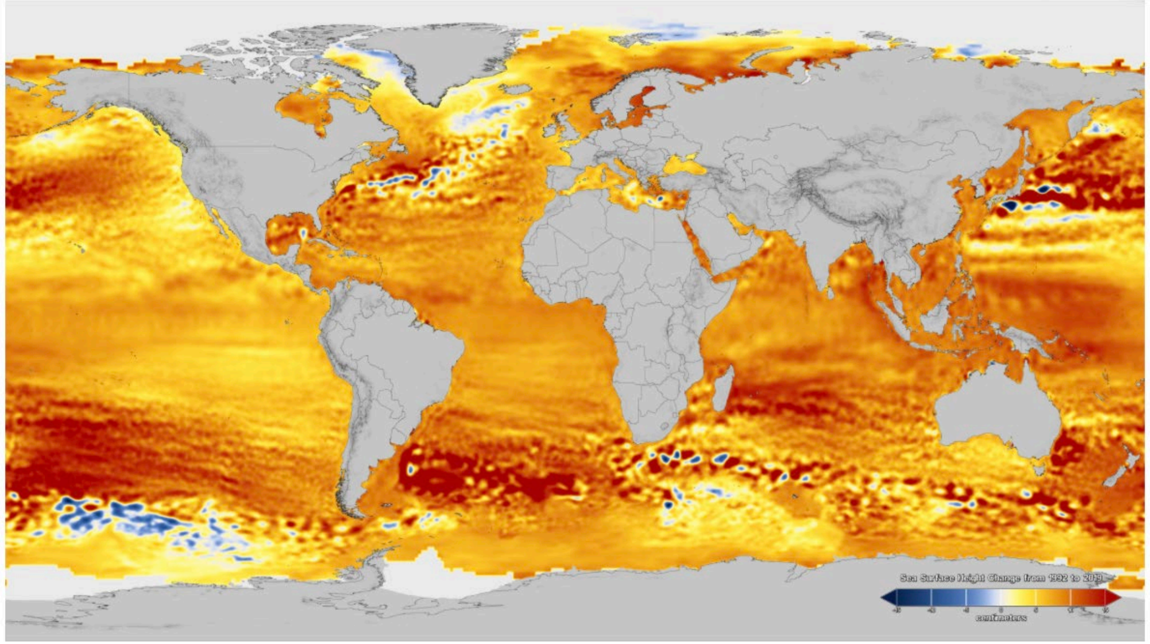
Regional sea-level variations

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.



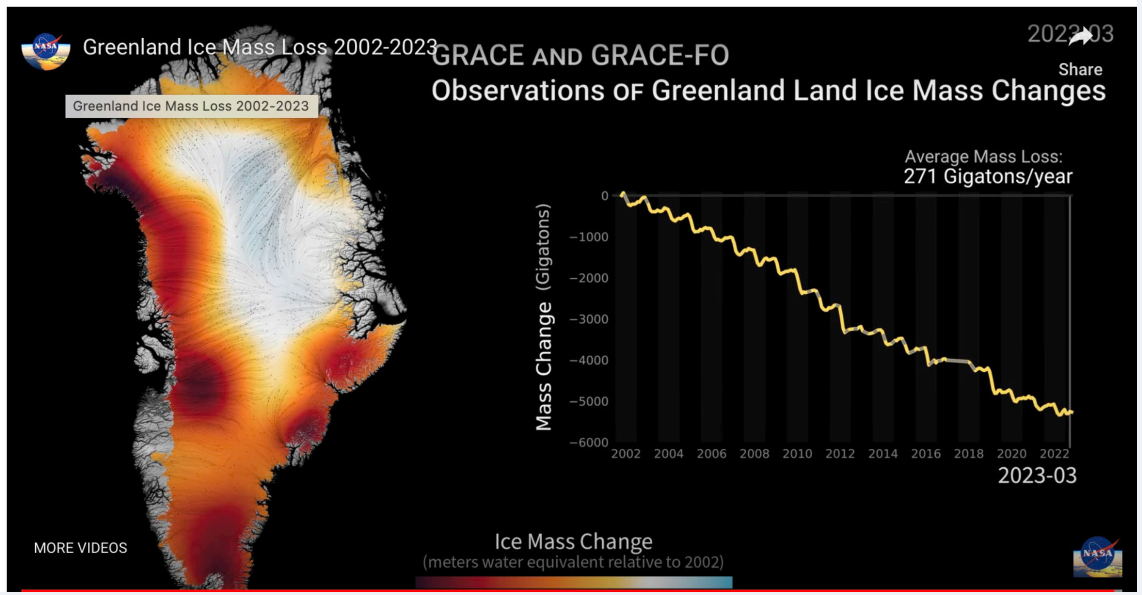
Relative sea-level change from retreat of the Antarctic Ice Sheet (left) and Greenland Ice Sheet (right) (Mitrovica et al. 2011).



Change in sea surface height, 1993–2019, as measured by satellite altimetry.
Credit: NASA.

Greenland Ice Sheet

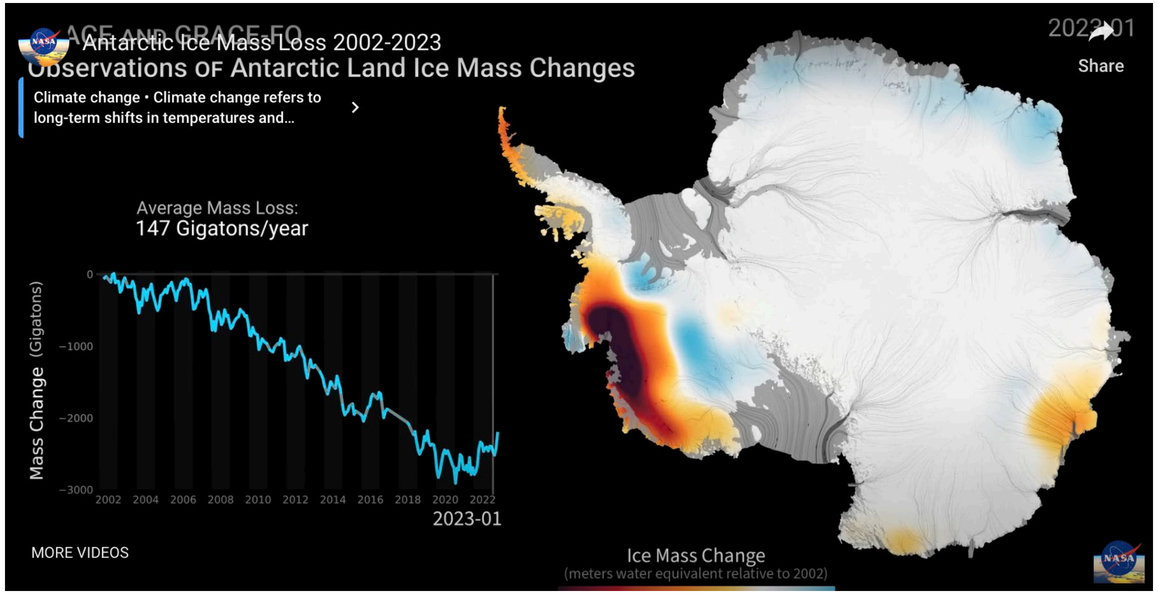
- **7 m** sea level equivalent (SLE)
- **Snowfall** balanced by **surface runoff** and **iceberg calving**
- Mass loss of **270 Gt/year** since 2002



Greenland mass change from GRACE, 2002–2023

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 **150 Gt/year** since 2002



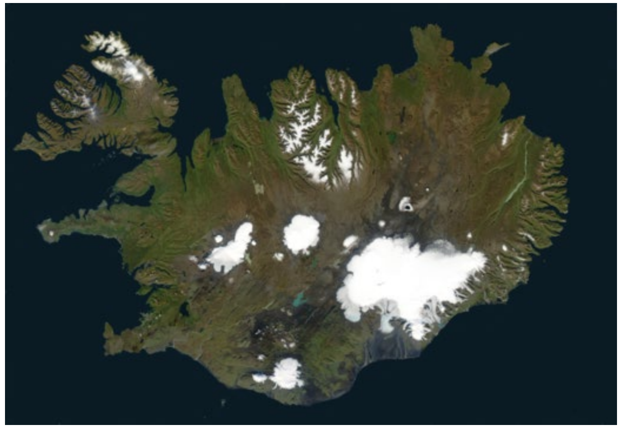
Antarctic mass change from GRACE, 2002–2023

Credit: NASA and JPL/Caltech

Mountain glaciers

- Glaciers outside the two ice sheets contain about **0.4 m** sea level equivalent.
- The volume is small compared to ice sheets, but the relative rate of loss is large: about **230 Gt/yr**, 2006–2018.

Mer de Glace, French Alps



Vatnajokull ice cap, Iceland

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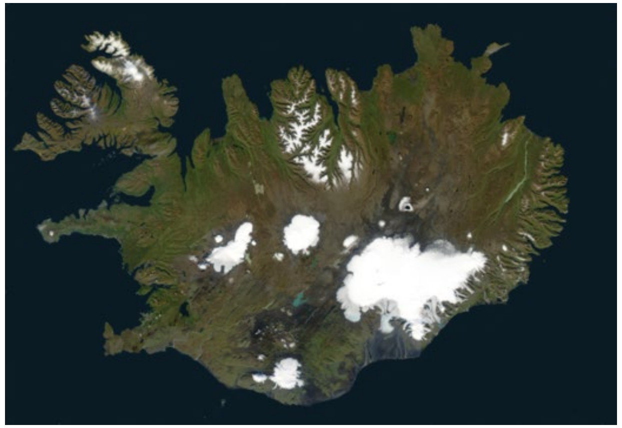


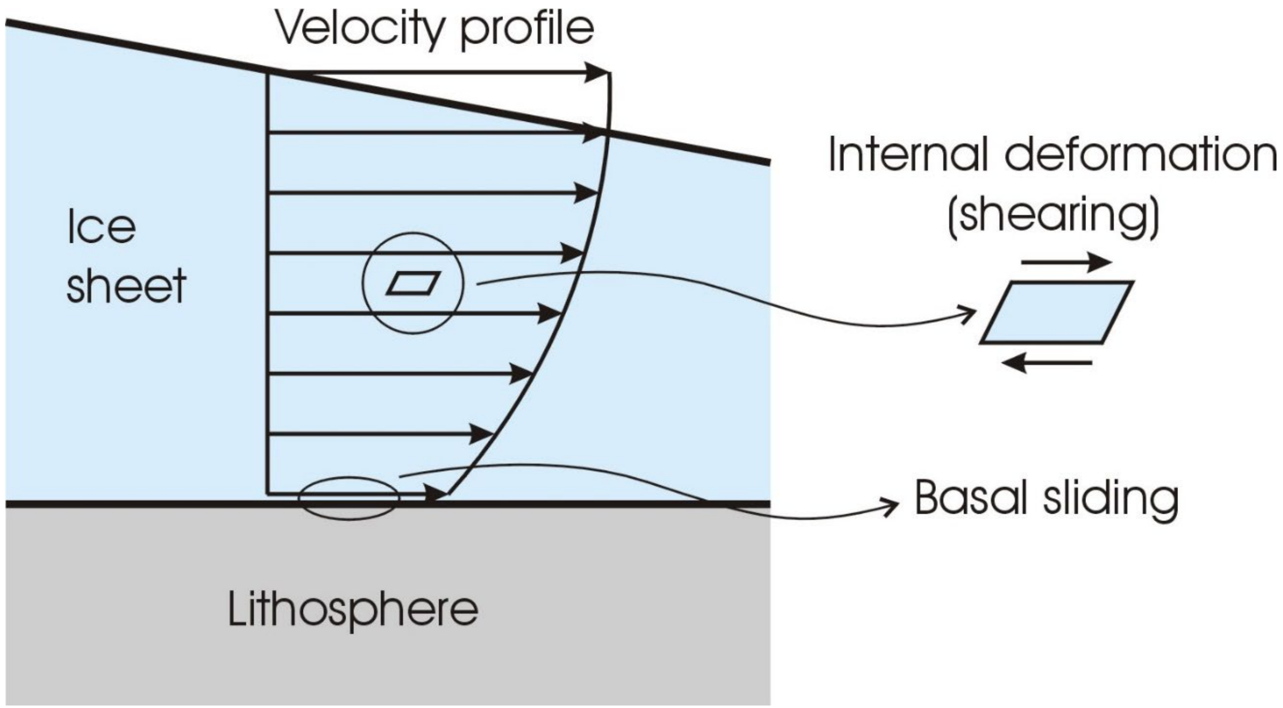
Vatnajokull ice cap, Iceland

- Besides raising sea level, glacier melting can endanger **water supplies**, **collapse** on nearby population, and trigger **outburst flooding**.

Glacier outburst flood
near Juneau Alaska, 08-06-24

How glaciers move

- **Glaciers flow downhill** under the force of gravity.
- Ice deforms like a **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

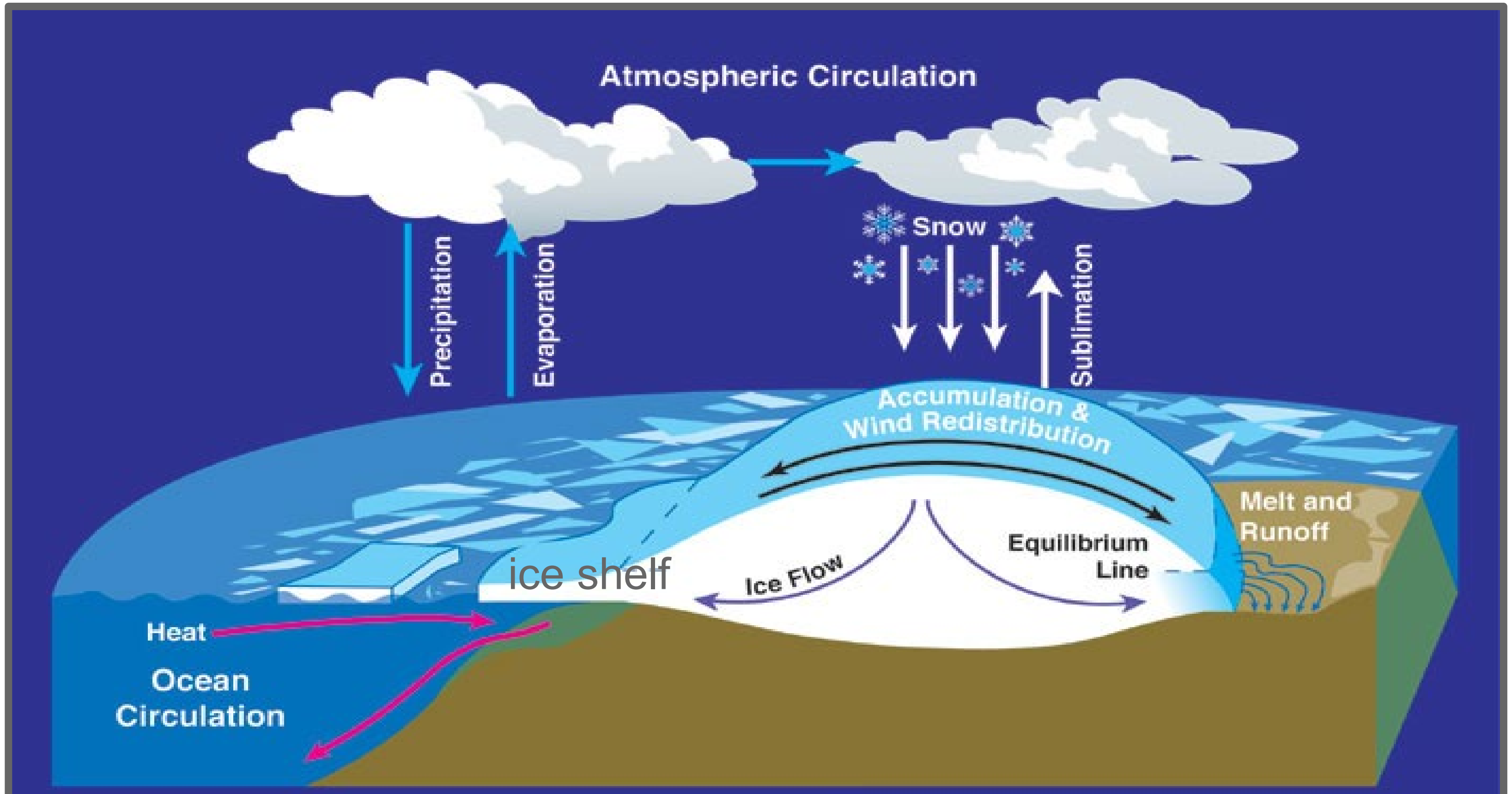


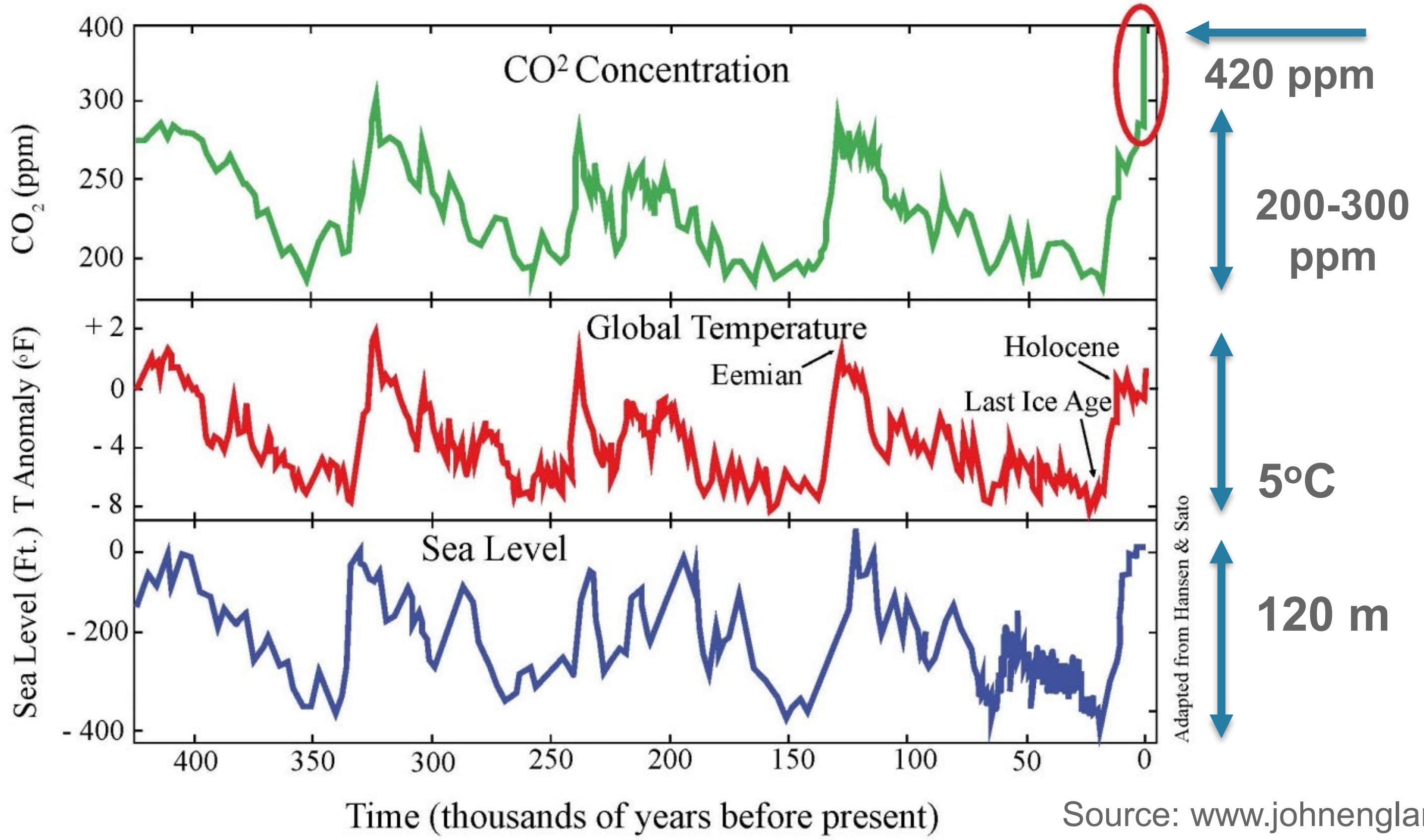
Image source: http://www.nasa.gov/images/content/53743main_atmos_circ.jpg

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**.

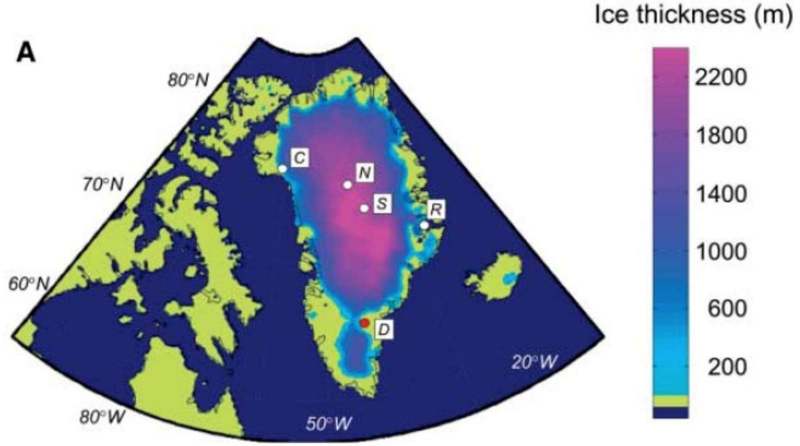


Source: www.johnenglander.net

Ice sheets in warm climates

Last Interglacial (125,000 years ago)

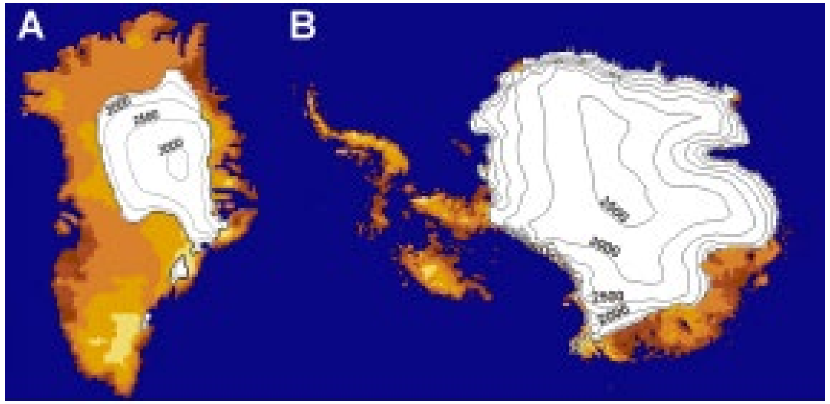
- Warming **1-2°C**, CO_2 = **280 ppm**
- Global sea level **6–9 m higher** than now
- About 2–4 m from Greenland, > 2 m from Antarctica



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

Pliocene (3 million years ago)

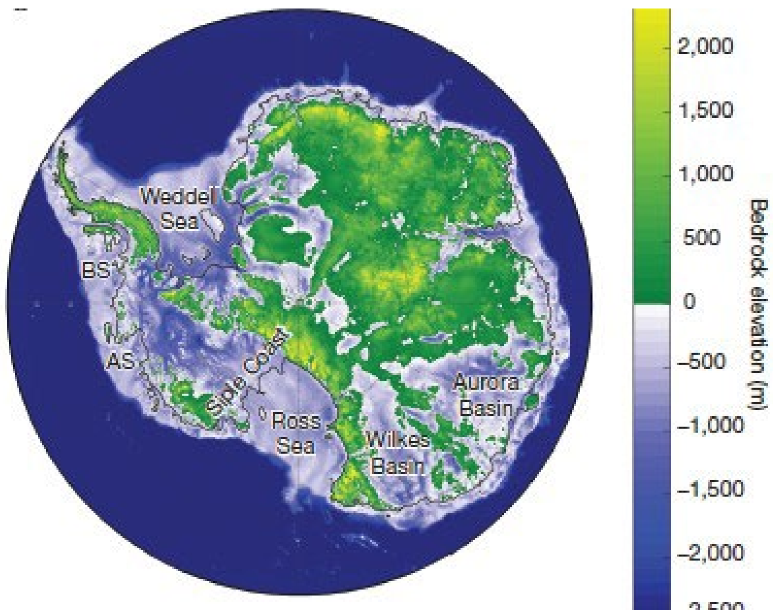
- Warming **2-3°C**, CO_2 = **400 ppm**
- Global sea level **5–20 m higher** than now
- Up to 7 m from Greenland, 5 m from West Antarctica, and possibly retreat from East Antarctica



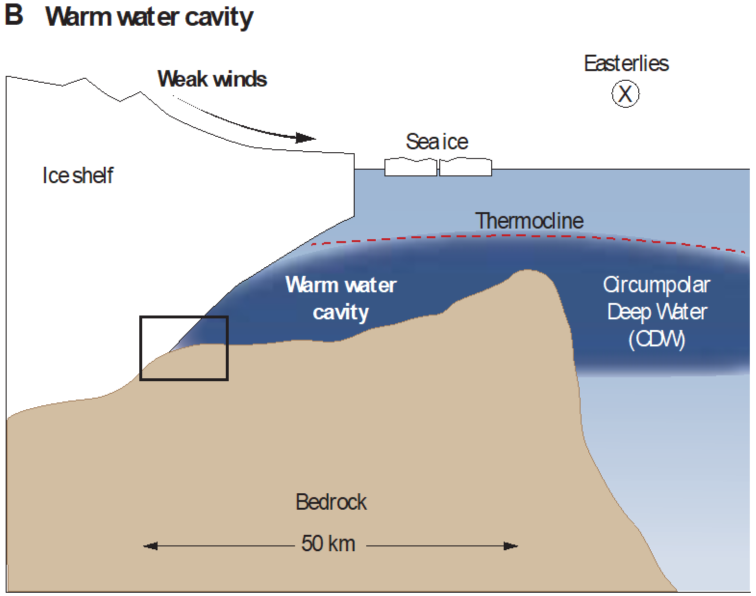
Pliocene ice sheet reconstructions (Haywood et al. 2010)

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



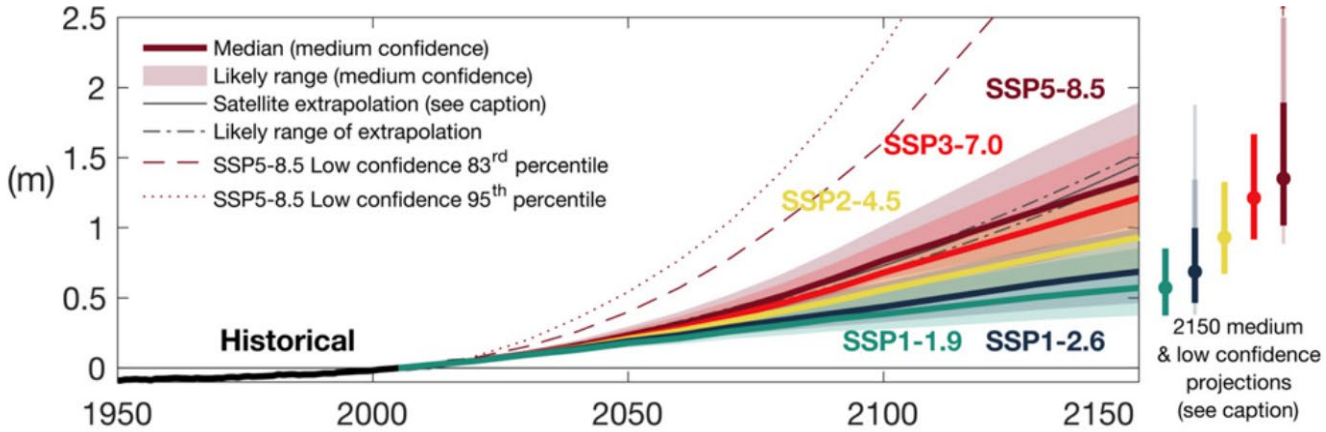
Schematic of a warm sub-ice-shelf cavity (Holland et al. 2020)

IPCC AR6 sea level projections

Chapter 9: Ocean, cryosphere, and sea level

- "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**", including 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)

Outline

Part 2: Ice Sheets in CESM

Ice sheets in the Community Earth System Model (CESM)

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

- Dynamic ice sheets break the assumption of fixed boundaries between land, atmosphere and ocean.

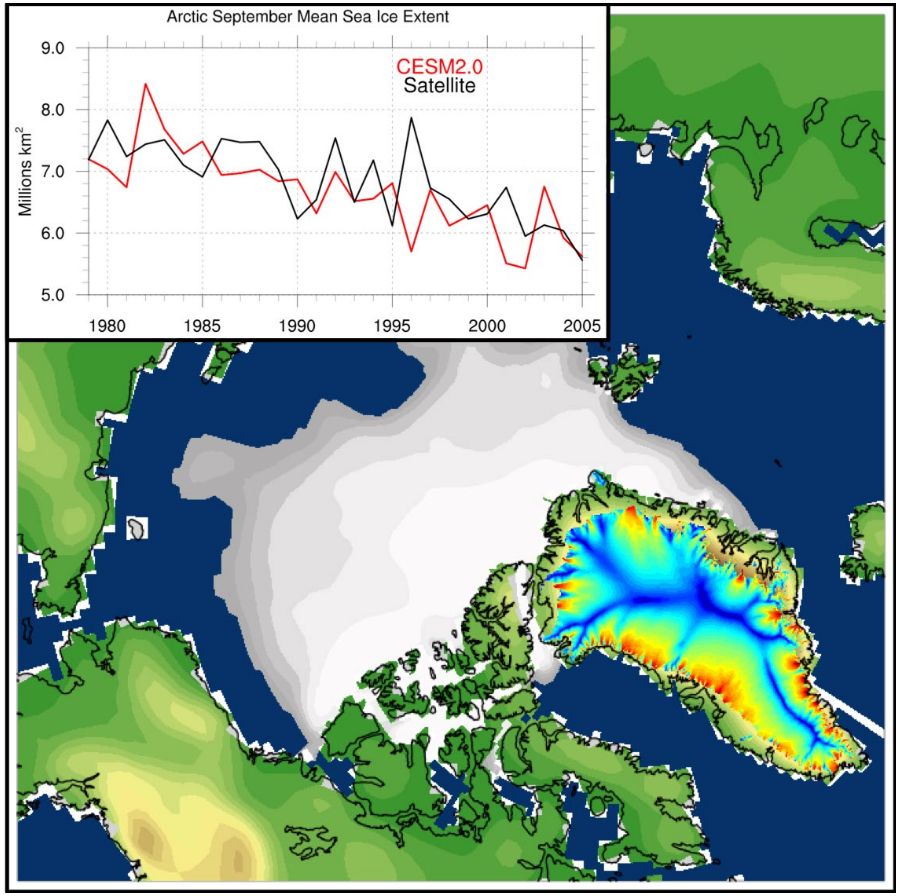
Simplifying assumptions in CESM1:

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

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 (~4 km).
- The **Community Ice Sheet Model (CISM)** computes ice flow.

Ice sheets in CESM2



CESM2 (2018+) 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 and passes it to CISM.
  - CISM returns the new ice sheet area and elevation.
  - Land types evolve dynamically (glacier ⇔ vegetated).

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

Ice sheet coupling in CESM2

Land -> Ice sheet

(10 classes + bare land)

- Surface mass balance
- Surface elevation
- Surface temperature

Ice sheet -> Land

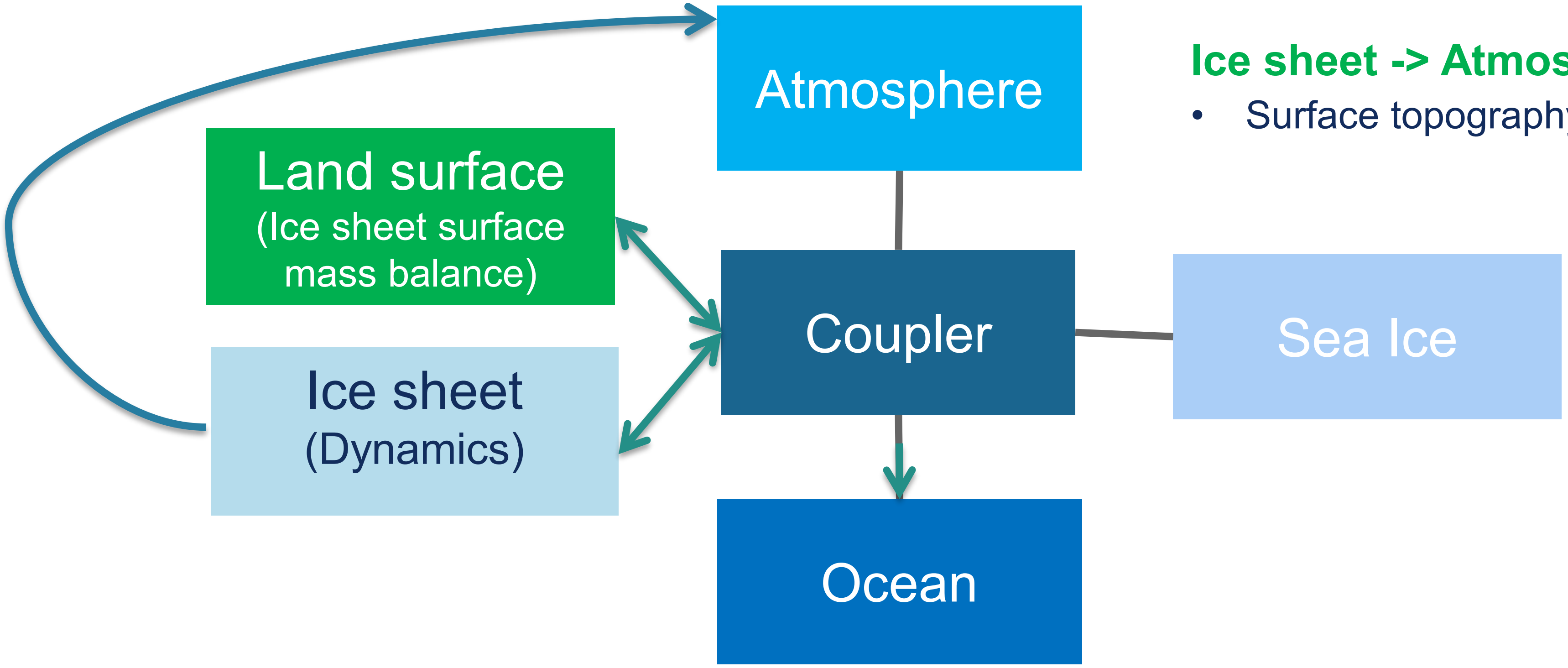
- Ice extent
- Ice surface elevation

Ice sheet -> Ocean

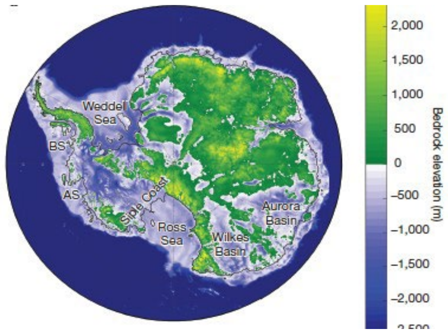
- Solid and liquid fluxes

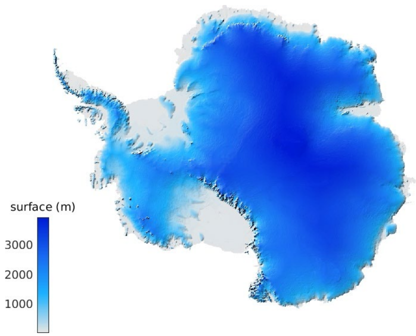
Ice sheet -> Atmosphere (offline)

- Surface topography



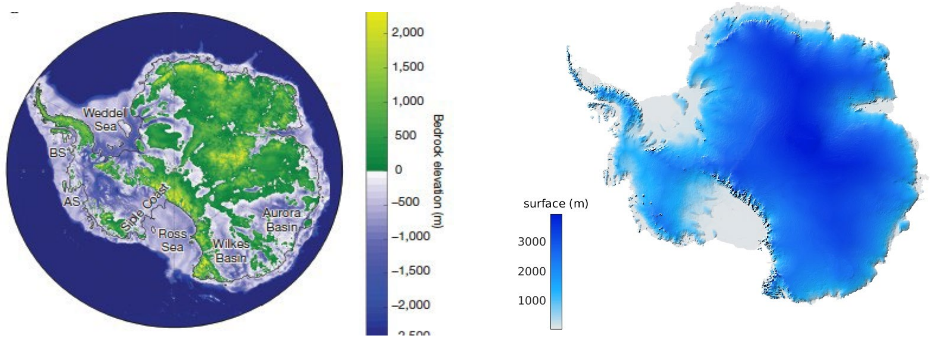
Ice sheet initialization





Bed topography and ice surface elevation
(Morlighem et al. 2019)

Ice sheet initialization



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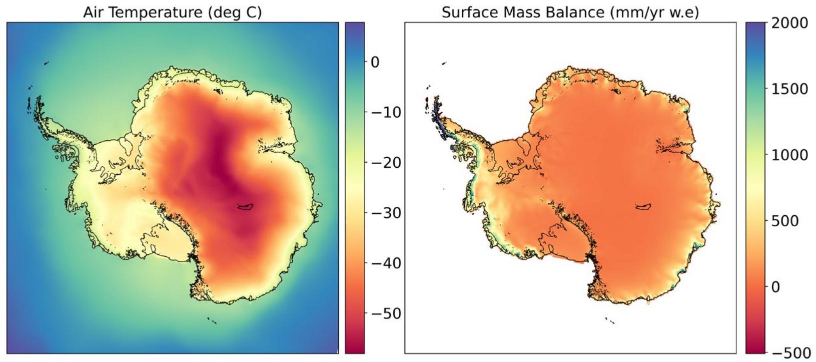

Surface temperature and mass balance
(van Wessem, 2018)

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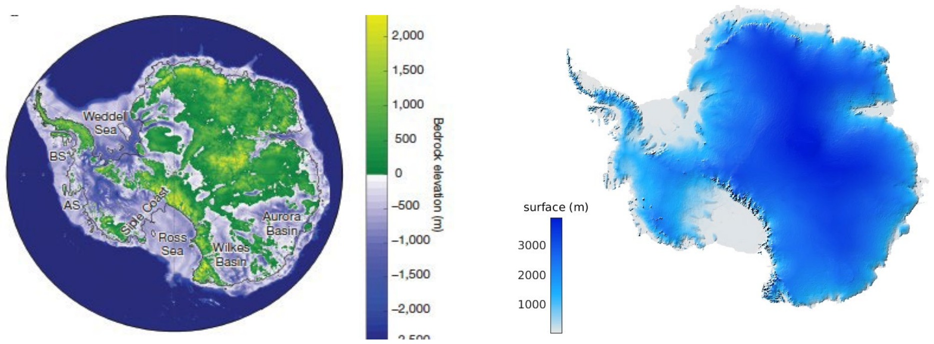

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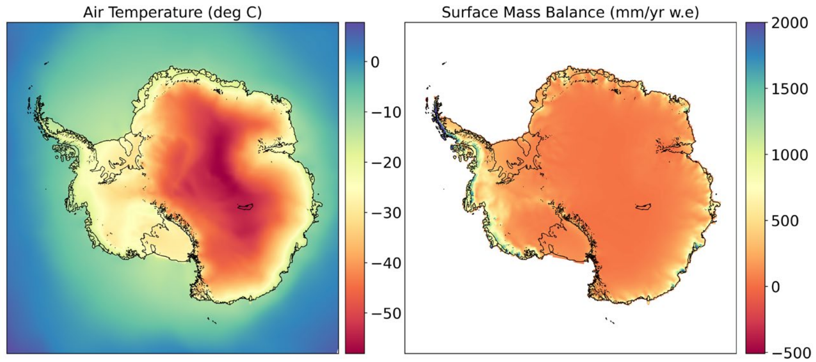

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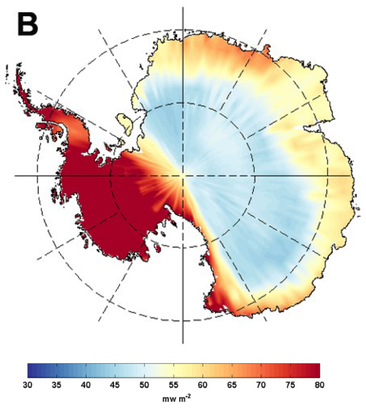
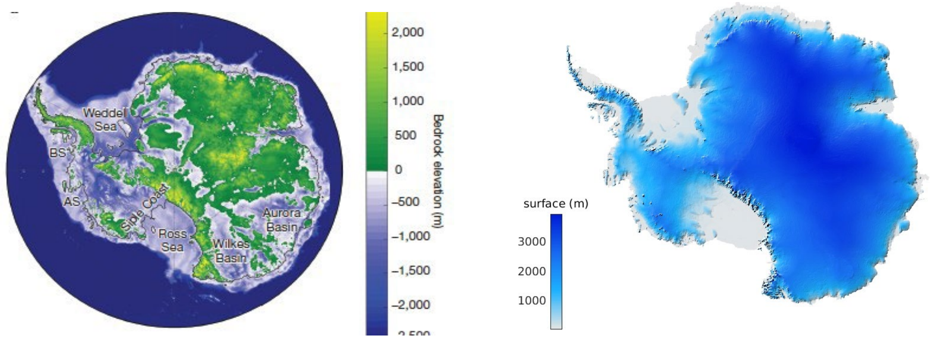


Geothermal heat flux
(Shapiro and Ritzwoller, 2004)

Ice sheet initialization



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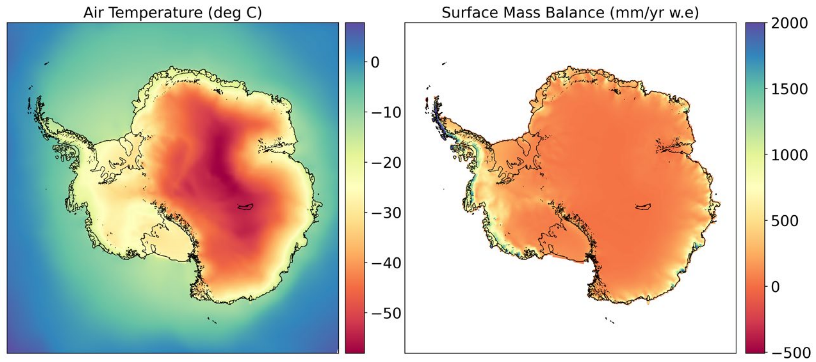

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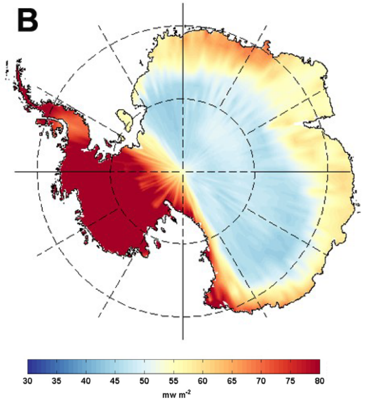

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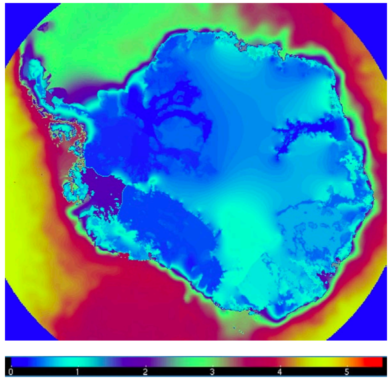
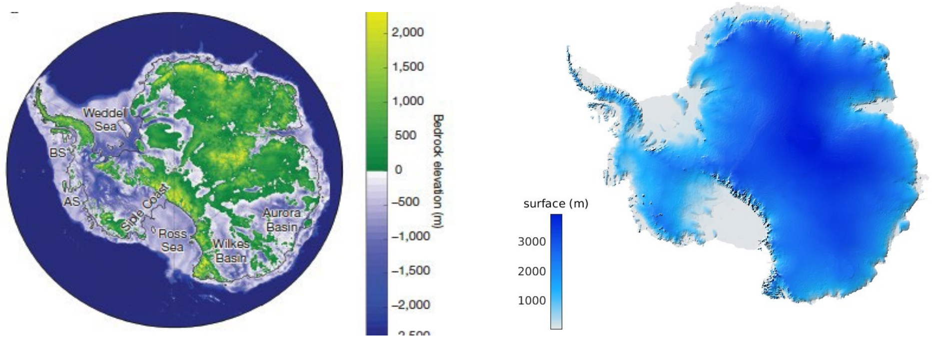


Ocean thermal forcing
(Jourdain et al., 2020)

Ice sheet initialization



Bed topography and ice surface elevation
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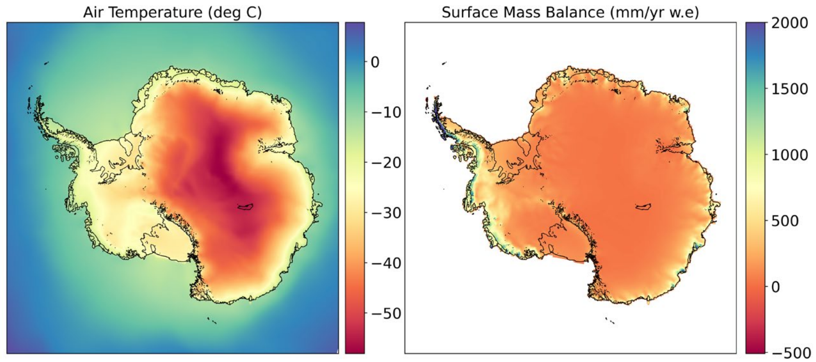

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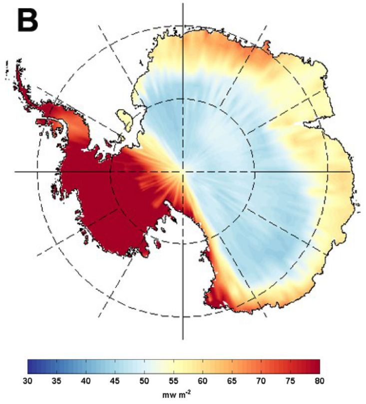
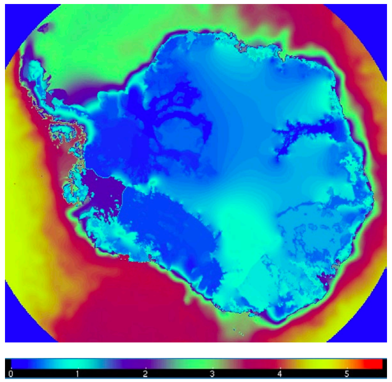


Geothermal heat flux
(Shapiro and Ritzwoller, 2004)

Run the model for 10,000 to 20,000 years and invert for basal friction coefficients



Ocean thermal forcing
(Jourdain et al., 2020)

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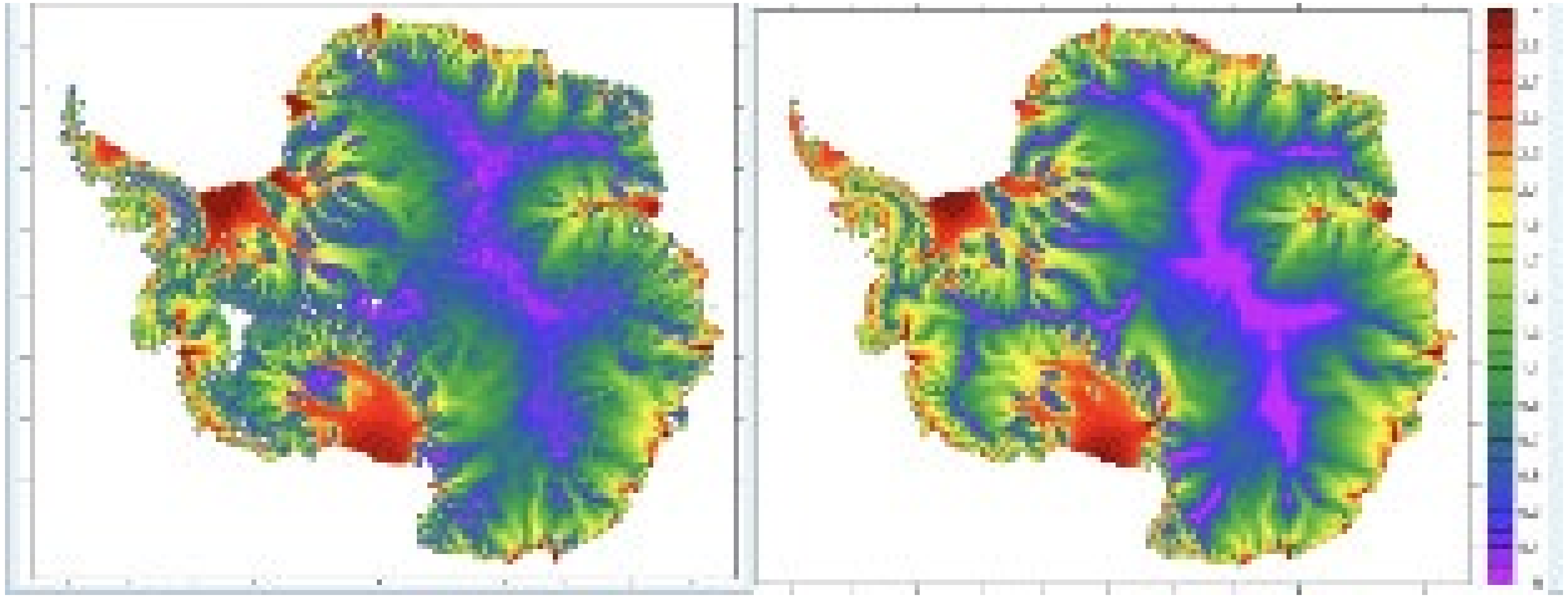
Ice sheet initialization

Surface ice speed (m/yr, log scale)



Observed
(Rignot et al., 2011)

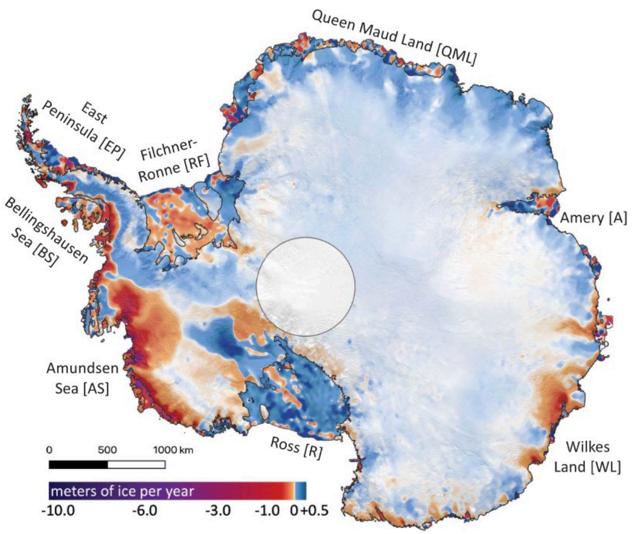
Modeled

With this method, the ice sheet is stable meaning if we run the model forward with the same forcing, nothing would (should) happen

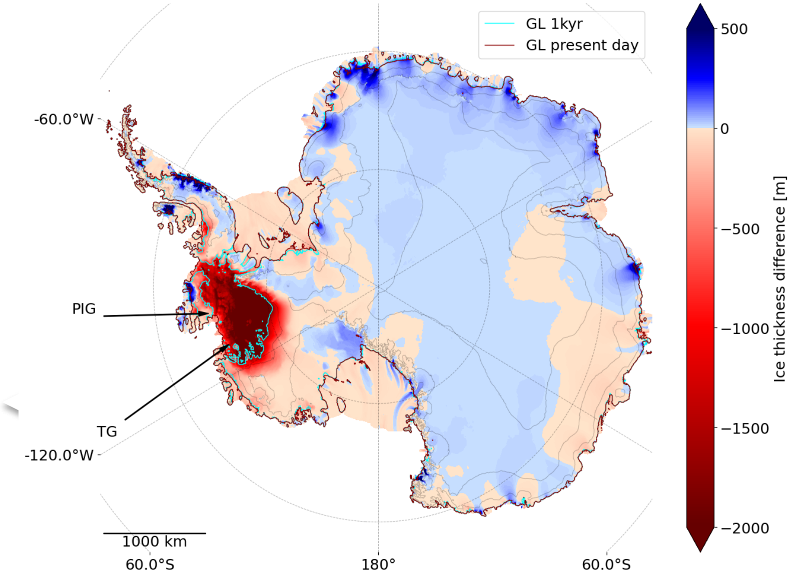
Ice sheet initialization

A new spin-up technique optimizes the match to both **observed thickness** and observations of **recent thickness change**.

Simulations suggest that the **Pine Island and Thwaites basins will likely collapse** over the next several centuries **even without further warming**.



Van den Akker et al. (2024, in review)

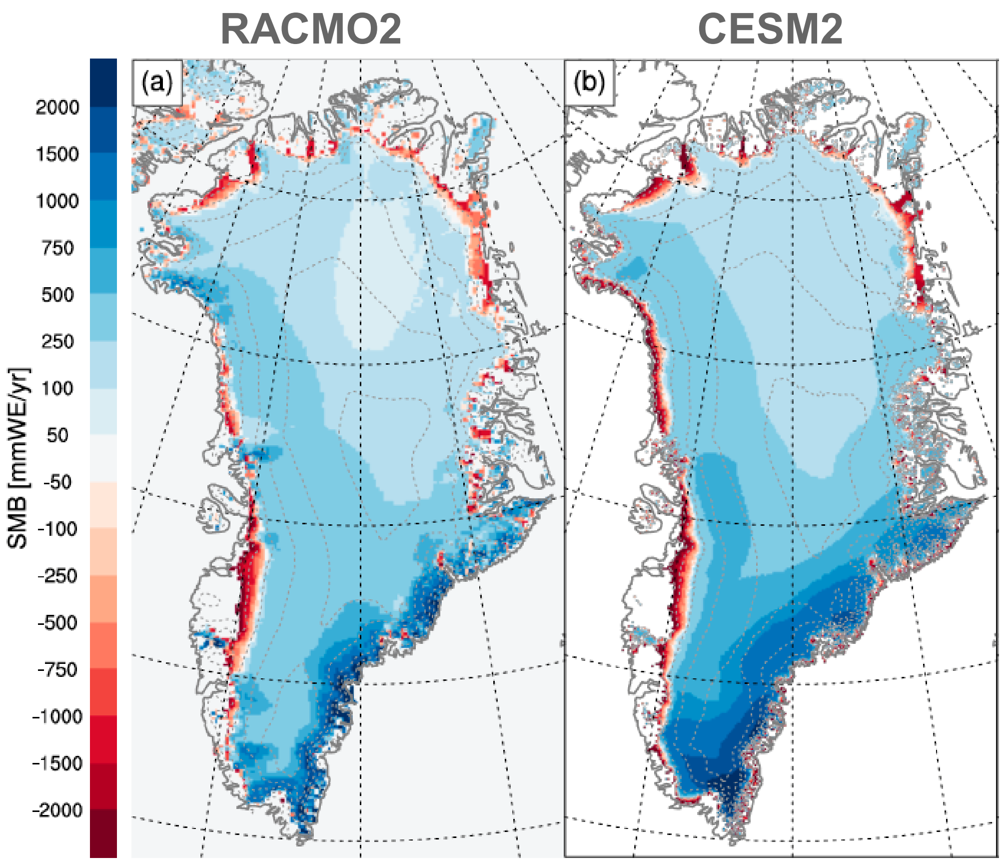


Observed rate of ice thickness change (m/yr), 2003–2019 (Smith et al. 2020)

Simulated thickness change (m) over 1000 years after a spin-up with observed thinning rates.

Greenland surface mass balance in CESM2

- The Greenland surface mass balance in CESM2 compares well with **regional Arctic models** that are run at ~5x higher resolution (~10–20 km).
- However, there is **too much snowfall** in the interior of southern Greenland, mainly because of coarse topography.



Courtesy of Leo van Kampenhout.

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

Greenland surface mass balance in CESM2

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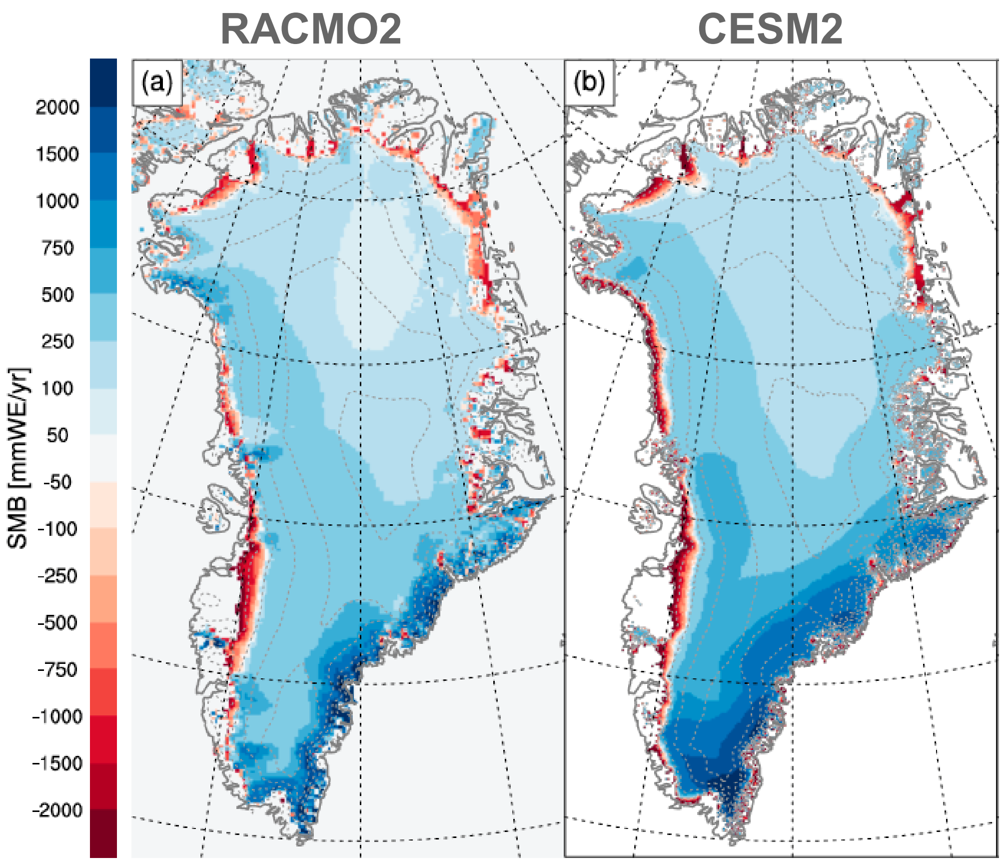
In CESM3, the SMB looks similar to the one in CESM2



Courtesy of Leo van Kampenhout.

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

Outline

Part 3: Research highlights

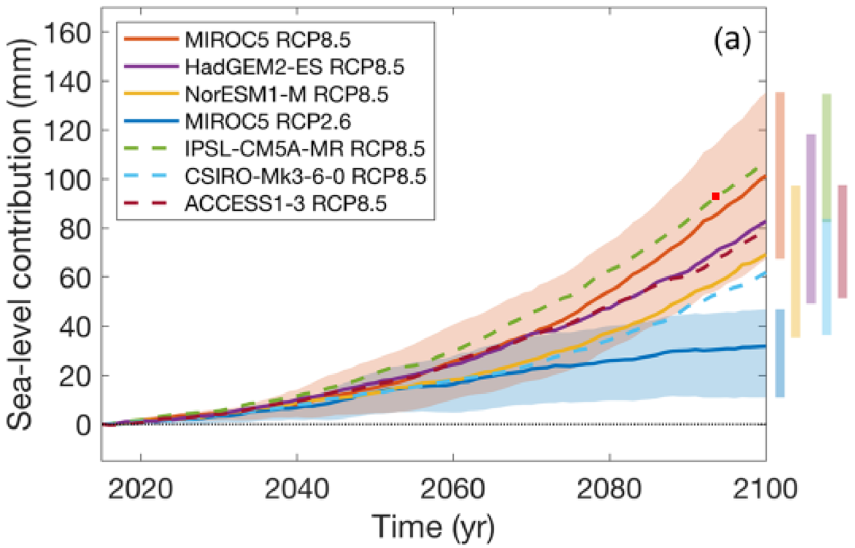
Ice Sheet Model Intercomparison Project

Greenland (Goelzer et al. 2020)

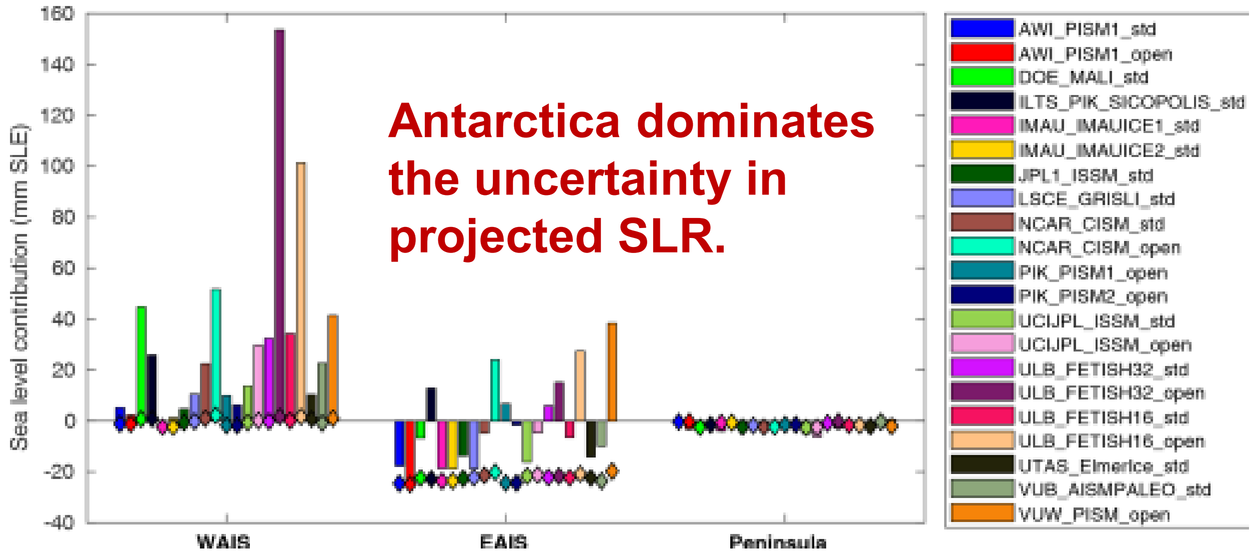
- SLR by 2100: **90 ± 50 mm (**RCP 8.5), mainly from **increased surface melting**. Good agreement across models.

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

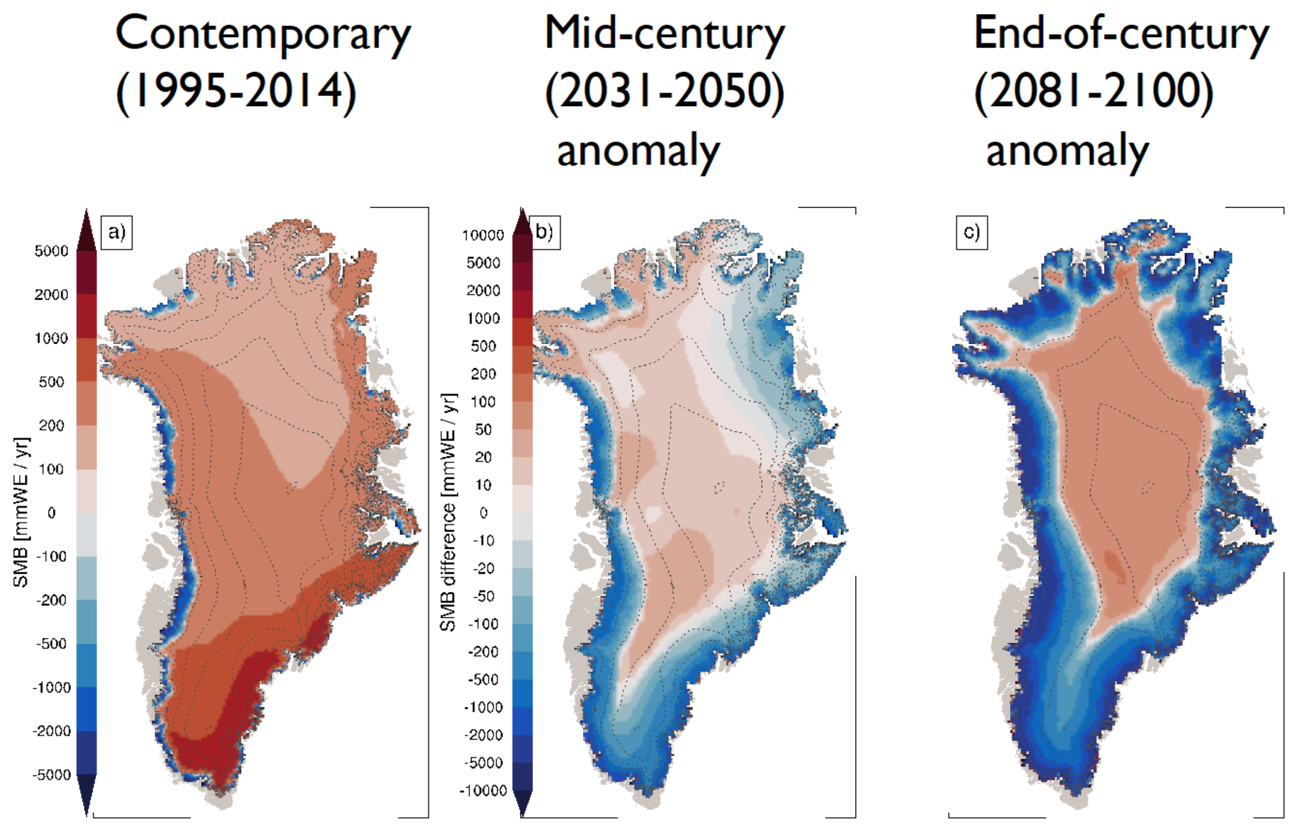


Antarctic regional sea-level contributions (mm SLE) from multiple ice sheet models under RCP 8.5 forcing

Coupled Greenland ice sheet evolution in CESM-CISM

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

- Global CO_2 rises to **~1100 ppm,** global surface air temperature increases by **5.4°C**.
- The Greenland ice sheet contributes SLR of **110 mm by 2100**, with greatly increased melting.

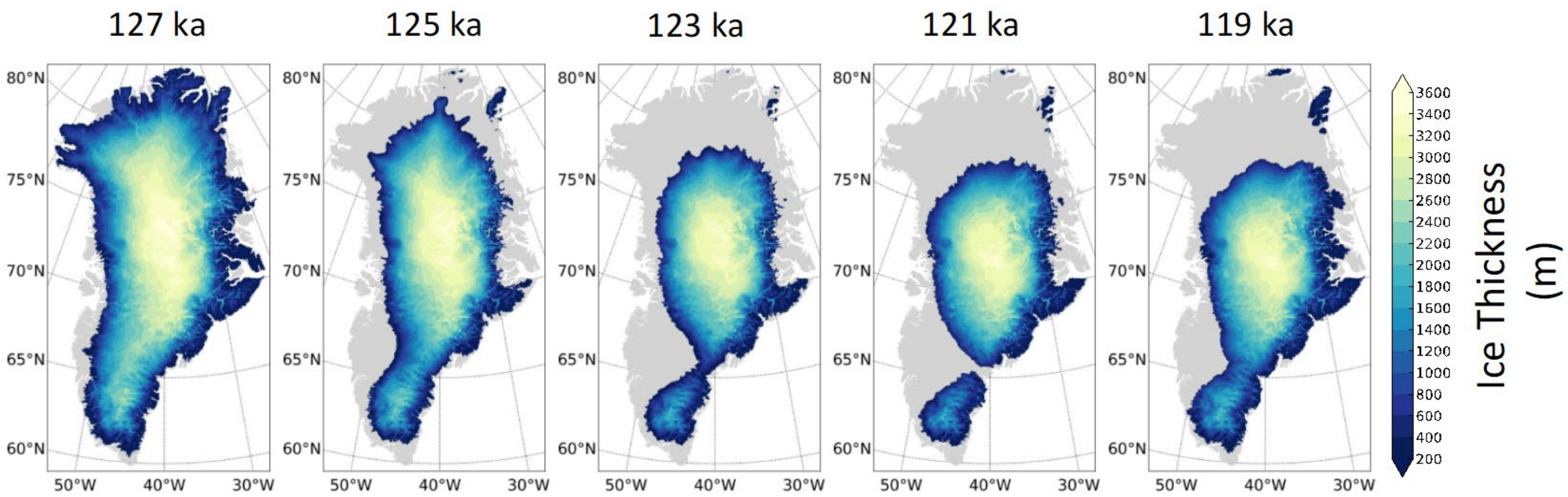


Increased melting of the **Greenland Ice Sheet** in CESM2 (Muntjewerf et al., 2020) under the ssp5-85 warming scenario. The expanding melt region is **blue**.

Coupled Greenland simulations of the Last Interglacial

CESM-CISM simulations of the **Last Interglacial** with an interactive Greenland ice sheet

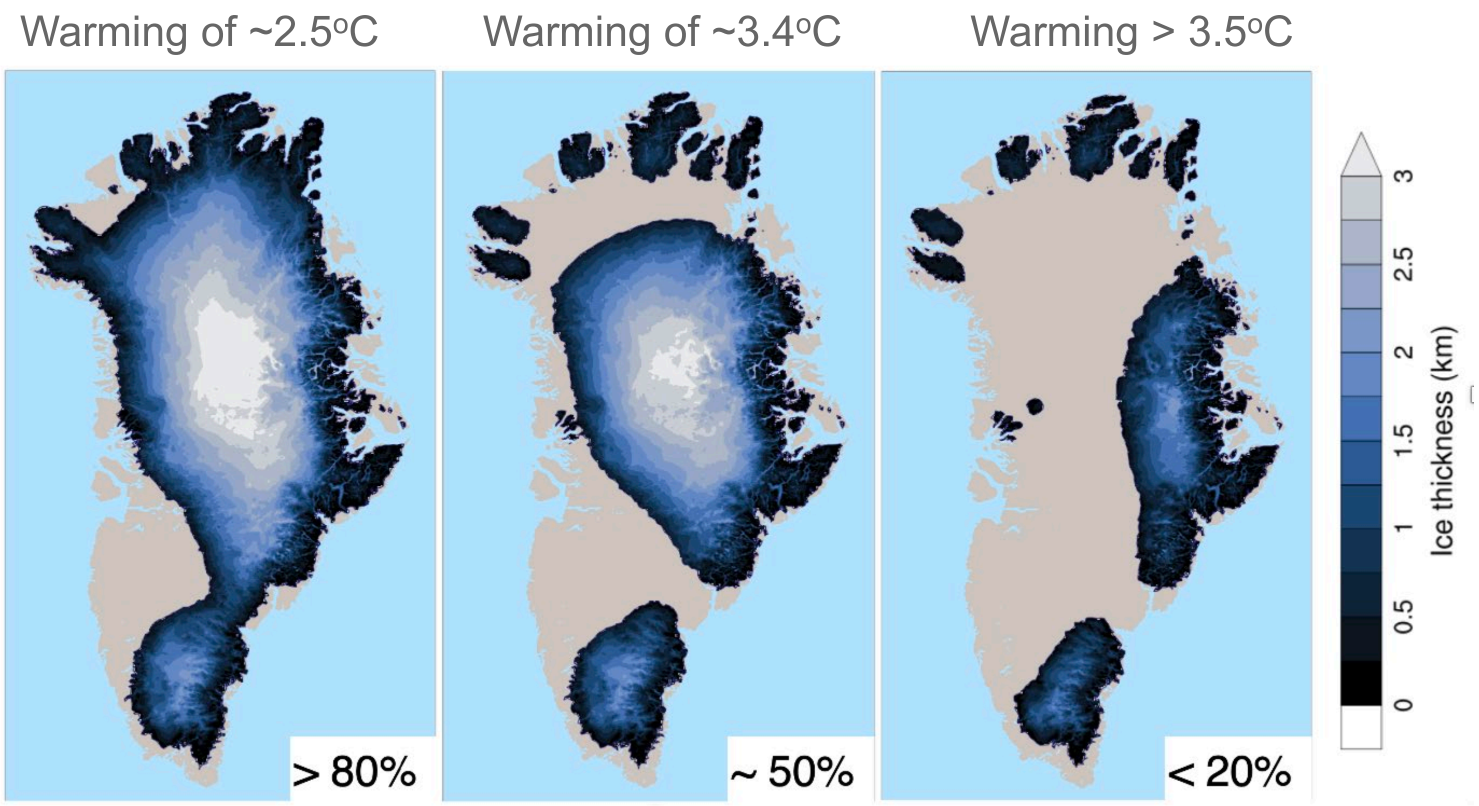
- The Greenland Ice Sheet shrinks from **8.3 m SLE** at 127 ka to **4.2 m SLE** at 122 ka, then slowly recovers.
- Interactive **vegetation** warms the climate and enhances the retreat.



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. (2021)

Thresholds for Greenland deglaciation



Petrini et al. (2024)

- CISM Greenland runs forced by CESM output suggest a deglaciation threshold at warming of ~3.4°C.
- Most of the ice sheet is lost after unpinning from topography in west Greenland.

Outline

Part 4: Recent and ongoing rsearch

Land ice goals for CISM3 and CESM3

CISM3

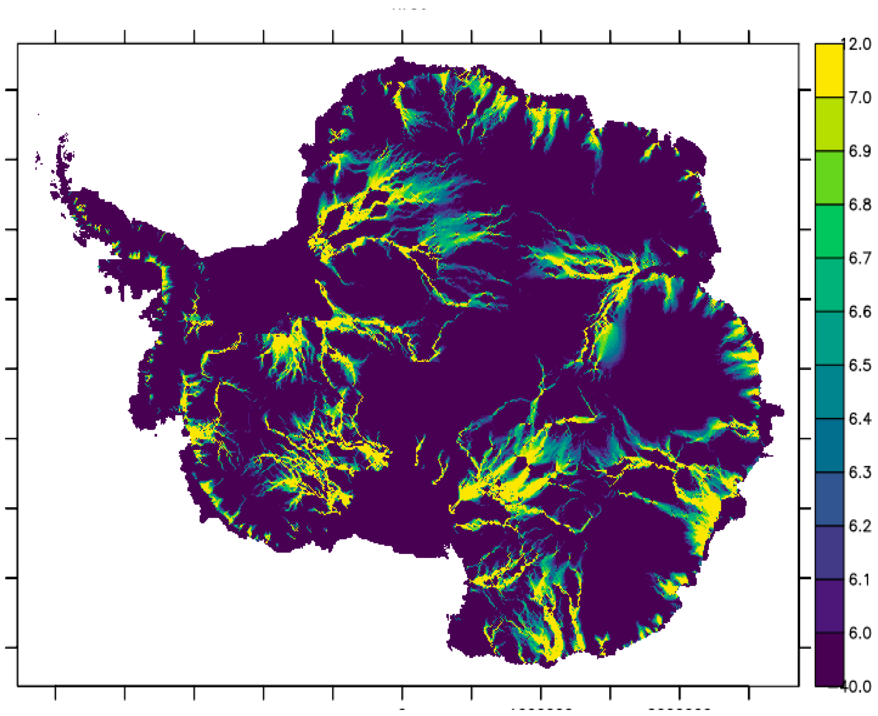
- Improve parameterizations of **subglacial hydrology, basal sliding,** and **iceberg calving** in CISM.
- Improve ice sheet **initialization methods.**
- Use CISM to simulate **mountain glaciers.**

CESM3

- Minimize biases in the **Greenland surface mass balance**.
- Support fully coupled climate – ice sheet simulations with **Antarctica** and **paleo ice sheets.**

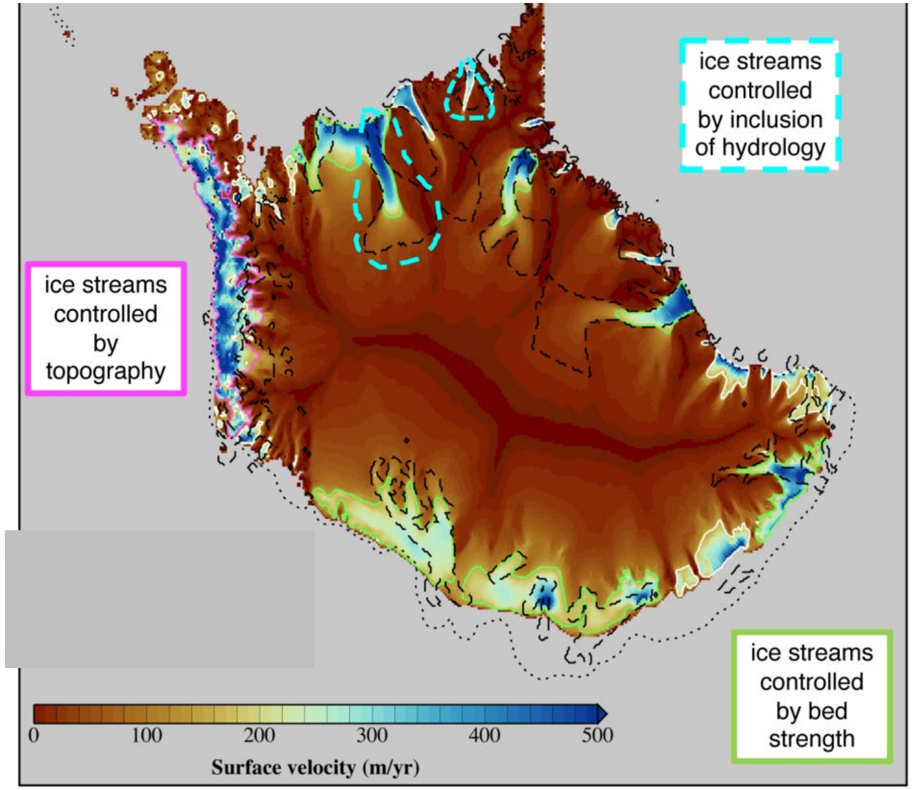
Subglacial hydrology

CISM now includes an efficient subglacial hydrology scheme.



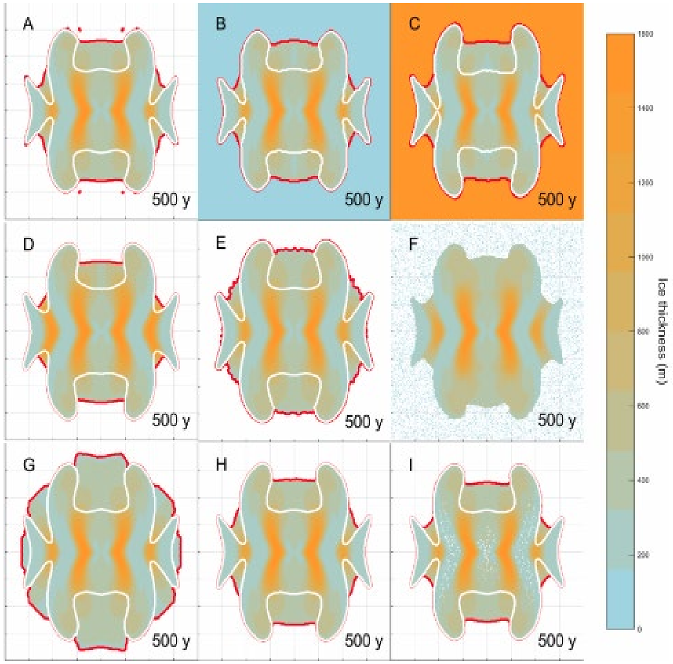
Basal water flux for Antarctica in a steady-state subglacial water model

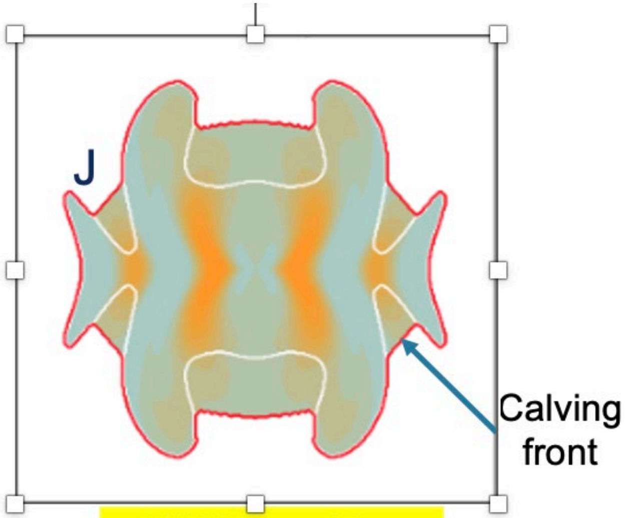
For simulations of the North American Ice Sheet complex during the **Last Glacial Maximum** (21 ka), ice streams are in good agreement with the paleoclimate record, as a result of **subglacial hydrology** (Arctic margin), **steep bed topography** (Pacific margin), and **weak basal till** (southern margin). (Courtesy of Sarah Bradley)



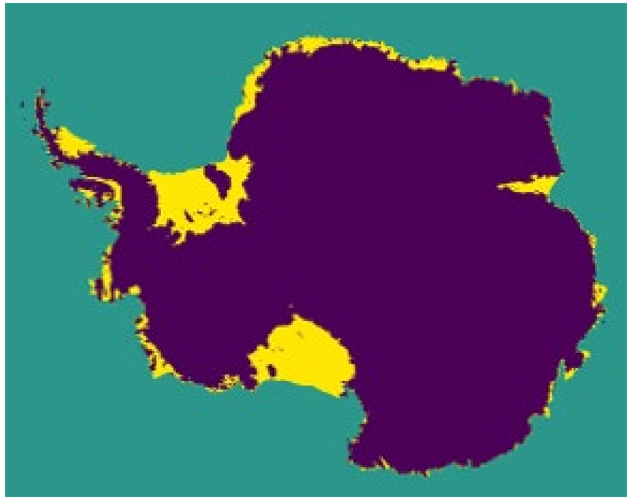
Iceberg calving

We are participating in the CalvingMIP project, which aims to improve the representation of damage and calving in ice sheet models.

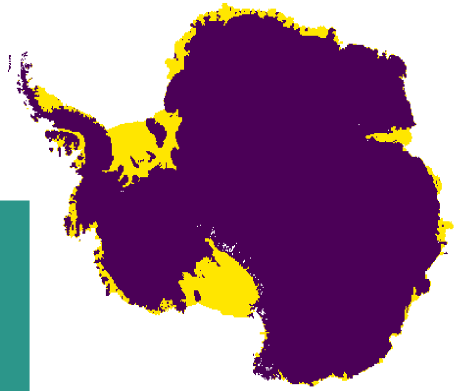




Simulated ice-shelf retreat in CISM (above) and other models (left)



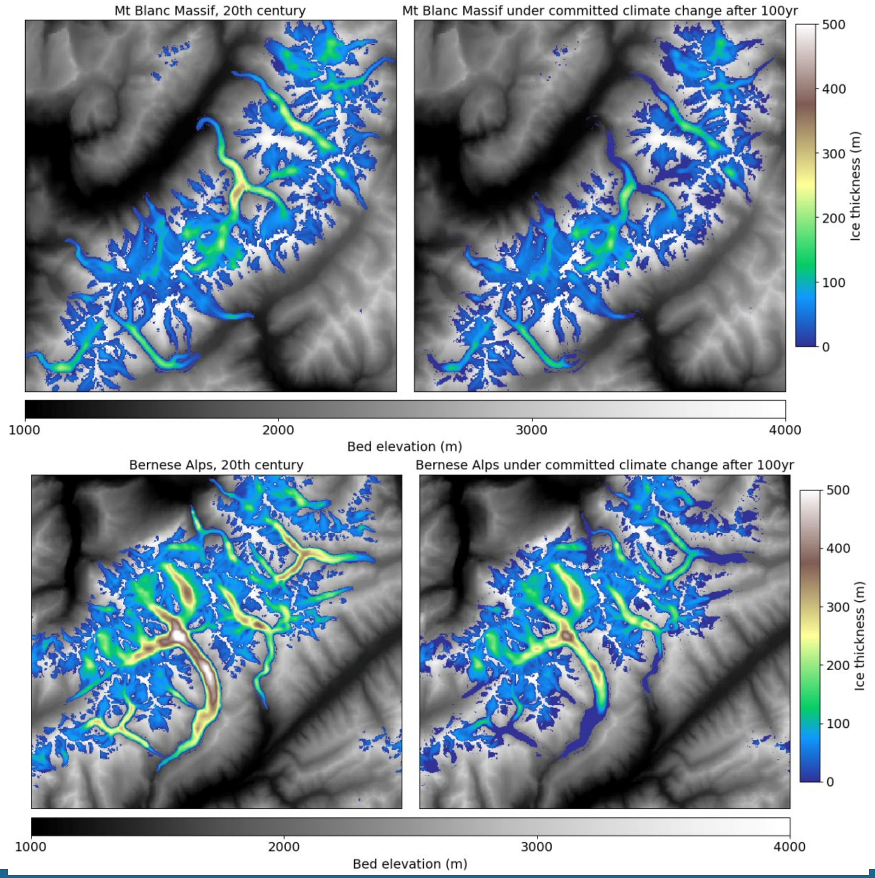
Simulated Antarctic ice shelves with a calving law based on a stress threshold



Observed ice shelves

Mountain glaciers

CISM can now be run as a regional glacier model. For the **GlacierMIP3** project, we simulated ~4000 glaciers in the European Alps at 100-m resolution.



Mont Blanc

Left: 1984
Right: 2084

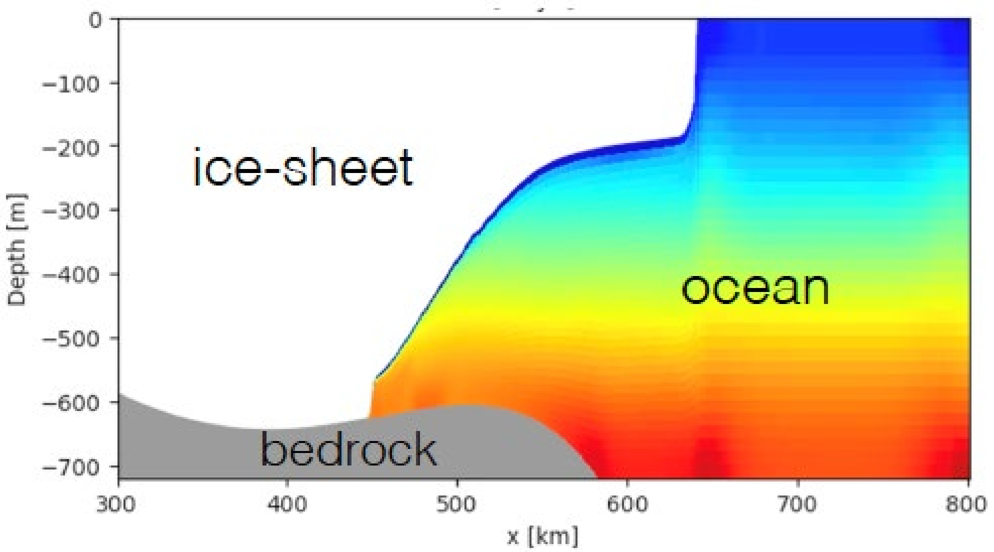
Bernese Alps

Left: 1984
Right: 2084

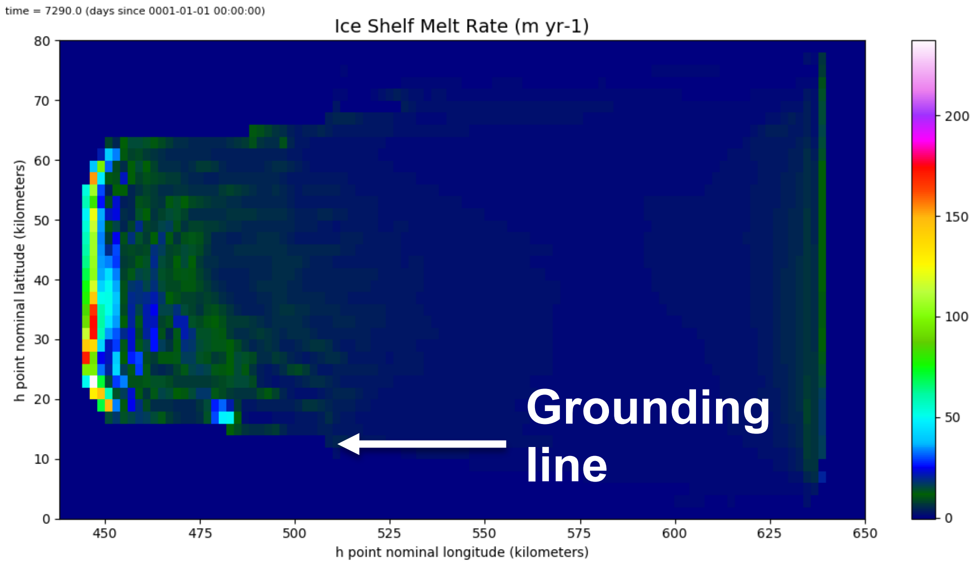
- CISM was the first 3D ice-flow model to participate in GlacierMIP.
- In an optimistic scenario with no further warming, we simulate **volume loss of 63% for the Alps** (relative to the 1980s) mostly in the first 100 years.

Multiple, fully-coupled ice sheets

- We have added support for running **Antarctica** out-of-the box and for running **multiple ice sheets** in a single simulation.
- We have implemented interactive coupling between CISM and the MOM6 ocean model, which allows circulation in ice sheet cavities.



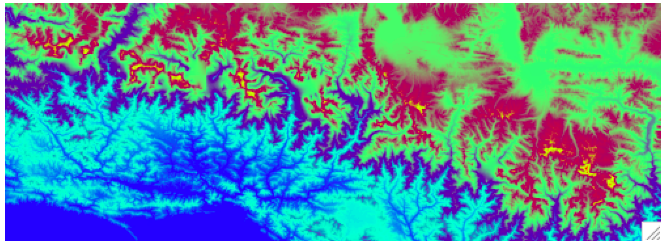
Schematic of sub-ice-shelf cavity with MOM6 coupled to CISM



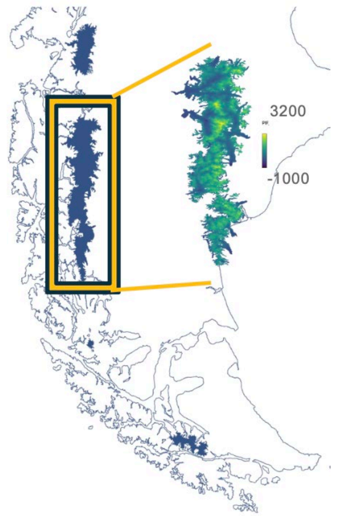
Sub-ice-shelf melt rate (m/yr) for an idealized experiment with CISM coupled to MOM6 (G. Marques).

Future CISM development

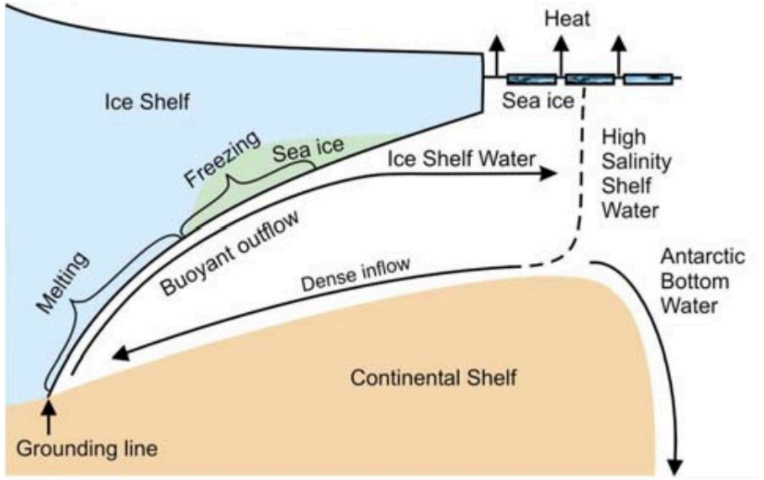
- **Glacier projections** in other regions (High Mountain Asia, Patagonia, Svalbard)
- **Ice shelf cavity circulation** module
- **Solid Earth and sea level** model (with ice sheet self-gravity)

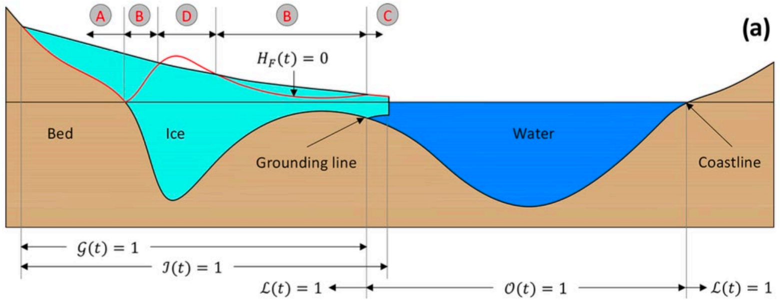


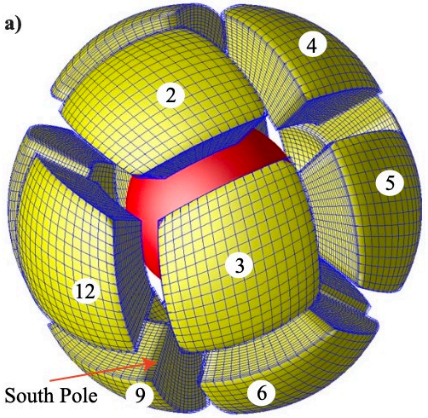
Subglacial bed elevation (m)
Fürst et al. (2024)



Above: Bed topography in the Nepal Himalaya.
Right: Patagonian ice fields.







Left: Schematic of sub-ice shelf circulation.
Above: Schematic mass distribution in a sea-level model.
Right: Finite-element grid for a global solid Earth model.

Summary

- CESM2 and CISM2 included scientific and software advances enabling interactive simulations with the Greenland ice sheet.
- CESM3 and CISM3 will support first-of-a-kind simulations of the Antarctic ice sheet, paleo ice sheets, and mountain glaciers.
- Coupling of ice sheets to the land and atmosphere is fairly mature, but ocean–ice sheet coupling is just getting started.
- Antarctic ice loss remains the largest uncertainty for sea-level rise.

Contact information

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

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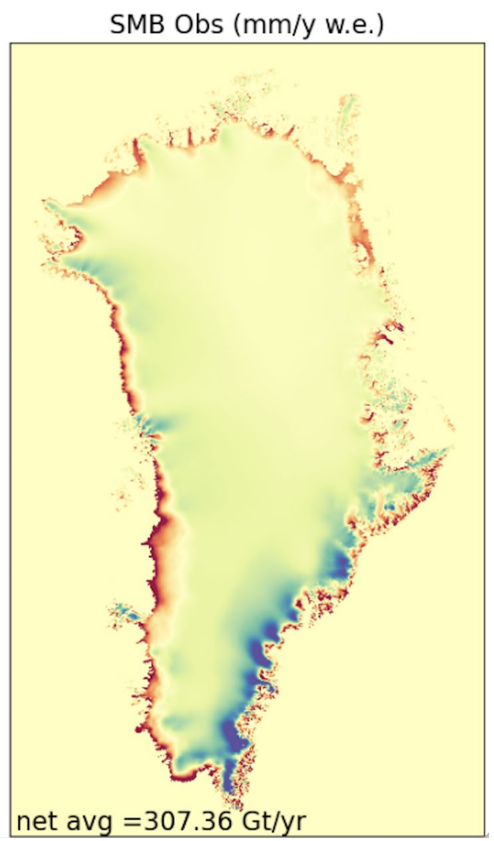
Please join us for our winter and summer meetings in 2026.

Extra slides

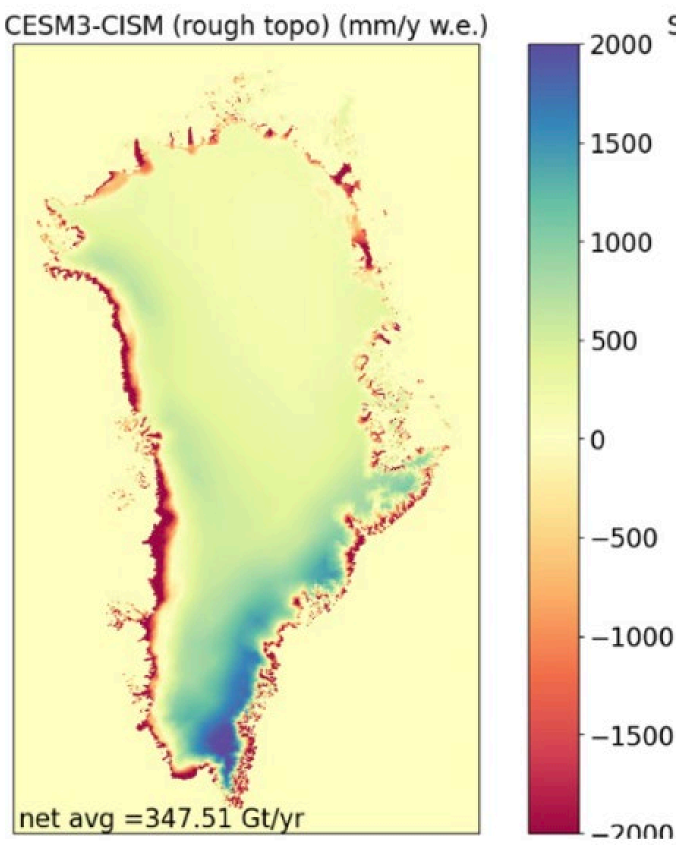
Greenland surface mass balance in CESM3

RACMO2



Net SMB = **307 Gt/yr**

CESM3–CISM



Net SMB = **348 Gt/yr**

- An early version of CESM3 does well at reproducing Greenland's net SMB and spatial patterns of accumulation and melting.
- As in CESM2, there is too much accumulation in the southern interior.
- Ablation is high along the west coast.

What questions can we ask CESM with land ice capabilities?

How will sea level impact the places we live in?

What questions can we ask CESM with land ice capabilities?

Will we have enough water?

How will sea level impact the places we live in?

What questions can we ask CESM with land ice capabilities?

Will we have enough water?

How will GLOFs impact population living downstream glaciers?

How will sea level impact the places we live in?

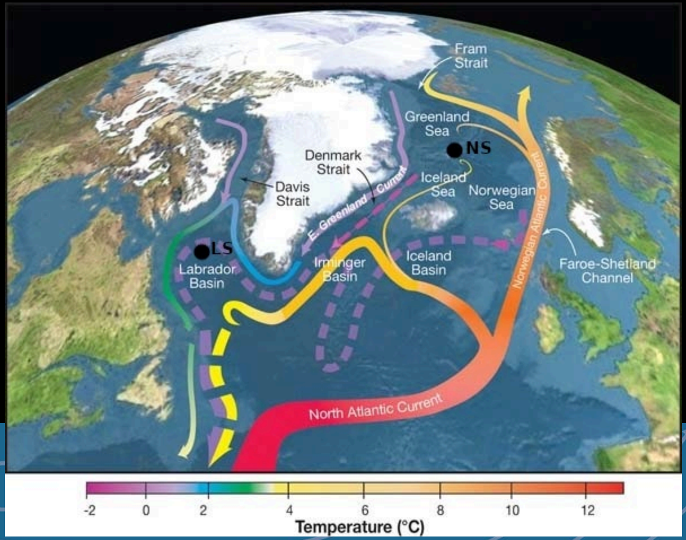
What questions can we ask CESM with land ice capabilities?

Will we have enough water?

How will GLOFs impact population living downstream glaciers?

How will sea level impact the places we live in?

How will ice melt impact AMOC and the climate system?



What questions can we ask CESM with land ice capabilities? Depend on perspective!