# Modeling Land Ice in the Community Earth System Model

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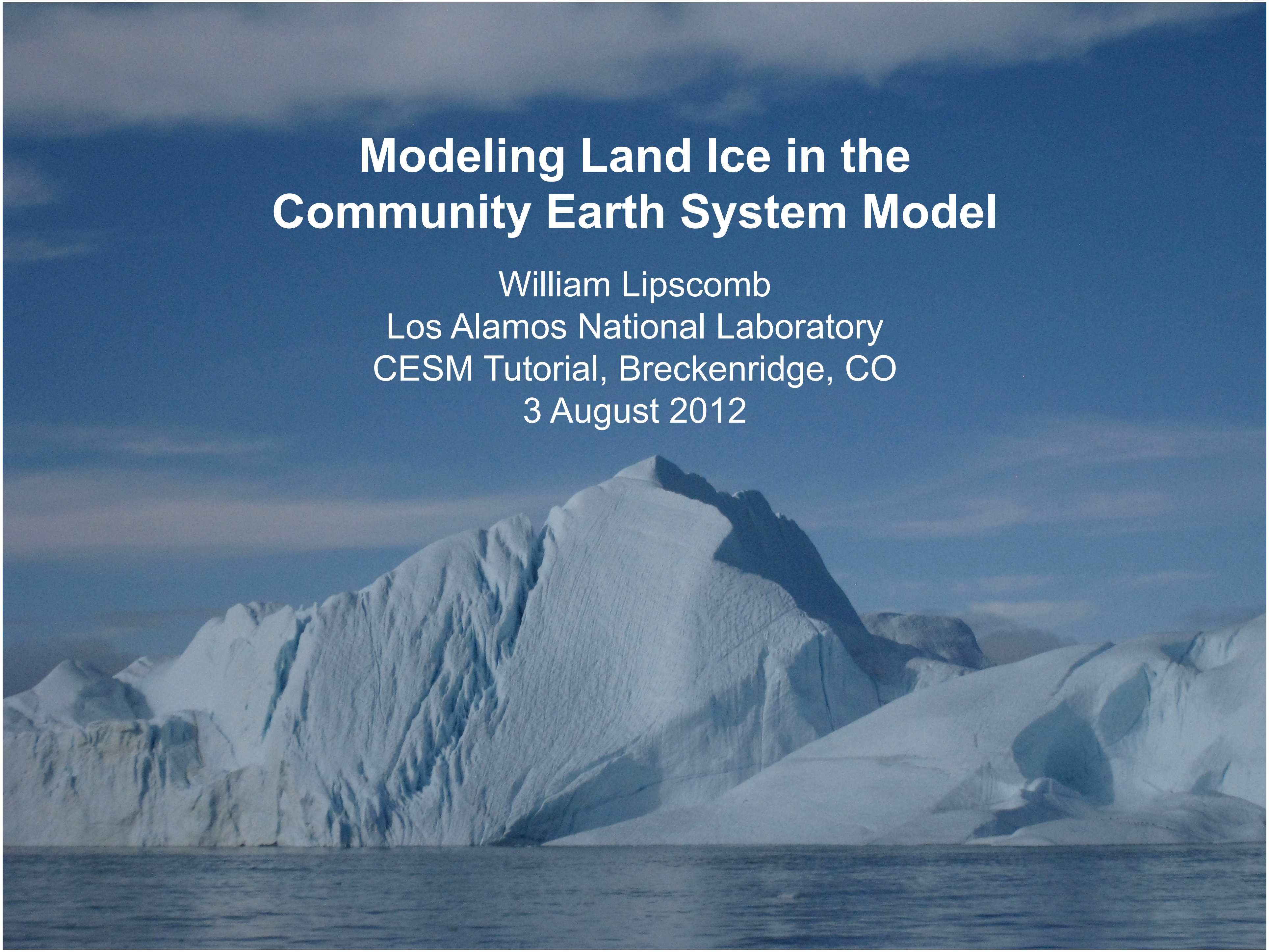


# Outline

- Motivation for simulating land ice in Earth-system models
- Introduction to ice sheet models
- Ice sheets in CESM1.0
- Work under way
  - Glacier/ice-cap model
  - Improved ice-sheet models
  - Coupling to ocean model

# Definitions

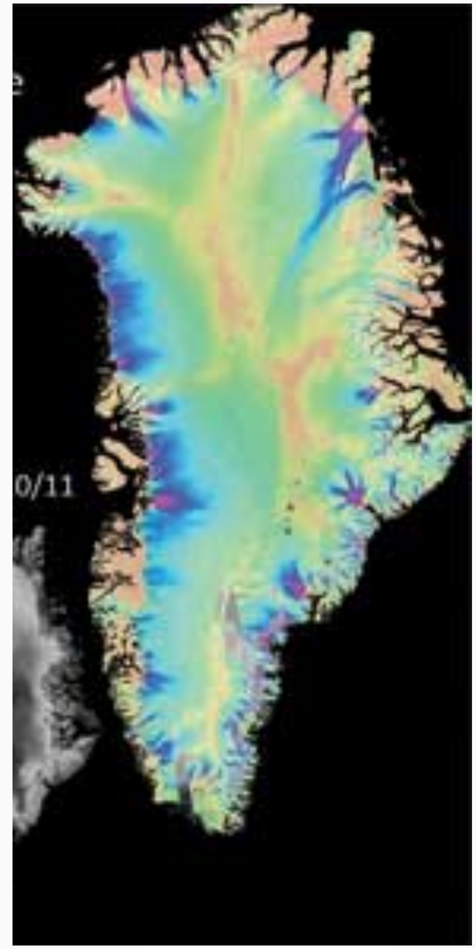
- A **glacier** is a mass of ice, formed from compacted snow, flowing over land under the influence of gravity.
- An **ice sheet** is a mass of glacier ice greater than 50,000 $km^2$ (Antarctica, Greenland).
- An **ice cap** is a mass of glacier ice smaller than 50,000 $km^2$ (e.g., in Iceland, Canadian Arctic) but large enough to make its own topography.
- 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.
- **Land ice** includes all forms of glacier ice (ice sheets, ice shelves, ice caps, mountain glaciers).
- **Sea ice** is ice that forms from frozen seawater on the ocean surface.

# Motivation for modeling land ice

- **Provide useful predictions of land-ice retreat and the resulting sea-level rise.**
  - Even modest sea-level rise greatly increase the odds of damaging floods from storm surges.
  - Projections of $21^{st}$ century sea-level rise are very uncertain.
  - The biggest uncertainties are associate with the evolution of land ice (ice sheets and glaciers).
- **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)

# Greenland Ice Sheet

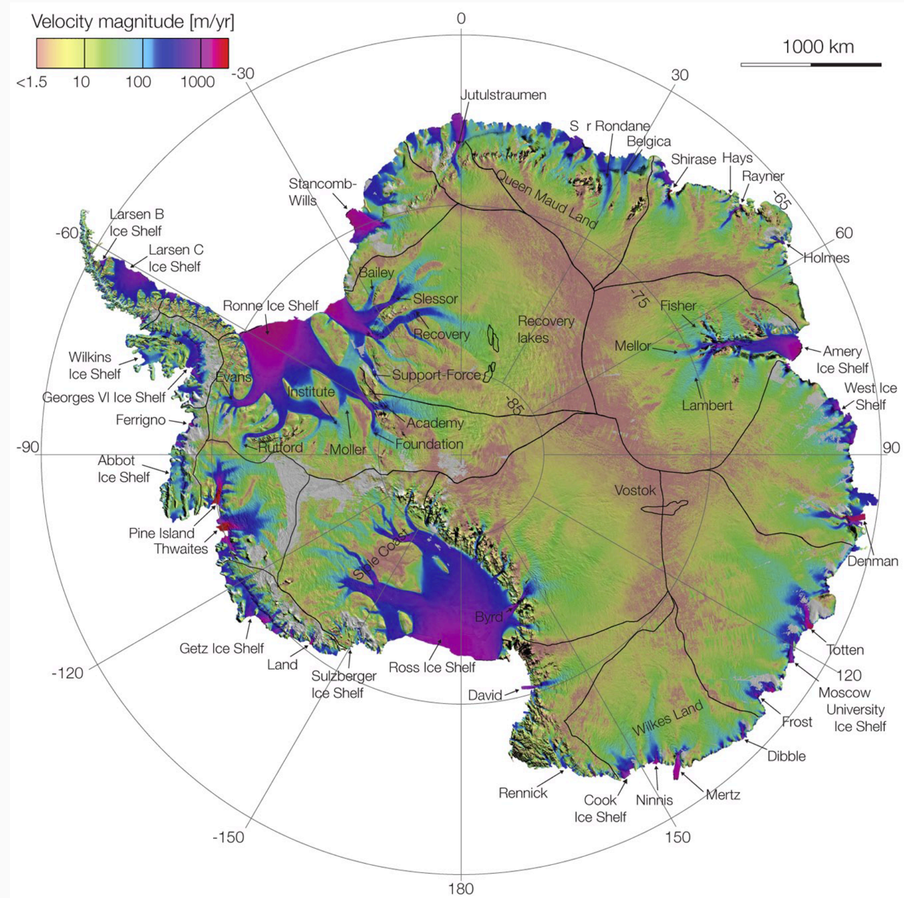
- **7 m** sea-level equivalent
- Accumulation balanced by surface runoff and iceberg calving
- Increasing mass loss (**~200 Gt/yr**) since late 1990s from increased surface melting, combined with thinning and acceleration of large outlet glaciers



Greenland winter flow speed (Greenland Ice Mapping Project)

# Antarctic Ice Sheet

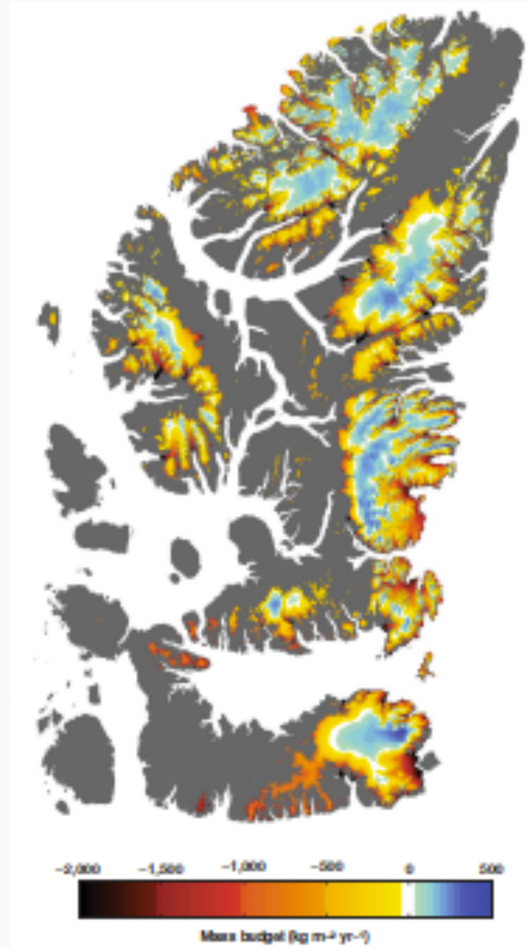
- **60 m** sea-level equivalent (**~5 m** in marine-grounded parts of West Antarctica)
- Accumulation balanced by flow into floating ice shelves; little surface melting
- Increasing mass loss (**~150 Gt/yr**) from West Antarctica and the Antarctic Peninsula, triggered by warm ocean water reaching the base of ice shelves




Antarctic ice flow speed (Rignot et al. 2011)

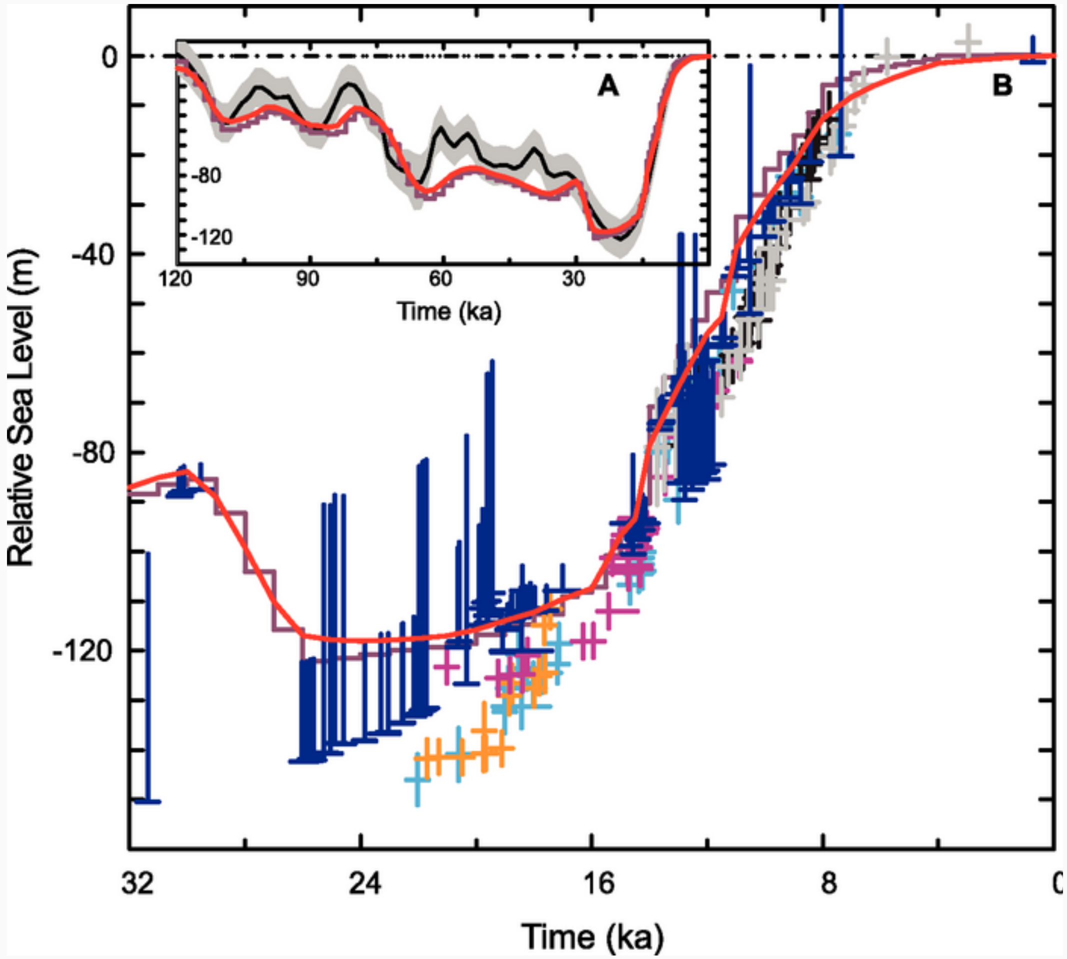
# Glaciers and ice caps

- 200,000+ glaciers and ice caps worldwide
- Only **0.6 m** sea-level equivalent (Radic & Hock 2010), but short response times
- Most glaciers are out of balance with the climate and are retreating
- Total mass loss (**~350 Gt/yr**) has usually been estimated by upscaling observations from a few dozen glaciers




Modeled surface mass budget, Canadian Archipelago, 2003–2009 (Gardner et al. 2011)

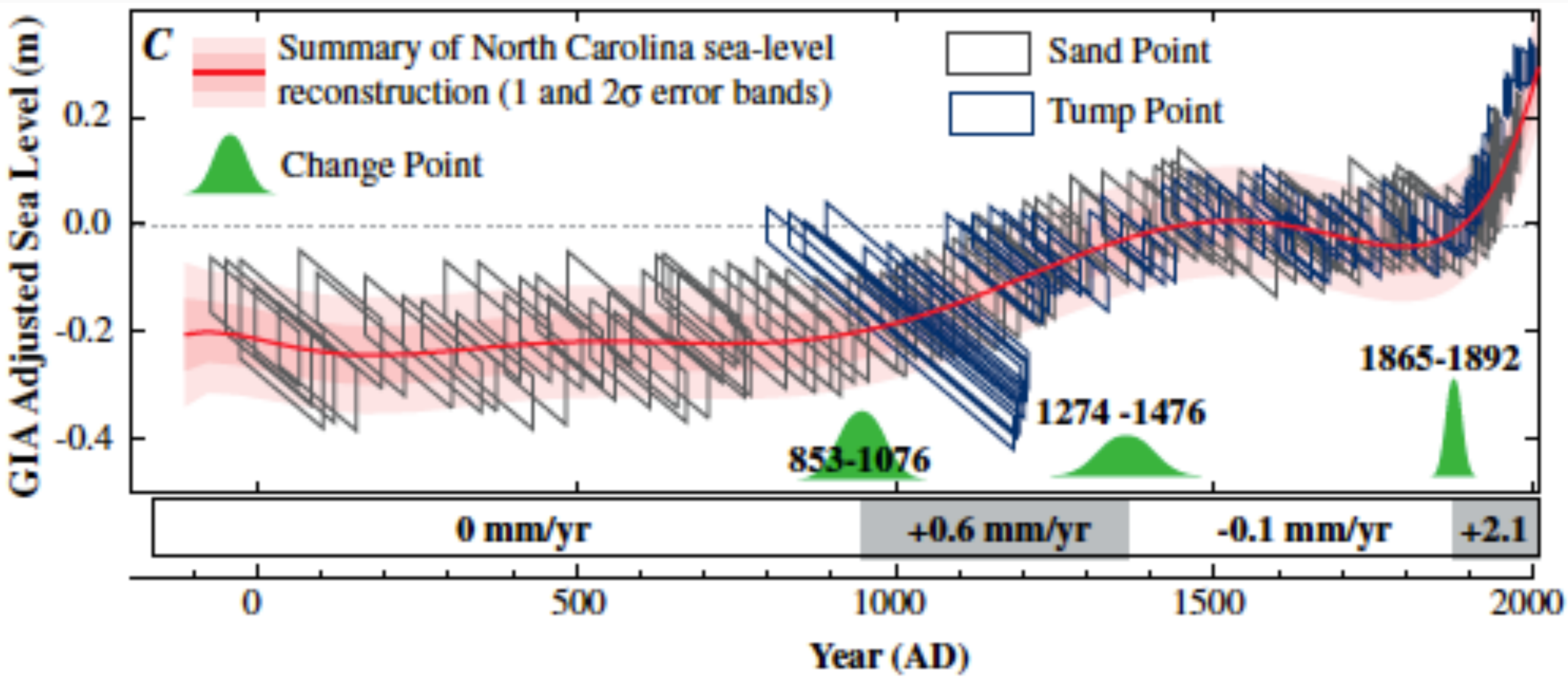
# Sea-level change since the last interglacial




IPCC AR4; from Waelbroeck et al. 2002

- Global mean sea level rose by 120 m from 20 ka to 6 ka
- Sea level was 6–10 m higher during the Last Interglacial (125 ka).

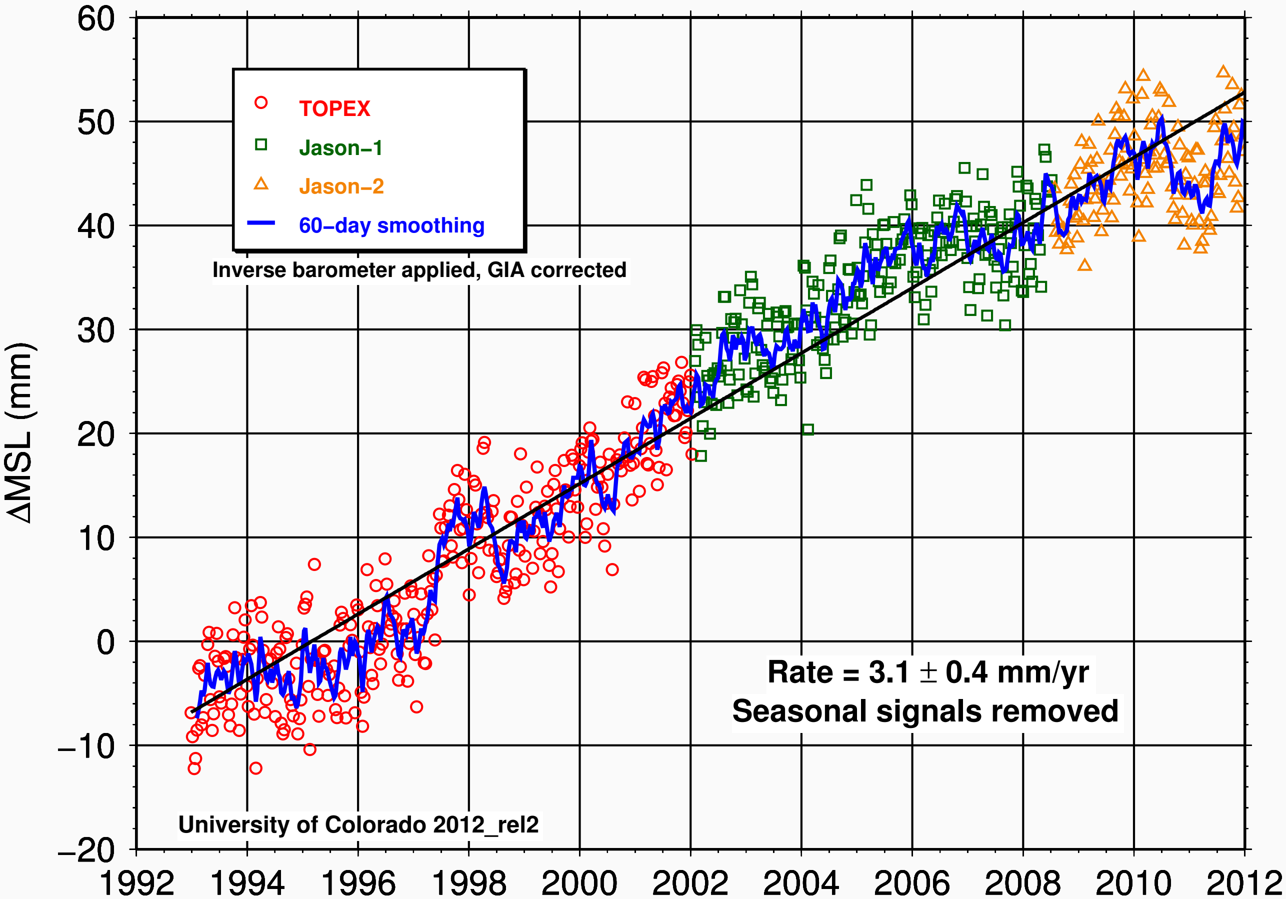
# Sea-level change over the past two millennia




Reconstructed sea level at coastal sites in N. Carolina
(Kemp et al. 2011)

SLR rate = **2.1 mm/yr** since late 19$^{th}$ century; fastest in 2000 years

# Sea-level rise over the past two decades



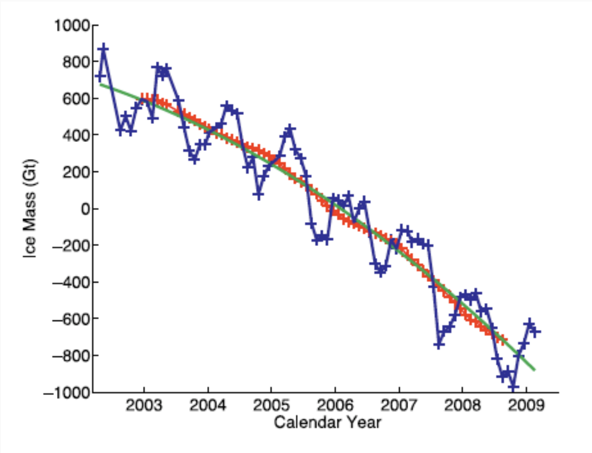

Global mean sea-level rise from satellite altimetry
(Nerem et al. 2010)

SLR rate **= 3.1 ± 0.4 mm/yr**, 1993–2012

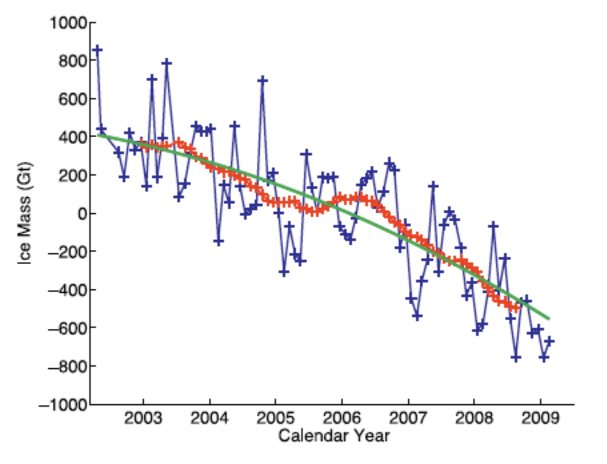
# Global sea level budget

- **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
- **Terrestrial storage**: ~0 mm/yr
  - Dam retention -0.3 mm/yr
  - Groundwater depletion 0.3 mm/yr

The ice sheet contribution has roughly doubled since 2000 and will likely continue to increase.




**Greenland ice mass loss**

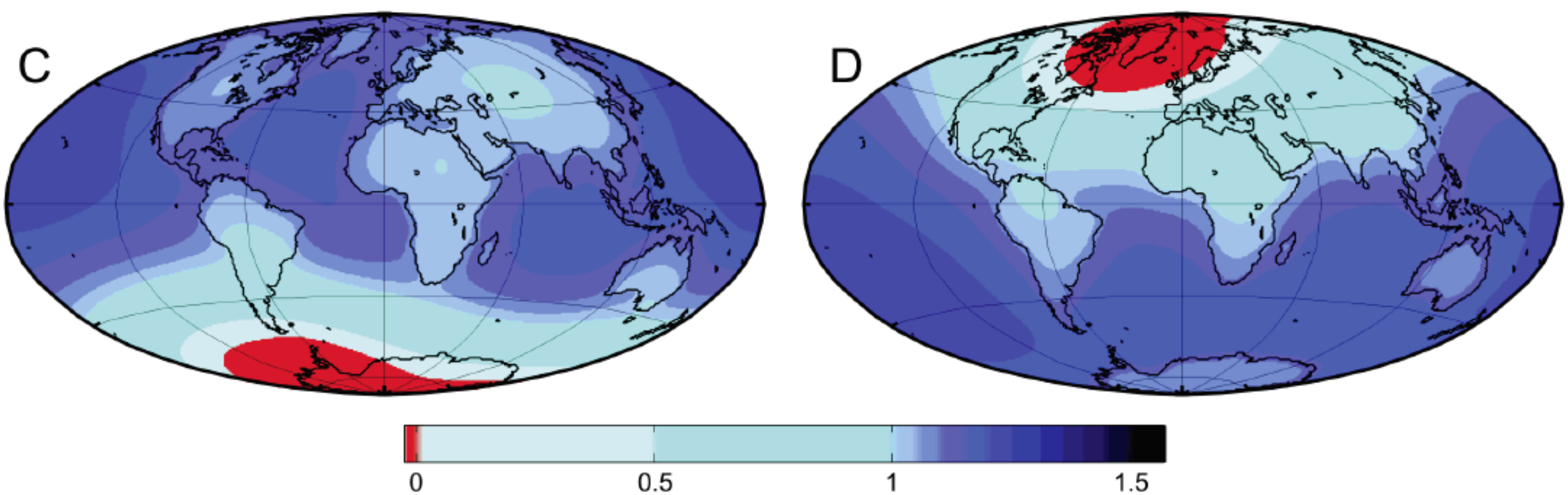



**Antarctic ice mass loss**

(Velicogna 2009)

# Regional variations from ice-sheet mass loss

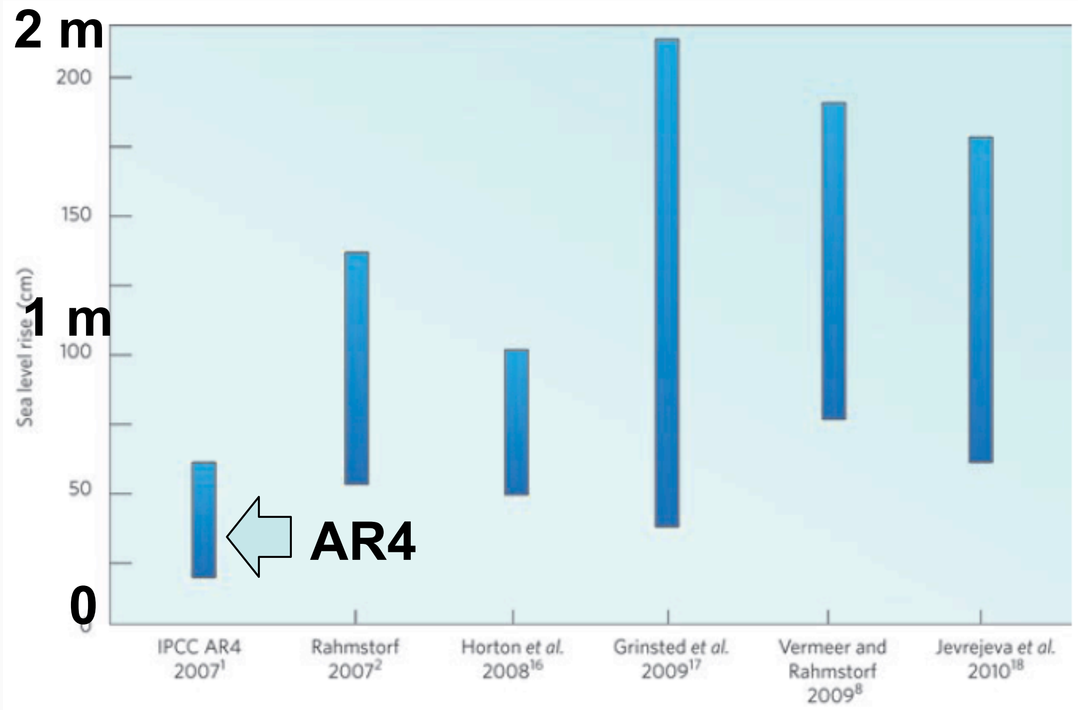
- Ice-sheet mass loss results in instantaneous elastic rebound and changes in self gravity and the Earth's rotation.
- Migration of water away from shrinking ice sheets will tend to stabilize marine ice.




Relative sea-level change from retreat of the West Antarctic Ice Sheet (left) and Greenland Ice Sheet (right) (Mitrovica et al. 2011).

# 21st century sea-level projections

- **IPCC AR4: 0.2–0.6 m**, excluding ice-sheet dynamic feedbacks
- **Semi-empirical models:** **0.5–1.5 m** (based on simple relationships between SLR and temperature/radiative forcing)
- **Pfeffer et al. 2008: 0.8-2 m** (kinematic constraints for ice sheets)




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

- Semi-empirical models project more SLR than physics-based models used in AR4; not clear why.
- More realistic physical models are needed to better constrain the uncertainty (especially **ice sheet models coupled to climate models**).

# 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:**

$$\rho c \frac{\partial T}{\partial t} = \nabla\cdot\, \left(k\nabla T\right) - \mathbf{u}\cdot\, \left(\nabla T\right) + \boldsymbol{\sigma} : \dot{\varepsilon}$$

**Conservation of Mass:**

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

# Conservation of momentum

**"deviatoric" stress = full stress - pressure**

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

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

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

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

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

$$2\dot{\varepsilon}_e = \dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}$$ effective strain rate

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

$$\tau_{ij} = 2\eta\dot{\varepsilon}_{ij}$$ constitutive relation

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

Assume static balance of forces by ignoring acceleration

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

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

# (2) Climate Coupling: Mass Balance Terms

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

**momentum balance**

**(dycore)**

**coupling to atmos. and land model**

**coupling to ocean model**

## (3) Physics (everything else)

**Constitutive laws**

**Basal sliding submodels / parameterizations**

**Surface and subglacial hydrology**

**Iceberg calving**

**etc…**

# Ice sheets in global climate models

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

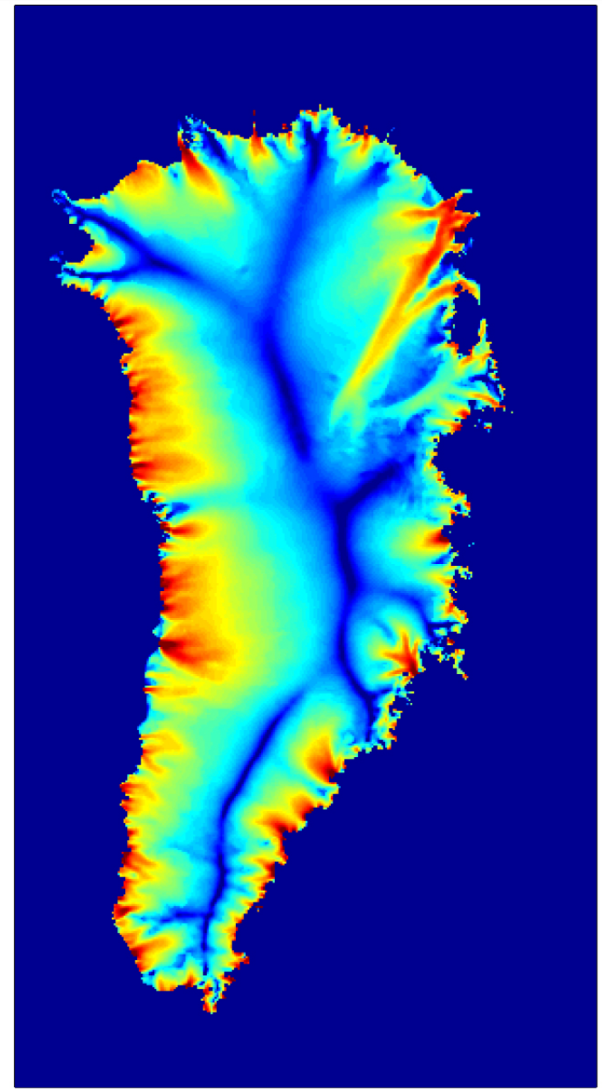
- Interactions with the **atmosphere**:
  - *Albedo feedback:* Warmer temperatures result in increased melting, darker surface, and additional warming.
  - *Ice geometry feedbacks*: As an ice sheet shrinks, its surface warms, and regional circulation can change.
- Interactions with the **ocean**:
  -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

# Ice sheets in CESM 1.0

- CESM 1.0 (released in June 2010) includes the **Glimmer Community Ice Sheet Model (Glimmer-CISM)**
  - Supports a dynamic Greenland ice sheet on a 5 km grid
  - Currently shallow-ice (Glimmer-CISM 1.6)
  - A higher-order version (Glimmer-CISM 2.0) will be added to CESM later this year.
- 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 the coupler and downscaled to the local ice sheet grid.
  - This scheme can be applied in all glaciated regions, not just ice sheets.

# Glimmer Community Ice Sheet Model

- Evolved from the Glimmer model developed by Tony Payne (U. Bristol) and colleagues
- Open-source code written mostly in Fortran 90
- Version 1.0 (in CESM) is a serial code that uses the shallow-ice approximation.
- Version 2.0, to be released later this year, is a parallel code with a higher-order dycore.



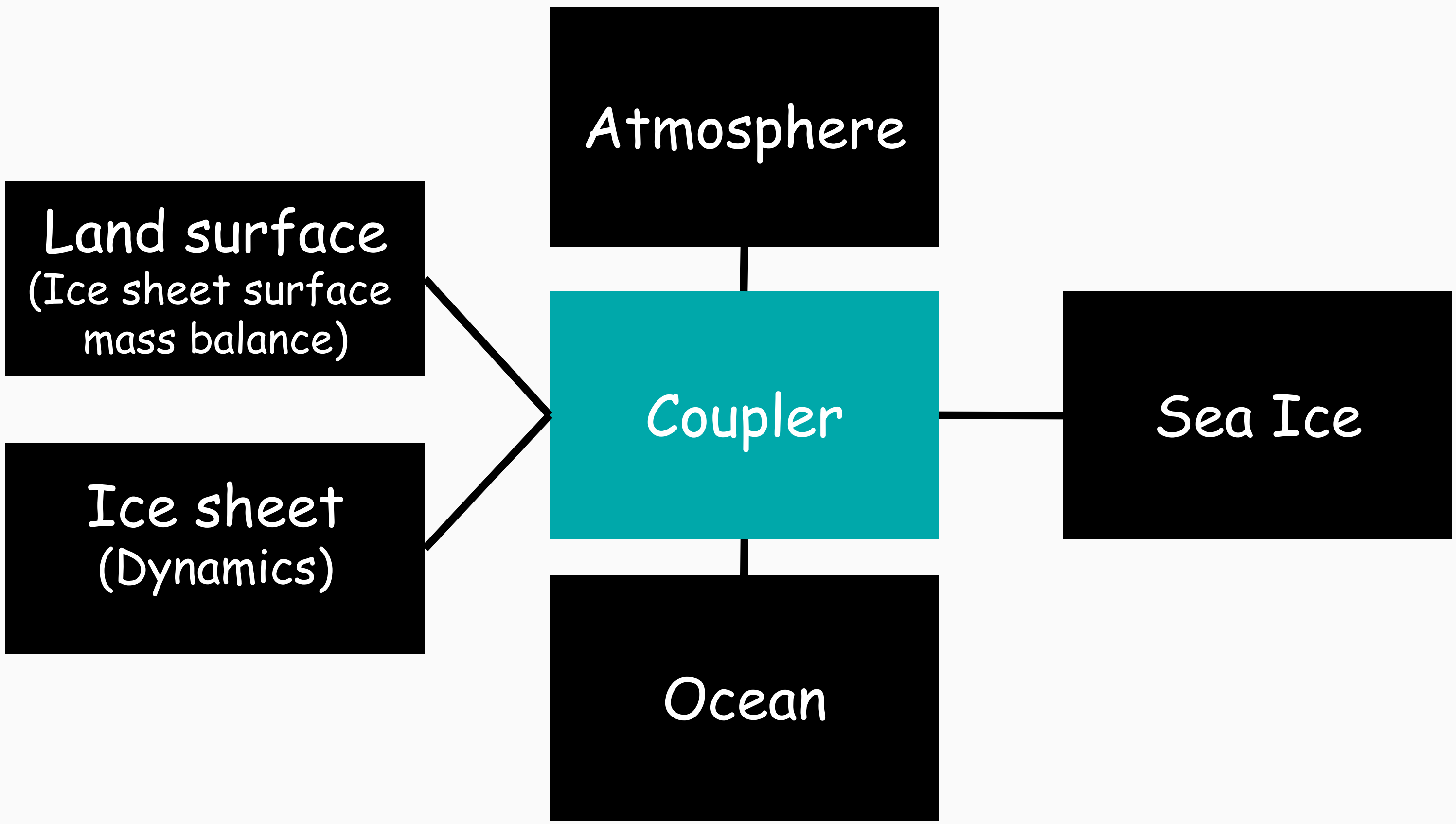
# Ice sheets in CESM 1.0

Land -> Ice sheet (10 classes)

- Surface mass balance
- Surface elevation
- Surface temperature

Ice sheet -> Land (10 classes)

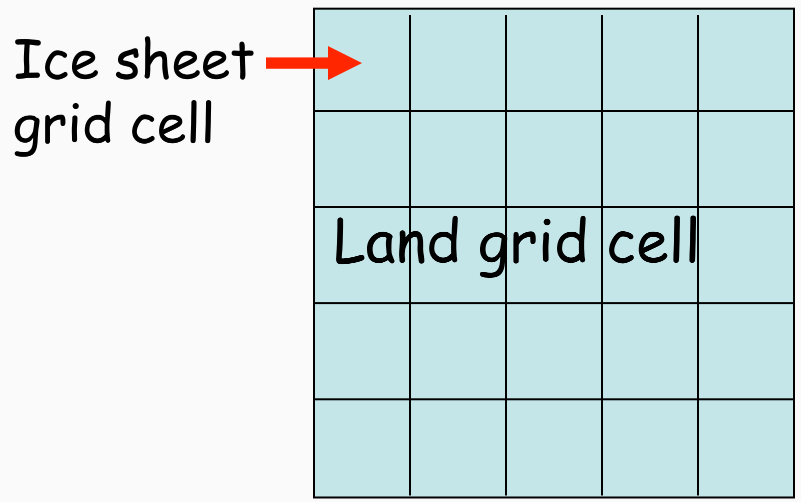
- Ice fraction and elevation
- Runoff and calving fluxes
- Heat flux to surface



# Ice sheet surface mass balance in CESM

- Traditional approach: Pass temperature and precipitation fields to the ice sheet model and compute the mass balance using a positive-degree-day scheme

- CESM computes the SMB in the land model (CLM) on a coarse (~100 km) grid in 10 elevation classes
  - Cost savings (~1/10 as many columns)
  - Energetic consistency
  - Avoid code duplication
  - Surface albedo changes feed back on the atmosphere



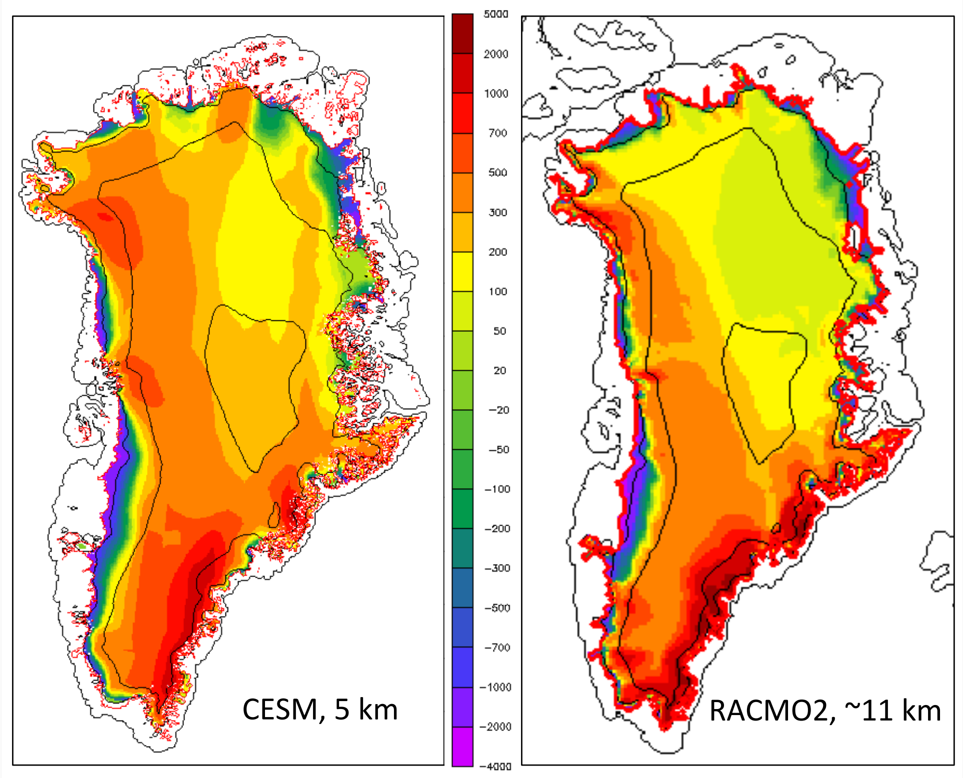
# Two modes of coupling

- **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:**
  - CLM surface topography and surface types change as the ice sheet evolves.
  - This requires dynamic landunits (glacier←→ vegetated), which are under development.

# Comparison with RACMO

| | CESM | RACMO2 |
|---|---|---|
| SMB (Gt/yr) | **359** ± 120 | **376** ± 117 |

**Greenland ice sheet SMB (kg m$^{-2}$ yr$^{-1}$), 1960-2005**




Courtesy of M. Vizcaíno

- Good match in ablation zones
- Accumulation is overestimated in the interior and underestimated in the southeast (smoother orography in CESM)

# Greenland surface mass balance in CESM

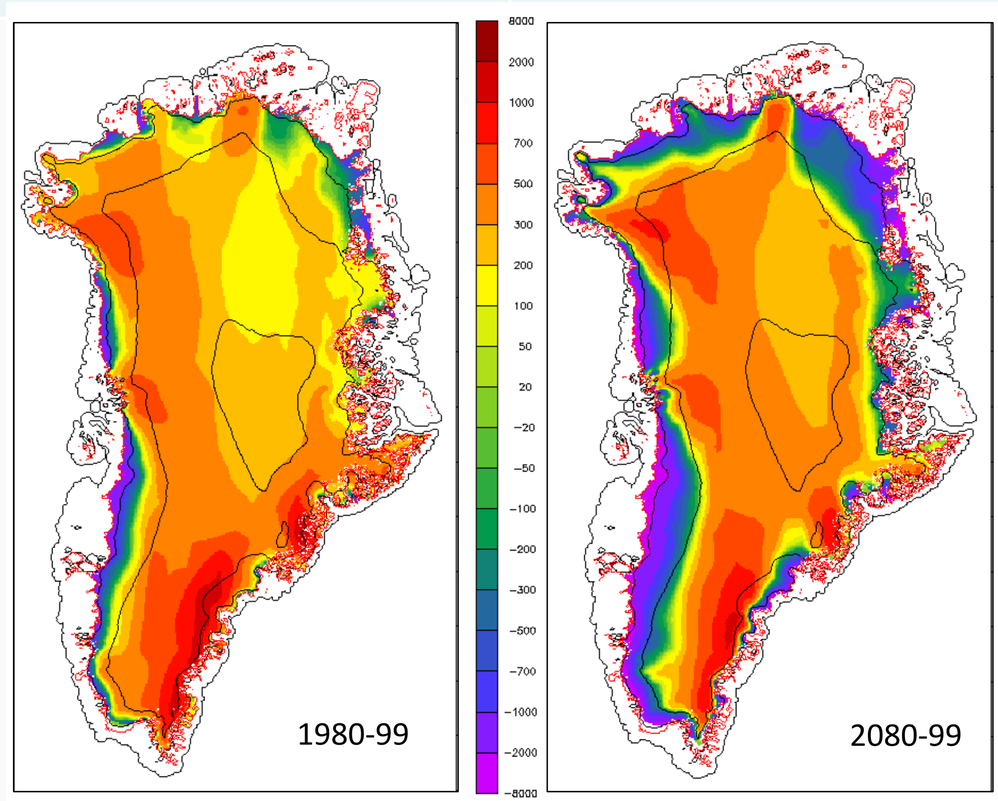
| | 20th-century (1980-1999) | RCP8.5 (2080-2099) |
|---|---|---|
| **SMB (Gt/yr)** | **372** ± 100 | **-78** ± 143 |

**Greenland ice sheet SMB (kg $m^{-2}$ $yr^{-1}$)**

**Red = net accumulation**

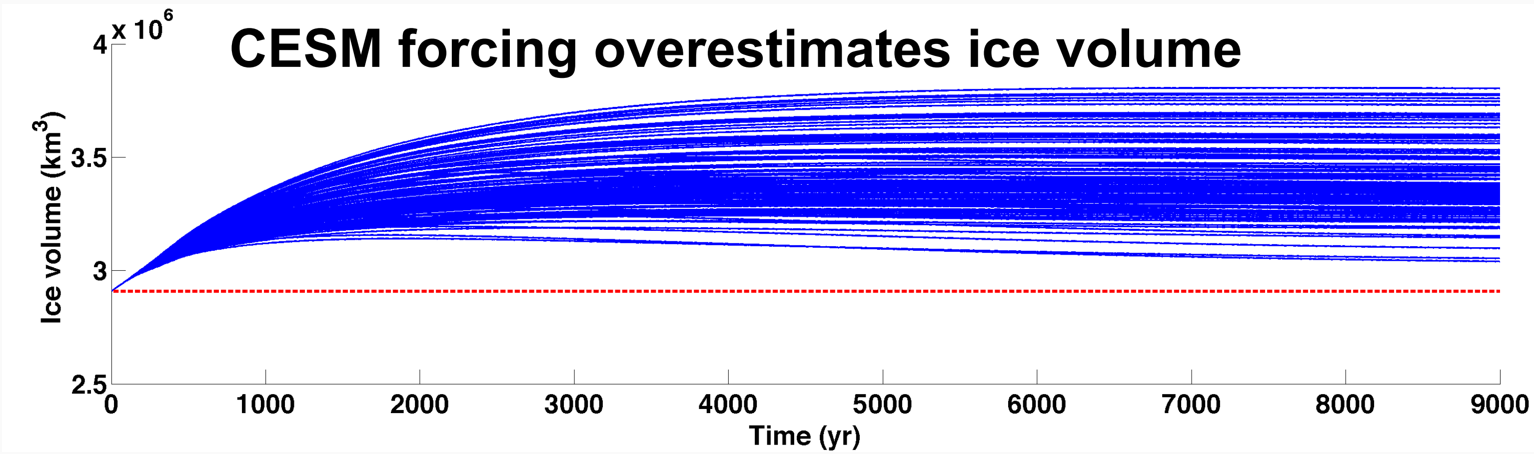
**Purple = net melting**

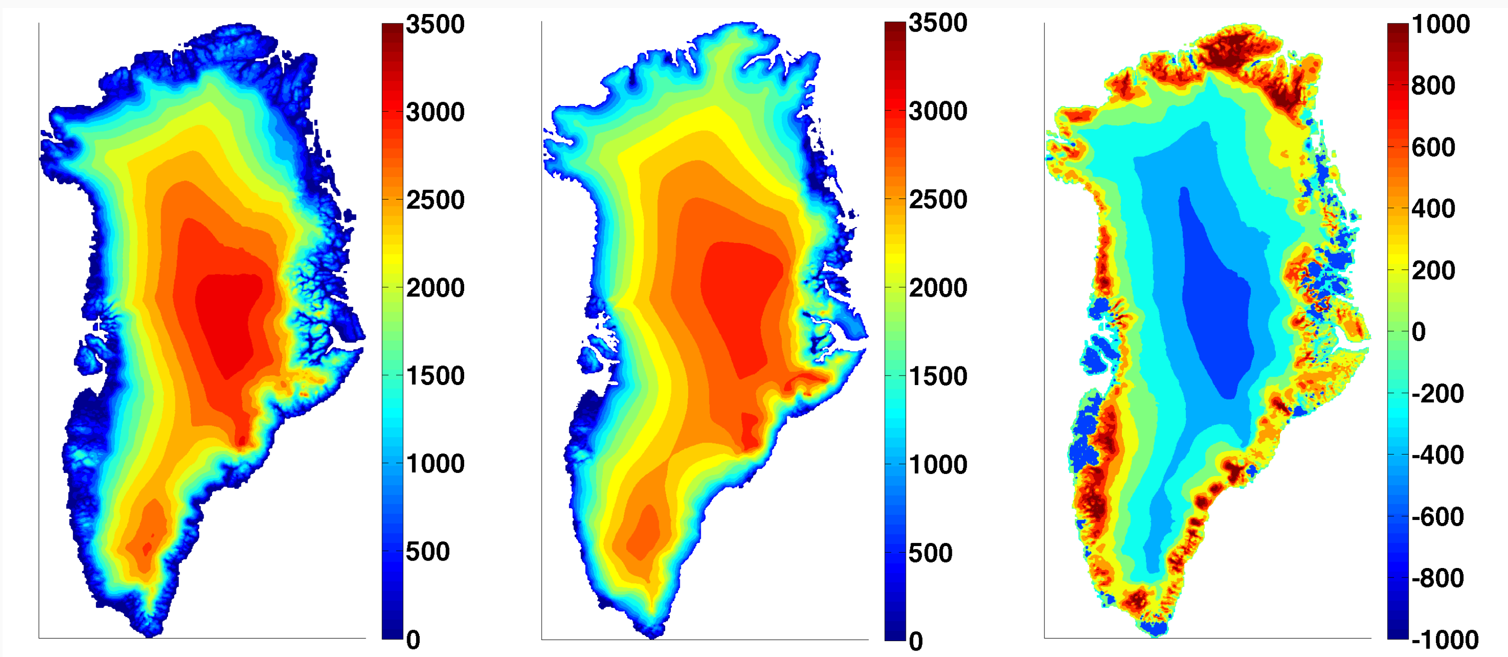
Courtesy of M. Vizcaíno




- For RCP8.5, precipitation increases, but melt and runoff increase more.
- Warming is greatest in north (less sea ice), least in southeast (weaker MOC).
- Average SMB is negative by 2100, implying long-term decay of ice sheet.

# Greenland ice sheet spin-up




**Observed** **Best tuned model** **Difference**

Courtesy of J. Fyke

# Planned experiments with CISM in CESM

(1$^o$ atm, 1$^o$ ocn)

**CMIP5 scenarios** (preindustrial, 20$^{th}$ century, RCP4.5/8.5)

- CAM5 atmosphere
- 2-way coupling between CISM and CLM (requires dynamic topography and landunits)

**Multi-century**

- Long-term Greenland stability
- Last Interglacial (130-110 ka, asynchronous)
- N. Hemisphere ice sheet inception (115 ka)

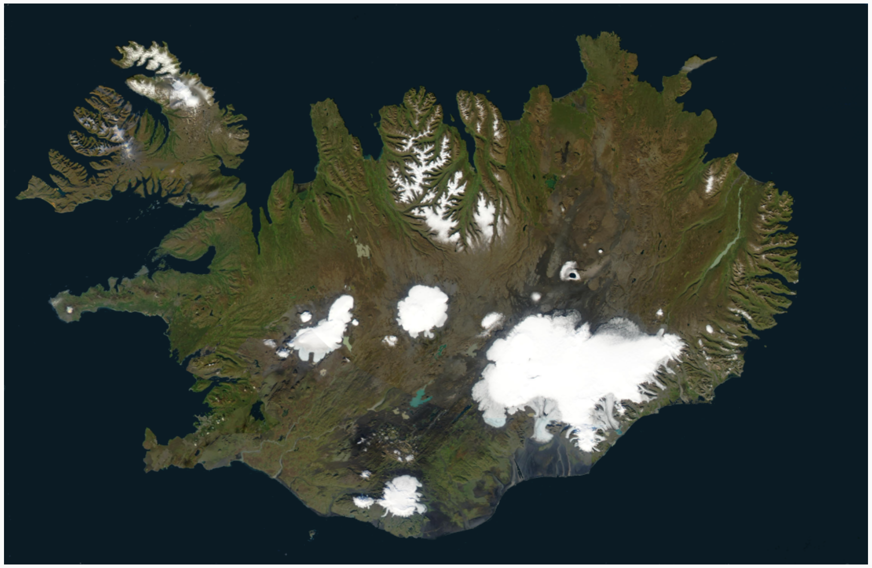
# What's next?

1. Improved models of glaciers and ice caps
2. More realistic ice sheet models
3. Coupling of ice-sheet and ocean models

# Glaciers and ice caps

- Too many glaciers, too little data to model the dynamics of each glacier
- Instead, use a statistical model based on relationships between glacier area and thickness.
  - Complete glacier outlines  from Randolph Glacier Inventory
- Force model with glacier surface mass balance *b(z)* from CLM.
  - Need to improve and validate CLM's surface mass balance scheme for glaciers (downscaling, ice albedo)

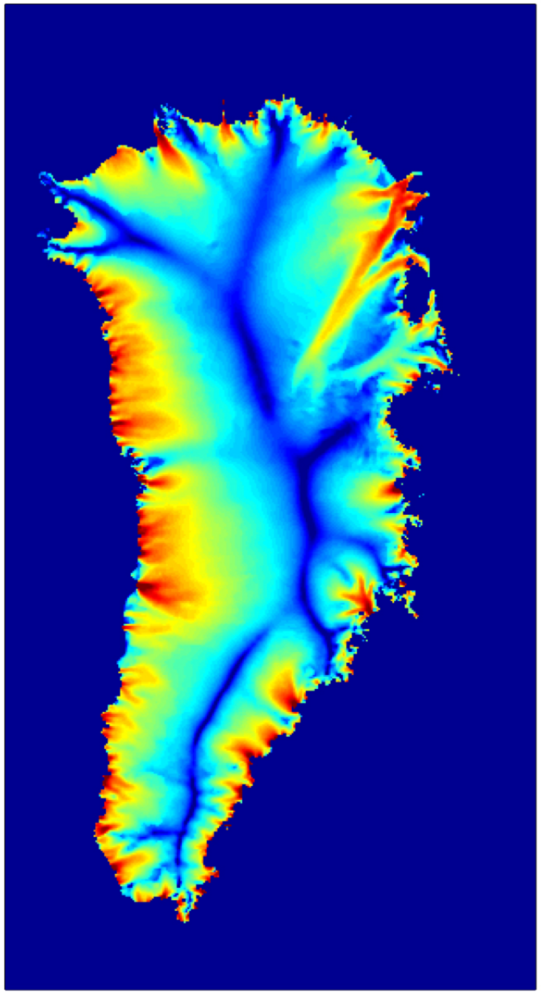
Grosser Aletschgletscher, Switzerland



Iceland (Vatnajökull ice cap in lower right)

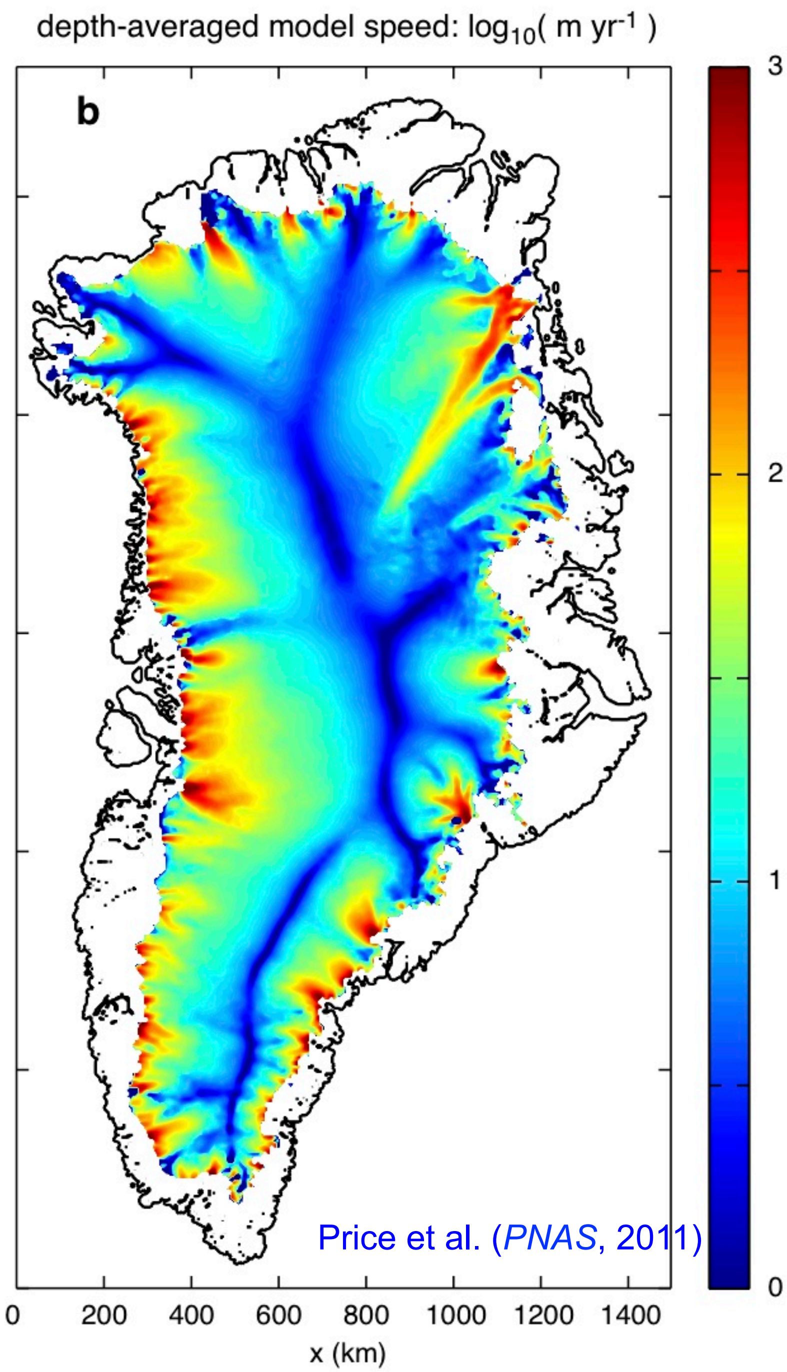
# More realistic ice-sheet models

- Higher-order ice-flow models that can simulate fast flow in ice shelves, ice streams, and outlet glaciers.
- More realistic treatments of physical processes (subglacial water transport, basal sliding, iceberg calving).
- Grid resolution of ~1 km or less, requiring scalable parallel codes and adaptive or unstructured meshes.
- New dycores have been developed under the DOE **ISICLES** project



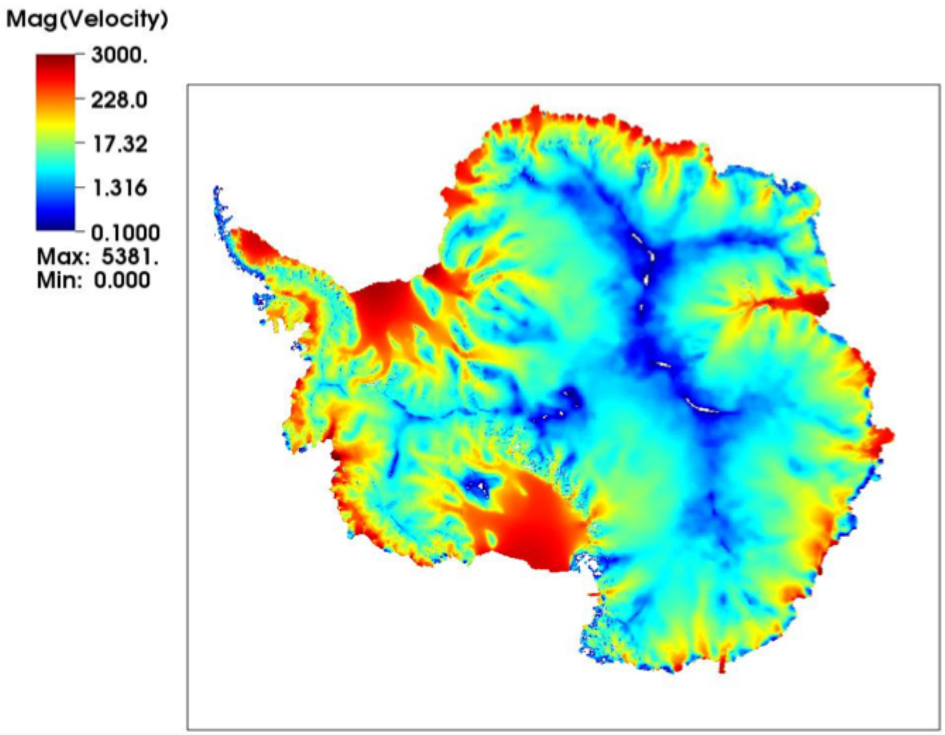
# SEACISM

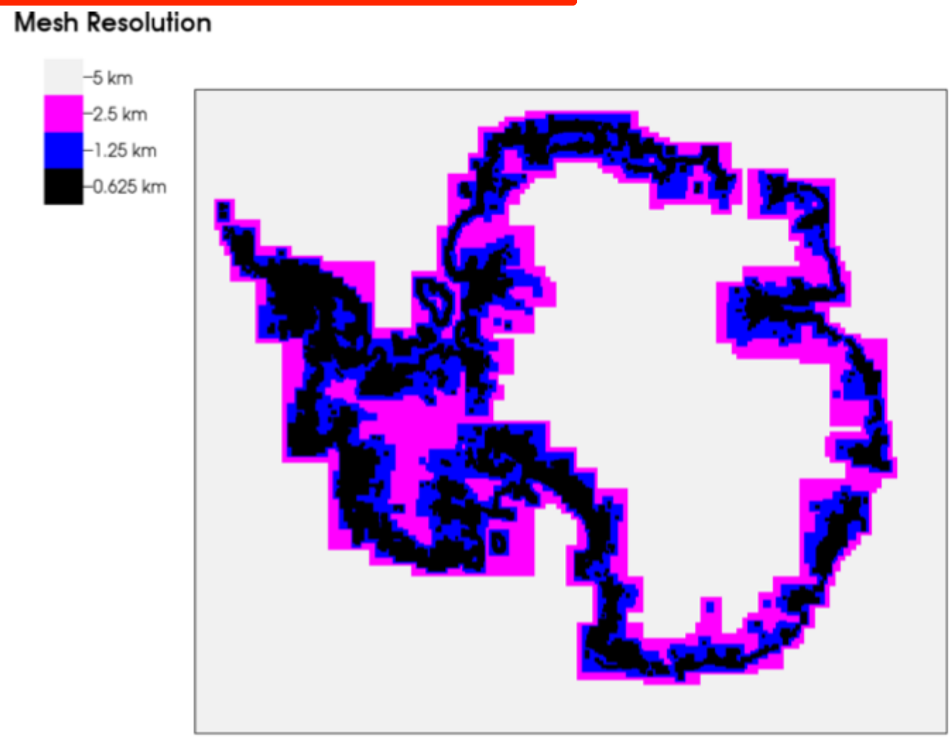
- Fully distributed, parallel treatment of conservation equations (momentum, heat, and mass balance)
- Nonlinearity handled with Picard and/or Newton-based methods
- Uses *Trilinos* solver library
- For realistic problems and boundary conditions, strong scaling to 2-6 K cpus
- For larger problems, reasonable scaling on as many as 20 K cpus



# BISICLES

- Refinement based on Laplacian(velocity), grounding lines
- 5 km base mesh with 3 levels of refinement
  - base level (5 km): 409,600 cells (100% of domain)
  - level 1 (2.5 km): 370,112 cells (22.5% of domain)
  - Level 2 (1.25 km): 955,072 cells (14.6% of domain)
  - Level 3 (625 m): 2,065,536 cells (7.88% of domain)

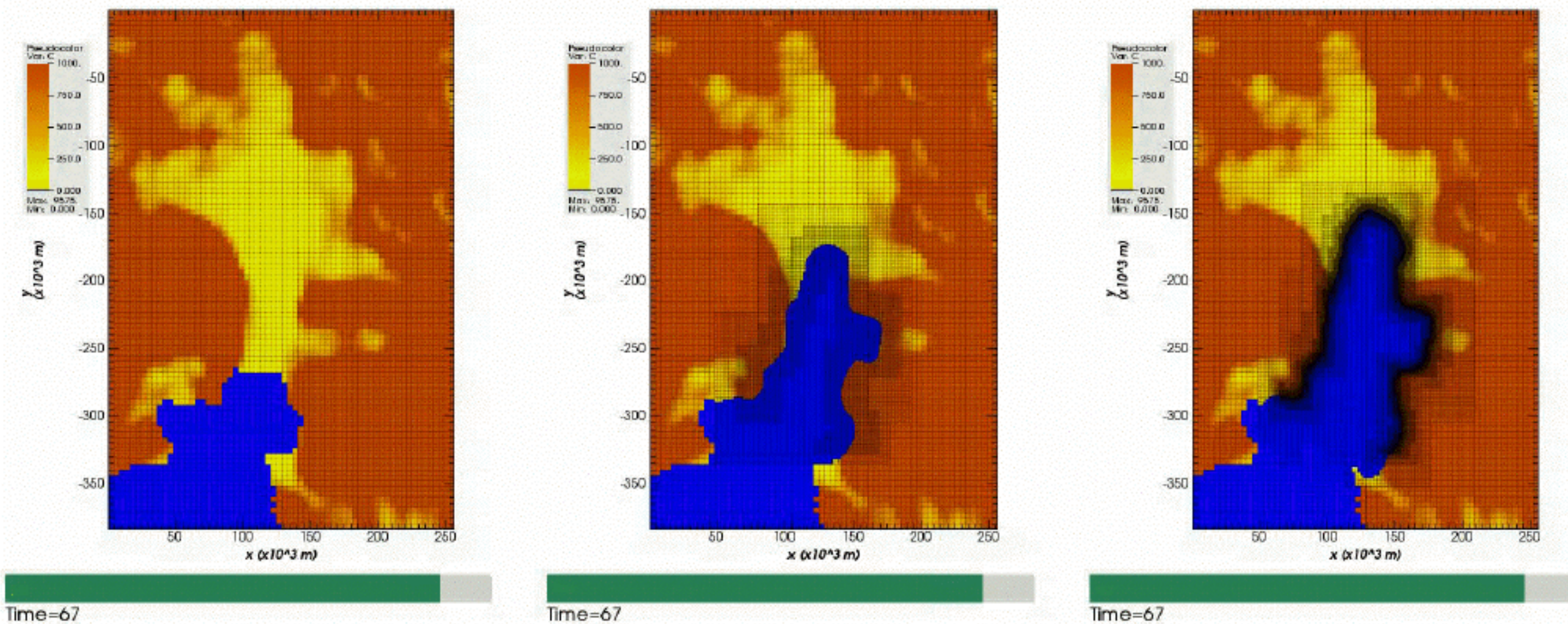



Simulations and figures courtesy of Steph Cornford (UOB) and Dan Martin (LBL)

# Simulating grounding-line retreat

- Pine Island Glacier simulation with BISICLES adaptive-mesh model.
- Fine grid resolution (< 1 km) is needed to track grounding line.

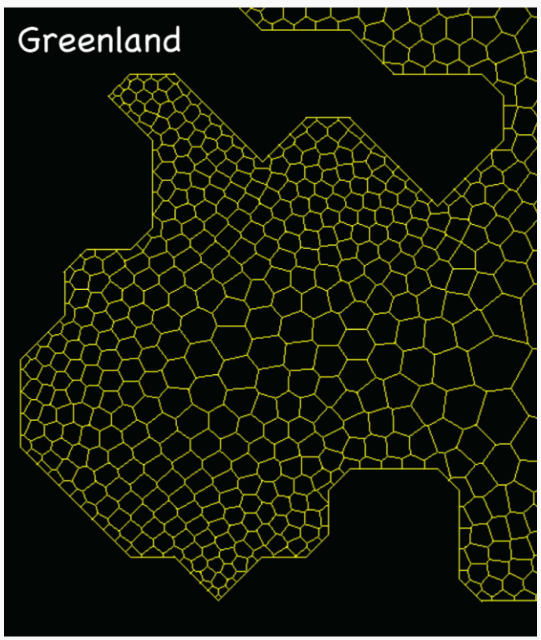



Grounding line retreat over 75 years simulated by BISICLES model using three levels of adaptive refinement. *Left*: 4-km mesh (no refinement). *Center:* Refined to 1 km. **Right:** refined to 250 m. Courtesy of S. Cornford and D. Martin.

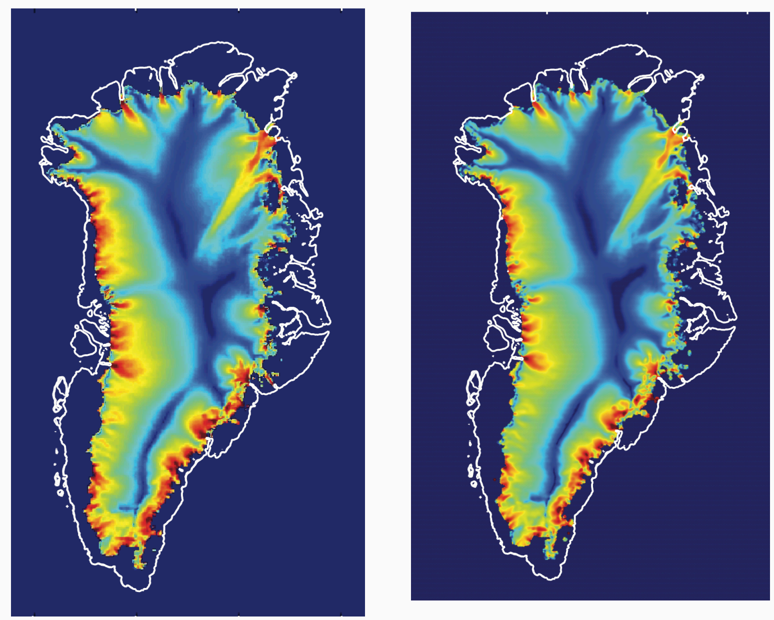
# PISCEES

## Predicting Ice Sheet and Climate Evolution at Extreme Scales

- 5-year (2012-2017) DOE SciDAC project to further improve ice sheet models and assess their uncertainties
- Includes development of a new dycore (FELIX) using finite-element techniques on unstructured, variable-resolution meshes
- Also includes verification, validation, uncertainty quantification

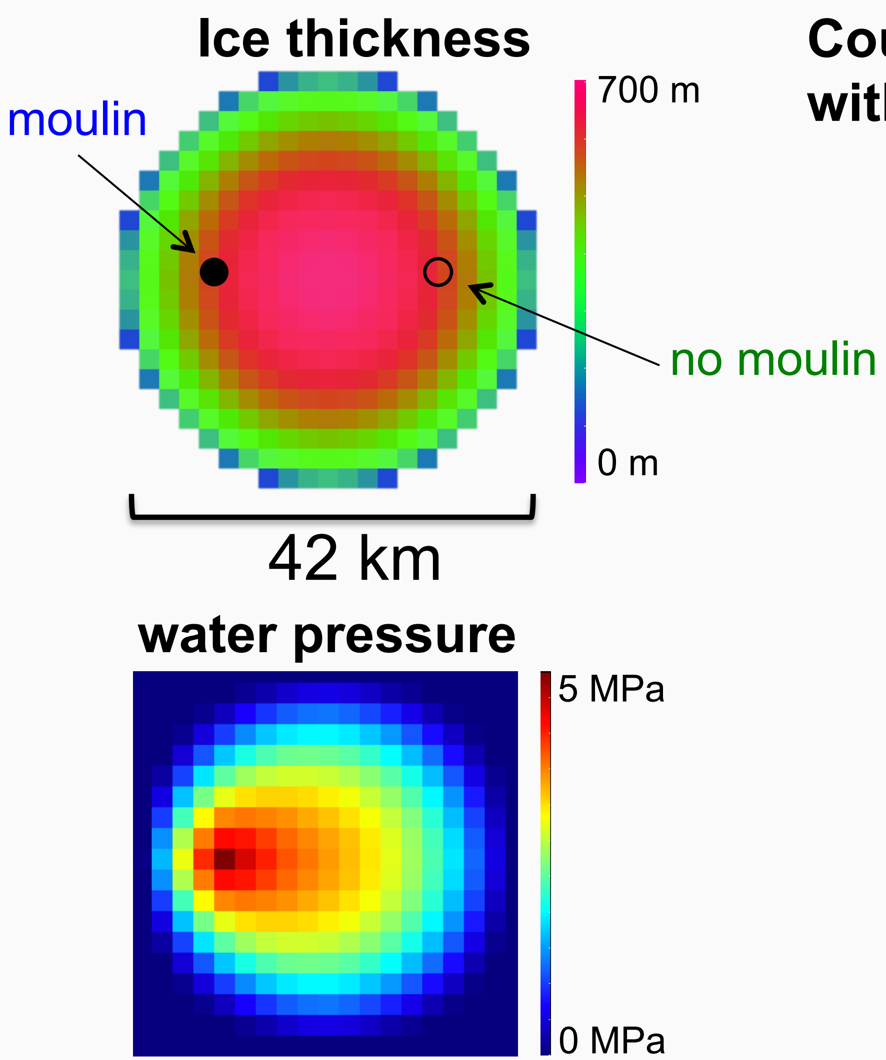



Variable-resolution mesh for Greenland

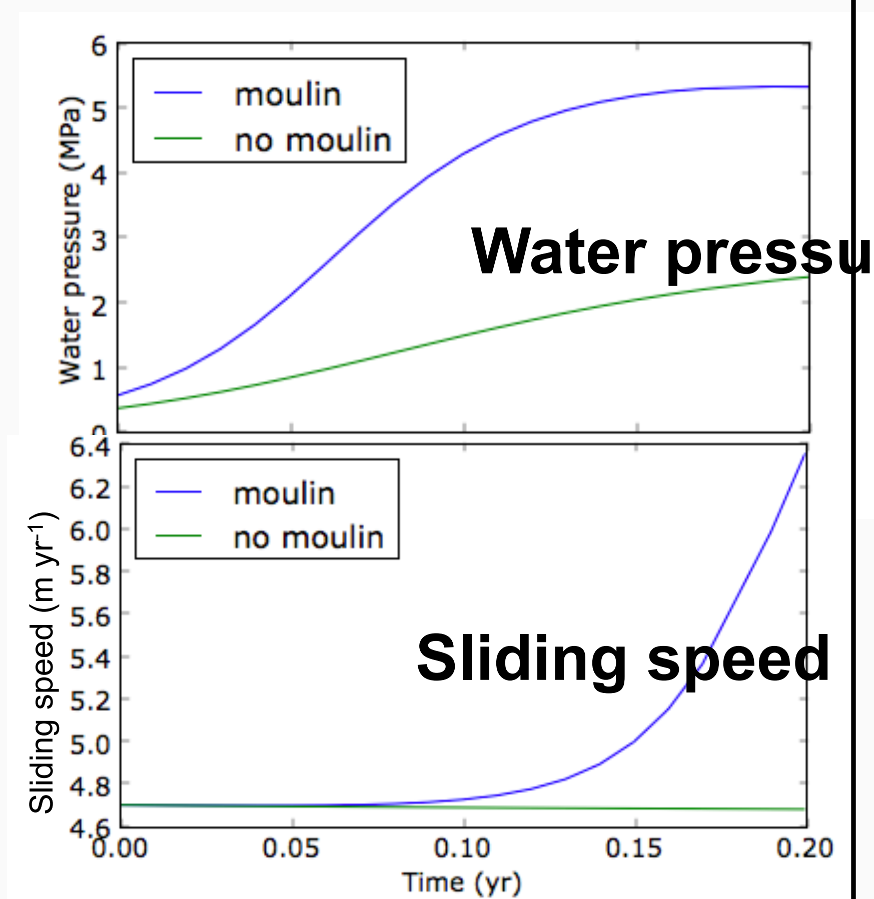


Greenland flow speed: SEACISM (left), prototype FELIX dycore (right)

# Sliding and subglacial hydrology



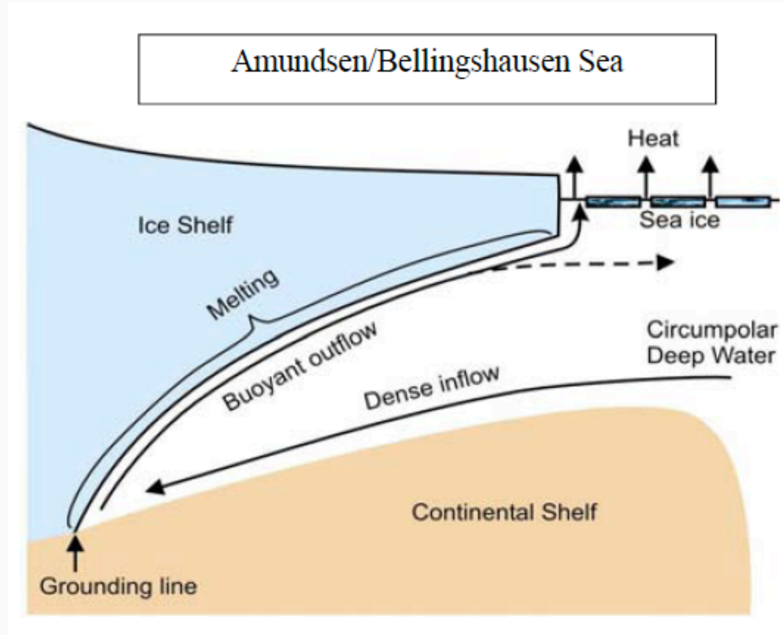

**Coupled sliding, subglacial hydrology with "moulin" water source.**



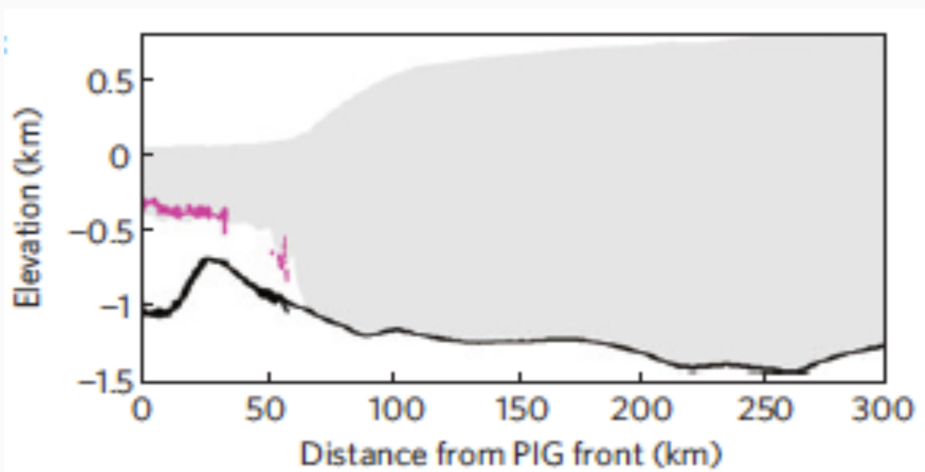

Courtesy of M. Hoffman

# Marine ice sheet instability

- Ice in the Amundsen/ Bellingshausen region of West Antarctica is 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 ice shelves.




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




Topography of Pine Island Glacier (Jenkins et al. 2010 )

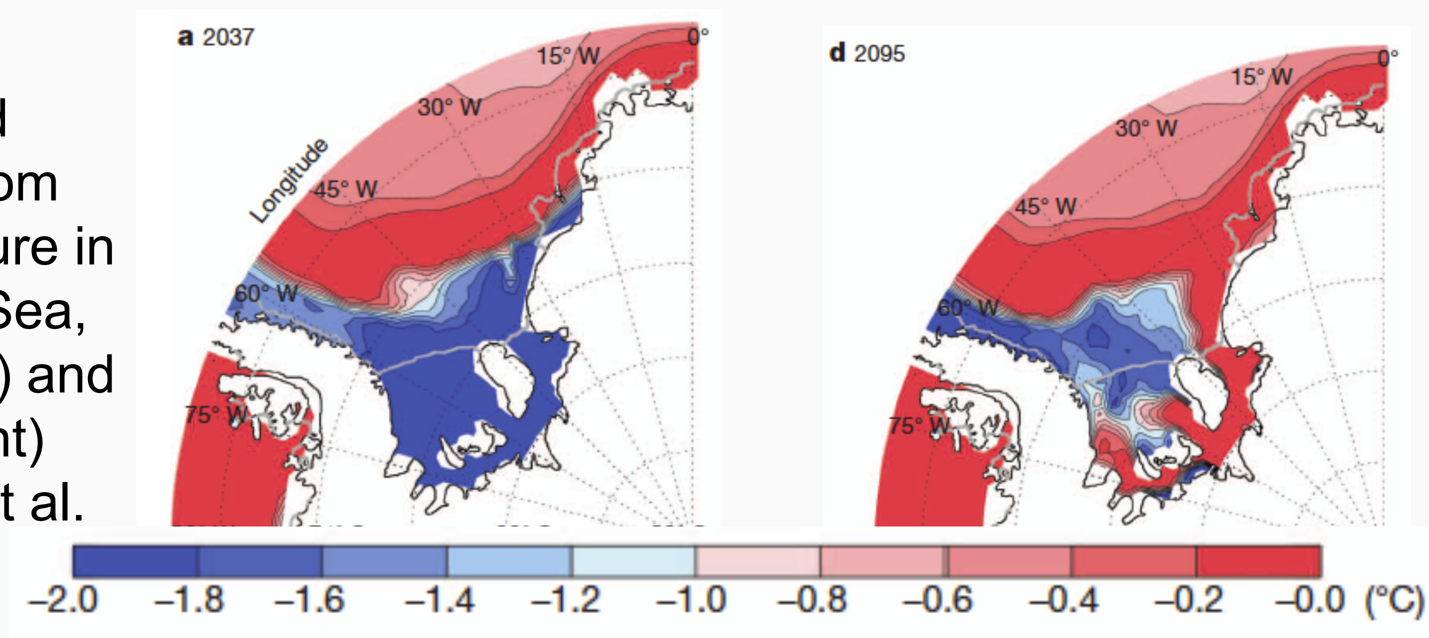
# Vulnerability of the Ronne-Filchner Ice Shelf

Hellmer et al. 2012:

- Regional ocean simulations show warm water redirected beneath the Ronne-Filchner shelf after 2050
- The ocean changes are caused by increased surface stress associated with sea ice thinning.
- Average basal melting increases from 80 Gt/yr to **1600 Gt/yr**.

Ross et al. 2012: Reverse-sloping sea bed could promote fast retreat.

Simulated near-bottom temperature in Weddell Sea, 2037 (left) and 2095 (right) (Hillmer et al. 2012)



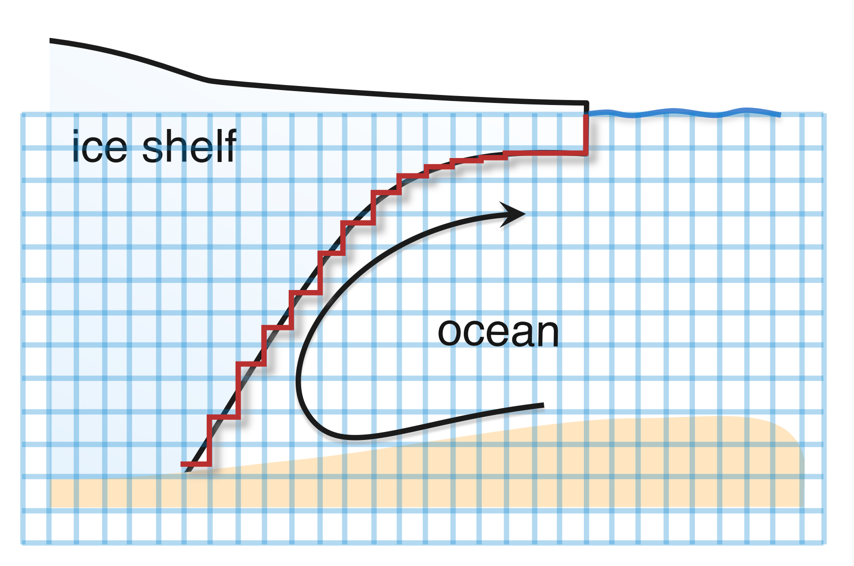
# Ice-sheet/ocean coupling

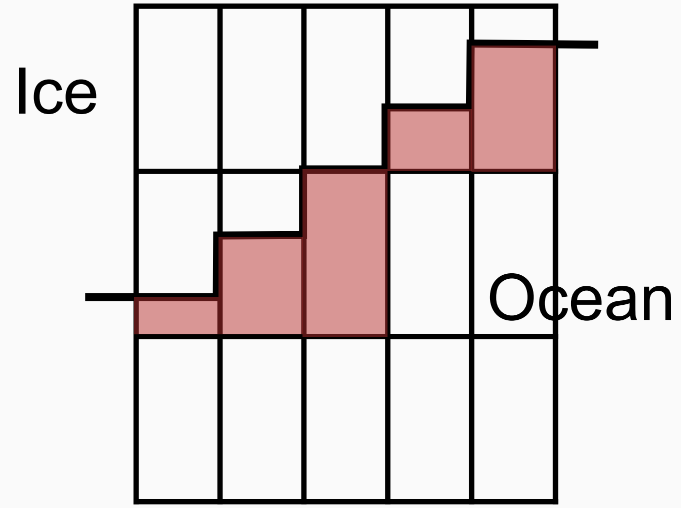
These recent results suggest that

- Changes in wind forcing (possibly associated with greenhouse forcing) can drive large changes in sub-ice-shelf melting and outflow of grounded ice in West Antarctica.
- Ice shelves that are now stable might destabilize within decades, with resulting SLR of tens of cm per century.
- To simulate these changes, we need coupled ice-sheet/ ocean models.

# Ice-sheet/ocean interface in POP

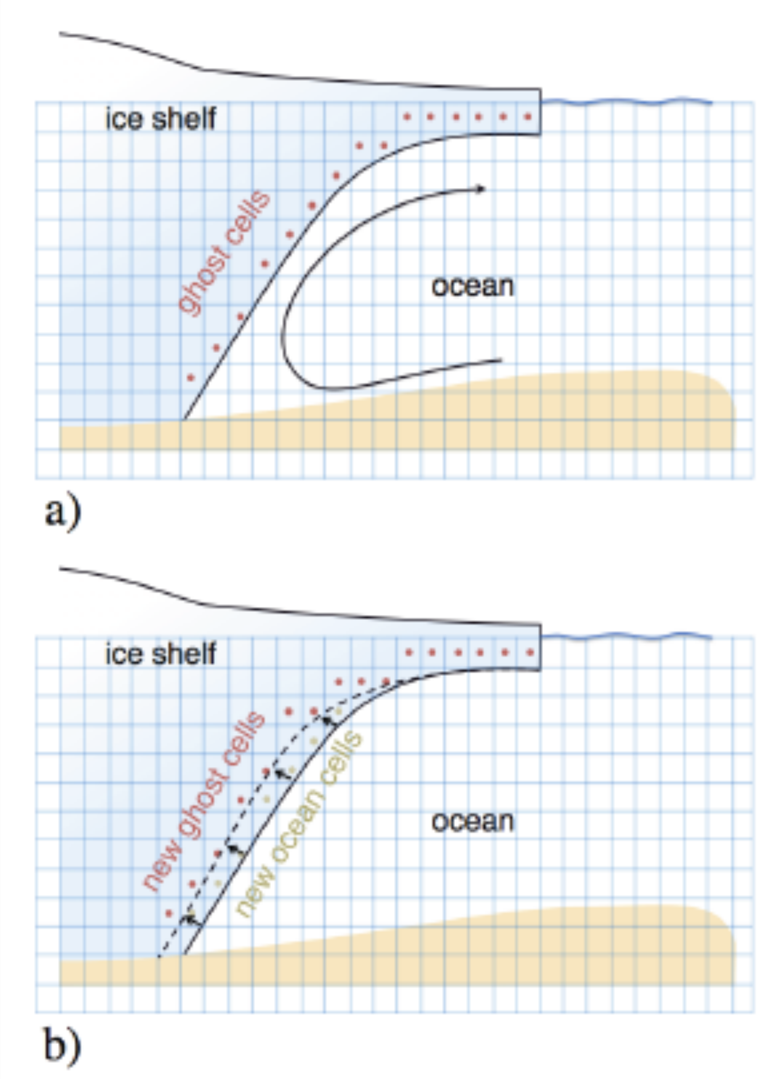
- As part of the DOE IMPACTS project on abrupt climate change, we have developed POP2X, which includes cavities beneath ice shelves.
- Ice/ocean boundary defined by partial-top cells (analogous to partial-bottom cells; based on Losch 2008)



# Future work: Moving boundaries

- **Immersed Boundary Method**
  - includes **ghost cells** adjacent to boundary
  - implicit representation of sloped interface geometry
  - as ice sheet retreats, **ghost cells** become **new ocean cells**
  - no partial cells, so never have infinitesimally thin cells



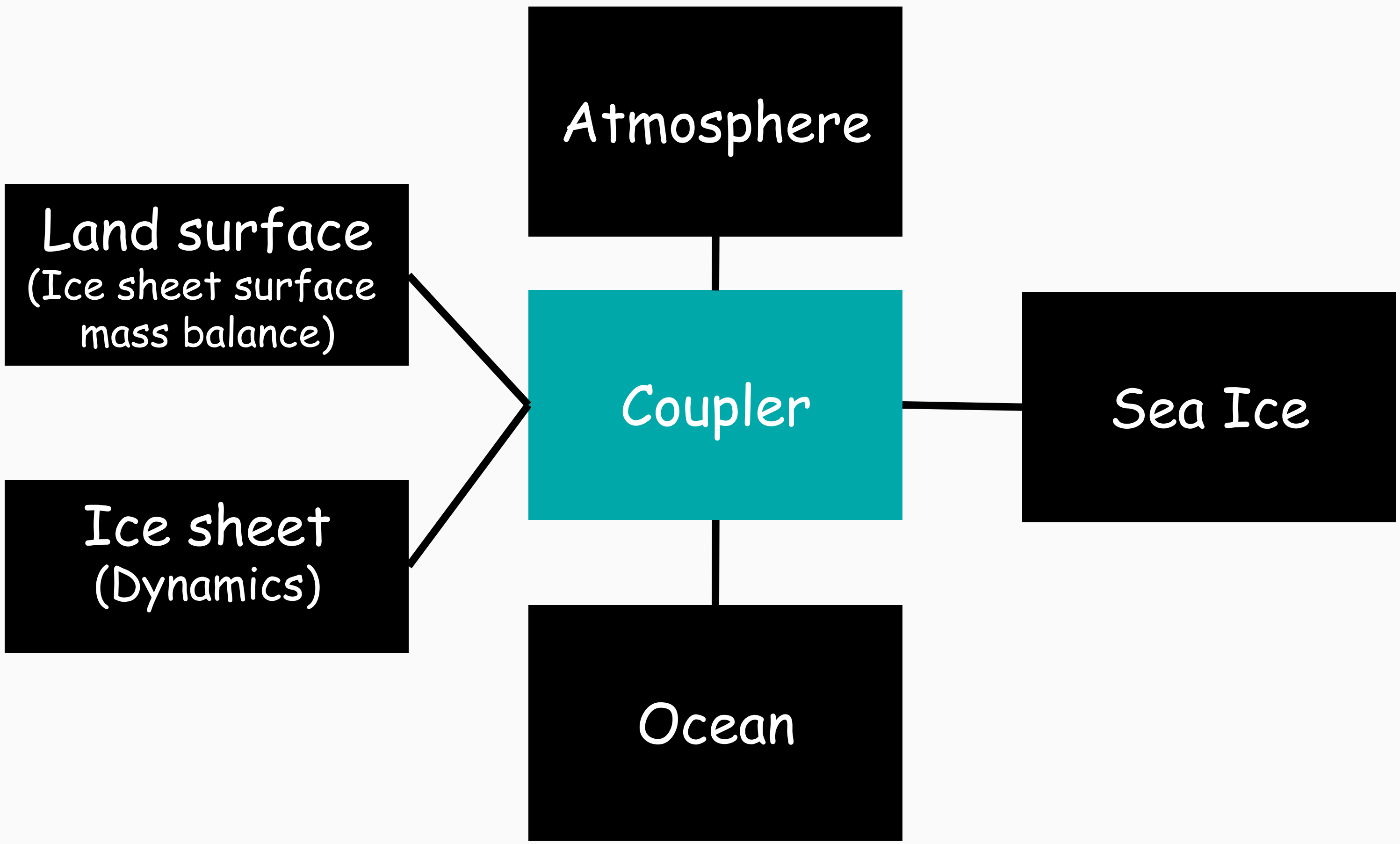
# Ice-sheet/ocean coupling in CESM (in progress)

Ocean -> Ice sheet/shelf

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

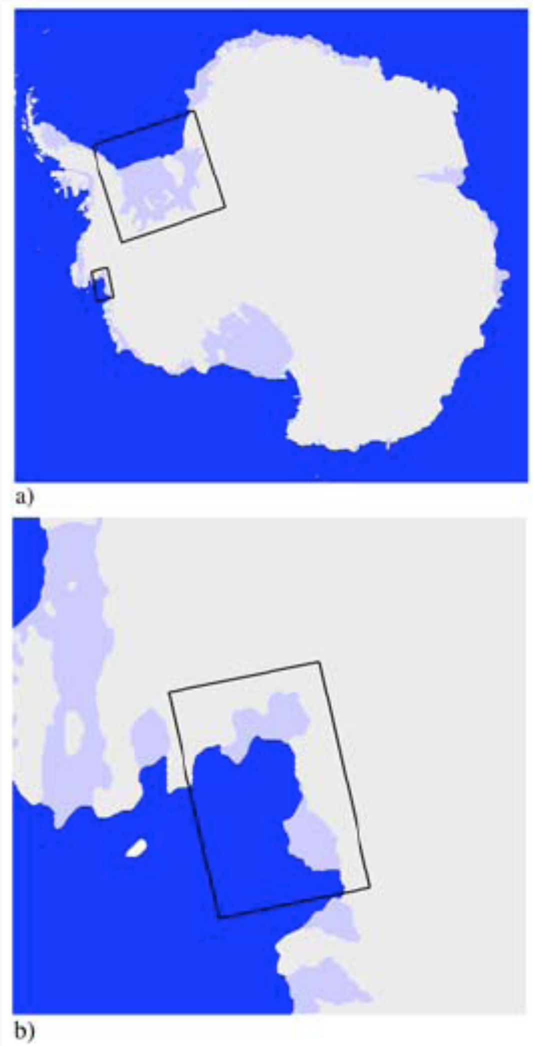
Ice sheet -> Ocean

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



# Future experiments

- Standalone ocean simulations with modified POP and fixed ice shelves
  - Realistic geometry at regional scales (Ronne-Filchner Ice Shelf, Amundsen Sea Embayment)
  - Realistic geometry at global scale (~10-km grid resolution)
- Coupled ice-sheet/ocean simulations with POP and CISM
  - Regional, high-resolution with simplified coupling (not supported in current CESM)
- Long-term goal: Global, high-resolution, fully coupled simulations

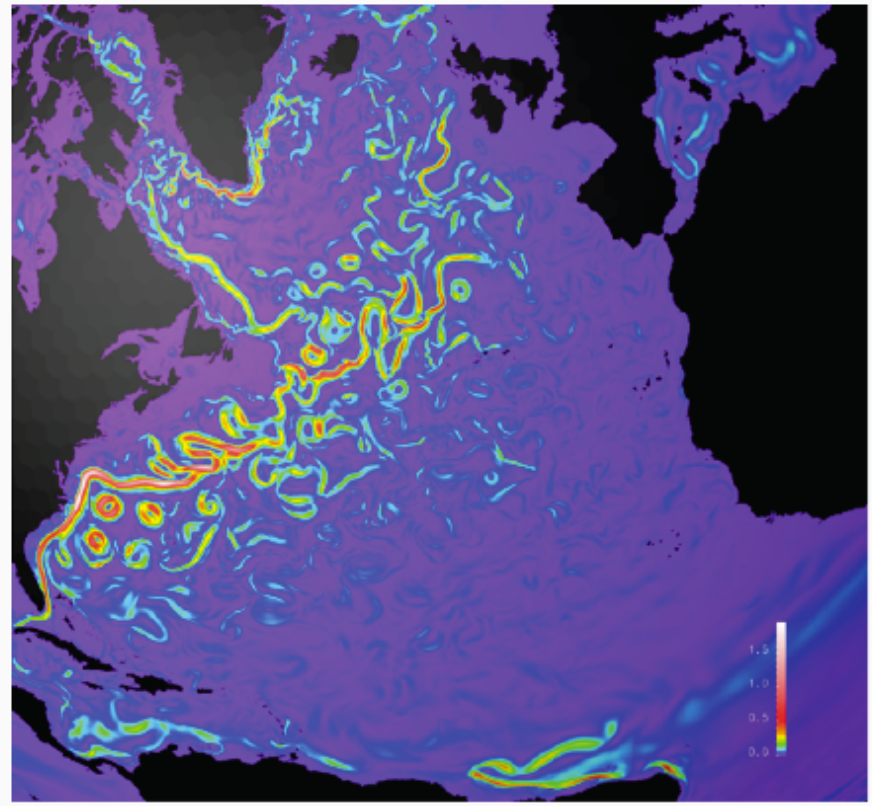


a)

b)

# Global modeling at regional scales

- The Model for Prediction Across Scales (**MPAS**) is an unstructured-grid approach to climate system modeling.
- MPAS supports dynamical cores on both quasi-uniform and variable-resolution meshes, using quadrilaterals, triangles, and Voronoi tesselations.
- Researchers at NCAR and LANL are developing MPAS atmosphere, ocean and ice models.



Kinetic energy from a global ocean simulation with 7.5 km resolution in N. Atlantic (courtesy of Todd Ringler)

# CESM Land Ice Working Group

## Leadership

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

## Meetings

- Winter (Boulder), summer (Breckenridge)

## LIWG info

- Web site:  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

- 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


Thank you!