Land Ice Modeling Update

William Lipscomb
Los Alamos National Laboratory

SSC / CAB / WG Co-Chairs Meeting
CESM Workshop
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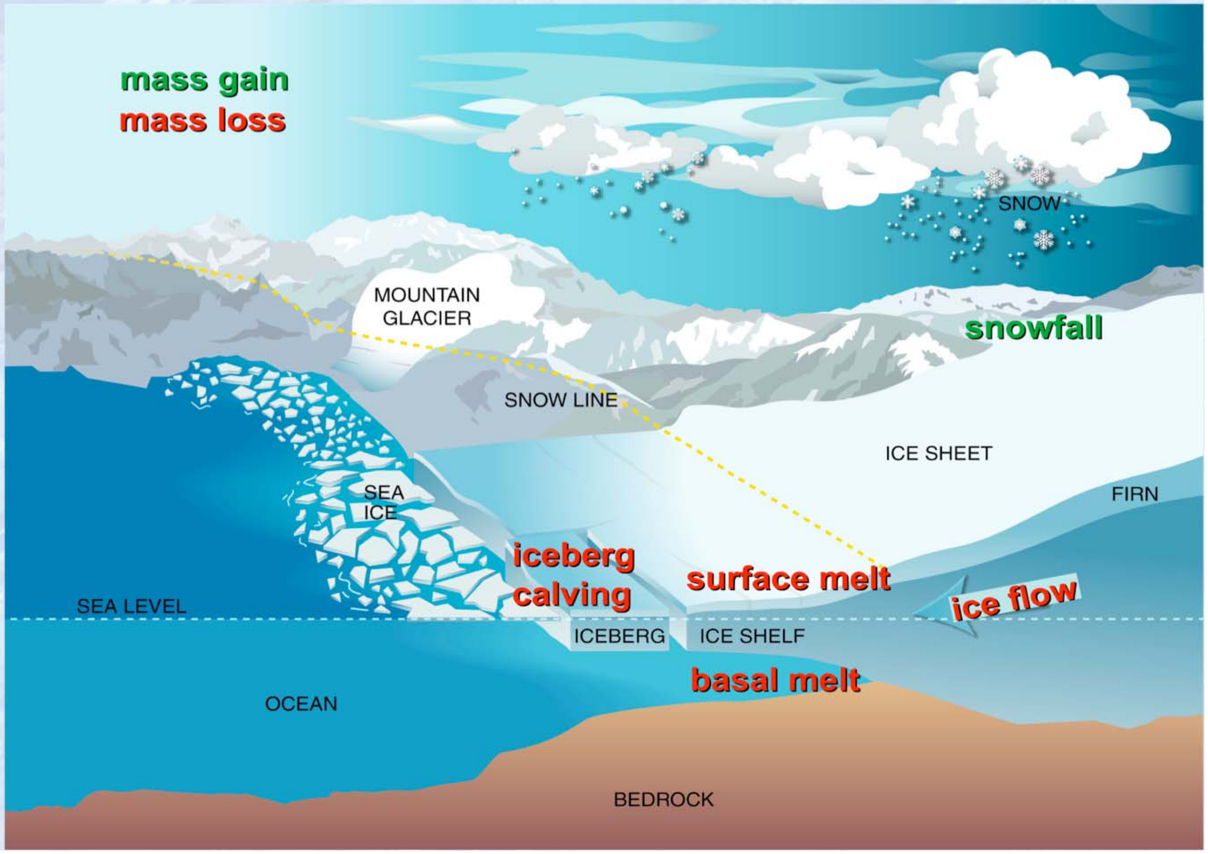
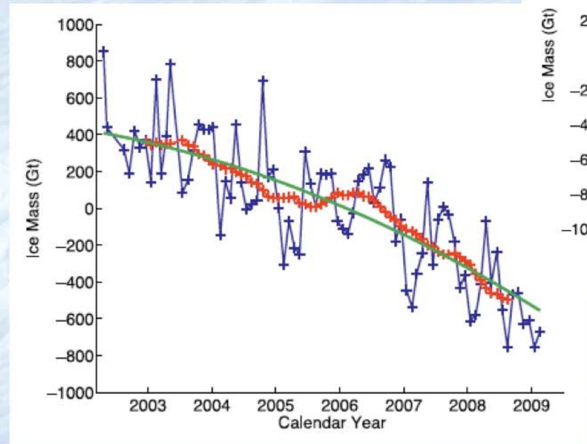
Outline

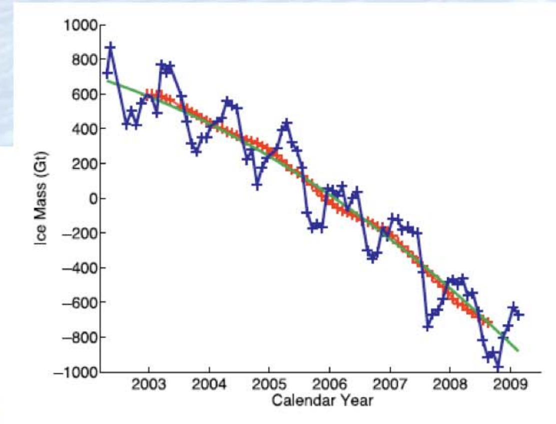
- Motivation
- Current status
  - Ice sheet model development
  - Coupling to CESM
- Future directions



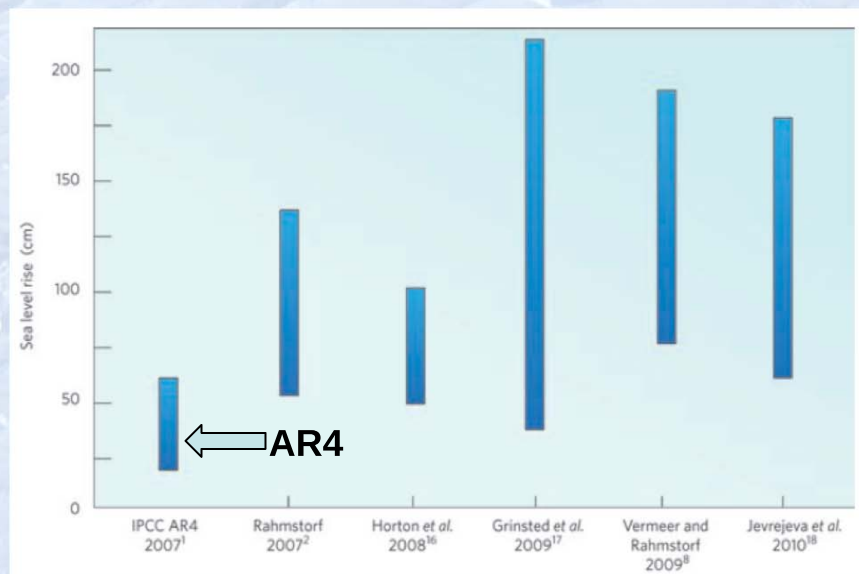
Global sea-level rise

- Global mean sea level is increasing at a rate of ~3 mm/year.
  - Ocean expansion: ~1 mm/yr
  - Glaciers and ice caps: ~1 mm/yr
  - Ice sheets: ~1 mm/yr
    - Greenland ~0.6 mm/yr
    - Antarctica ~0.4 mm/yr
- The land-ice contribution is growing and will likely continue to increase.
- The most credible current predictions are based on semi-empirical relationships that may not hold in the future.
- Realistic physical models are needed to understand changes and to better bound the range of uncertainty.





Ice mass loss from Antarctica (left) and Greenland (right), from GRACE (Velicogna 2009)



Predicted 21st century sea-level rise (Rahmstorf 2010)

Why couple ice sheets to global climate models?

As ice sheets evolve, they interact with the ocean and atmosphere in ways that modify their own evolution.

- Interactions with the atmosphere:
  - Albedo feedback: Warmer temperatures result in increased melting, darker surface, and additional warming.
  - Ice geometry feedbacks: As an ice sheet shrinks, its surface warms (temperature-elevation feedback), and regional circulation can change.
- Interactions with the ocean:
  - Sub-shelf growth and melting rates depend on time-varying interactions among various water masses, including glacier meltwater.
  - These circulations are likely to change as ice shelves advance and retreat over complex topography.

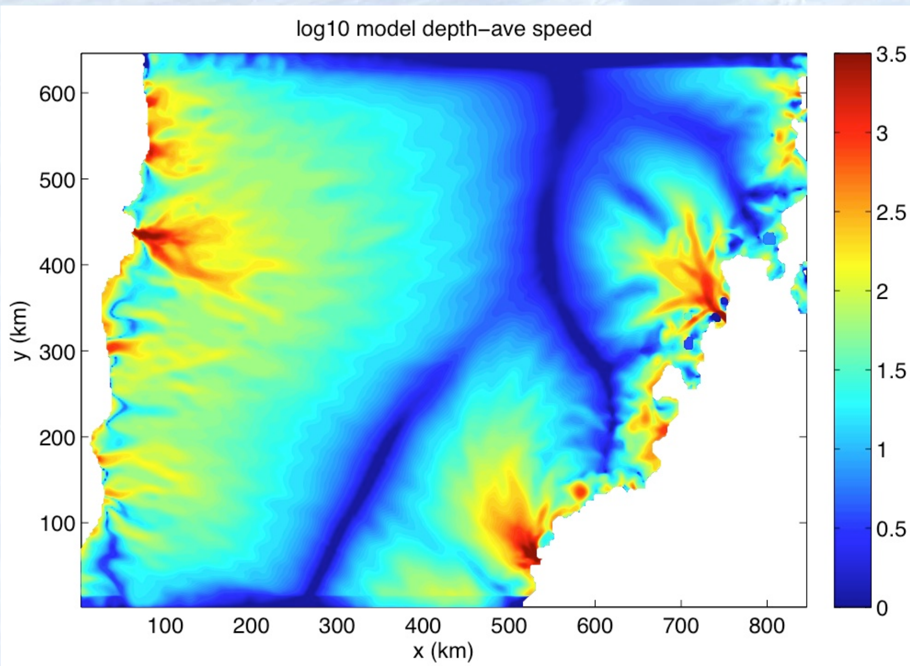
Summary

- **Ice-sheet models have improved significantly,** thanks in part to research carried out under the DOE ISICLES projects.
  - We have new dynamic cores that can solve full-Stokes and higher-order ice-flow equations on adaptive and unstructured meshes using parallel solvers.
  - We are making progress on ice-sheet physics (e.g., basal hydrology, the focus of a workshop at the winter 2011 LIWG meeting).
- **Integration of ice sheet models in CESM has been slower than expected**.
  - Ice sheets move; land/atmosphere and land/ocean boundaries are not fixed.
  - Ice sheets evolve on long time scales and short spatial scales.
  - Dynamic ice sheets therefore require significant rethinking and re-engineering of model infrastructure (new compsets, grids, spin-up methods, coupling mechanisms, etc.).
  - Progress should improve with the hiring of a new NCAR software engineer (funded by NSF) who will support the Land Ice Working Group.

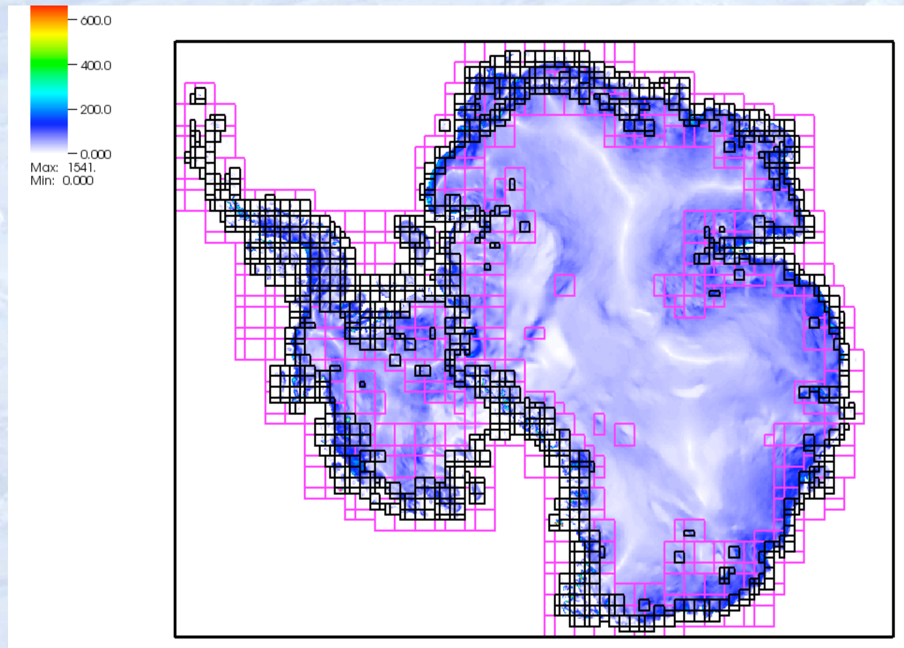
Community Ice Sheet Model (CISM)

New model version: **Glimmer-CISM 2.0**

- Includes Payne-Price higher-order ice flow model
- Uses Trilinos parallel solver library
- Other new dynamical cores under development (DOE ISICLES project)
- New repository: **svn-cism-model.cgd.ucar.edu**



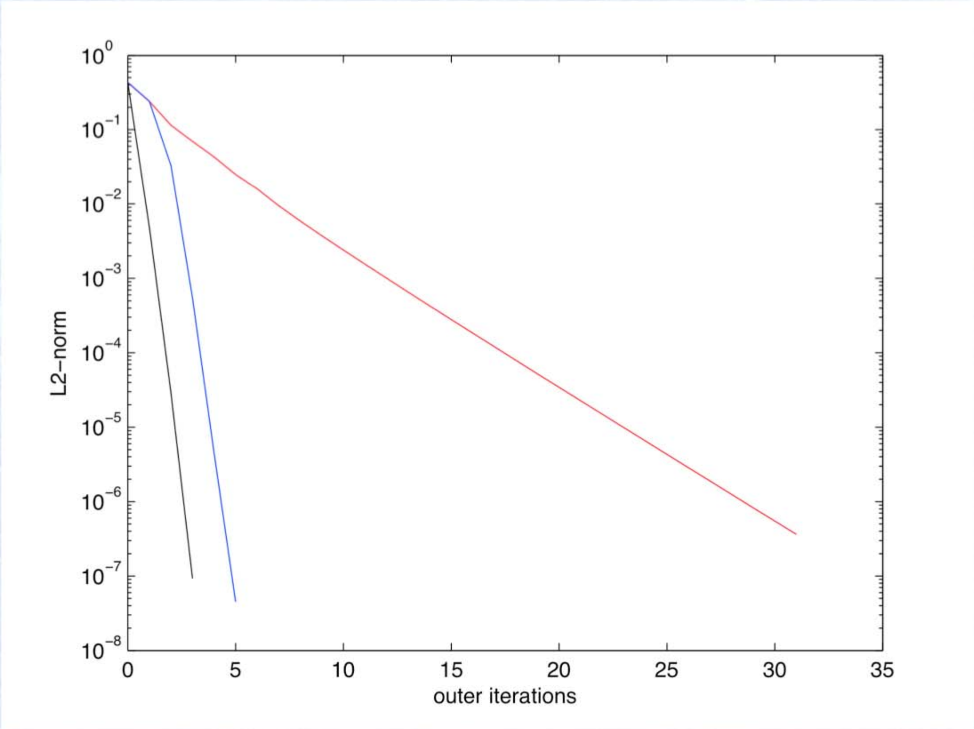
Greenland depth-averaged ice speed with 3D higher-order solver, 2-km resolution.
Model used to constrain future sea-level rise from ice-sheet dynamics (S. Price et al., 2011).



Antarctic ice speed with 2D higher-order solver on a fully adaptive mesh (10, 5, and 2.5 km) using Chombo software. (Courtesy of D. Martin)

Parallel nonlinear solver for higher-order model

- Using JFNK solver with Trilinos software to solve accurately and efficiently for highly nonlinear velocity field
- Iteration counts are reduced by an order of magnitude, solution time reduced by a factor of 2 to 3.5 for suite of test cases
- Efficient parallel scaling up to 400+ processors for test problem on jaguar; scaling now limited by remaining serial code

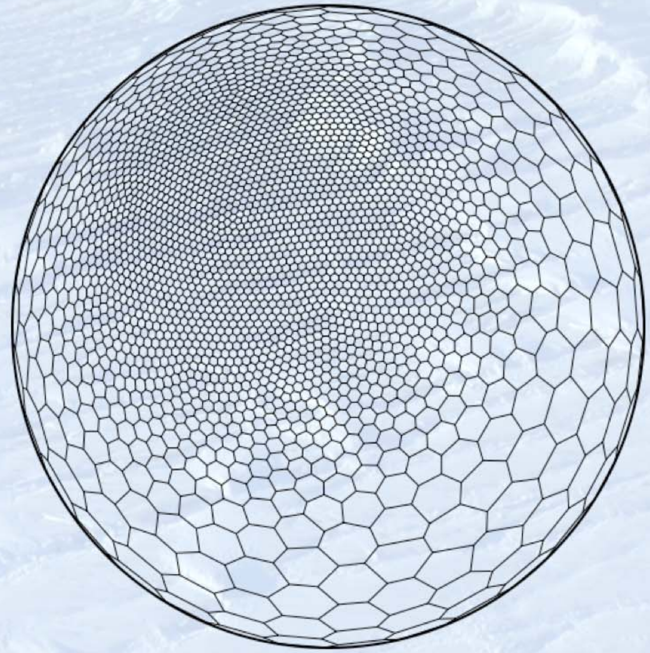


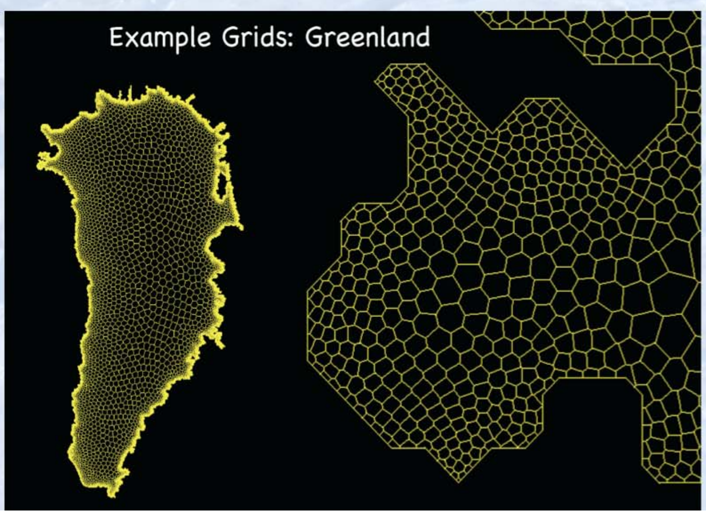
Number of iterations for 10-km Greenland problem
Red: original Picard solver
Blue: new preconditioned JFNK solver
Black: JFNK with looser initial tolerance settings
Refer to Lemieux et al. (2011)

ASCR SEACISM project: ORNL, SNL, LANL, NYU, FSU

Variable-resolution grids

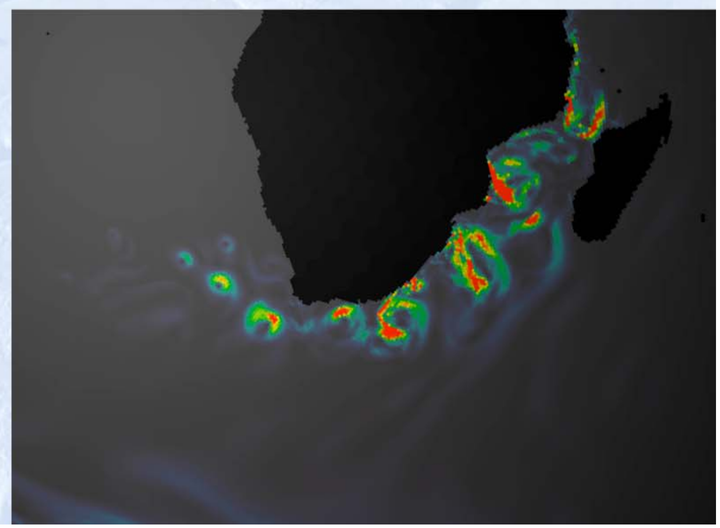
- **MPAS** (Model for Prediction Across Scales): A climate modeling framework that supports dynamical cores on unstructured Voronoi meshes
- Allows high resolution in regions of interest (e.g., ice streams, grounding lines, sub-ice-shelf cavities). Can reduce number of grid cells by a factor of ~10.
- We have begun developing an MPAS ice sheet model using methods developed at LANL and NCAR for atmosphere and ocean models.



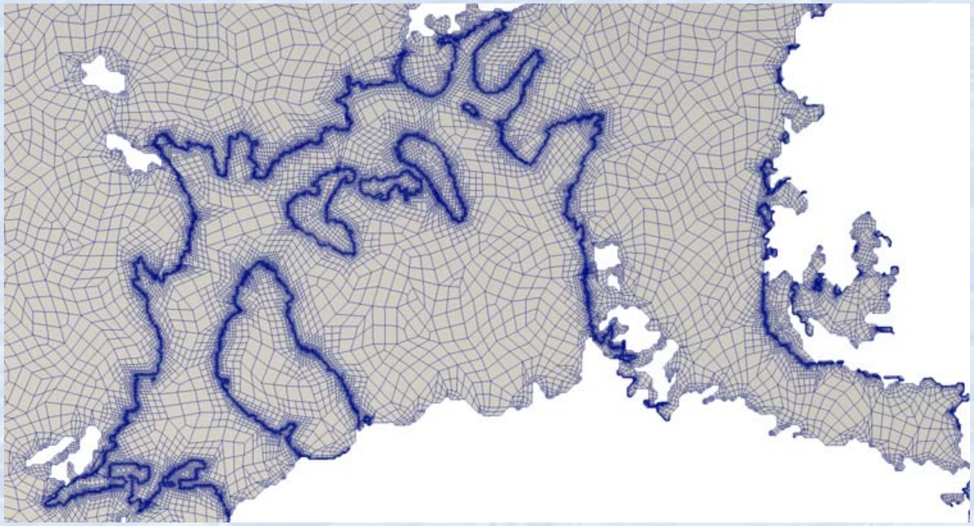


Left: Voronoi mesh for the Greenland ice sheet

Right: Global variable-resolution mesh for POP, 120 K nodes



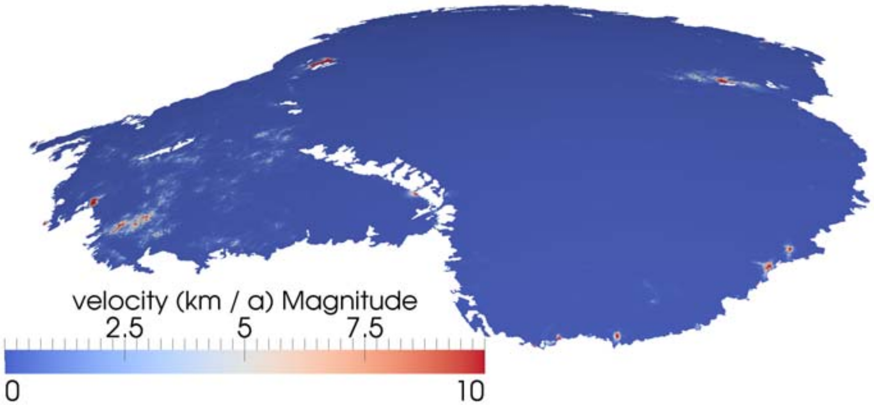
Continental-scale 3D full-Stokes ice sheet simulation



# degrees of freedom	# processors	# iterations
2.6 M	64	348
16 M	512	244
111 M	4096	214

Weak scalability of linear solver iterations for continental-scale simulations. Scalable multigrid preconditioners ensure that the number of iterations does not grow with problem size or number of processors.

- Adaptive mesh refinement for localized flow features keeps problem size reasonable
- Stable higher order finite element discretizations of the velocity and pressure variables for computational efficiency and accuracy
- Physics-based preconditioners for the linearized equations that are robust for varying flow regimes and basal conditions



UT/LANL PARADICE project

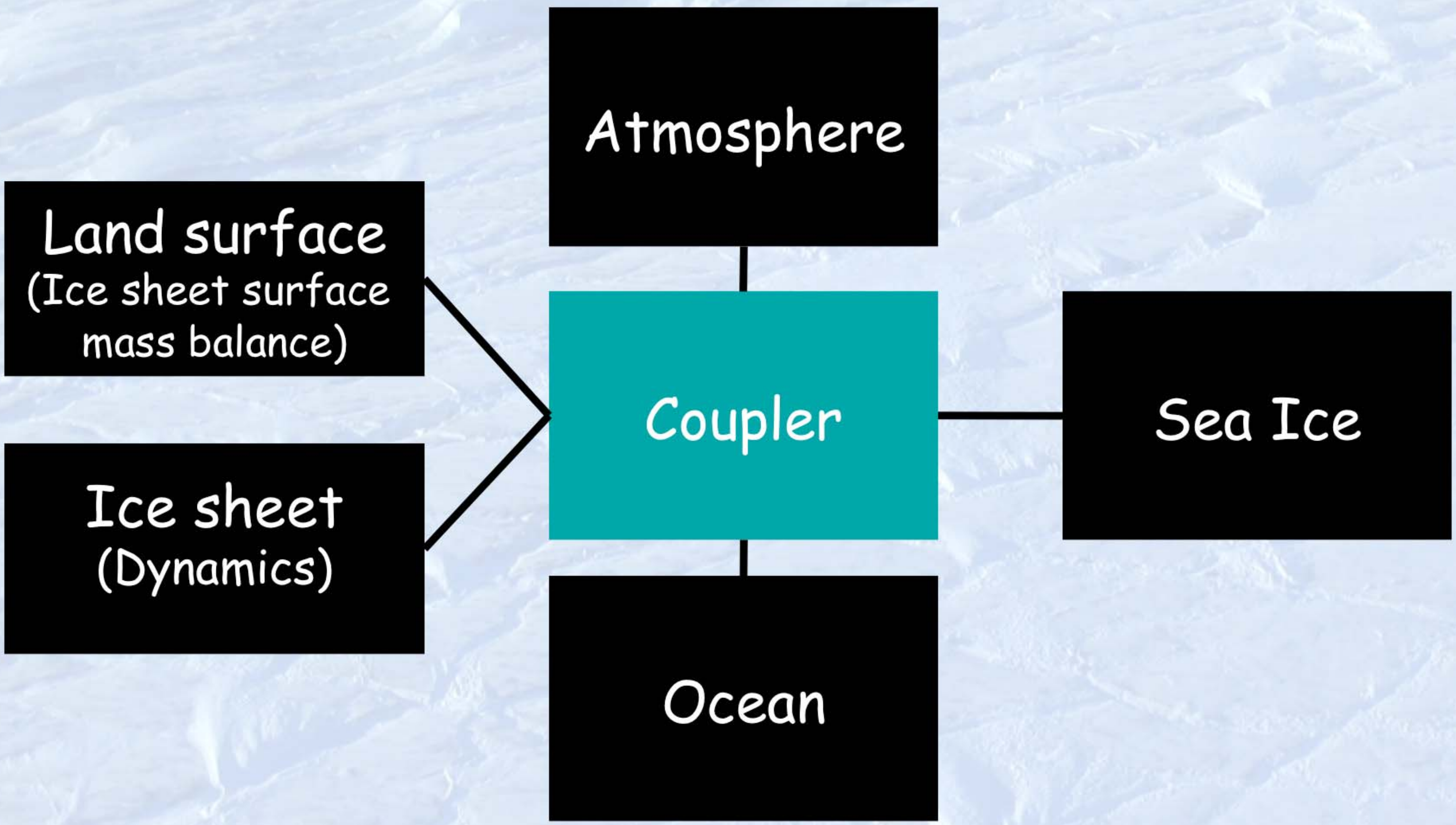
Ice sheets in CESM

Land -> Ice sheet (~10 classes)

- Surface mass balance
- Surface elevation
- Surface temperature

Ice sheet -> Land (~10 classes)

- Ice fraction and elevation
- Runoff and calving fluxes
- Heat flux to surface



Ice sheets in CESM

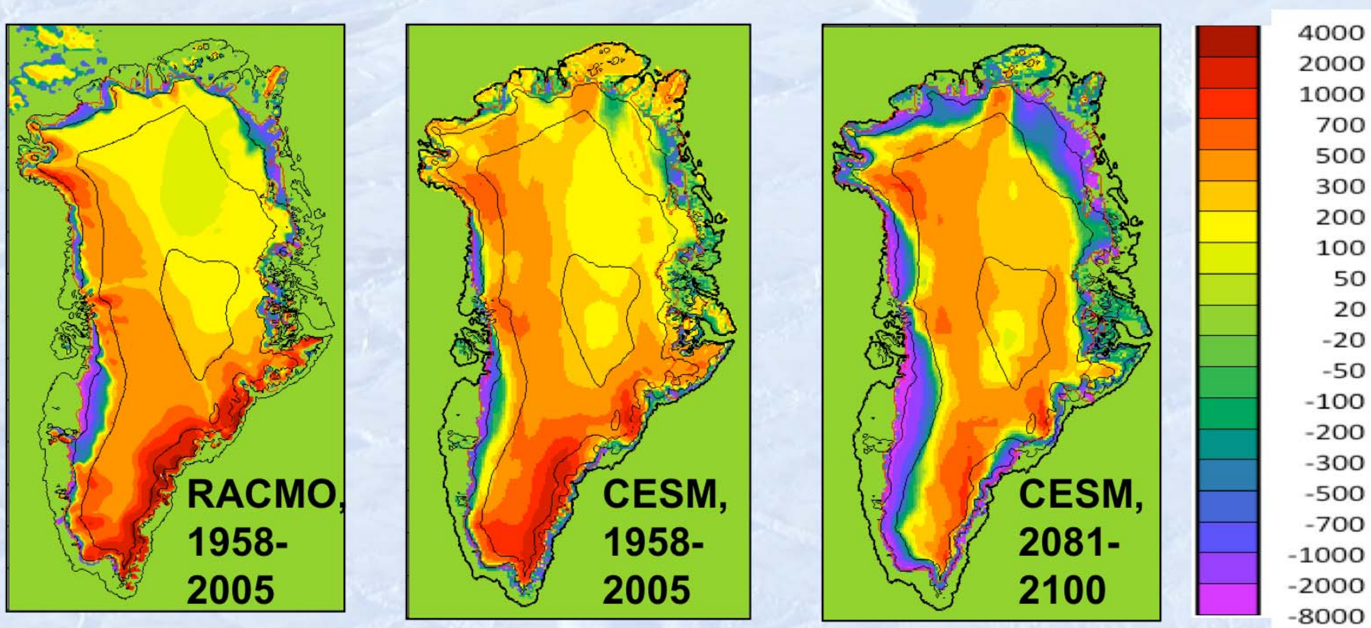
Near-term model improvements (summer 2011):

- Glimmer-CISM 2.0 for ice-sheet dynamics
- New compsets (1850, 20th century, RCP 8.5) for CMIP5 simulations
- Improved initialization data sets for Greenland and Antarctica

Longer-term development:

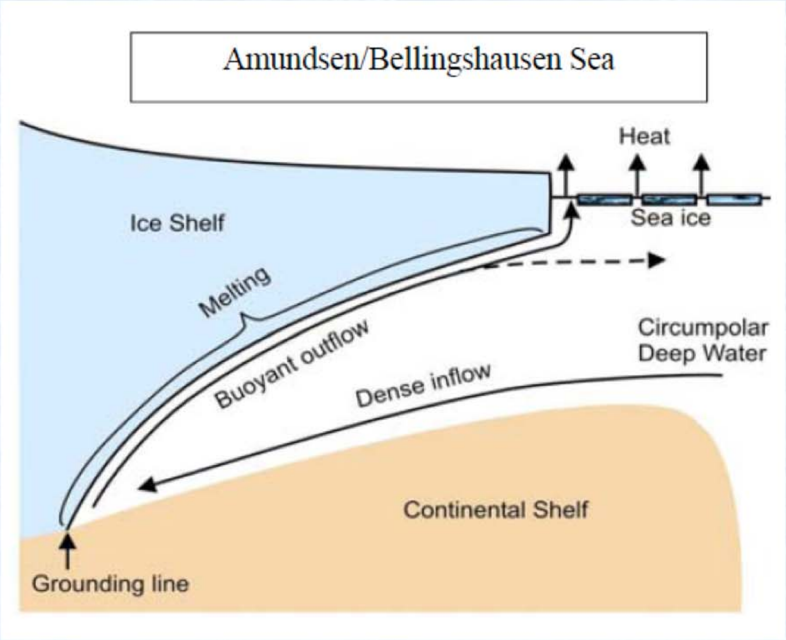
- Ice-ocean coupling with marine ice sheets (e.g., West Antarctica)
- Paleo ice sheet simulations with dynamic glacier/vegetated landunits
- Evolution of mountain glaciers and ice caps

Greenland surface mass balance (mm/yr).
Left: RACMO regional climate model.
Center: CESM, 1958-2005 mean.
Right: CESM, 2081-2100 mean, RCP8.5 scenario.
Red = net accumulation
Blue = net ablation
(Courtesy of M. Vizcaíno)

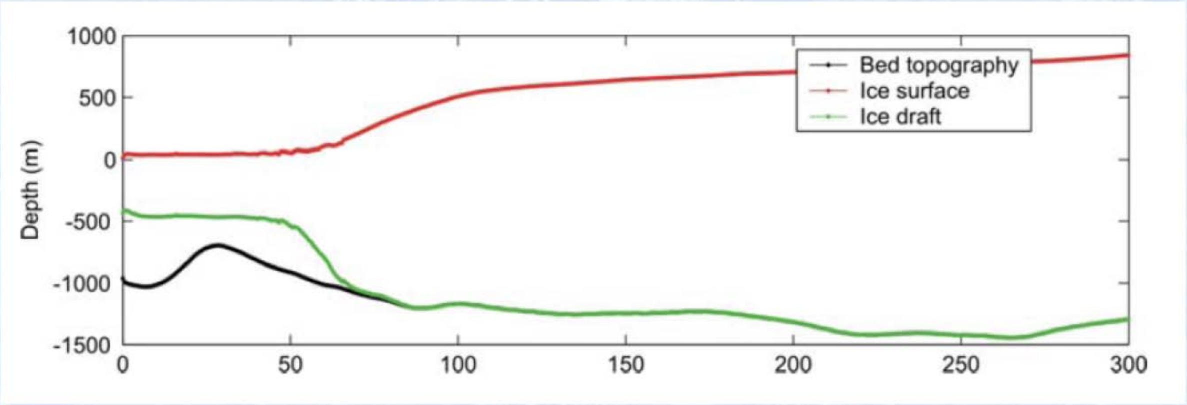


Ice-ocean coupling

- Ice in the Amundsen/ Bellingshausen region is especially vulnerable to intrusions of warm Circumpolar Deep Water. (Note reverse-sloping beds.)
- Modest changes in wind forcing could drive large changes in delivery of warm CDW to the base of the ice shelf.
- To simulate these small-scale processes, the ocean model must be able to circulate beneath ice shelves, exchanging heat and mass at the shelf boundary.



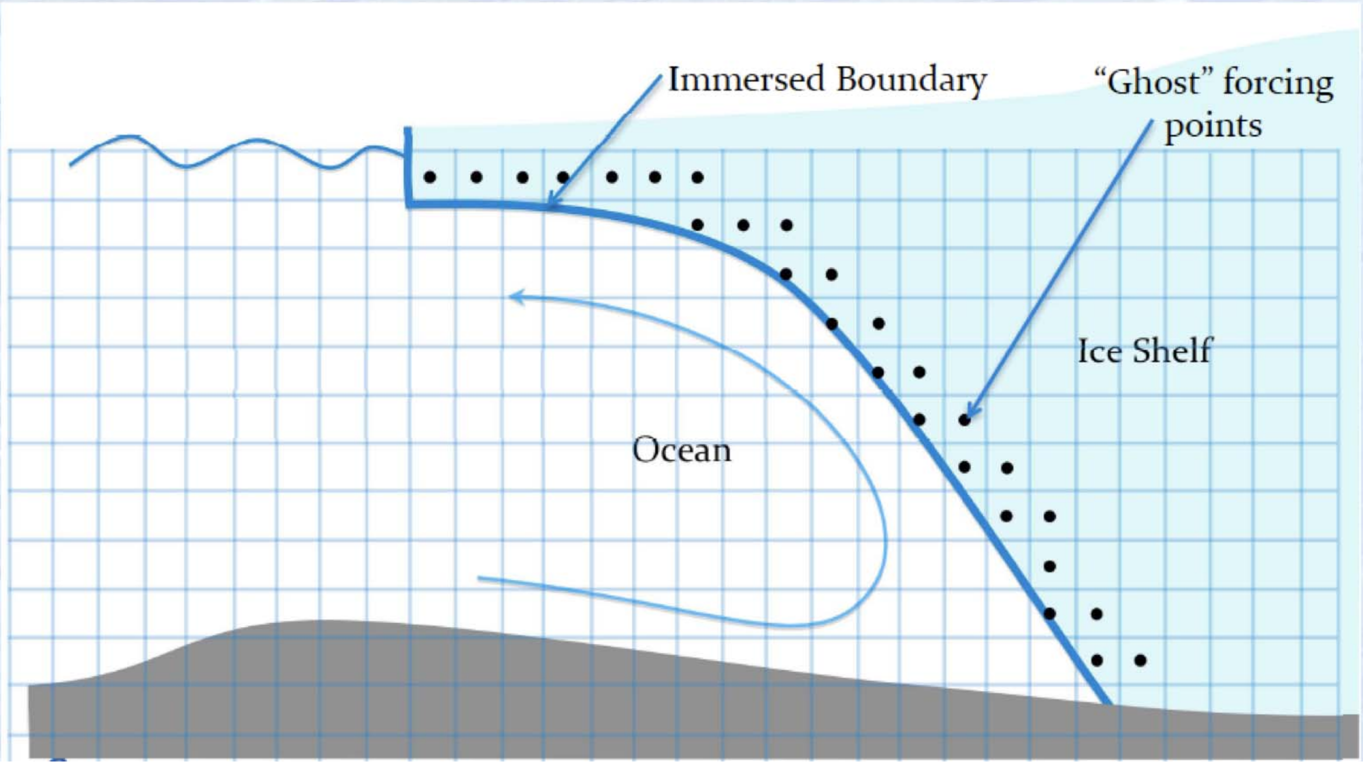
Schematic of warm CDW reaching the grounding line (courtesy of A. Jenkins)



Topography of Pine Island Glacier (courtesy of A. Jenkins)

Coupling ice shelves to POP

- As part of the DOE IMPACTS project on abrupt climate change, the POP ocean model is being modified to simulate ocean circulation beneath dynamic ice shelves.
- We have attempted to use immersed boundary methods to simulate processes at the ice-ocean interface.
- Because of technical difficulties associated with the barotropic mode, we may need to switch to a partial-cell method (Lösch 2008).



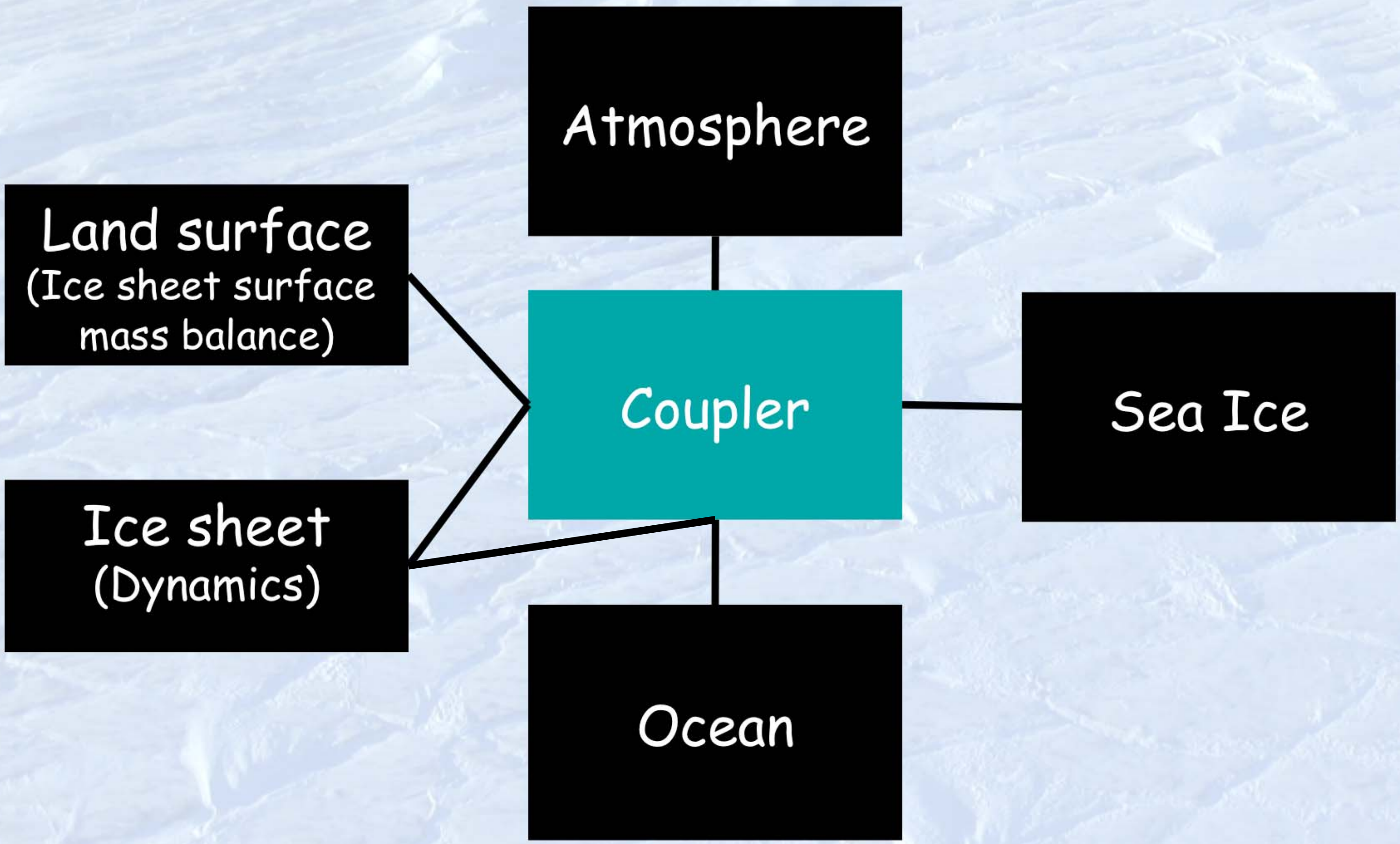
Ice-sheet/ocean coupling in CESM (in progress)

Ocean -> Ice sheet/shelf

- Basal heat flux
- Basal mass flux
- Ocean density (avg over ice column)

Ice sheet -> Ocean

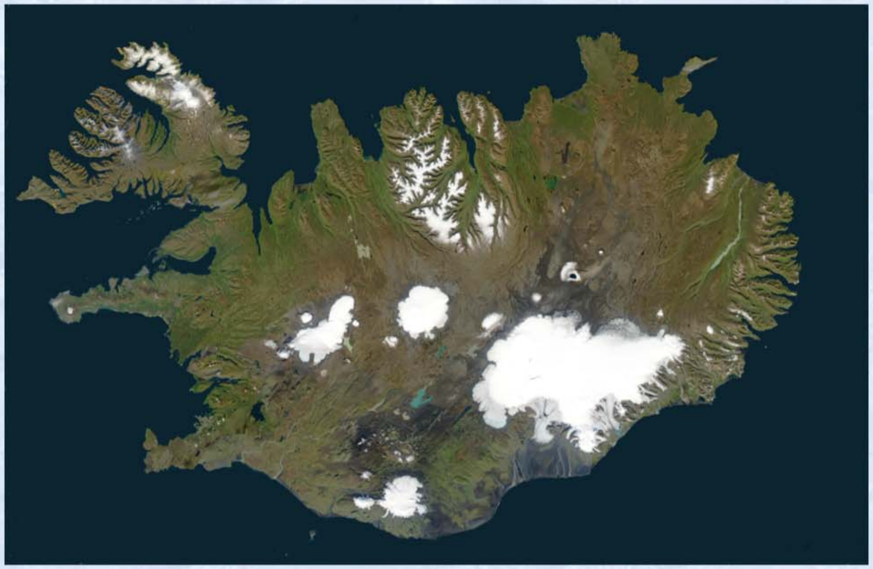
- Lower surface elevation
- Grounded/floating ice fraction
- Basal temperature info (for computing heat flux)



Glaciers and ice caps

- The area of glaciers and ice caps (GIC) outside of ice sheets is ~700,000 km^2.
- The ice volume of GIC is enough to raise mean sea level by ~60 cm.
- As measured by accumulation areas, most GIC are far from equilibrium with present-day climate (Mernild et al., in prep).
- The CLM surface-mass-balance (SMB) scheme with multiple elevation classes could be the core of a sub-grid-scale GIC parameterization.
- Using scaling relationships, we will need to convert the SMB in elevation classes to GIC area and volume changes.

Grosser Aletschgletscher, Switzerland



Iceland (Vatnajökull ice cap in lower right)

Planned simulations

- **Near term** (next 6 months):
  - Coupled CESM/CISM simulations, focusing on Greenland SMB (CMIP5, possibly Eemian interglacial)
  - Standalone ice-sheet simulations with higher-order CISM (Greenland and Antarctica)
  - Ice-ocean coupling in idealized cases
- **Medium term** (6-12 months):
  - Coupled CESM/CISM simulations with higher-order Greenland ice sheet (possibly with two-way coupling between CLM and CISM)
  - Coupled ice-ocean simulations at regional scales (e.g., Amundsen Sea Embayment, Filchner-Ronne ice shelf)
- **Long term**
  - Global, fully coupled CESM simulations with dynamic Greenland and Antarctic ice sheets (using variable-resolution ocean model)
  - Simulations of the Laurentide and other paleo ice sheets
  - Simulations of glacier and ice cap evolution