Ice Sheet Modeling and Sea Level Rise

William Lipscomb, NCAR
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Ice sheets in IPCC AR4

- The IPCC Fourth Assessment Report (AR4) projected 0.18 to 0.59 m of sea level rise in the 20th century, "*excluding future rapid dynamical changes in ice flow*."

- "Larger values cannot be excluded, but understanding of [ice sheet dynamical] effects is too limited to assess their likelihood or provide a best estimate or upper bound for sea level rise."

- Bottom line: Ice sheet models were inadequate. Most models at the time used the **shallow-ice approximation** (SIA; valid for slow-flowing interiors) or **shallow-shelf approximation** (SSA; valid for floating ice shelves), without including the full range of internal stresses.

Ice sheet modeling advances

- After AR4, new ice sheet models (Elmer-Ice, ISSM, PISM, Penn State, BISICLES, CISM, MPAS Landice,...) were developed and released, with some or all of these features:
  - Higher-order velocity solvers (Stokes, Blatter-Pattyn, depth-integrated, hybrid)
  - Parallel models on unstructured or adaptive grids
  - Accurate treatment of grounding lines
  - More realistic physics (basal sliding, iceberg calving, etc.)
- Regional models (RACMO, MAR) were developed to better simulate ice sheet surface mass balance (SMB).
- Dynamic ice sheet models were added to several global climate models, including CESM (mostly 1-way coupling).

Ice sheets in IPCC AR5

- "**Confidence in projections of global mean sea level rise has increased since the AR4** because of the improved physical understanding of the components of sea level, the improved agreement of process-based models with observations, and the inclusion of ice-sheet dynamical changes."
- 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)
  - **Up to 0.98 m** by 2100 (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.

Ice sheets in CESM

2009: CESM Land Ice Working Group formed

Start of DOE ISICLES project: development of Glimmer Community Ice Sheet Model, BISICLES and other models

2010: Release of CESM1.0 with Glimmer-CISM (serial SIA; 1-way Greenland coupling; multiple elevation classes in CLM)

2011: Bill Sacks becomes LIWG software liaison

2013: First published evaluations of ice sheets in CESM1

2014: CISM2 release (parallel, higher-order dynamics)

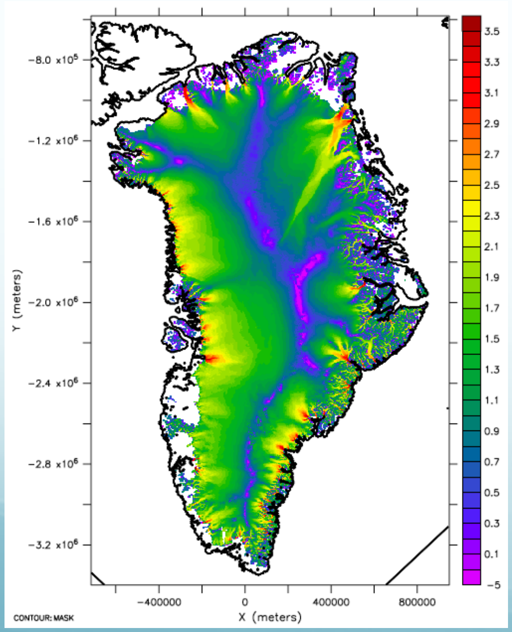
2016: NSF Supplemental: supports land-ice modeling at NCAR

2017: New land-ice hires (Lipscomb, Leguy)

2018: CESM2 release with CISM2.1

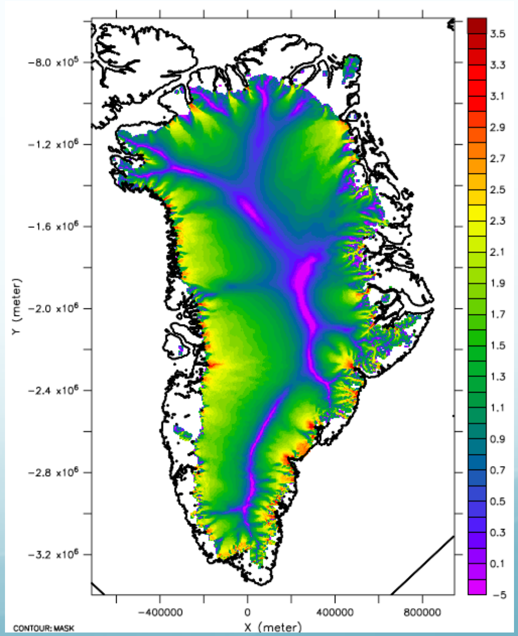
Ice sheets in CESM2

- The CESM2 release will include CISM2.1 (more capable than the original Glimmer-CISM in CESM1)
- By default, CLM computes a surface mass balance for ice sheets in multiple elevation classes (Jan's talk)
- CESM2 will supports 1-way or 2-way coupling to a dynamic Greenland ice sheet
- Dynamic Antarctic coupling deferred to CESM3



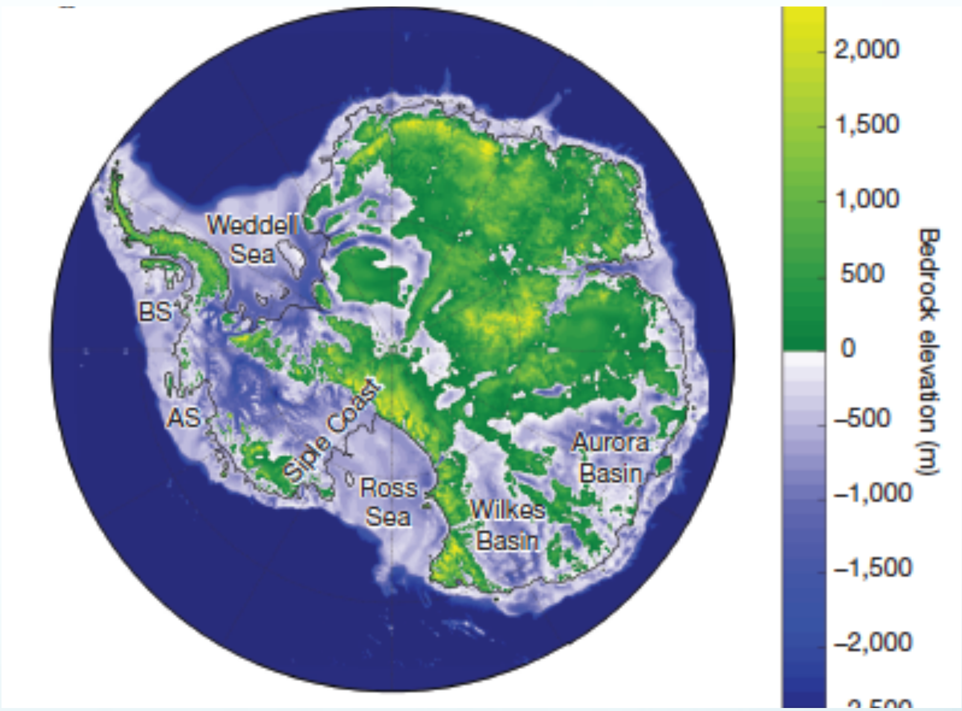
Left: Observed Greenland ice surface speed (m/yr, log scale).

Right: Modeled speed in CISM



Antarctic ice sheet instability

- Most of the West Antarctic Ice Sheet (WAIS) and large parts of the East Antarctic Ice Sheet (EAIS) are grounded below sea level.
- ~5 m sea-level equivalent in marine-based part of WAIS, ~20 m in marine-based part of EAIS
- *Marine ice sheet instability*: Flow on a reverse-sloping bed (upward in direction of ice flow) can be dynamically unstable.

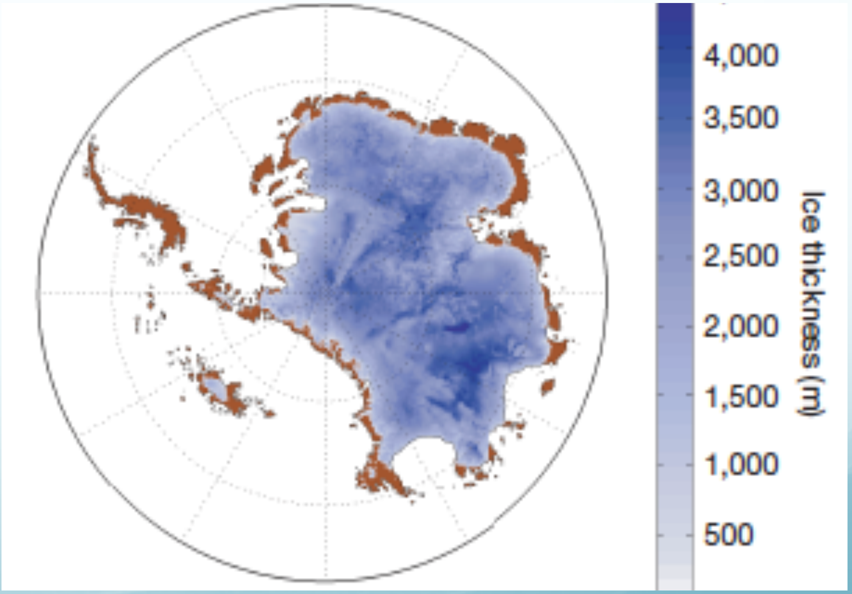


Antarctic ice sheet instability

- Pollard & DeConto (2016) introduced new mechanisms for Antarctic ice sheet retreat: **marine ice cliff instability (MICI) and ice-shelf hydrofracture** (driven by atmospheric warming).
- Retreat is much faster than previous projections (and more consistent with Pliocene and Last Interglacial paleo records):
  - **RCP4.5**: *32 cm by 2100*, *5 m by 2500*
  - **RCP8.5**: *77 cm by 2100*, *12 m by 2500*

Caveats:

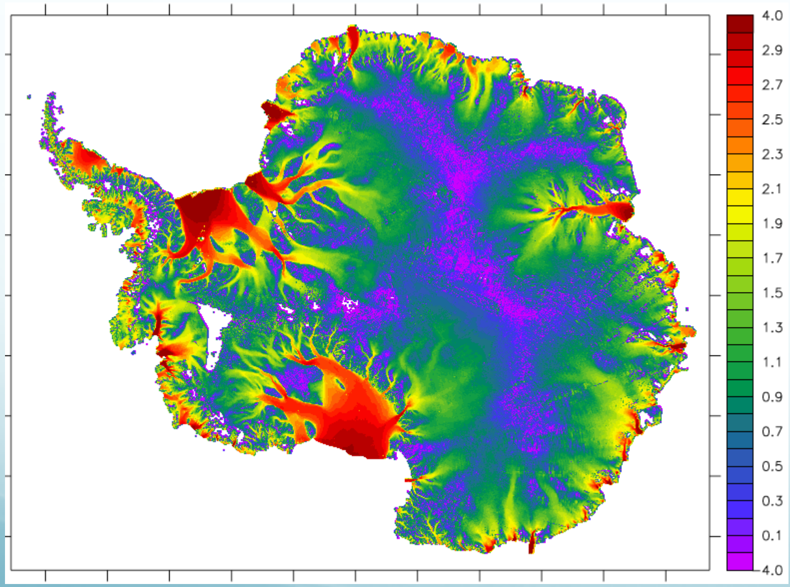
- Coarse resolution (10 km)
- Highly parameterized physics
- Crude ocean melt rates



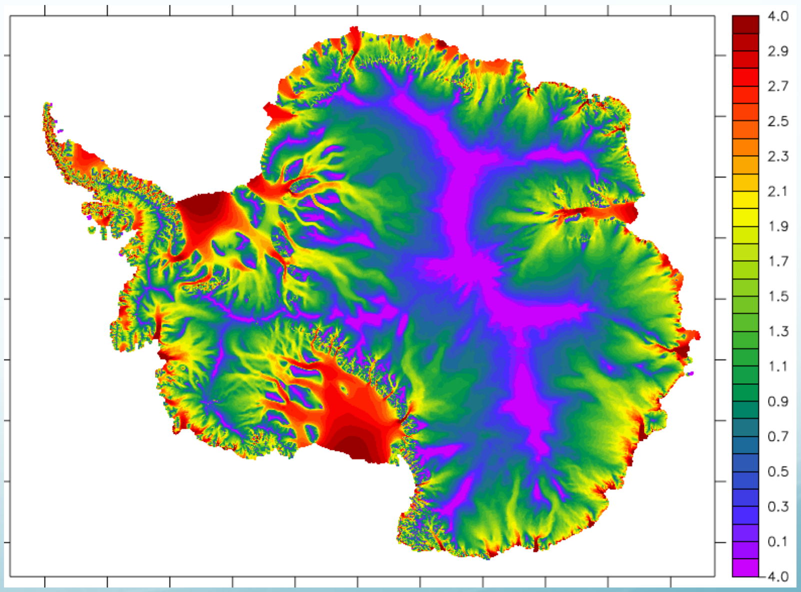
Modeled ice thickness (m) in 2500, RCP8.5

CISM Antarctic simulations

- **initMIP-Antarctica**: standalone Antarctic Ice Sheet simulations with CISM at resolutions of 4 and 8 km
- **Spin-up**: Run to quasi-steady state with prescribed SMB, relaxing toward observed thickness by inverting basal friction (for grounded ice) and sub-shelf melt rates (for floating ice).
- **Sensitivity experiments**: Apply a melt rate anomaly based on observations or a regional ocean model.



Observed surface speed (m/yr, log scale)



Modeled surface speed with inversion

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 experiment

Experimental design for ISMIP6

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

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

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

CMIP6 expts 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

Standalone ISMIP6 expts (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

New proposed ISMIP6 expts (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

Challenges ahead

- Continue developing CISM for whole-ice-sheet science applications on decadal-to-millennial time scales
  - More realistic physics (basal sliding, calving, gravity, …)
  - Code speedup to support 1–2 km resolution
- Work toward ice sheet–ocean coupling
  - Start with melt rates generated by regional ocean models
  - Fully interactive coupling down the road
- Community outreach
  - Broaden the CESM–CISM user base
  - Couple CESM to other ice sheet models (e.g., ISSM)
- Communicate risks and uncertainties to coastal stakeholders
  - *Co-production* of actionable sea-level science by managers, policy makers, scientists and funders (Beier et al. 2016)