Modeling Land Ice in the Community Earth System Model

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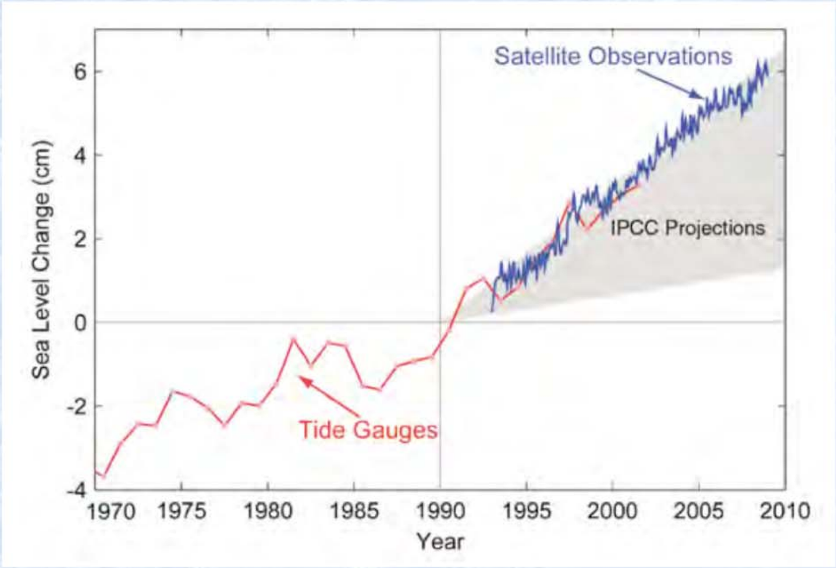
Outline

- Motivation and goals
- Recent accomplishments
- Work in progress
- Long-term model development

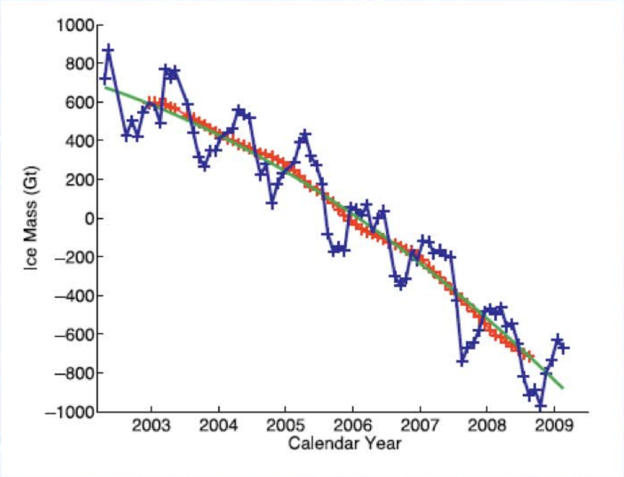
Sea-level rise

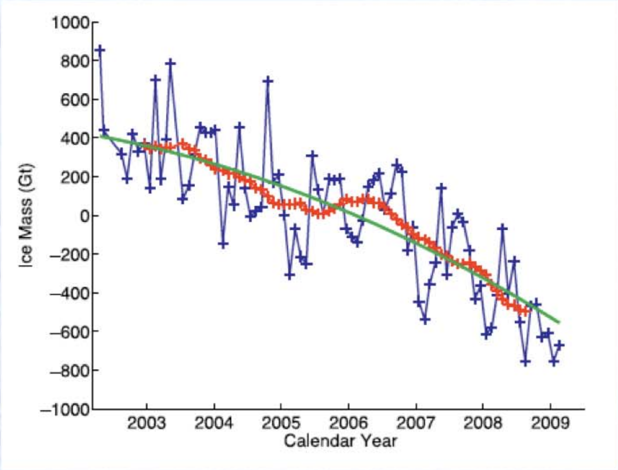
- **Global mean sea level is increasing at a rate of ~3 mm/year**.
  - Ocean thermal expansion: ~1 mm/yr
  - Glaciers and ice caps: ~1 mm/yr
  - Ice sheets: ~1 mm/yr
    - Greenland ~0.6 mm/yr
    - Antarctica ~0.4 mm/yr



Copenhagen Diagnosis (2010)

- Mass loss from land ice has grown during the past two decades and will likely continue to increase.
- Realistic physical models are needed to estimate future mass loss and bound the uncertainties.





Greenland ice mass loss   Antarctic ice mass loss
From GRACE gravity measurements (Velicogna 2009)

Overarching science goals

- **Provide useful physically-based predictions of land-ice retreat and sea-level rise.**
  - Decade to century time scales
  - Regional as well as global spatial scales (sea-level rise is not uniform)
  - Include uncertainty ranges
- **Predict effects of ice-sheet changes on other parts of the climate system** (e.g., meridional overturning circulation).
- **Predict changes in regional water supply.**
  - Large populations rely on seasonal runoff from mountain glaciers.

Model development goals

- **Develop and apply a Community Ice Sheet Model (CISM) capable of simulating the dynamic evolution of the Greenland and Antarctic ice sheets.**
  - Current model is Glimmer-CISM (**http://glimmer-cism.berlios.de/**)
  - Add new dynamical cores and physics as available
- **Fully incorporate land ice in the Community Earth System Model (CESM).**
  - Interactive coupling between ice sheets and land, atmosphere, ocean, sea ice
  - New models of glaciers and ice caps

These are the primary goals of the CESM Land Ice Working Group (**http://www.cesm.ucar.edu/working_groups/Land+Ice/**)

Ice sheet modeling priorities

CISM priorities identified by a 2008 LANL workshop:

- **Improved dynamical cores (“dycores”)**
  - Full-Stokes and higher-order ice-flow models (unified treatment of internal stresses)
  - Accurate treatment of grounding lines
  - Scalable parallel codes using modern solvers
- **Improved physics**
  - Basal sliding and subglacial hydrology
  - Sub-ice-shelf growth/melting
  - Iceberg calving
- **Integrated ice-sheet / climate models**
  - Two-way coupling with atmosphere and ocean

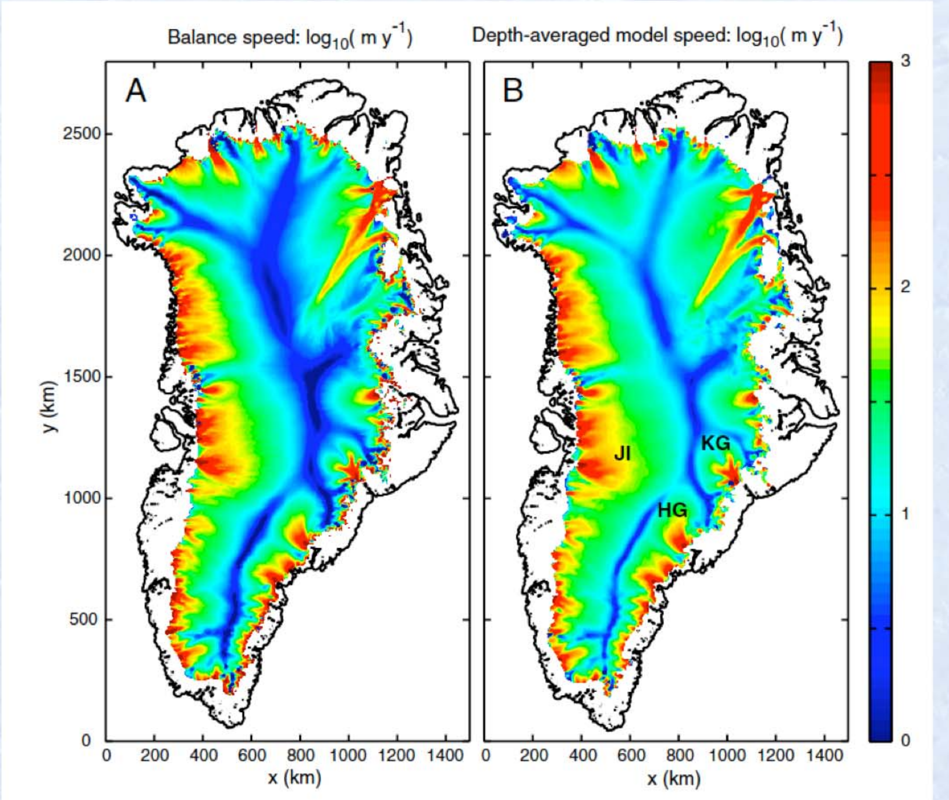
Community Ice Sheet Model (CISM)

- Glimmer-CISM version 2.0 to be released imminently
- Includes parallel, higher-order Payne-Price velocity solver using Trilinos software, Jacobian-free Newton-Krylov methods (DOE ISICLES project); scales to ~1000 processors
- Version with fully distributed parallelism (including mass and energy transport) is nearly complete

- The higher-order model has been used to project committed sea-level rise from the Greenland ice sheet (Price et al. 2011)

Left: Balance speed inferred from observations

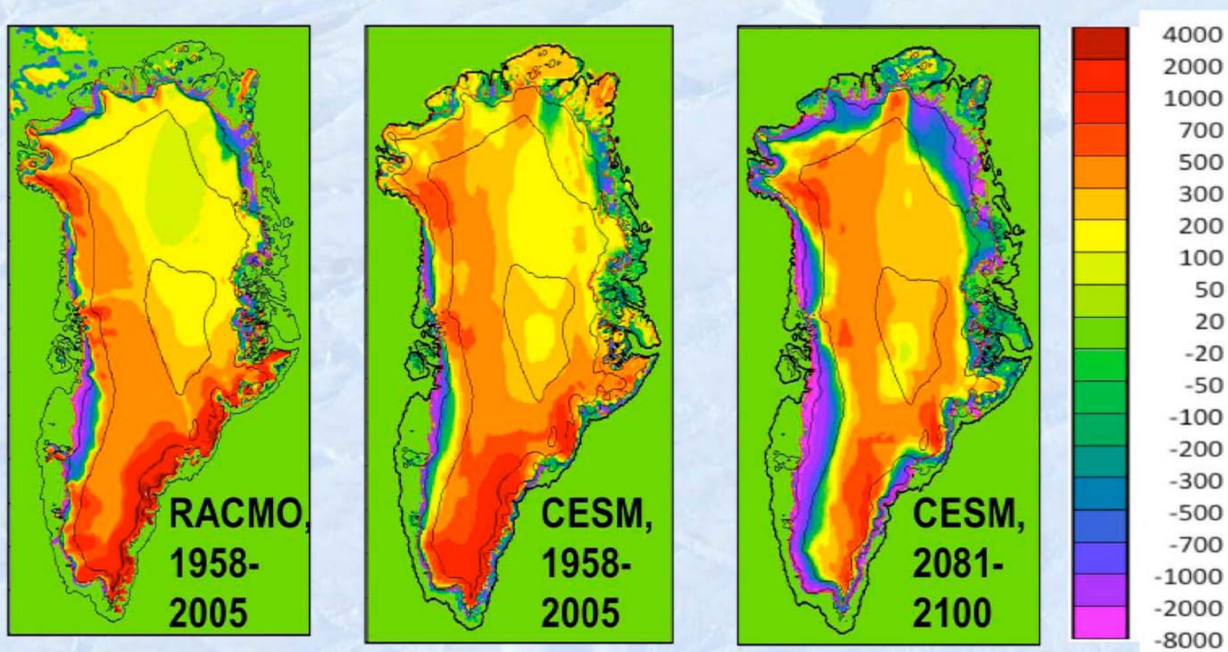
Right: Depth-averaged model ice speed



Ice sheets in CESM

- CESM 1.0 (released 2010) included shallow-ice version of Glimmer-CISM; first publicly released IPCC-class model with dynamic ice sheets.
- Glimmer-CISM 2.0 (higher-order model) will be coupled to CESM.
- CESM also includes a new surface-mass-balance scheme for glaciers and ice sheets (multiple elevation classes for improved accuracy).
- Work to date has focused on Greenland's surface mass balance; good agreement with regional climate models.
- New repository (**svn-cism-model.ucar.edu**) for ongoing CISM development

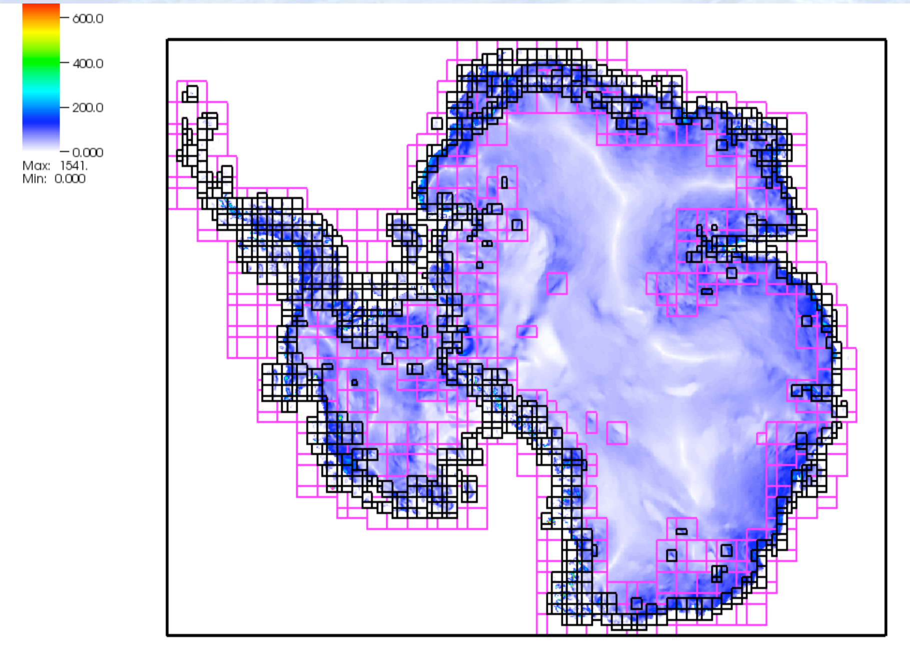
Greenland surface mass balance (mm/yr).
Left: RACMO regional climate model.
Center: CESM, 1958-2005 mean.
Right: CESM, 2081-2100 mean, RCP8.5 scenario.
Red = net accumulation
Blue = net ablation
(Courtesy of M. Vizcaíno)



New dycore: Adaptive mesh refinement

The Berkeley ISICLES project (BISICLES) has developed a new finite-volume dycore based on Chombo adaptive-mesh-refinement (AMR) software. (See poster by D. Martin).

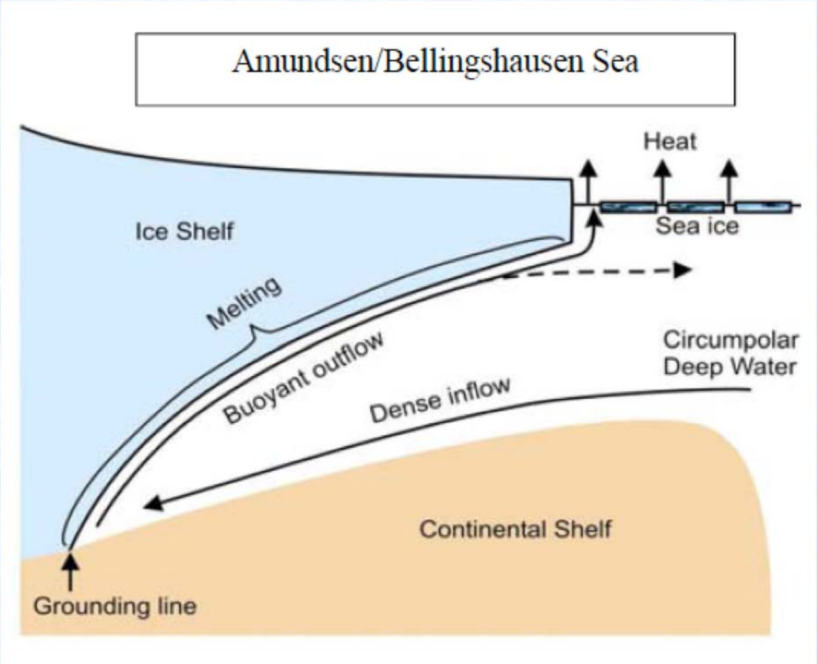
- AMR allows high resolution (~1 km or less) in the vicinity of ice streams and grounding lines.
- Have developed a parallel, vertically integrated higher-order velocity solver and applied it to Pine Island Glacier in West Antarctica
- New interface between Glimmer-CISM (Fortran90) and Chombo/ BISICLES (C++). This interface will serve as a template for other dycores.
- Model to be used for standalone ice-sheet and coupled ice-ocean simulations as part of DOE IMPACTS project

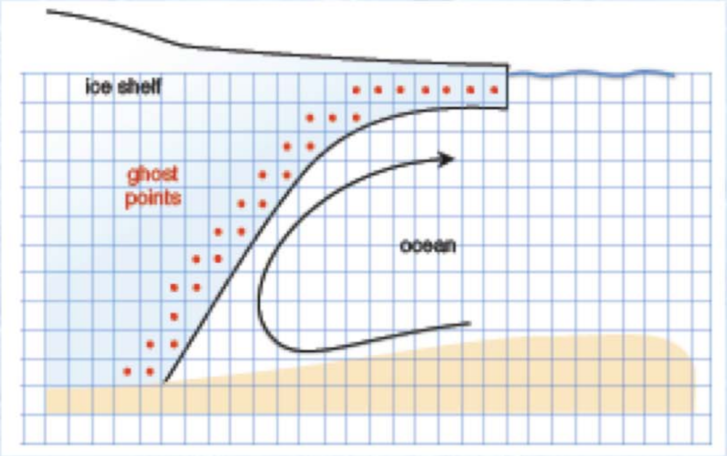


Antarctic ice speed with 2D higher-order solver on a fully adaptive mesh (10, 5, and 2.5 km) using BISICLES dycore. (Courtesy of D. Martin)

Ice-ocean coupling

- Ice-ocean interactions are critical for the evolution of marine ice sheets. Warm waters delivered to grounding line could trigger dynamic instability.
- These interactions have not yet been studied with an ocean GCM coupled dynamically to a whole-ice-sheet model.
- As part of the DOE IMPACTS project, we are modifying POP to simulate ocean circulation and heat/mass exchange beneath floating ice. (Described in talk by X. Asay-Davis.)
- We are now implementing an ice-ocean coupling framework in CESM.





Left: Schematic of Circumpolar Deep Water delivering heat to the grounding line

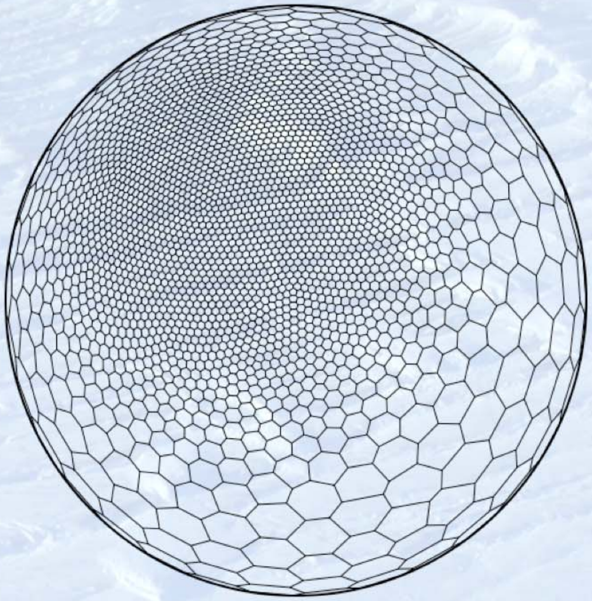
Right: Sub-ice-shelf circulation using immersed boundary method with ghost points

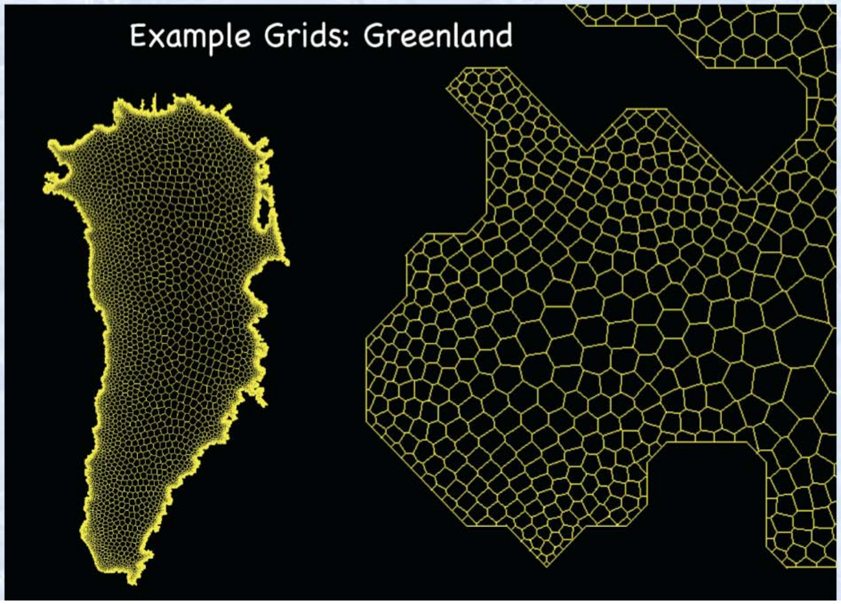
Science applications

- Using CESM we will carry out a suite of coupled climate simulations: pre-industrial, 20th century, RCP 4.5/8.5 (work with M. Vizcaíno, W. Sacks).
    - Start with “shallow-ice” Glimmer-CISM, repeat with higher-order model
- We are participating in two international projects aimed at assessing century-scale contributions of ice sheets to sea-level rise:
    - **SeaRISE** (R. Bindschadler et al.): Estimate upper bounds on mass loss driven by surface warming, basal lubrication, and sub-shelf melting.
        - Using Payne-Price dycore, standalone and coupled to CESM
        - Working with C. Jackson (U. Texas) on sensitivity analysis
    - **Ice2sea** (European Union): Global and regional climate models provide forcing for ice-sheet models.
        - Collaborating with U. Bristol (T. Payne, S. Cornford) using Glimmer-CISM with BISICLES dycore
- With resources from the ASCR Leadership Computing Challenge, we will carry out coupled ice-sheet/ocean simulations, focusing on regional scales.

New dycore: Finite elements and MPAS

- Max Gunzburger (FSU) and colleagues have developed higher-order and full-Stokes solvers using finite elements on a centroidal Voronoi mesh.
- These solvers will be implemented in the Model for Prediction Across Scales (MPAS) framework, already being used for atmosphere and ocean models.
- This framework allows high resolution in regions of interest (ice streams, grounding lines, sub-shelf cavities, fjords) without the complications of nesting.

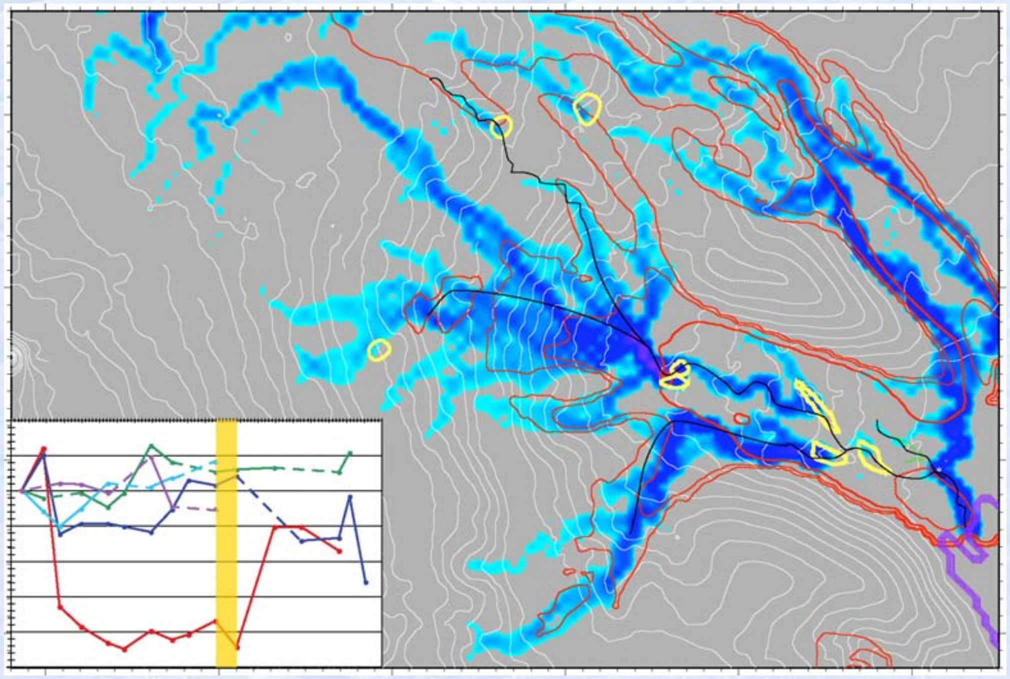




Variable-resolution mesh for Greenland ice sheet

New physics: Sliding and calving

- We will implement a general basal sliding law (based on work of C. Schoof) that is consistent with theory and observations.
- We are working with university collaborators (G. Flowers and C. Schoof) to develop evolutionary models of subglacial hydrology that allow both distributed and channelized flow.
- We are also working with university collaborators (J. Bassis) on new calving laws.



Subglacial hydrologic system of MacAyeal Ice Stream, West Antarctica. Yellow circles are subglacial lakes.

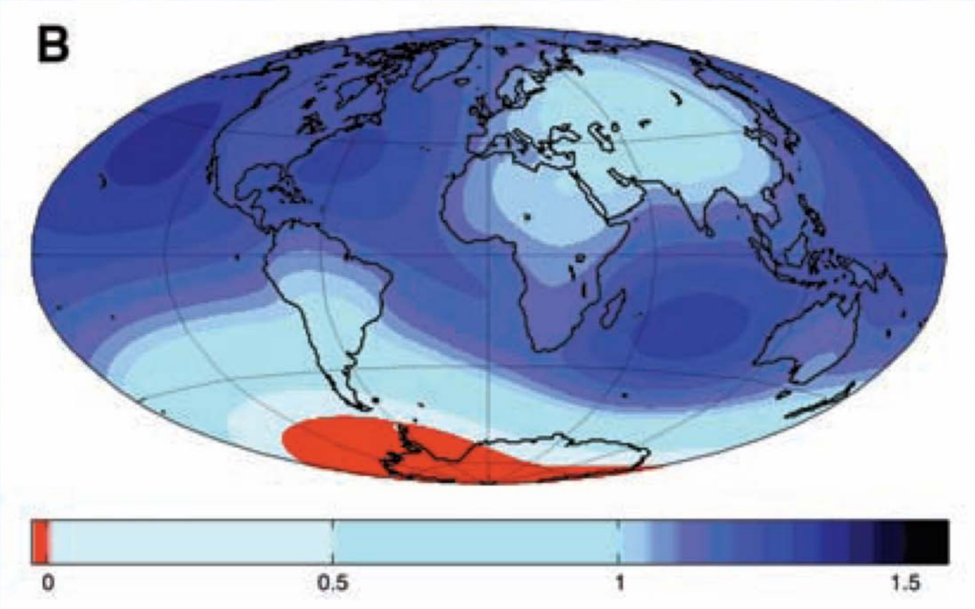
Inset: Lake volume changes inferred over several years from ICESat laser altimetry.

(Courtesy of S. Carter)

Other model development

- Two-way land/ice-sheet coupling with dynamic land topography and surface types (glacier to vegetated and vice versa), to enable long-term simulations (e.g., glacier inception, Laurentide ice sheet evolution)
- New initialization techniques (e.g., spinning up ice sheets to steady state with the model climate)
- Improved model diagnostics (verification test suites, validation data sets) and uncertainty quantification
- Standard interfaces for coupling to Earth-system models, new dycores
- Model self-gravity of ice sheets (non-uniform sea-level changes)

Relative sea-level change from collapse of the West Antarctic ice sheet (Mitrovica et al. 2009)



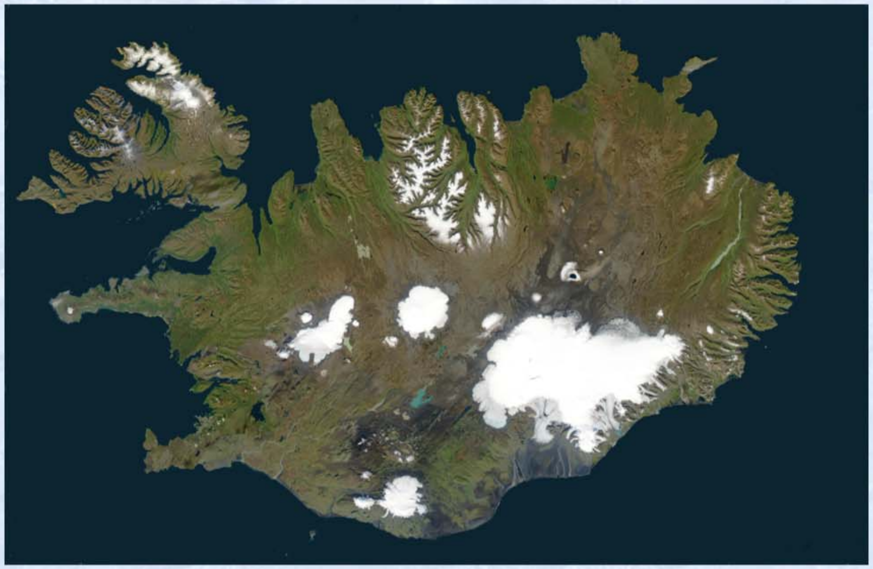
Not just ice sheets...

There are an estimated 300,000 to 400,000 glaciers with a volume equivalent to ~60 cm of sea-level rise. These are not well represented in current climate models.

Modeling glaciers and ice caps

- There are too many glaciers (and not enough thickness data) to model the dynamics of each glacier in CESM.
- We will use statistical relationships (e.g., area–volume scaling) to model the evolution of glaciers and ice caps in a changing climate.
- The CLM surface-mass-balance (SMB) scheme with multiple elevation classes could be the core of a sub-grid-scale GIC parameterization for CESM.
- Model development and validation will be carried out under the new Regional Arctic System Modeling (RASM) project.

Grosser Aletschgletscher, Switzerland



Iceland (Vatnajökull ice cap in lower right)

Summary

Accomplishments

- Developed a Community Ice Sheet Model with two parallel, higher-order dynamical cores
- Coupled Glimmer-CISM to the Community Earth System Model
- Formed productive collaborations among glaciologists, applied mathematicians, and climate modelers

Goals

- Ongoing advances in modeling ice-sheet dynamics and physics
- Full two-way coupling of ice sheets in CESM
- Model of glaciers and ice caps in CESM
- Improved verification, validation, and uncertainty quantification for land-ice models
- Global, fully coupled, high-resolution CESM simulations of land-ice evolution and sea-level rise