# An Update on Land-Ice Modeling in CESM

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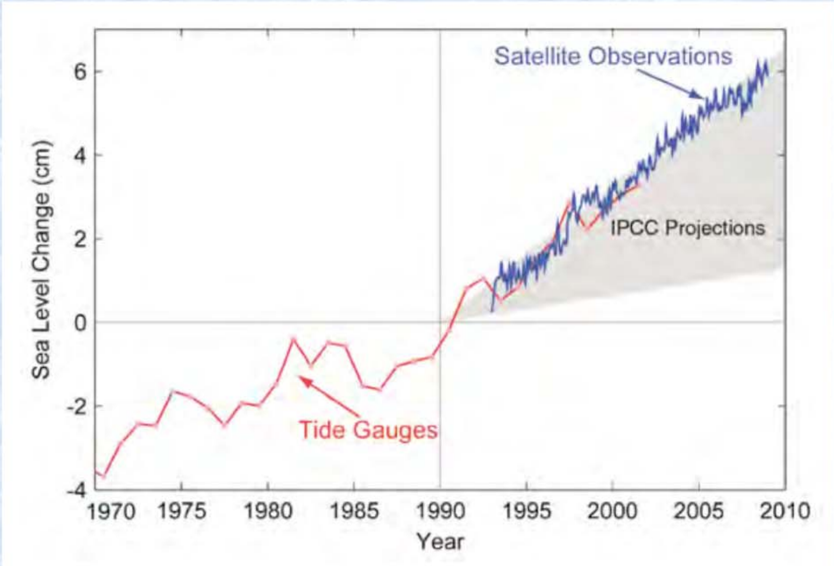
Land Ice Working Group meeting

# CESM Land Ice Working Group

- Formed in 2009; one of 12 working groups responsible for developing and applying the Community Earth System Model
- Meets twice a year: once in winter (usually Boulder), once in summer (CESM workshop in Breckenridge)
- Two main 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 Jesse Johnson (U. Montana), William Lipscomb (LANL)
  - Scientific liaison Steve Price (LANL)
  - Software liaison TBD
- Web page: **http://www.cesm.ucar.edu/working_groups/Land+Ice/**

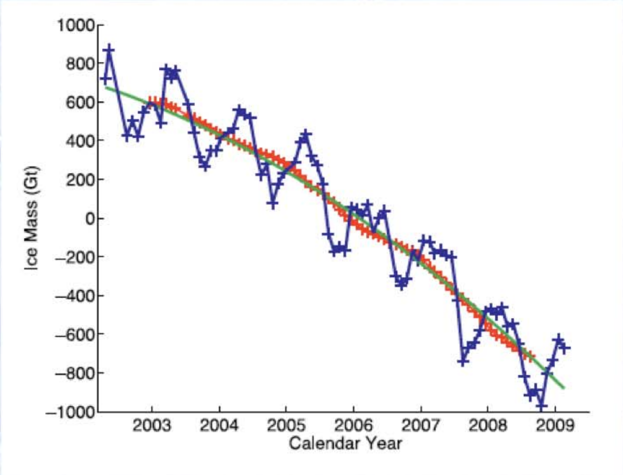
# Contributions to global sea-level rise

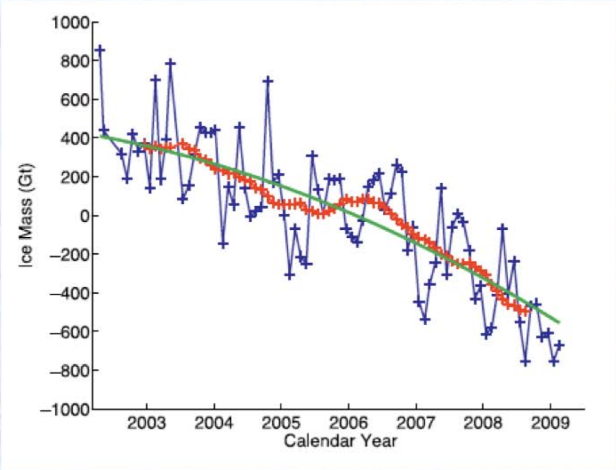
- Global mean sea level is increasing at a rate of ~3 mm/year.
  - Ocean thermal expansion: ~1 mm/yr
  - Glaciers and ice caps: ~1 mm/yr
  - Ice sheets: ~1 mm/yr
    - Antarctica ~0.5 mm/yr
    - Greenland ~0.5 mm/yr




Copenhagen Diagnosis (2010)

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



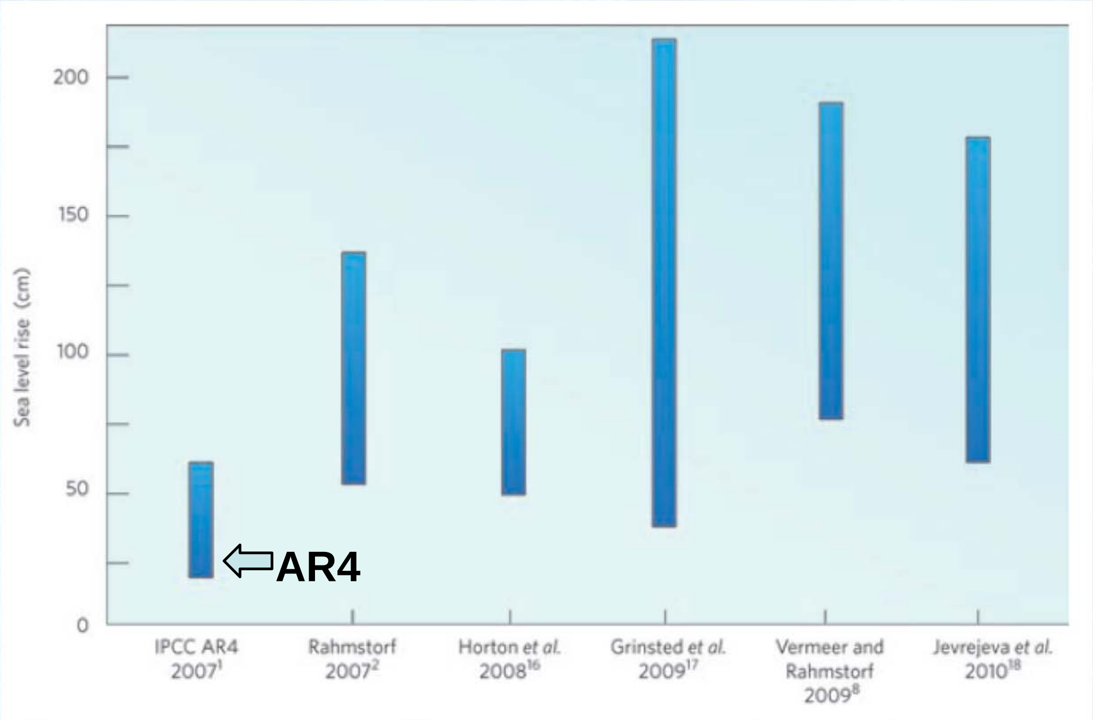




Greenland ice mass loss Antarctic ice mass loss

From GRACE gravity measurements (Velicogna 2009)

# Sea-level predictions to date

- **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 21st 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.

# Sea-level prediction with Earth-system models

Most ESMs already have some of the components needed for physically based sea-level predictions:  e.g., a fully coupled atmosphere-ocean GCM that can provide ocean thermal expansion and dynamic SLR.

**What's missing?**

- **Dynamic ice-sheet models**
  - "Higher-order" or full-Stokes dynamics for fast flow in ice streams and outlet glaciers
  - Realistic treatment of physical processes (e.g., subglacial water transport, basal sliding, iceberg calving)
  - Fine grid resolution (~1 km)
- **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** (using scaling relationships**)**
- **Regional sea-level variations** from self gravitation, elastic rebound, etc.

# Land ice in CESM

- 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

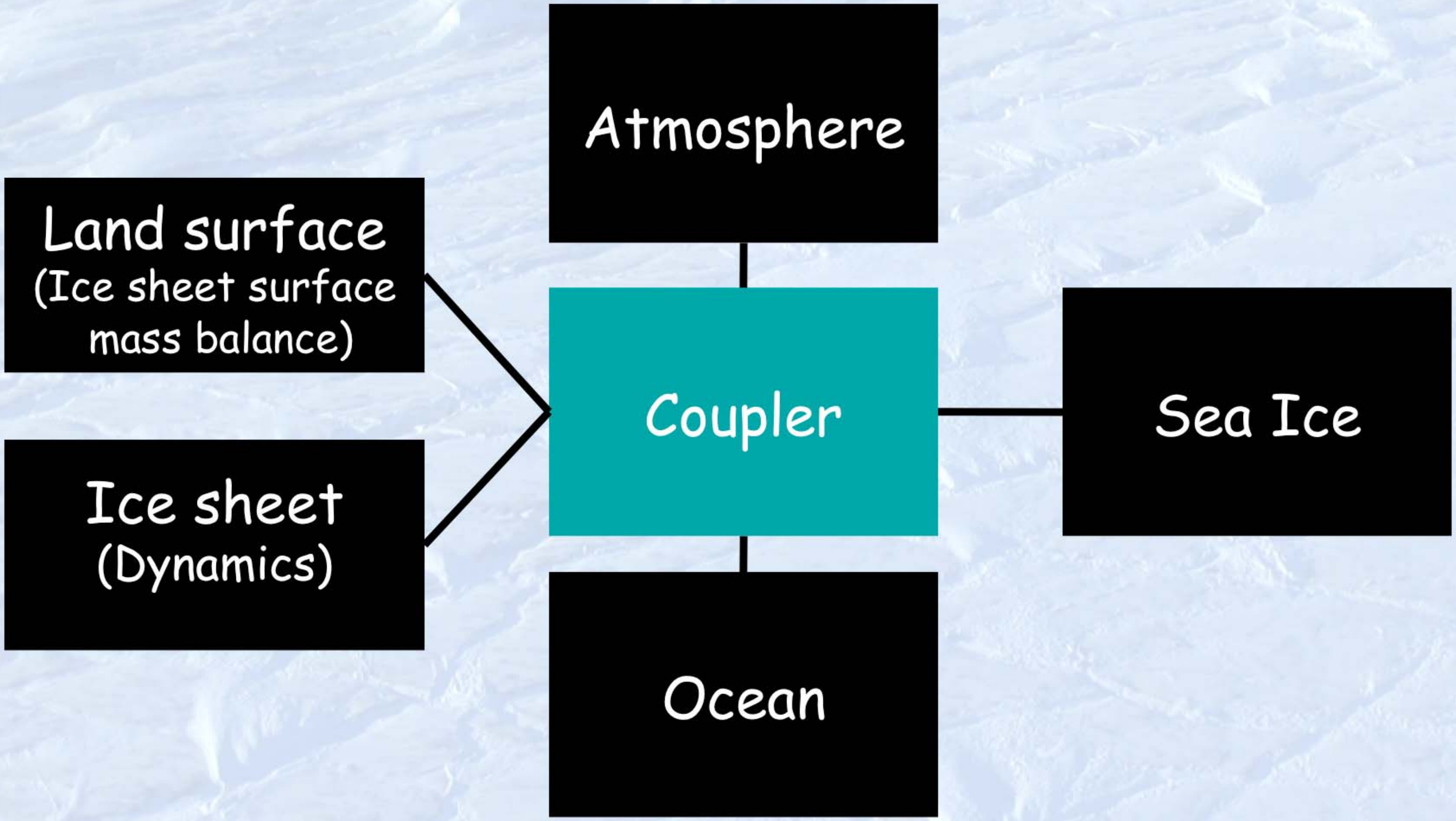
# Ice sheet coupling in CESM

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

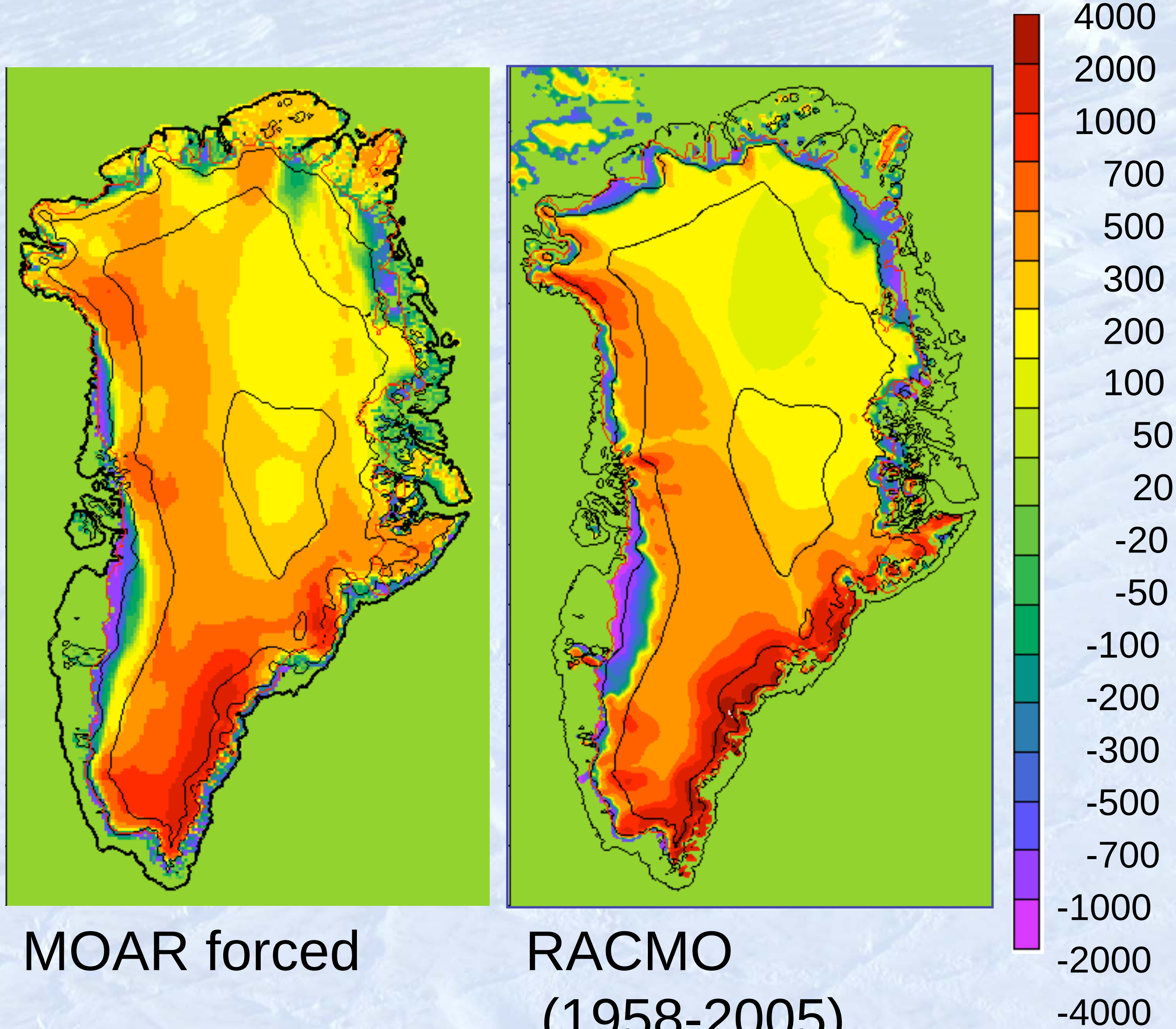


# Greenland surface mass balance in CESM

(IG with MOAR atmosphere forcing)

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

*Red = Net accumulation*
*Blue = Net ablation*

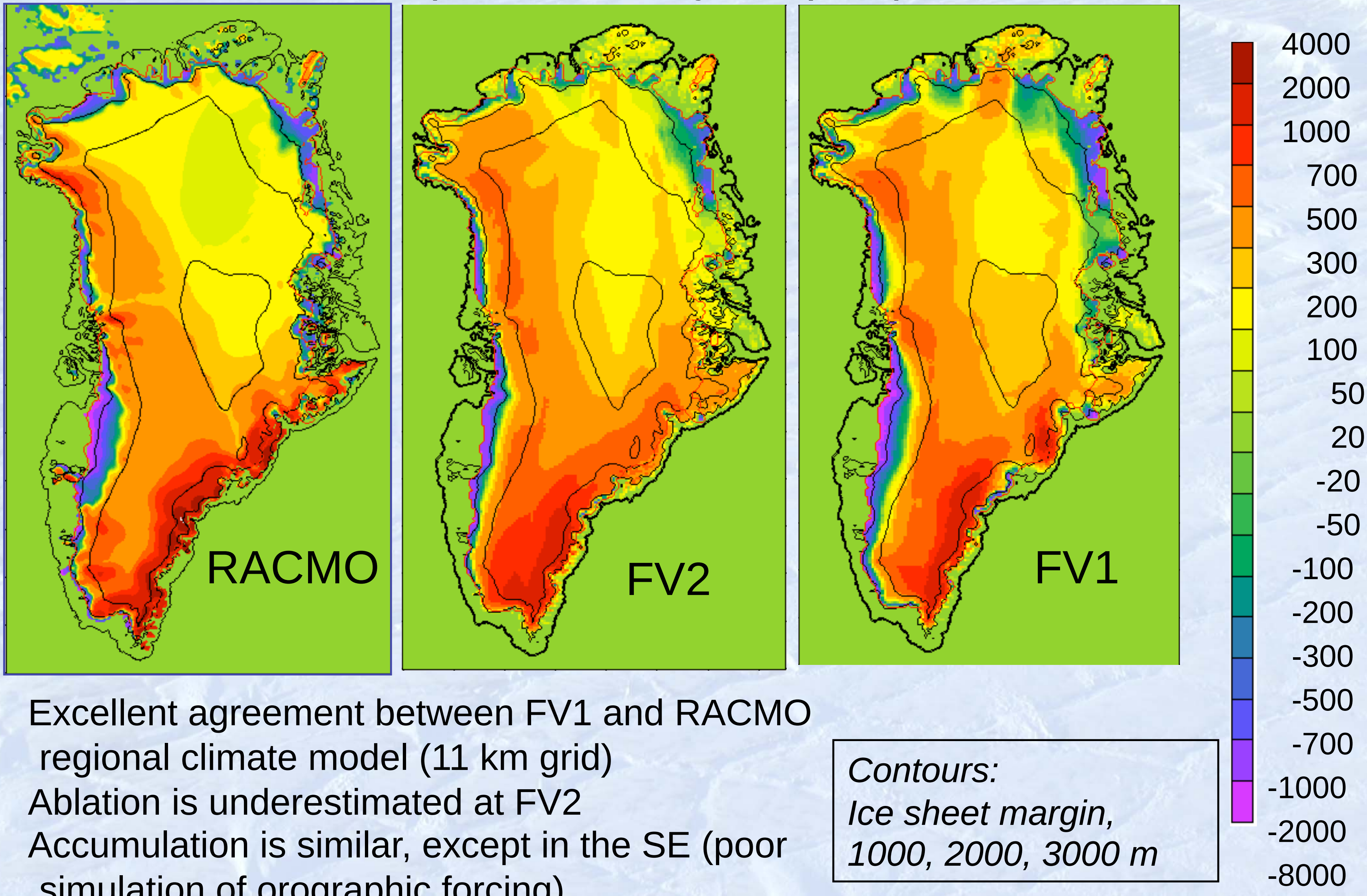



MOAR forced

RACMO (1958-2005)

# 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*

# CMIP5 experiments with Glimmer-CISM

(0.9$^o$ x 1.25$^o$ atm, 1$^o$ ocn)

## 1. Control

- Pre-industrial control, ~150 yrs (from B1850 spinup)
- 20$^{th}$ 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)
- $CO_2$ stabilization scenarios (study irreversibility)
- Eemian interglacial

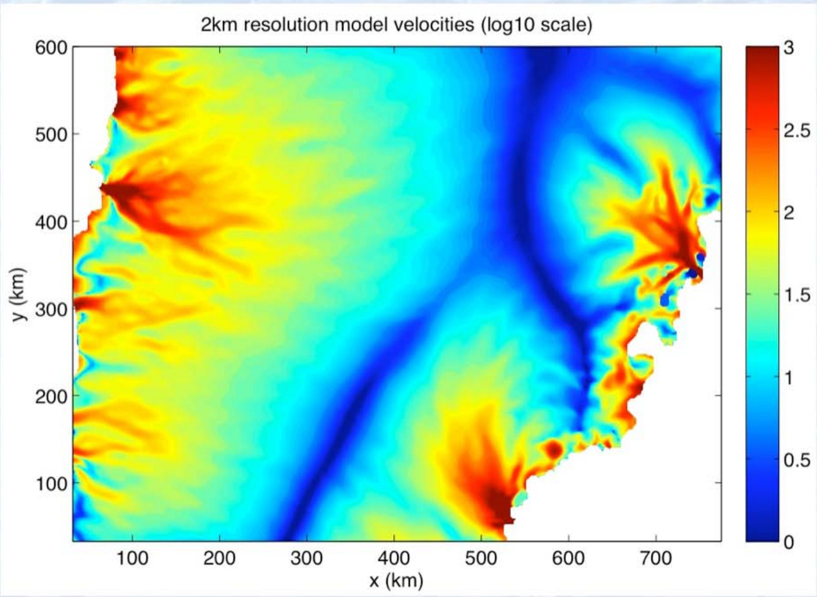
- Shallow-ice model first, then higher-order model
- Results to appear in J. Climate special issue on CESM

# Upcoming model development

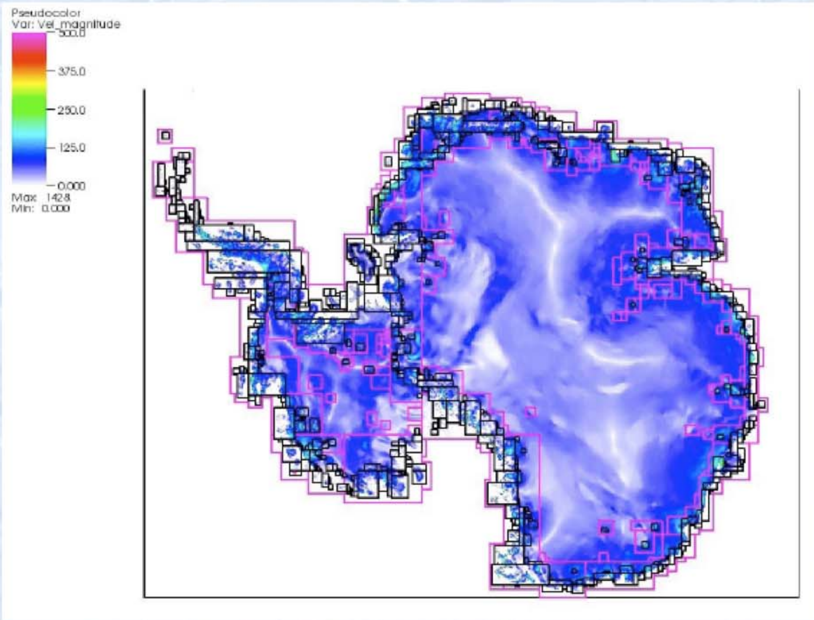
- Implement a **parallel, higher-order ice sheet model (**part of ISICLES project).
- **Two-way coupling of land and ice sheets**: Modify the land topography on the fly, and allow gridcells to change between ice-covered and vegetated.
- Implement **coupling between ocean and ice sheets**, using immersed boundary methods at the interface (part of IMPACTS project).
- Simulate **the Antarctic ice sheet** (and later paleo ice sheets).
- Model the evolution of **small glaciers and ice caps**.
- Simulate **fast changes caused by land-ice mass loss** (e.g., elastic rebound and changes in ice-sheet self gravitation).
- Improve the treatment of **ice-sheet hydrology**.
- Develop an improved **surface-mass-balance scheme** (e.g., more realistic bare-ice albedo).
- **Quantify uncertainties** in ice-sheet models.

# ISICLES

- ISICLES (Ice Sheet Initiative for Climate ExtremeS) is a 3-year (2009-2012) initiative of the DOE Office of Advanced Scientific Computing Research.
- The goal of ISICLES is 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.



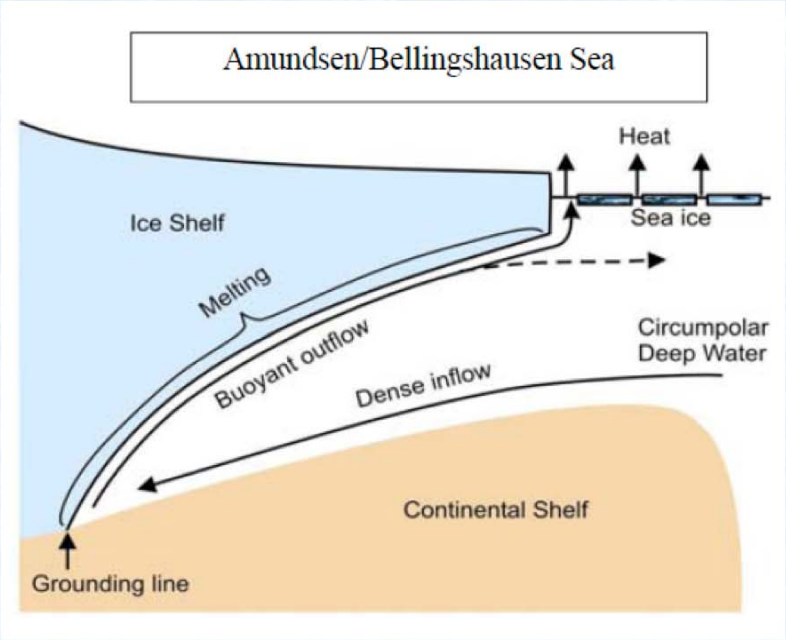

Greenland surface ice velocity ($\log_{10}$ scale), 2-km grid, higher-order flow model (courtesy of S. Price)



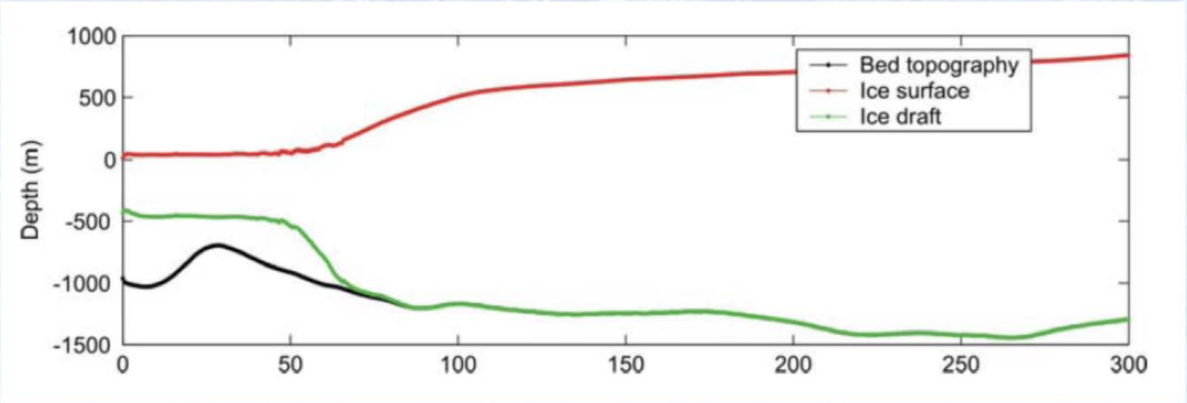

Antarctic surface ice velocity on adaptive mesh (courtesy of D. Martin)

# Ice-ocean coupling

- Recent Antarctic mass loss has been driven by intrusions of warm Circumpolar Deep Water beneath marine ice sheets
- Modest changes in wind forcing could drive large changes in delivery of warm CDW to the base of ice shelves.
- Models suggest that marine ice sheets on reverse-sloping beds (e.g., West Antarctica) could retreat unstably.



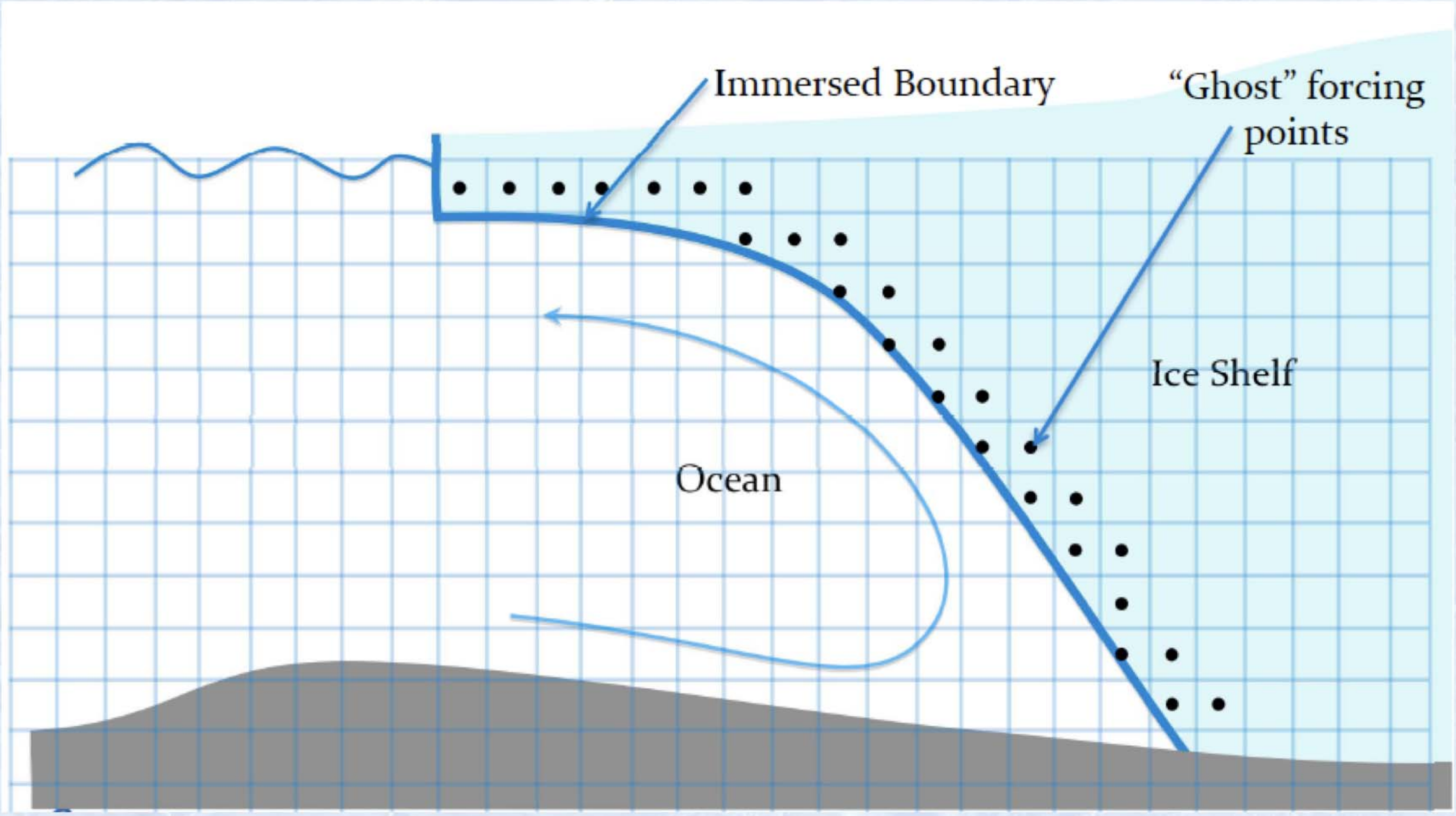

Schematic of warm CDW reaching the grounding line (courtesy of A. Jenkins)




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

# IMPACTS

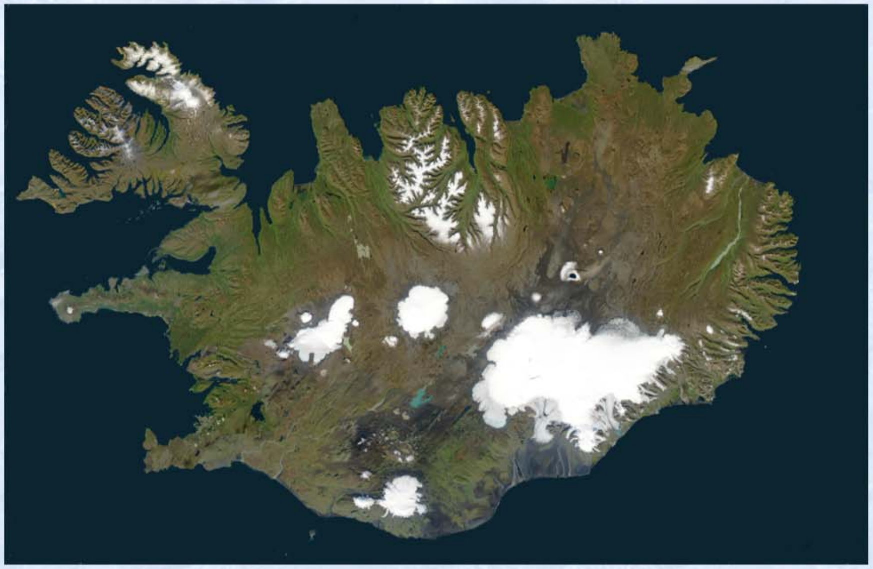
- As part of the DOE IMPACTS project on abrupt climate change, the POP ocean model is being modified to simulate ocean circulation beneath dynamic ice shelves.
- We are using immersed boundary methods to simulate processes at the ice-ocean interface.



# Glaciers and ice caps

- The area of glaciers and ice caps (GIC) that are not part of ice sheets is ~700,000 km$^2$.
- The ice volume of GIC is enough to raise mean sea level by ~60 cm (based on area-volume scaling relationships).
- Using scaling relationships, we would like to convert ice volume changes in elevation classes to area and volume changes for many thousands of glaciers (in CLM and in a new Regional Arctic System Model).

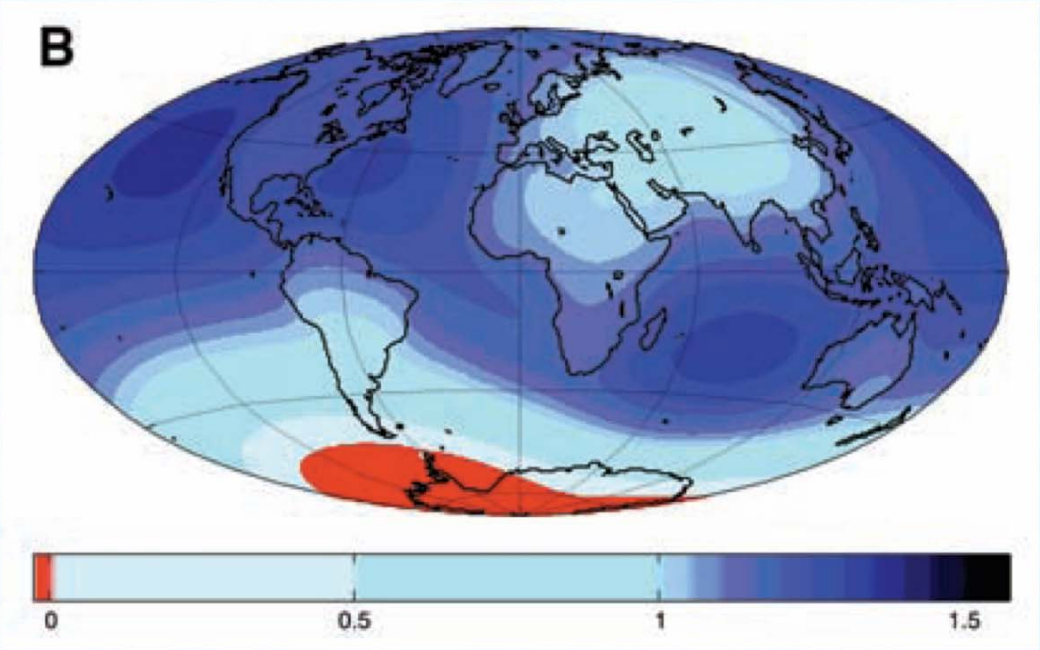
Grosser Aletschgletscher, Switzerland



Iceland (Vatnajökull ice cap in lower right)

# 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).

# Other coupled modeling efforts

- **Ice2sea:** Large European project aiming to predict land-ice contributions to sea level over the next 200 years
  - Global climate models → regional atm/ocean models → ice-sheet models (no two-way coupling)
- **JPL:** Will couple ISSM dynamically to the MITgcm (used for ECCO ocean data assimilation project)
- **NASA Goddard:** Will couple Glimmer-CISM to two NASA climate models (ModelE and GEOS-5)
- **GFDL:** Has coupled the GOLD ocean model to an ice-sheet/ice-shelf model for idealized experiments

As these and other efforts mature, it would be helpful to establish **benchmark experiments** for model comparison.

# Upcoming meetings

- **IGS International Symposium on Interaction of Ice Sheets and Glaciers with the Ocean**, 5-10 June 2011, San Diego, CA
  - Abstracts due Mar. 4
- **16th Annual CCSM/CESM workshop**, 20-23 June 2011, Breckenridge, CO
  - Next LIWG meeting
  - Some travel support available
- **CESM Tutorial**, 1-5 August 2011, Boulder, CO
  - Application deadline Mar. 25
- **WCRP Open Science Conference: Climate Research in Service to Society**, 24-28 October 2011, Denver, CO
  - Abstracts due Apr. 30

# Outlook

- Within 1-2 years, CESM will likely be able to provide decadal-scale sea-level predictions using advanced ice-sheet models fully coupled to other climate components.
- Some model results will be available in time to be included in IPCC AR5 (papers submitted by July 2012).
- Many long-term challenges will remain:
  - Understand coupled ice-ocean-atmosphere interactions
  - Acquire observations to better constrain the models (e.g., beneath ice shelves)
  - Compare results from different ESMs
  - Quantify uncertainties (essential for decision support)
  - Communicate results to planners and policymakers in a timely and user-friendly fashion

Thanks to all who have contributed to this effort!