Land Ice and Earth System Models

CSU Guest Lecture

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Outline

Part 1: Ice sheets and glaciers
Ice sheets and glaciers; sea level; ice sheet physics; modeling ice sheets using the Community Ice Sheet Model (CISM); MIPs and simulation results.

Part 2: Land Ice in Earth System Models (CESM2)
Coupling GrIS and AIS to CESM: a brief history and the coupling feedbacks; Greenland VS Antarctic coupling; Projections and paleo modeling; The challenges to ocean coupling

Part 3 Conclusion
The questions we can answer with ice sheets in ESMs; What's next.

Part 1: ice sheets and glaciers (land ice)

Causes of global sea level rise (SLR)

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

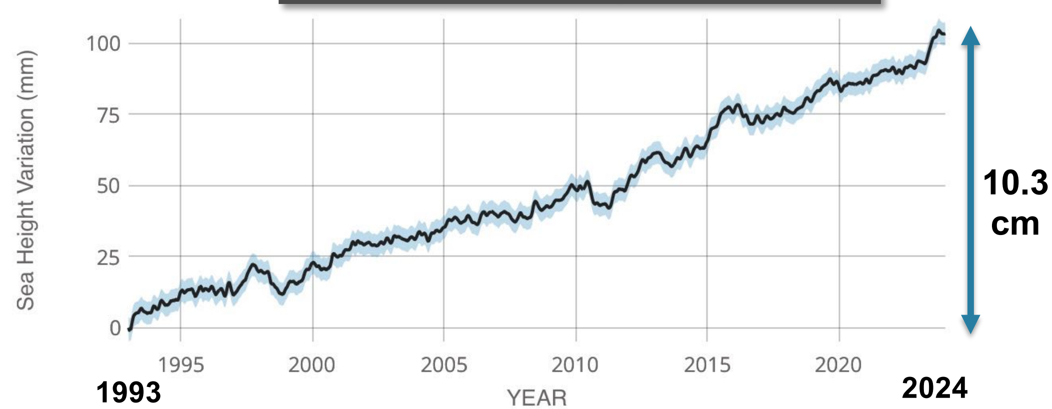
The **Greenland and Antarctic ice sheets** began losing mass around 1990 and now account for about 35% of sea level rise.

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

Global mean sea level rise from satellite altimetry since 1993

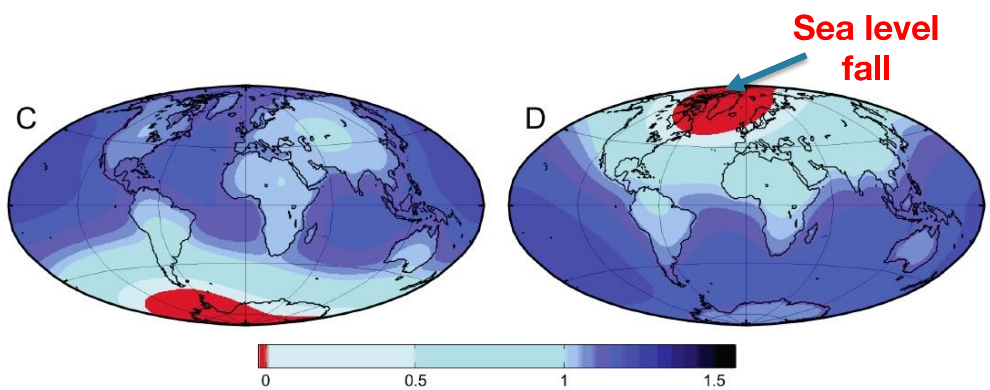


Credit: NASA GSFC/PO.DAAC

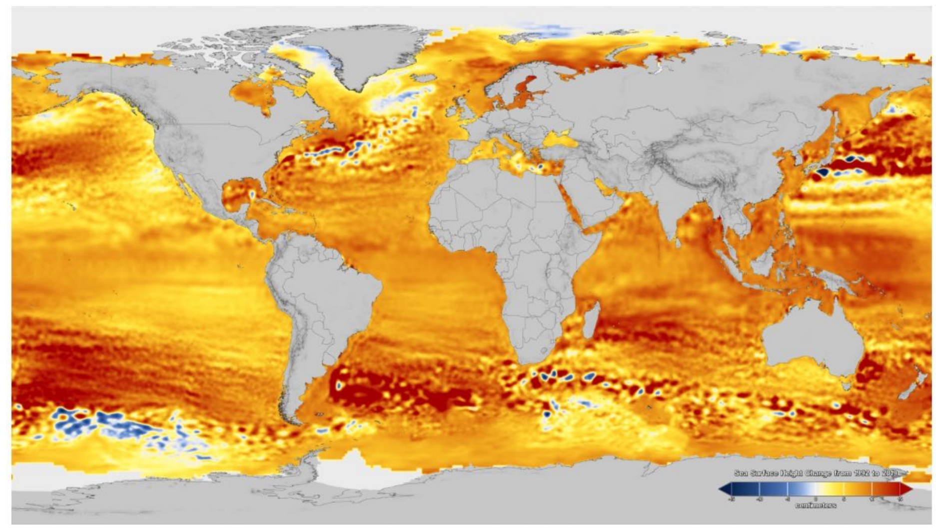
Regional sea-level variations

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.



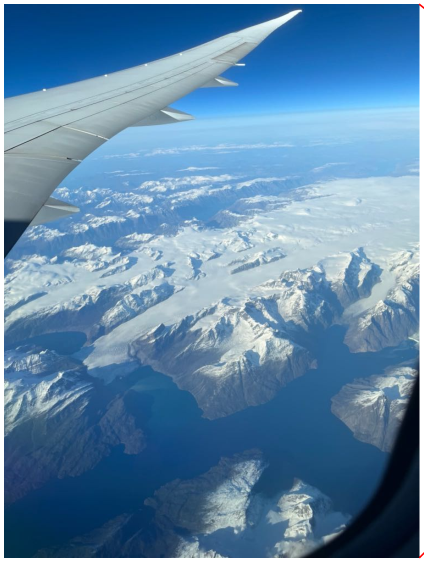
Relative sea-level change from retreat of the Antarctic Ice Sheet (left) and Greenland Ice Sheet (right) (Mitrovica et al. 2011).



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

2 continental ice sheets

Picture of a Greenland outlet glacier in April 2024

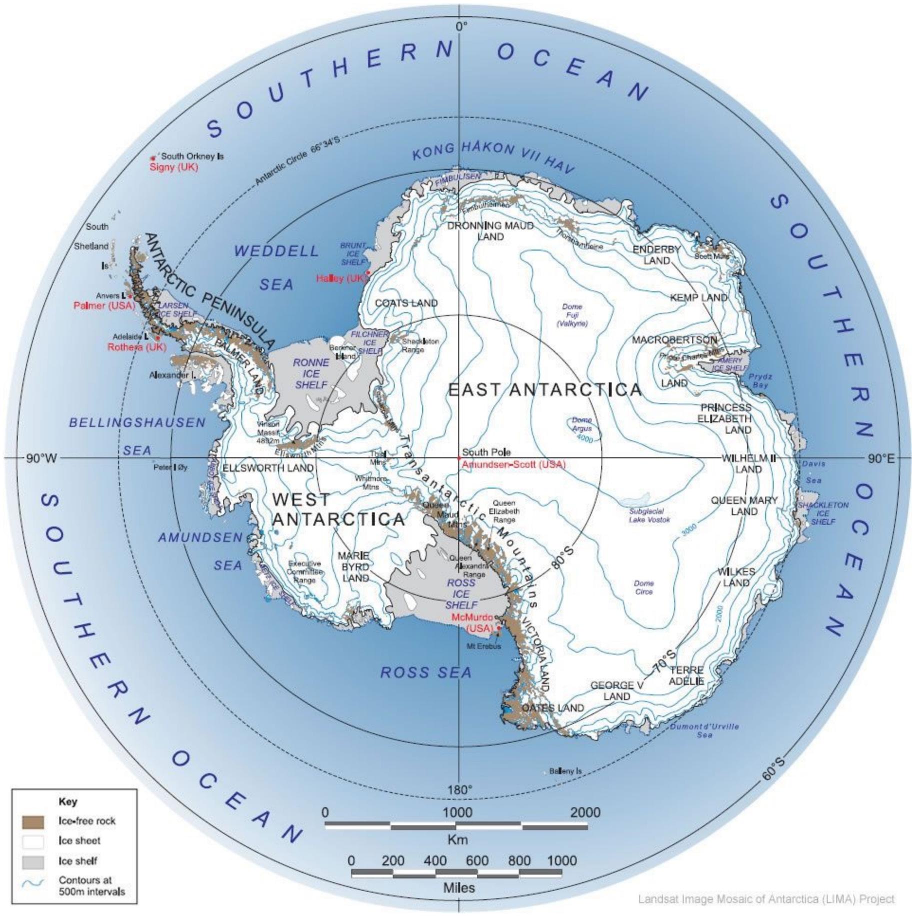


Greenland

Antarctica

First step on Antarctic ice on the way to McMurdo (courtesy Scott Landolt)

Antarctic geography



3 main regions

- The Antarctic Peninsula (AP)
- The West Antarctic Ice Sheet (WAIS)
- The East Antarctic Ice Sheet (EAIS)

WAIS

- 2 biggest ice shelves: Ross and Ronne-Filchner each about the size of France.
- Bed topo mostly below sea level.
- Contains ~ 5 m of sea level equivalent
- Fastest retreating part of Antarctica.

EAIS

- Contains ~53 m of sea level.
- Is higher and colder than WAIS or AP.

Antarctic Ice flow

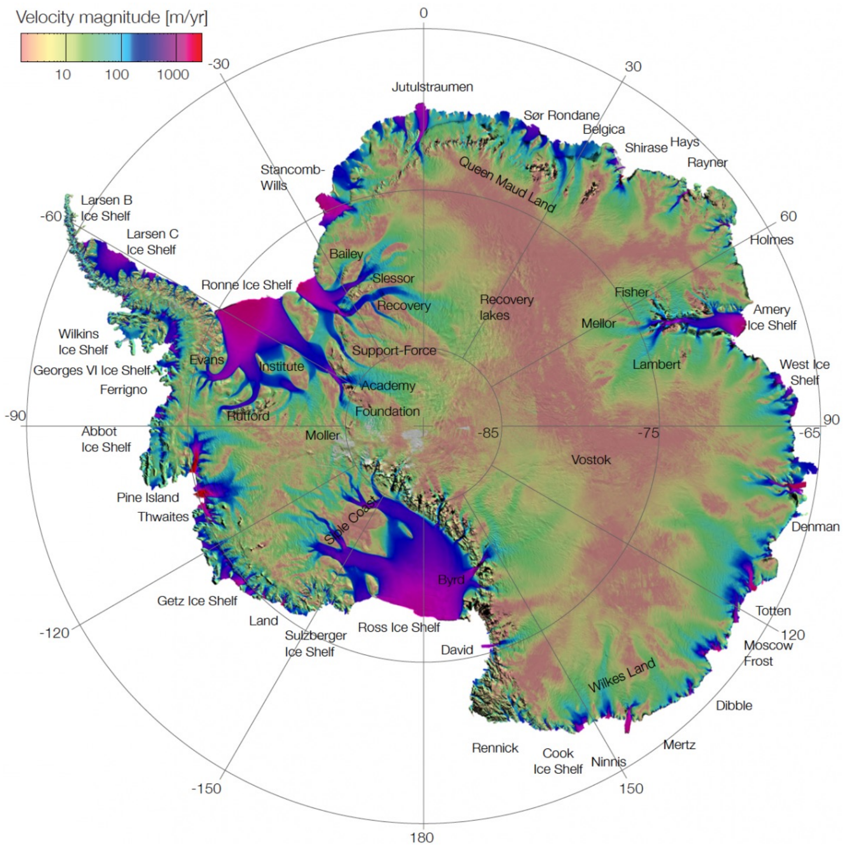


Fig: Antarctic ice velocity (m/yr, Rignot et al. 2011)

Slow moving (grounded) ice

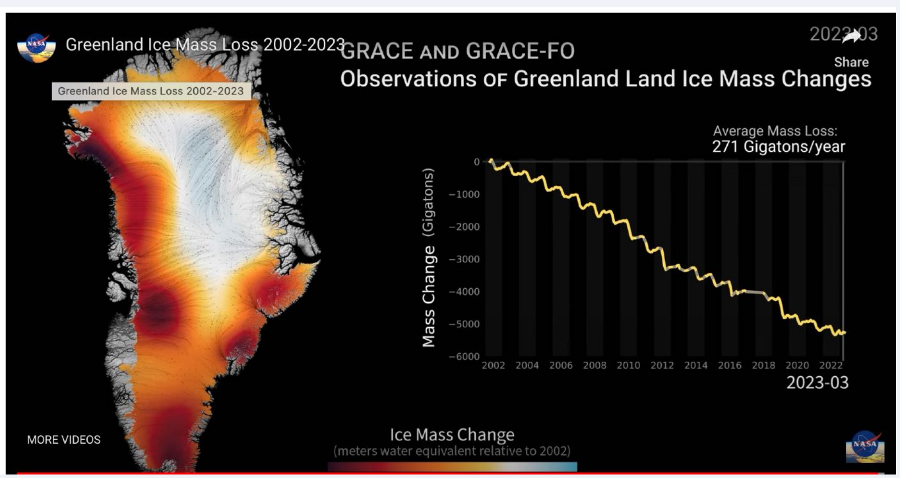
- In the interior
- The ice that is quasi static is called the ice divide.

Fast flowing grounded ice: ice streams

- Flows faster than surrounding ice
- Sits on more lubricated bed
- Represents ~10% of Antarctic ice
- Responsible for 90% of the ice discharge

Greenland Ice Sheet

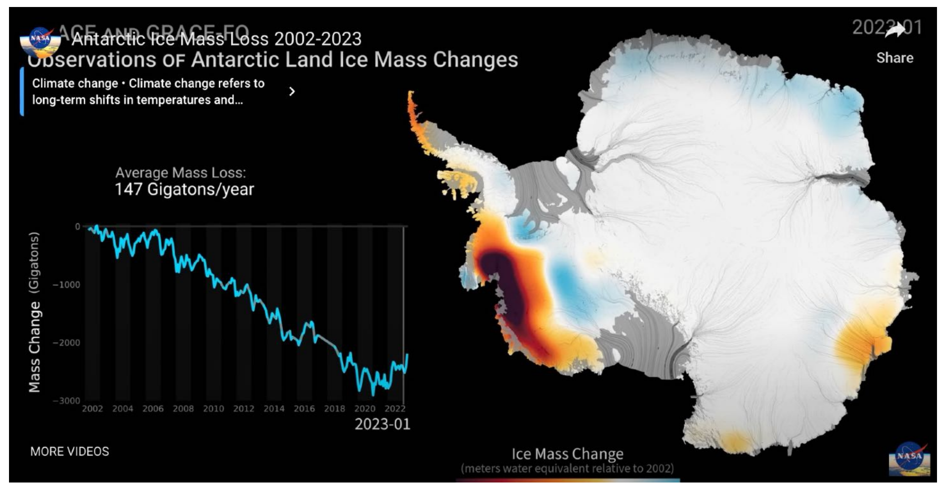
- **7 m** sea level equivalent (SLE)
- **Snowfall** balanced by **surface runoff** and **iceberg calving**
- Mass loss of **270 Gt/year** since 2002
- Most vulnerable to atmospheric changes



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
- Most vulnerable to oceanic changes

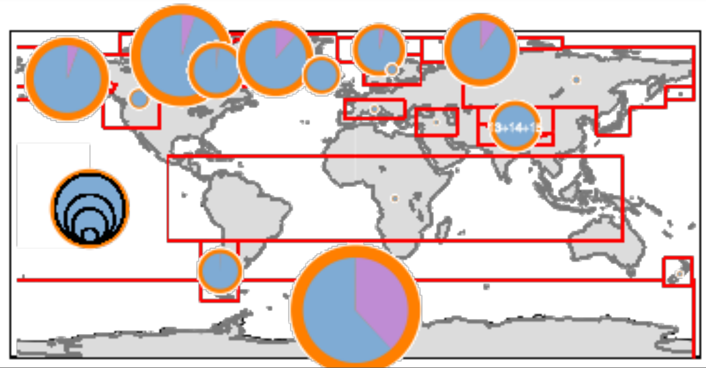


Antarctic mass change from GRACE, 2002–2023

Credit: NASA and JPL/Caltech

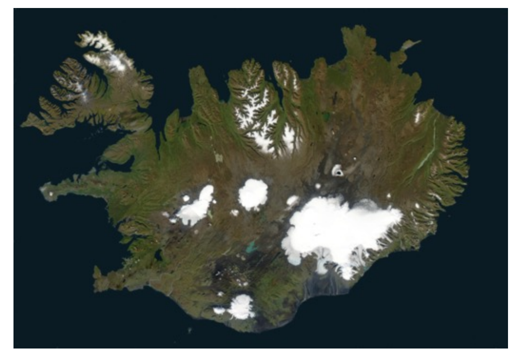
Mountain glaciers

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



Regional glacier volume (Farinotti et al. 2019)

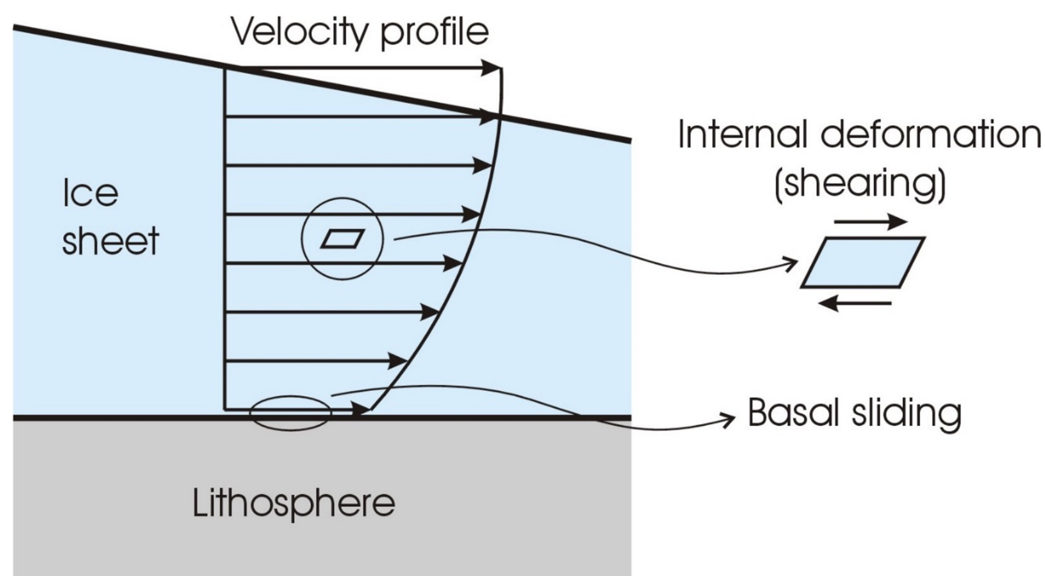
Mer de Glace, French Alps



Iceland with Vatnajokull ice cap

How glaciers move

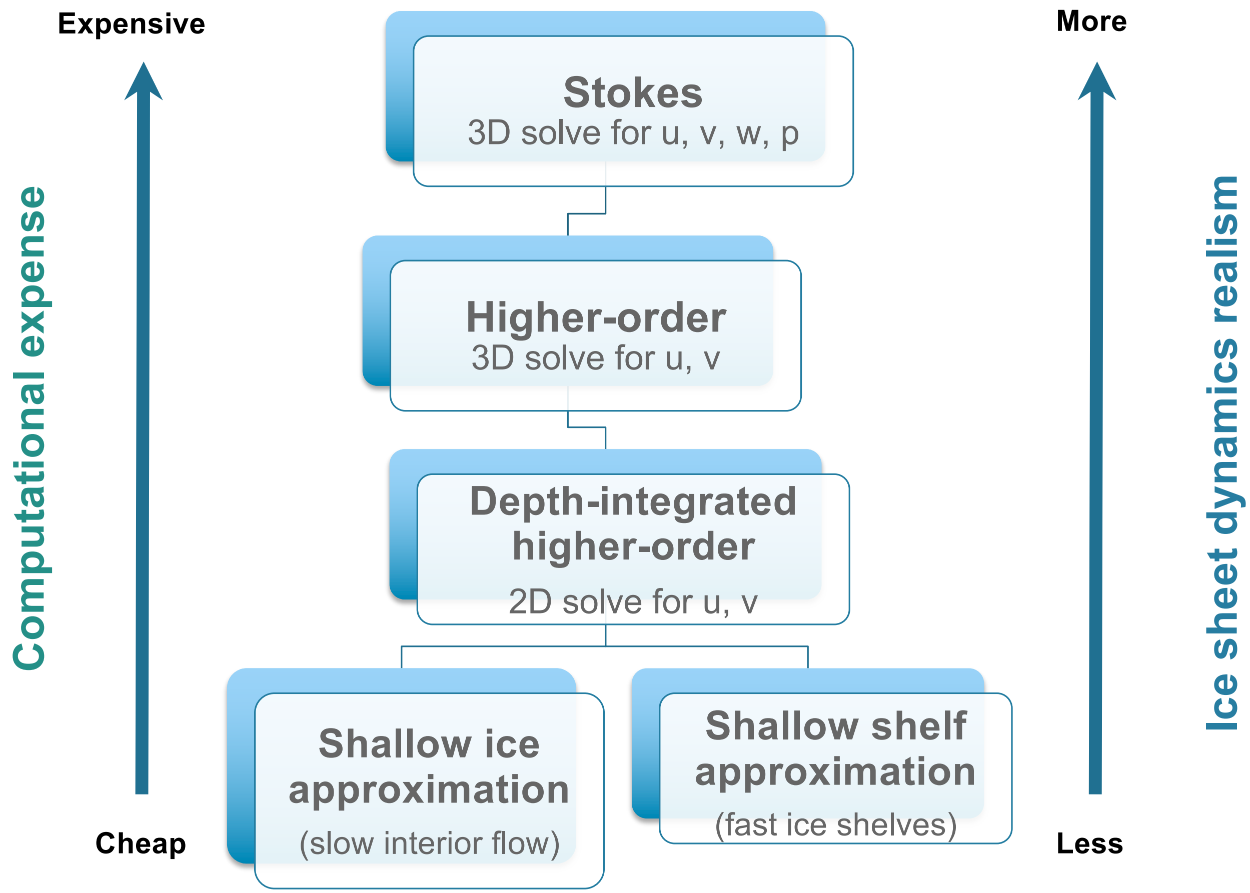
- **Glaciers flow downhill** under the force of gravity.
- Ice deforms like a very **viscous fluid**. Warmer ice is softer and flows faster.
- When there is water at the bed, glaciers can **slide** at speeds up to several km/year.



- 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.**

Ice sheet dynamics in the Community Ice Sheet Model (CISM)

- CISM includes a **hierarchy of velocity solvers**, including higher-order solvers valid over most or all of the ice sheet.
- CISM also solves equations for **conservation of mass and internal energy**.
- The model includes parameterizations of physical processes such as **iceberg calving, basal sliding**, and **grounding-line migration**.



How ice sheets gain and lose mass

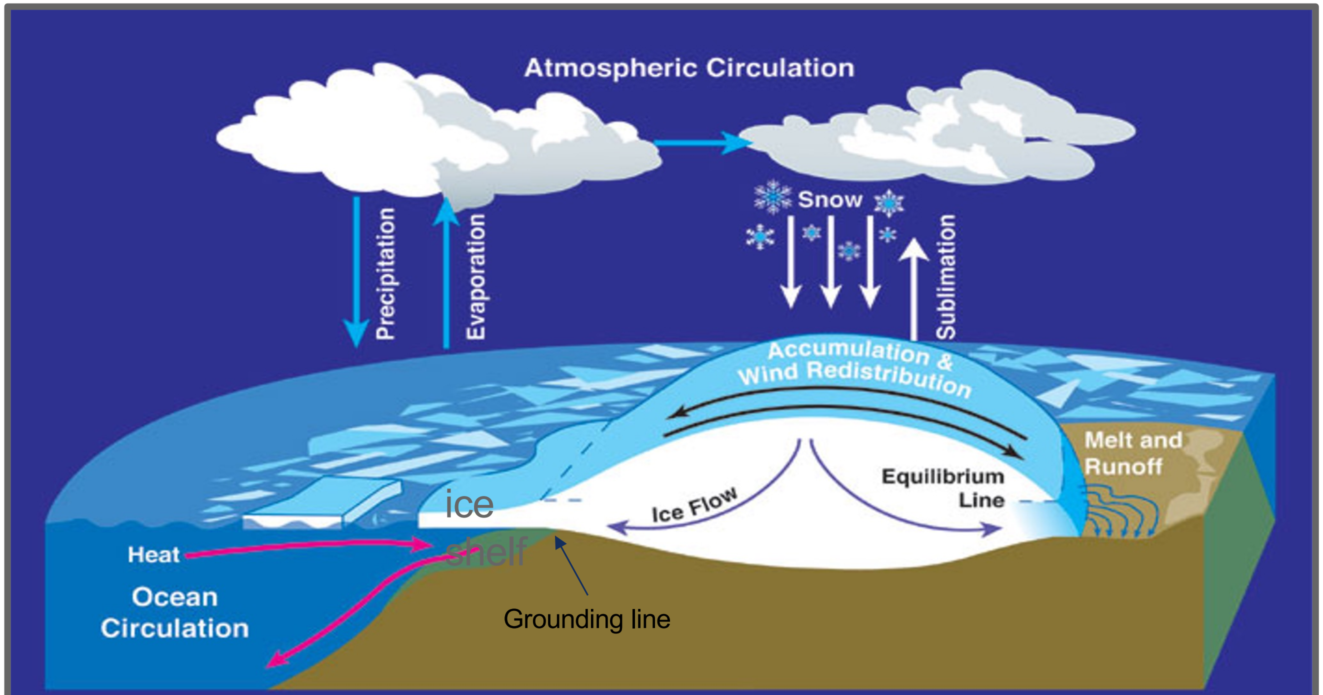


Image source: http://www.nasa.gov/images/content/53743main_atmos_circ.jpg

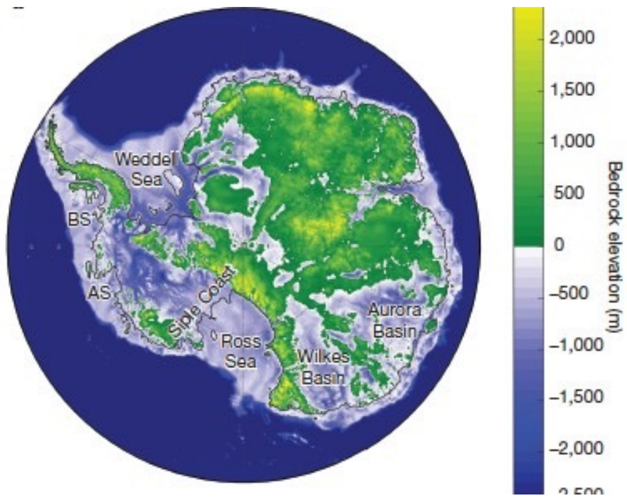
Mass Balance: Change in ice sheet mass = mass in – mass out

Snowfall melting, calving

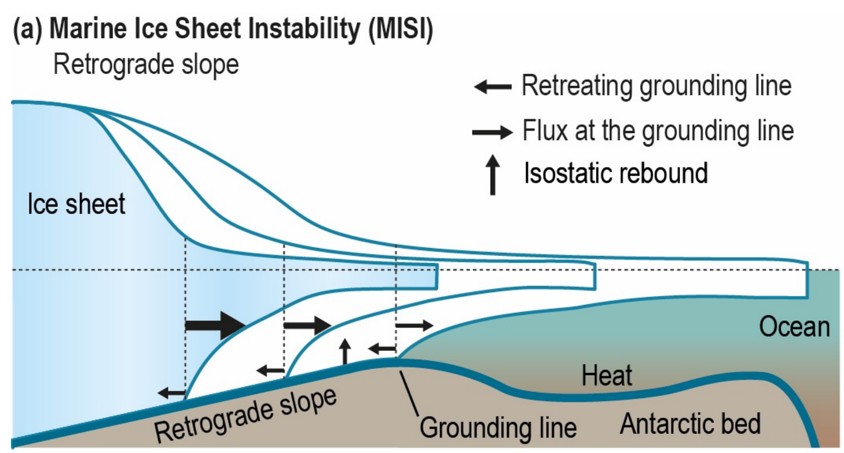
Sea level change!

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



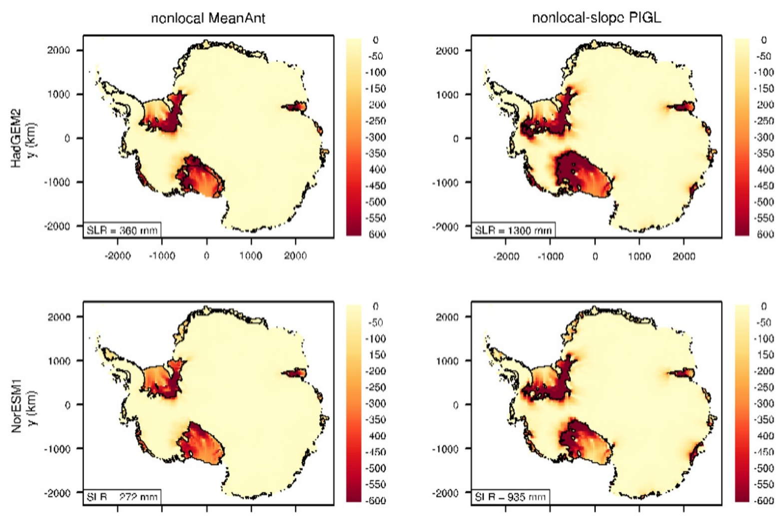
Schematic of a warm sub-ice-shelf cavity
(Holland et al. 2020)

Ocean-forced Antarctic projections with CISM

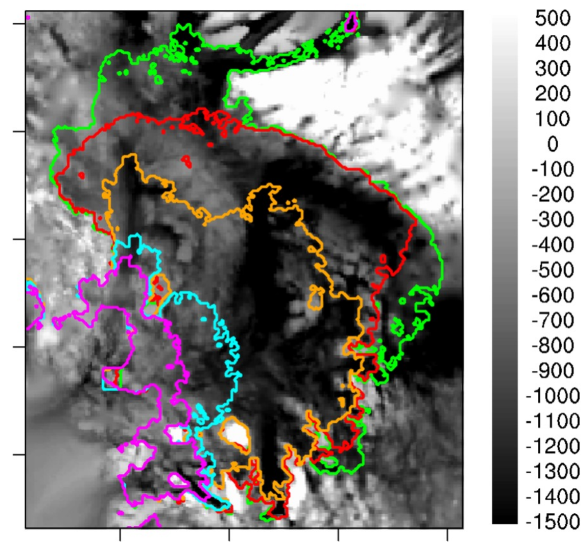
Question: Could ocean warming projected for 2100 drive irreversible retreat of the **West Antarctic Ice Sheet**?

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

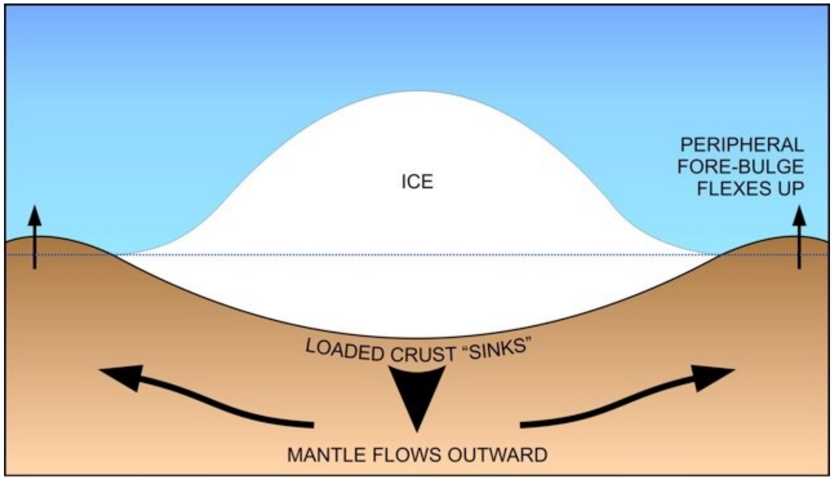


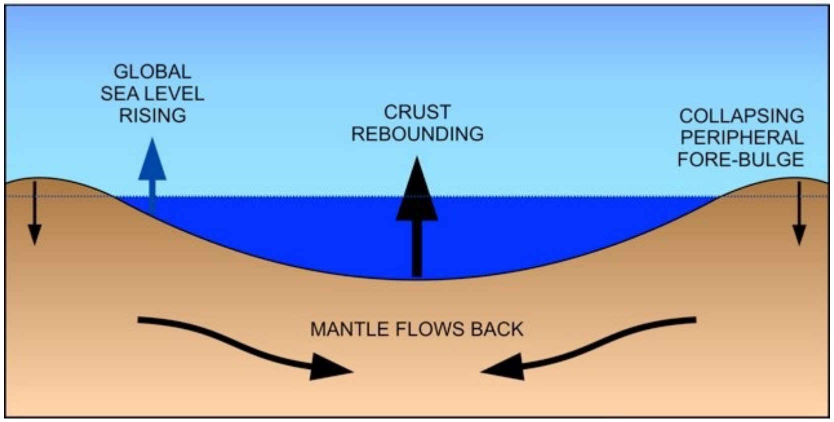
Modeled Antarctic ice thickness change (m), 1950–2500, with two basal melt schemes and ocean forcing from two global ESMs (Lipscomb et al., 2021)



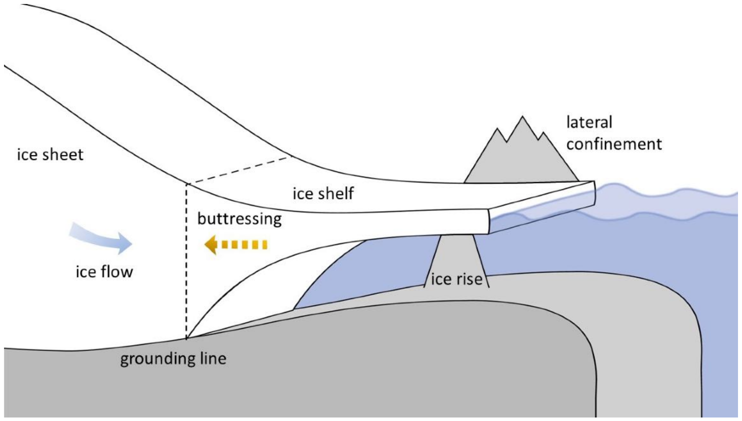
Simulated ice retreat in the Amundsen sector. Bright lines show grounding-line position at 100-year intervals from 2100.

Glacial Isostatic adjustment (GIA)





- Ice sheets have a lot of mass and create a deformation on top of the Earth's crust. Under their mass, the Earth's crust subside ("sinks").
- As an ice sheet loses mass/retreats, the crust rebounds and relaxes to a new state.
- This effect has the potential to increase the stability of an ice stream via increased buttressing (in particular in the presence of ice rises).

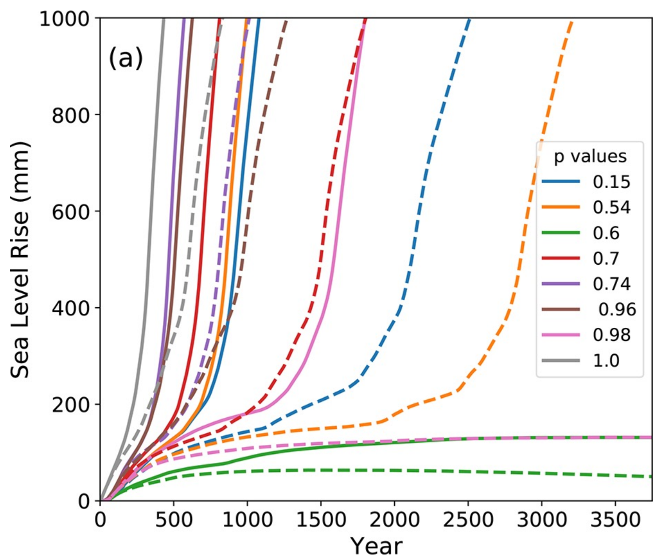


Ocean-forced Antarctic projections with CISM

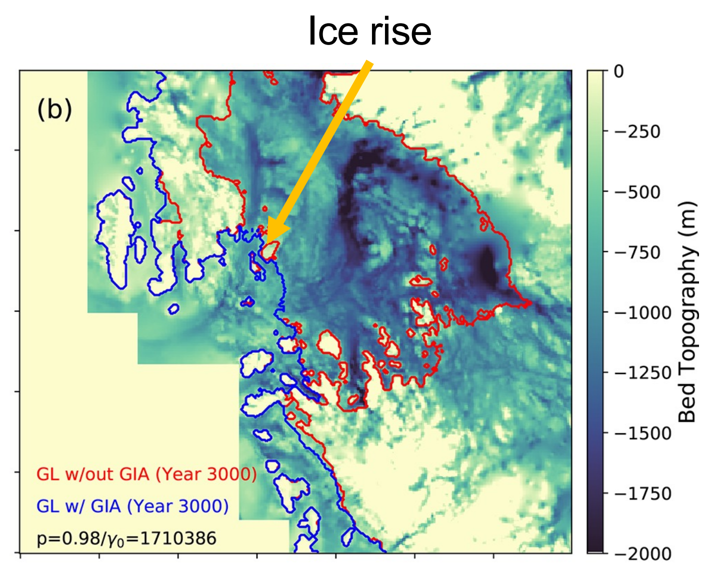
Question: What role does GIA play in the retreat of the **West Antarctic Ice Sheet**?

Results:

- Collapse of Thwaites is **delayed by about 300-900 years** in most configurations when **using GIA**.
- **GIA prevented** Thwaites **collapse** in one case.



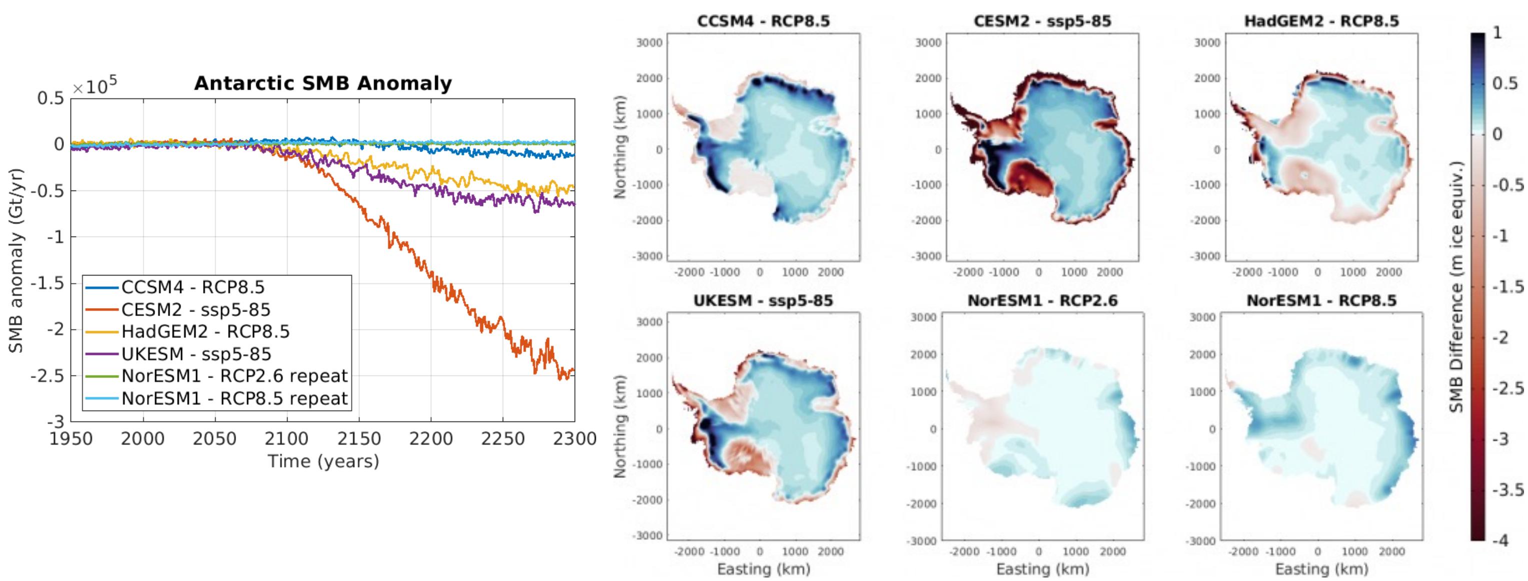
Modeled sea level rise evolution (m) as a function of basal friction and ocean forcing parameters. Dashed/Solid lines show results with/without GIA (Berdahl et al., 2023).



Simulated grounding line retreat in the Amundsen sector after 3000 simulated years. Blue/Red line show results with/without GIA.

Ice Sheet Model Intercomparison Project

- Extended thermal forcing and SMB anomalies for 4 GCMs.
- Some runs use forcing randomly repeated from 2081–2100.
- High (8.5) and low (2.6) emission scenarios from CMIP5 and CMIP6



- Wide spread of mean anomaly, from ~10 up to -700 mm/y.
- Models have different anomaly patterns.

Figs. : (left) SMB anomaly (Gt/yr) timeseries. (right) : Change in SMB between the projection start and end date (2300 minus 2015) for the AOGCMs shown in (left). (Figures from extended protocol: https://www.climate-cryosphere.org/wiki/index.php?title=ISMIP6-Projections2300-Antarctica)

Ice Sheet Model Intercomparison Project

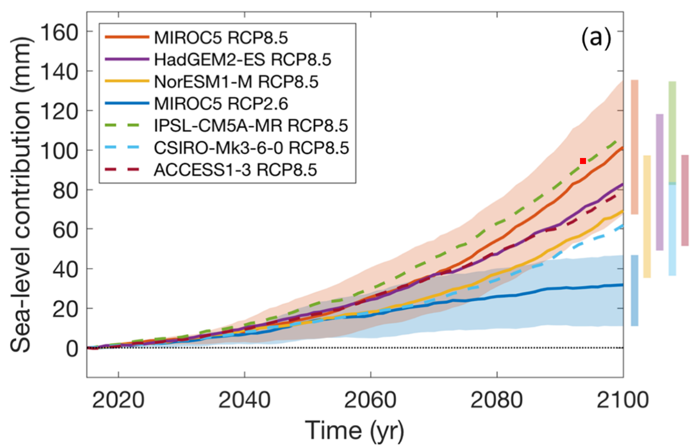
ISMIP6 — Ice Sheet Model Intercomparison Project for CMIP6

Greenland (Goelzer et al. 2020)

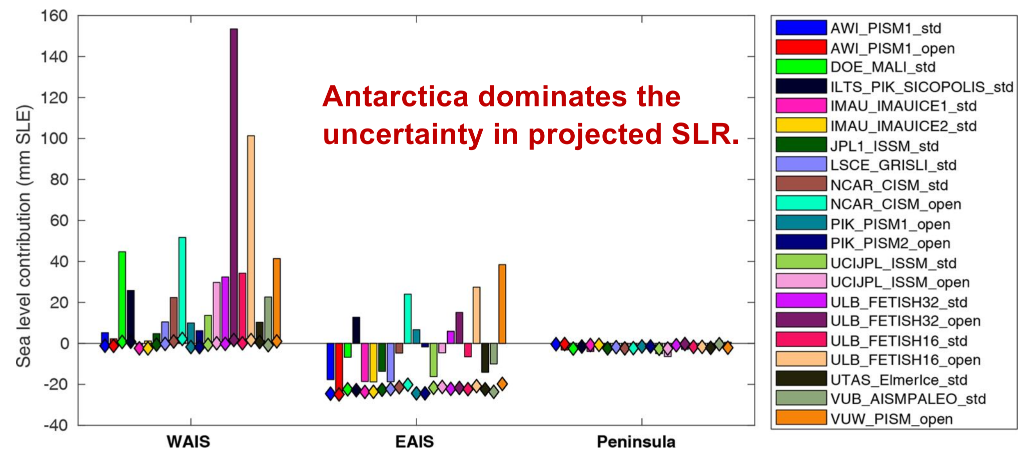
- SLR by 2100: **90 ± 50 mm (**RCP 8.5), mainly from **increased surface melting**. Good agreement across models.

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 NorESM RCP 8.5 forcing

Ice Sheet Model Intercomparison Project

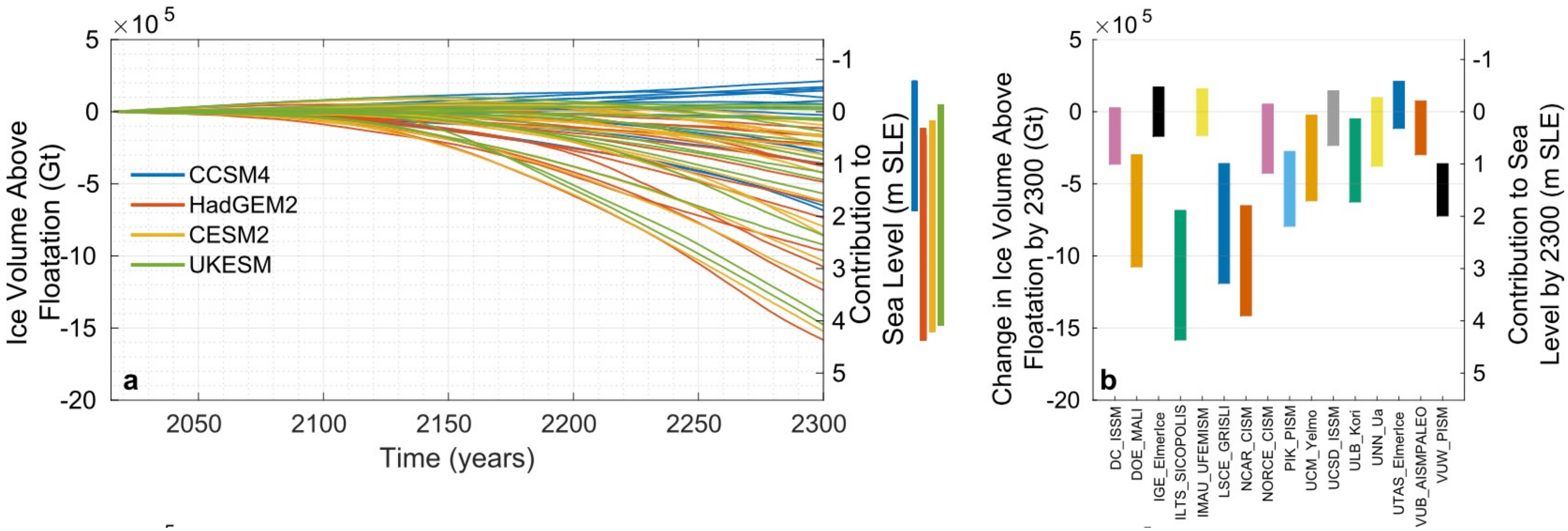
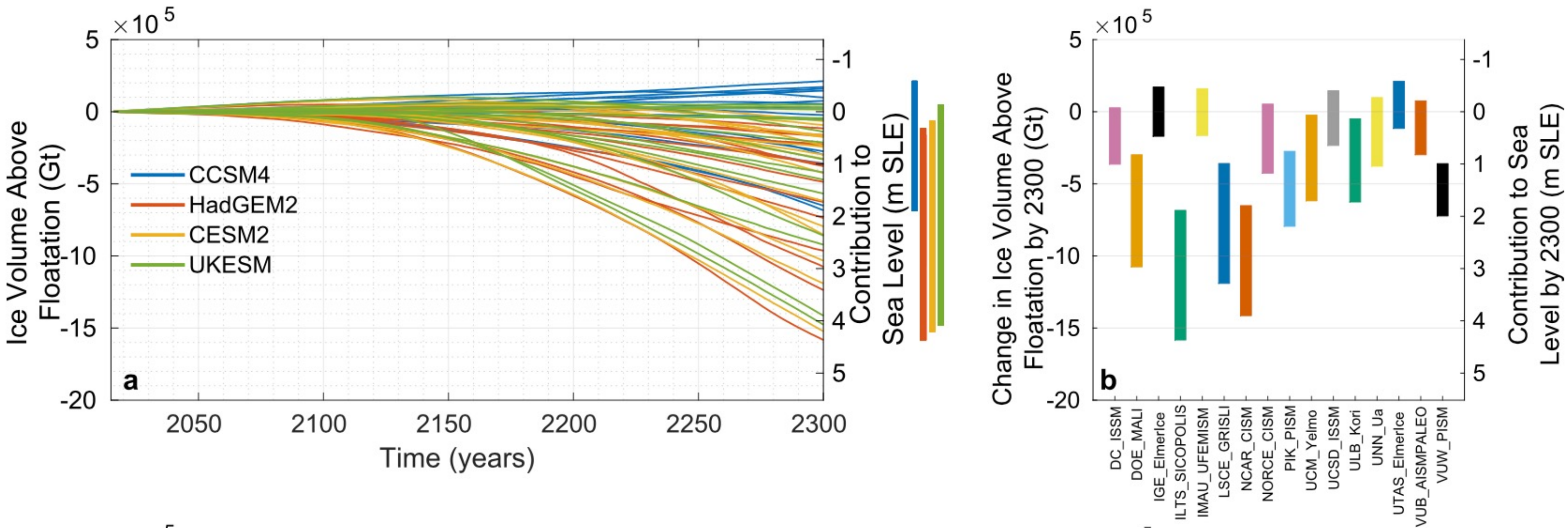


Figure 4. Evolution of volume above floatation (VAF) converted into mass for experiments with high emission scenario and forcing simulated until 2300. Cumulative evolution of VAF during (a). Bars on the right show the spread of results in 2300 for simulations forced by each climate model. Change of ice VAF in 2300 compared to 2015 and converted into for each ice flow model for the four high-emission scenarios with 2300 forcing (b). (Seroussi et al. 2024)

Ice Sheet Model Intercomparison Project



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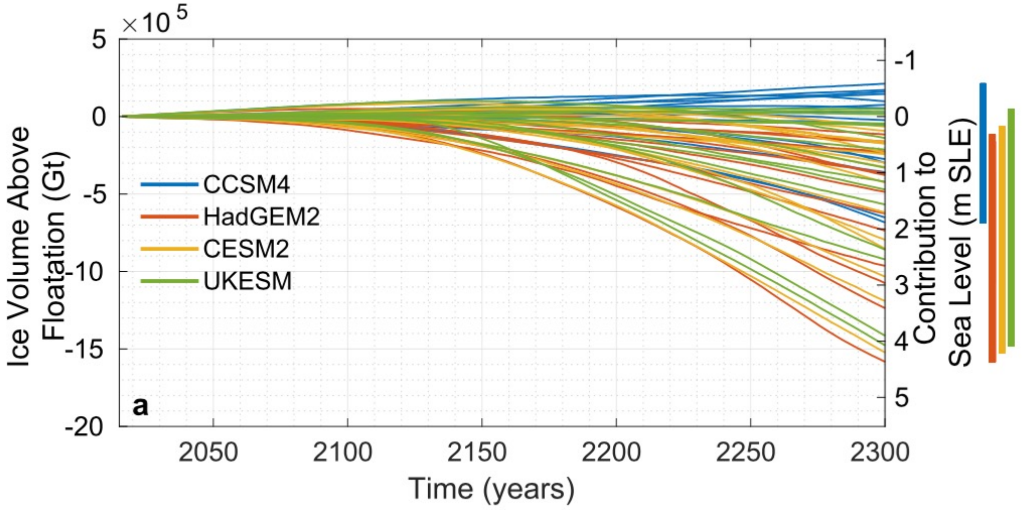
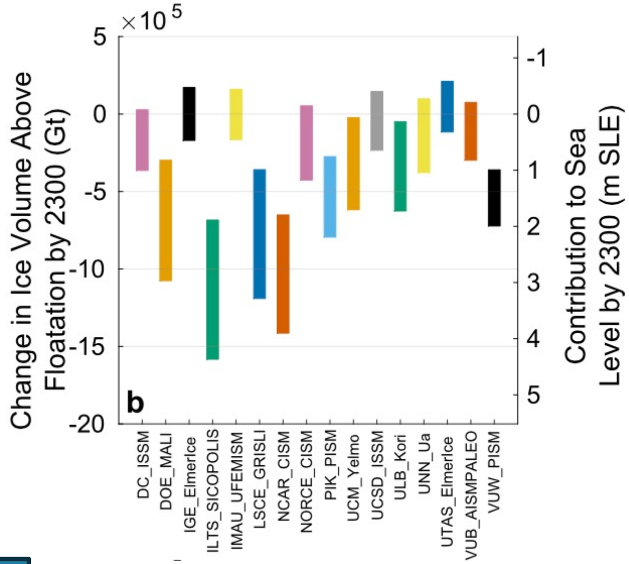
What do you think about these results? Are they useful?

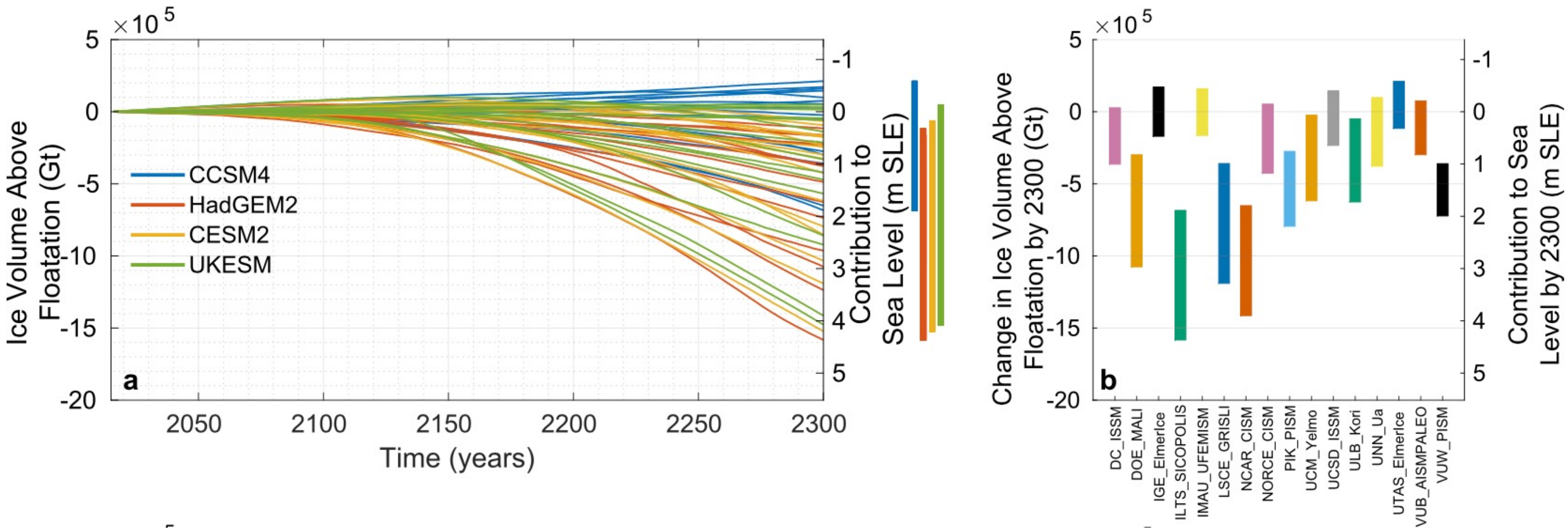
Ice Sheet Model Intercomparison Project





- The uncertainty spread increases beyond 2100.
- The spread highly depends on the AOGCM forcing.
- The spread highly depends on the ice sheet model used.
- Some ice sheet models are more sensitive than others.

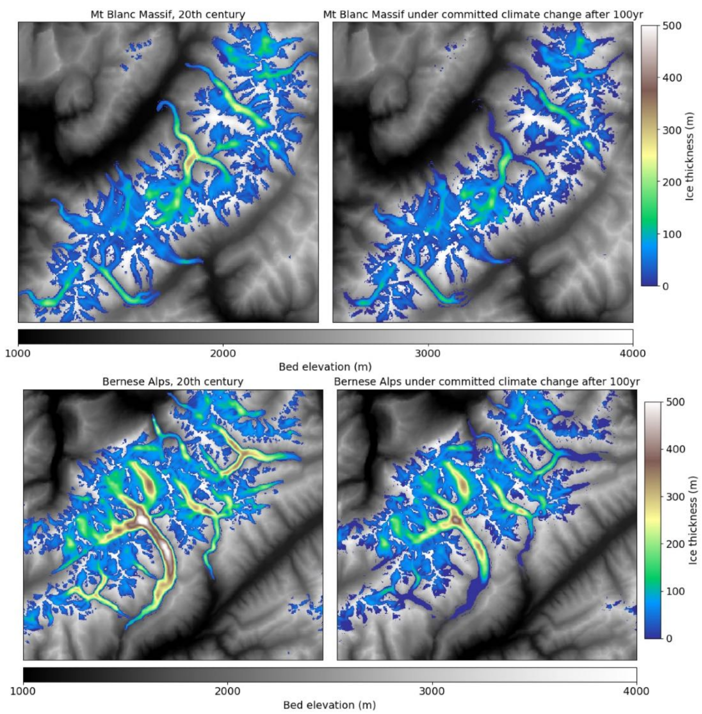
Ice Sheet Model Intercomparison Project



- This spread of uncertainty is what policy makers are using to make decision (albeit for now they are looking at the spread until 2100!).
- Ice sheet modelers are working really hard in reducing these uncertainties.
- We also need to understand why ESMs have such a wide range of forcing -> strong impact on ice sheet responses.

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.

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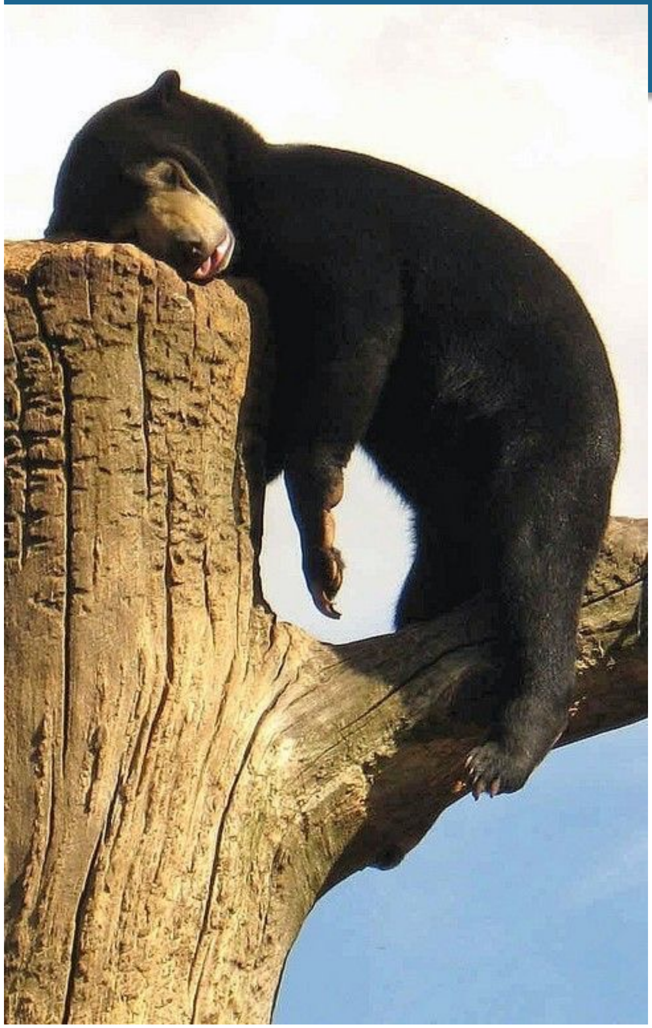


BREAK?

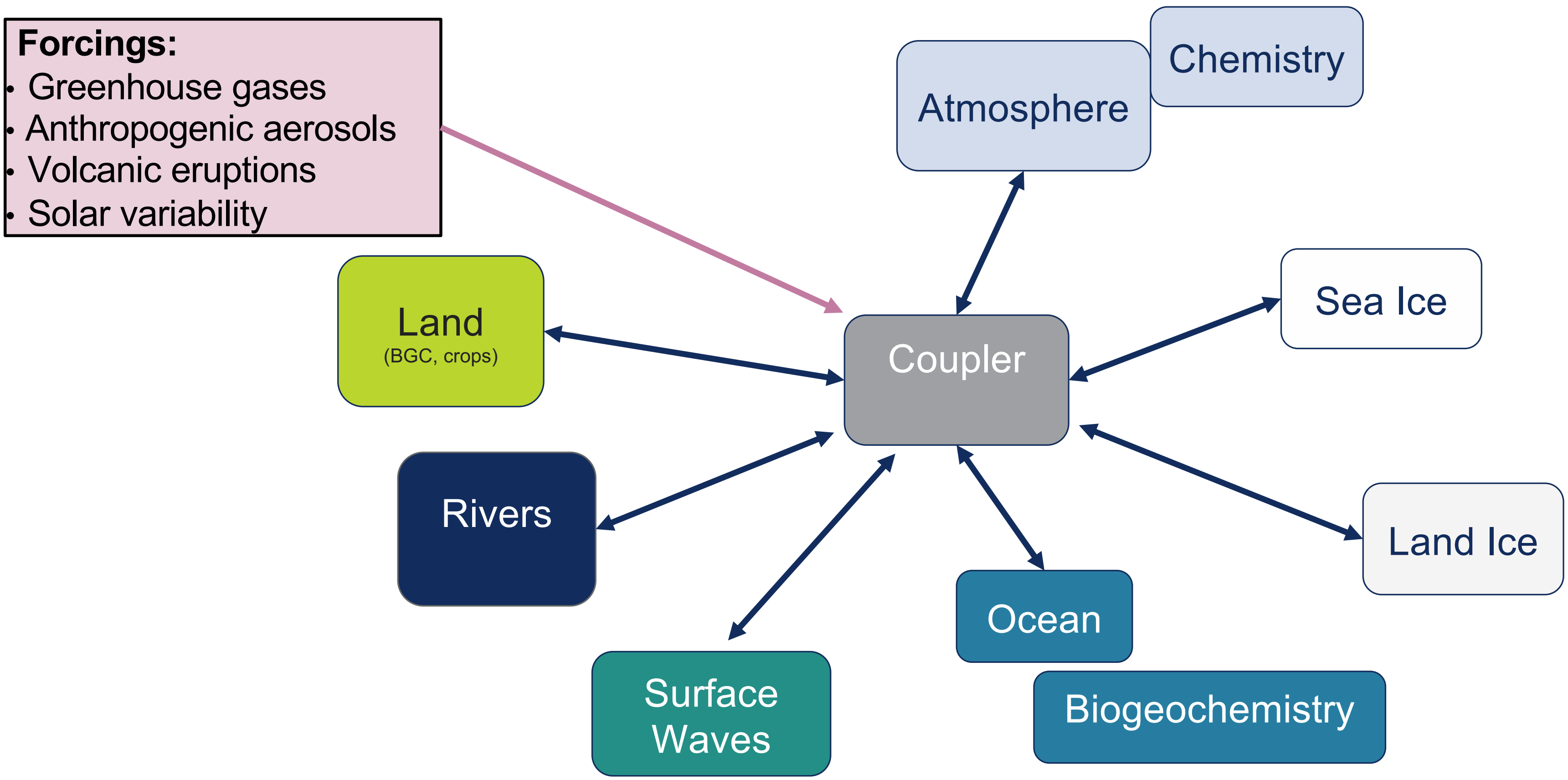
Part 2: ice sheets in climate models

Ice sheets in Earth System Models

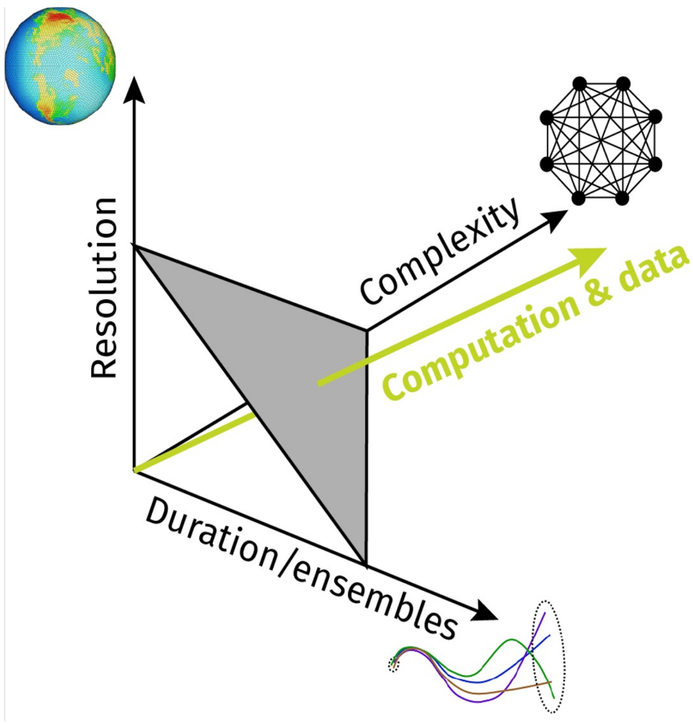
The Community Earth System Model

The Community Earth System Model (CESM)

Structure of a fully coupled Earth System Model

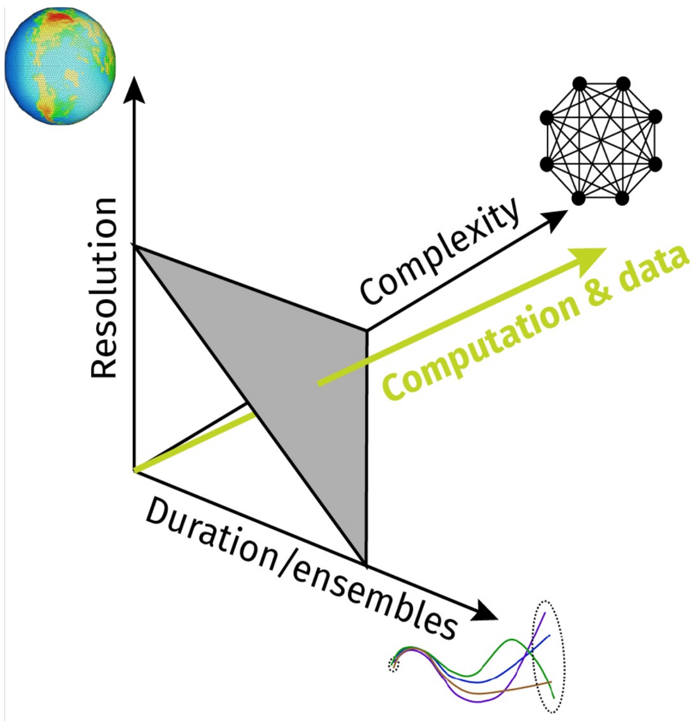


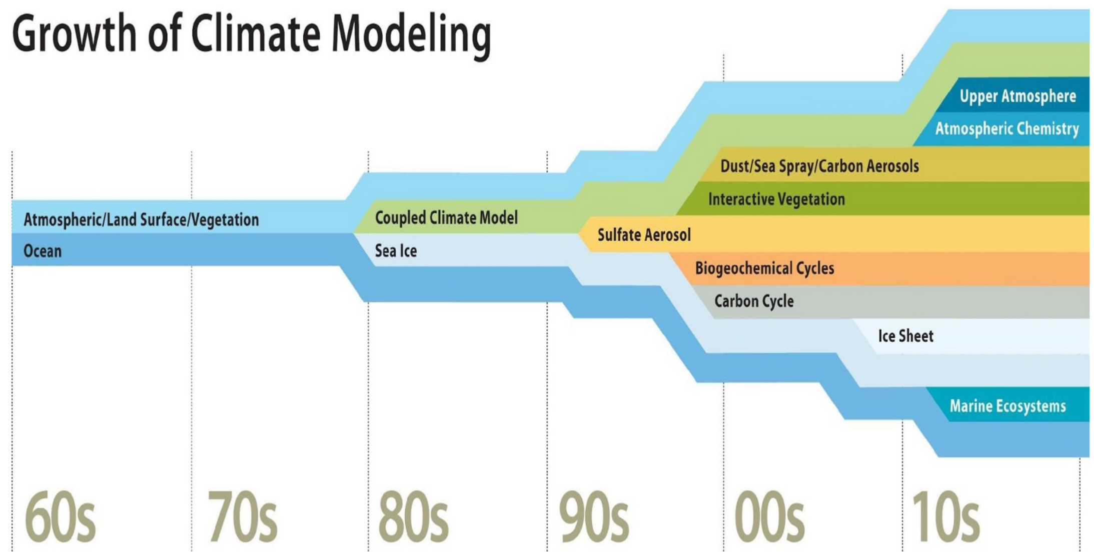
Different research questions require different considerations



Different research questions require different considerations

Complexity





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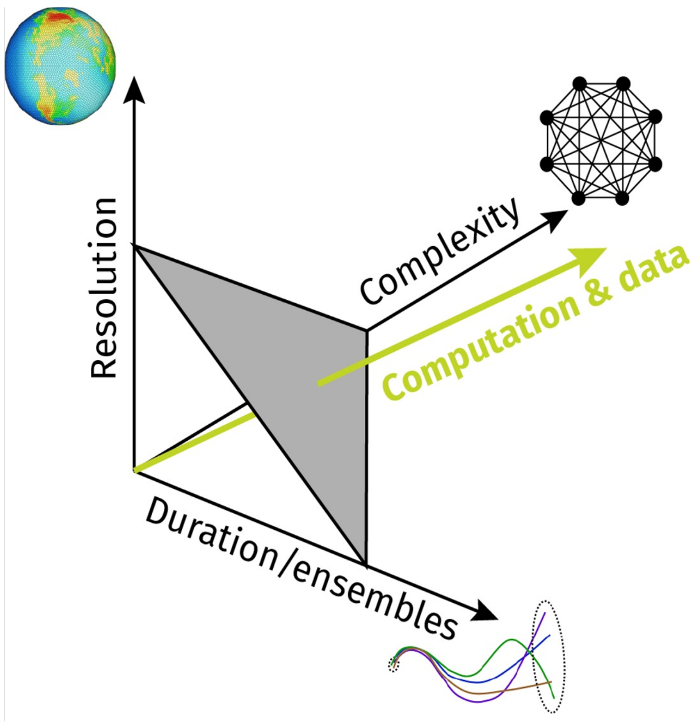

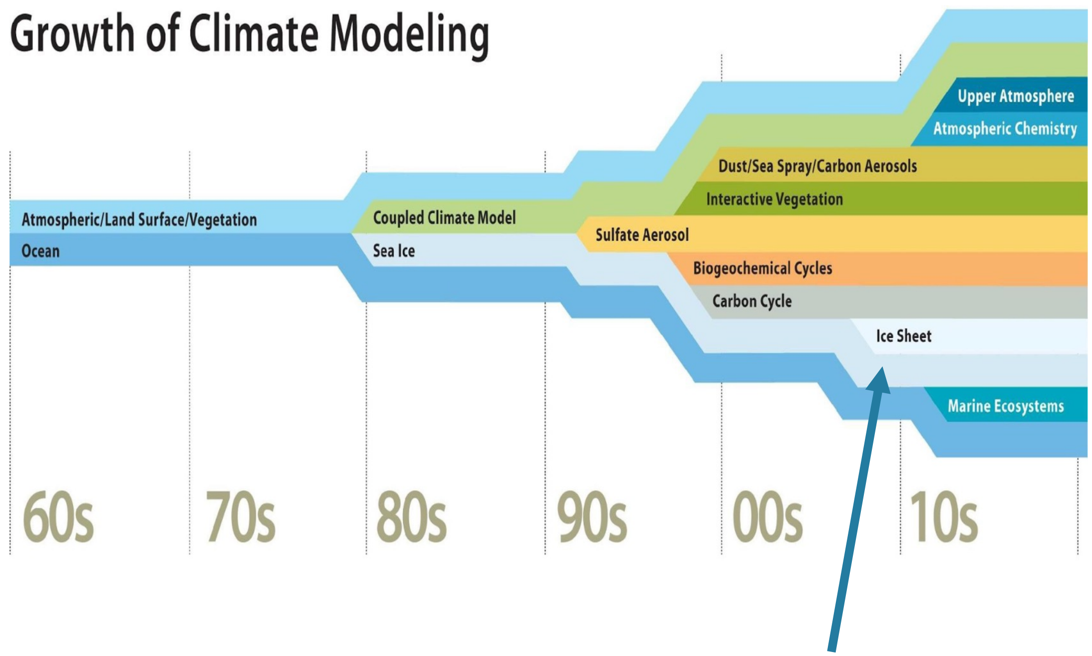

Recently

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 + …

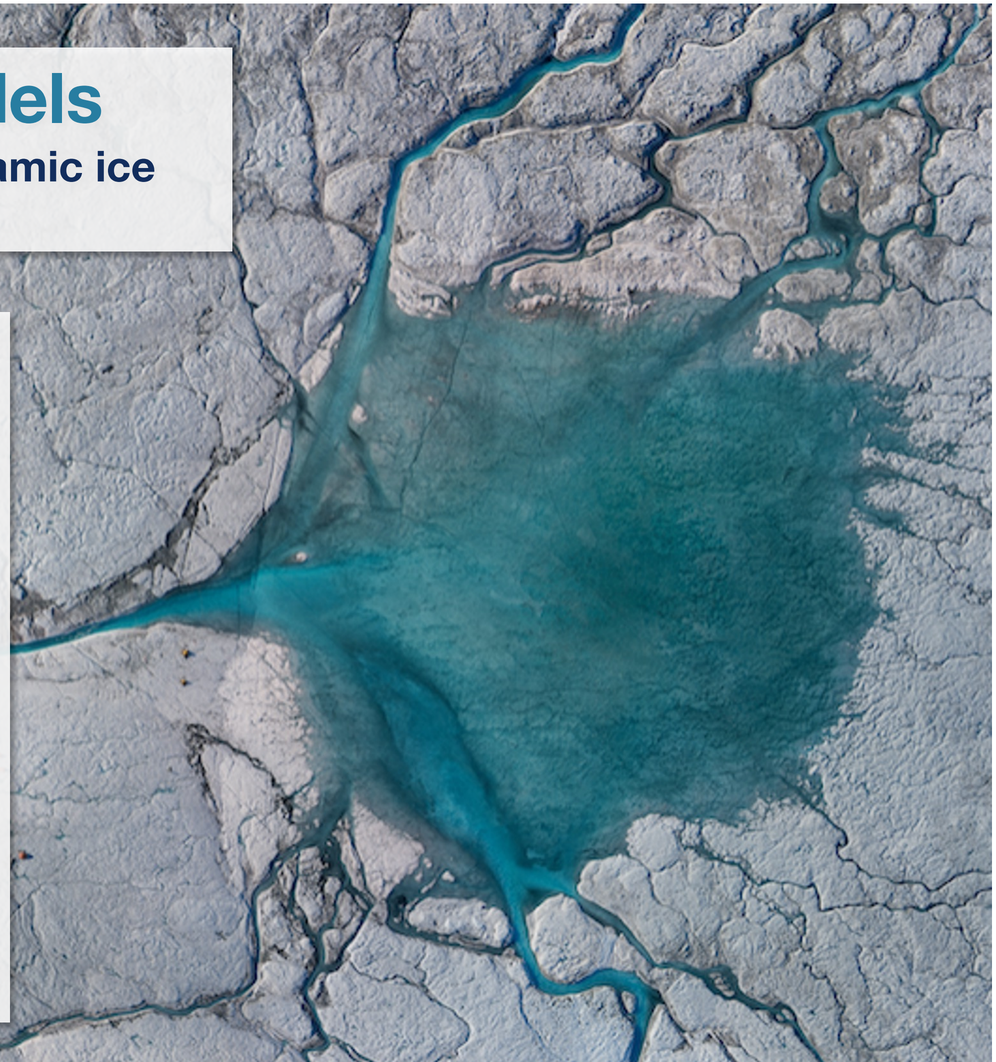

Image: Greenland ice sheet/NASA

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Ice sheets are trouble makers for ESMs

- Moving boundaries (lateral and vertical)
- Have stricter conservation of mass principles (compared to other components in CESM)

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.

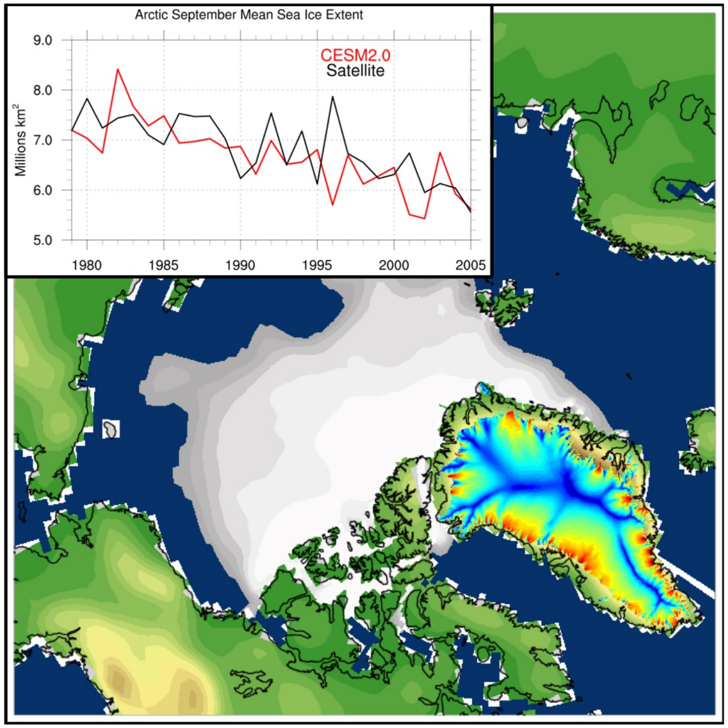
Division of labor:

- 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

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.

Ice sheets in CESM2

Land -> Ice sheet

(10 classes + bare land)

- Surface mass balance
- Surface elevation
- Surface temperature

Ice sheet -> Land

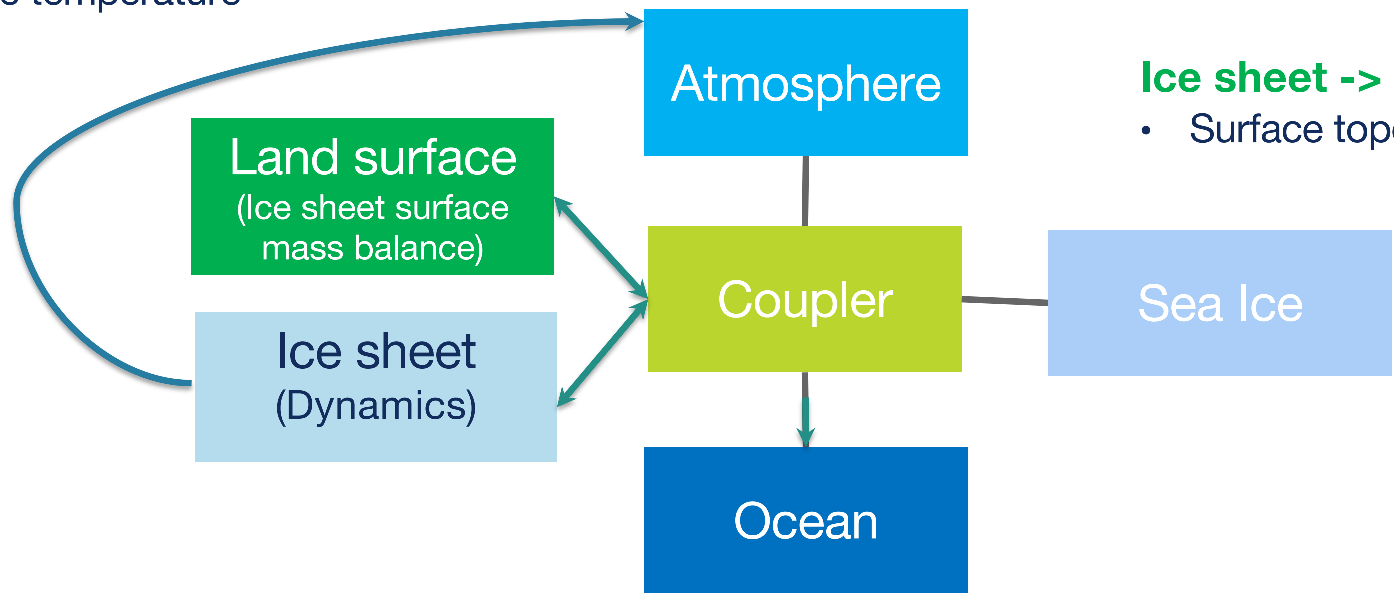
- Ice extent
- Ice surface elevation

Ice sheet -> Ocean

- Solid and liquid fluxes

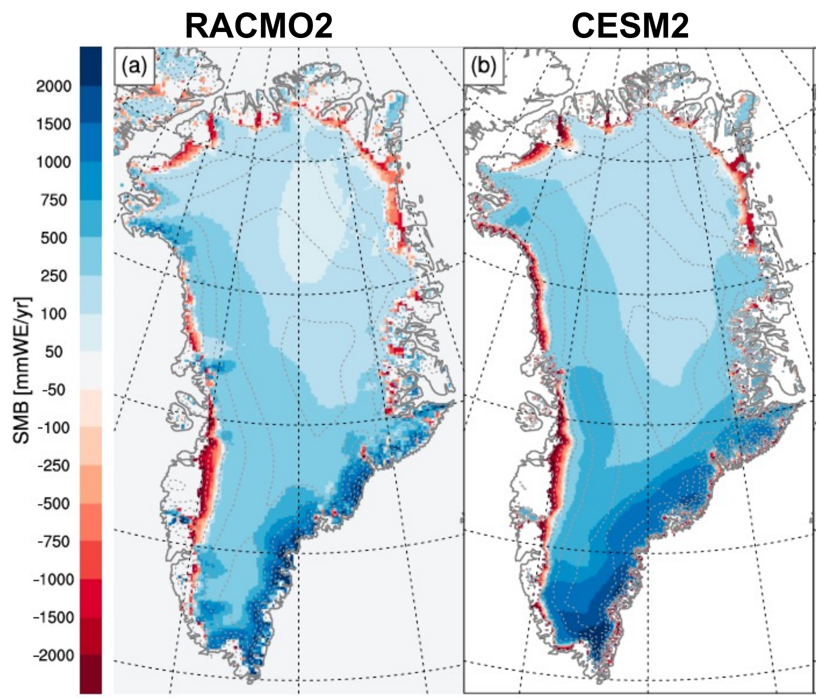
Ice sheet -> Atmosphere (offline)

- Surface topography (not by default)



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**.

Coupled Greenland Ice Sheet evolution in CESM-CISM

First published ISMIP6 runs with an **interactive Greenland ice sheet** (includes the Evolving atmosphere topography)

Climate evolution:

•Global CO_2 rises to ~**1100 ppm**

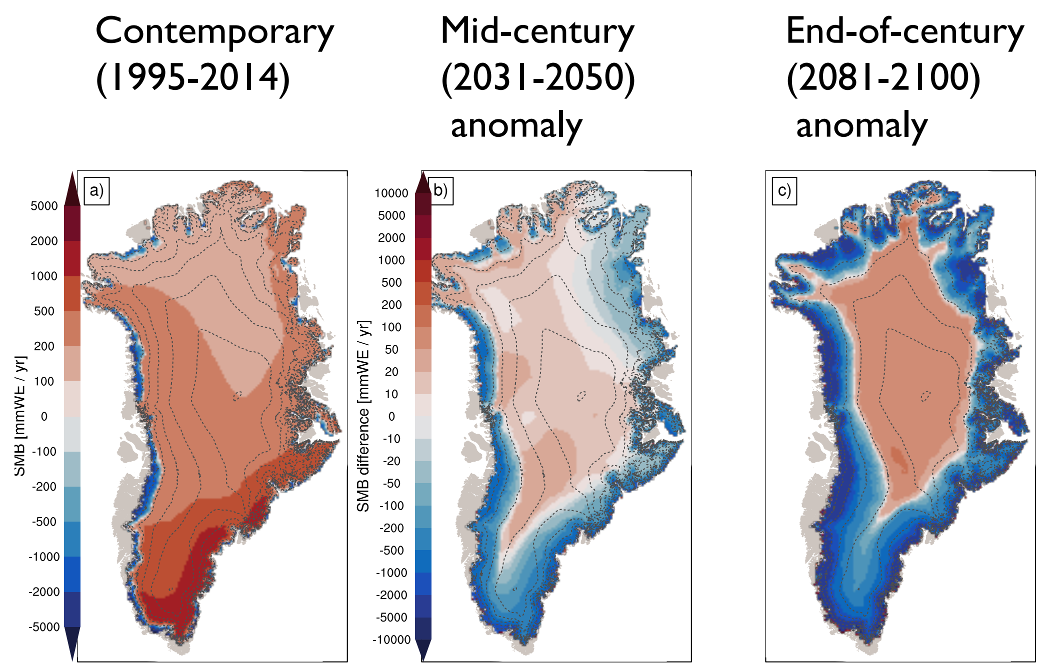
•Global surface air temperature rises by **5.4°C**

GrIS evolution:

•Ice thins near margins with increased melting

•Modest increase in interior snowfall

•**Global mean SLR of 110 mm by 2100**

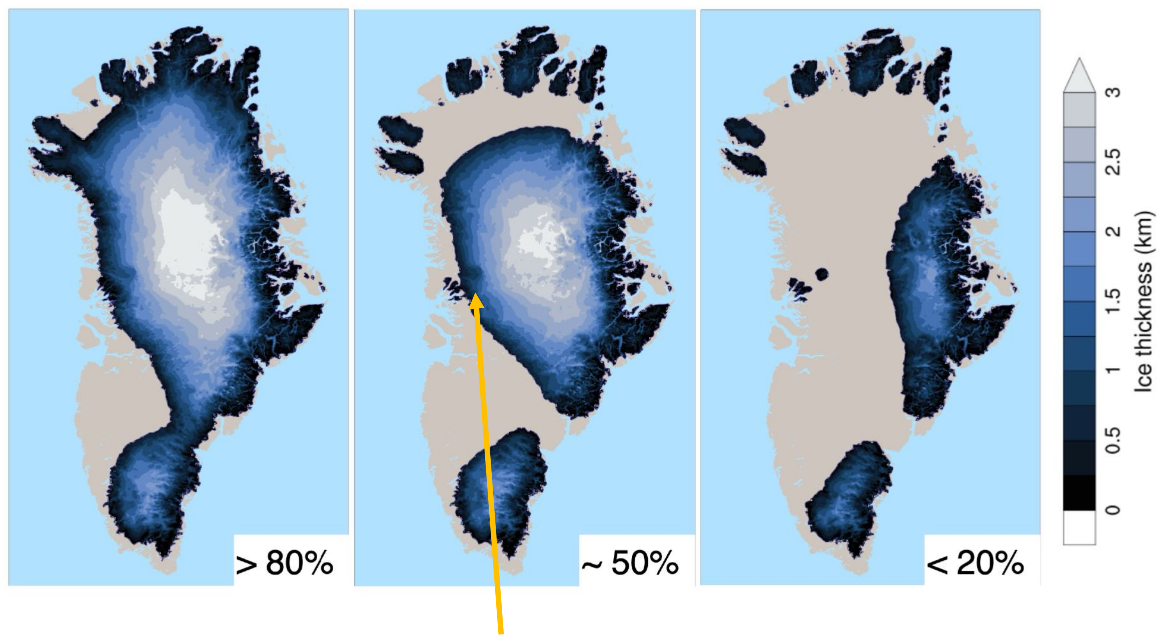


Increased melting of the **Greenland Ice Sheet** in CESM2 (Muntjewerf et al., 2020) under the ssp5-85 warming scenario. The expanding melt region is **blue**.

Thresholds for Greenland deglaciation

(1) **> 80%** (SMB > 317±97 Gt/yr), (2) **~ 50%** (SMB 286±94 - 255±83 Gt/yr), (3) **< 20%** (SMB < 230±84 Gt/yr)

Petrini et al. (2024)



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

Thresholds for Greenland deglaciation

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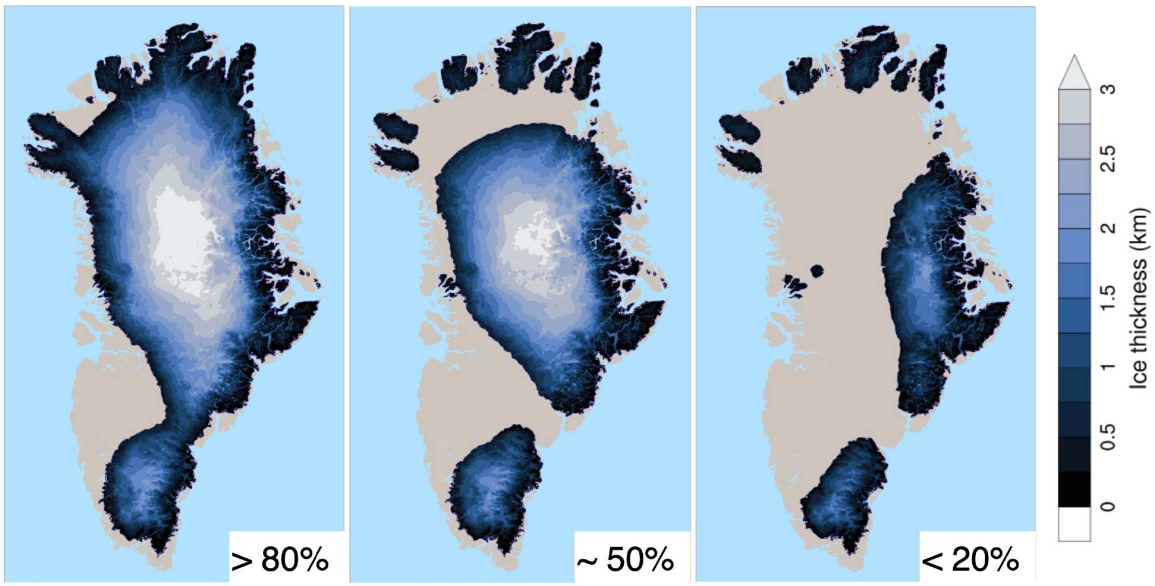


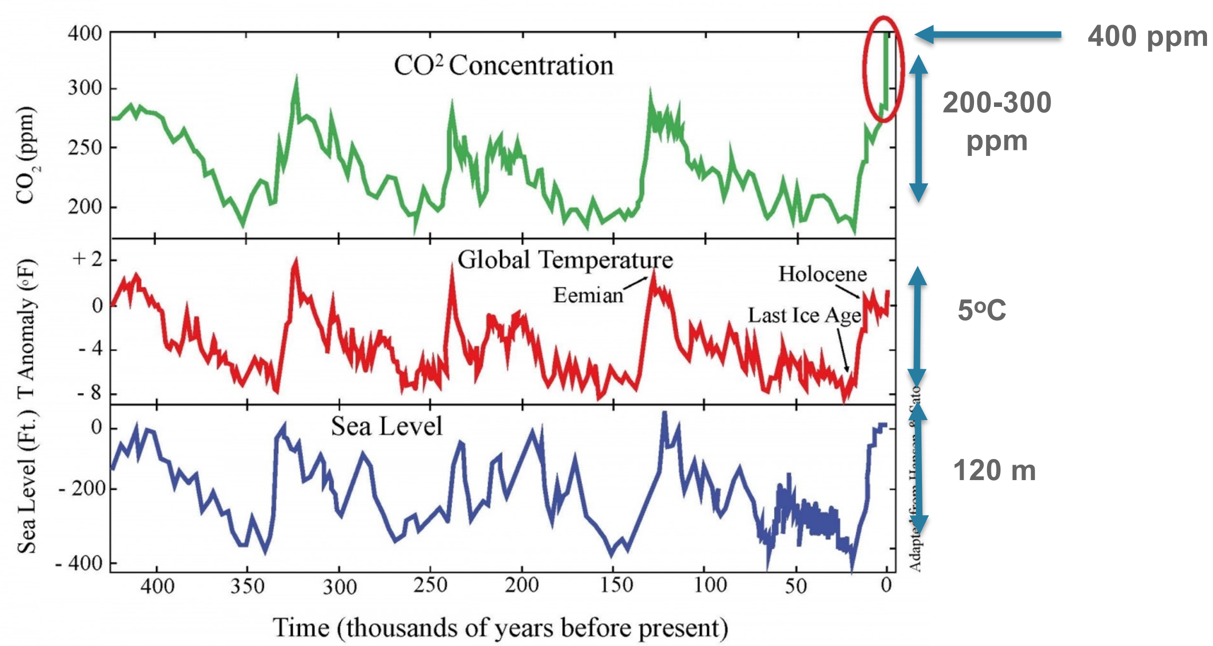
- CISM Greenland runs forced by CESM output (offline coupling) suggest a deglaciation threshold at warming of ~3.4^{o}C.
- Most of the ice sheet is lost after unpinning from topography in west Greenland.

Expected increases in temperatures by 2100 compared to PI w.r.t climate policies (theworldcount.com)

- No climate policies implemented: 4.1-4.8°C warming -> Greenland is gone
- Current climate policies implemented: 3.1-3.7°C warming
- If all countries achieve their current pledges set within the Paris climate agreement, 2.6-3.2°C warming.

Paleoclimate science: understand past sea level change

- **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**.

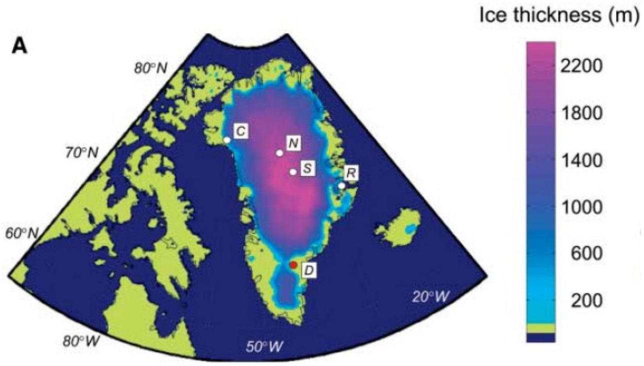


Source: www.johnenglander.net

Ice sheets in warm climates

Last Interglacial (125,000 years ago)

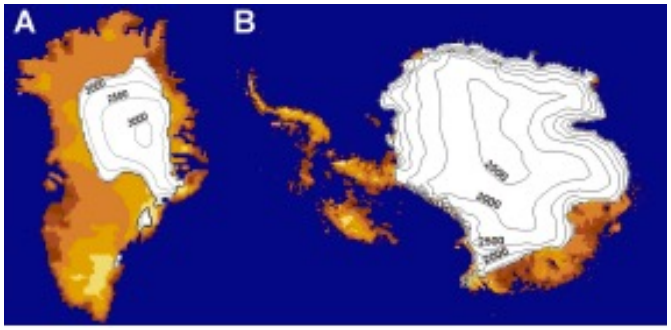
- Warming **1-2ºC**, CO_2 = **280 ppm**
- Global sea level **6–9 m higher** than now
- About 2–4 m from Greenland, > 2 m from Antarctica



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

Pliocene (3 million years ago)

- Warming **2-3ºC**, 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

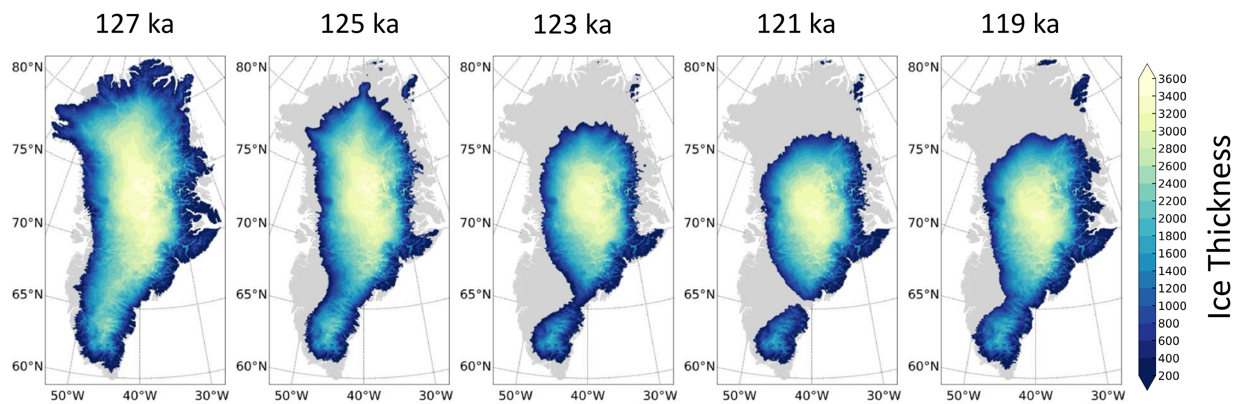


Pliocene ice sheet reconstructions (Haywood et al. 2010)

Coupled Greenland simulations of the Last Interglacial

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

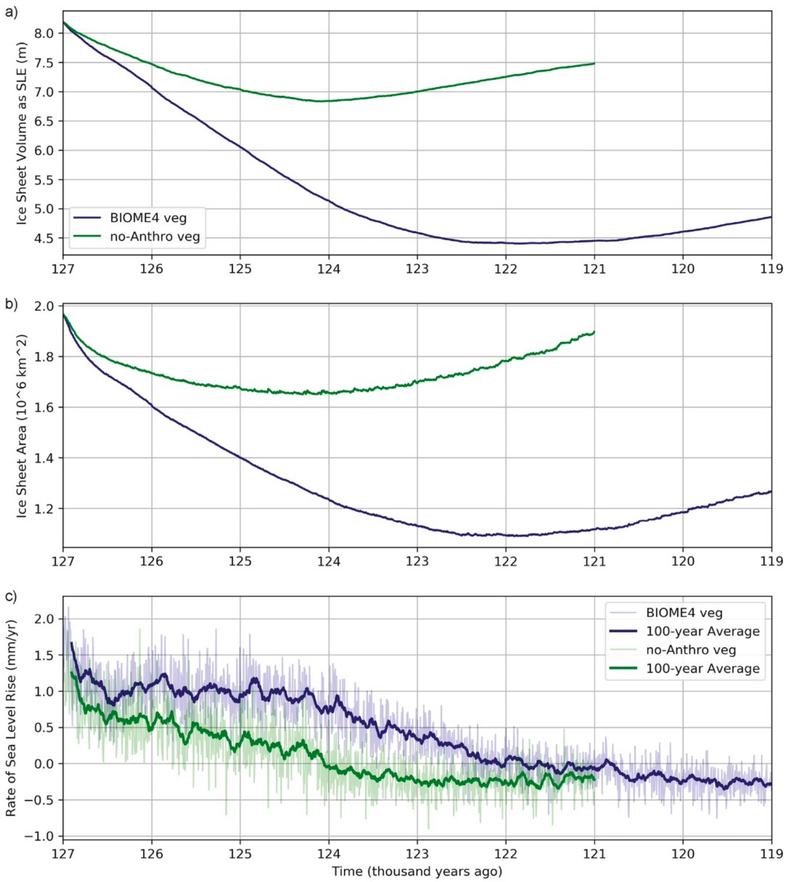
- The Greenland Ice Sheet shrinks from **8.3 m SLE** at 127 ka to **4.2 m SLE** at 122 ka, then slowly recovers.
- Interactive **vegetation** warms the climate and enhances the retreat.



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)

Coupled Greenland simulations of the Last Interglacial



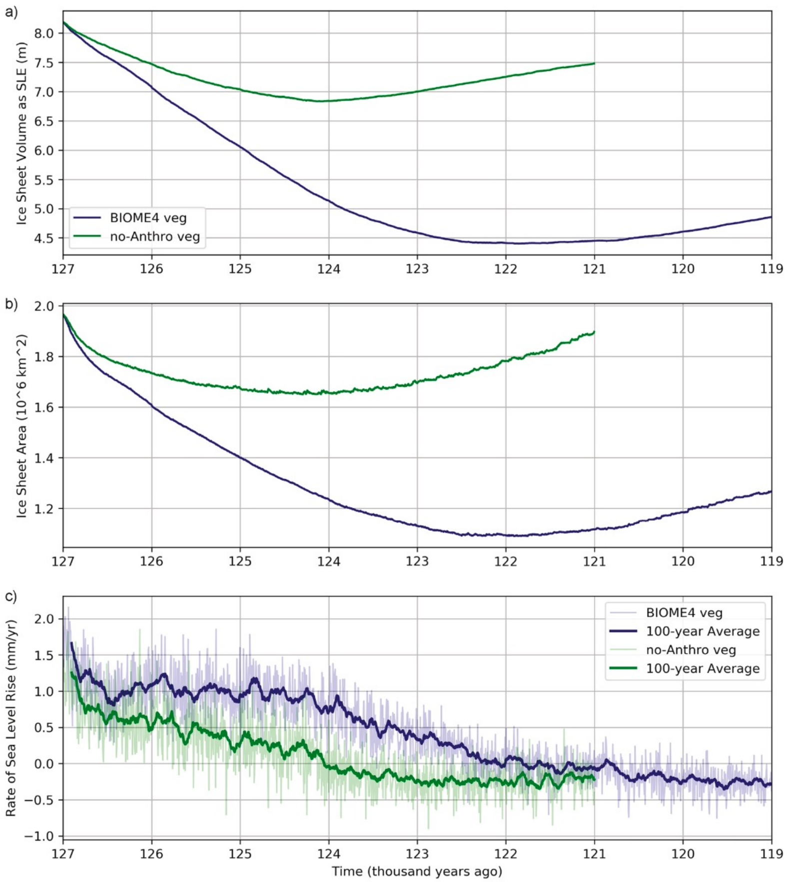
Sommers et al. (2021)

The importance of coupling feedbacks

2 simulations

- 1 including the same constant vegetation as the one during the Pre Industrial (no-anthro).

Coupled Greenland simulations of the Last Interglacial



Sommers et al. (2021)

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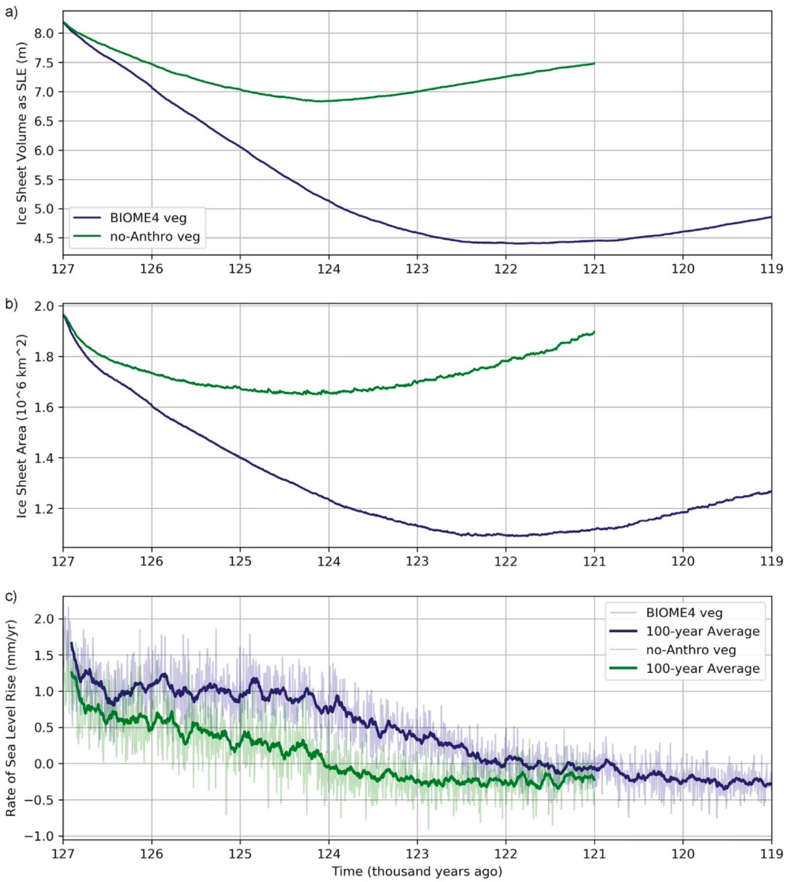
- 1 including the same constant vegetation as the one during the Pre Industrial (no-anthro).
- 1 including updated vegetation based on changes in climate conditions (BIOME4-veg). The extension of the boreal forest in the Arctic coast with corresponding lower albedo and increased transpiration enhanced Arctic warming.

Coupled Greenland simulations of the Last Interglacial



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The importance of coupling feedbacks

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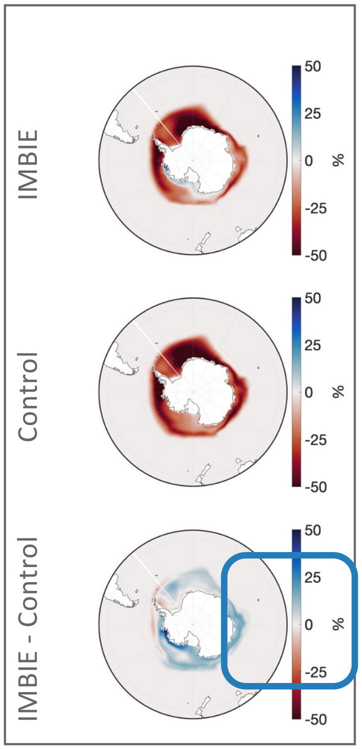
- 1 including the same constant vegetation as the one during the Pre Industrial (no-anthro).
- 1 including updated vegetation based on changes in climate conditions (BIOME4-veg). The extension of the boreal forest in the Arctic coast with corresponding lower albedo and increased transpiration enhanced Arctic warming.
- Updating the vegetation alone plays an important role in understanding past sea level changes and potentially increases sea level responses by a factor of 4!

Feedback on Earth's system

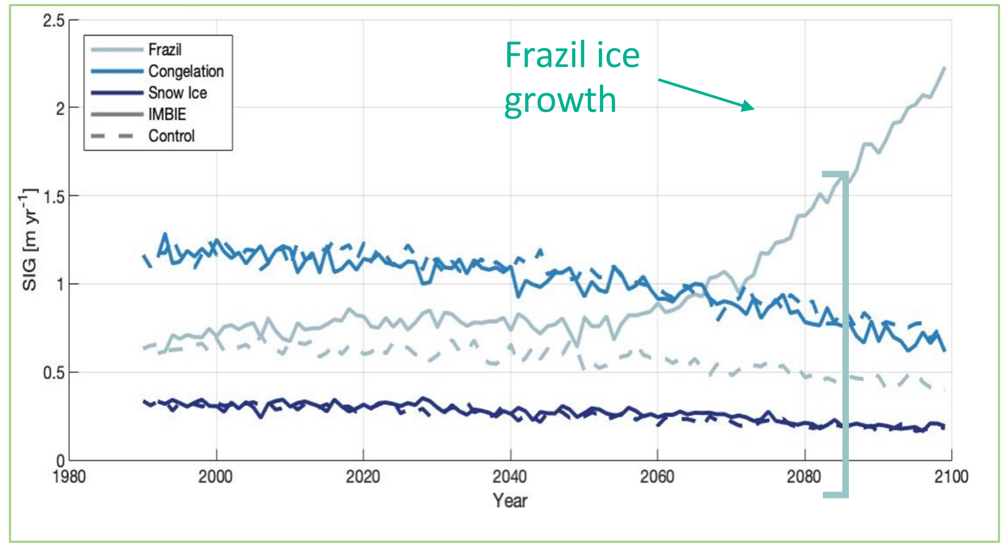


Sea ice fraction, difference between end and beginning of century

Impacts of Antarctic freshwater input to the Southern Ocean

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)



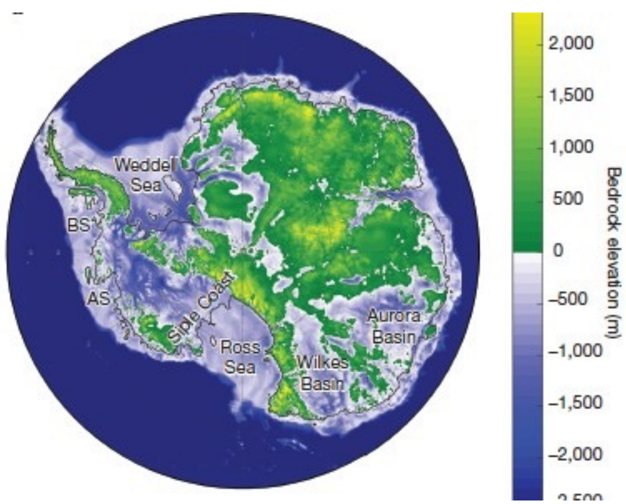
Courtesy of Tessa Gorte

What is driving the difference in sea ice?

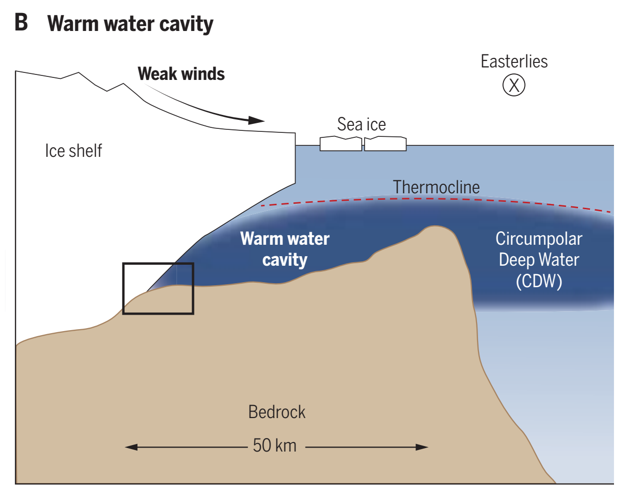
- In addition to being fresher, the surface ocean is also cooler. The cooler, fresher surface ocean is trapping more warm water at depth.
- Also, there is a reduction of the AMOC weakening signal.

What about coupling Antarctica?
Why is it harder?

The ocean!



Antarctic basal topography
Global Warming Art Project

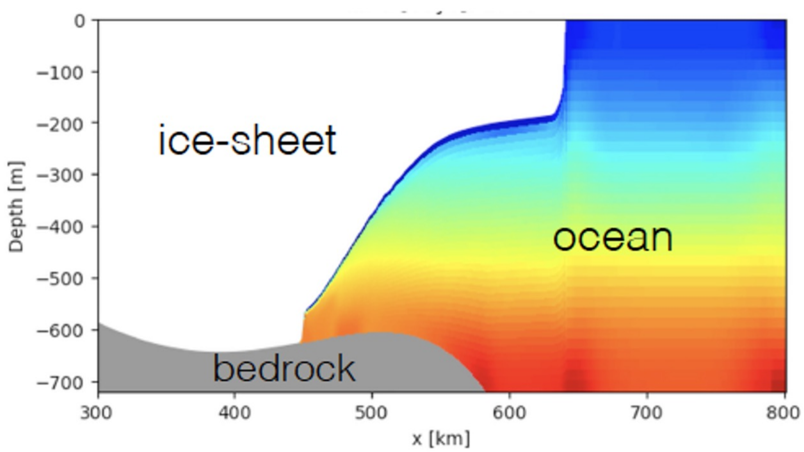


Schematic of a warm sub-ice-shelf cavity
(Holland et al. 2020)

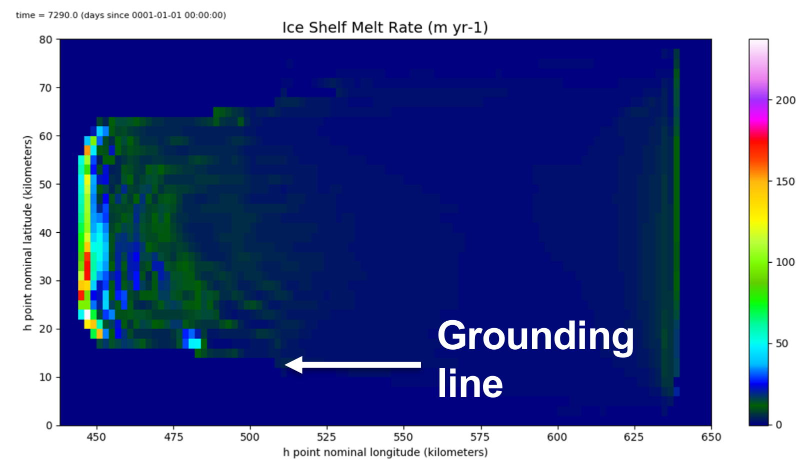
Ice-Ocean (Antarctic) coupling

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.



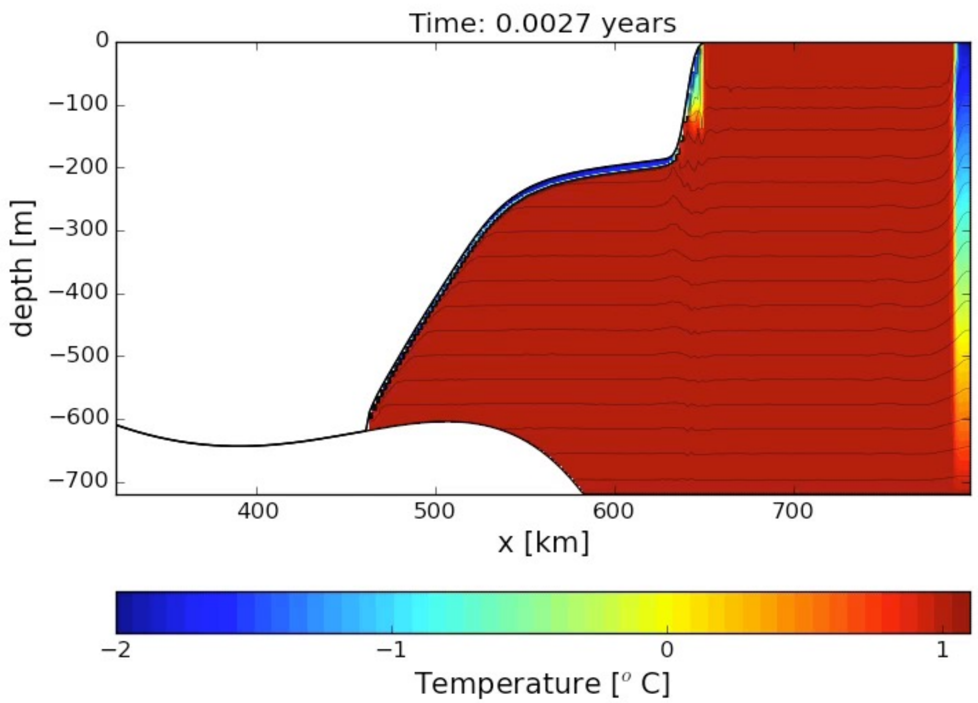
Schematic of sub-ice-shelf cavity



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

Ice-Ocean (Antarctic) coupling

- Coupling test in idealized test case looks promising (thank you MISOMIP)



Representation of melt rate in ice shelf cavities

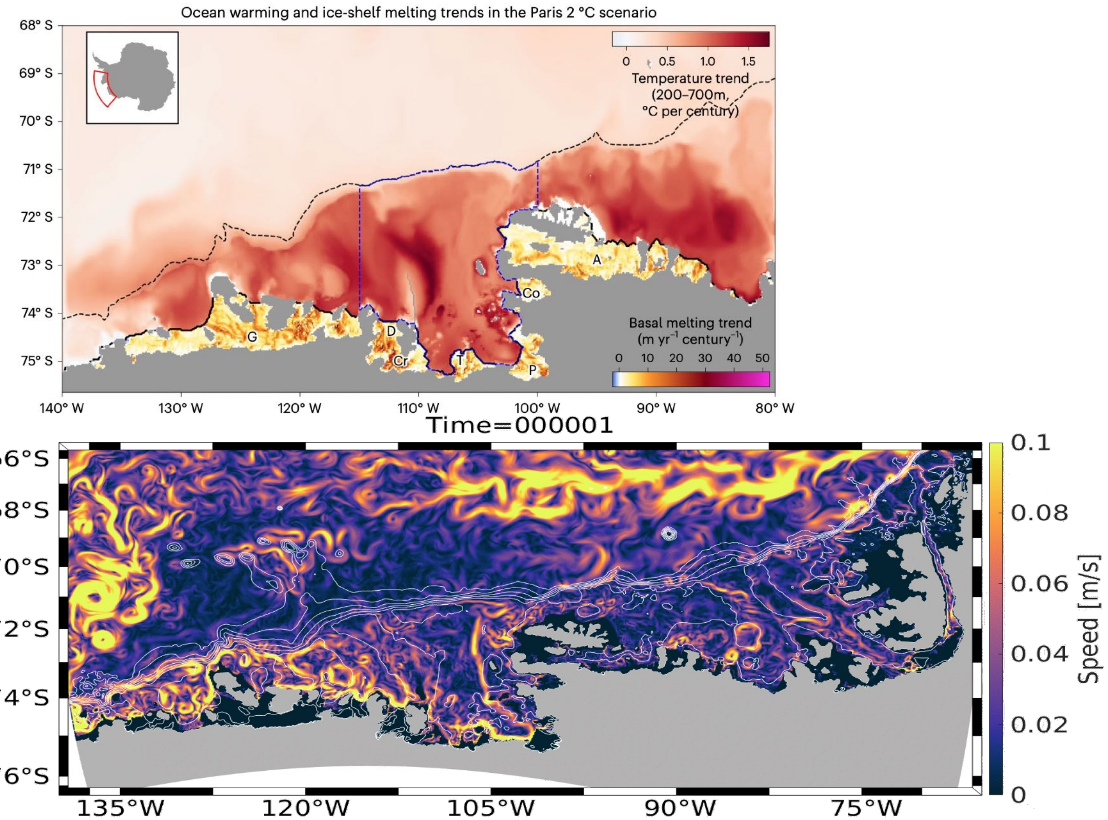


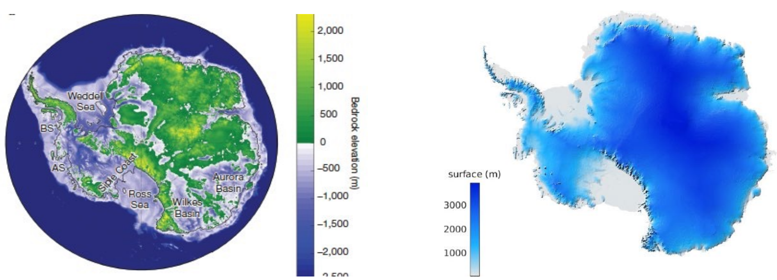
Fig: (top) Map of ensemble mean trends in ocean temperature and ice-shelf basal melting in the Paris 2C scenario (Naughten et al. 2023, resolution of 1/10 degree ~3-5 km). (Bottom) Daily ocean speed at 300m depth in 1998 (credit: Shuntaro Hyogo)

- The ice sheet requires melt rates from the ocean as a forcing in its cavities in order to evolve dynamically.
- Without ocean circulation, CISM needs to parameterize the melt rate based on ocean temperature and salinity.
- Current melt parameterization are crude and do not represent ocean output well!
- While we do need high ocean model resolution to best diagnose sub-shelf cavity circulation, ocean modelers do not agree on how high.
- In CESM2, the Southern Ocean had strong temperature biases (up to 2 deg).

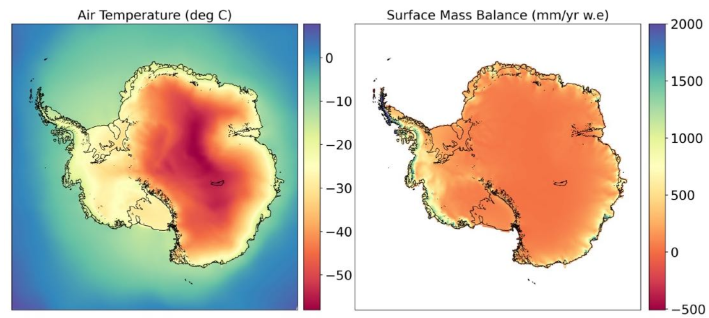
Challenge for ice sheet models: Initialization

Typically, we Initialize ice sheets to a **steady state** with climate conditions from AOGCMs or regional model outputs.

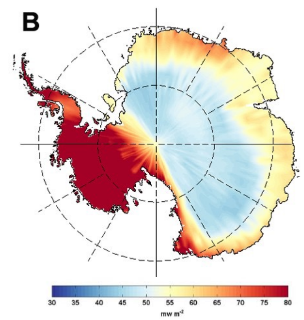
What we need for initialization: Geothermal heat flux; Air temperature and Surface mass balance; Bed topography and Ice surface elevation; Ocean thermal forcing.



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



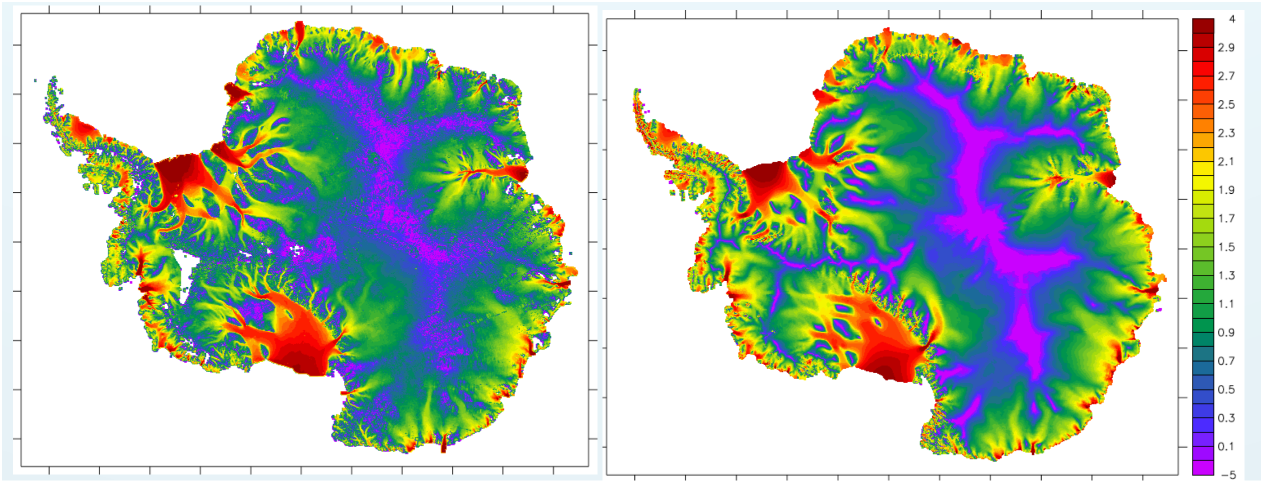
Air temperature and Surface mass balance (van Wessem, 2018)



Geothermal heat flux (Shapiro and Ritzwoller, 2004)

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

Challenge for ice sheet models: Initialization



Observed surface ice speed m/yr, log scale (Rignot et al., 2011)

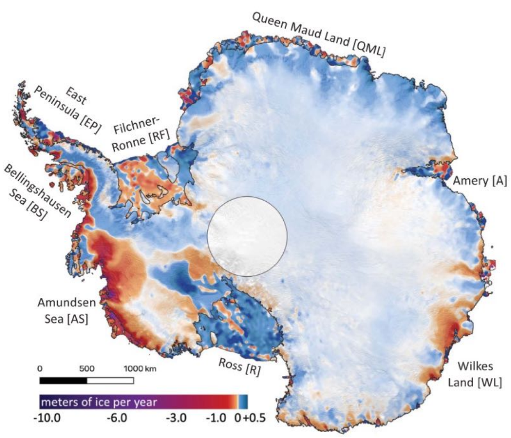
Modeled surface speed at the end of a 20 000-year spin-up

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

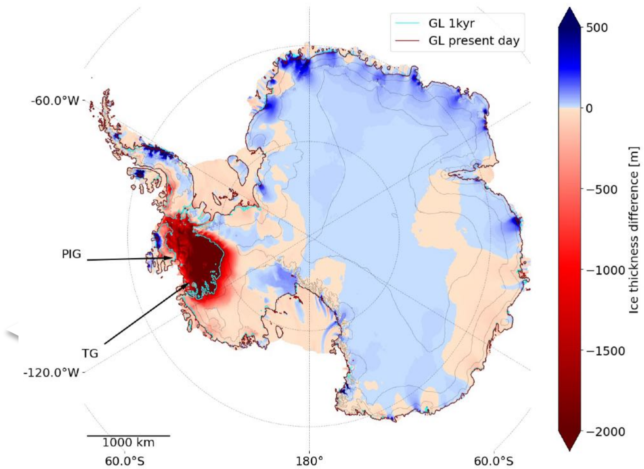
Challenge for ice sheet models Ice sheet initialization

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.

NSF | NCAR Operated by UCAR

Challenge for ice sheet models Ice sheet initialization

Stable spin-up method

Pros
- No drift in the model due to initialization process.
- Can assimilate the impact of model parameters and forcing on ice sheet behavior.
- Good for paleo time scale simulations.

Cons
- Currently the ice sheets are not in equilibrium with the climate and are losing mass.
- It takes a long time (~50-100 years) to get an ice sheet going once it's stable -> impacts the interpretation of ice sheet contribution to sea level by 2100.

Transient spin-up method

Pros
- More realistic with today's observations.
- Could help study sea level remediations.
- Good for shorter time scale simulations.

Cons
- We have to assume the mass change rate constant throughout the simulation.
- Impacts longer time scale simulation that might not be realistic.
- Lack of mass change rate information in the future.

The initialization of the ice sheet model is key to diagnose sea level projection.

Why care about ice sheets?

What questions can we ask an Earth System Model like CESM?

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?

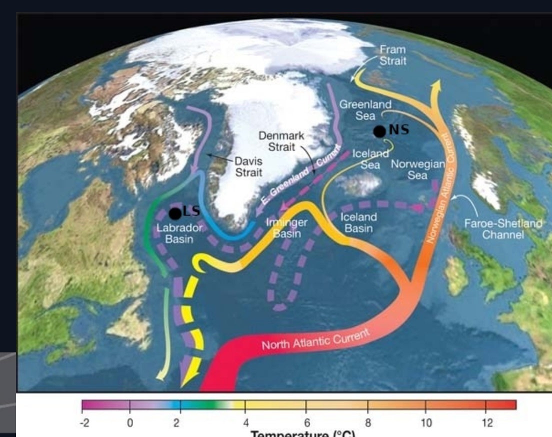
What questions can we ask CESM with land ice capabilities?

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?



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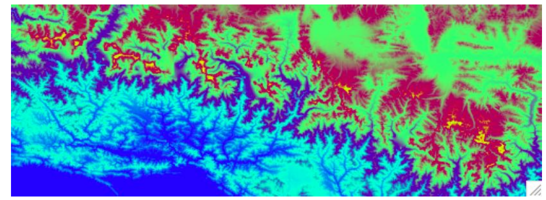
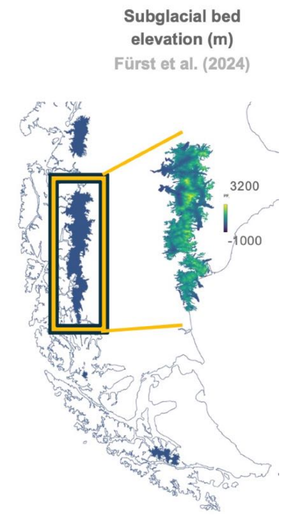
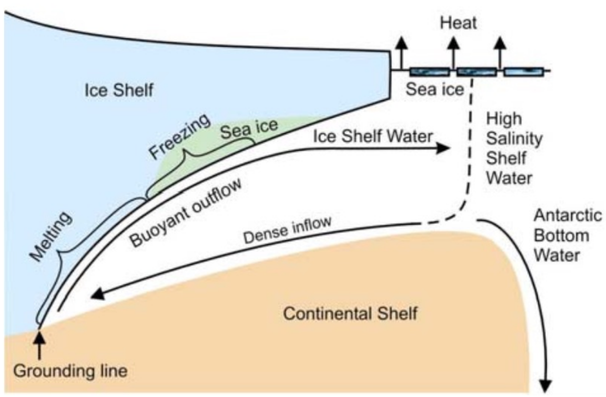
Future CISM development

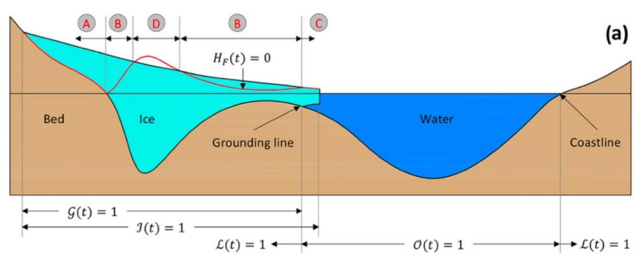
- **Glacier projections** in other regions (High Mountain Asia, Patagonia, Svalbard)
- **Ice shelf cavity circulation** module
- **Solid Earth and sea level** model (with ice sheet self-gravity)



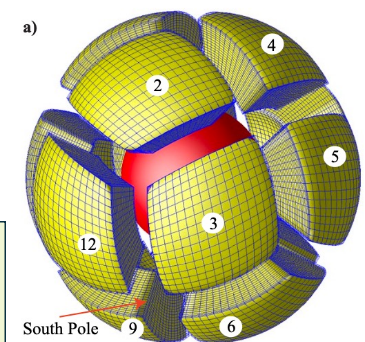


Above: Bed topography in the Nepal Himalaya.
Right: Patagonian ice fields.





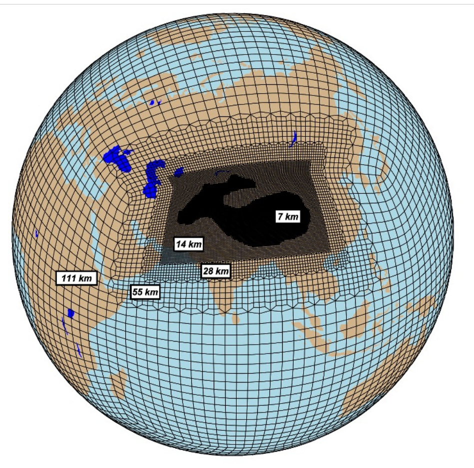
Left: Schematic of sub-ice shelf circulation.
Above: Schematic mass distribution in a sea-level model.
Right: Finite-element grid for a global solid Earth model.



Simulating mountain glaciers with CESM and CISM

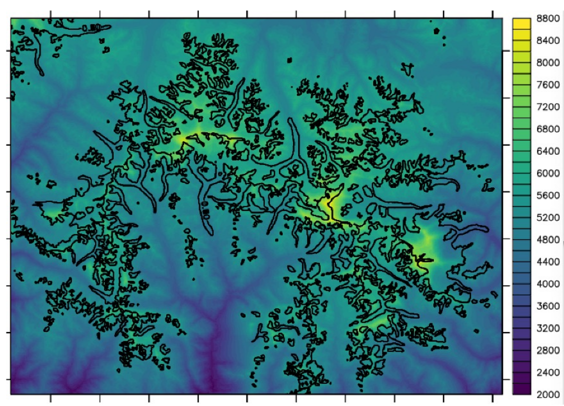
We have run 20-year simulations of glacier surface mass balance using a **variable-resolution atmosphere grid refined to 7 km over High Mountain Asia** (Wijngaard et al., in prep)

Using CISM, we will carry out **3D, fully dynamic, high-resolution (200 m) simulations** of thousands of glaciers in the Himalayas and other regions (Minallah et al., in prep)

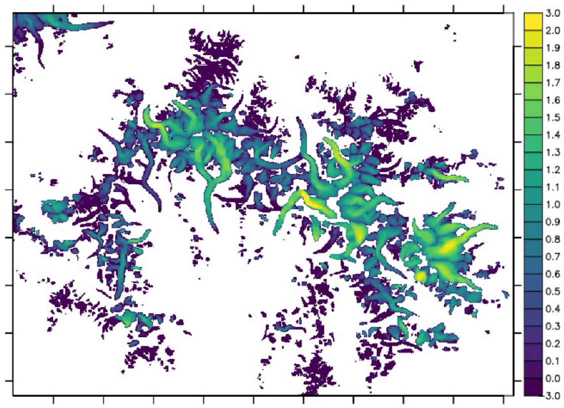


Variable-resolution CAM grid focused on High Mountain Asia (A. Herrington)

CISM glacier simulations in the Nepal Everest region



Initial surface elevation and glacier outlines



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

Learning more about ice sheet processes

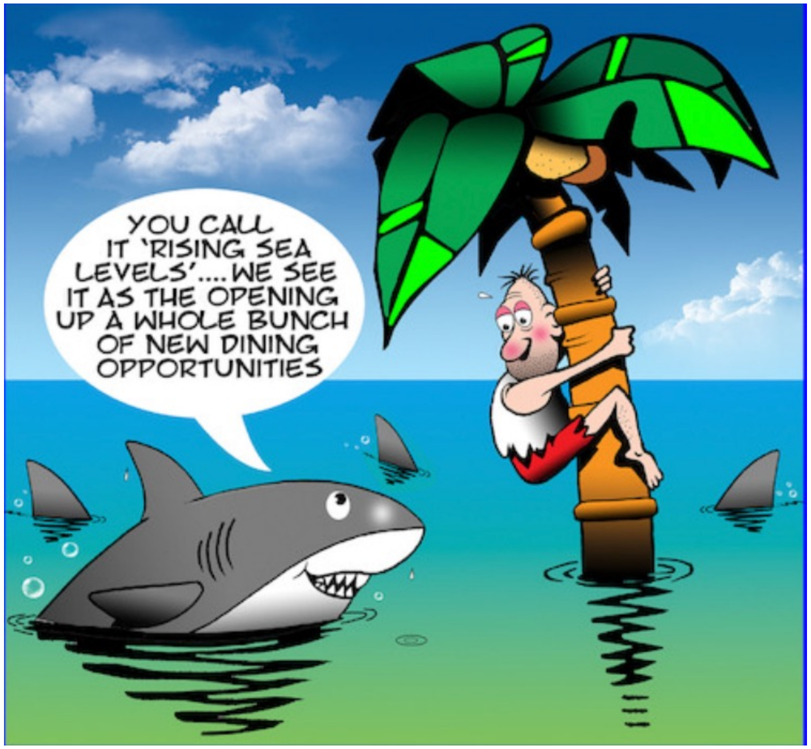
- You can read books with words and equations
  - The Physics of Glaciers 4th edition (Cuffey & Paterson, 2006)
  - Dynamics of Ice Sheets and Glaciers (Greve and Blatter, 2009)
- Play a video game (Anne LeBrocq): http://www.iceflowsgame.com
  - Have penguins/seals fish without being eaten by seals while learning about ice sheet facts and processes.
  - Did you know that the Ronne ice shelf was named after Jackie Ronne? She was the first American woman setting foot on the Antarctic continent and spent 15 months there between 1946-1948?

Contact information

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

- Gunter Leguy, NCAR, gunterl@ucar.edu

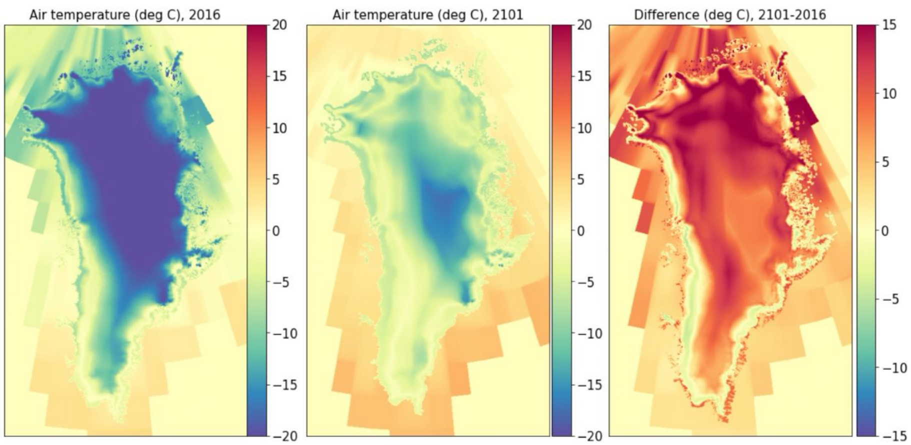
Thank you

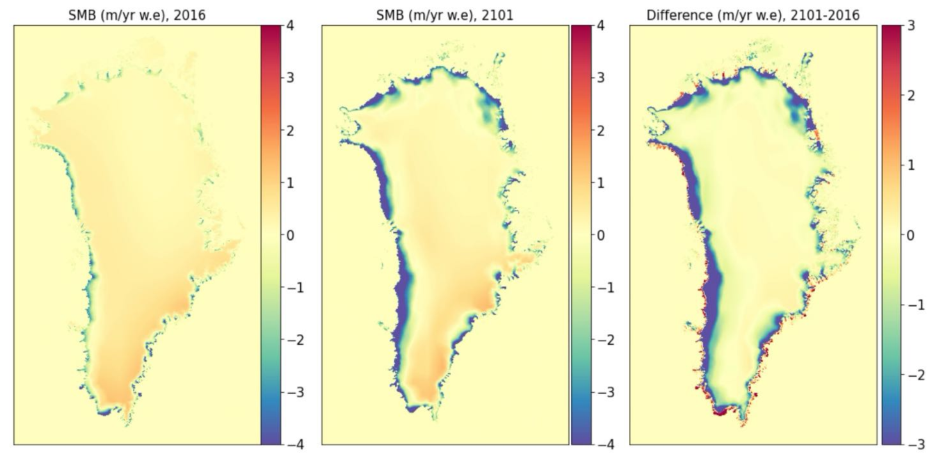

YOU CALL IT 'RISING SEA LEVELS'.... WE SEE IT AS THE OPENING UP A WHOLE BUNCH OF NEW DINING OPPORTUNITIES

A CESM test case

We run a CESM experiment forcing the Greenland ice sheet (GrIS) with atmospheric forcing spanning 2015-2100 that were created from a 2 degree fully-coupled SSP5-8.5 scenario experiment.
The Greenland ice sheet has been initialized before hand.

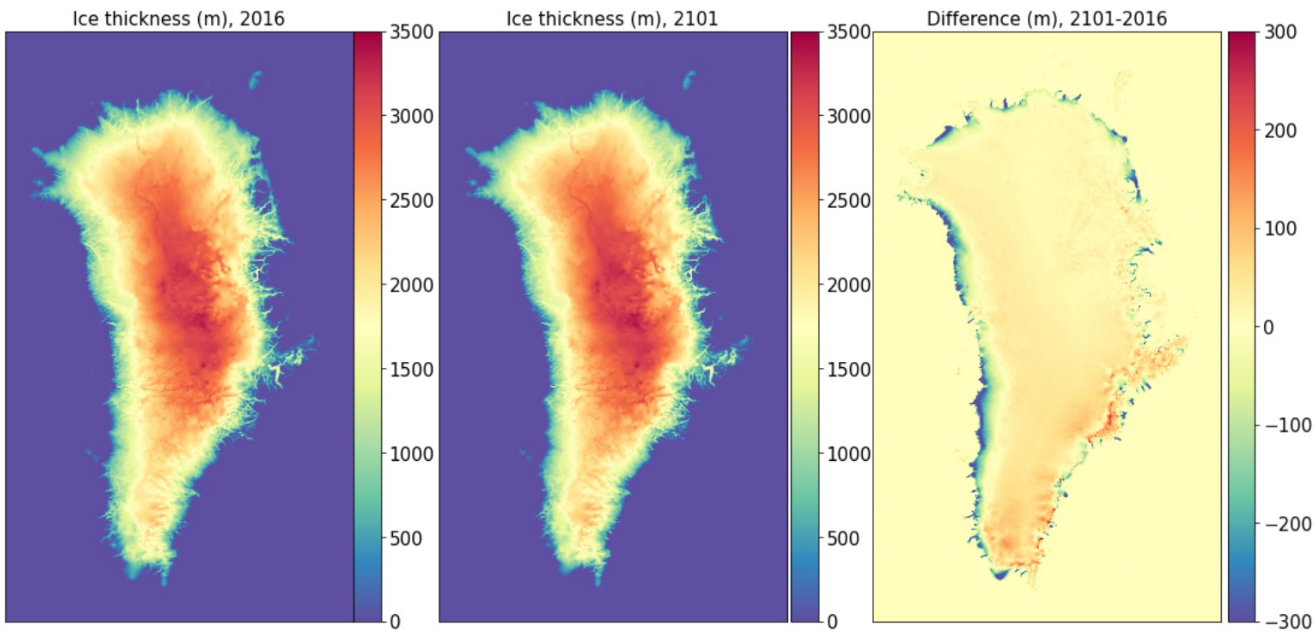
We show the air temperature and surface mass balance at the beginning (year 2016) and end (2100) of the simulation along with their differences.





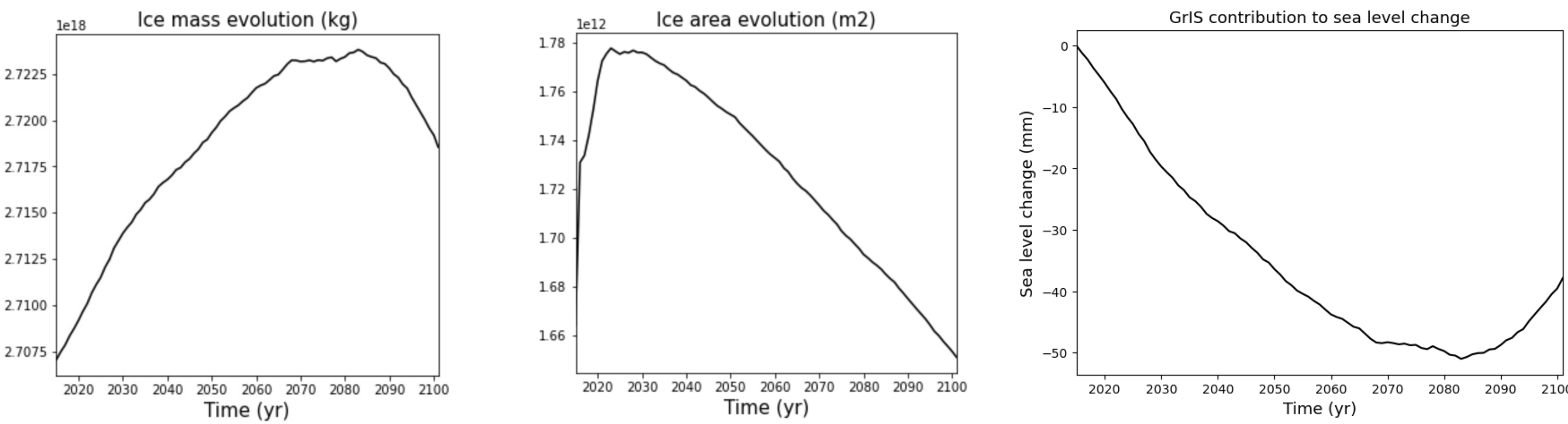
A CESM test case

Once we performed the simulation we see the following output for ice thickness at the beginning of the experiment (2016, left) and end (2101, middle) of the experiment, and their difference.



A CESM test case

Once we performed the simulation we see the following time series output for ice mass (left), ice area (middle), and sea level change (right).



A CESM test case

Questions

- (1) Based on the sea level change figure, the Greenland ice sheet has been accumulating more ice than it has lost leading to a sea level sink. What do you think about these results?
- (2) Do you have any suspicions about the forcing used in this experiment? If so, what are they?
- (3) What else could you be suspicious about?
- (4) What would you do to validate these results?