Introduction to Antarctic ice sheet modeling

Bill Lipscomb
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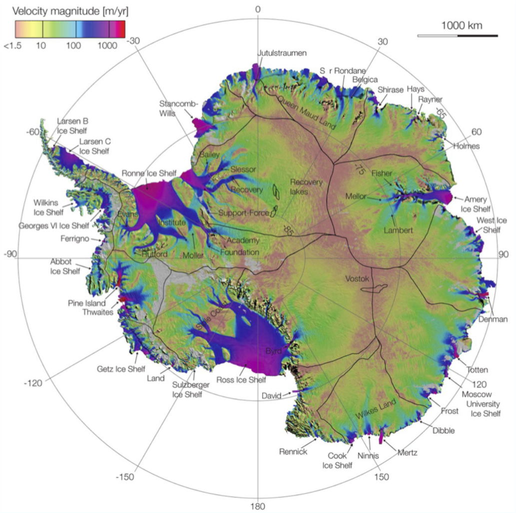
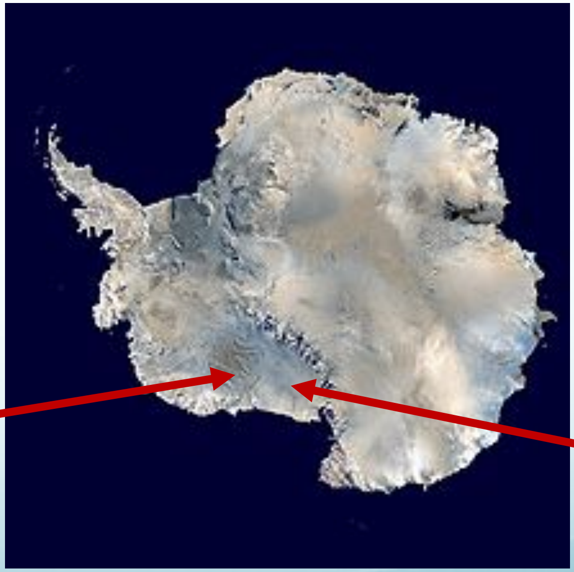
Antarctic ice sheet

- An **ice sheet** is a mass of glacier ice larger than 50,000 km² (Antarctica, Greenland).
- An **ice shelf** is a large sheet of floating ice attached to a grounded ice sheet.
- An **ice stream** is a region of fast-flowing ice in a grounded ice sheet.



Antarctic ice flow speed

(Rignot et al. 2011)



Antarctic ice sheet: 60 m SLE

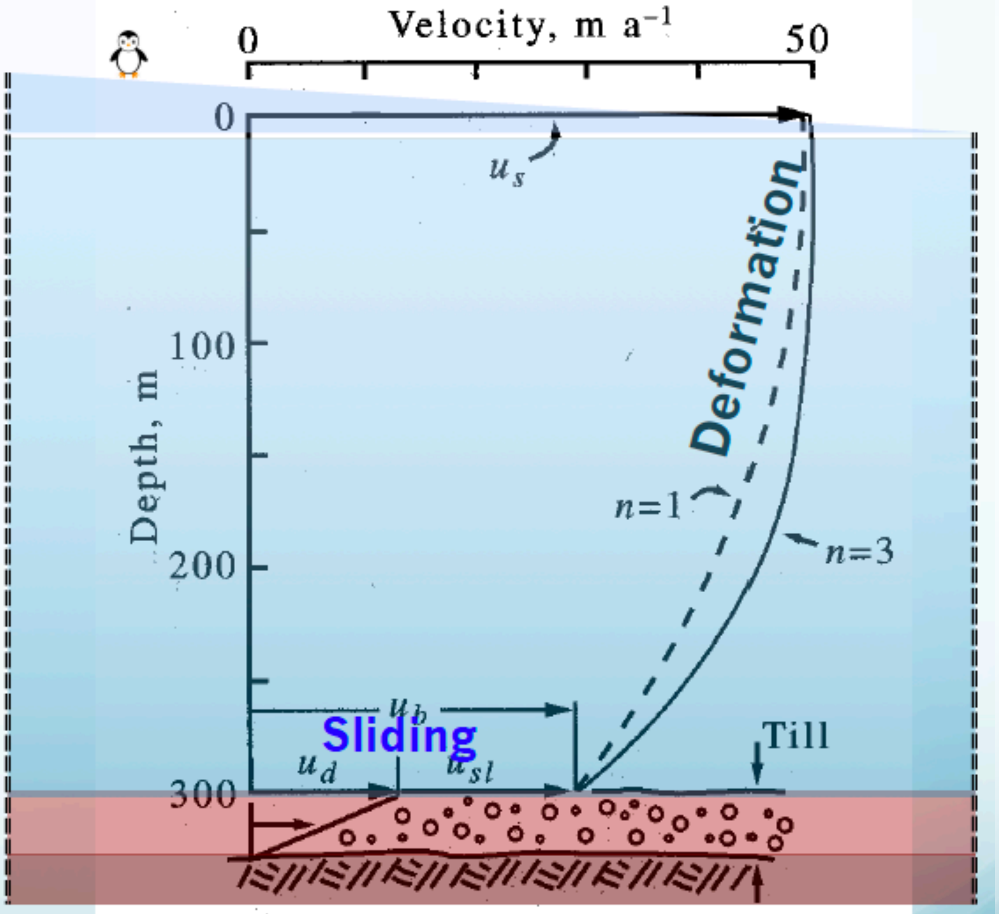
Siple Coast ice streams

Ross ice shelf

Photo credit: Dave Pape
(using NASA Blue Marble data)

How glaciers move

- Glaciers flow downhill under the force of gravity.
- Ice deforms like a very viscous fluid. Warm 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**.



Modified from Hooke (1998)

- General ice flow is described by the **Stokes equations** or **higher-order approximations.**

How ice sheets gain and lose mass

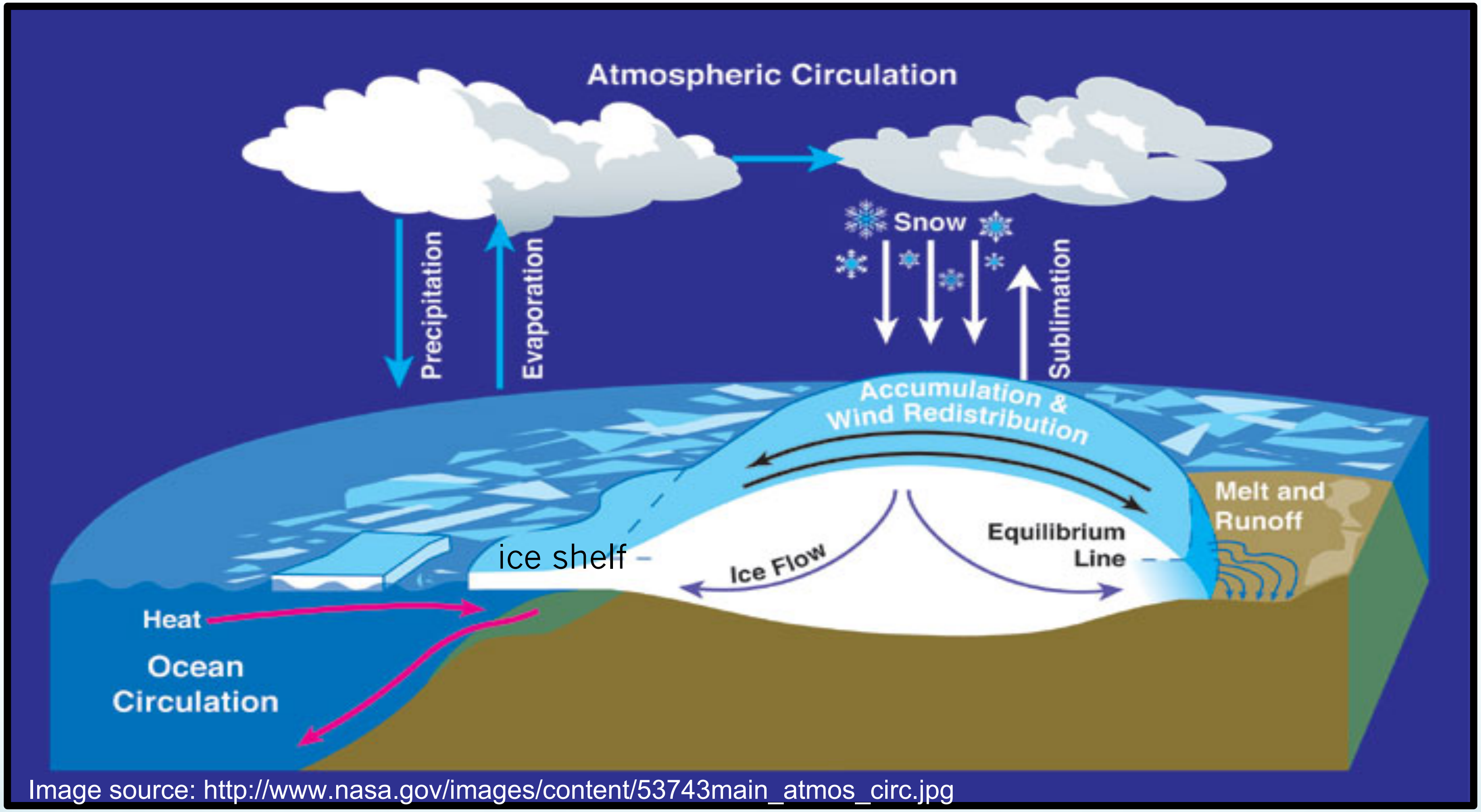


Image source: http://www.nasa.gov/images/content/53743main_atmos_circ.jpg

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

Sea level change!

snowfall

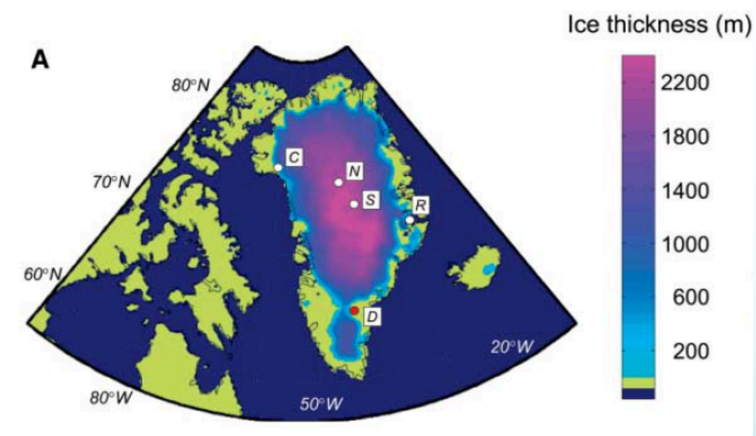
melting
sublimation
calving

Ice sheets in warm climates

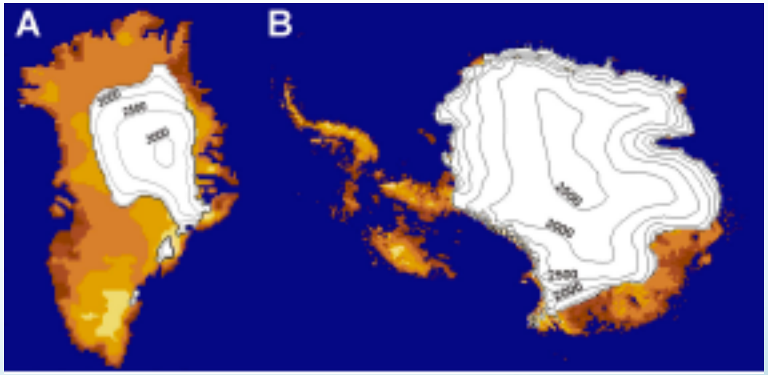
- **Last Interglacial** (125,000 years ago)
  - Warming **1-2°C**, CO_2 = **280 ppm**
  - Global sea level **6–9 m higher** than today
  - About 2 m from Greenland, 0.4 m from ocean thermal expansion, so an Antarctic contribution of ~5 m

Pliocene (3 million years ago)

- Warming **2-3°C**, CO_2 = **400 ppm**
- Global sea level **10–20 m higher** than today
- Up to 7 m from Greenland, 5 m from West Antarctica, and possibly some of East Antarctica



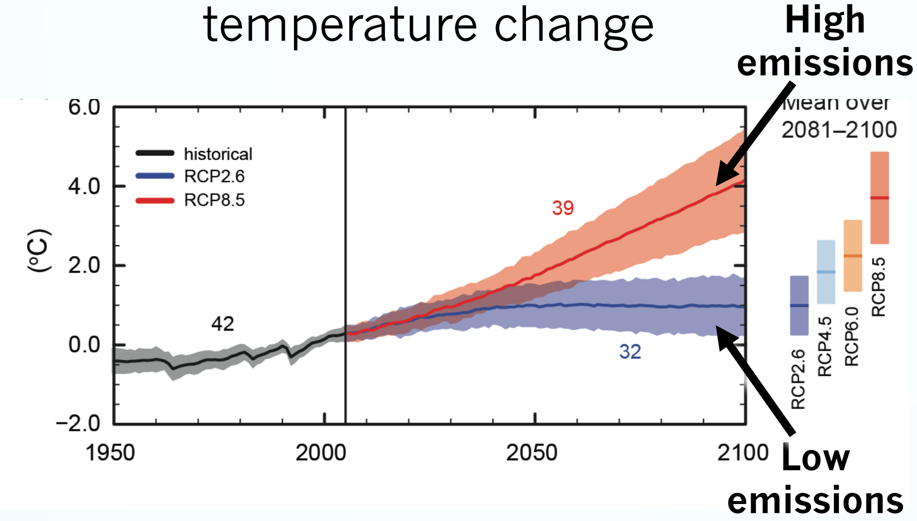
Modeled Greenland ice thickness for the Last Interglacial (Otto-Bliesner et al. 2006)



Pliocene ice sheet reconstructions (Haywood et al. 2010)

Projections: IPCC Fifth Assessment Report

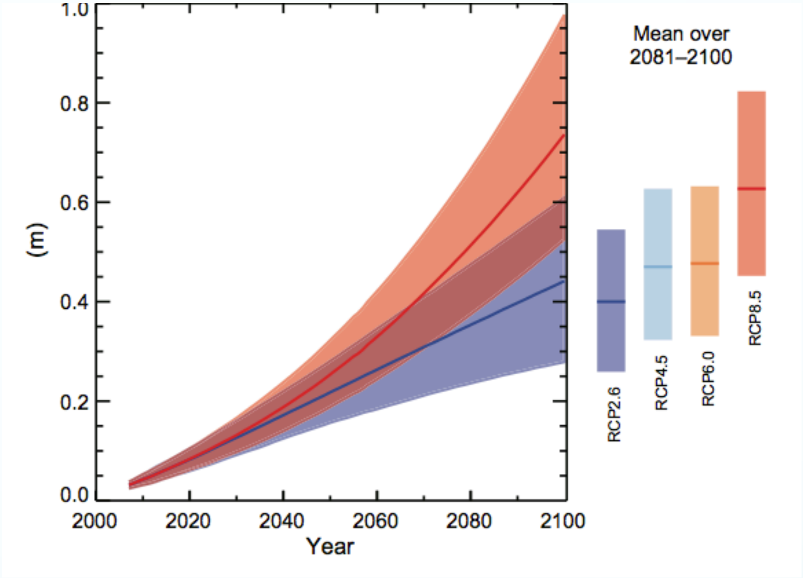
Global mean surface temperature change



High emissions

Low emissions

Global mean sea level rise



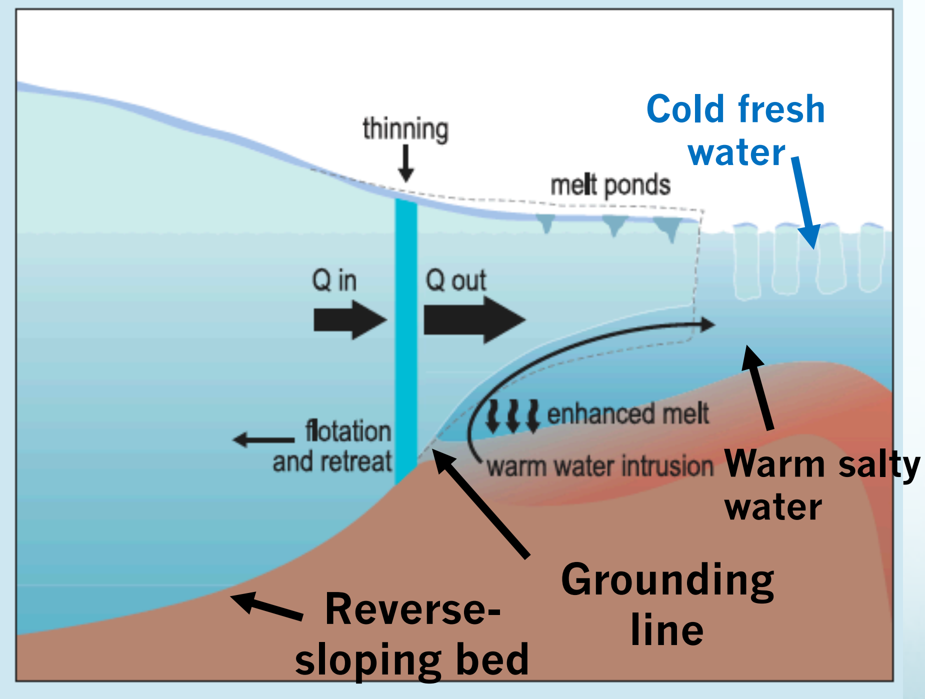
Likely range of sea level rise by 2100:

- **28 to 61 cm** with low greenhouse emissions (RCP2.6)
- **52 to 98 cm** with high emissions (RCP8.5)

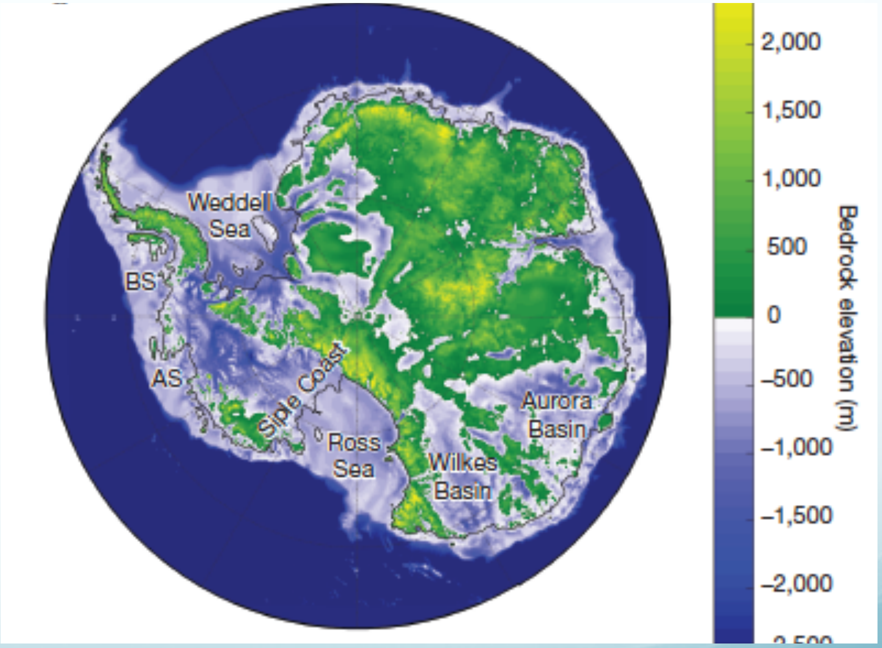
"Only the **collapse of marine-based sectors of the Antarctic ice sheet**, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century...."

Antarctic ice sheet instability

- Much of the Antarctic ice sheet is grounded below sea level (~5 m SLE in W. Antarctica, 20 m in E. Antarctica).
- This ice is vulnerable to intrusions of warm Circumpolar Deep Water, especially in the Amundsen Sea region.
- Unbuttressed ice on a reverse-sloping sea bed is unstable.



Schematic of marine ice sheet instability
(IPCC AR5)



Antarctic basal topography

Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6)

- ISMIP6 is the first CMIP project focused on ice sheets.
    - *Primary goal*: To estimate past and future sea level contributions from the Greenland and Antarctic ice sheets, along with associated uncertainty
    - *Secondary goal*: To investigate feedbacks due to dynamic coupling between ice sheet and climate models, and impacts of ice sheets on the Earth system
- Includes both standalone ice sheet experiments and coupled ice sheet–climate experiments (Nowicki et al. 2016)

CISM, CESM and ISMIP6

1. **Analysis of CMIP6 global model results that are relevant for ice sheets** (Lenaerts et al.)
2. **Standalone ice sheet experiments** based on CMIP6 model output to estimate past and future sea level rise, explore uncertainty (Lipscomb and Leguy)
3. **Coupled climate – ice sheet experiments** to explore ice sheet impacts and feedbacks (Vizcaíno et al.)

CMIP6 experiments used by ISMIP6 (AOGCM)

- Pre-industrial control
- AMIP
- 1% per yr CO_2 to 4xCO_2
- Abrupt 4xCO_2
- CMIP6 historical simulation
- ScenarioMIP SSP5-8.5 (to year 2300)
- Last Interglacial PMIP

Standalone ISMIP6 experiments (ISM only)

- ISM control
- ISM for last few decades (AMIP)
- ISM for the historical period
- ISM forced by 1% per yr CO_2 to 4xCO_2
- ISM for 21st / 23rd century (SSP5-8.5)
- ISM specific experiments to explore uncertainty

Coupled AOGCM-ISM experiments

- Pre-industrial control
- 1% per yr CO_2 to 4xCO_2
- Historical + SSP5-8.5 (to year 2300)

ISMIP6 standalone ice sheet experiments

- Initialize ice sheet as desired (spin-up and/or data assimilation).
- Run forward for 100 years using RCP2.6 or RCP8.5 forcing.
- Scenarios are derived from an ensemble of CMIP models that score well on historical metrics and have a range of sensitivities.

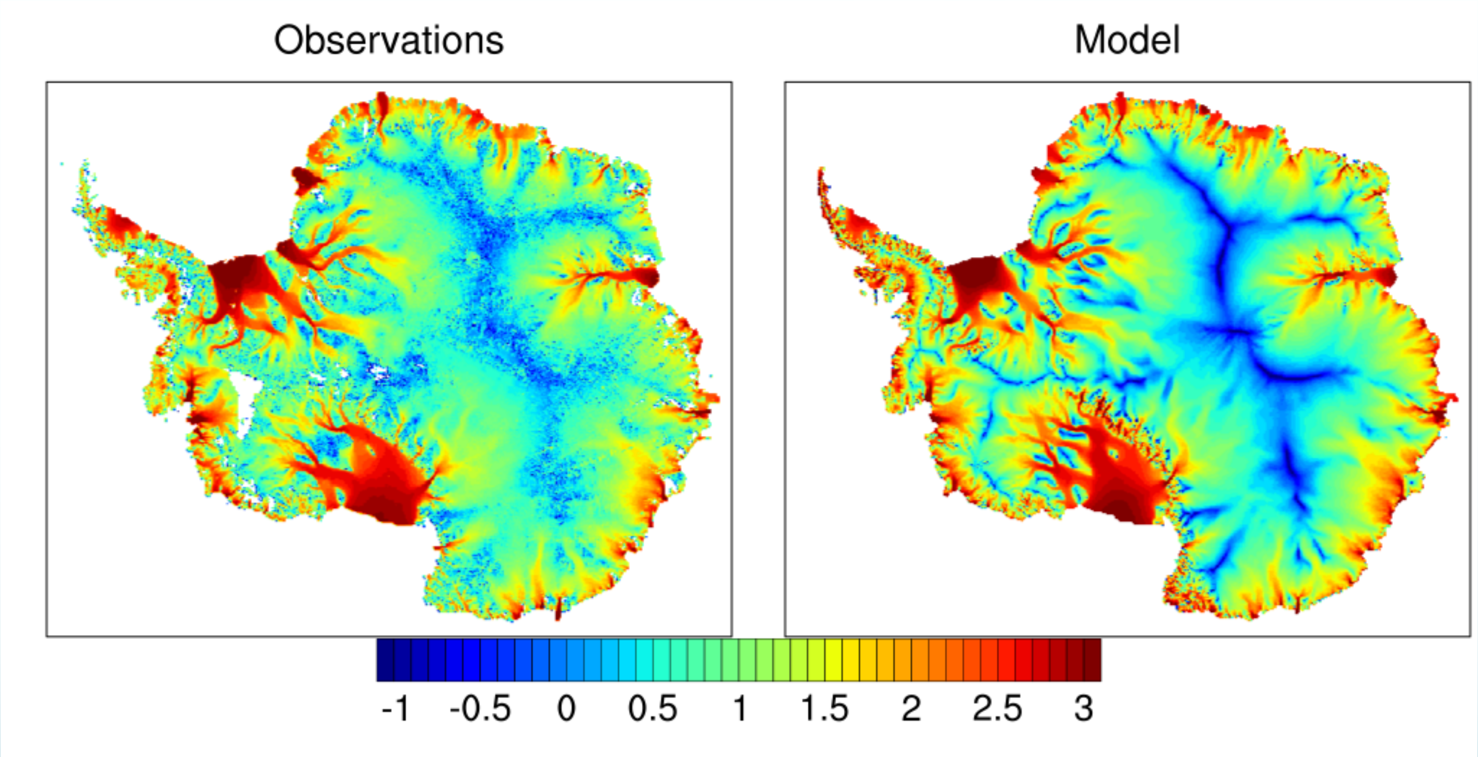
Antarctica:

- Surface mass balance derived from an ensemble of CMIP models
- Sub-ice-shelf melt rates parameterized as a function of 3D thermal forcing anomalies in CMIP ocean models

Detailed descriptions: http://www.climate-cryosphere.org/wiki/index.php?title=ISMIP6_wiki_page

CISM Antarctic simulations: Spin-up

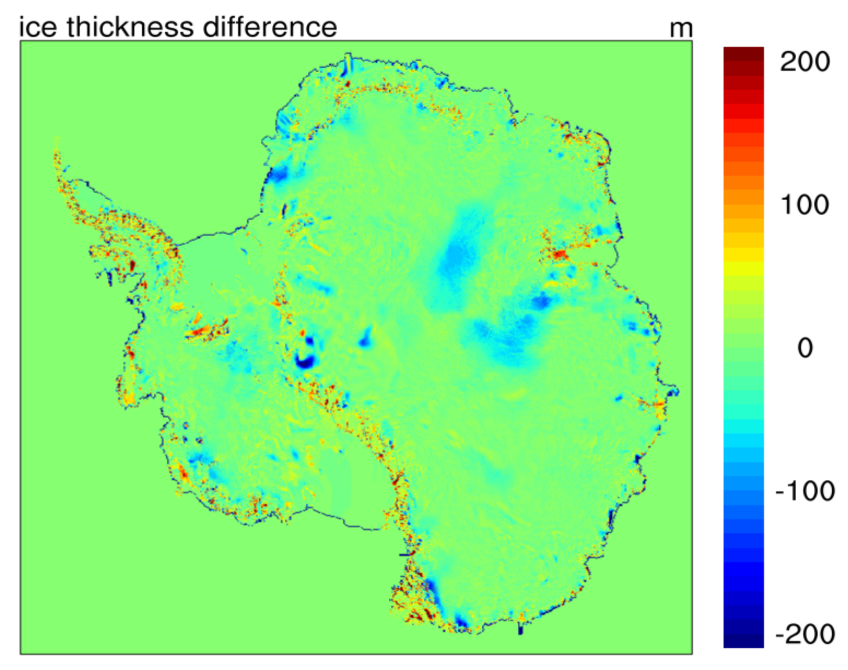
- *Goal:* Spin up Antarctica to a steady state consistent with modern observations, given a prescribed SMB. More challenging than Greenland.
- *Method:* Nudge **basal friction parameters** (for grounded ice) and **sub-shelf melt rates** (for floating ice) to match the **observed surface elevation.**



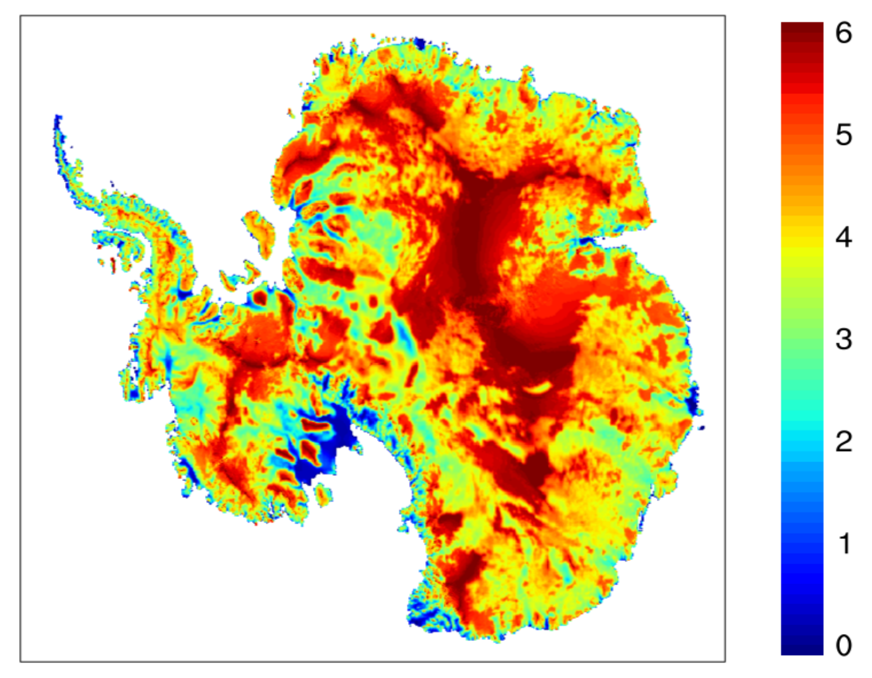
Antarctic surface ice speed (m/yr, log scale).
Red = fast, **blue = slow**

CISM Antarctic simulations: Spin-up

- *Spin-up:* 75 ka on an 8 km grid. Nudging is phased out over the last 35 ka.
- Ice thickness in good agreement with observations; errors < 200 m
- Basal friction parameter adjusts to support fast-flowing ice streams



Difference (m) between final thickness and observational target



Basal friction parameter (Pa/m/yr)
Red = low slip, **blue = high slip**

Standard basal melt parameterization

Standard experiments use a **nonlocal quadratic parameterization** suggested by Favier et al. (2019) based on comparison with a coupled ice–ocean model:

$$m(x,y) = \gamma_0 \times \left(\frac{\rho_{sw} c_{pw}}{\rho_i L_f}\right) \times \left[TF(x,y,z_{\mathrm{draft}}) + \delta T_{\mathrm{basin}}\right] \times \left|\langle TF_{\mathrm{draft} \in \mathrm{basin}}\rangle + \delta T_{\mathrm{basin}}\right|$$

$$\begin{aligned} m &= \text{basal melt rate} \\ TF(x,y,z_{\mathrm{draft}}) &= \text{thermal forcing at ice}-\text{ocean interface} \\ \langle TF\rangle &= \text{basin mean thermal forcing} \\ \gamma_0 &= \text{empirical melt coefficient} \\ \delta T_{\mathrm{basin}} &= \text{basin}-\text{dependent temperature correction} \end{aligned}$$

- Thermal forcing (TF) from observations is extrapolated into sub-shelf cavities, and then interpolated to the ice shelf base at runtime.
- The nonlocal term accounts for stronger ocean circulation in warmer cavities.

Open basal melt parameterization

Open experiments use the same thermal forcing data, but can use any basal melt scheme.

We modify the standard scheme to **focus melting near the grounding line**:

$$m(x,y) = \gamma_0 \times \left(\frac{\rho_{sw} c_{pw}}{\rho_i L_f}\right) \times \left[TF(x,y,\mathrm{z}_{\mathrm{draft}}) + \delta T_{\mathrm{basin}}\right] \times \left|\langle TF_{\mathrm{draft} \in \mathrm{basin}} \rangle + \delta T_{\mathrm{basin}}\right|$$

$$\boldsymbol{m'(x,y) = m(x,y) \times K\, sin(\theta)}$$

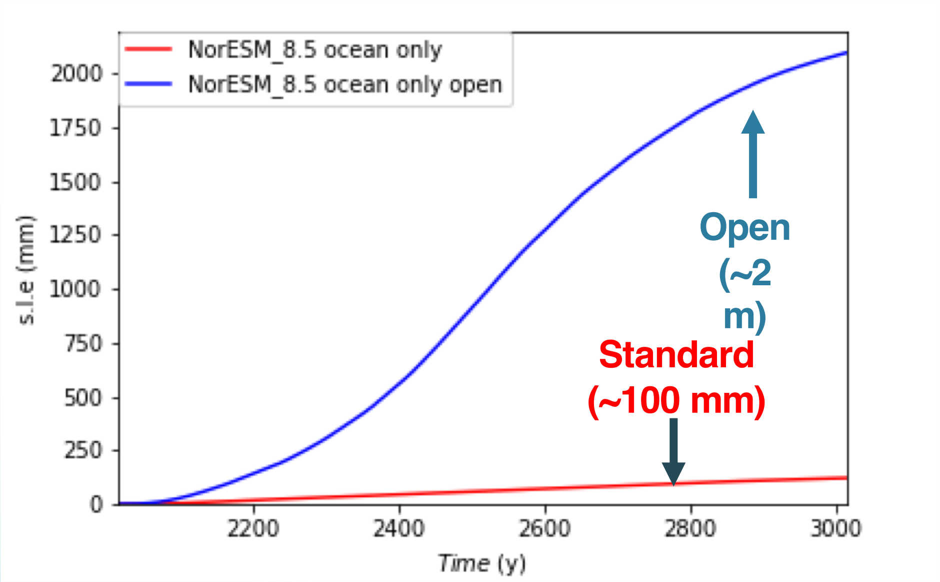
θ is the angle of the ice shelf base with the horizontal

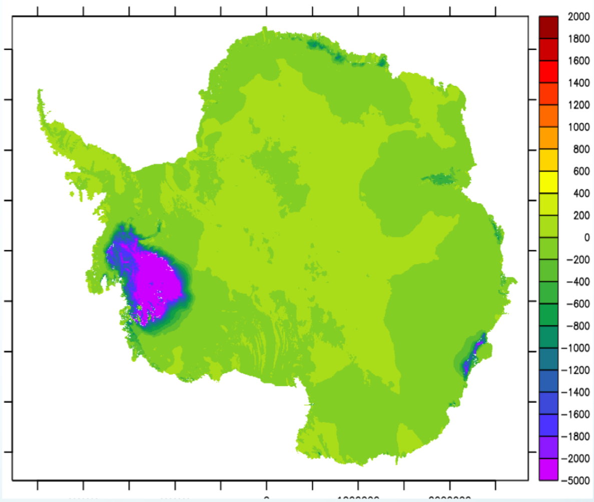
$K \sim 100$ is an empirical coefficient

- Favier et al. (2019) noted that the standard scheme yields melt rates that are too large near the calving front and too small near the grounding line.
- Jenkins et al. (2018) suggested that the rate of entrainment of warm ambient water into the sub-shelf boundary current is proportional to $\sin(\theta)$.

BMB anomaly: Extended open experiments

- When the open run is extended for several centuries with late 21st century thermal forcing (NorESM1 climatology, 2080-2100), much of the West Antarctic Ice Sheet collapses, giving about 2 m of sea level rise.





Thickness change (m) over 1000 years, with
late 21st century thermal forcing from NorESM

Your experiment

- Start from a steady-state Antarctic ice sheet at the end of a 40,000 CISM spin-up, with basal melt rates adjusted to nudge ice thickness toward observations.
  - 8 km grid (coarse, but runs quickly)
- Apply an idealized thermal forcing anomaly at the base of ice shelves.
  - Thermal forcing is the difference between the in situ temperature and the local (salinity- and depth-dependent) freezing temperature
  - Use the "open" scheme to convert thermal forcing to a basal melt rate
- Run the model forward for 100 years and look at the results.