9 July 2026

Land Ice Modeling in CESM

Annual CESM Tutorial

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Land Ice

Snow ⇒ Ice ⇒ Flow

Outline

Part 1: Land ice and sea level

Part 2: Ice sheet dynamics

Part 3: Ice Sheets in CESM

Part 4: Recent and ongoing research

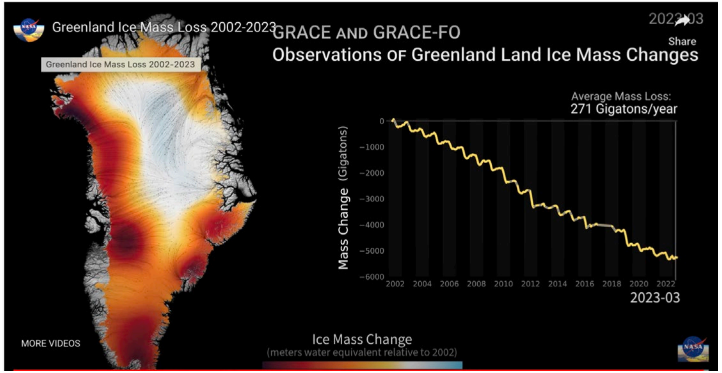
Outline

Part 1: Land ice and sea level

Ice Sheets

Greenland Ice Sheet

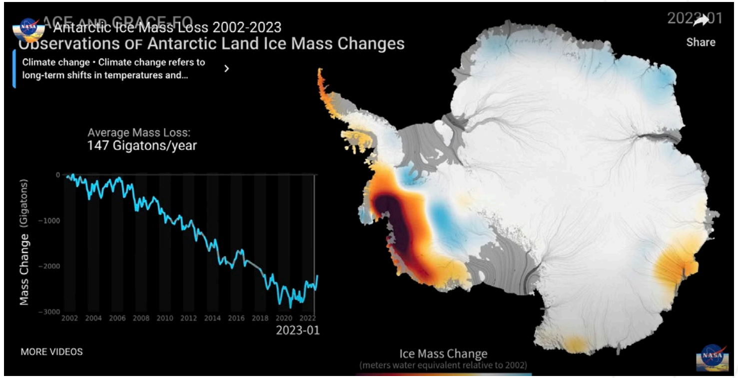
- **Northern hemisphere**
- **~1/4 the size of the continental US**
- **7 m** sea level equivalent (SLE)
- Mass loss of **270 Gt/year** since 2002



Greenland mass change from GRACE, 2002–2023
Credit: NASA/JPL-Caltech.

Antarctic Ice Sheet

- **Southern hemisphere**
- **1.5 time the size of the continental US**
- **58 m** SLE (**5 m** in West Antarctica)
- Mass loss of **150 Gt/year** since 2002

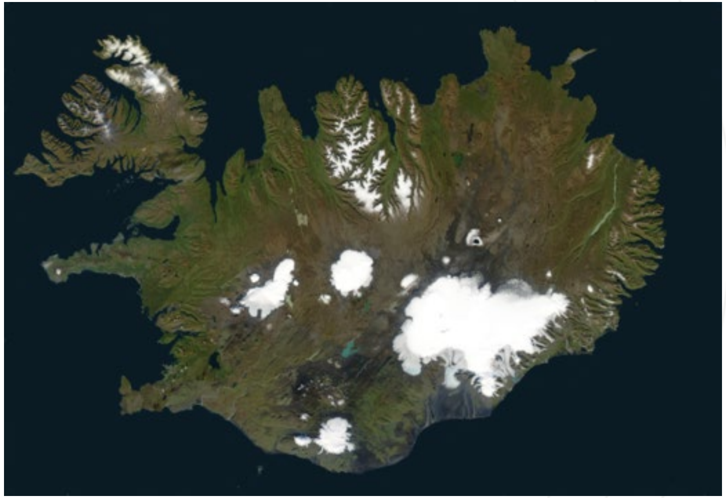


Antarctic mass change from GRACE, 2002–2023.
Credit: NASA/JPL-Caltech.

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



Vatnajökull ice cap, Iceland

Causes of Global Sea Level Rise (SLR)

Sea level estimate	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

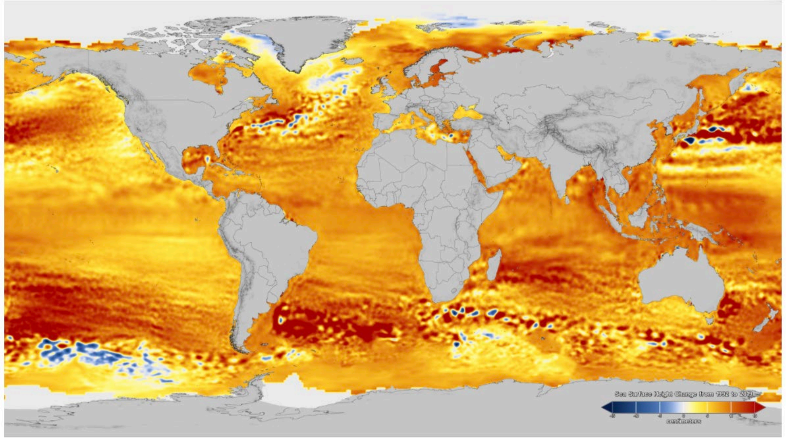
Most 20th century sea-level rise was dominated by **ocean thermal expansion**

The **Greenland and Antarctic ice sheets** contribution increased around 1990 and now account for about 40% of SLR.

SLR rate in the **21st century** is 3 time that of the 20th century

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** .



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

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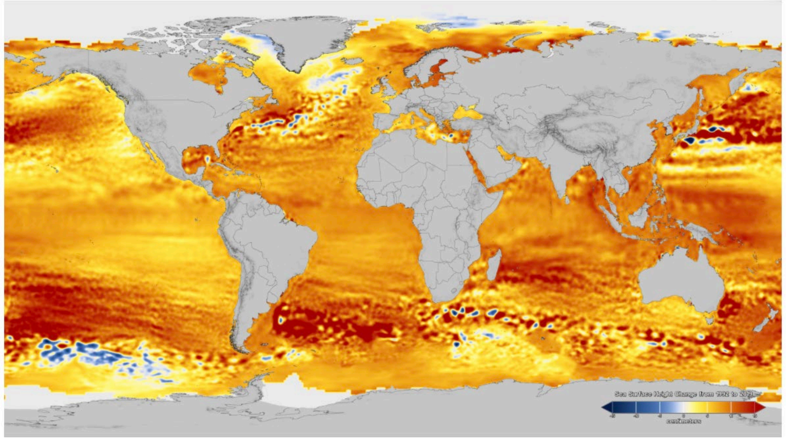
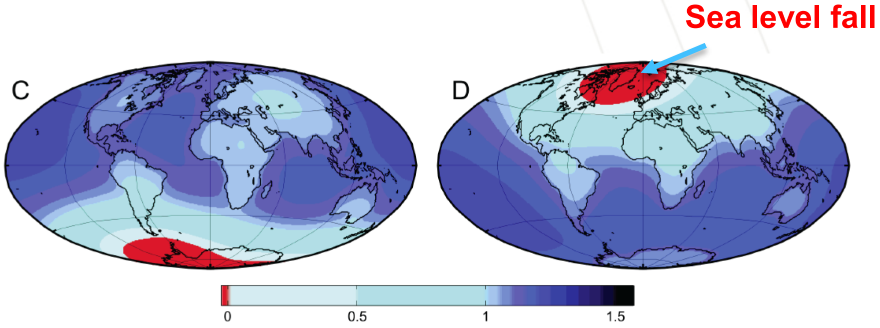


Change in sea surface height, 1993–2019, as measured by satellite altimetry. (Credit: NASA)

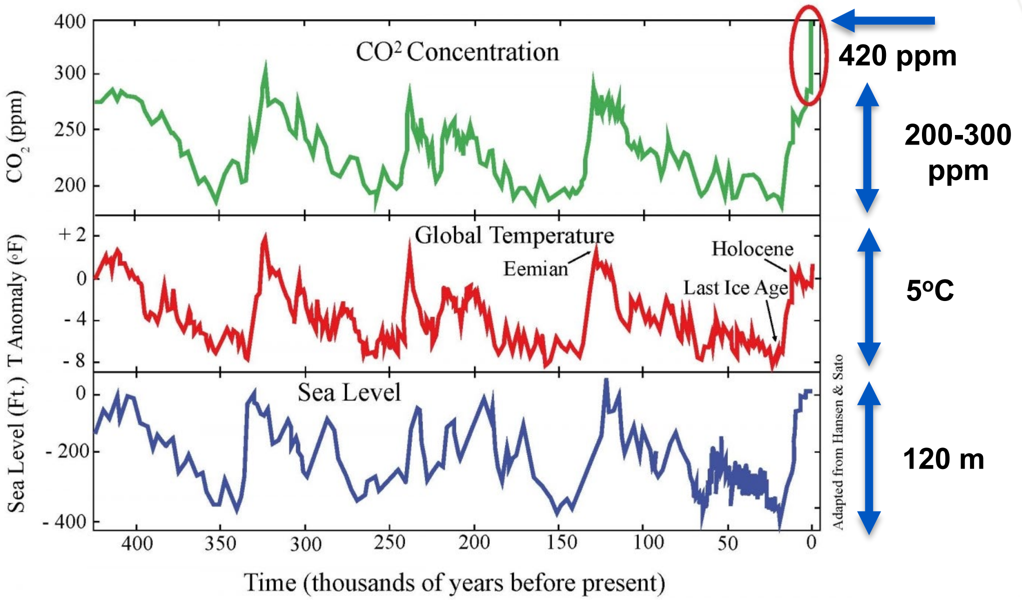
With **weaker** self-gravity, water moves **away** from shrinking ice sheets and piles up elsewhere.



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

Carbon Dioxide, Temperature, and Sea Level

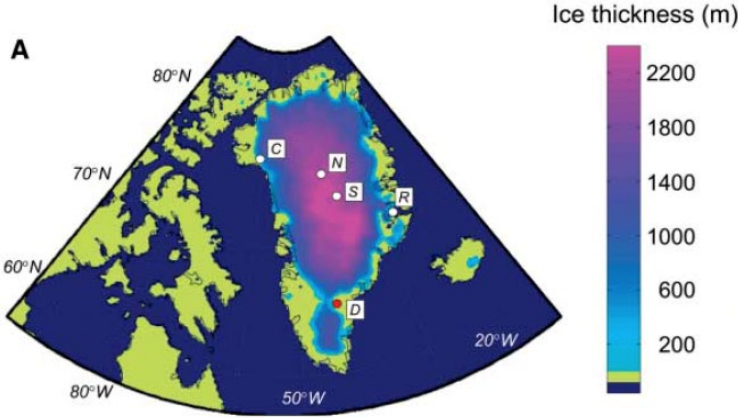
- **Sea level** is closely linked to global average **temperature** and **CO_2 concentration**.
- In past climates, temperature co-evolved with CO_2. Now CO_2 is the main driver.
- Ice sheets tend to **build up slowly** and **melt quickly**.



Ice Sheets in Warm Climates

Last Interglacial (125,000 years ago)

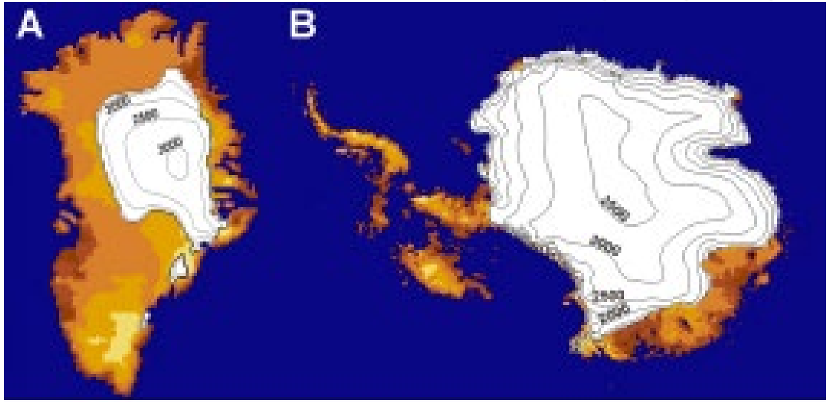
- Warming **1-2°C**, CO_2 = **280 ppm**
- Global sea level **6–9 m** higher than now
- About 2–4 m from Greenland, > 2 m from Antarctica



Modeled Greenland ice thickness, 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, possibly retreat from East Antarctica



Pliocene ice sheet reconstructions (Haywood et al. 2010)

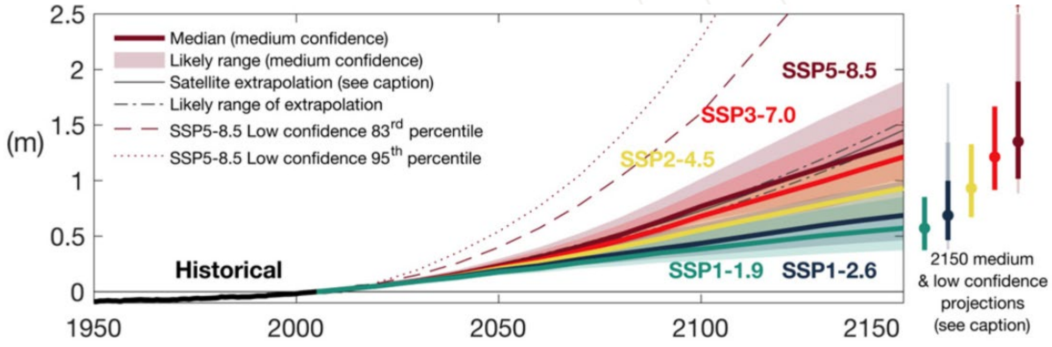
IPCC AR6 Sea Level Projections

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** ice-sheet-related processes 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

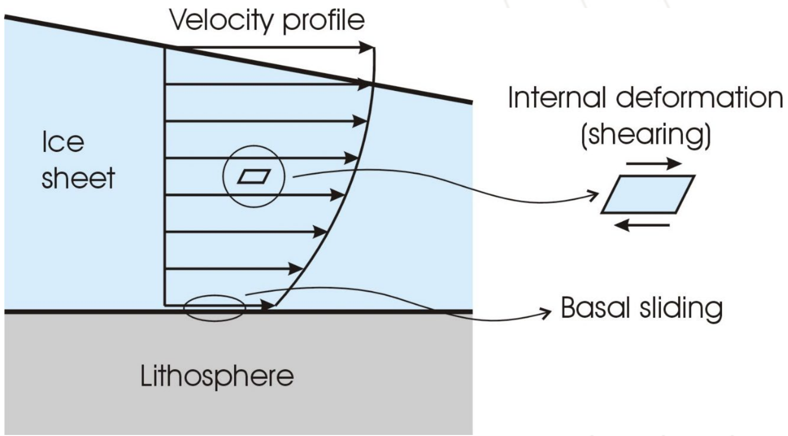
- **28 to 55 cm** for low emissions (ssp1-19)
- **63 to 102 cm** for high emissions (ssp5-85)

Outline

Part 2: Ice Sheet dynamics

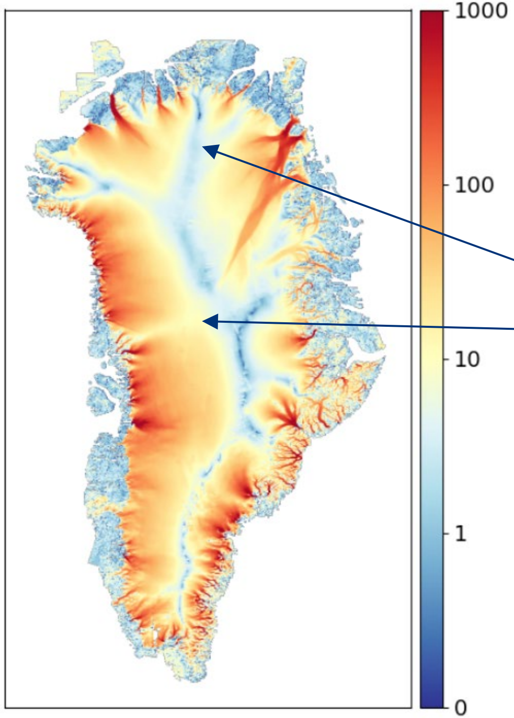
How Glaciers Move

- **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.



How Glaciers Move

Ice velocity (m/yr)



(Data from Joughin et al. 2010)

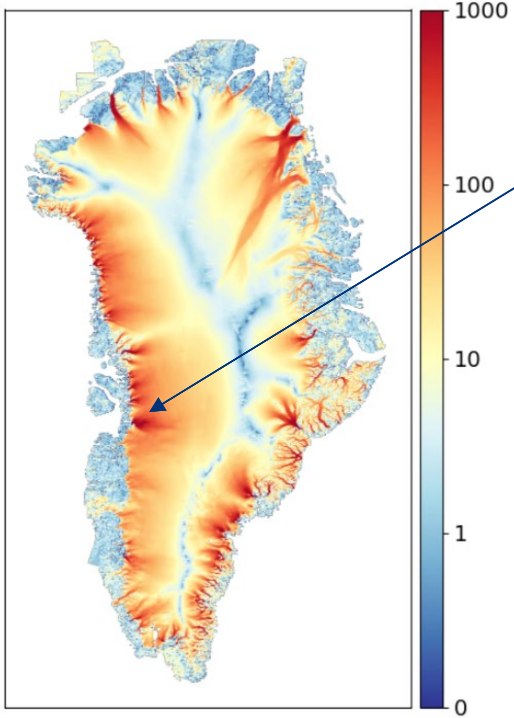
Slowly deforming, ice frozen at the bed:

shallow ice approximation

- Ice flows up to 10s of m/yr
- Analytical solution
- Computationally cheap

How Glaciers Move

Ice velocity (m/yr)



(Data from Joughin et al. 2010)

Ice sliding with little vertical shear:

shallow shelf approximation

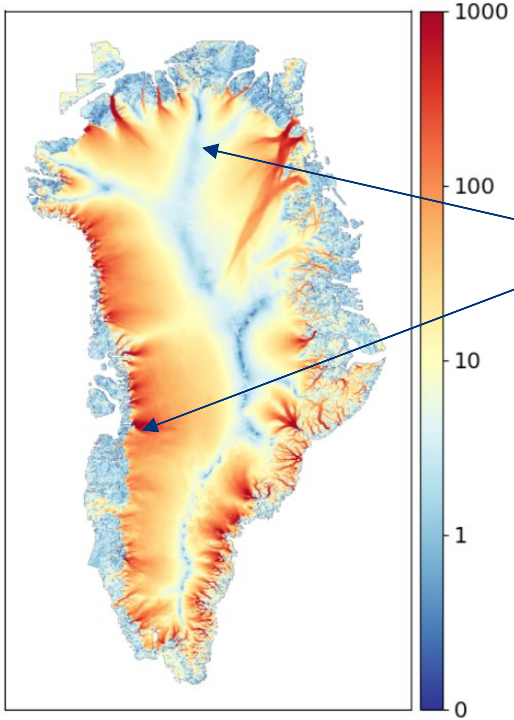
- Ice flows 100s m/yr to several km/yr
- Computationally cheap
- Water at the bed

Moulin

Marine termini glacier

How Glaciers Move

Ice velocity (m/yr)



(Data from Joughin et al. 2010)

General ice flow:

Stokes equations or higher-order approximations

- Good representation of any ice flow
- Computationally more expensive

How Ice Sheets Gain and Lose Mass

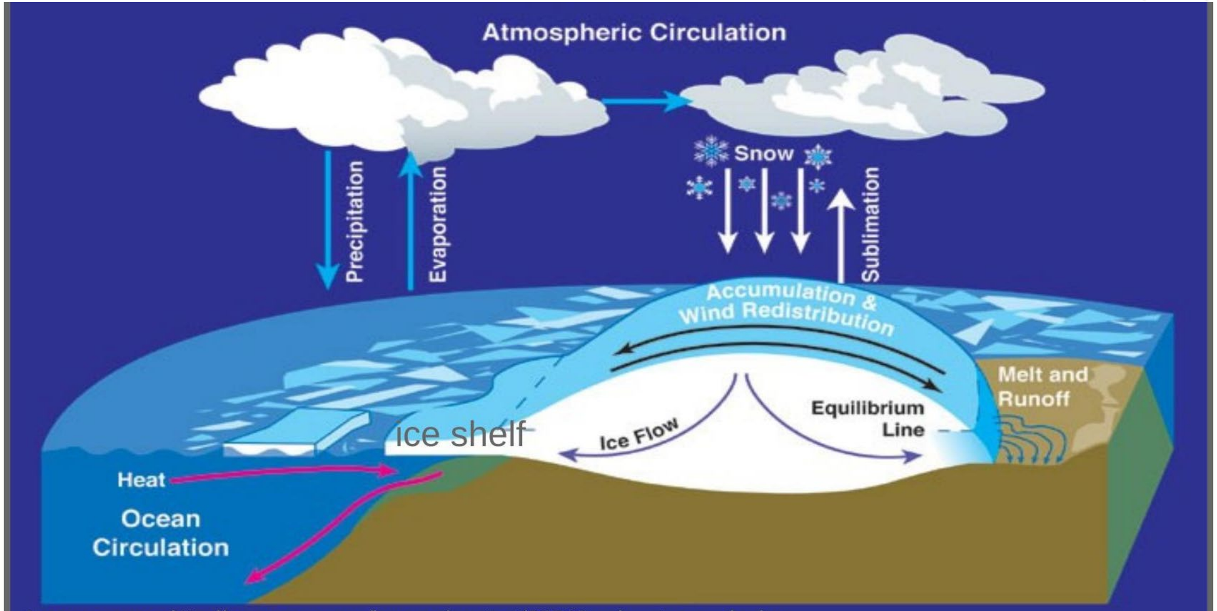


Image source: http://www.nasa.gov/images/content/53743main_atmos_circ.jpg

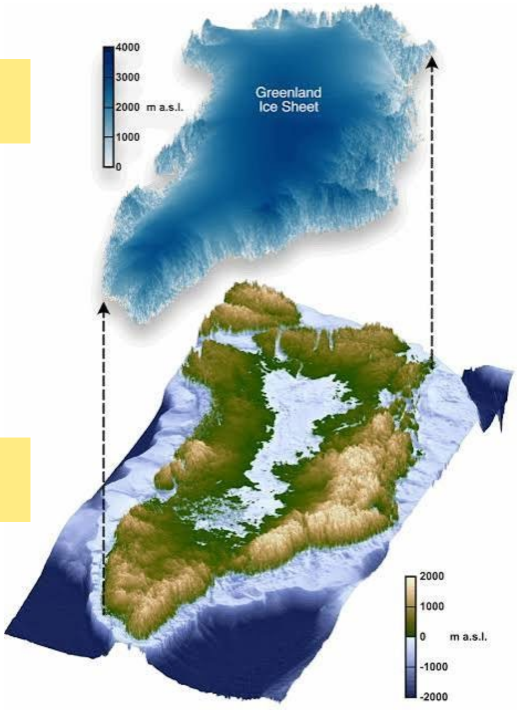
Mass Balance: Change in ice sheet mass = mass in – mass out

Sea level change! Snowfall melting, calving

Understanding the ice sheets

Ice Thickness

Bedrock elevation



Snowfall balanced by

surface runoff and **iceberg calving**

Understanding the ice sheets

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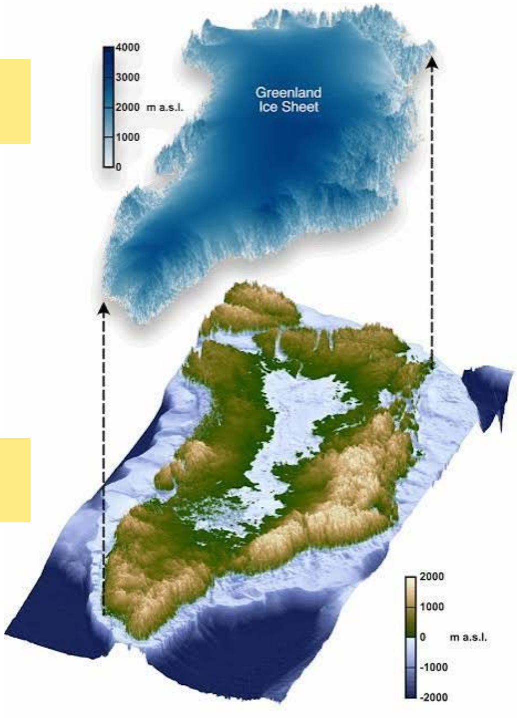
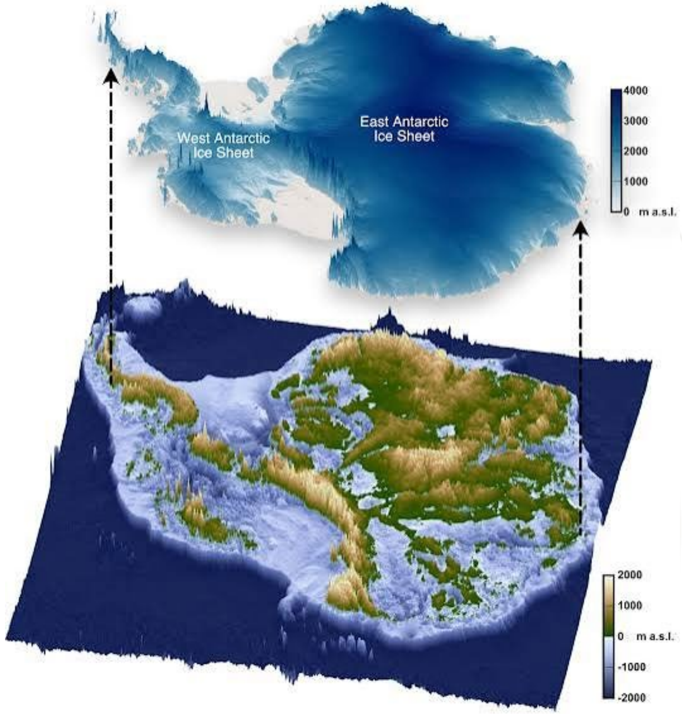




Snowfall balanced by

surface runoff and **iceberg calving**

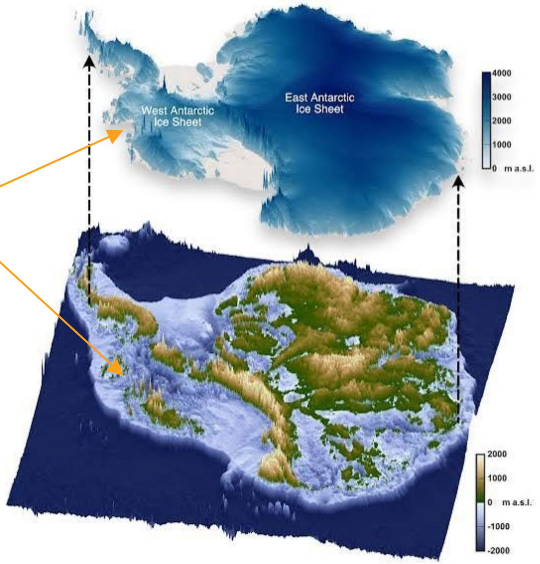
Snowfall balanced by

iceberg calving and **ice shelf melting**

Antarctic Ice Sheet Instability

Much of the Antarctic ice sheet is grounded below sea level

Amundsen Sea: Thwaites and Pine Island Glaciers



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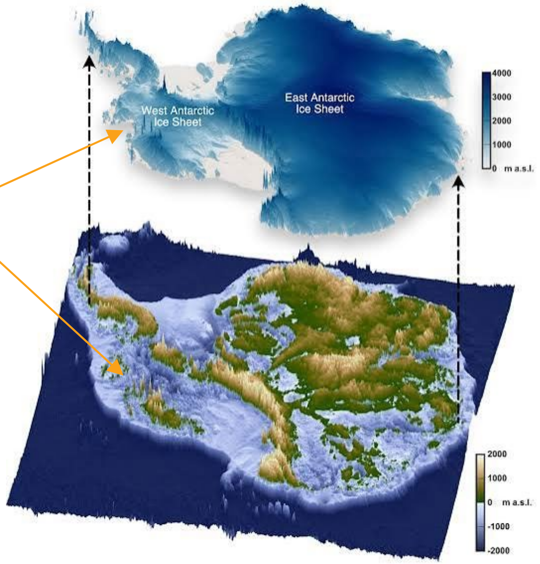
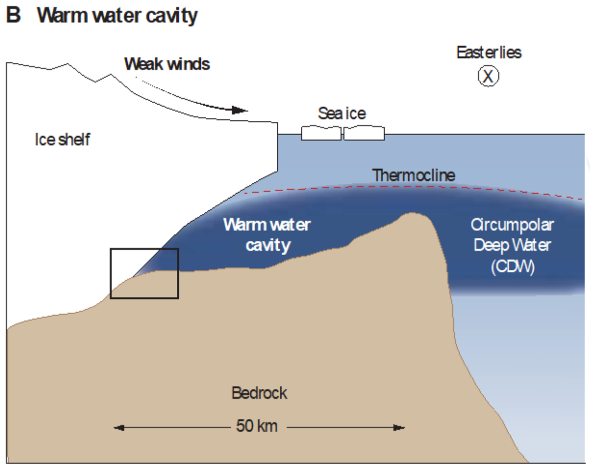


Ice is vulnerable to intrusions of **warm Circumpolar Deep Water** (Amundsen Sea region,Thwaites and Pine Island Glaciers)



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

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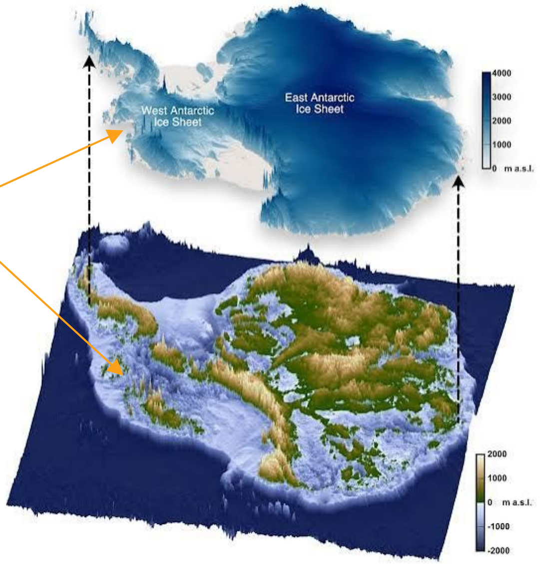

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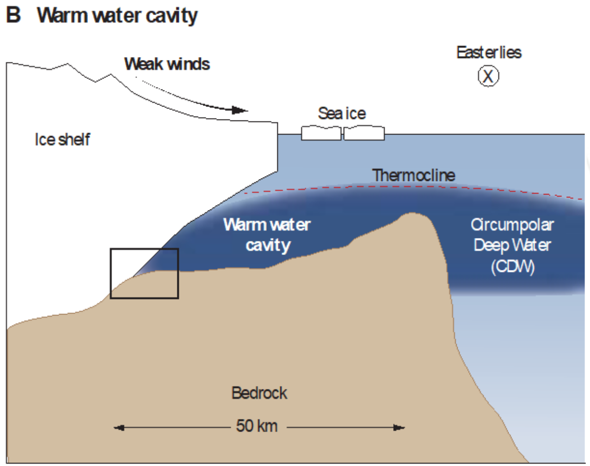


Schematic of a warm sub-ice-shelf cavity (Holland et al. 2020)

Ice sheets on reverse-sloping sea beds may be subject to the **Marine Ice Sheet Instability**.

Outline

Part 3: 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

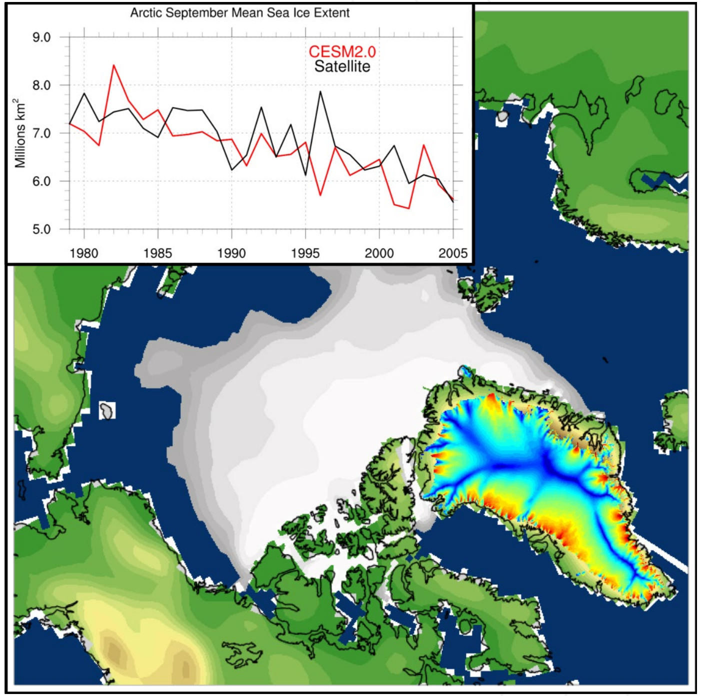
Division of labor

- The **Community Land Model (CLM)** computes the **surface mass balance**, using subgrid elevation tiles 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).



Ice Sheet Coupling in CESM 3

Land -> Ice sheet

(10 classes + bare land)

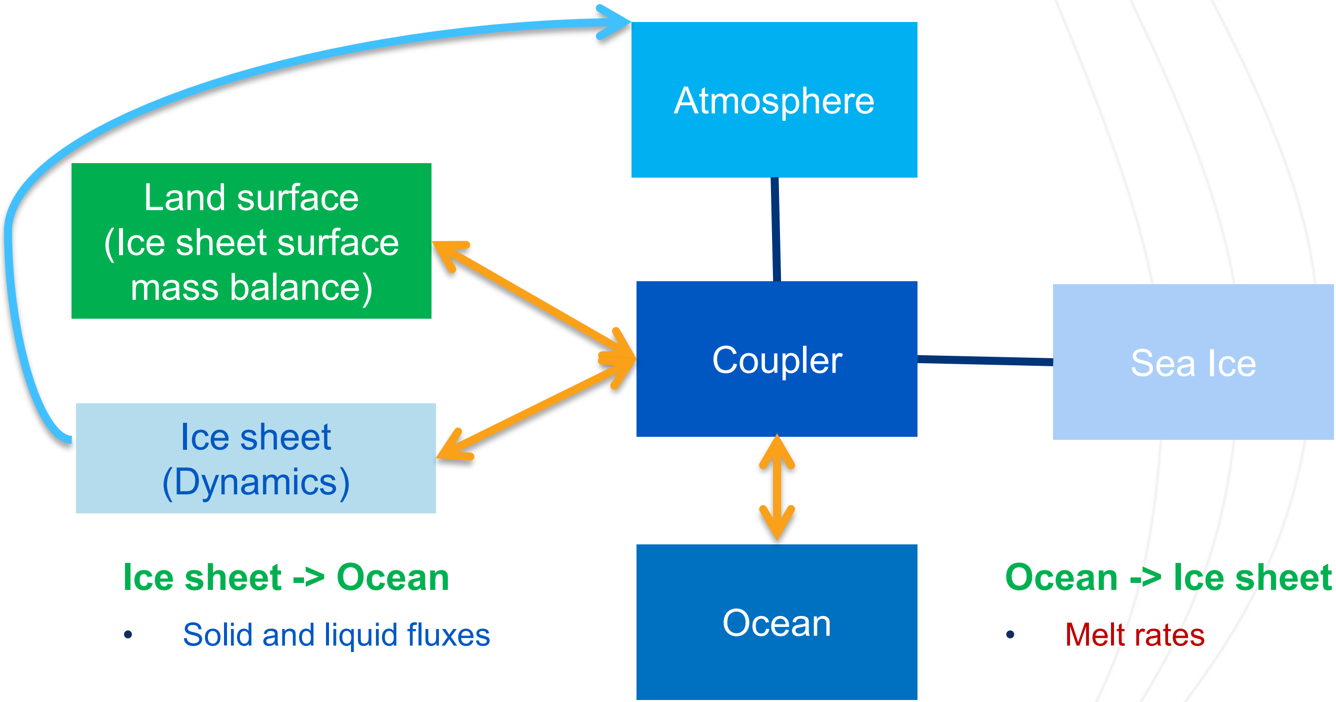
- Surface mass balance
- Surface elevation
- Surface temperature

Ice sheet -> Land

- Ice extent
- Ice surface elevation

Ice sheet -> Atmosphere (offline)

- Surface topography



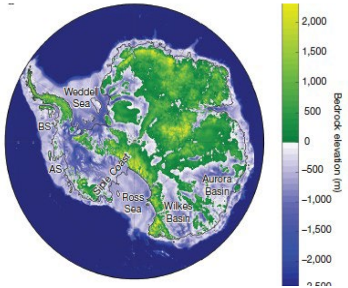
Ice sheet -> Ocean

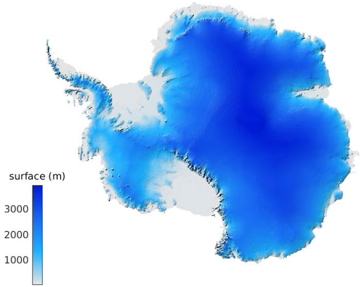
- Solid and liquid fluxes

Ocean -> Ice sheet

- Melt rates

Ice Sheet Initialization





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

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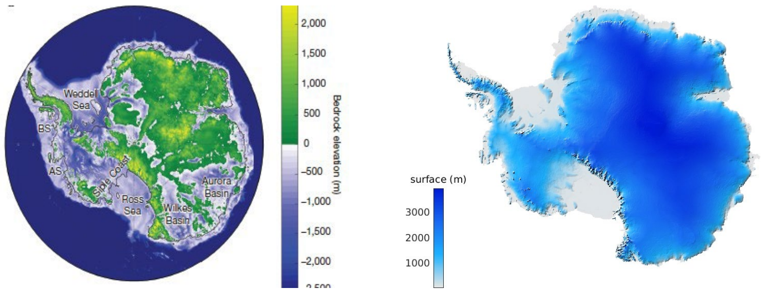

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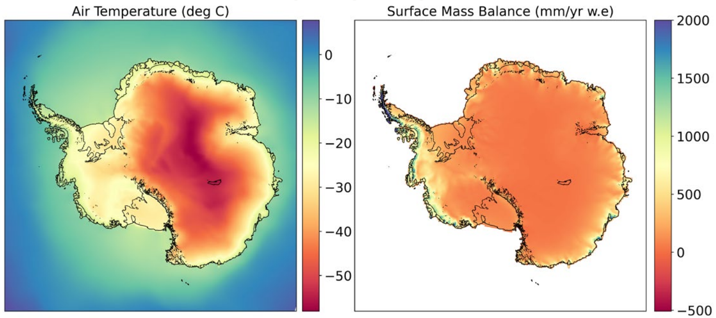

Surface temperature and mass balance
(van Wessem, 2018)

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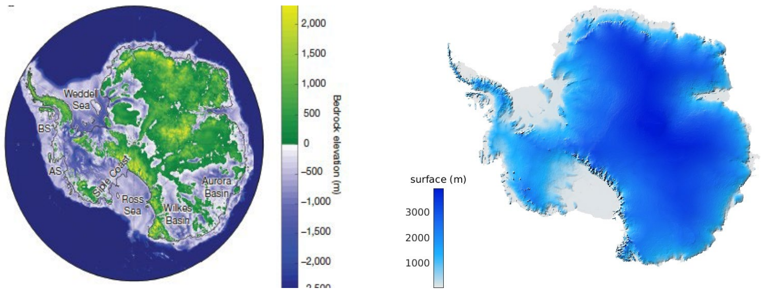

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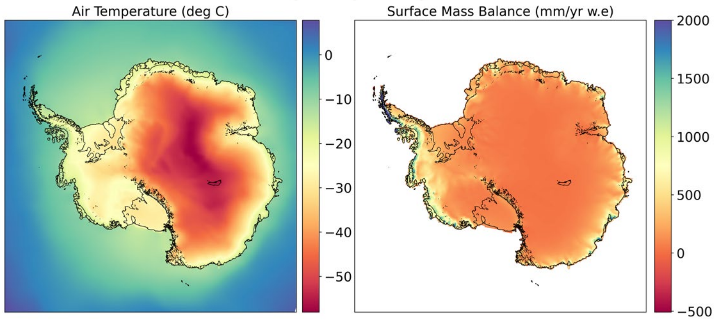

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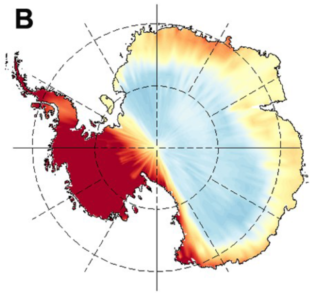

Geothermal heat flux
(Shapiro and Ritzwoller, 2004)

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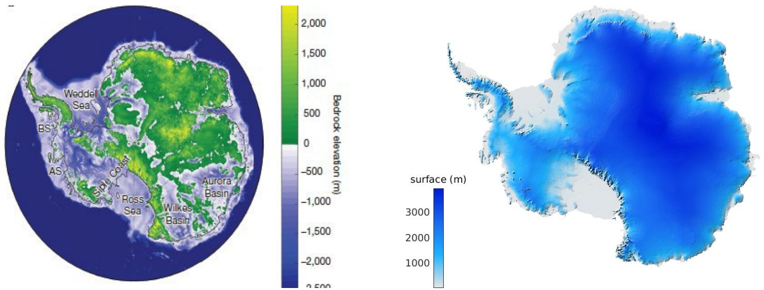

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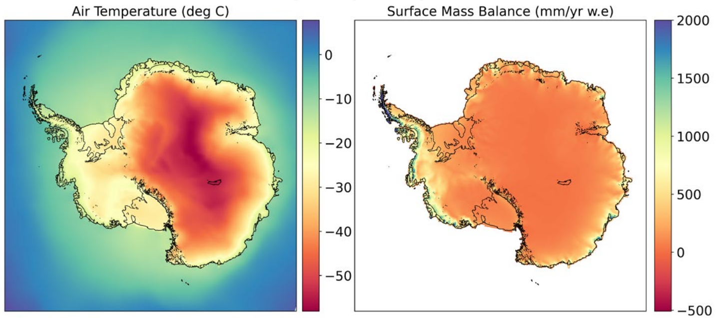

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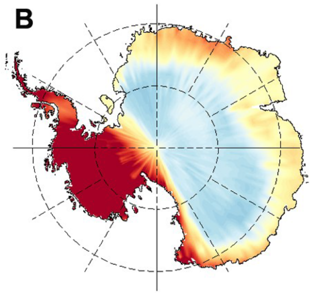

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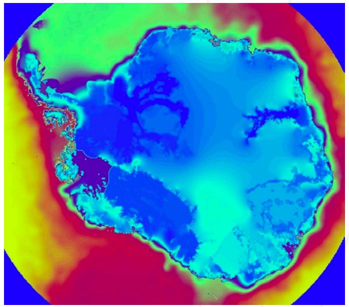
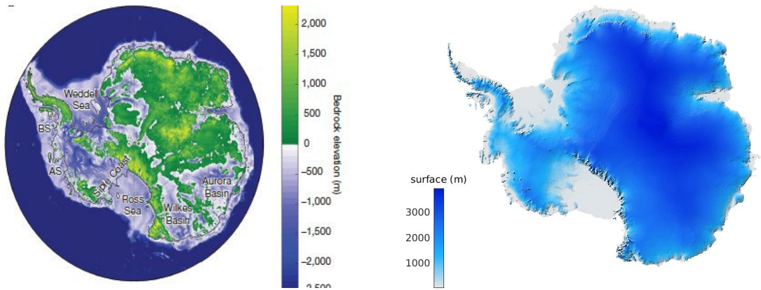


Ocean thermal forcing
(Jourdain et al., 2020)

Ice Sheet Initialization



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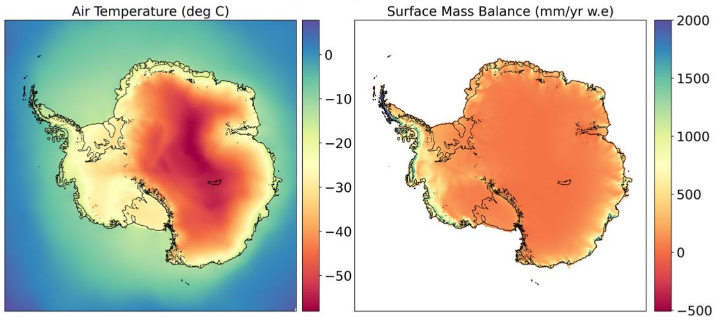

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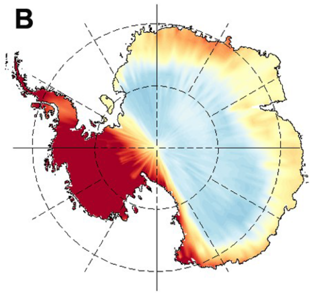

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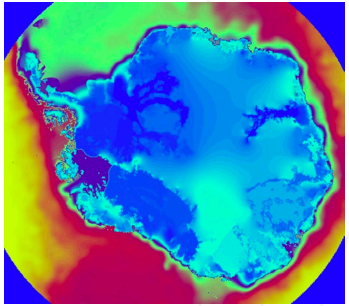
Run the model for 10,000 to 20,000 years and invert for basal friction coefficients



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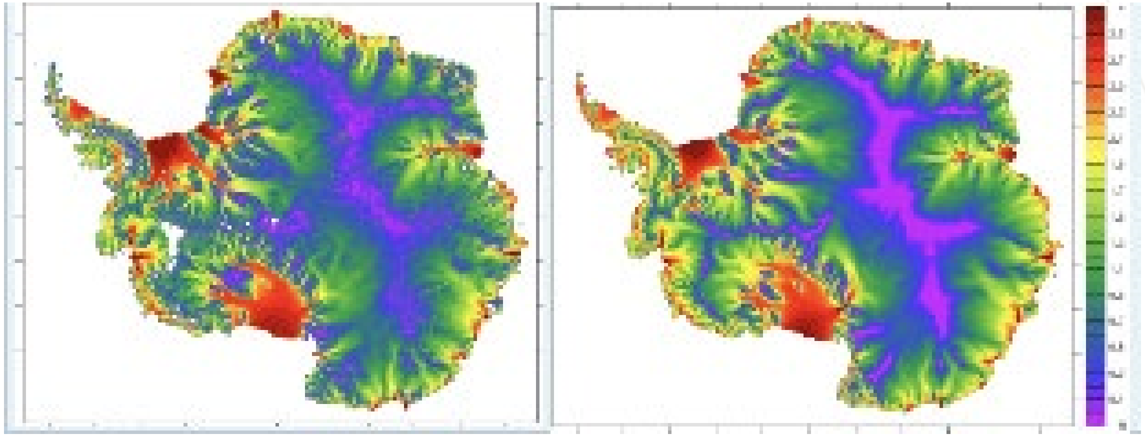
Ice Sheet Initialization



Observed
(Rignot et al., 2011)

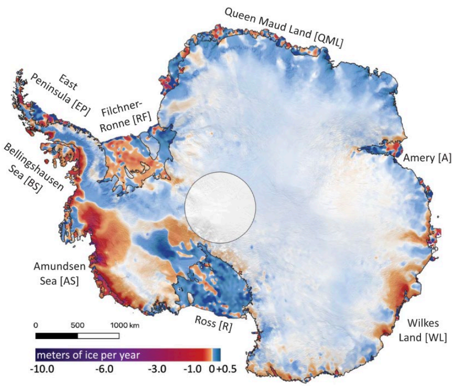
Modeled

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

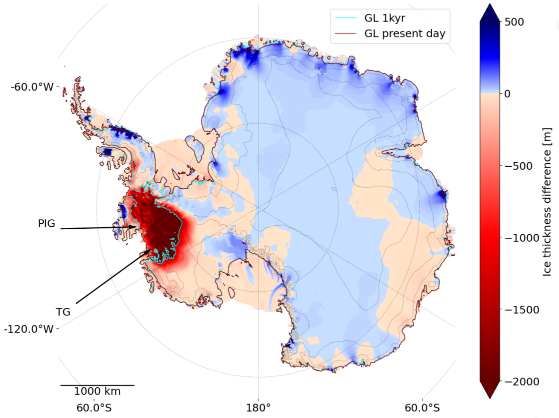
Ice Sheet Initialization

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.**



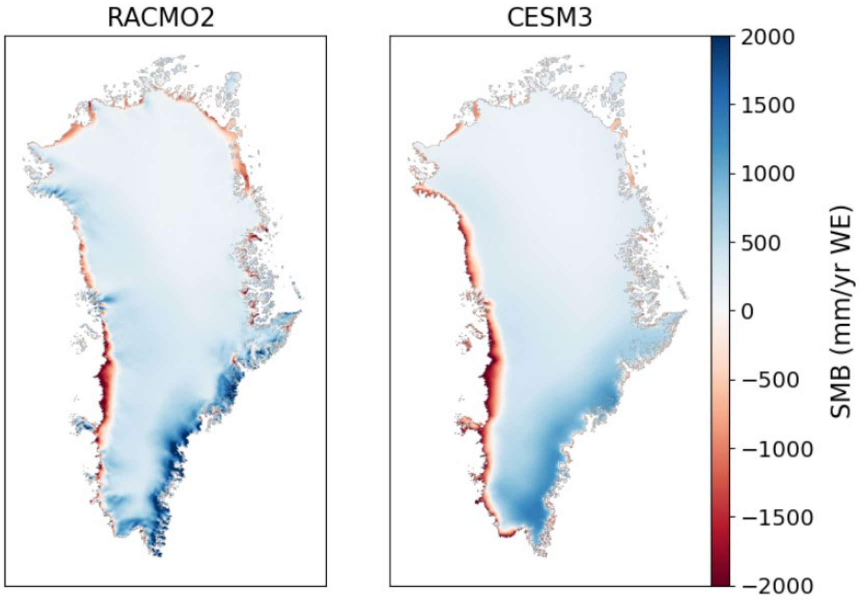
Observed rate of ice thickness change (m/yr), 2003–2019 (Smith et al. 2020)



Simulated thickness change (m) over 1000 years after a spin-up with observed thinning rates. Van den Akker et al. (2025)

Greenland Ice Sheet in CESM 3

Greenland Ice Sheet fulling evolving by default



Greenland surface mass balance (mm/yr).
Left: RACMO regional model. *Right:* CESM3.
Blue = accumulation, **red = ablation**.

- The Greenland surface mass balance in CESM3 compares well with **regional Arctic models** that are run at ~5x higher resolution (~10–20 km).
- Differences along coastlines mainly because of coarse topography: South East and North.

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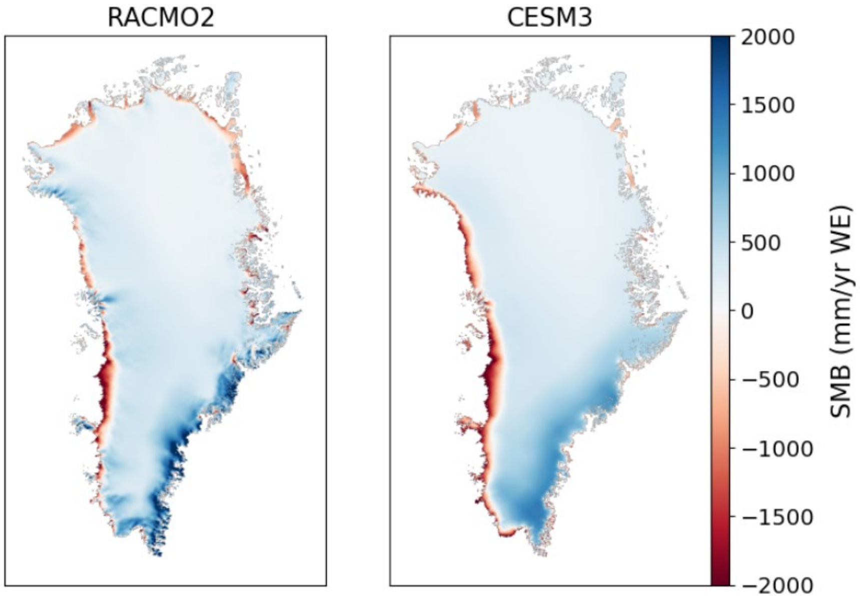

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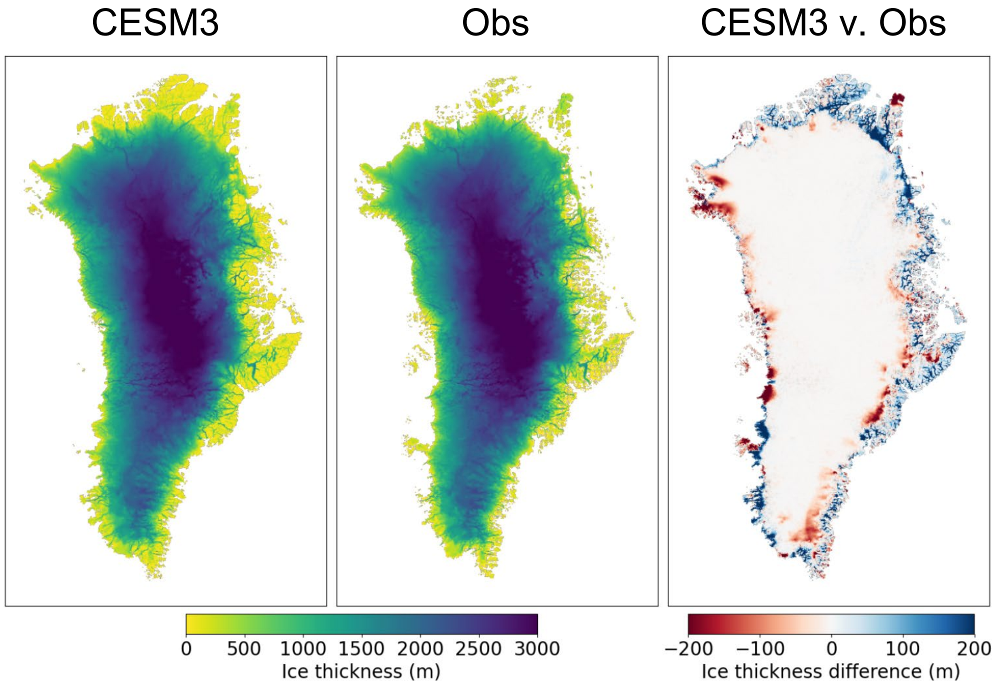
This is an SMB associated with a Pre-Industrial climate for CESM3!

Greenland Ice Sheet in CESM 3



% error CESM v. Obs	CESM2	CESM 3
Ice extent	15.0	7.1
Ice volume	12.2	0.003

- Initial Greenland ice sheet (spun up with preindustrial surface mass balance) is **greatly improved** in CESM3 compared to CESM2
- In a fully coupled spin-up CESM3-Greenland simulation, the ice sheet **mass drift** is ~5 Gt/yr

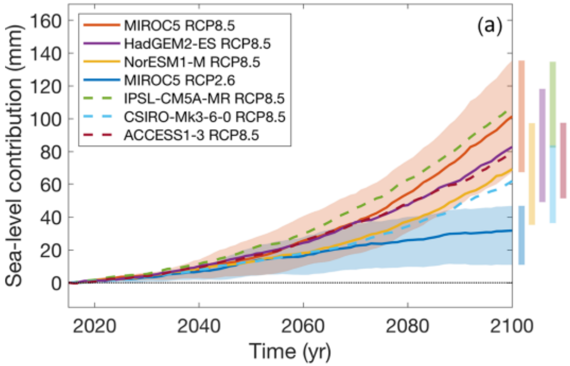
Outline

Part 4: Recent and ongoing research

Ice Sheet Model Intercomparison Project

Greenland (Goelzer et al. 2020)

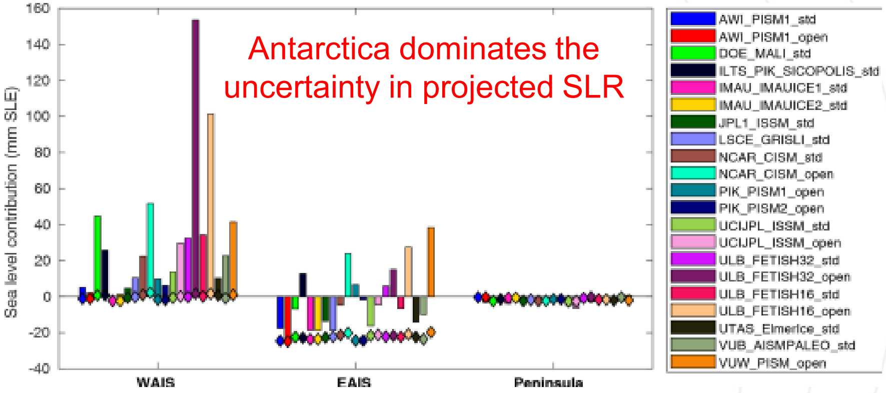
- SLR by 2100: 90 ± 50 mm (RCP 8.5), mainly from increased surface melting. Good agreement across models.



Greenland ensemble mean sea-level projections

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**

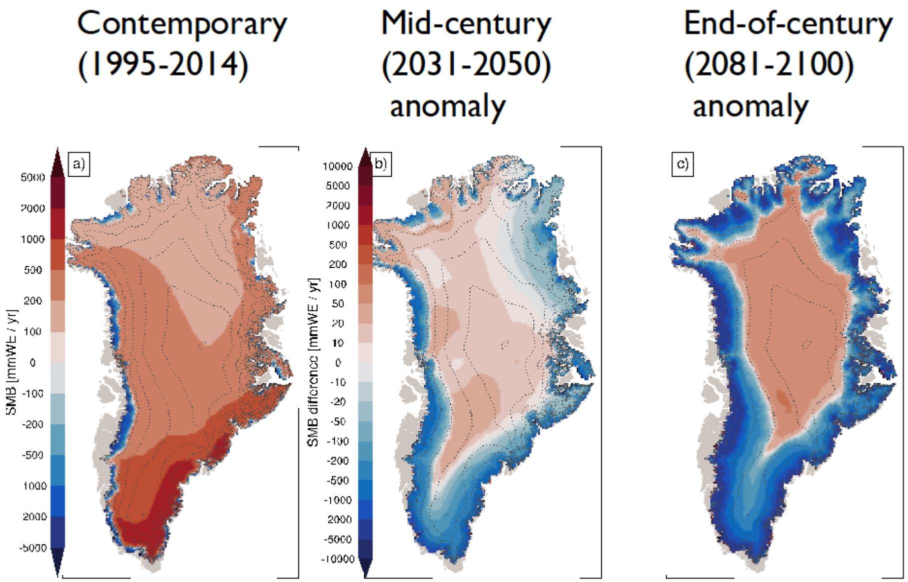


Antarctic regional sea-level contributions (mm SLE) from multiple ice sheet models under RCP 8.5 forcing

Coupled Greenland Ice Sheet Evolution in CESM- CISM

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

- Global CO2 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.

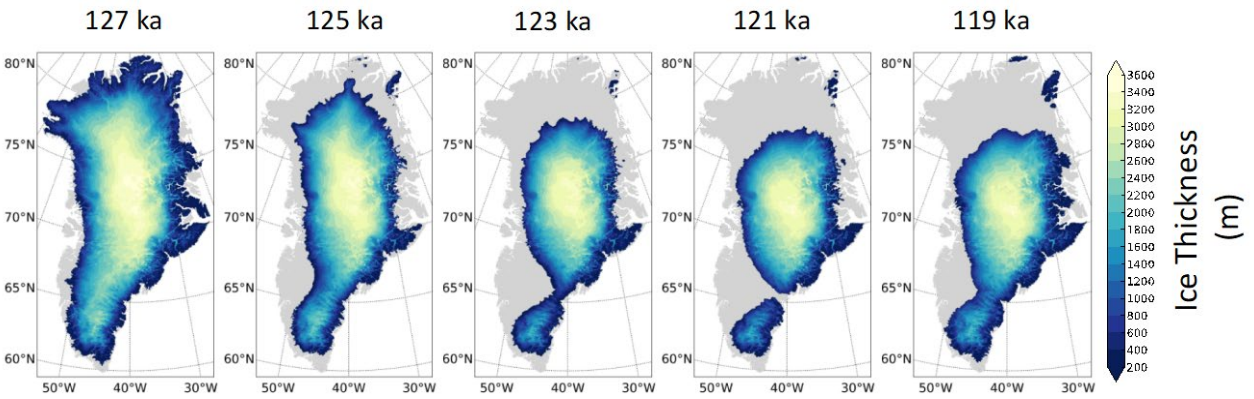


Increased melting of the **Greenland Ice Sheet** in CESM2 (Muntjewerf et al., 2020) under ssp5-8.5. Expanding melt region in **blue**.

Coupled Greenland Simulations of the Last Interglacial

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

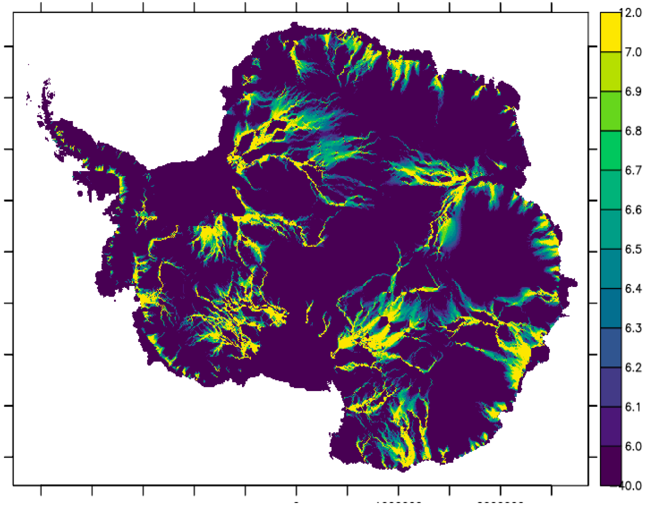
- The Greenland Ice Sheet shrinks from **8.3 m SLE** at 127 ka to **4.2 m SLE** at 122 ka, then slowly recovers.
- Interactive **vegetation** warms the climate and enhances the retreat.



Evolution of ice thickness (m), Greenland Ice Sheet, 127–119 ka, with vegetation updated every 500 CISM years (Sommers et al., 2021).

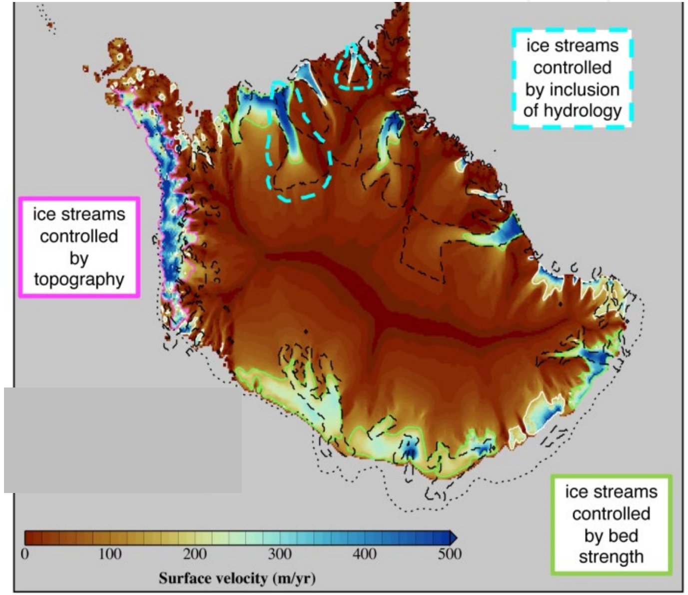
Subglacial Hydrology

CISM now includes an efficient subglacial hydrology scheme.

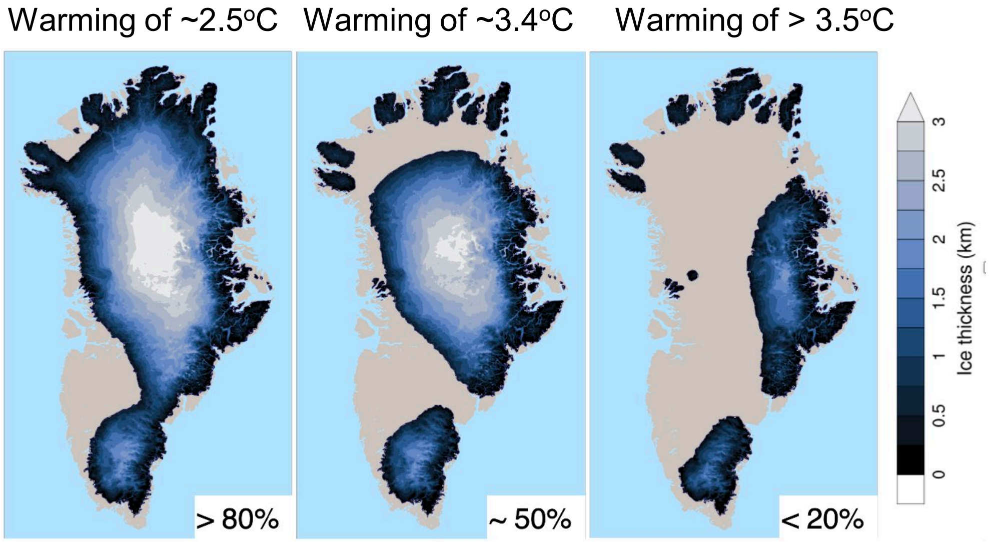


Basal water flux for Antarctica in a steady-state subglacial water model.

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)



Thresholds for Greenland Deglaciation

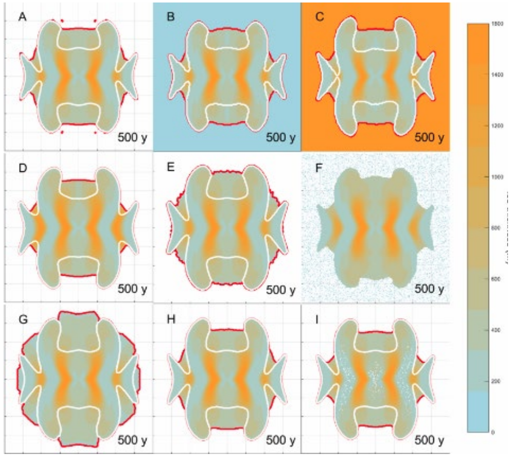


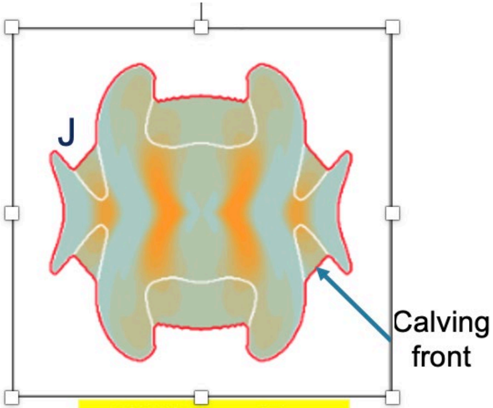
Petrini et al. (2025)

- 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.

Iceberg Calving

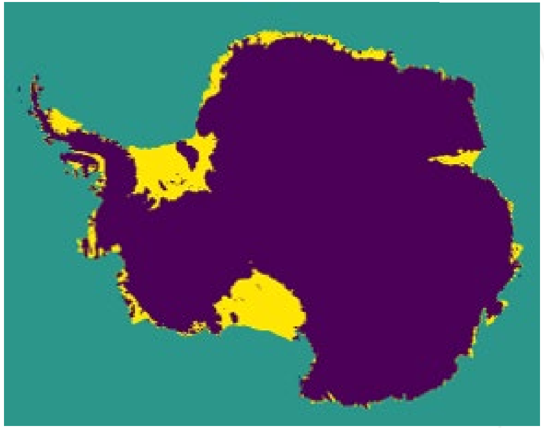
We participated in the **CalvingMIP** project, which aims to improve the representation of damage and calving in ice sheet models.



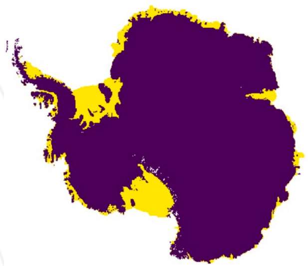


CISM, t = 500 yr

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



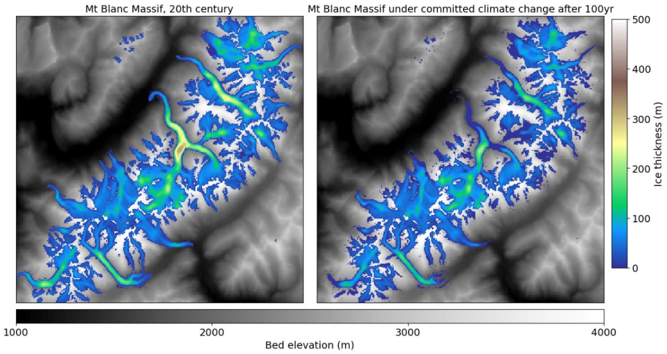
Simulated Antarctic ice shelves with a calving law based on a stress threshold



Observed ice shelves

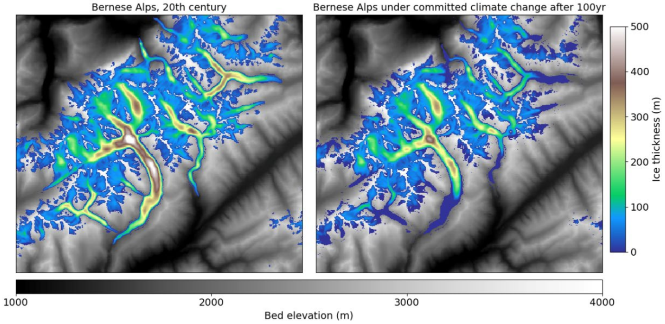
Mountain Glaciers

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.

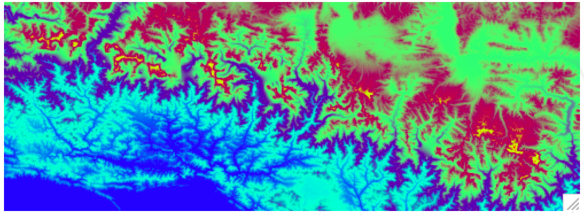
Mountain Glaciers

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

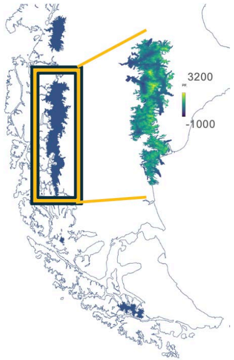
Glacier outburst flood near Juneau, Alaska, 08-06-24

Future CISM Development

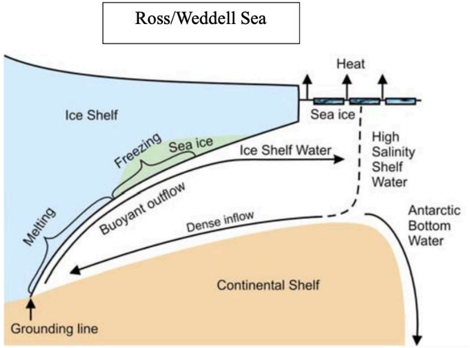
- **Glacier projections** in other regions (Alaska, High Mountain Asia, Patagonia)
- **Ice shelf cavity circulation** module
- **Solid Earth and sea level** model (with ice sheet self - gravity)

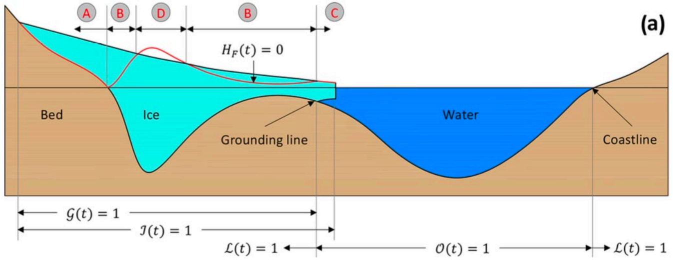


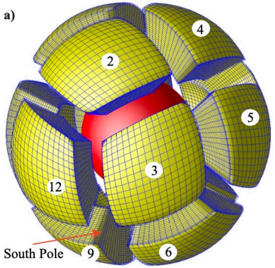
Subglacial bed elevation (m)
Fürst et al. (2024)



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



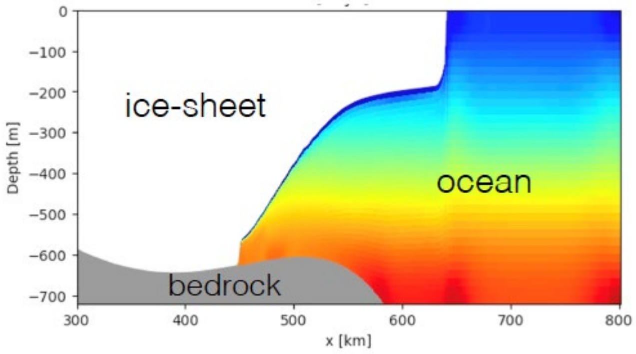


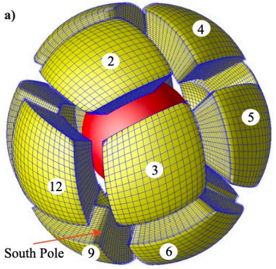


Left: Schematic of sub-ice shelf circulation.
Above: Schematic mass distribution in a sea-level model.
Right: Finite-element grid for a global solid Earth model.

Future Land Ice Goals for CESM3+

- Scientifically support fully coupled CESM3 simulation with evolving Antarctica
- Run CESM3 with Paleo ice sheets
- Add the capability in simulating Mountain glaciers.
- Contribute to ISMIP7
- Add a Solid Earth component





Contact Information

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

Co-chairs:

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Miren Vizcaino, TU Delft, M.Vizcaino@tudelft.nl

Liaisons:

Gunter Leguy, NCAR, gunterl@ucar.edu

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Lead CISM developer:

Bill Lipscomb, NCAR, lipscomb@ucar.edu

Please join us for our winter and summer meetings in 202 7.

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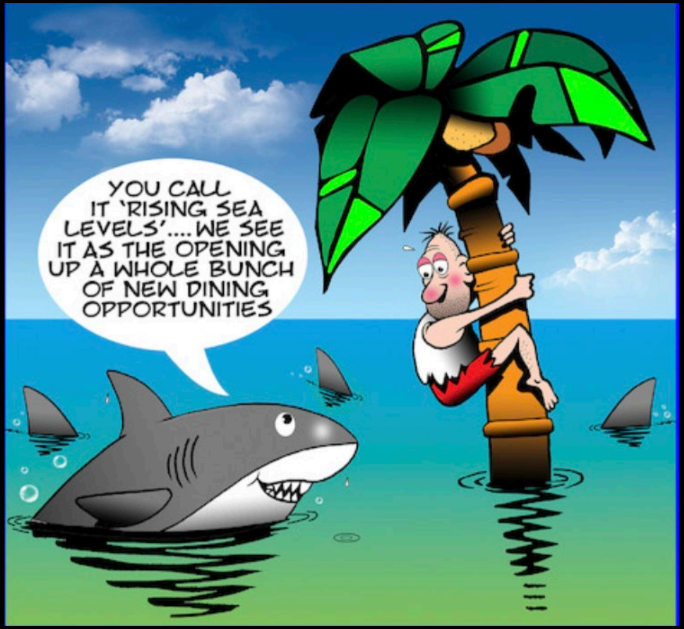
Please join us for our winter and summer meetings in 2027.

Join the Land Ice Community

What questions can we ask CESM with land ice capabilities?

Depend on perspective!



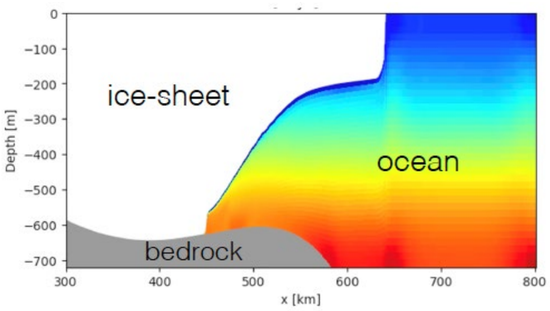
Extra Slides

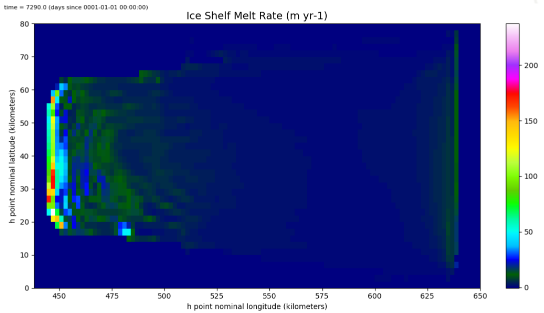
Summary

- 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.

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 (left); sub-ice-shelf melt rate for an idealized experiment (right, G. Marques)

What questions can we ask CESM with land ice capabilities?

How will sea level
impact
the places we live in?

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How will GLOFs impact population living downstream of glaciers?

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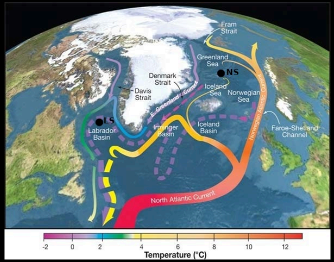

How will ice melt impact AMOC and the climate system?