

The background of the slide is a high-resolution aerial photograph of a vast, textured snowfield or ice sheet. The surface is uneven, with numerous small ridges, depressions, and crevasses, creating a complex, wavy pattern of light and dark blue/white tones. The overall appearance is that of a large-scale natural or modeled ice formation.

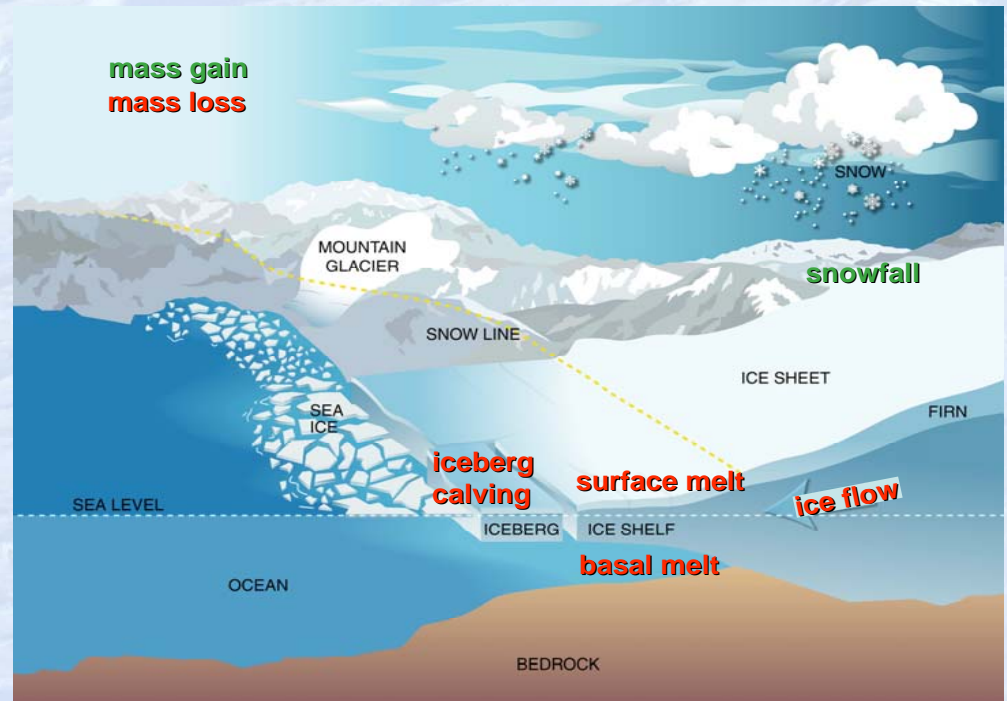
# **Modeling land ice in the Community Earth System Model**

William Lipscomb  
Los Alamos National Laboratory

CESM Tutorial  
5 August 2011

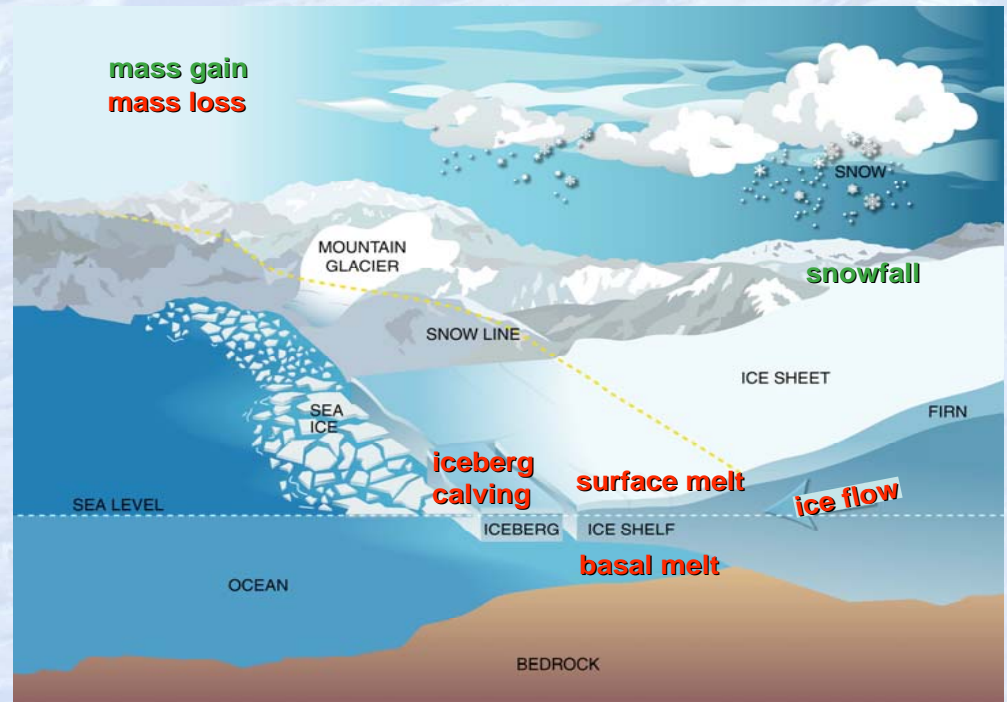
# Outline

- Motivation for simulating land ice in Earth-system models
- Introduction to ice sheet modeling
- Land ice in CESM1.0
- Work under way
  - Advanced ice-sheet models
  - Coupling to ocean model
  - Glaciers and ice caps



# Outline

- Motivation for simulating land ice in Earth-system models



# Motivation

- **Provide useful predictions of land-ice retreat and the resulting sea-level rise.**
  - Useful for both policymakers (e.g., climate treaty negotiators) and planners (e.g., coastal utility managers)
  - Cover regional as well as global 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.**
  - Much of the world's population relies on seasonal runoff from mountain glaciers (e.g., in the Himalayas)

# Definitions

- A **glacier** is a mass of ice, formed from compacted snow, flowing over land under the influence of gravity.
- An **ice sheet** is a mass of glacier ice greater than 50,000 km<sup>2</sup> (Antarctica, Greenland).
- An **ice cap** is a mass of glacier ice smaller than 50,000 km<sup>2</sup> (e.g., in Iceland, Canadian Arctic).
- An **ice shelf** is a large sheet of floating ice attached to a grounded ice sheet.
- An **ice stream** is a region of relatively fast-flowing ice in a grounded ice sheet.

# Glaciers, ice caps and ice sheets



WGMS = World Glacier Monitoring Service

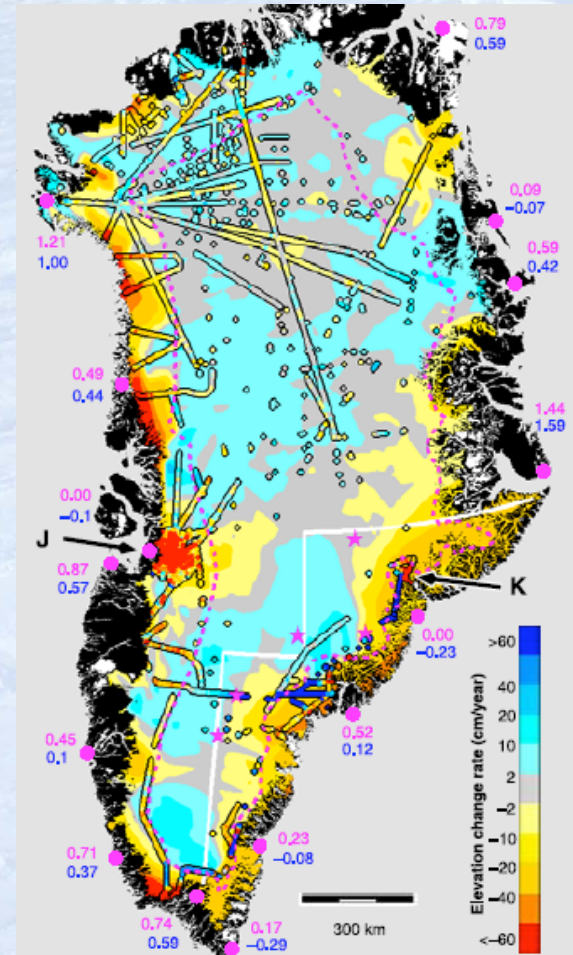
**Fig. 6.1 The selected eleven glacierised macroregions.**

The selected macroregions are presented in detail in the chapters 6.1 - 6.11. Source: ESRI Digital Chart of the World (DCW), WGMS.

Ice covers about 10% of the Earth's land surface  
(down from about 20% 20,000 years ago).

# Greenland ice sheet

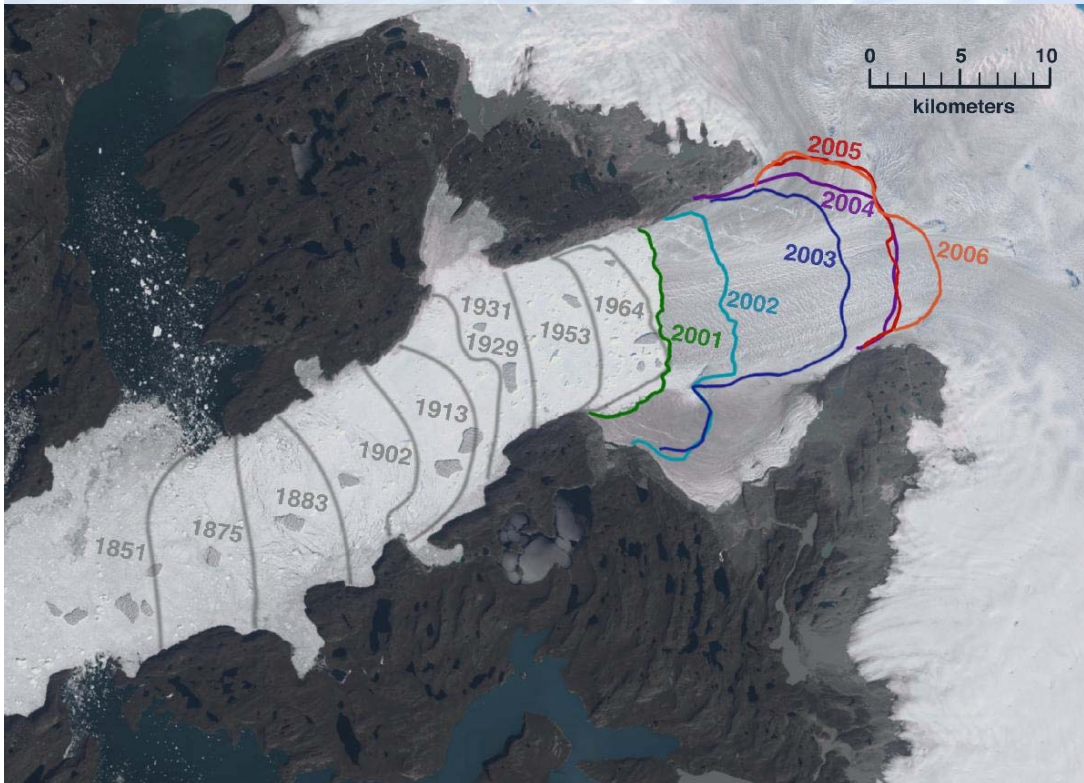
- **Volume** = 2.8 million km<sup>3</sup>  
(7 meters sea level equivalent)
- **Area** = 1.7 million km<sup>2</sup>
- **Mean thickness** = 1.6 km
- **Accumulation** = 600 km<sup>3</sup>/yr
- **Surface runoff** = 300+ km<sup>3</sup>/yr
- **Iceberg calving** = 300+ km<sup>3</sup>/yr



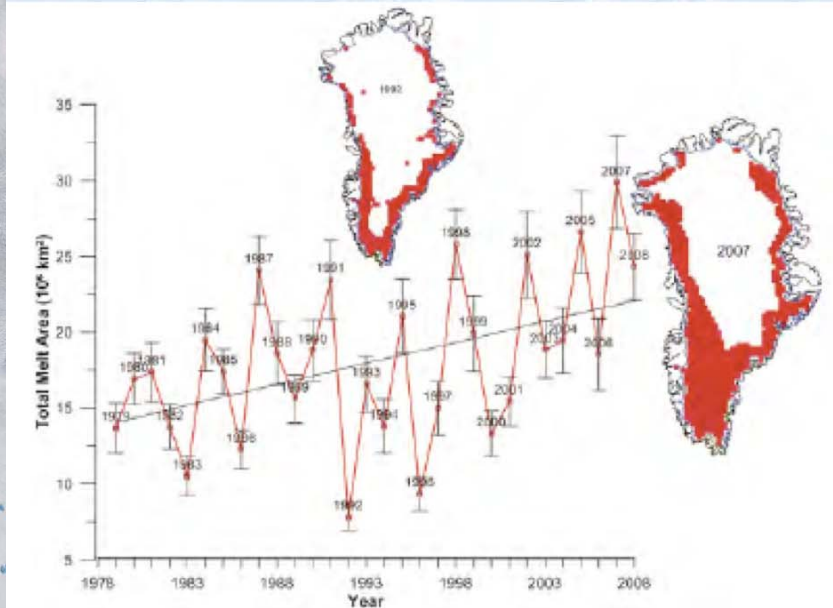
Ice elevation changes  
(turquoise = thickening,  
yellow/red = thinning;  
Krabill et al. 2004)

# Ice sheet mass loss: Greenland

- Significant and increasing mass loss ( $\sim 200 \text{ km}^3/\text{yr}$ ) since late 1990s
- Caused by increased surface melting and by acceleration of large outlet glaciers



Retreat of Greenland's Jakobshavn glacier

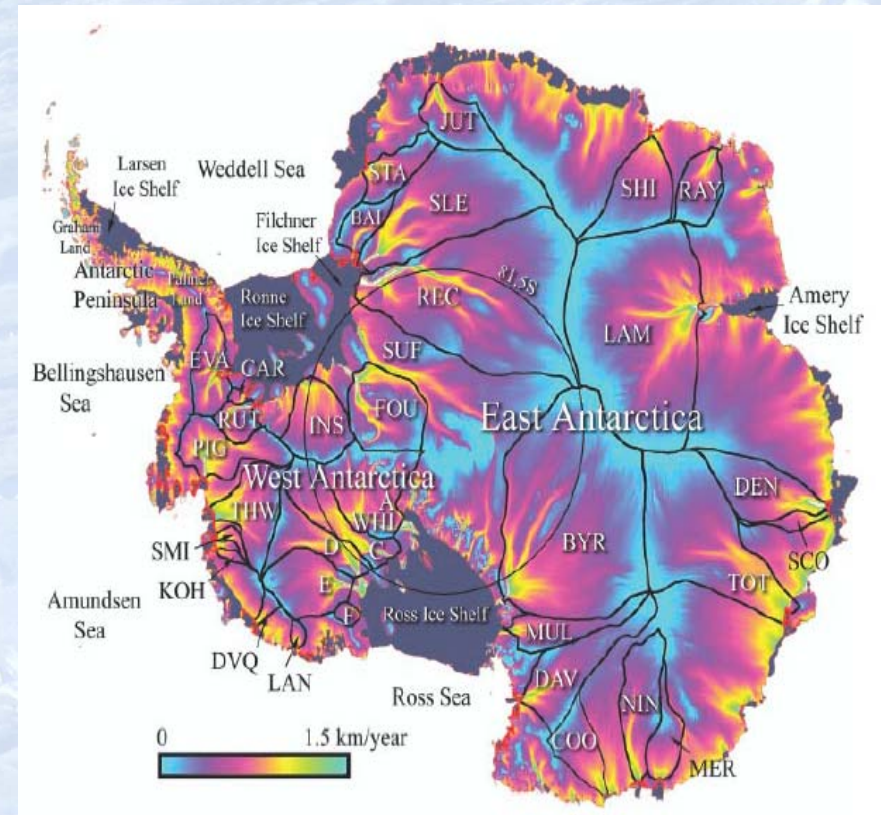


Increased surface melting,  
1979-2008  
(Copenhagen Diagnosis, 2009)



# Antarctic ice sheet

- **Volume** = 26 million km<sup>3</sup>  
(60 meters sea level equivalent)
- **Area** = 13 million km<sup>2</sup>
- **Mean thickness** = 2 km
- **Accumulation** = 2000 km<sup>3</sup>/yr, balanced mostly by iceberg calving
- Little surface melting

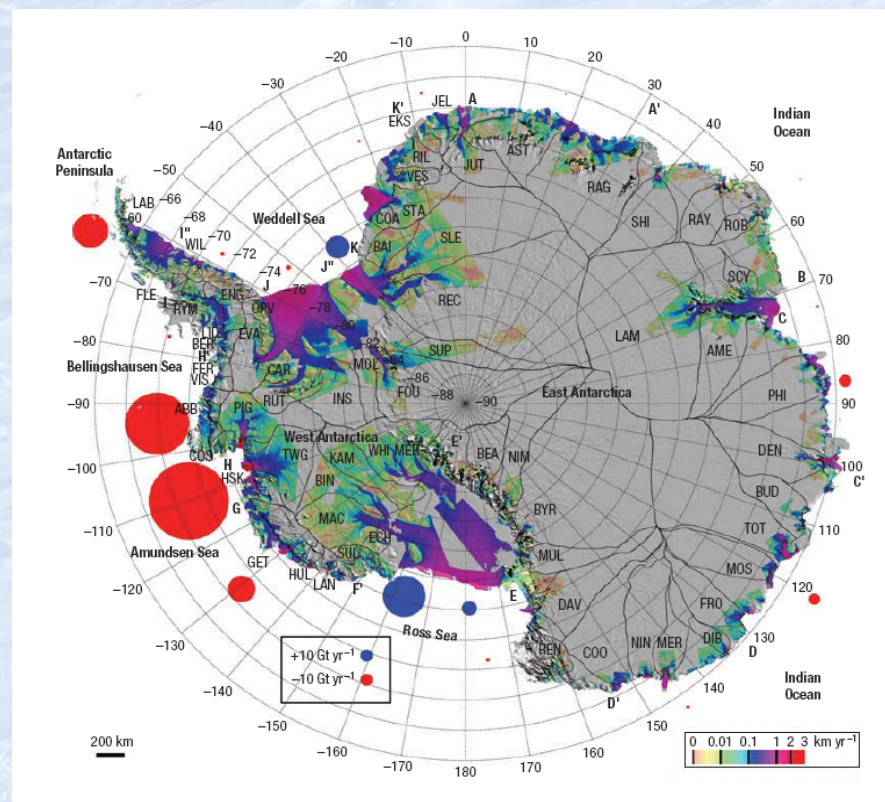


## Ice flow speed

(purple/blue = slow,  
orange/yellow = fast;  
Rignot and Thomas 2002)

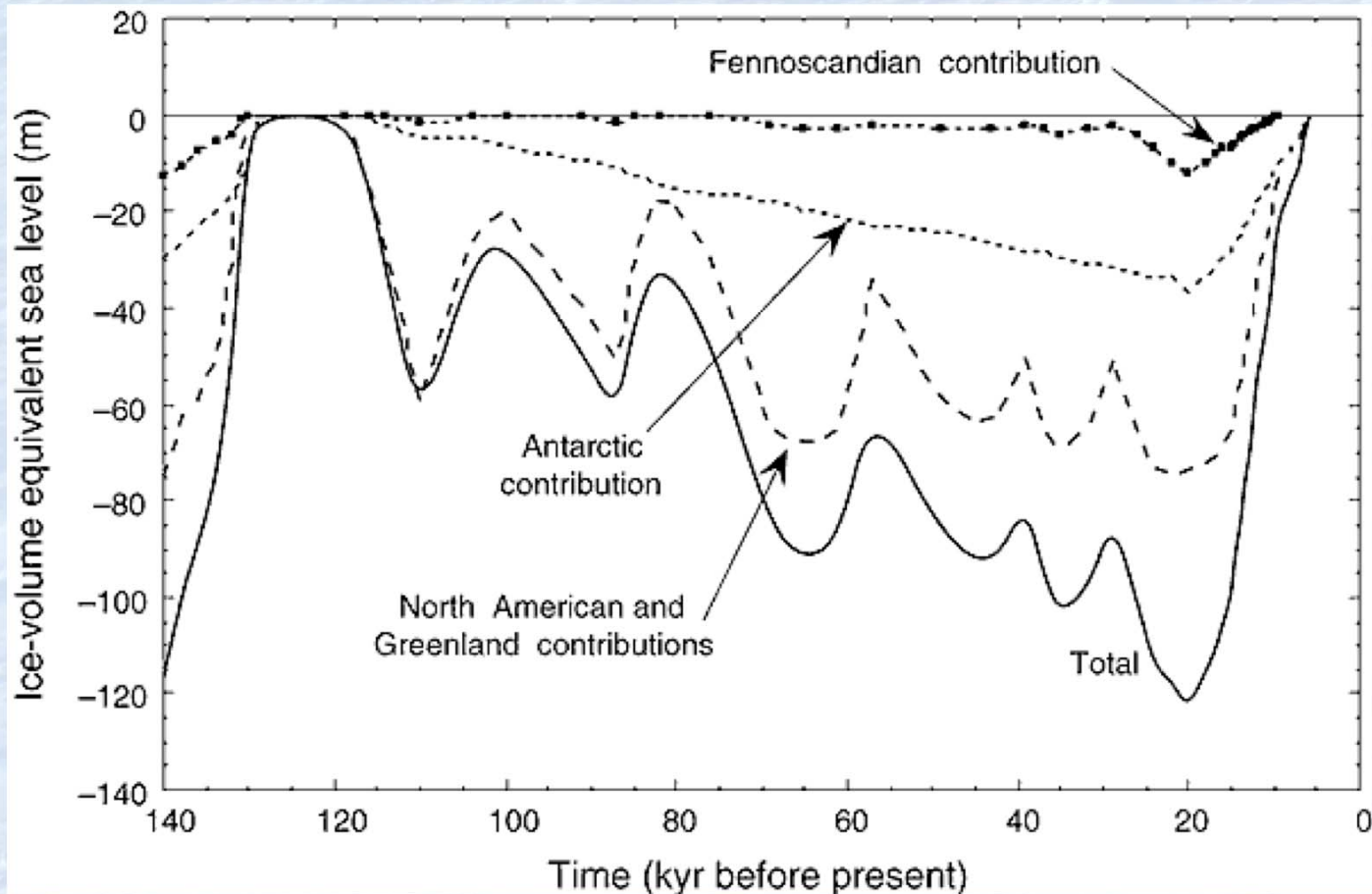
# Ice sheet mass loss: Antarctica

- Antarctica is losing ice at a rate of  $\sim 150 \text{ km}^3/\text{yr}$ , mostly from West Antarctica and the Antarctic Peninsula.
- Outlet glaciers in the Amundsen Sea embayment are accelerating and thinning, probably because of warm ocean waters reaching the base of ice shelves.



Antarctic ice velocity and mass loss  
(Rignot et al. 2008)

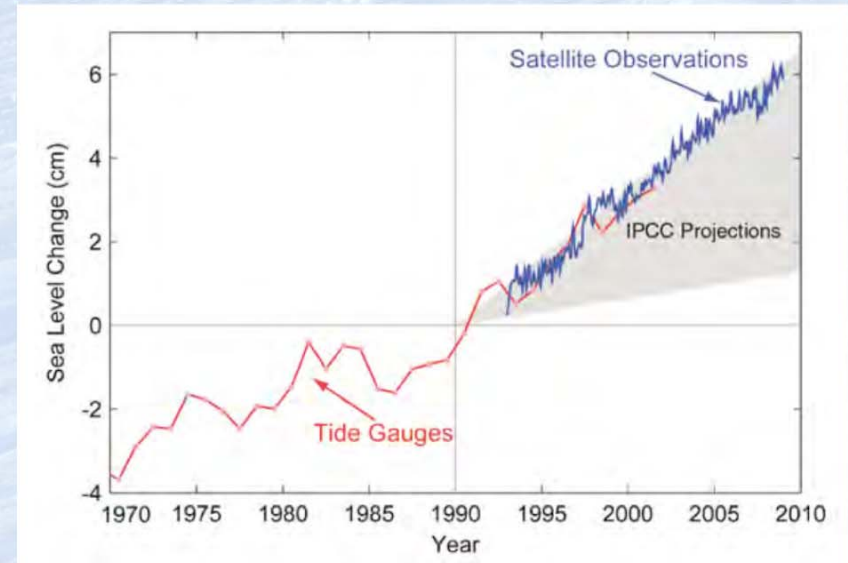
# Sea level change since last interglacial



- Ice sheets grow slowly and melt relatively quickly.
- Past rates of sea level rise were up to 10 times greater than today.

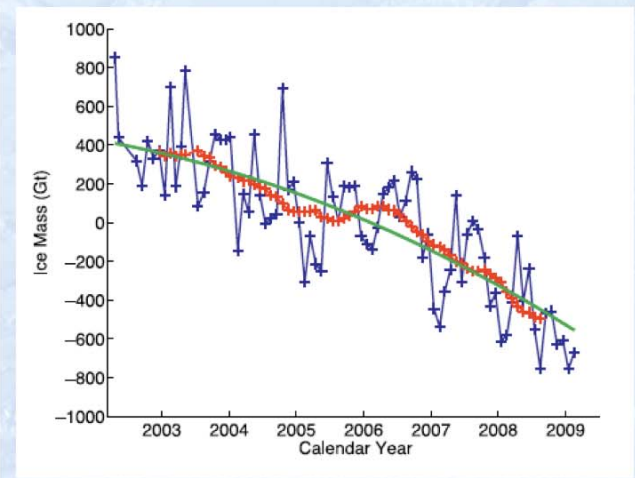
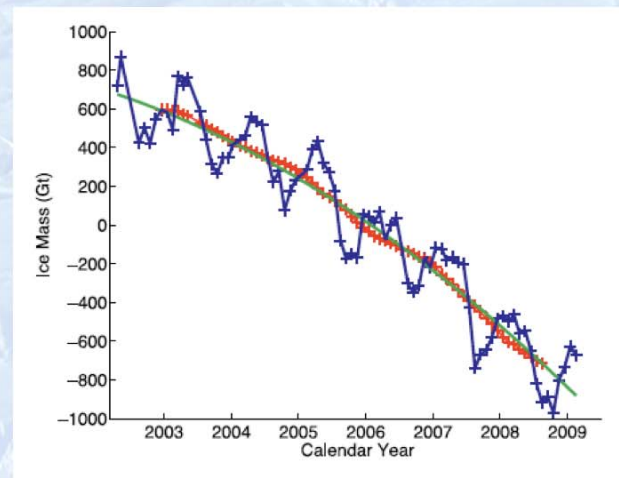
# Current sea-level rise

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



Copenhagen Diagnosis (2010)

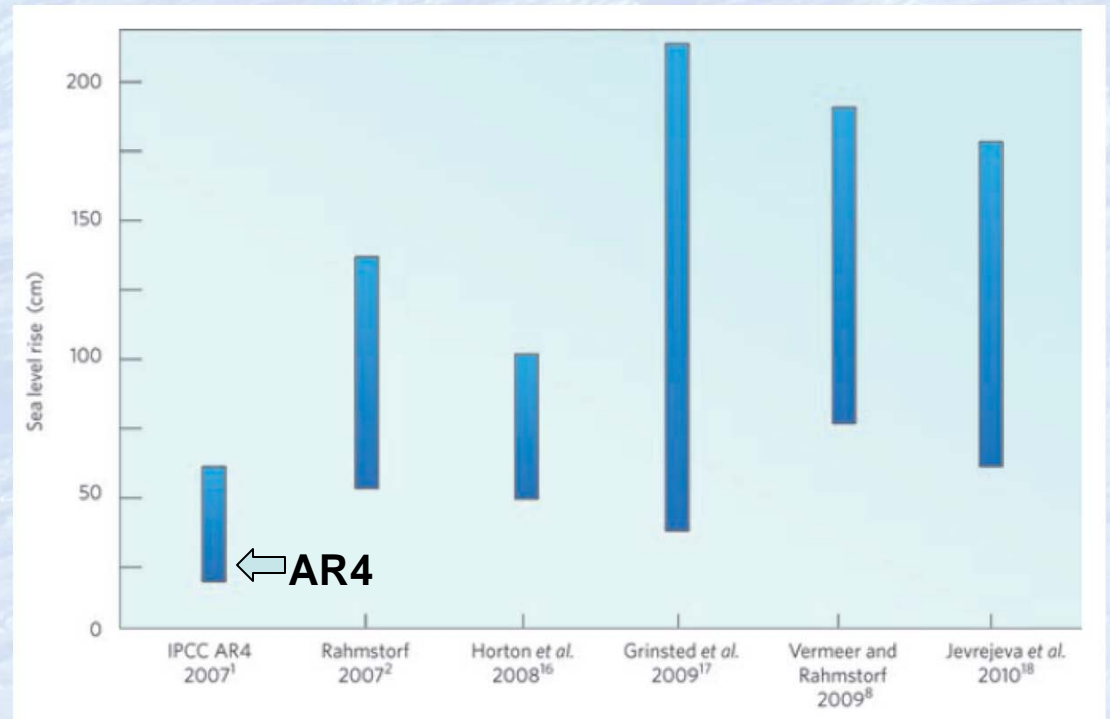
- Mass loss from ice sheets has grown during the past decade and will likely continue to increase.



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

# Sea-level projections

- **IPCC AR4 (2007): 18-59 cm** of sea-level rise by 2100 (excluding ice-sheet dynamic effects)
- **Rahmstorf 2007: 50-140 cm** (semi-empirical model)
- **Jevrejeva et al. 2010: 60-160 cm** (semi-empirical statistical model)
- **Pfeffer et al. 2008: 80-200 cm** (kinematic constraints for ice sheets)



Predicted 21<sup>st</sup> century sea-level rise (Rahmstorf 2010)

- The IPCC AR4 projections are almost certainly too low.
- The most credible current predictions are based on **semi-empirical relationships** between global mean surface temperature and the rate of sea-level rise.
- These simple relationships may not hold in the future as new physical processes come into play (e.g., ice-sheet dynamic feedbacks).
- **Realistic physical models are needed** to better bound the range of uncertainty.

# 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 (e.g., Ridley et al. 2005).
- 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.

# Sea-level prediction in Earth-system models

ESMs already have many of the components needed for physically-based sea-level predictions: in particular, fully coupled atmosphere-ocean GCMs (can provide ocean thermal expansion and dynamic SLR).

## What's missing?

- **Improved ice-sheet models**

- “Higher-order” dynamics for fast flow in ice streams, outlet glaciers
- More realistic treatment of physical processes (e.g., subglacial water transport, basal sliding, iceberg calving)
- Higher grid resolution (~1 km, requiring scalable parallel codes and adaptive/unstructured meshes)

- **Coupling of ice-sheet models to other climate components**

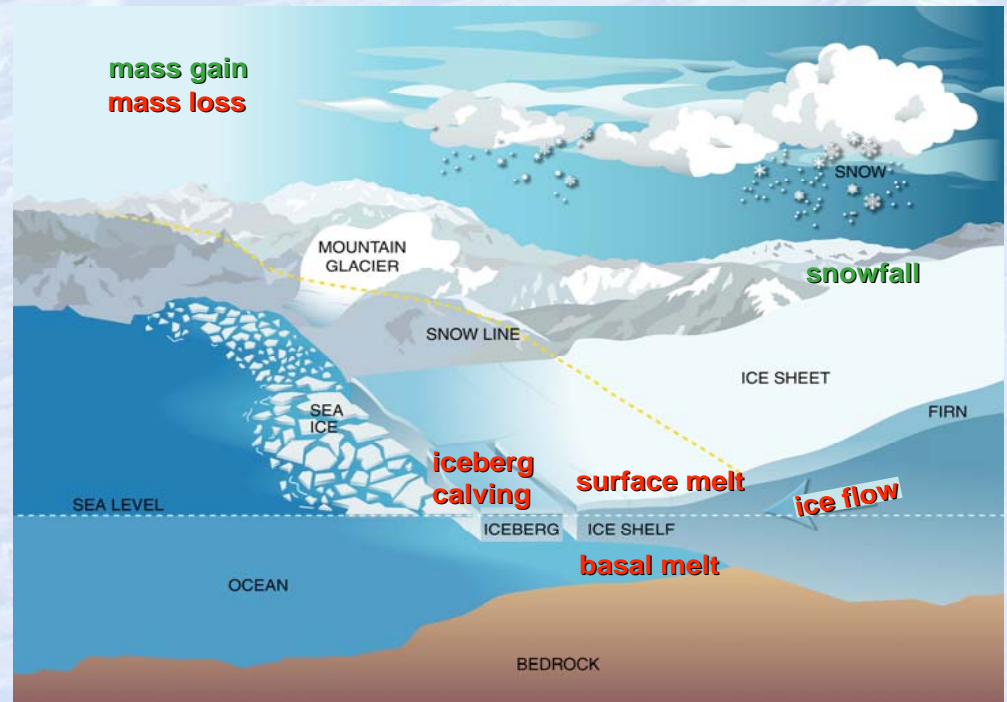
- Ice-atmosphere coupling (for surface mass balance)
- Ice-ocean coupling (for retreat of marine-based ice)

- **Improved models of glaciers and ice caps**

- **Regional sea-level fingerprints** from self gravitation, elastic rebound, etc.

# Outline

- Introduction to ice sheet modeling





# Components of an Ice Sheet Model

**(1) Conservation Equations**

**(2) Coupling to Climate**

**(3) Physics**

# Components of a Land Ice Model

## (1) Conservation Equations

“dynamical core” of model

## (2) Coupling to Climate (external forcing)

reanalysis / proxy data, climate model

## (3) Physics

physical processes through submodels,  
parameterizations, etc. (everything else)

## (1) Conservation equations (dynamical core)

**Conservation of Momentum:**

$$0 = \nabla \cdot \sigma(\mathbf{u}, T) + \rho \vec{g}$$

**Conservation of Energy:**

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) - \mathbf{u} \cdot (\nabla T) + \sigma : \dot{\epsilon}$$

**Conservation of Mass:**

$$\frac{\partial H}{\partial t} = -\nabla \cdot (\bar{\mathbf{U}} H) + \dot{b} - \dot{m}$$

# Conservation of momentum

“deviatoric” stress = full stress - pressure

$$\tau_{ij} = \sigma_{ij} + P\delta_{ij}$$

$$\begin{bmatrix} \tau_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \tau_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \tau_{zz} \end{bmatrix} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} P$$

$$\underline{\underline{\tau}} = \underline{\underline{\sigma}} + \underline{\underline{I}}P$$

$$\tau_{ij} = B \dot{\epsilon}_e^{\frac{1-n}{n}} \dot{\epsilon}_{ij}, \quad B = B(T) \quad \text{Glen's law (empirical)}$$

$$\dot{\epsilon}_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad \text{strain rate tensor}$$

$$2\dot{\epsilon}_e = \dot{\epsilon}_{ij} \dot{\epsilon}_{ij} \quad \text{effective strain rate}$$

$$\eta \equiv \frac{1}{2} B \dot{\epsilon}_e^{\frac{1-n}{n}} \quad \text{effective viscosity}$$

$$\tau_{ij} = 2\eta \dot{\epsilon}_{ij} \quad \text{constitutive relation}$$

# Equations of Stress Equilibrium in Cartesian Coordinates (Stokes Flow)

Assume static balance of forces by ignoring acceleration

$$x: \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} - \frac{\partial P}{\partial x} = 0$$

$$z: \frac{\partial \tau_{zz}}{\partial z} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial x} - \frac{\partial P}{\partial z} = \rho g$$

## (1) Full Stokes (FS) ( $u, v, w, P$ ) [everywhere]

$$\hat{x}: \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} - \frac{\partial P}{\partial x} = 0, \quad \hat{z}: \frac{\partial \tau_{zz}}{\partial z} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{xz}}{\partial x} - \frac{\partial P}{\partial z} = \rho g$$

## (2) Climate Coupling: Mass Balance Terms

$$\frac{\partial H}{\partial t} = -\nabla \cdot (\bar{\mathbf{U}}H) + \dot{b} + \dot{m}$$

**momentum balance  
(dycore)**

**coupling to atmos.  
and land model**

**coupling to ocean  
model**



An aerial photograph of a glacier surface, showing a complex pattern of ridges and grooves. The image has a light blue tint. The text is overlaid on the left side of the image.

## **(3) Physics (everything else)**

**Constitutive laws**

**Basal sliding submodels / parameterizations**

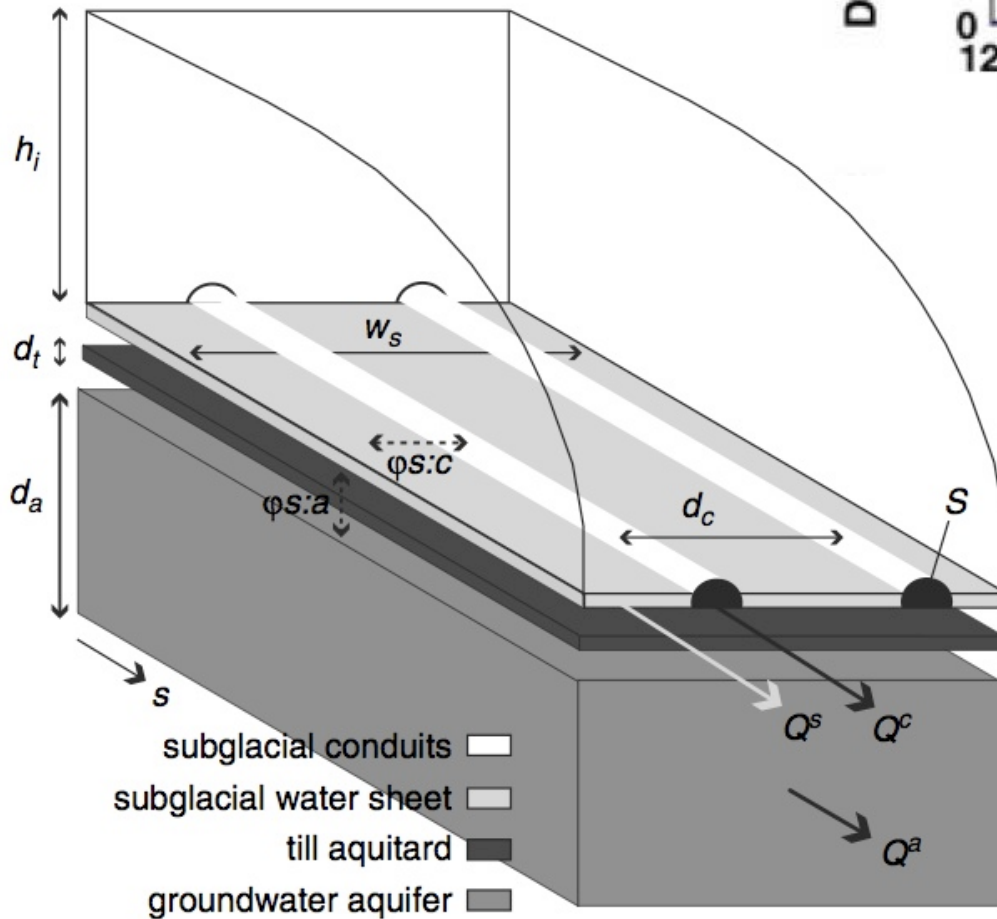
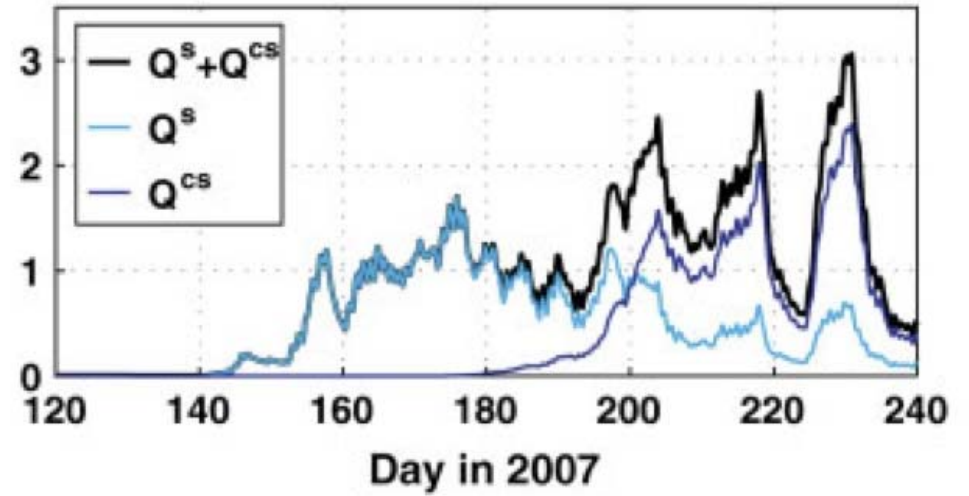
**Surface and subglacial hydrology**

**Iceberg calving**

**etc ...**

# Subglacial hydrology models

(a)  
Discharge ( $\text{m}^3 \text{s}^{-1}$ )

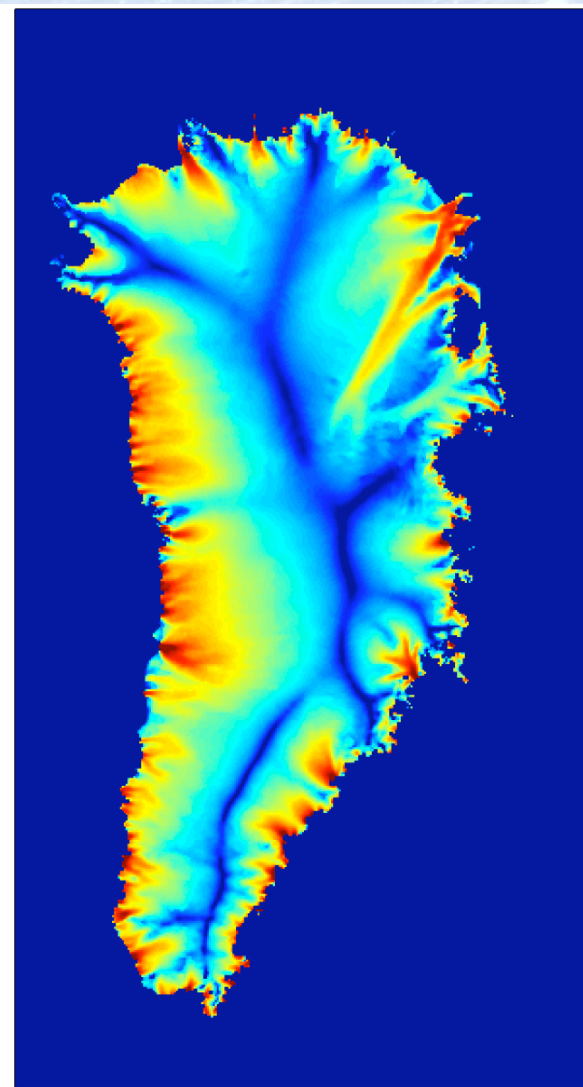


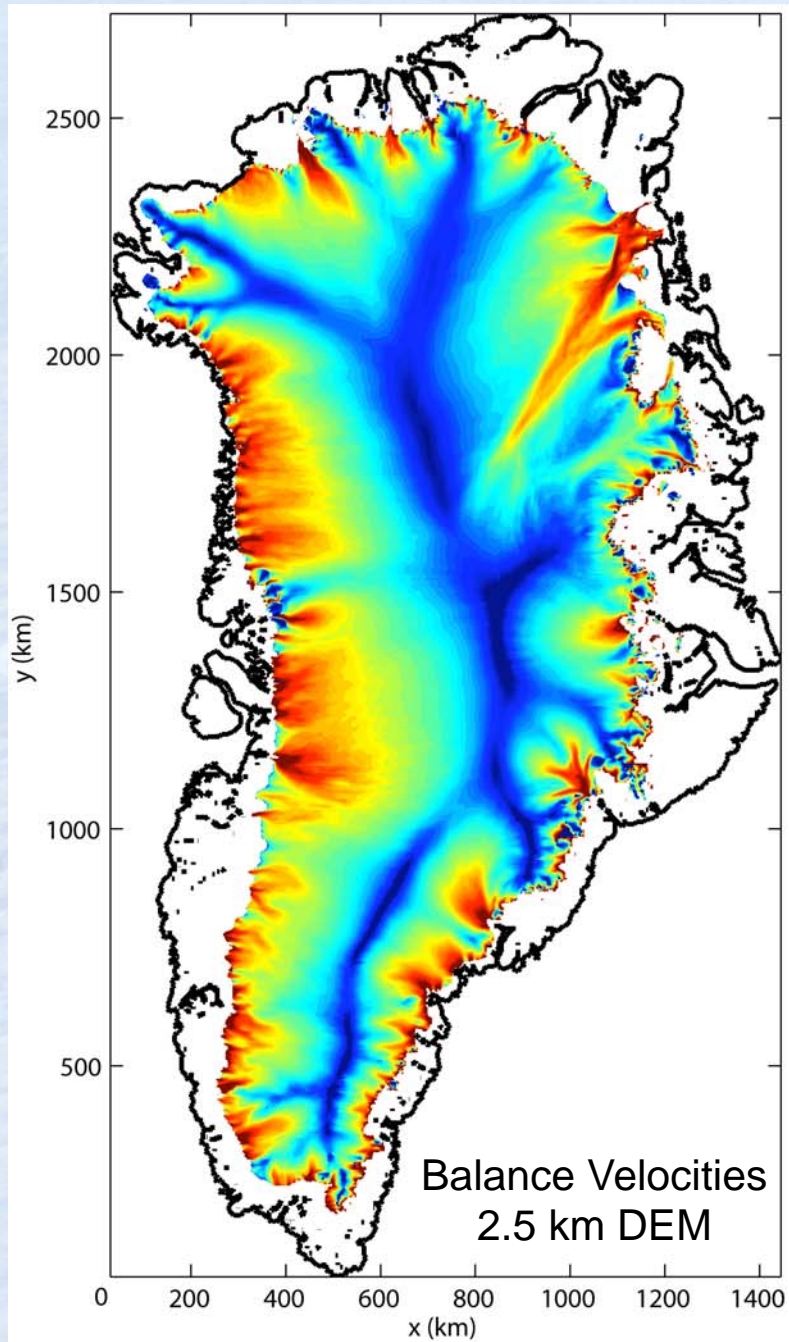
— Total flux  
 — Distributed  
 — Channelized

Flowers, *Hydrol. Process.* **22** (2008)

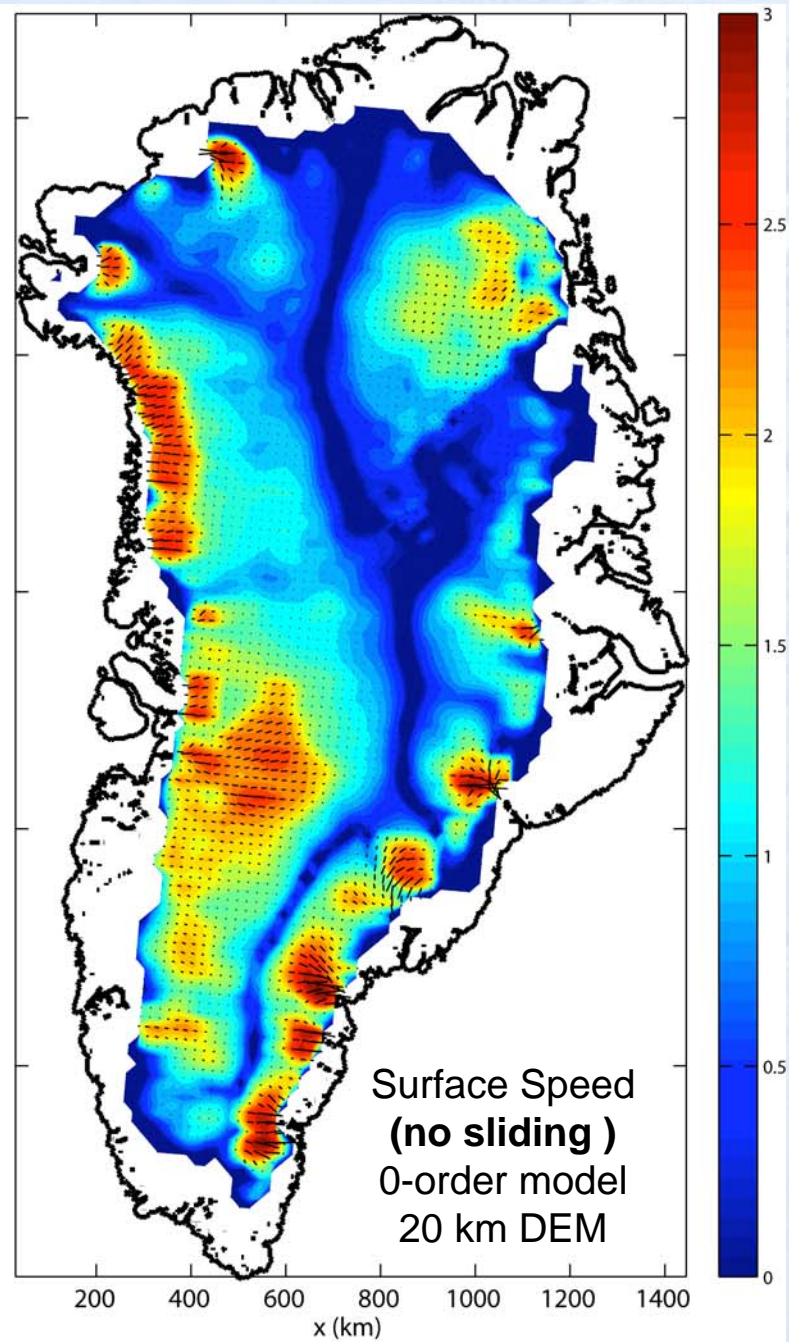
# Glimmer Community Ice Sheet Model

- Evolved from the Glimmer model developed by Tony Payne (U. Bristol) and colleagues; supported by NERC, NSF, DOE
- Available at <http://glimmer-cism.berlios.de/>
- New dycores are being developed under the DOE ISICLES project
  - Parallel, scalable codes with efficient solvers
  - More accurate ice-flow dynamics
  - Adaptive and unstructured meshes
- New version, Glimmer-CISM 2.0, to be released soon
  - Includes Payne-Price higher-order dycore with Trilinos solver packages

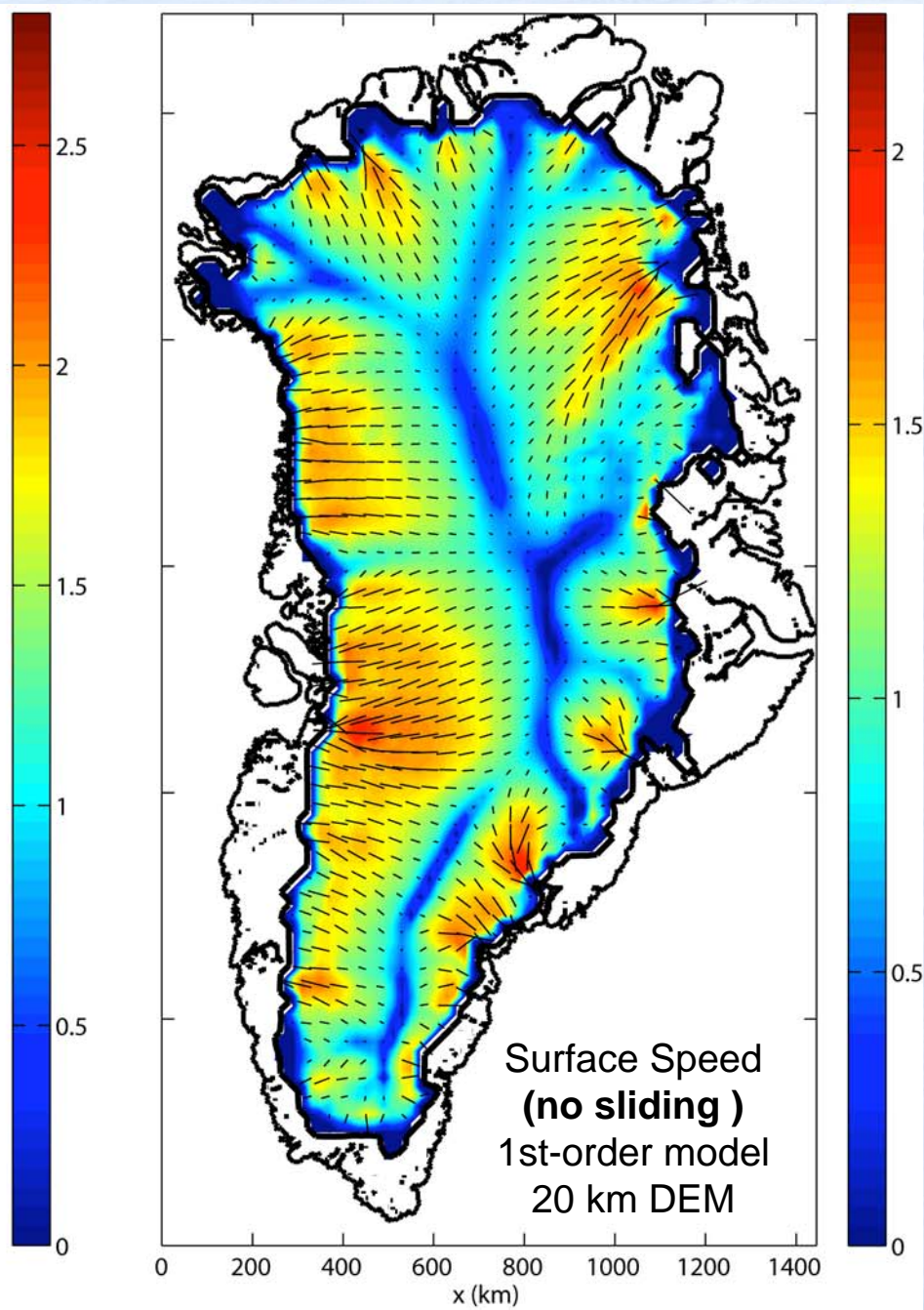
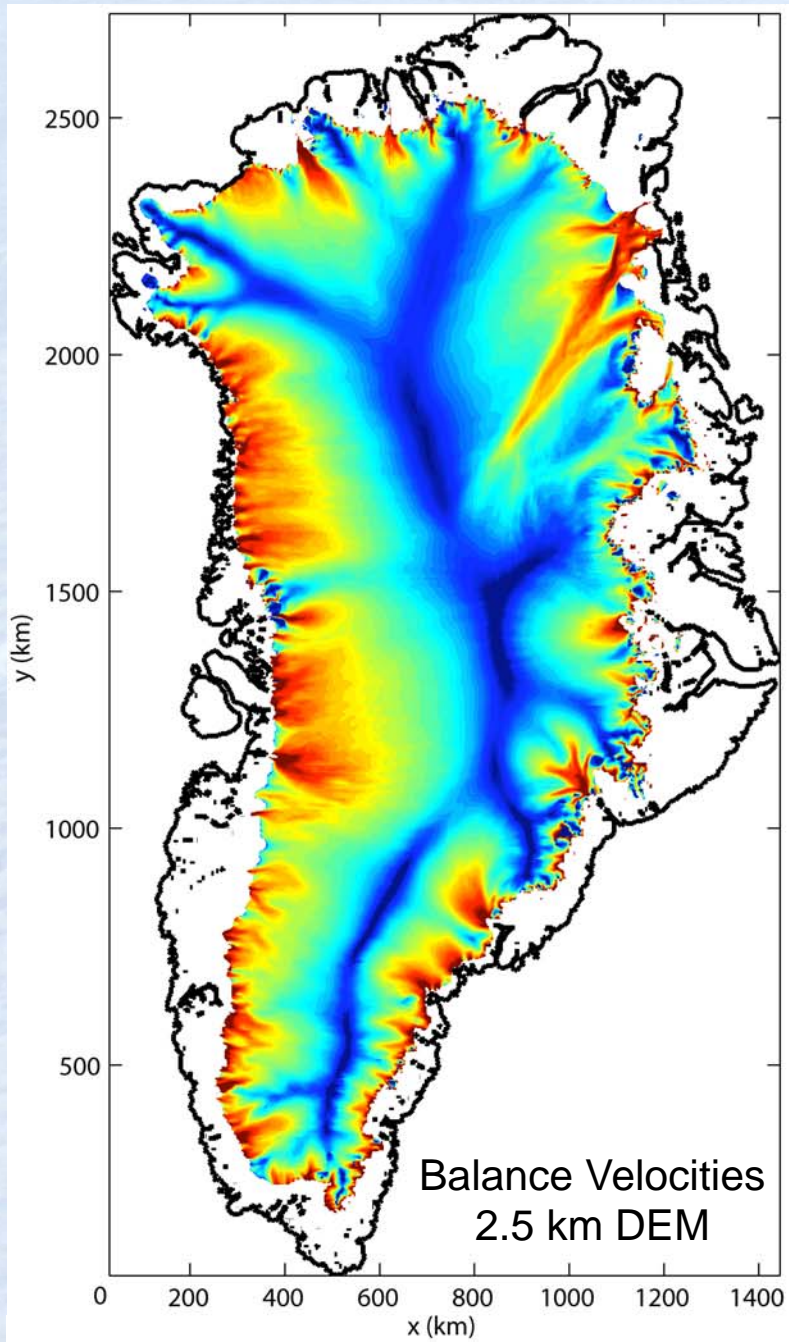




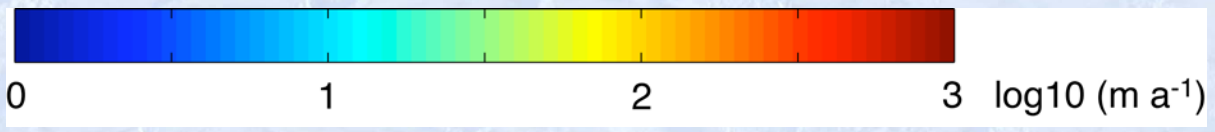
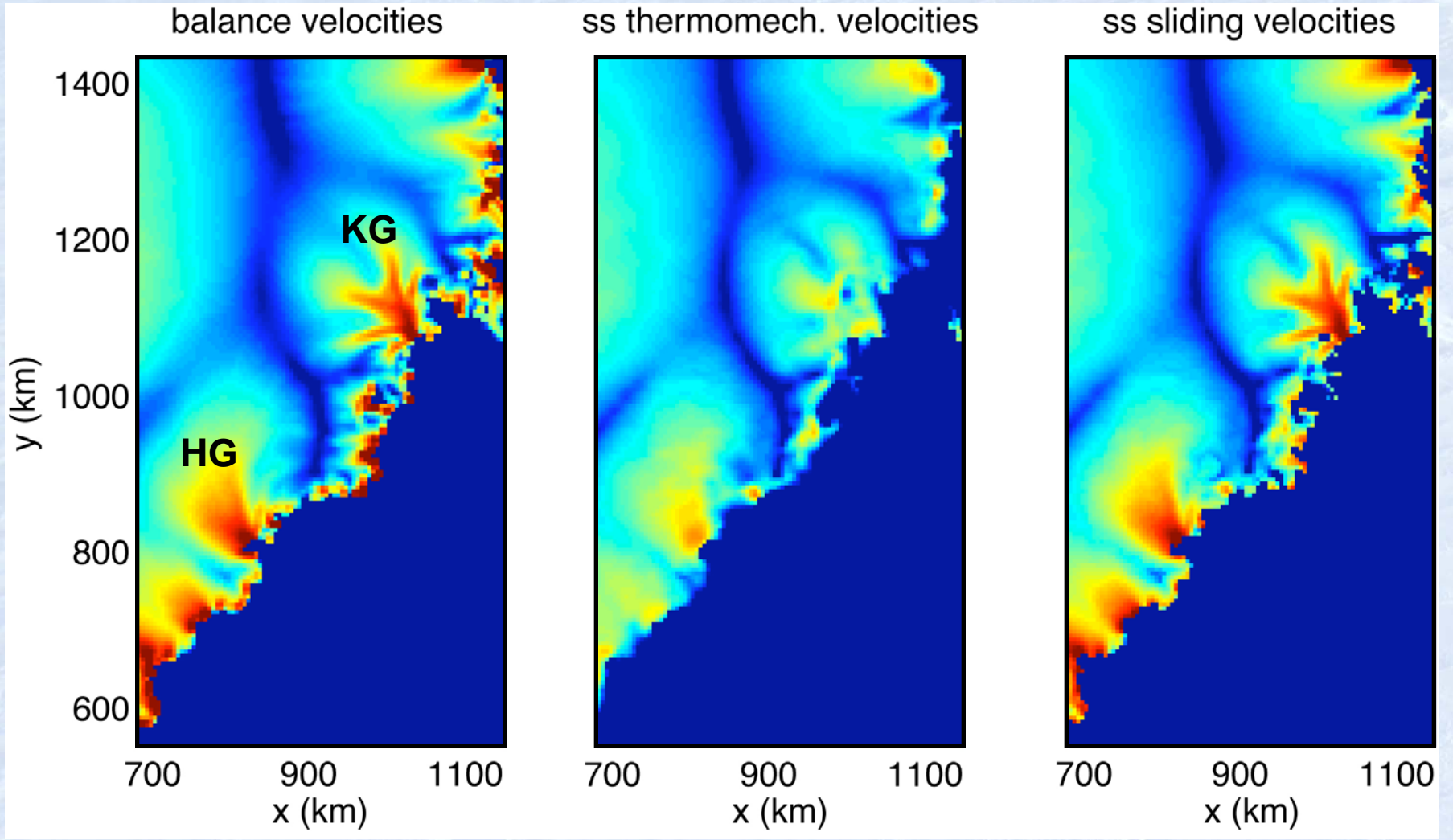
Bamber et al. (*J.Glac.*, v.46, 2000)



Bamber et al. (*Ann.Glac.*, v.30, 2000)

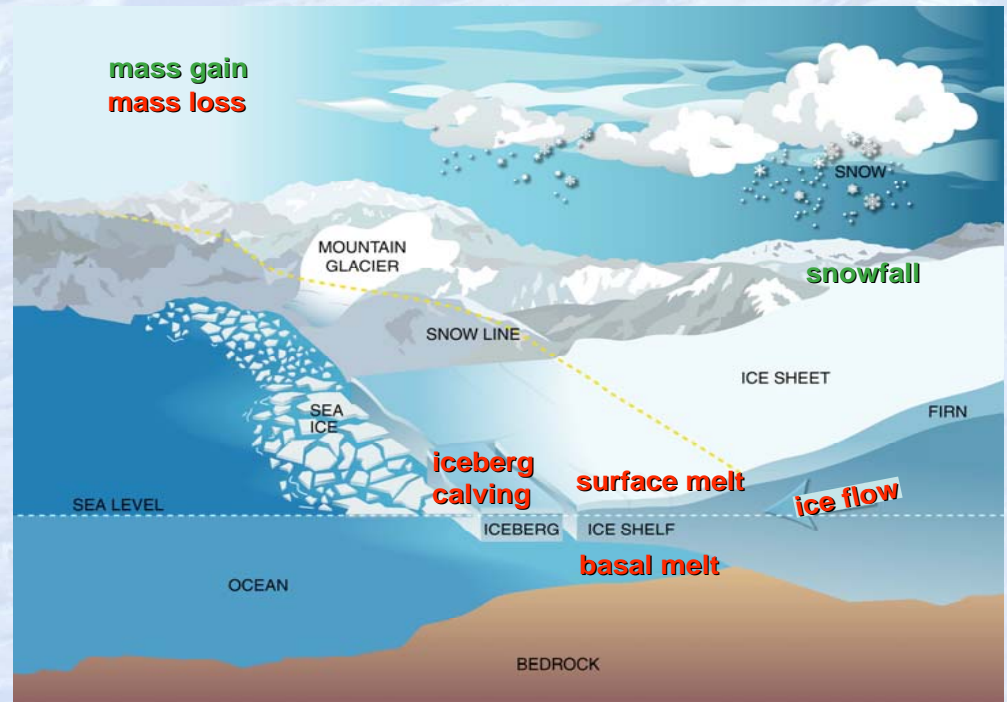


Bamber et al. (*J.Glac.*, v.46, 2000)



# Outline

- Land ice in CESM1.0



# CESM Land Ice Working Group

## Objectives

- To couple a well validated, fully dynamical ice sheet model to CESM
- To determine the likely range of decade-to-century-scale sea-level rise associated with the loss of land ice.

## Leadership

- Co-chairs: William Lipscomb (LANL), Jesse Johnson (U. Montana)
- Science liaison: Stephen Price (LANL)
- Software liaison: William Sacks (NCAR)

## LIWG info

- Web site: [http://www.cesm.ucar.edu/working\\_groups/Land+Ice/](http://www.cesm.ucar.edu/working_groups/Land+Ice/)
- Email list: <http://mailman.cgd.ucar.edu/mailman/listinfo/ccsm-liwg>

## Community Ice Sheet Model (CISM) development

- New subversion repository: <https://svn-cism-model.cgd.ucar.edu/>
- Repo access form:  
[http://www.cesm.ucar.edu/working\\_groups/Software/secp/repo\\_access\\_form.shtml](http://www.cesm.ucar.edu/working_groups/Software/secp/repo_access_form.shtml)



# Climate modeling assumptions, c. 2007

- The climate system consists of four components (atmosphere, land, ocean and sea ice) linked by a coupler.
- The extent and elevation of ice sheets are fixed for all time.
- The boundary between the land surface and the atmosphere is fixed.
- The boundary between the land and the ocean is fixed.
- The upper surface of the ocean is the atmosphere (possibly with a thin layer of sea ice in between). At the lateral edge of an ice shelf, the ocean sees a vertical wall.

**Conventional wisdom:** Ice sheets were not included in global climate models because they were believed to be too sluggish to respond to climate change on time scales of human interest.

**Alternate view:** Ice sheets were not included in global climate models because they move. (And for this reason require a thorough rethinking and re-engineering of the model infrastructure.)

# Ice sheets in CESM 1.0

- CESM 1.0 (released in June 2010) includes the **Glimmer Community Ice Sheet Model (Glimmer-CISM)**, an open-source code available at <http://glimmer-cism.berlios.de/>.
  - Supports a dynamic Greenland ice sheet on 5, 10 and 20 km grids
  - Currently shallow-ice (Glimmer-CISM 1.6), but a higher-order version (Glimmer-CISM 2.0) will be added to CESM this year.
  - Coupling framework is designed so that Glimmer-CISM updates can be incorporated easily.
- CESM also includes a **surface-mass-balance scheme for land ice**.
  - The surface mass balance is computed by the land surface model (CLM) in multiple elevation classes, then sent to Glimmer-CISM and downscaled to the local ice sheet grid.
  - This scheme can be applied in all glaciated regions, not just the Greenland and Antarctic ice sheets.
  - Supported on FV1, FV2 and T31 grids

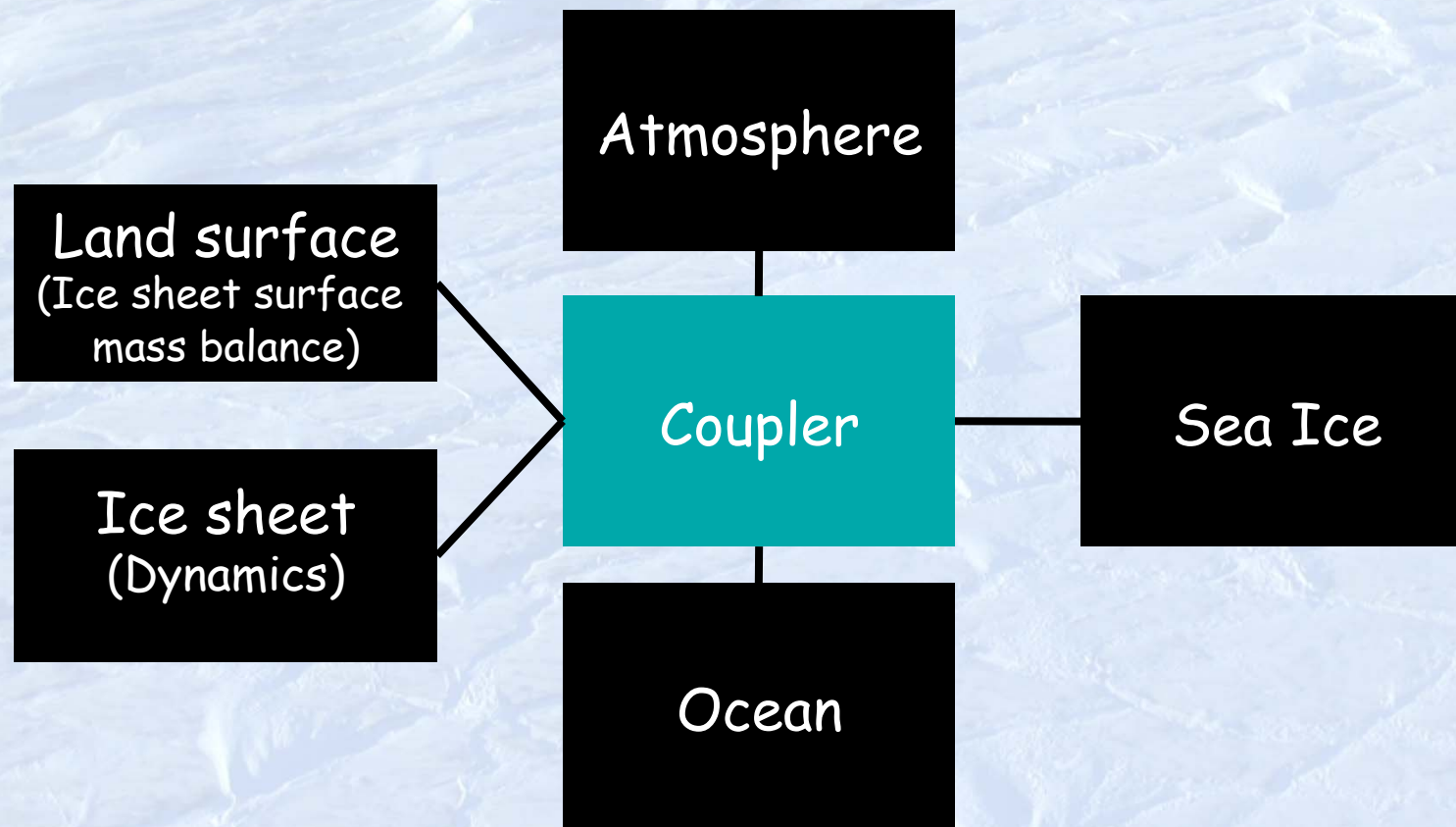
# Ice sheets in CESM

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



# Surface mass balance in CESM

- Traditional approach: Pass surface radiation and temperature fields to the ice sheet model and compute the mass balance on the fine (~10 km) ice sheet grid.
- We are computing the mass balance in the land model (CLM) on a coarse (~100 km) grid in ~10 elevation classes. Ice thickness changes are then interpolated to the ice sheet grid.
  - Energetic consistency
  - Cost savings (~1/10 as many columns)
  - Avoid code duplication
  - Surface albedo changes feed back on the atmosphere

Ice  
sheet  
grid  
cell



## Surface mass balance in CLM

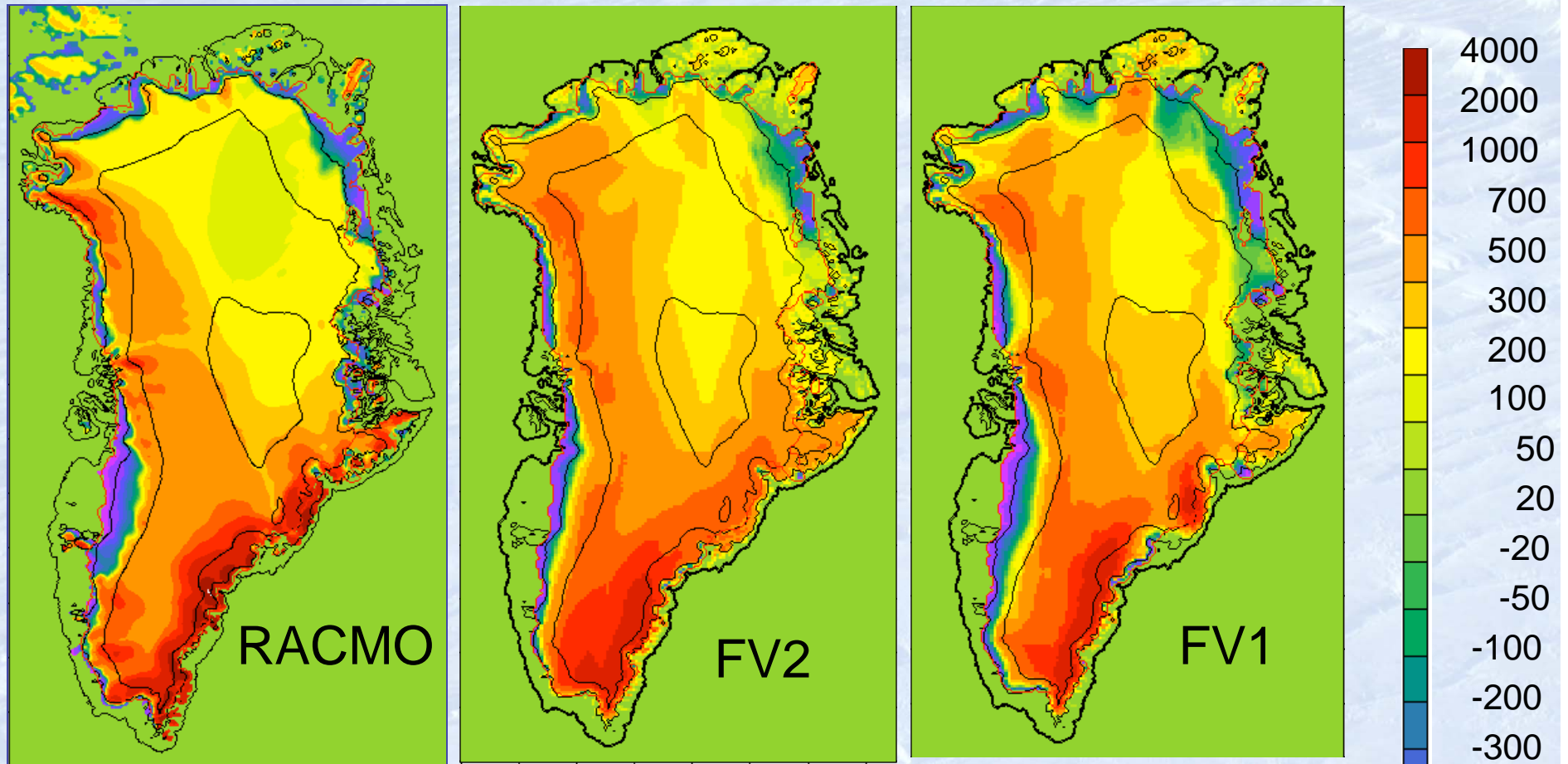
- The land model, CLM, has multiple landunits (vegetated, wetland, lake, urban, glacier) in each gridcell and allows multiple columns in each landunit.
- We have introduced a new landunit type, **glacier\_mec**, with multiple(~10) elevation classes in each gridcell. Each elevation column has its own surface fluxes and vertical temperature/snow profile.
- The surface temperature and specific humidity are downscaled to each column based on an assumed lapse rate. (Might try something fancier later.)
- CLM has fairly sophisticated surface energy-balance and snow models, which are used with modest modifications.

## Two modes of coupling

- **One-way coupling:**
  - The land model (CLM) passes the surface mass balance to the ice sheet model, but land topography is fixed.
  - Ice sheets evolve dynamically. Accuracy of forcing fields is not much affected if changes in elevation and extent are small.
- **Two-way coupling:**
  - The CLM surface topography changes as the ice sheet evolves. (In progress)

The ice sheet model supplies a freshwater flux that is routed to the ocean, but the ocean topography does not yet evolve.

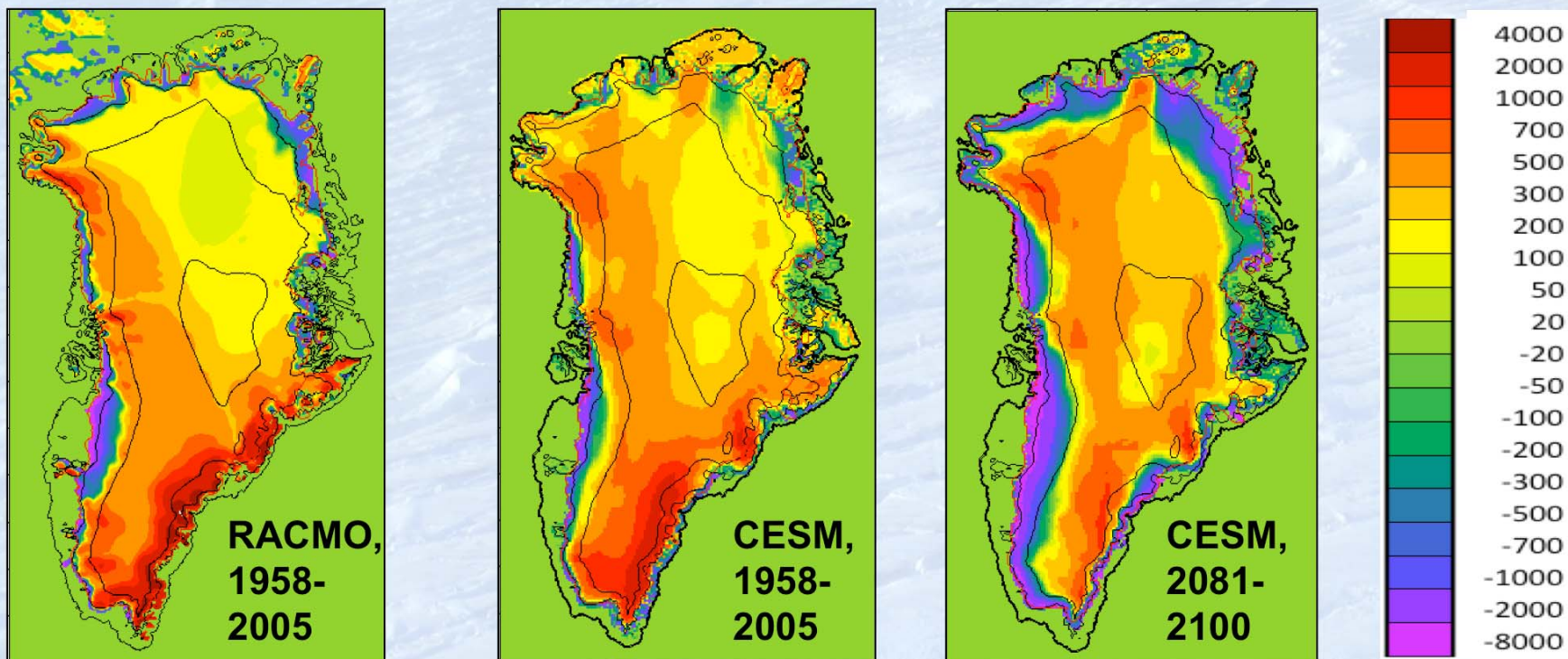
# Greenland surface mass balance in CESM (BG2000, fully coupled)



- Excellent agreement between FV1 and RACMO regional climate model (11 km grid)
- Ablation is underestimated at FV2
- Accumulation is similar, except in the SE (poor simulation of orographic forcing)

*Contours:  
Ice sheet margin,  
1000, 2000, 3000 m*

## Greenland's future surface mass balance



Land model (CLM) forced by output from coupled 21<sup>st</sup> century CESM simulations (RCP8.5)

**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)



# CMIP5 experiments with Glimmer-CISM

(0.9° x 1.25° atm, 1° ocn)

## 1. Control

- Pre-industrial control, ~150 yrs (from B1850 spinup)
- 20<sup>th</sup> century (1850-2005)

## 2. IPCC AR5 scenarios

- RCP4.5, 100+ yrs
- RCP8.5, 100+ yrs

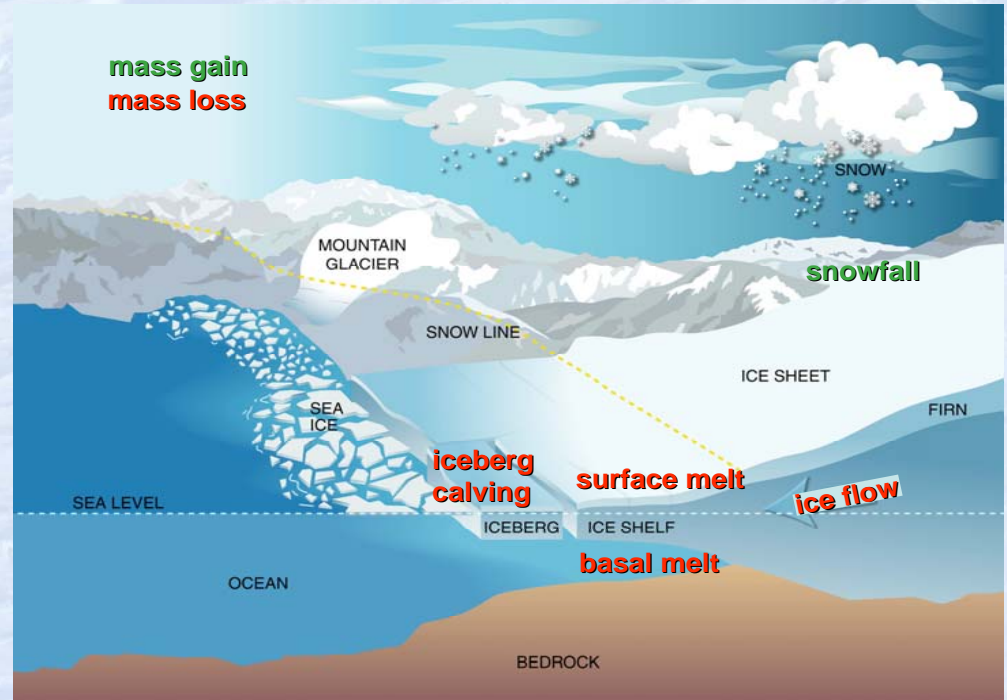
## 3. Long-term (asynchronous)

- Continuation of RCP8.5, 100 yrs (AOGCM), 1000 yrs (ice sheet)
- CO<sub>2</sub> stabilization scenarios (study irreversibility)
- Eemian interglacial

- Shallow-ice model first, then higher-order model
- Results to appear in *J. Climate* special issue on CESM

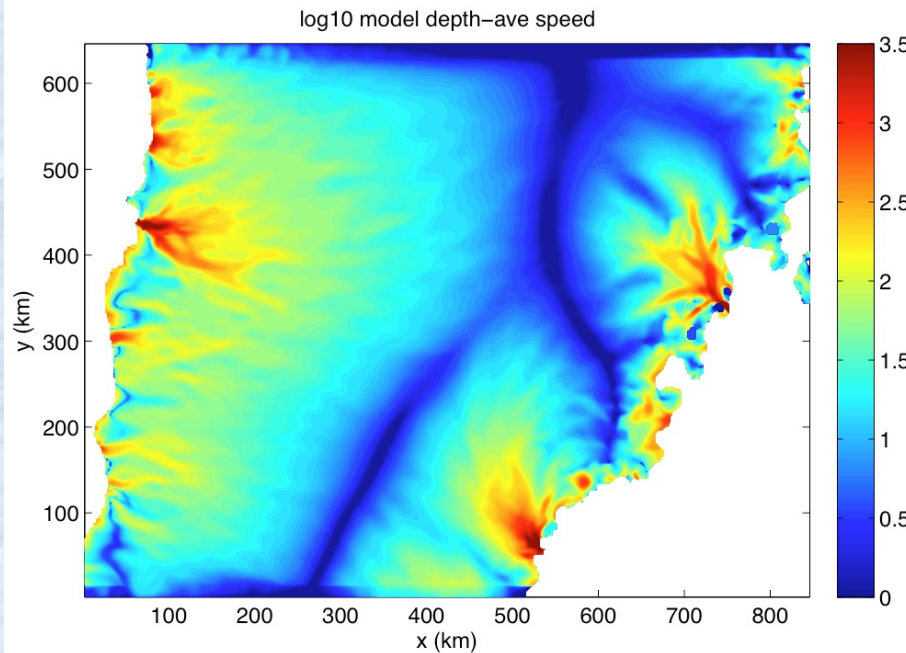
# Outline

- **Work under way**
  - Advanced ice-sheet models
  - Coupling to ocean model
  - Glaciers and ice caps

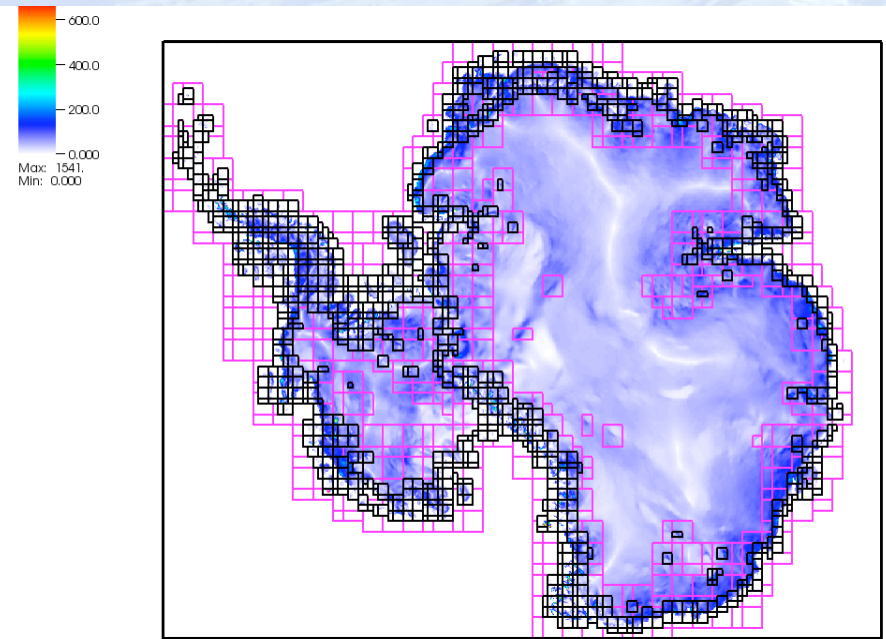


# ISICLES

- ISICLES is a 3-year DOE project that aims to use advanced numerical and computational methods (e.g., the Trilinos, PETSc, and Chombo software packages) to develop accurate, efficient, scalable ice sheet and characterize their uncertainties.



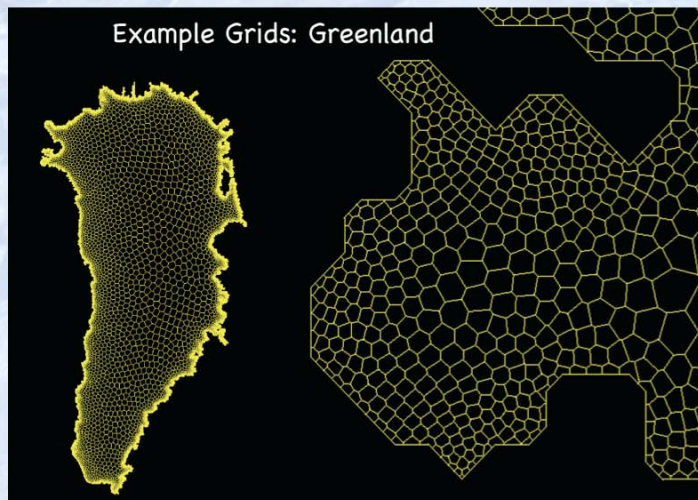
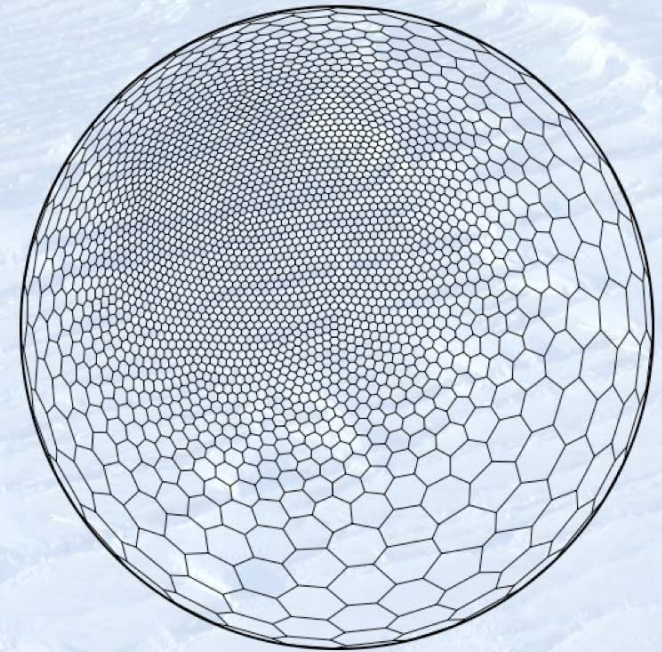
Greenland depth-averaged ice speed with 3D higher-order solver, 2-km resolution. Model used to constrain future sea-level rise from ice-sheet dynamics (S. Price et al., 2011).



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)

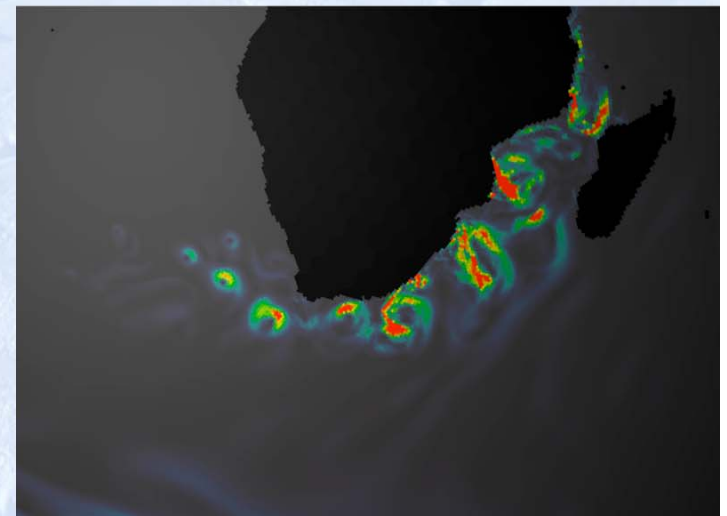
# Variable-resolution grids

- **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  $\sim 10$ .
- We have begun developing an MPAS ice sheet model using methods developed at LANL and NCAR for atmosphere and ocean models.



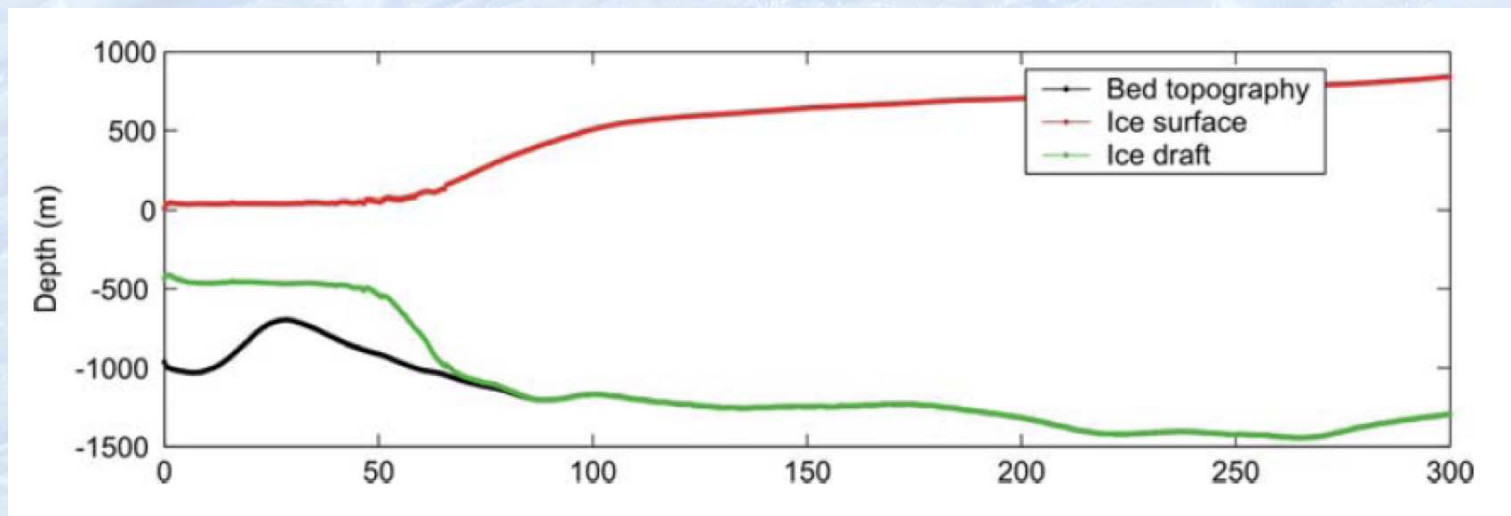
*Left:* Voronoi mesh for the Greenland ice sheet

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



# Ice-ocean coupling

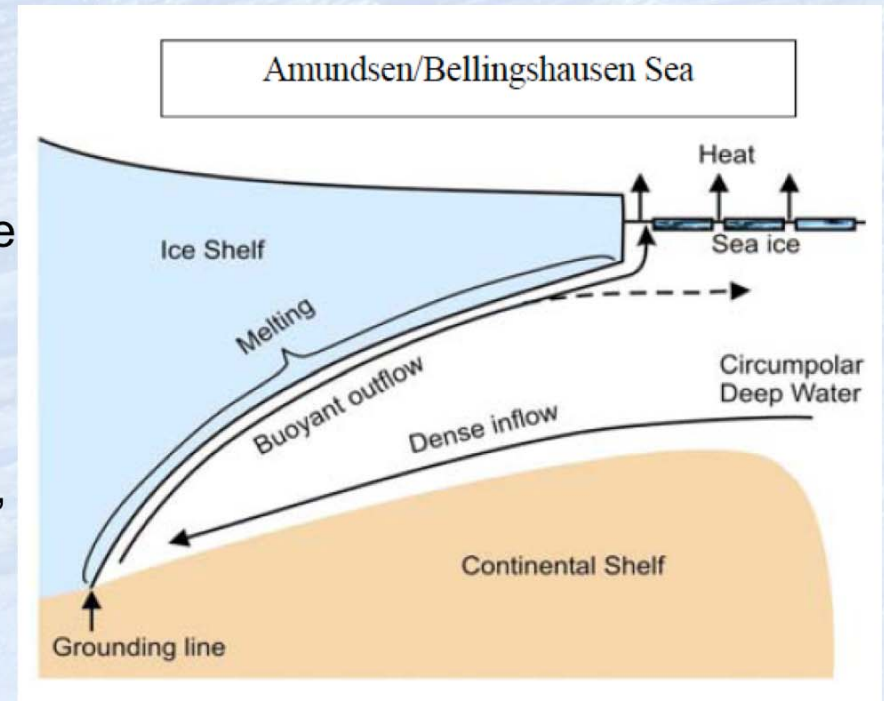
- Ice in the Amundsen/ Bellingshausen region is especially vulnerable to intrusions of warm Circumpolar Deep Water. (Note reverse-sloping beds.)
- Modest changes in wind forcing could drive large changes in delivery of warm CDW to the base of the ice shelf.
- We need to model coupled ocean/ice/atmosphere processes at small scales.



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

# Ice-ocean coupling challenges

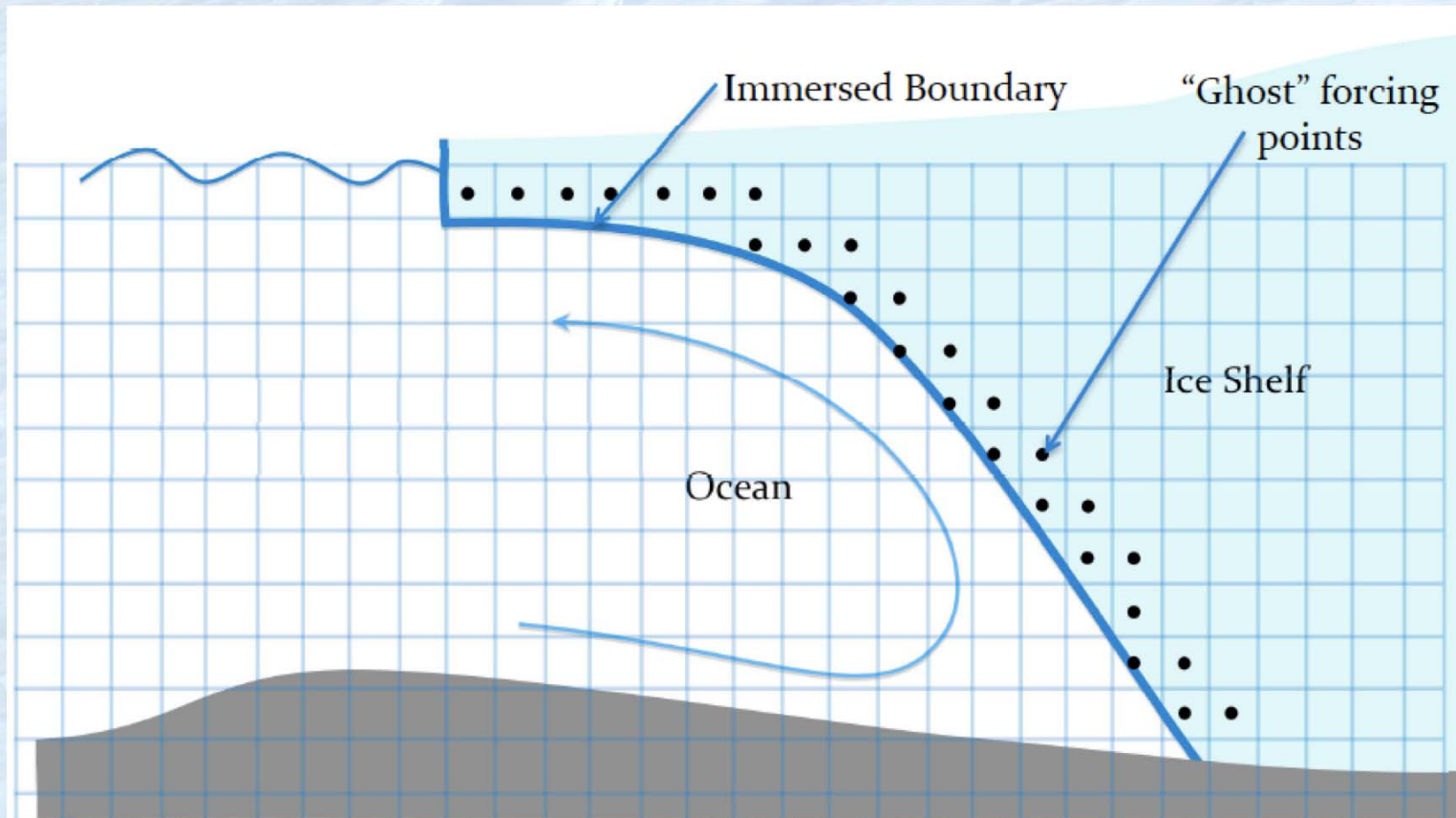
- The ocean model must be able to circulate beneath ice shelves, exchanging heat and mass at the shelf boundary.
- The ice/ocean boundary must change as ice shelves advance and retreat.
- The ice-sheet/ocean system must be spun up to steady state, with little or no climate drift. Spinup times are  $\sim 10^3$  yr for the ocean,  $\sim 10^4 - 10^5$  yr for ice sheets.
- Ocean flows near marine ice involve complex interactions at small spatial scales ( $\sim 10$  km or less) in regions that are sparsely observed.
  - Global ocean models are usually run at scales of  $\sim 100$  km.



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

# IMPACTS

- 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 are developing immersed-boundary and partial-cell methods to simulate processes at the ice-ocean interface.



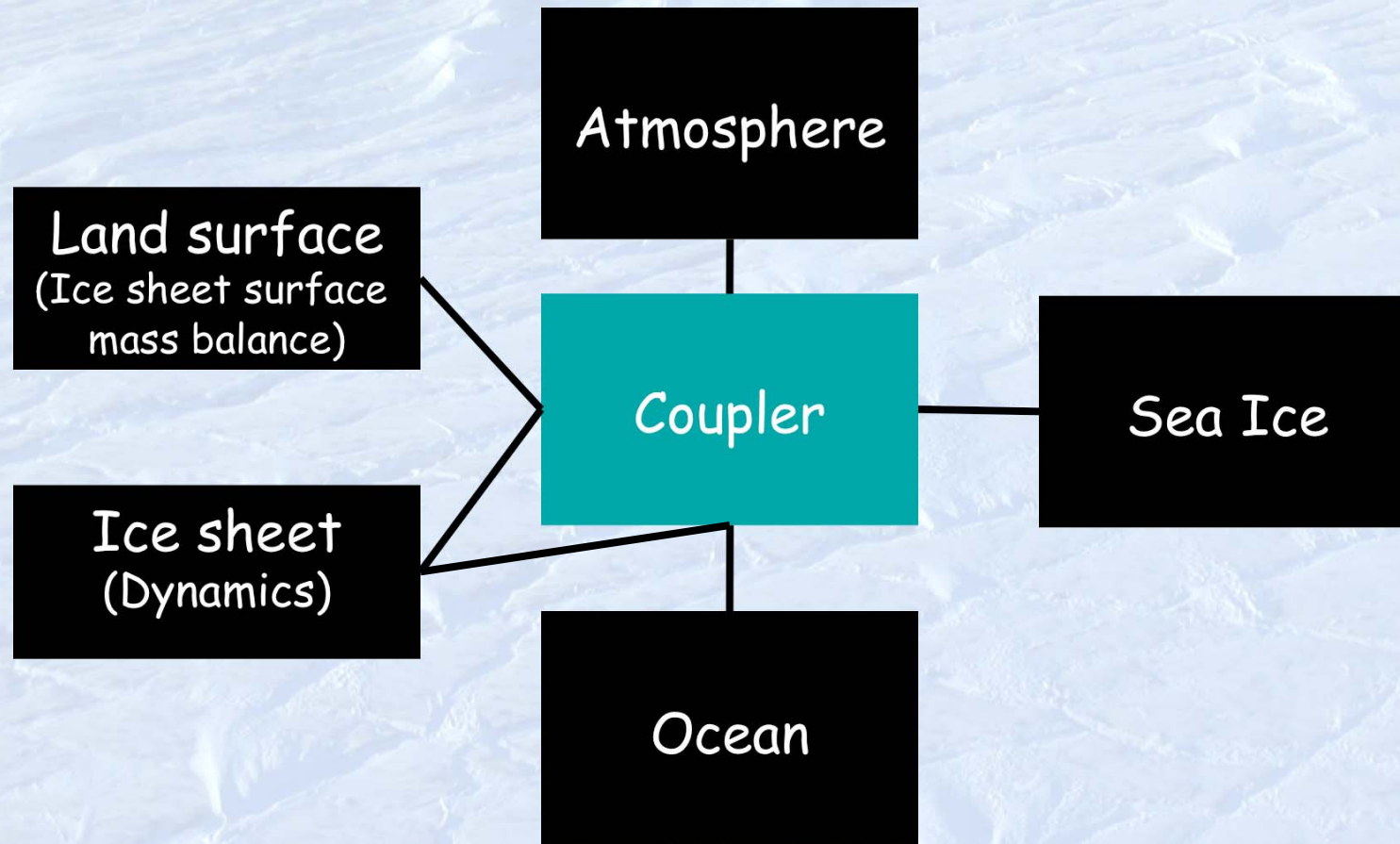
# Ice-sheet/ocean coupling in CESM (in progress)

## Ocean -> Ice sheet/shelf

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

## Ice sheet -> Ocean

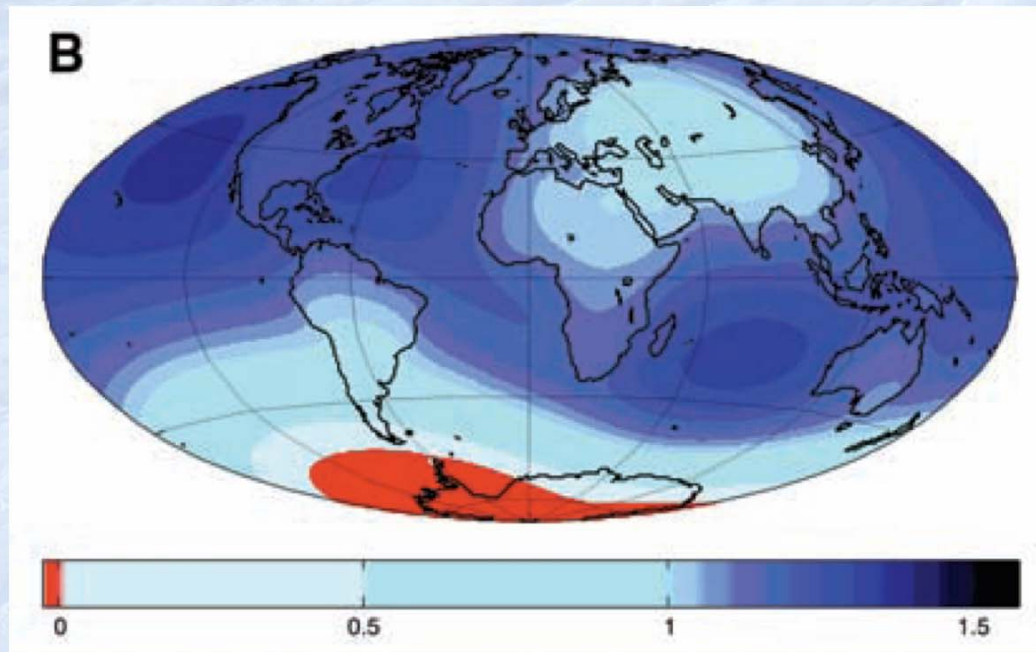
- Lower surface elevation
- Grounded/floating ice fraction
- Basal temperature info (for computing heat flux)





# Regional sea-level fingerprint

- Ice-sheet mass loss results in instantaneous elastic rebound and changes in self gravity. Sea-level changes are far from uniform.
- Migration of water away from melting ice sheets will tend to stabilize marine ice.
- We would like to include this effect in CESM (e.g., by modifying the ocean bathymetry).



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

# Glaciers and ice caps

- The area of glaciers and ice caps (GIC) outside of ice sheets is  $\sim 700,000 \text{ km}^2$ .
- The ice volume of GIC is enough to raise mean sea level by  $\sim 60 \text{ cm}$ .
- As measured by accumulation areas, most GIC are far from equilibrium with present-day climate (Mernild et al., submitted).
- 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)

# Summary

- CESM 1.0 has limited ice-sheet modeling capabilities (Greenland, shallow-ice, one-way coupling).
- Future model versions will be more realistic:
  - Higher-order dynamical cores
  - Improved physics parameterizations
  - Two-way land/ice-sheet coupling
  - Two-way ocean/ice-sheet coupling
  - Antarctic and paleo ice sheets
  - Glaciers and ice caps
- Once these features are in place, CESM will have the technical capabilities needed to model decade-to-century scale evolution of glaciers and ice sheets, and resulting sea-level rise
- However, many long-term challenges will remain:
  - Understand coupled interactions
  - Constrain models with new observations
  - Quantify uncertainties

# Tutorials

CISM tutorials prepared at LANL are available here:

<http://oceans11.lanl.gov/twiki/bin/view/Cosim/MaterialCISM>

These are for the machine *mapache*, but most of the material applies to *bluefire* and other machines.

# Acknowledgments

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