Modeling Land Ice in CESM

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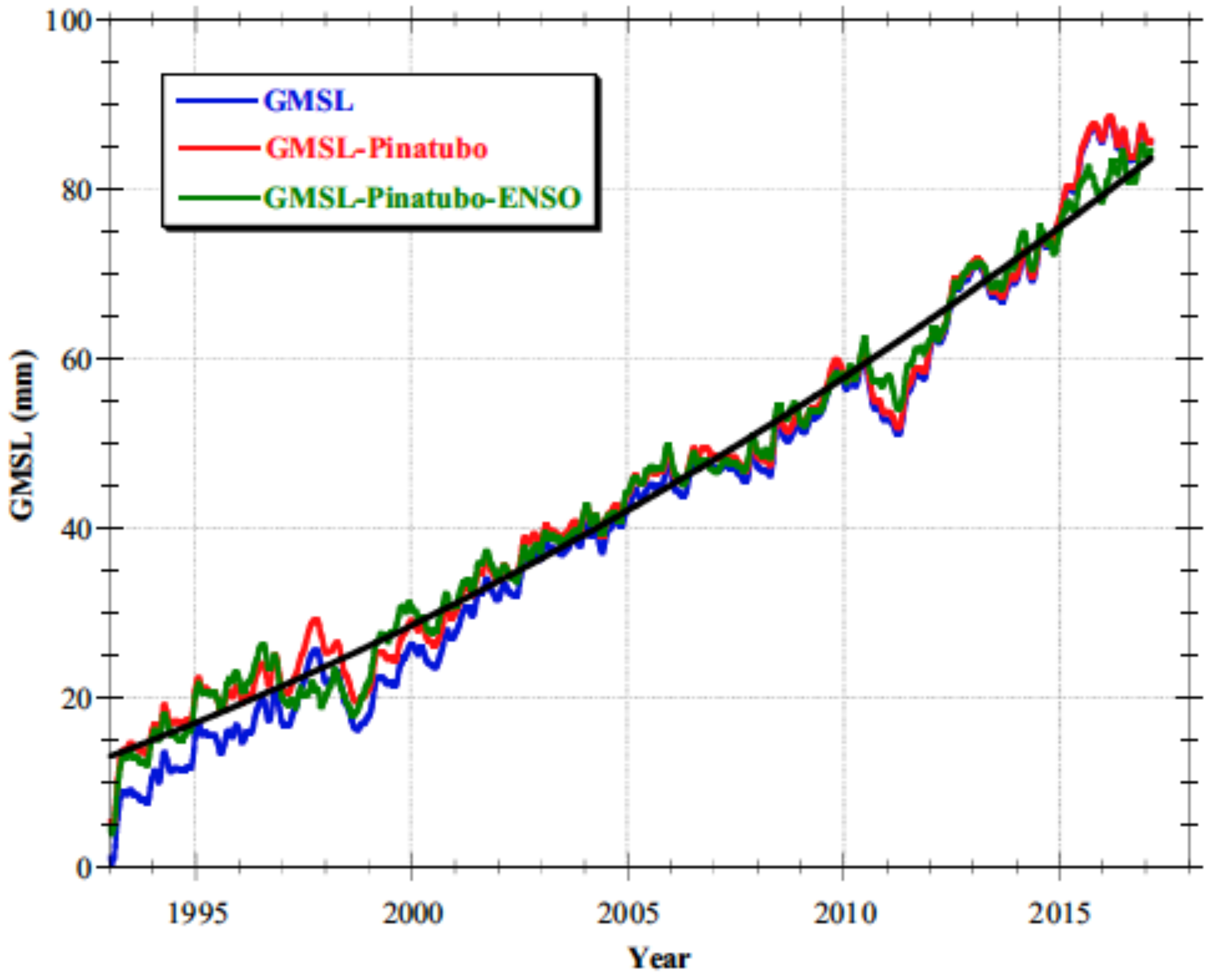
Outline

- Land ice and sea level rise
- Brief history of ice sheets in CESM
- Ice sheets in the CESM2 release
- Current and future ice sheet model development
- Ice sheet model intercomparison projects

Sea-level rise since 1993

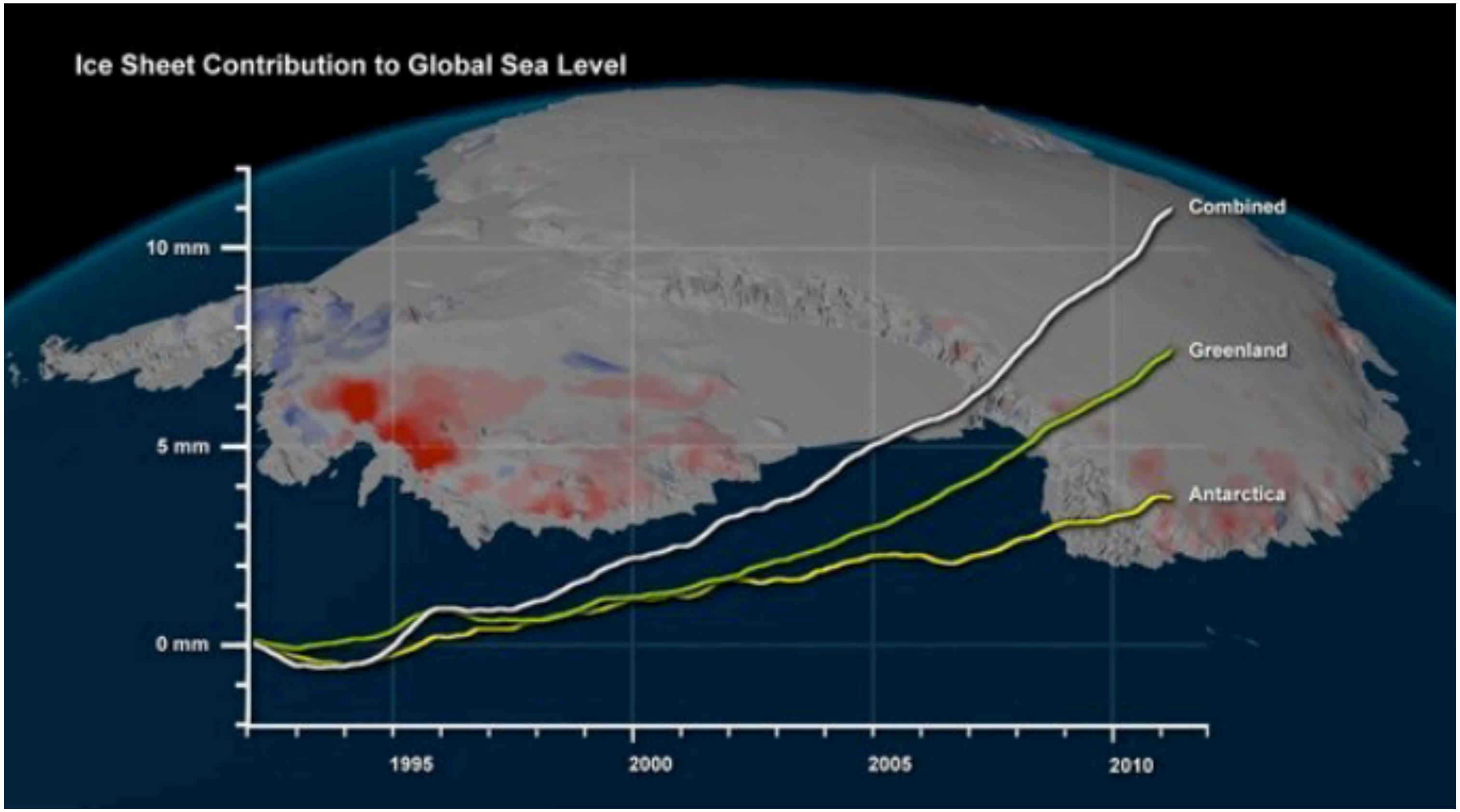


Nerem et al. 2018

Global mean sea-level rise from satellite altimetry

SLR rate **= 2.9 mm/yr**, with acceleration of 0.084 ±0.025 mm/yr^2

Growing ice sheet contribution to sea level

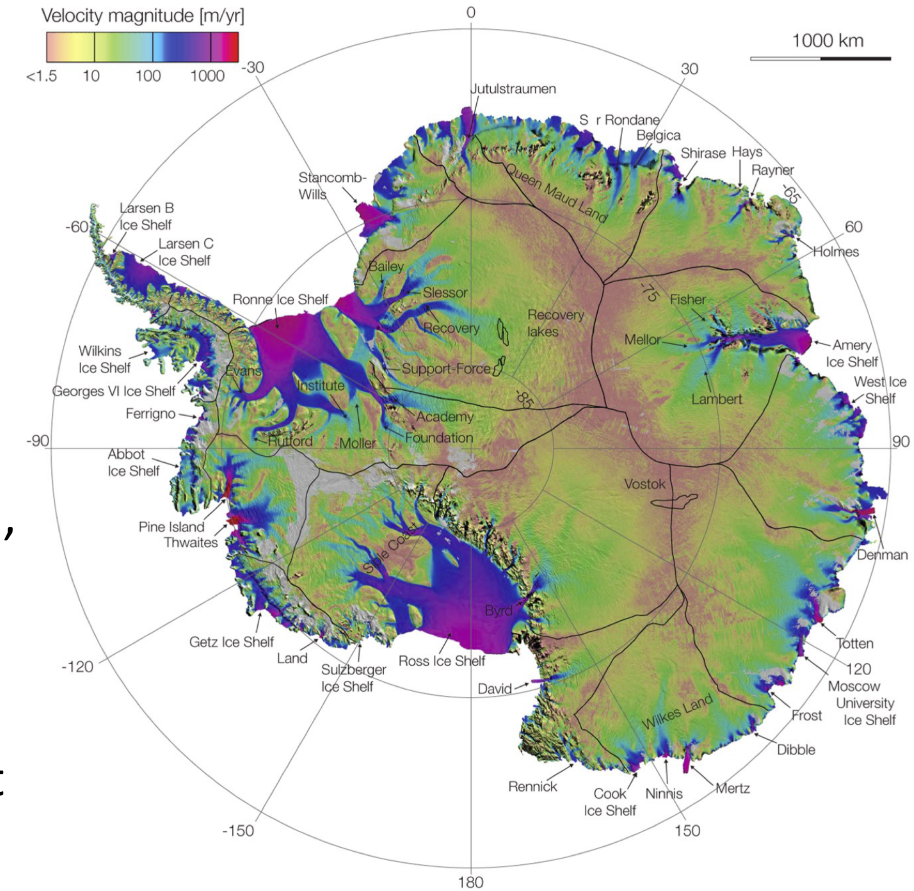


Credit: ESA/NASA/Planetary Visions

~1 mm/yr from Greenland and Antarctic ice sheets (~60% Greenland)
~1 mm/yr from glaciers and ice caps
~1 mm/yr from ocean thermal expansion

Antarctic Ice Sheet

- **60 m** sea-level equivalent
  - **5 m** in marine-based parts of West Antarctica, **20 m** in marine-based parts of E. Antarctica
- Accumulation balanced by flow into ice shelves; little surface melting
- Growing mass loss in West Antarctica, triggered by warm ocean water reaching the base of ice shelves
  - Total Antarctic mass loss of about 220 Gt/yr in 2012-2017, compared to near balance in 1990s (IMBIE 2018)



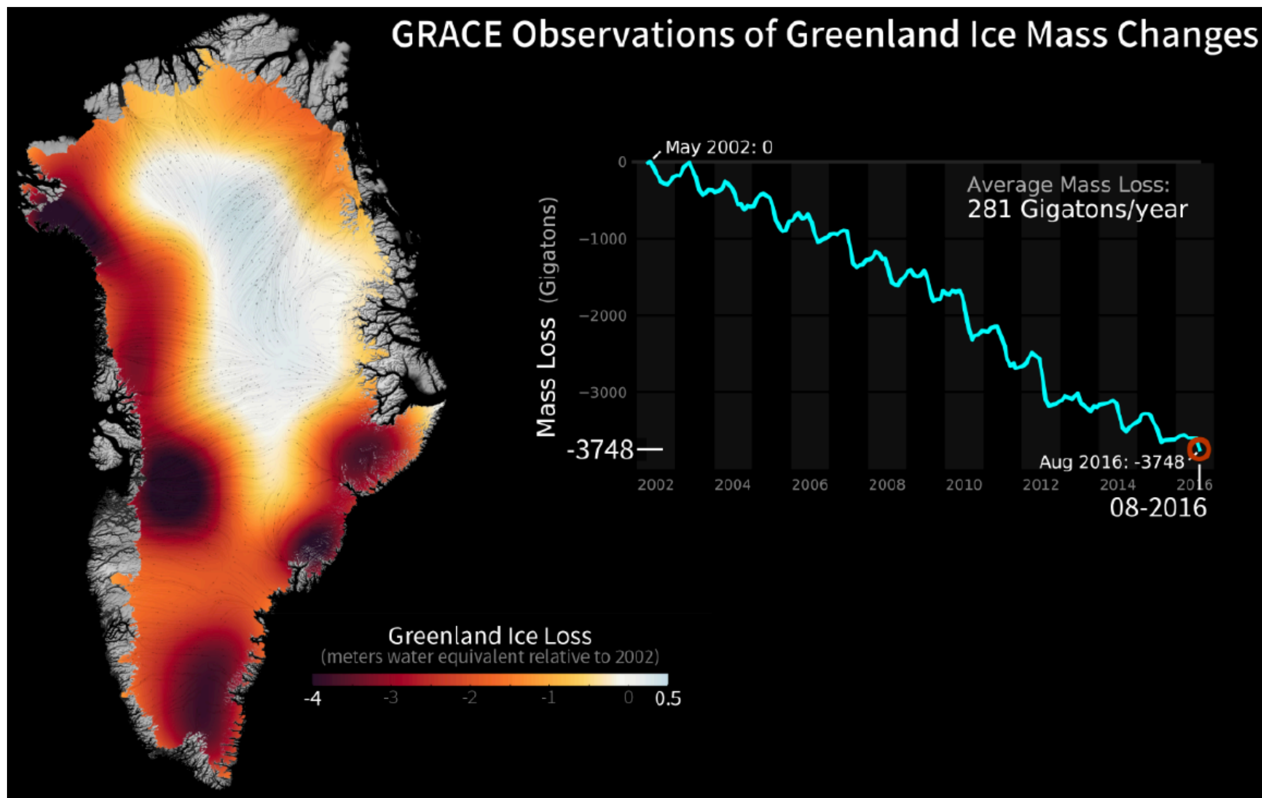
Antarctic ice flow speed (Rignot et al. 2011)

Greenland Ice Sheet

- **7 m** sea-level equivalent
- Accumulation balanced by surface runoff and iceberg calving
- Growing mass loss in recent years from increased surface melting and runoff, and from thinning and acceleration of outlet glaciers
  - Average loss of about 280 Gt/yr, 2002-2016

Greenland ice mass loss from GRACE gravity observations.

Credit: NASA

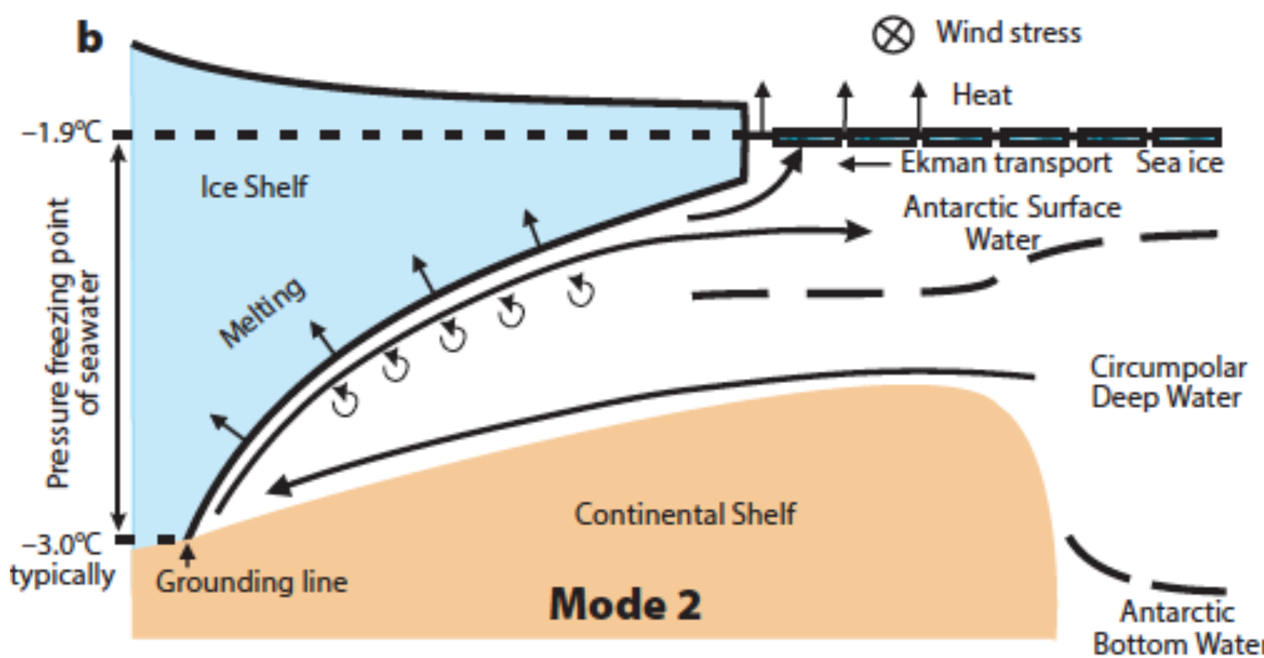


Ice sheets in IPCC AR5

- “Under all RCP scenarios **the rate of sea level rise will *very likely* exceed that observed during 1971–2010** due to increased ocean warming and increased loss of mass from glaciers and ice sheets.”
- Likely range of 21st century global mean sea level rise:
  - **0.32 to 0.63 m** (RCP4.5, 2081-2100)
  - **0.45 to 0.82 m** (RCP8.5, 2081-2100)
- “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….”

Marine ice sheet instability (MISI)

- Ice in parts of Antarctica, especially the Amundsen Sea region, is vulnerable to intrusions of warm Circumpolar Deep Water (possibly driven by changes in wind forcing).
- Unbuttressed marine ice on a reverse-sloping bed is unstable.
- MISI may already be active for Pine Island and Thwaites glaciers.



Schematic of warm CDW reaching the grounding line (Jenkins et al. 2016)

Antarctic ice sheet sensitivity

- **Last Interglacial** (125K years ago, CO_2 = 280 ppm)
  - Global mean sea level **6–9 m higher** than today
  - Only ~2 m from Greenland, 0.4 m from ocean thermal expansion, hence an Antarctic contribution of ~5 m
- **Pliocene** (3M years ago, CO_2 = 400 ppm)
  - Global mean sea level **10–30 m higher** than today
  - Max of ~7 m from Greenland, ~5 m from W. Antarctica, so probably an E. Antarctic contribution
- Even with MISI included, it is difficult to simulate this much retreat with current models.
  - Are critical mechanisms missing?

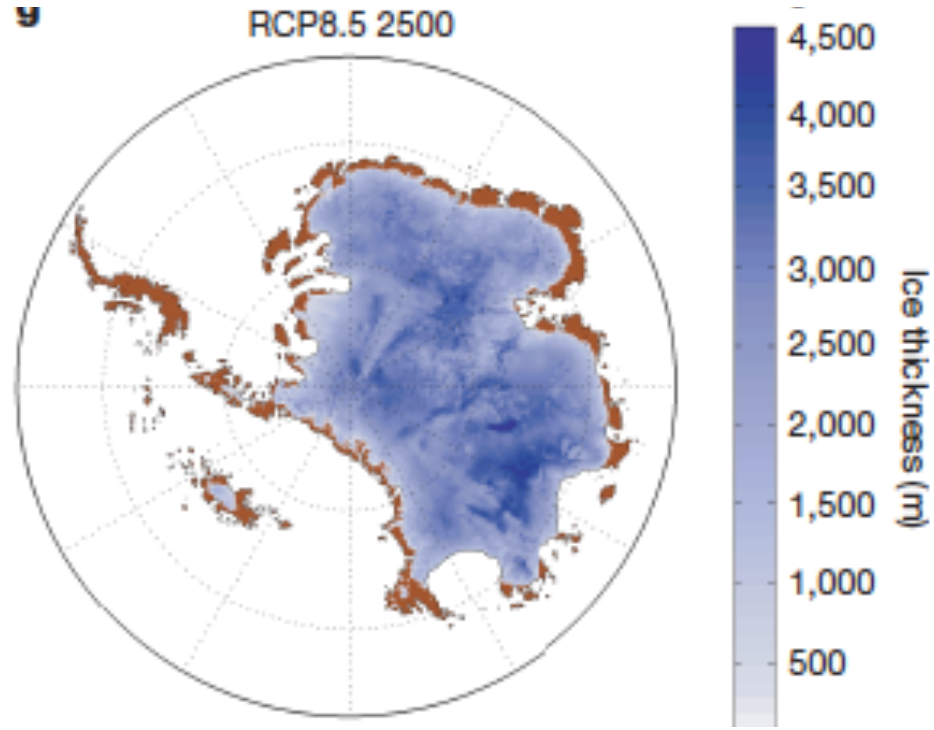
Mechanisms for large Antarctic SLR?

DeConto & Pollard (2016) suggested two mechanisms:

- **Marine ice cliff instability (MICI)**
  - Ice cliffs at the edge of outlet glaciers can be ~1 km thick
  - When more than ~100 m of ice sits outside the water, a typical ice cliff will collapse (stress > 1 Mpa)
  - Cliff retreat on a reverse-sloping bed is dynamically unstable (similar to MISI).
- **Hydrofracture**
  - Increased melting on ice shelves could grow crevasses and increase calving (e.g., Larsen B collapse in 2002)
  - Lose of buttressing shelves could trigger cliff instability (e.g., Jakobshavn in Greenland)

Simulated Antarctic retreat
DeConto & Pollard (2016)

- **RCP8.5**: *77 cm by 2100*, *12 m by 2500*
  - WAIS collapse by 2250
  - Major retreat in Wilkes and Aurora Basins
- Atmospheric warming is the main driver, but ocean thermal memory inhibits recovery.



DeConto & Pollard 2016

- Mechanisms are plausible, but rates are highly uncertain.
  - Coarse-resolution ice sheet model (10 km) with parameterized ice fluxes at the grounding line
  - Prescribed ocean melt rates with no coupling

Questions

- What range of sea-level rise should planners and policymakers assume?
  - Can we be confident that 21st century sea-level rise will not exceed 1 m?
- Can CESM and other Earth system models provide actionable sea-level science**?**
  - Surface mass balance projections from Earth system models are increasingly credible.
  - But it remains difficult to put an upper bound on the sea-level contribution from Antarctica.

History of ice sheets in CESM

- For many years, global climate models did not include dynamic ice sheets. Ice sheets were treated as big bright rocks.
  - The traditional view was that ice sheets evolved on multi-century and longer time scales. This view changed with observations of ice sheet mass loss in the 1990s and 2000s.
- In 2009, the CESM Land Ice Working Group formed with the goals of
  1) integrating a well validated, fully dynamical ice sheet model in CESM
  2) determining the likely range of decade-to-century-scale sea-level rise associated with the loss of land ice
- CESM v1.0 was released in 2010 with a preliminary implementation of dynamic ice sheets.

History of ice sheets in CESM

CESM1 included the **Glimmer Community Ice Sheet Model v. 1** (CISM1).

- Dynamic Greenland ice sheet on a 5 km grid
- Serial code; shallow-ice dynamics (valid for slow interior flows, but not fast flow in ice streams and ice shelves)

CESM1 also added a **surface-mass-balance scheme for land ice**.

- The surface mass balance (SMB) for glaciated regions is computed by the Community Land Model in multiple elevation classes, then sent to the coupler and downscaled to the local ice sheet grid.
- Advantages to computing SMB in the land model:
    - Couple ice albedo to atmosphere on hourly time scales
    - Avoid duplication of snow physics
    - Computational savings (land grid coarser than ice sheet grid)

Land ice progress: CESM1 to CESM2

CESM 1.0	CESM2.0
Serial, shallow ice approximation	Parallel, higher-order approximation
One-way coupling (CLM → CISM)	Two-way coupling (CLM ←→ CISM) with dynamic landunits
Downscaling in CISM, with SMB not conserved	Downscaling in the coupler, with SMB conserved
1-m snow pack in CLM	Firn model in CLM (10-m snow pack, improved snow density)
SMB computed only in runs done by LIWG	SMB computed in all runs

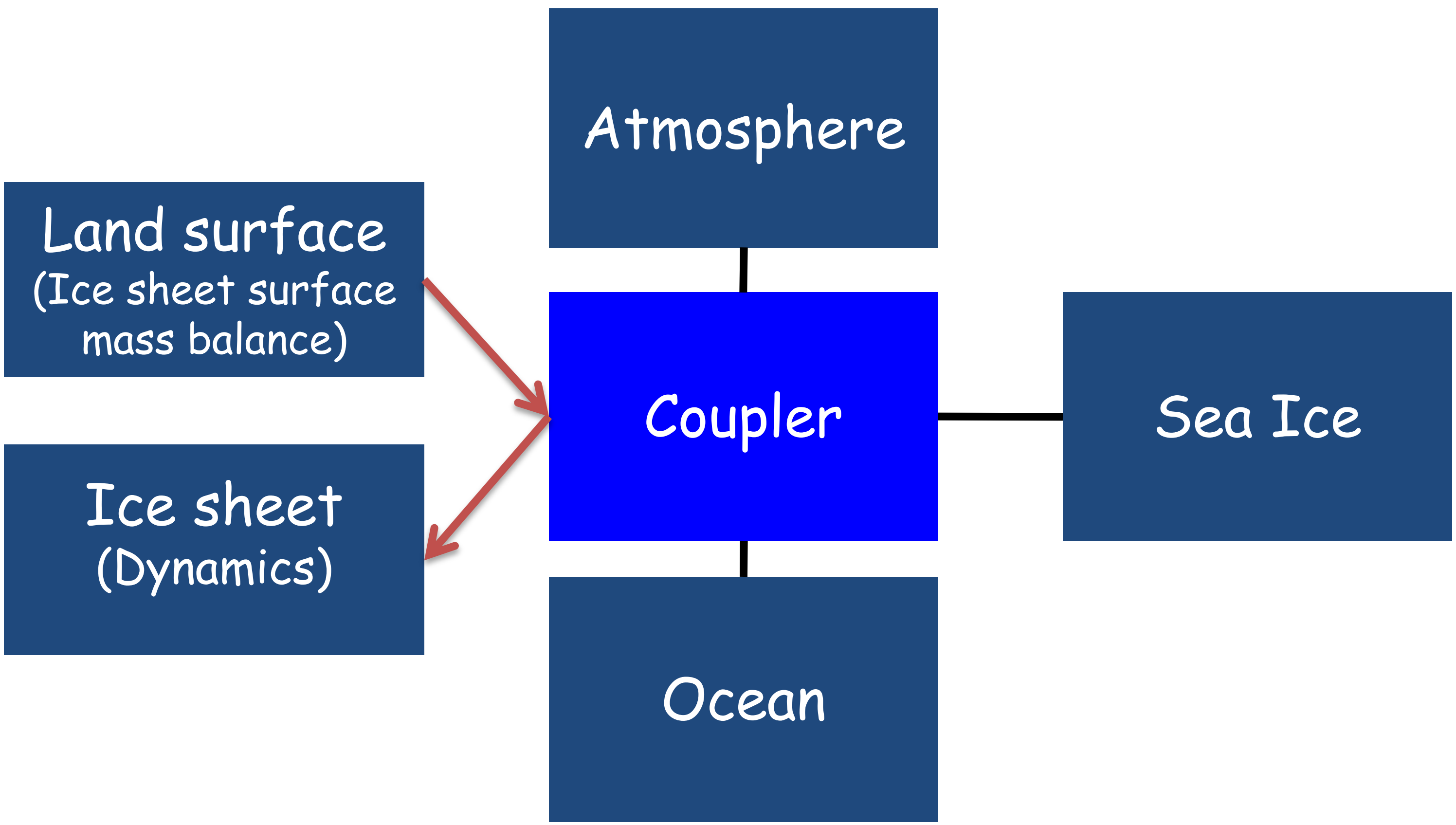
Ice sheets in CESM1

Land -> Ice sheet (10 classes)

- Surface mass balance
- Surface elevation
- Surface temperature

Ice sheet -> Land

- No fields passed; placeholders only



Ice sheets in CESM2

Land -> Ice sheet

(10 classes + bare land)

- Surface mass balance
- Surface elevation
- Surface temperature

Ice sheet -> Land

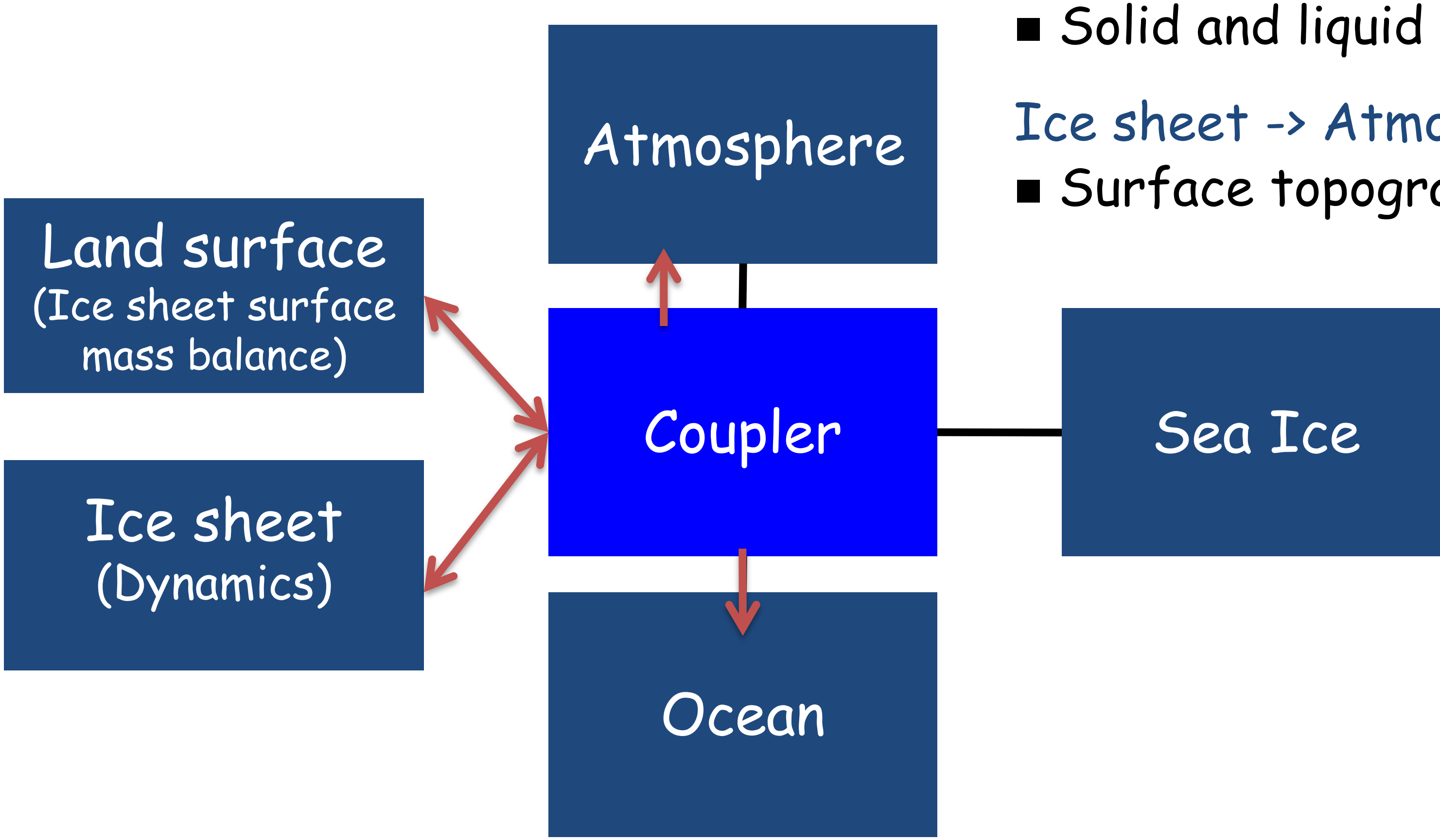
- Ice extent
- Ice surface elevation
- SMB mask

Ice sheet -> Ocean

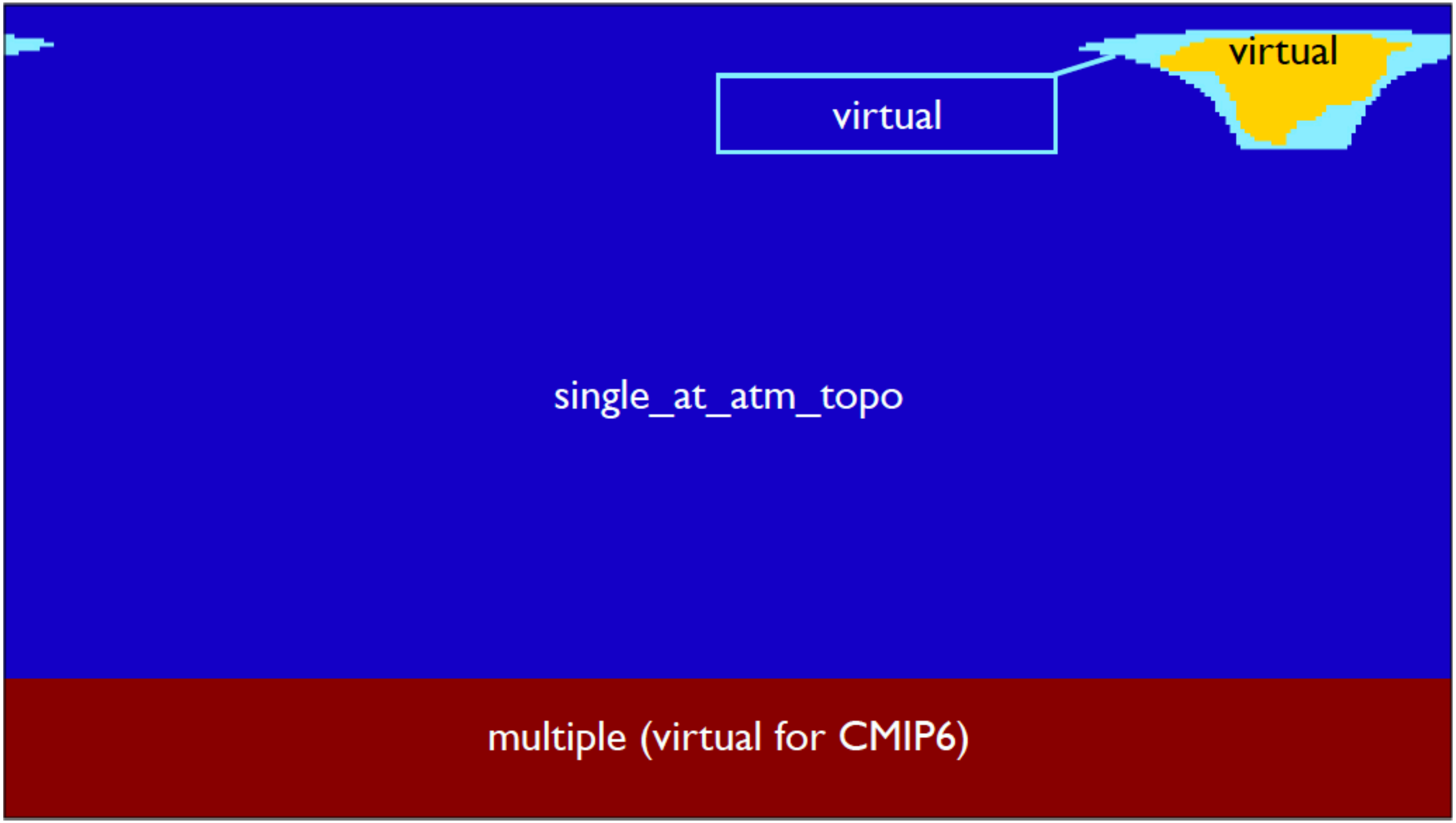
- Solid and liquid fluxes

Ice sheet -> Atmosphere

- Surface topography

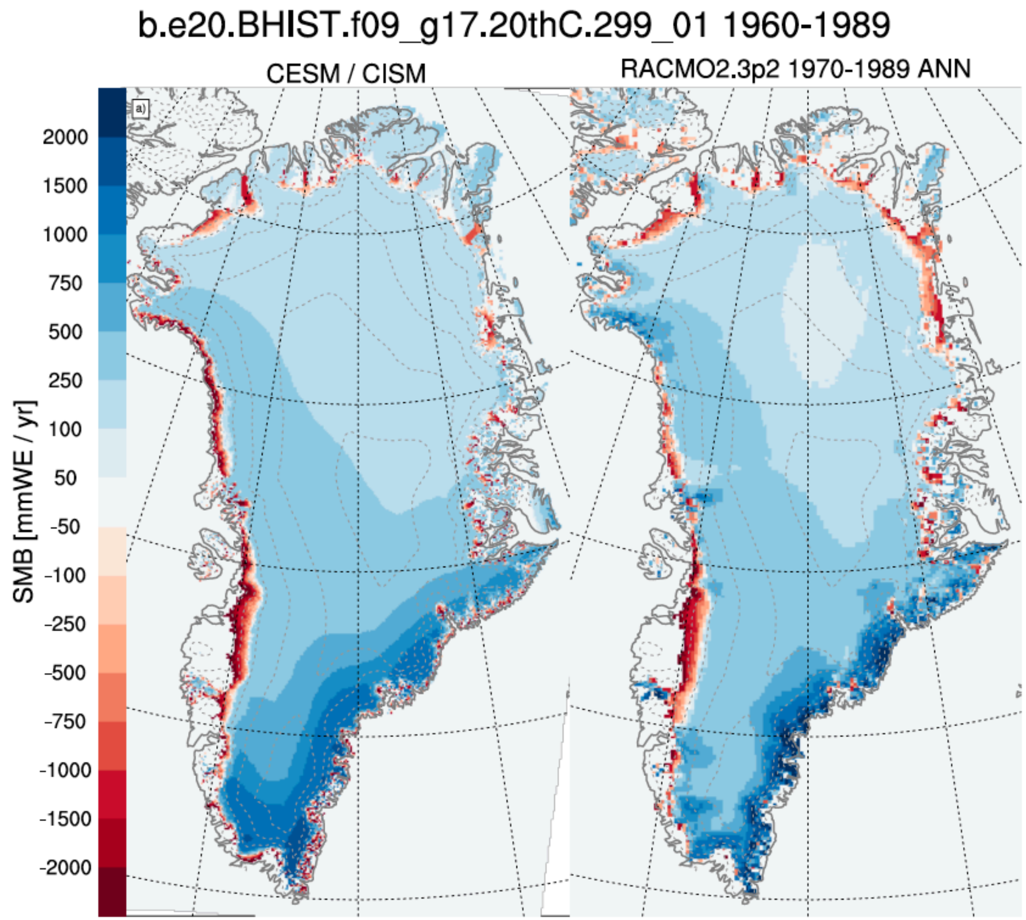


CLM glacier regions and elevation classes



Greenland surface mass balance in CESM2

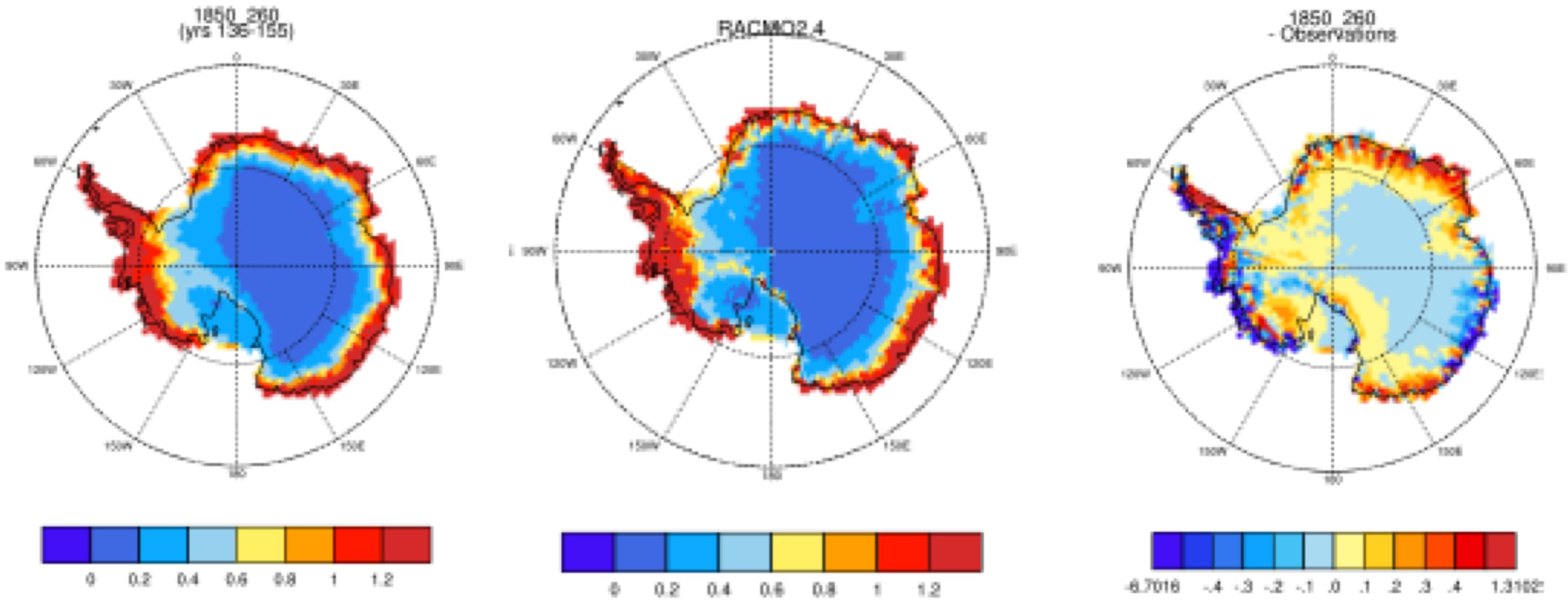
- Compares well with regional climate simulations by RACMO2
  - RACMO2 averaged between 1970 and 1989; CESM/CISM averaged from 1850
- Good agreement between CESM and RACMO in the ablation zone (**red**)
- Narrower southwest ablation zone in CESM2 might be due to earlier time period.
- CISM set to no-evolve: ice is not added where there is no ice originally. (But CLM can form ice over bare tundra.)



Greenland SMB in CESM2, downscaled to CISM grid (left), compared to RACMO2 (right). **Blue** = accumulation, **red** = ablation. Courtesy of L. van Kampenhout.

Antarctic SMB in CESM2

- CESM2 has a very good simulation of Antarctic surface mass balance.
- Some of the improvement since CESM1 is associated with a deeper snowpack, new snow physics parameterizations, and bug fixes (van Kampenhout et al. 2017).

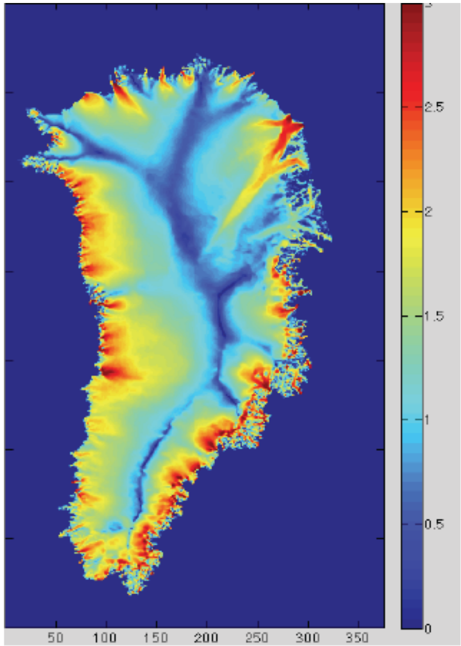


Antarctic annual snowfall (m). *Left:* CESM2 simulation 260 (1850 climate). *Center:* RACMO2.4. *Right:* Difference between CESM2 and RACMO.

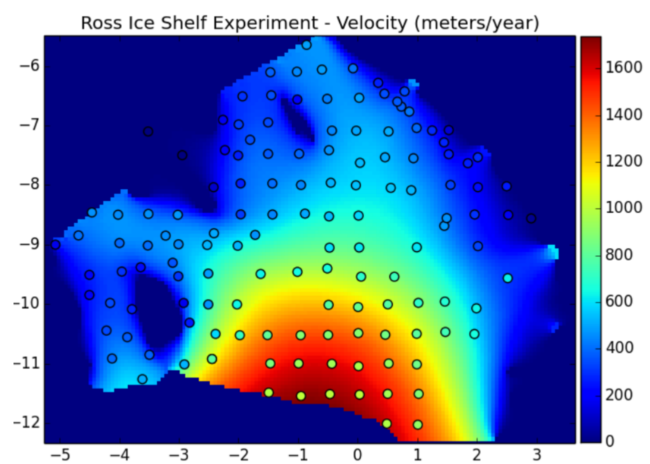
CISM2

CISM2.0 was released in 2014, followed by **CISM2.1** in 2018:

- Developed on git repo at https://github.com/escomp/cism, described by Lipscomb et al. (GMDD, 2018)
- Documentation (standalone and coupled) at https://escomp.github.io/cism-docs/
- Parallel dynamical core (Glissade) with suite of higher-order velocity solvers
- Improved physical processes such as basal sliding and iceberg calving
- Test cases with Python tools
- Coupled to CESM2

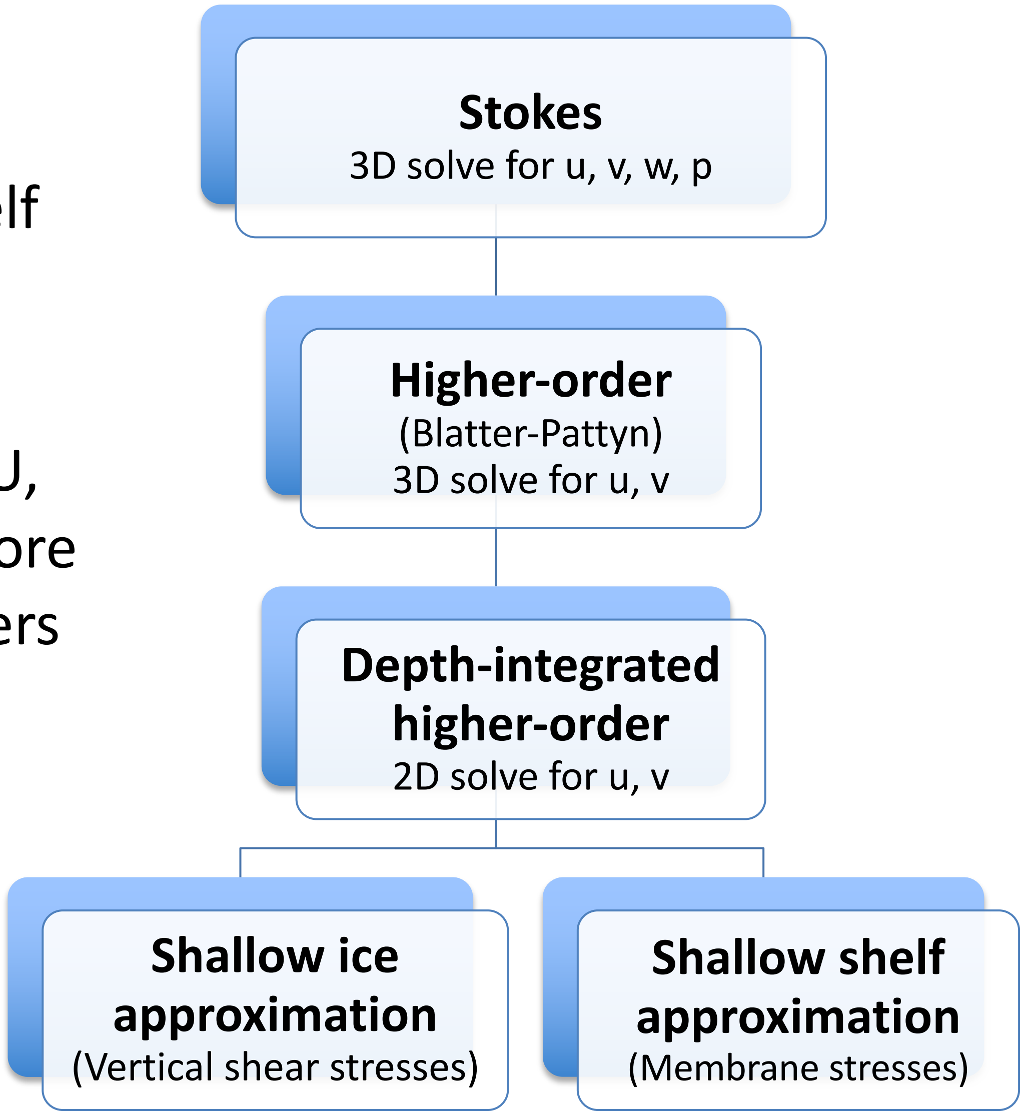


Simulated CISM2 velocities.
Top: Greenland ice sheet
Bottom: Ross Ice Shelf



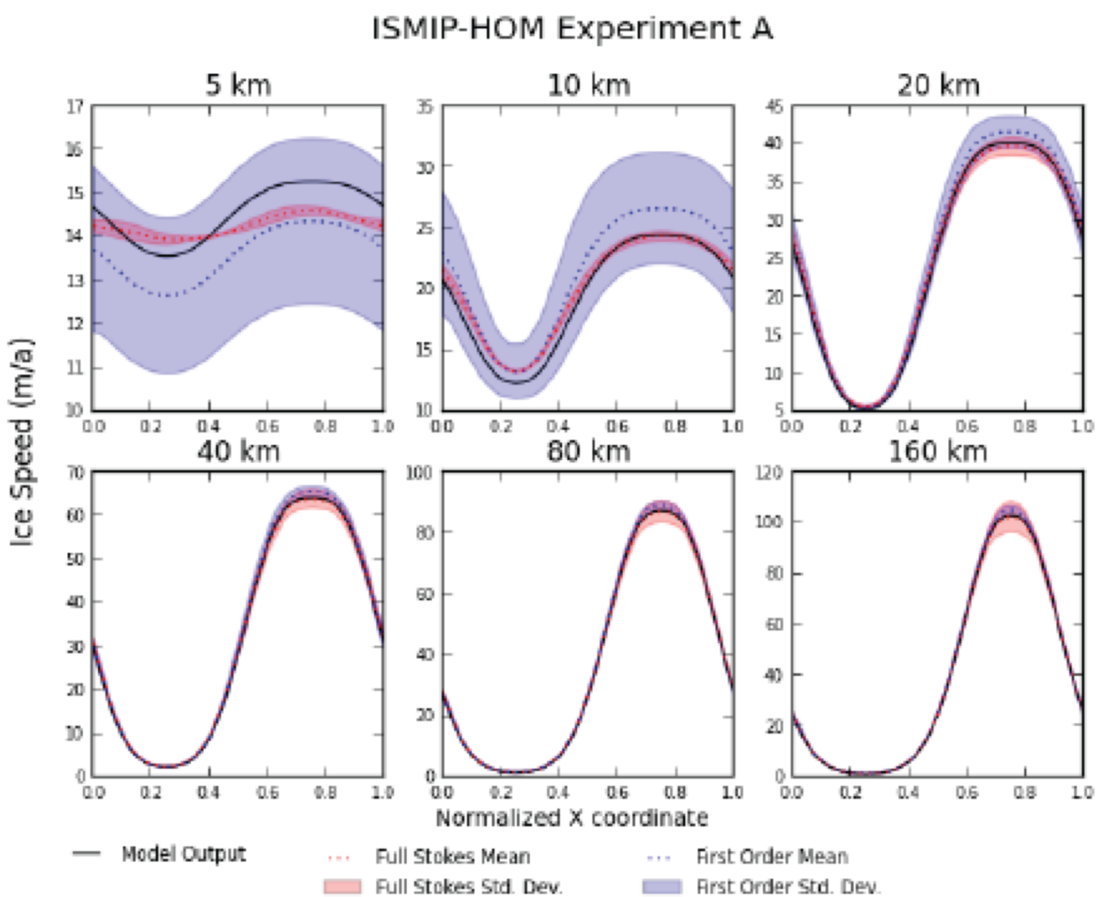
Hierarchy of Stokes approximations

- Previous generation of ice sheet models mostly used shallow-ice or shallow-shelf approximations
- Newer models (BISICLES, Elmer-Ice, ISSM, PISM, PSU, MALI, etc.) have one or more higher-order velocity solvers
- CISM2 incudes 3D higher-order, depth-integrated higher-order, SIA, and SSA



CISM2: ISMIP-HOM tests

- Compared higher-order model results to community benchmarks (Pattyn et al. 2008) for problems with small-scale variations in topography and basal traction
- Glissade's higher-order solvers agree well with benchmarks



ISMIP-HOM Test A: Sinusoidal pattern in basal topography at 6 grid scales (Glissade output shown by black lines)

Some CISM options

Velocity solver:

- Shallow-ice approximation
- Shallow-shelf approximation
- Depth-integrated HO (DIVA)
- 3D HO (Blatter-Pattyn)

Basal sliding:

- No sliding
- Sliding where bed is thawed (uniform friction coefficient)
- Read in 2D field of basal friction parameters
- Compute using pseudo-plastic sliding law

Iceberg calving:

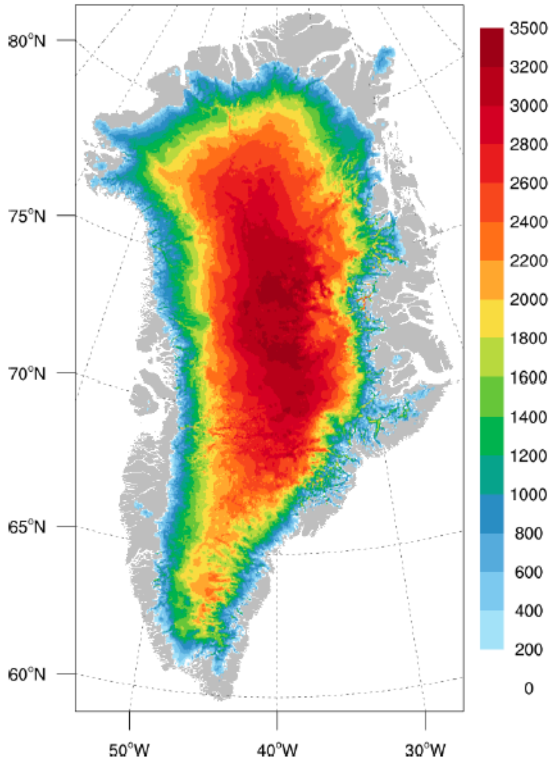
- Calve all floating ice
- No-advance calving front
- Calve based on ice thickness
- Calve based on eigenvalues of stress tensor ("eigencalving")

Sub-ice-shelf melting:

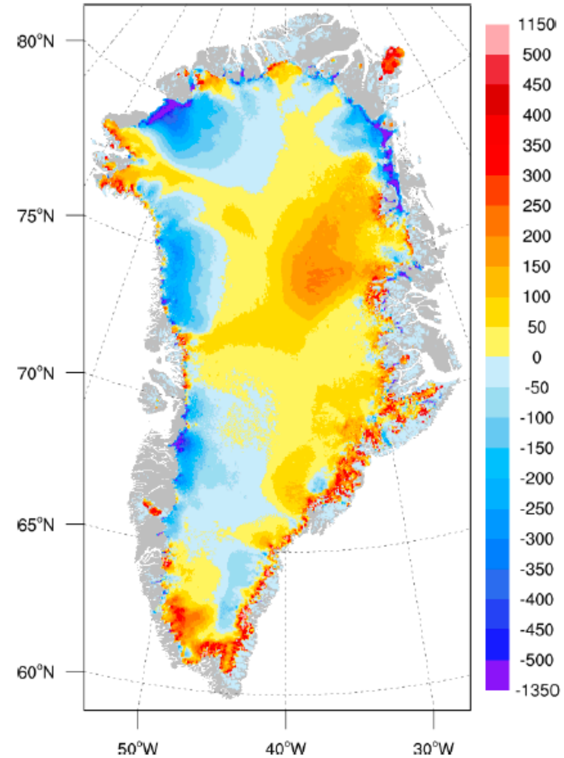
- No basal melting
- Uniform basal melt rate
- Read in 2D field of basal melt rates
- Compute basal melt rates as a function of depth

CISM2: Greenland thickness

- CISM2 is robust and efficient for long Greenland spin-ups (~2000 yr/wall clock hour on 4 km grid).
- After a 50 kyr spin-up with SMB forcing from RACMO2, model thickness is close to observations (a bit thin in north and west, thick in NE interior and SE coast).



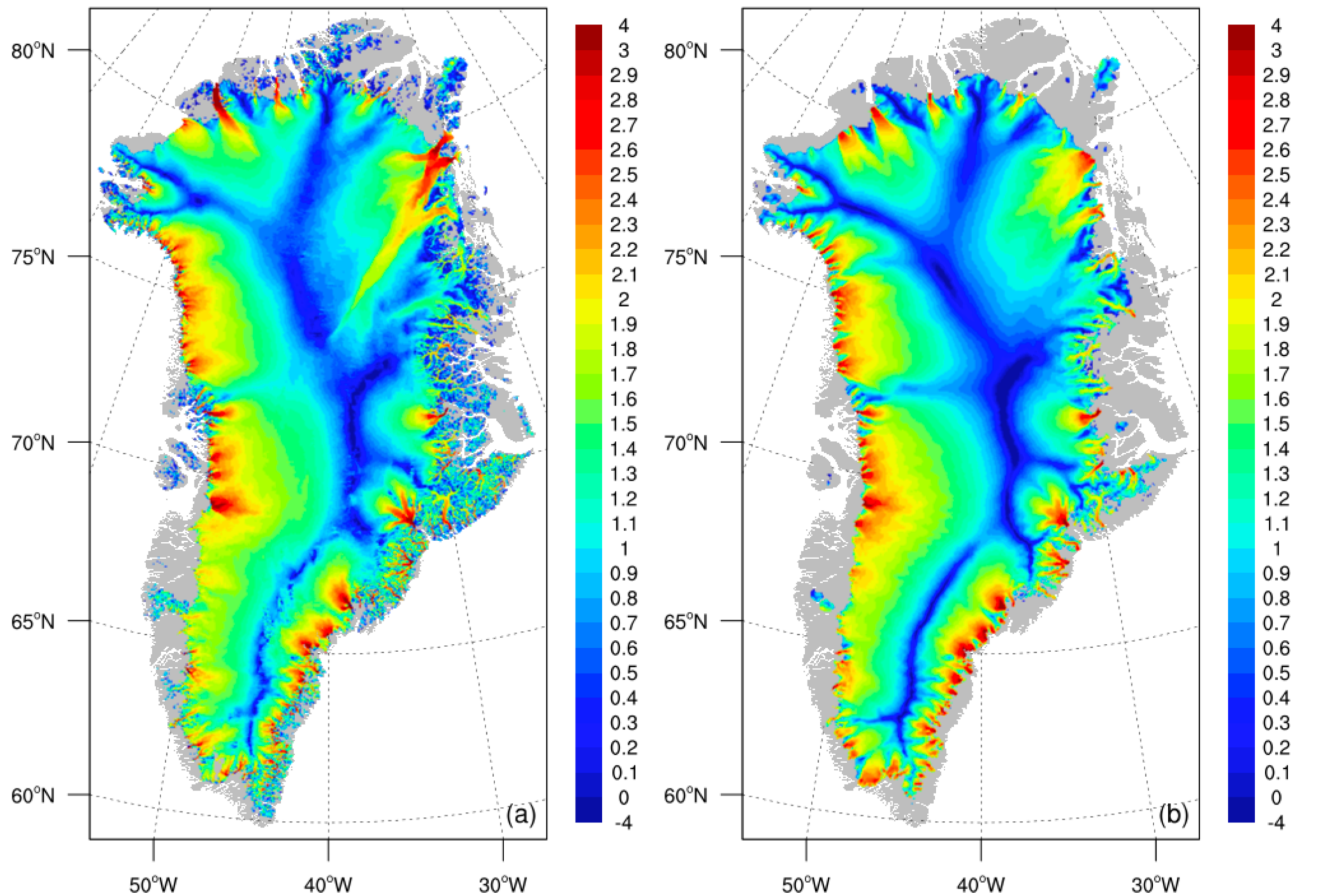
CISM ice thickness (m) after 50 ka spin-up



Simulated minus observed thickness (m)

CISM2: Greenland velocities

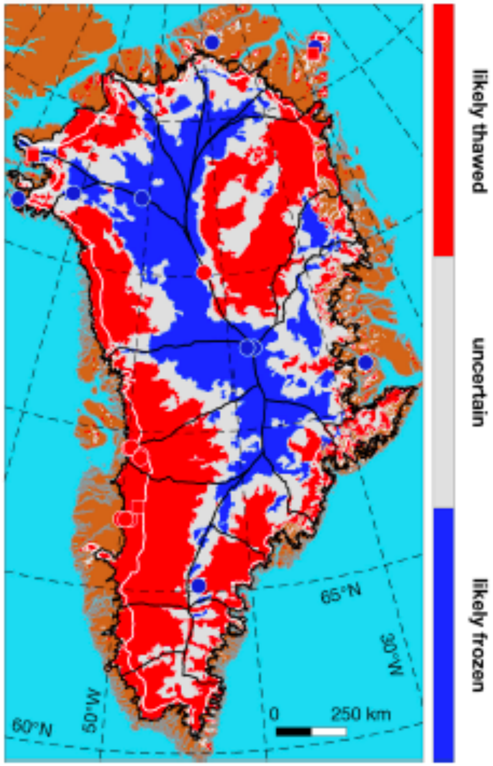
- Using a depth-integrated higher-order velocity solver and pseudo-plastic sliding law, CISM velocities are in good agreement with observations.



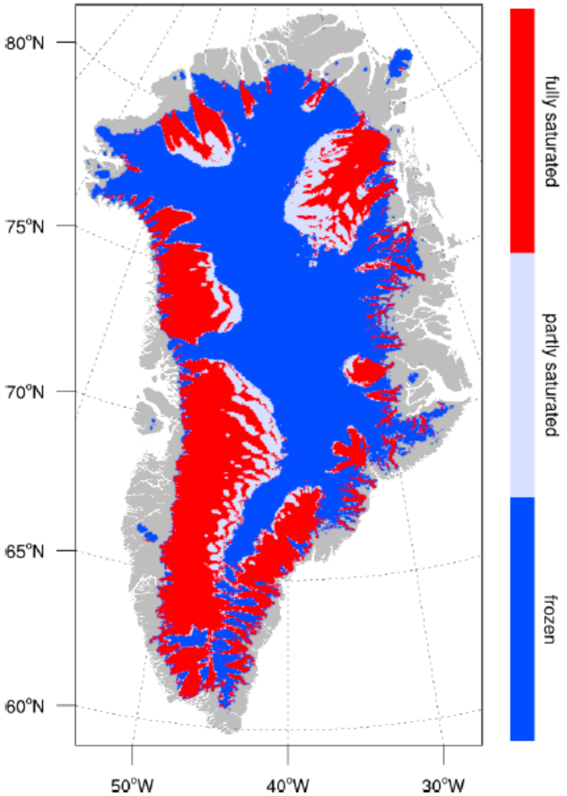
Greenland surface ice speed (m/yr, log scale).
Left: Observed (Joughin et al. 2010). Right: Simulated by CISM.

CISM2: Greenland basal state

- CISM's distribution of frozen and thawed regions is similar to estimates based on observations and other models.



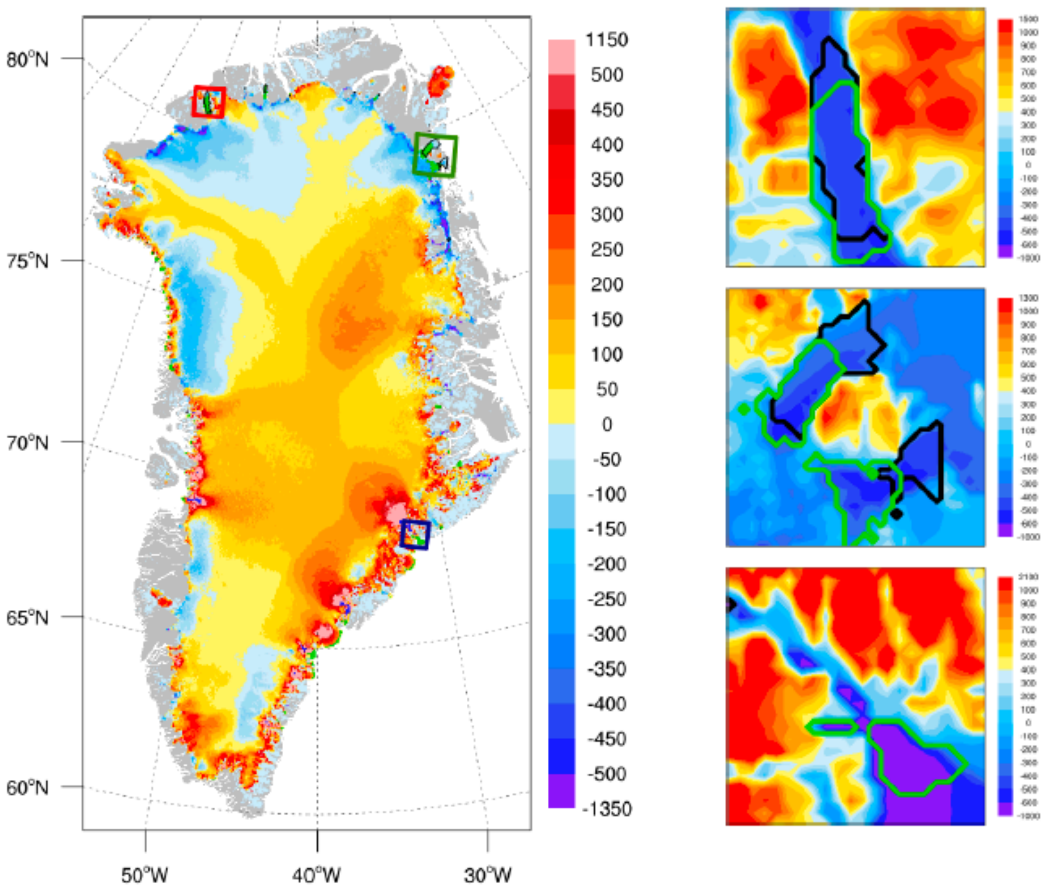
Synthesis of Greenland's basal thermal state from MacGregor et al. (2016)



Basal water depth (m) in CISM:
blue = frozen (no basal water),
red = thawed (water present).

CISM2: Greenland with floating ice shelves

- CISM can simulate Greenland's floating ice shelves, but requires careful tuning and generates some unrealistic shelves



Left: Model minus observed thickness (m) for a Greenland spin-up with ice shelves. Boxes show regions highlighted at right.

Right: Observed ice shelf outlines (**black**) and simulated outlines (green) for termini of Petermann Glacier (top), Northeast Greenland Ice Stream (center), and Kangerlussuaq Glacier (bottom).

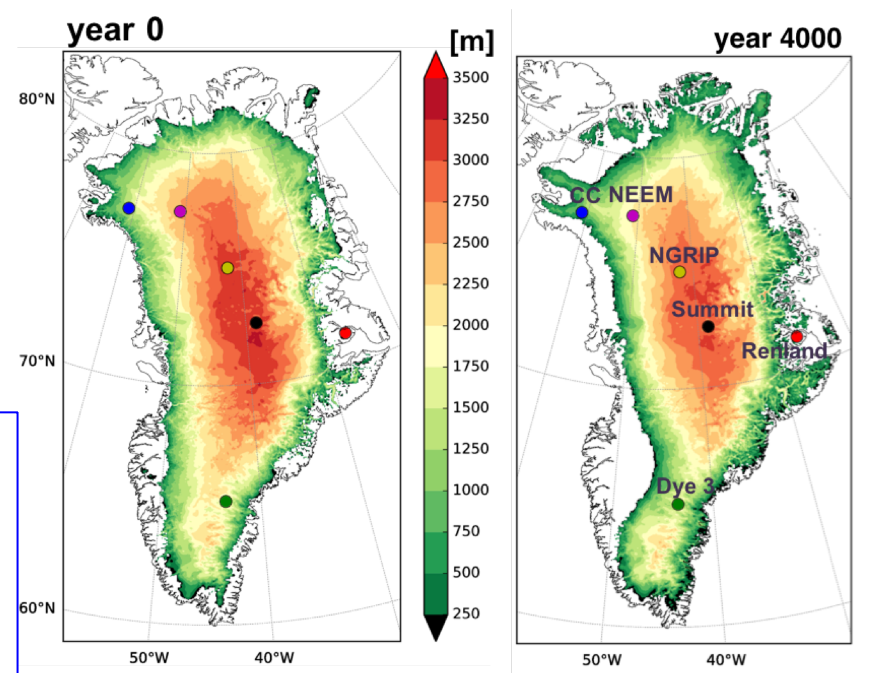
Paleo Greenland ice sheet

Studying the long term evolution of the climate and Greenland Ice Sheet during the Last Interglacial (Bette Otto-Bliesner, Marcus Lofverstrom, et al.)

- Last Interglacial, 127-116 ka: Stable GHG concentrations similar to late Holocene; continental and oceanic configurations almost identical to modern
- Early results: CISM1 (4km) coupled to CESM1.5 (FV1x1)
- Will be repeated with CESM2/CISM2; one-way and two-way ice sheet coupling

- ~ Thickness change at ice cores

CampCentury	-450m
NEEM	-400m
NGRIP	-200m
Summit	-40m
Renland	+20m
Dye 3	-200m



Ice thickness comparison from early LIG (128-124 ka)

CISM in CESM2

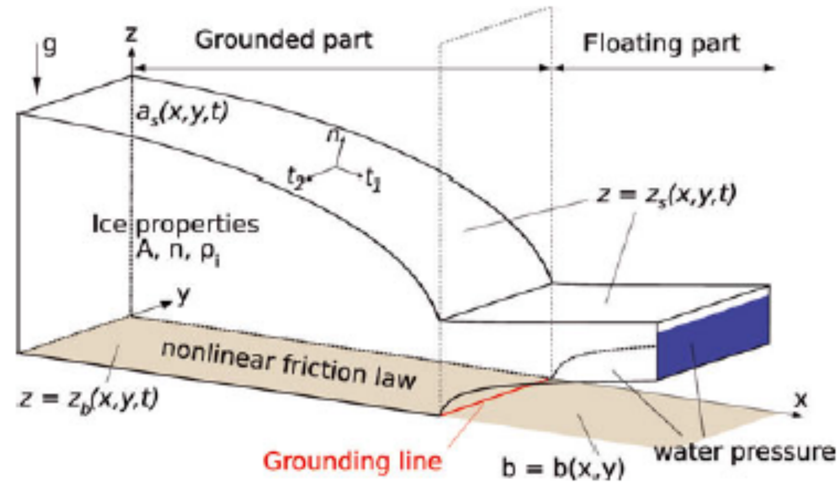
- For most standard configurations, CISM is set to **no-evolve**
  - Ice sheets are fixed, and the SMB is computed for all glaciated cells
  - User can specify single v. multiple/virtual elevation classes
- CISM can evolve with **one-way coupling**
  - SMB and surface temperature from CLM to CISM
  - Fixed elevation and surface types in CLM
- CISM and CLM can co-evolve with **two-way coupling**
  - Ice sheet extent and elevation are passed from CISM to CLM
  - Dynamic landunits in CLM (glacier ⇔ vegetated)
- Out-of-the-box Greenland settings:
  - 4 km grid, dt = 0.25 yr
  - Depth-integrated velocity solver (DIVA)
  - Pseudoplastic basal sliding with local till
  - No ice shelves (floating ice calves instantly)
  - Other settings optimized from standalone runs
- Simulations with a dynamic Antarctic ice sheet are not yet supported; this is a goal for CESM3.

Current and future CISM development

- **Grounding-line parameterizations** for basal stress and sub-shelf melting (complete)
- **Inversion for basal sliding parameters and subshelf melt rates**
  - Now being tested for Antarctic simulations
- **Damage-based calving scheme**
  - Damage evolves in response to stress, surface mass balance, and basal mass balance; under development
- **Sub-shelf plume model**
  - Inexpensive steady-state model of 2D circulation and melt rates beneath ice shelves; under development
- **Hydrofracture** (leading to calving and shelf breakup)
- **Evolutionary basal hydrology**
- **Code speedup** (to support 1–2 km resolution for whole ice sheets)

Marine Ice Sheet Model Intercomparison Project

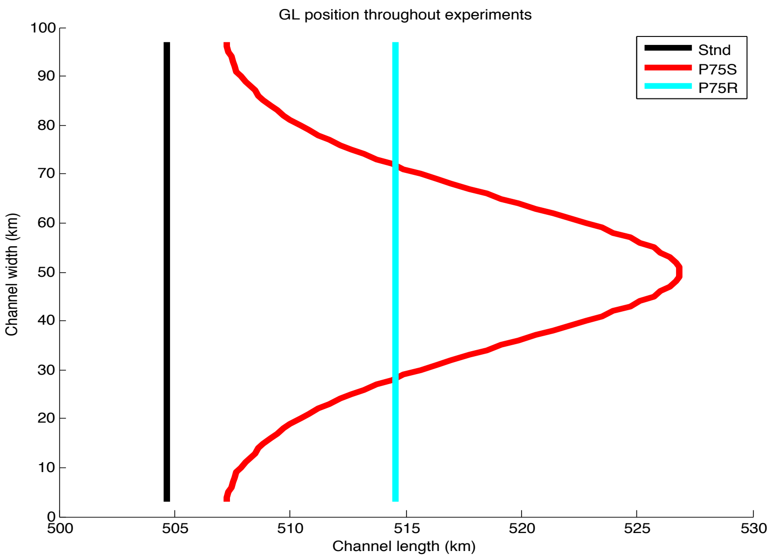
- MISMIP consists of idealized experiments that test a model's ability to track grounding-line advance and retreat. Does the GL return to its stable starting position?

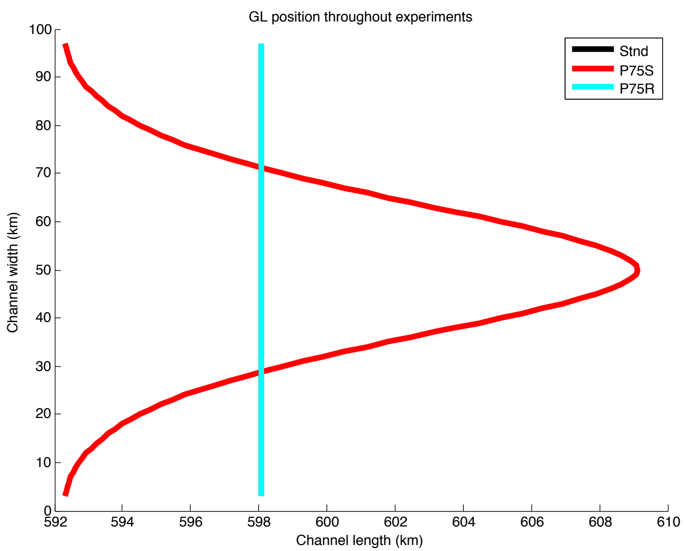


- **MISMIP3d** (Pattyn et al. 2013)
  - Perturbed basal sliding parameters give lateral variation and buttressing, with curved grounding lines
- CISM uses a **grounding line parameterization** (GLP) to resolve subgrid variations in basal friction
  - This allows us to model grounding lines accurately at practical resolutions (~1–2 km)

MISMIP3d: Applied basal perturbation

Start from steady state; run for 100 years with basal perturbation; turn off perturbation and return to steady state.





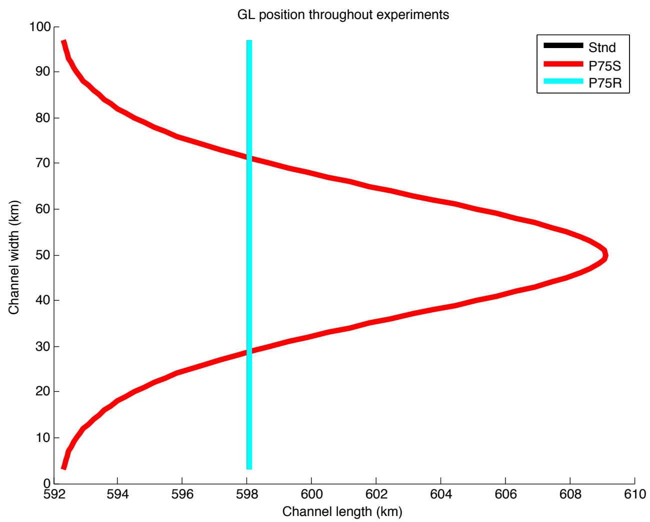
SSA without GLP (1 km):
GL too far retreated at start (504 km) and fails to return

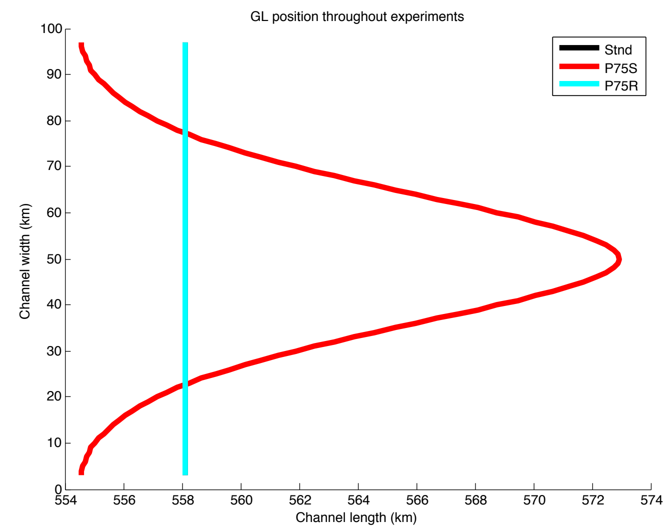
SSA with GLP (1 km):
GL returns to start position (598 km), close to analytic solution (612 km)

Black = starting position; **red** = advance; **lt. blue** = return

MISMIP3d: Applied basal perturbation

- SSA grounding line is close to analytic 1D solution.
- DIVA and BP results are close to benchmark Stokes solution.





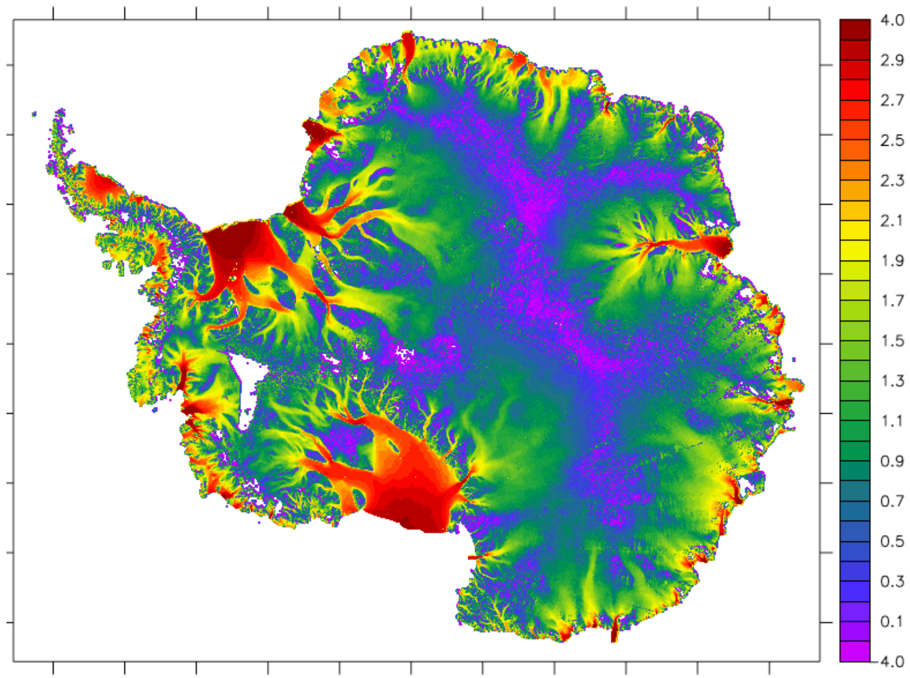
SSA with GLP:
GL returns to start position (598 km), close to analytic solution (612 km)

DIVA with GLP:
GL returns to start position (558 km); ice is softer with vertical shear stresses

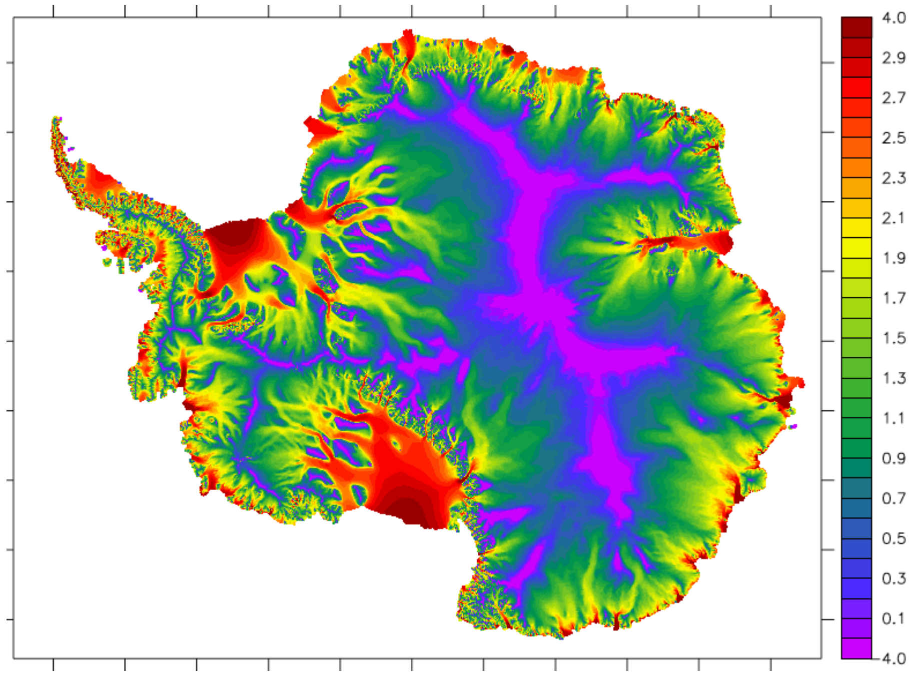
Black = starting position; **red** = advance; **light blue** = return

Inversion for basal parameters

- The goal is to spin up Antarctica to a steady state consistent with modern observations, given a prescribed SMB from RACMO.
- Method: Nudge basal traction parameters (for grounded ice) and sub-shelf melt rates (for floating ice) to match observed ice thickness.



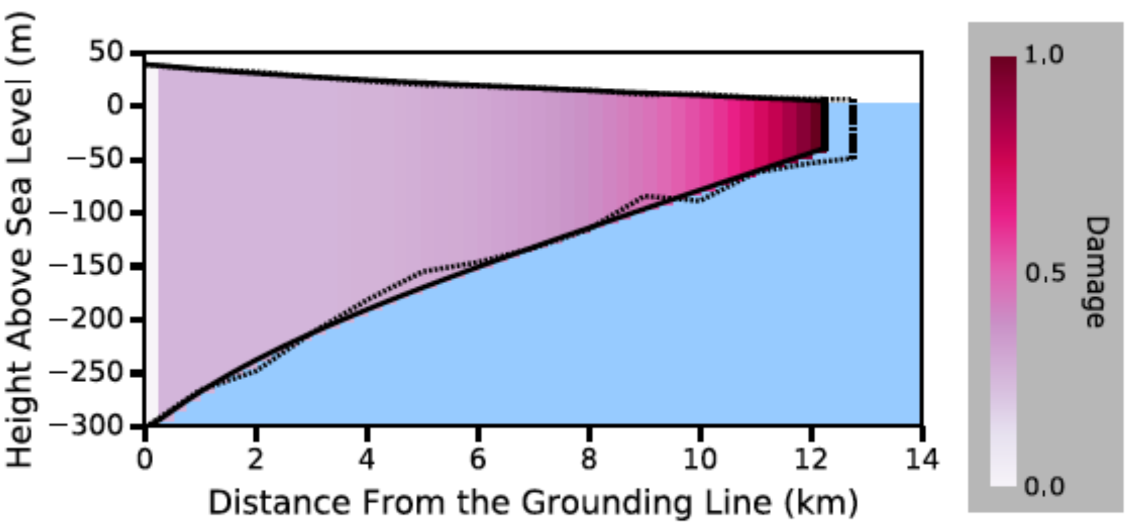
Observed surface speed for Antarctica (m/yr, log scale)



Modeled surface speed in CISM with inversion (m/yr, log scale)

Damage-based calving

- DOE collaboration to develop a damage-based calving model: U. Michigan (J. Bassis, M. Whitcomb), LANL
- Ice is described by a damage tracer representing crevasse depth. Calving occurs when D = 1.
- Tensile stress and basal melting open crevasses; gravitational forces close crevasses.
- Model applied to observed ice streams and ice tongues: Erebus, Drygalski, Pine Island, Petermann



Modeled damage of Erebus Ice Tongue, compared to observed thickness profile. Courtesy of M. Whitcomb.

Sub-shelf melting

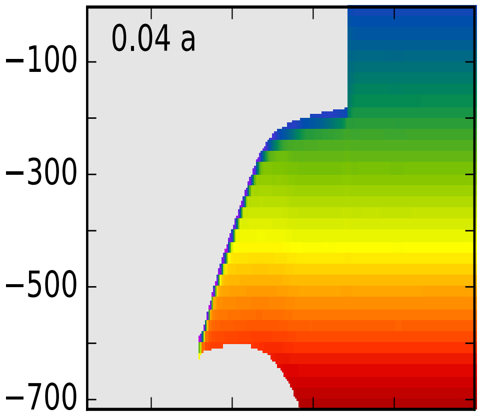
- Sub-shelf melt rates are sometimes parameterized as a function of depth, failing to capture the spatial structure of melting.
- It is expensive to run ocean GCMs beneath ice shelves (required grid resolution ~2 km), and not all ocean models have this capability.
  - POP grid has a vertical wall at the shelf edge.
  - MOM6 has been run with ocean cavities, but not yet operational for global simulations.
- Can we estimate sub-shelf melt rates with a model of intermediate complexity?

Plume model

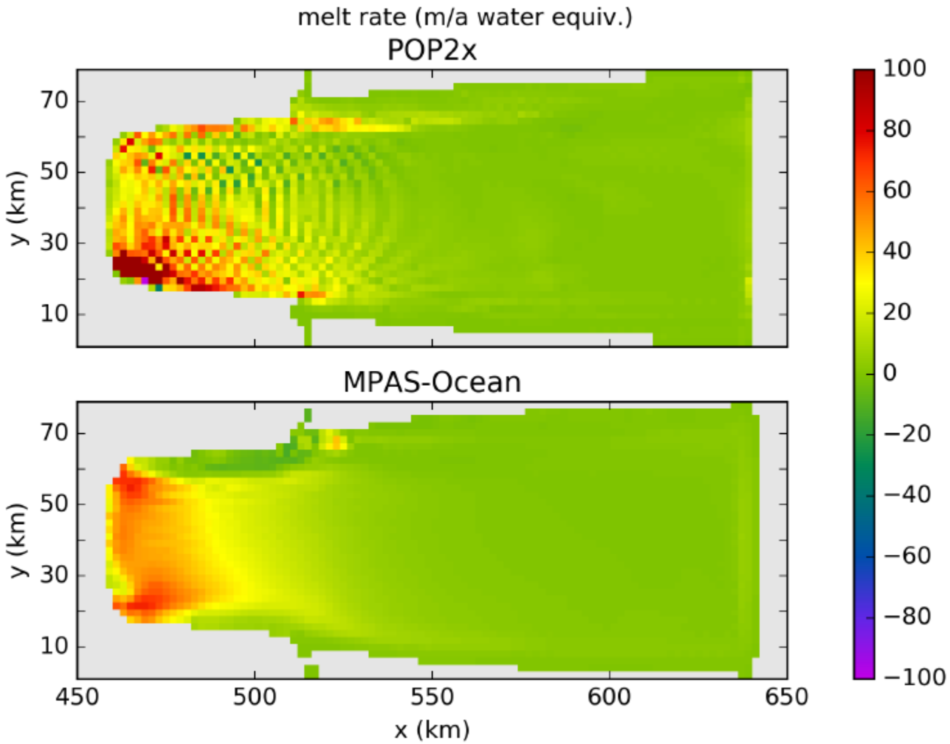
- Holland, Jenkins & Holland (2008) modeled ocean flow in the cavity beneath a static ice shelf. They suggested that ocean GCM results can be explained in terms of a **steady-state plume model**.
- The plume is a well-mixed, buoyant layer at the ice shelf base, with thickness *D,* temperature *T,* salinity *S*, and velocity ***u*** = (*u,v*).
- We are given the cavity geometry (shelf base, bed topography) and the ambient temperature and salinity T_a and S_a.
- Plume melt rates in ISOMIP+ experiments (Asay-Davis et al. 2016) are broadly comparable to results from ocean GCMS.

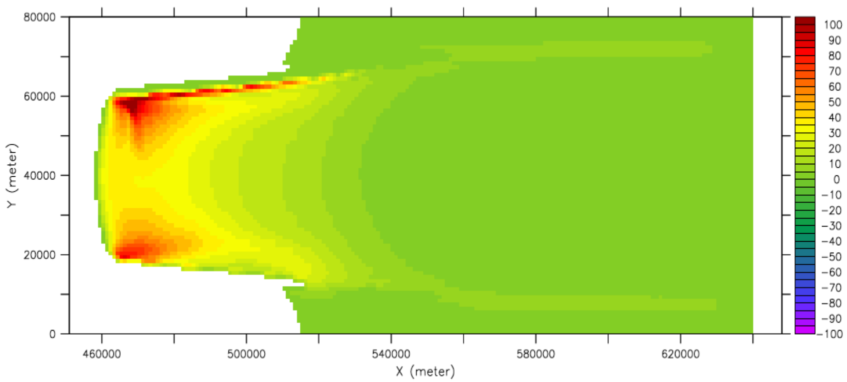
ISOMIP+ ambient ocean profile:

- T_0 = -1.9°C, T_{bot} = 1.0°C
- S_0 = 33.8 psu, S_{bot} = 34.7 psu



Basal melt rate





Plume model

- Preliminary ISOMIP+ results from POP2X and MPAS-Ocean, courtesy of X. Asay-Davis
- Largest melt rates tend to be in NW and SW corners of the deep cavity
- Plume model and MPAS-Ocean are less noisy than POP2x (noise associated with z-grid stair-stepping)

Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6)

- ISMIP6 is a new targeted activity of the Climate and Cryosphere (CliC) project of the World Climate Research Program.
  - *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
- The LIWG plans to run ISMIP6 standalone experiments with CISM (for both ice sheets) and coupled experiments with CESM (for Greenland).

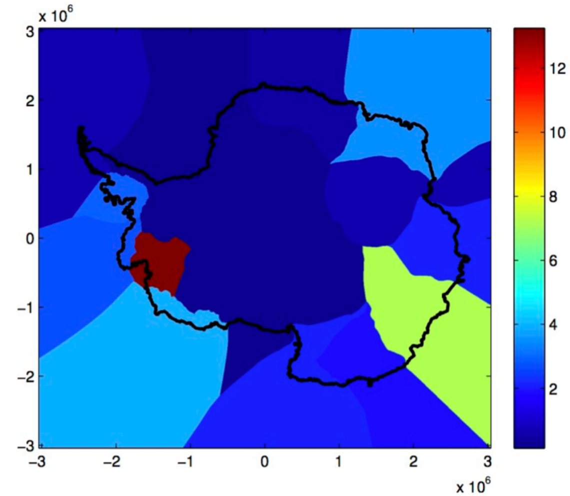
Ice sheet intercomparison projects

- **initMIP-Greenland** (led by Heiko Goelzer) and **initMIP-Antarctica** (led by Helene Seroussi), part of ISMIP6, http://www.climate-cryosphere.org/
  - Ice sheet response to initialization (GIS and AIS), SMB anomaly (GIS and AIS) and basal melt rate anomaly under ice shelves (AIS).

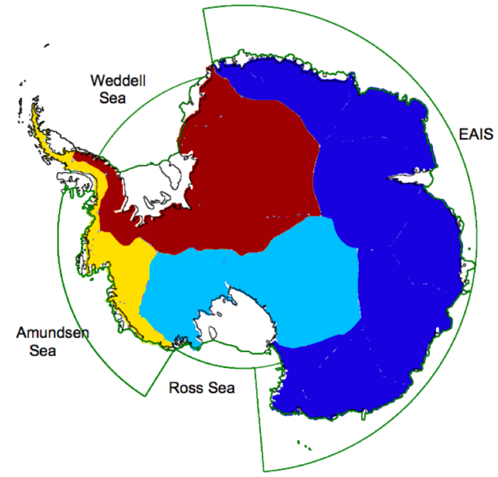
- **LARMIP** (Linear Antarctic Response MIP, https://www.pik-potsdam.de/larmip, suggested by Anders Levermann and Ricarda Winkelmann)
  - Linear response of Antarctic Ice Sheet to basal ice shelf melting. Apply basal melt rate under ice shelves in 4 sub-regions (1-32 m/a)

- **ABUMIP** (Antarctic Buttressing MIP, suggested by Franck Pattyn and Nicholas Golledge):
  - Ice sheet response to (1) complete loss of ice shelves and (2) extreme ice shelf melting

- CISM has participated in all these MIPs



Basal melt rates for initMIP-Antarctica (above) and LARMIP (below)



Experimental design for ISMIP6

1. **Existing CMIP6 experiments** to be analyzed in terms of ice sheet forcing

CMIP6 exp to be used by ISMIP6 (all AOGCM)
- Pre-industrial control
- AMIP
- 1% per yr CO_2 to $4xCO_2$
- Abrupt $4xCO_2$
- CMIP6 Historical Simulation
- ScenarioMIP RCP8.5/SSP5x (up to year 2300)
- Last Interglacial PMIP

2. **Standalone ice sheet experiments** based on CMIP6 model output to estimate past and future sea level rise, and explore uncertainty due to ice sheets

Standalone ISMIP6 exp (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 21^{st} / 23^{rd} century (RCP8.5/SSP5x)
- ISM for Last Interglacial
- ISM specific experiments to explore uncertainty

3. **Coupled AOGCM-ISM experiments** to explore impacts and feedbacks due to ice sheets

New proposed ISMIP6 exp (coupled AOGCM-ISM)
- Pre-industrial control
- 1% per yr CO_2 to $4xCO_2$
- Scenario RCP8.5/SSP5x (to year 2300)

ISMIP6 coupled climate simulations

"The aim is to produce a realistic non-drifting coupled state."

Preindustrial AOGCM/ISM spin-up

- piControl forced ISM
- 1pctCO2 forced ISM
- ssp5-8.5 forced ISM
- piControl with ISM
- 1pctCO2 with ISM
- ssp5-8.5 with ISM

forced ISM = standalone ice sheet model forced with AOGCM output

with ISM = ice sheet model interactively coupled to AOGCM

Summary

- Sea-level rise is still a wide-open scientific problem, largely because of uncertainties in the dynamics of marine ice sheets.
- The CESM community—with its interdisciplinary working group structure, links to the academic community, and experience in developing CESM—is well equipped to tackle the science.
- CESM2 includes major advances over CESM1 in ice sheet dynamics, land-ice surface physics, and climate/ice-sheet coupling. It is well suited for simulations of past, present, and future Greenland ice sheet evolution.
- Coupling of Antarctica and other marine ice sheets in CESM is still in the early stages.

Land Ice Working Group info

Web page: http://www.cesm.ucar.edu/working_groups/Land+Ice/

Liaisons: Gunter Leguy (gunterl@ucar.edu) and Bill Sacks (sacks@ucar.edu)

Co-chairs: Jan Lenaerts (Jan.Lenaerts@colorado.edu) and Bill Lipscomb (lipscomb@ucar.edu)

Upcoming meetings:

- Winter LIWG meeting, Boulder, week of February 4-8, 2019
- 24th annual CESM workshop, 17-20 June 2018