Modeling land ice in the Community Earth System Model

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- Motivation for simulating land ice in Earth-system models
- Land ice basics
- Current and upcoming state of land ice in CESM1.2/1.3
- Ongoing CESM-land ice science and development

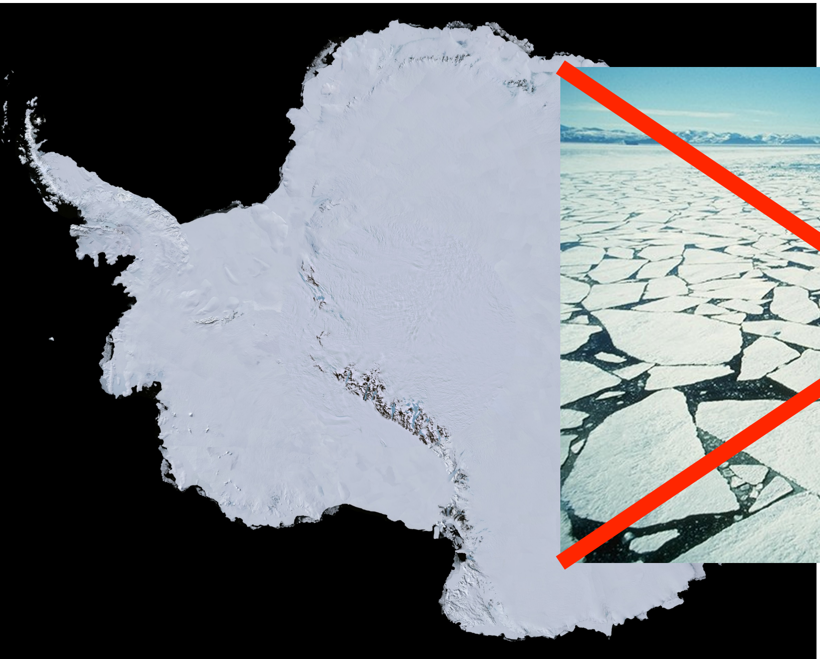
motivation for modeling land ice within CESM

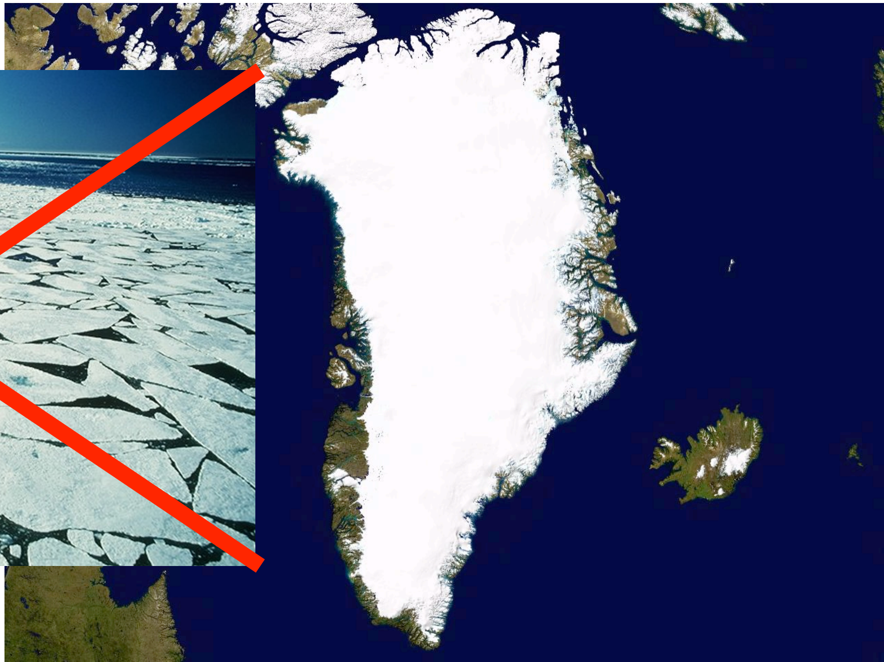
- Understand effects of climate change on land ice
- Understand effects of land ice change on climate
- Understand feedbacks between land ice & climate
- Understand past climate change
- Predict future land ice loss and sea level rise
- Predict changes in regional water supply

what is land ice?

glaciers

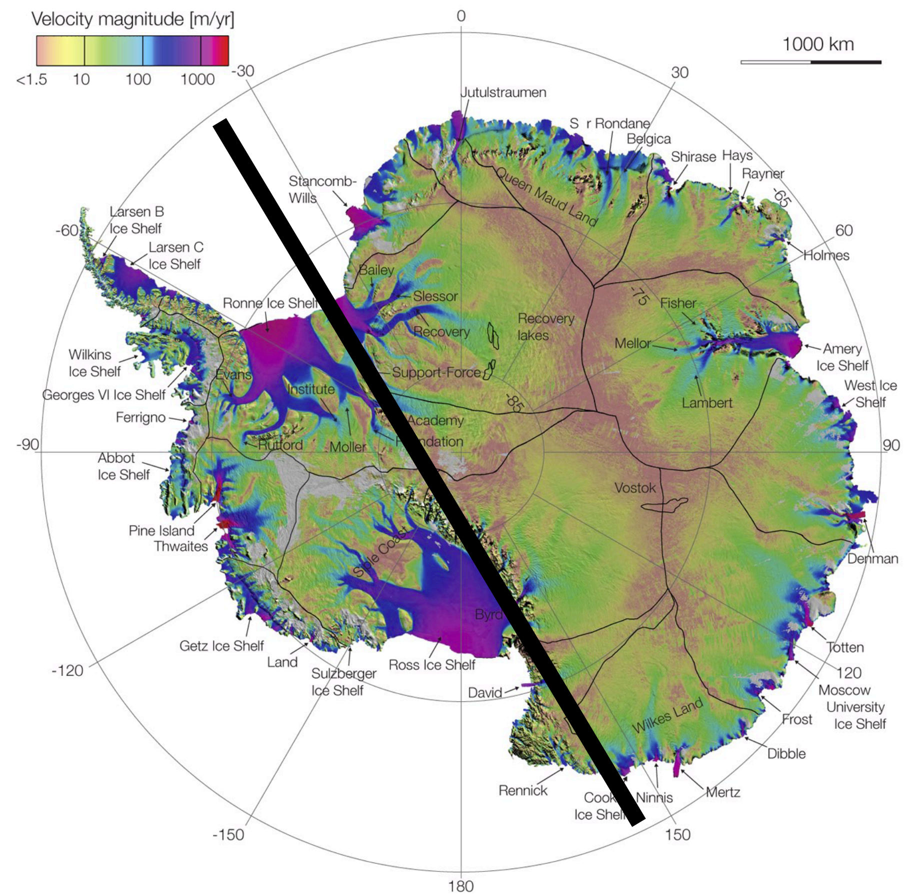
ice caps





Antarctic Ice Sheet

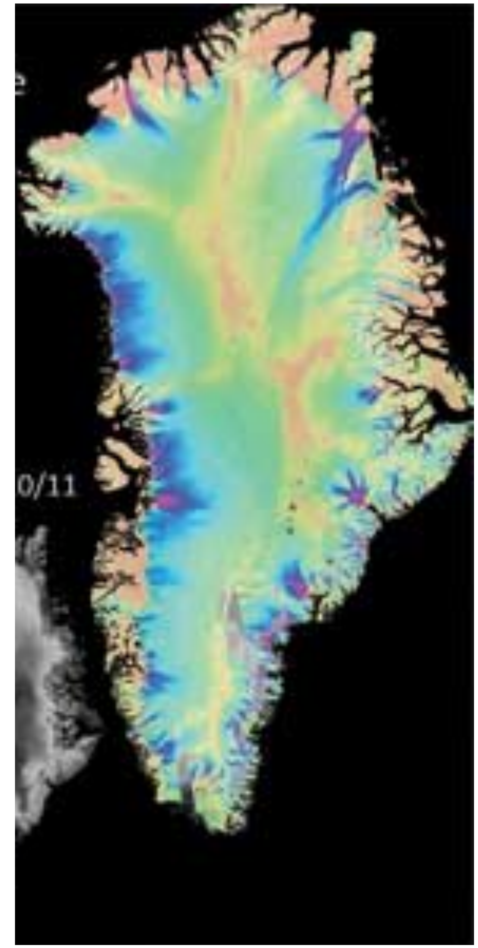
- **60 m** sea-level equivalent (~**5 m** in marine-grounded parts of West Antarctica)
- Accumulation balanced by flow into floating ice shelves; little surface melting
- Increasing mass loss (**~150 Gt/yr**) from West Antarctica and the Antarctic Peninsula



Antarctic ice flow speed (Rignot et al. 2011)

Greenland Ice Sheet

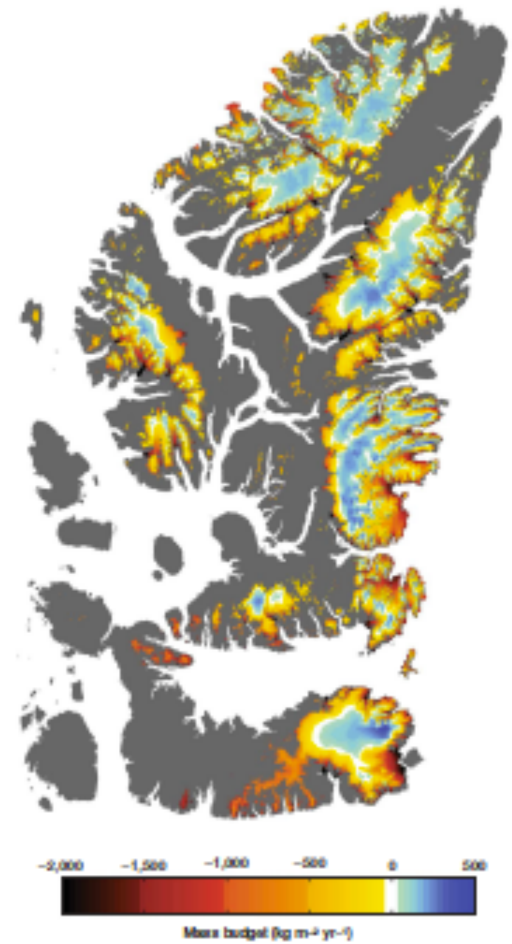
- **7 m** sea-level equivalent
- Accumulation balanced by surface runoff and iceberg calving (50/50)
- Increasing mass loss (**~200 Gt/yr**) since late 1990s from increased surface melting, combined with outlet glacier acceleration



Greenland winter flow speed (Greenland Ice Mapping Project)

glaciers and ice caps

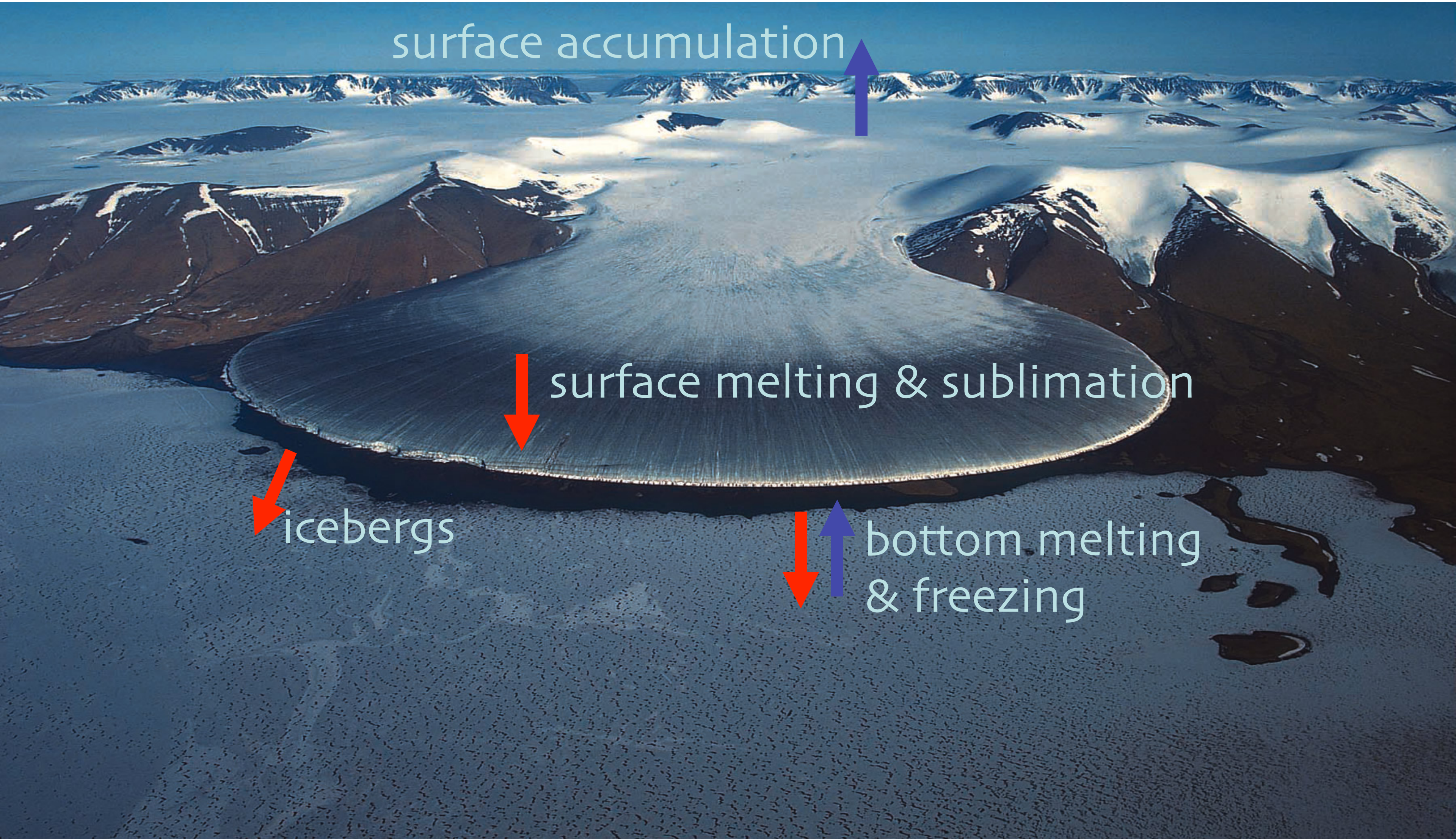
- 200,000+ glaciers and ice caps worldwide
- Only **0.6 m** sea-level equivalent (Radic & Hock 2010), but short response times
- Most glaciers are out of balance with the climate and are retreating



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

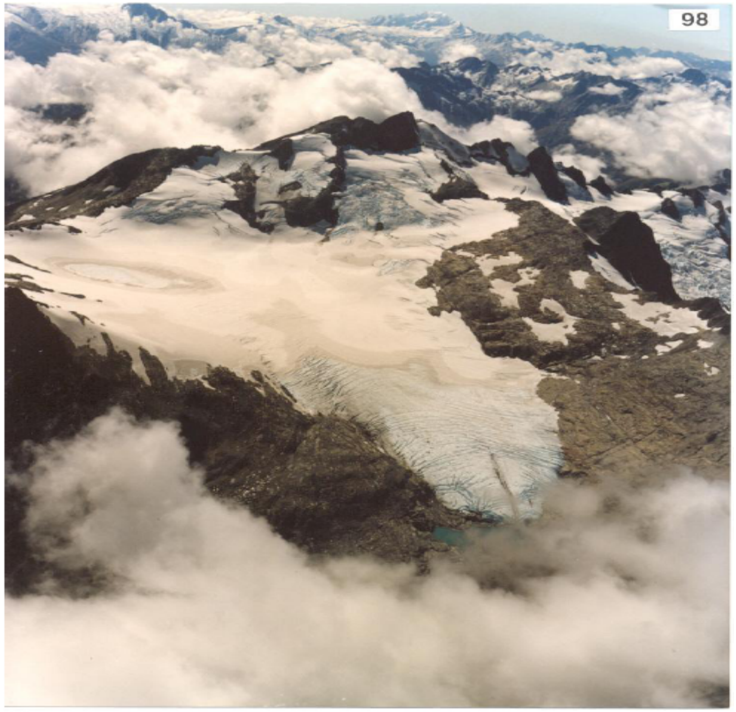
land ice basics: mass balance and dynamics

mass balance



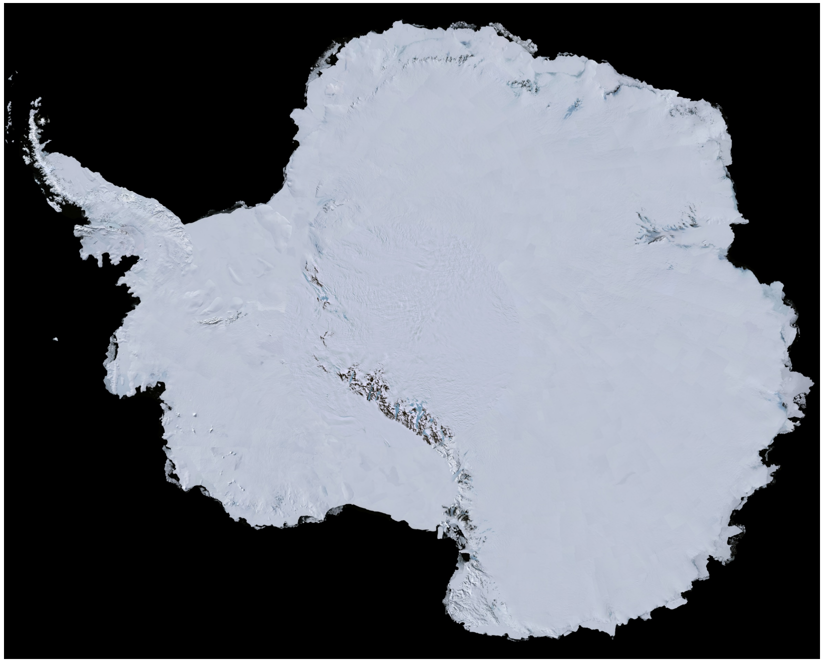
mass balance: atmospheric components

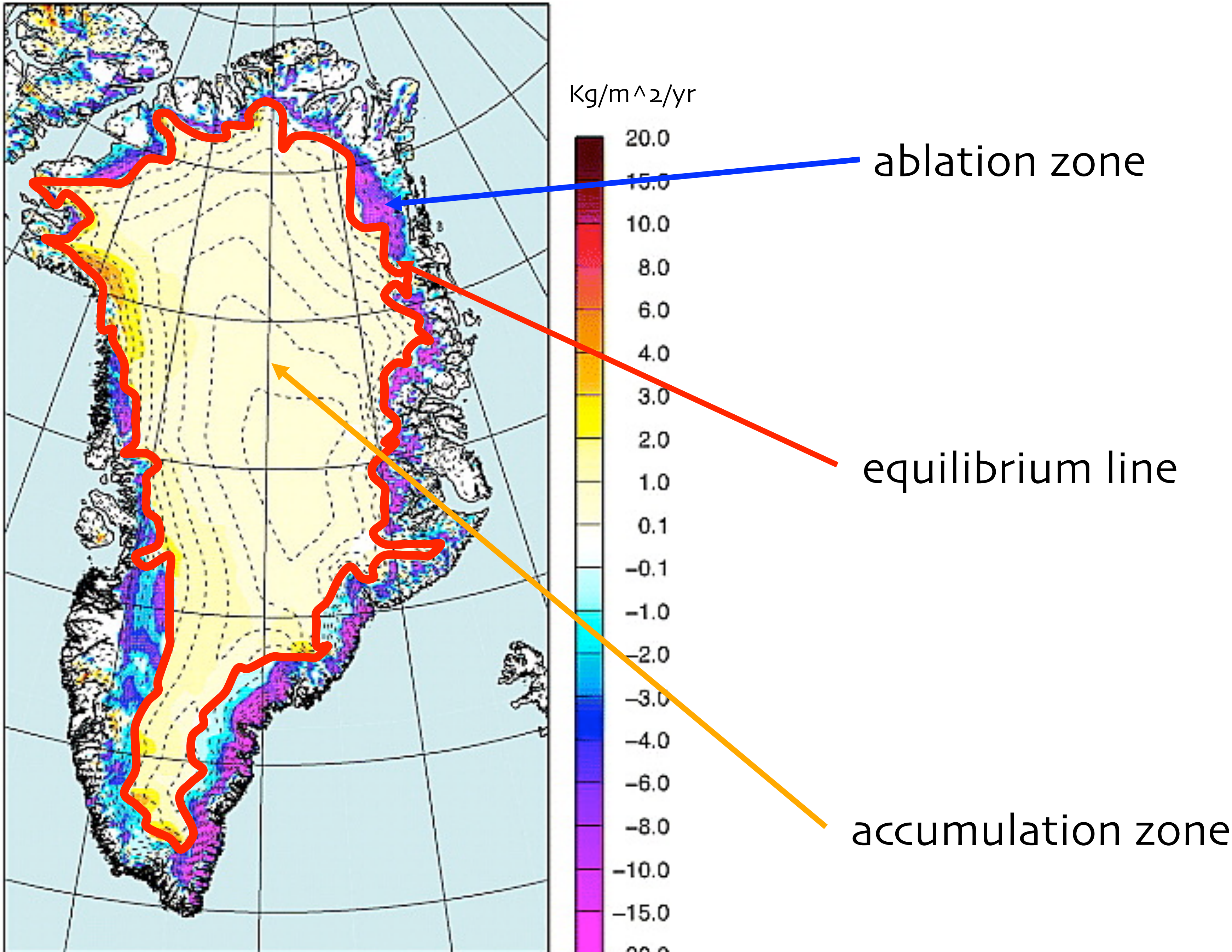
net mass change (kg/yr) =
∫(surface accumulation
-surface melt
-surface sublimation
~~-basal melt~~
~~-ice discharge)dA~~



mass balance: atmospheric + oceanic components

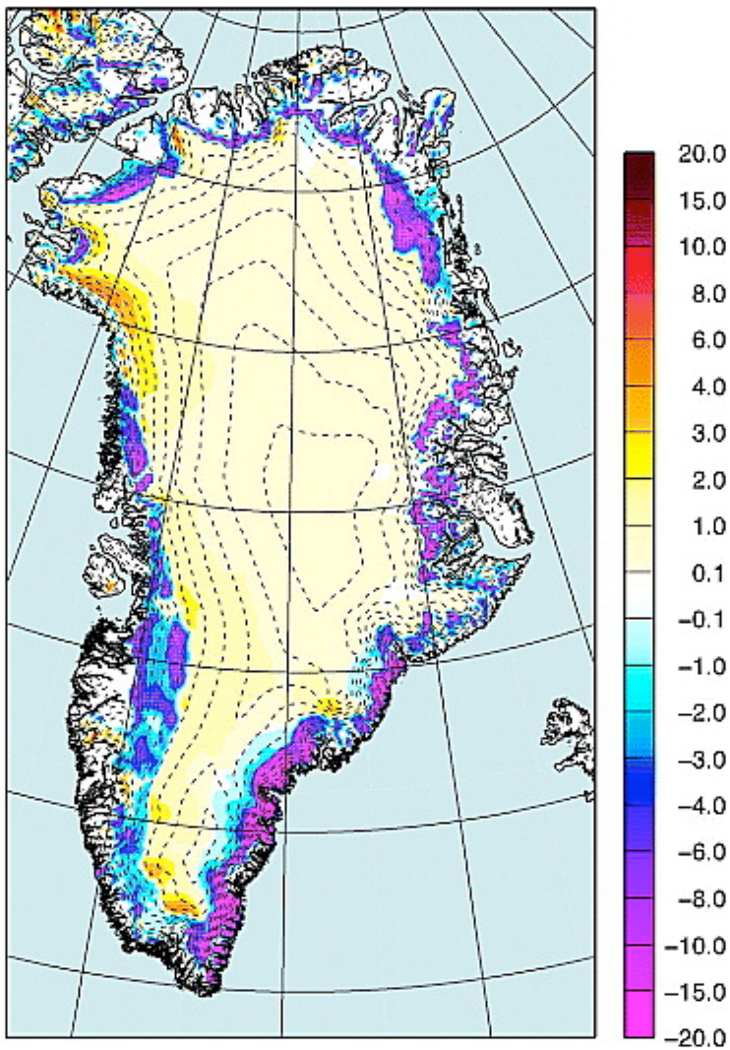
net mass change (kg/yr) =
∫(surface accumulation
-surface melt
-surface sublimation
-basal melt
-ice discharge)dA



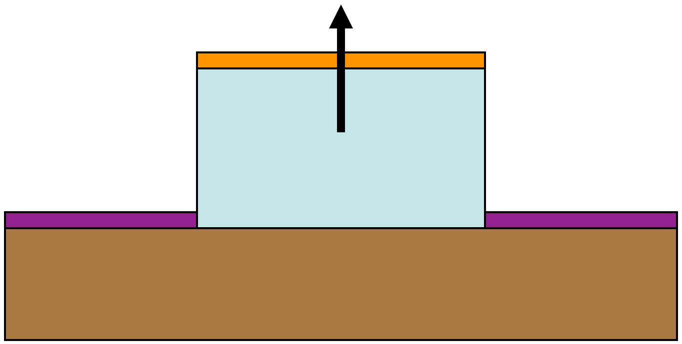


Ettema et al. (2009)

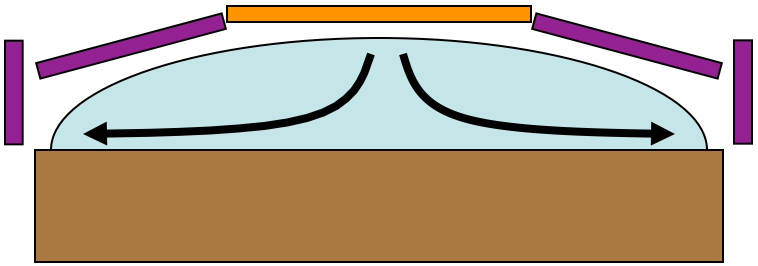
ice dynamics

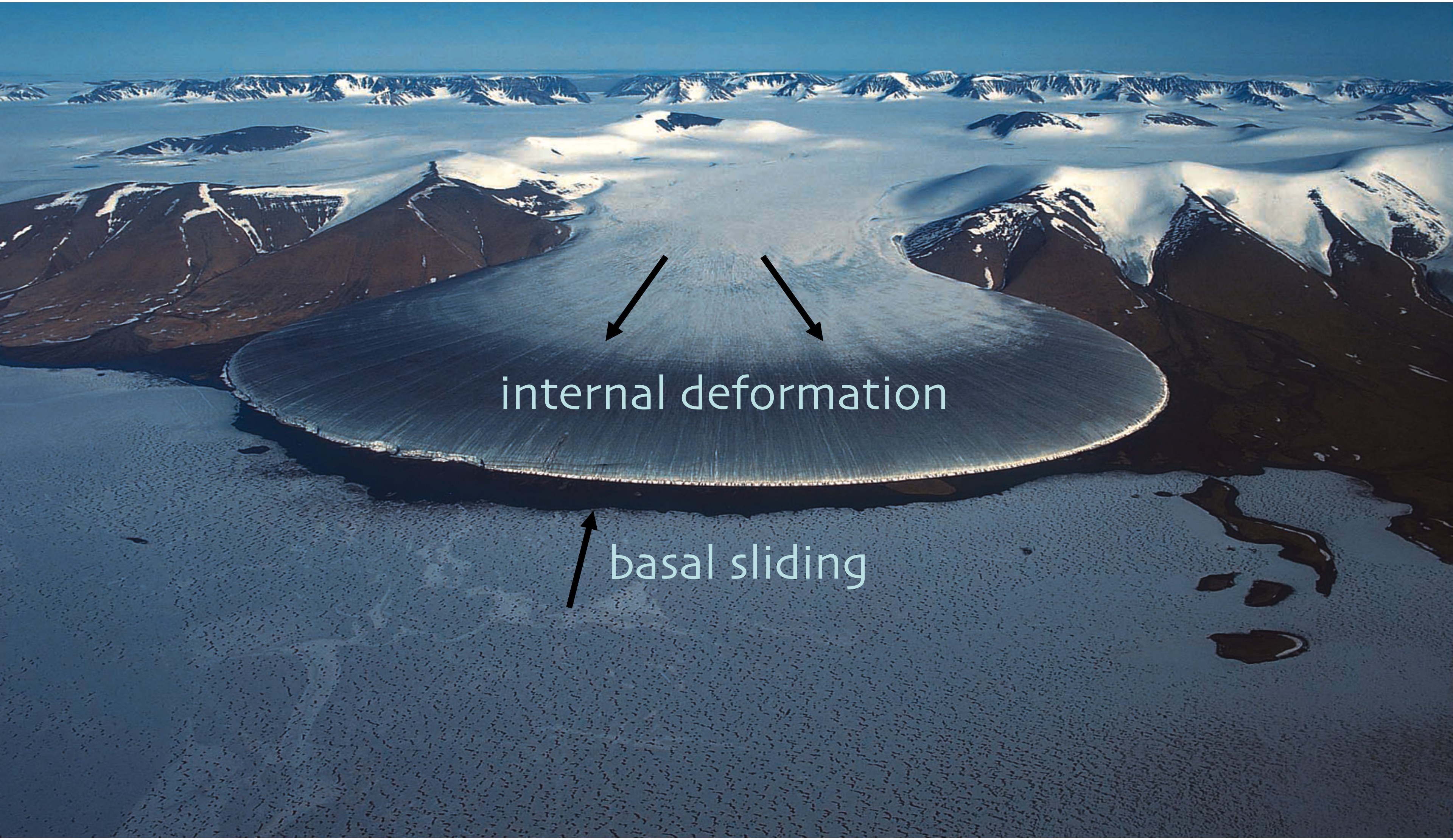


if ice were completely undeformable:



In reality:




internal deformation
basal sliding

how we model ice: coupled conservation equations (dynamical core)

Conservation of Momentum:

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

internal stress

gravity

Conservation of Energy:

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

diffusion

advection

internal energy

Conservation of Mass:

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

mass divergence

mass balance

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

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

modelled “physics” (everything besides dynamics)

- Constitutive models:
  translate stress tensor to stress-induced velocity
- Basal sliding:
  relates of basal slip to temperature, bed roughness, basal water pressure
- Surface and subglacial hydrology:
  determines basal water pressure (important for sliding, above)
- Iceberg calving:
  determines mass loss at ocean boundary

land ice in coupled global climate models

As land ice evolves, it interacts with the surrounding climate in ways that *feed back* on its own evolution.

Climate model passes:

- Surface mass balance
- Boundary temperatures
- Sub-shelf melting

Land ice model passes:

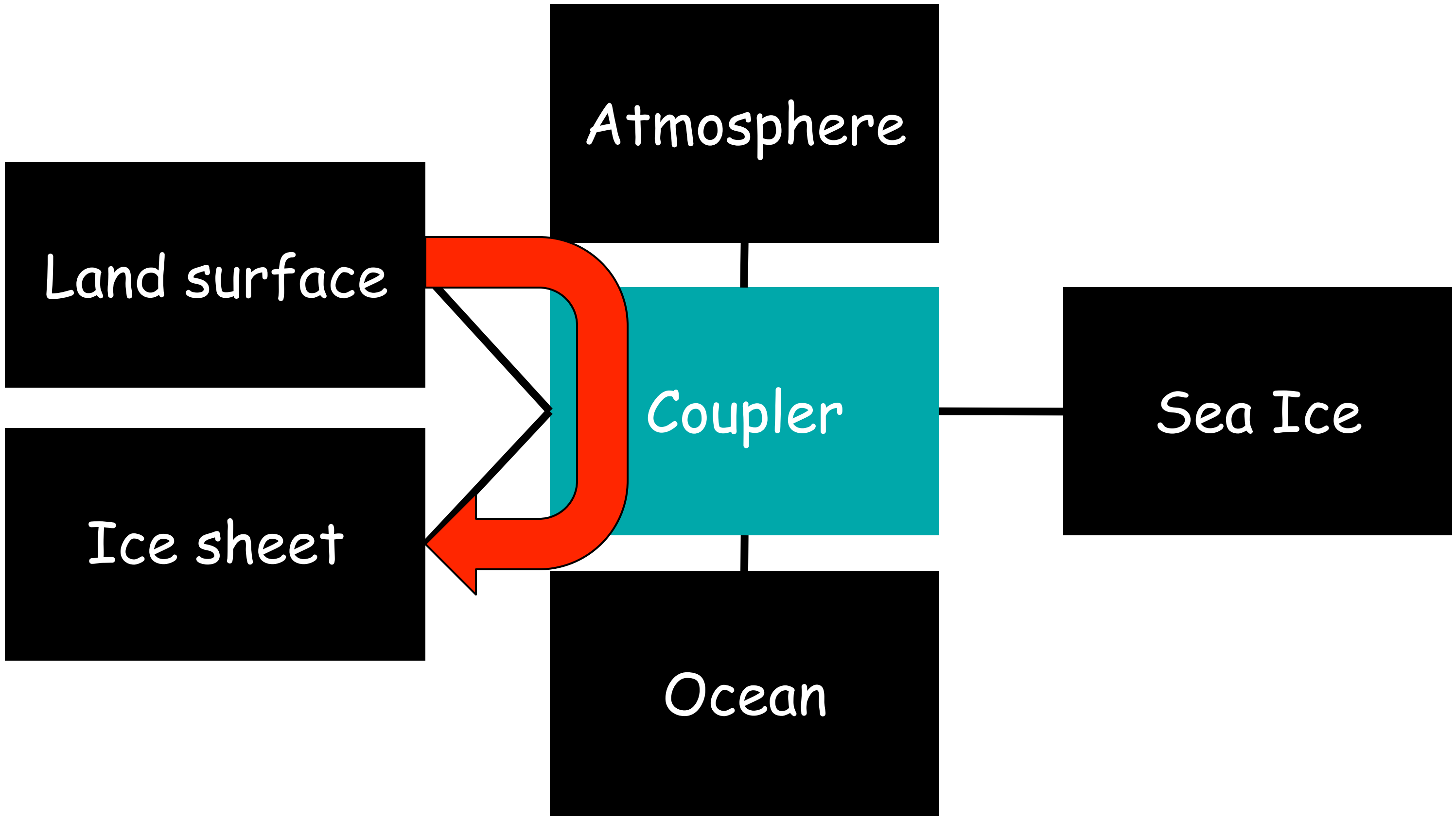
- Elevation
- Revised land ice distribution
- Oceanic heat and moisture fluxes (icebergs)
- Revised sub-shelf geometry

ice sheets in CESM

- Dynamics and physics: CESM 1.2 includes the **Community Ice Sheet Model (CISM)**
  - Supports a dynamic ***Greenland ice sheet*** on a 5 km grid
  - Currently operational: shallow-ice (based on Glimmer-1.6)
  - Higher-order version (CISM 2.0) available but undergoing testing within CESM
- Surface mass balance: CESM includes an energy-balance-based **surface-mass-balance scheme** for land ice
  - Computed by CLM in multiple elevation classes, then sent to the coupler, downscaled to ice sheet grid
  - Scheme can be applied in all glaciated regions, not just ice sheets

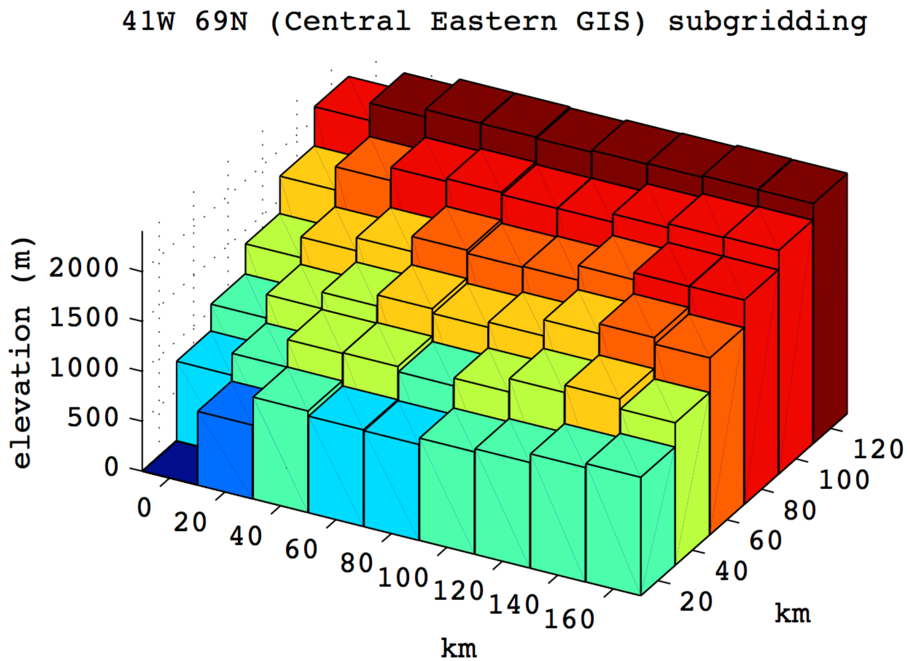
coupling of ice sheets in CESM 1.2

SMB and surface ice temperature



ice sheet surface mass balance in CESM

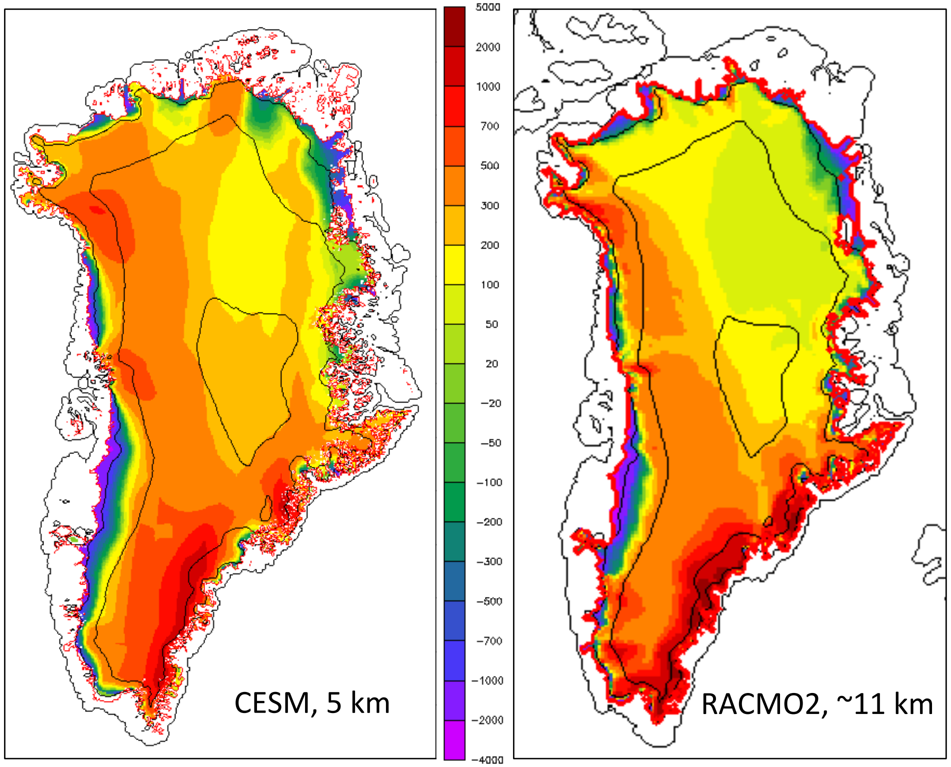
- CESM computes the SMB and surface ice temperture in the land model (CLM) on a coarse (~100 km) grid in 10 elevation classes
  - Cost savings (~1/10 as many columns)
  - Energetic consistency
  - Avoid code duplication
  - Surface albedo changes feed back on the atmosphere



comparison with RACMO ('state of the art' regional model)

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

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

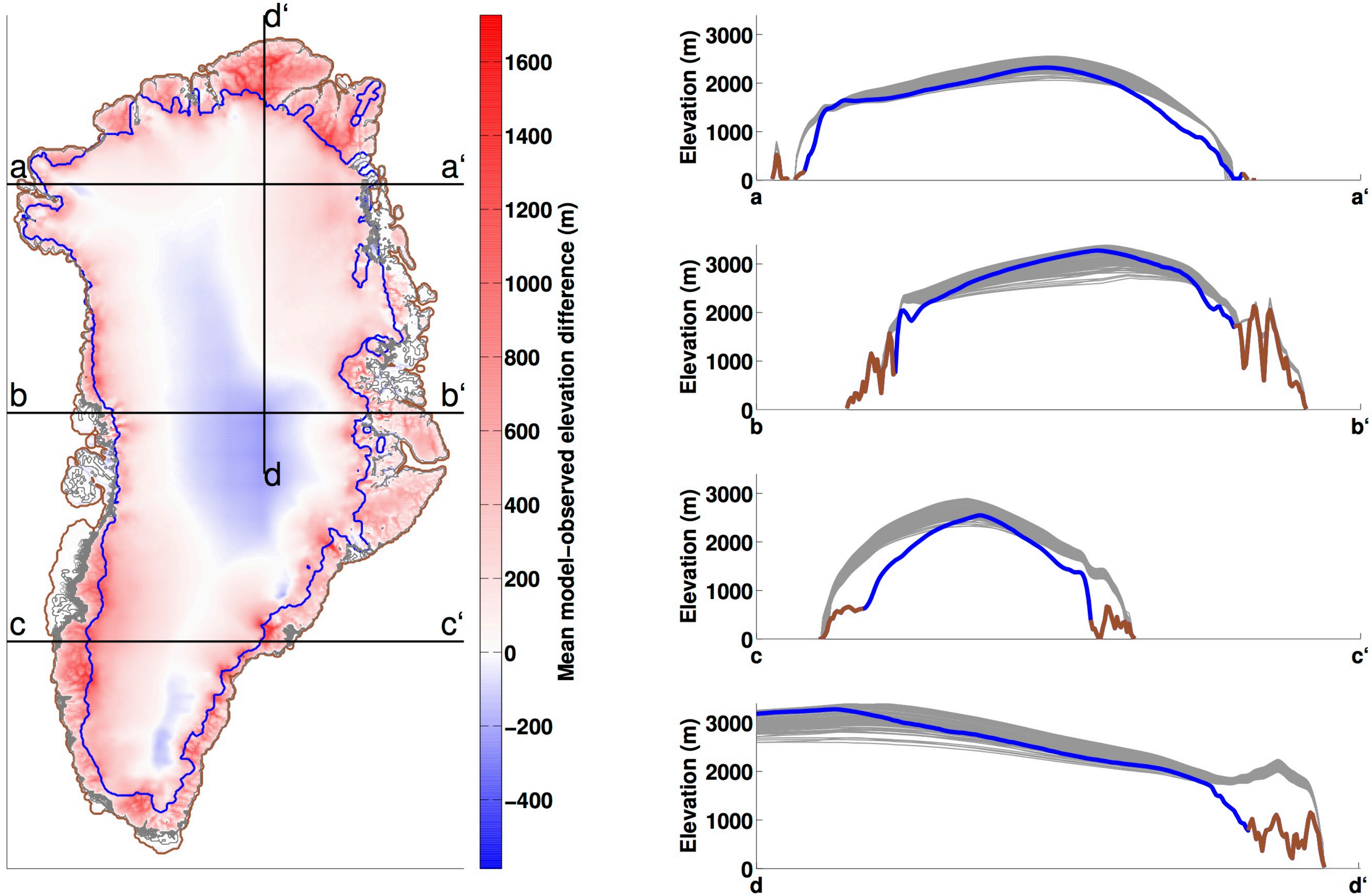


Courtesy of M. Vizcaíno

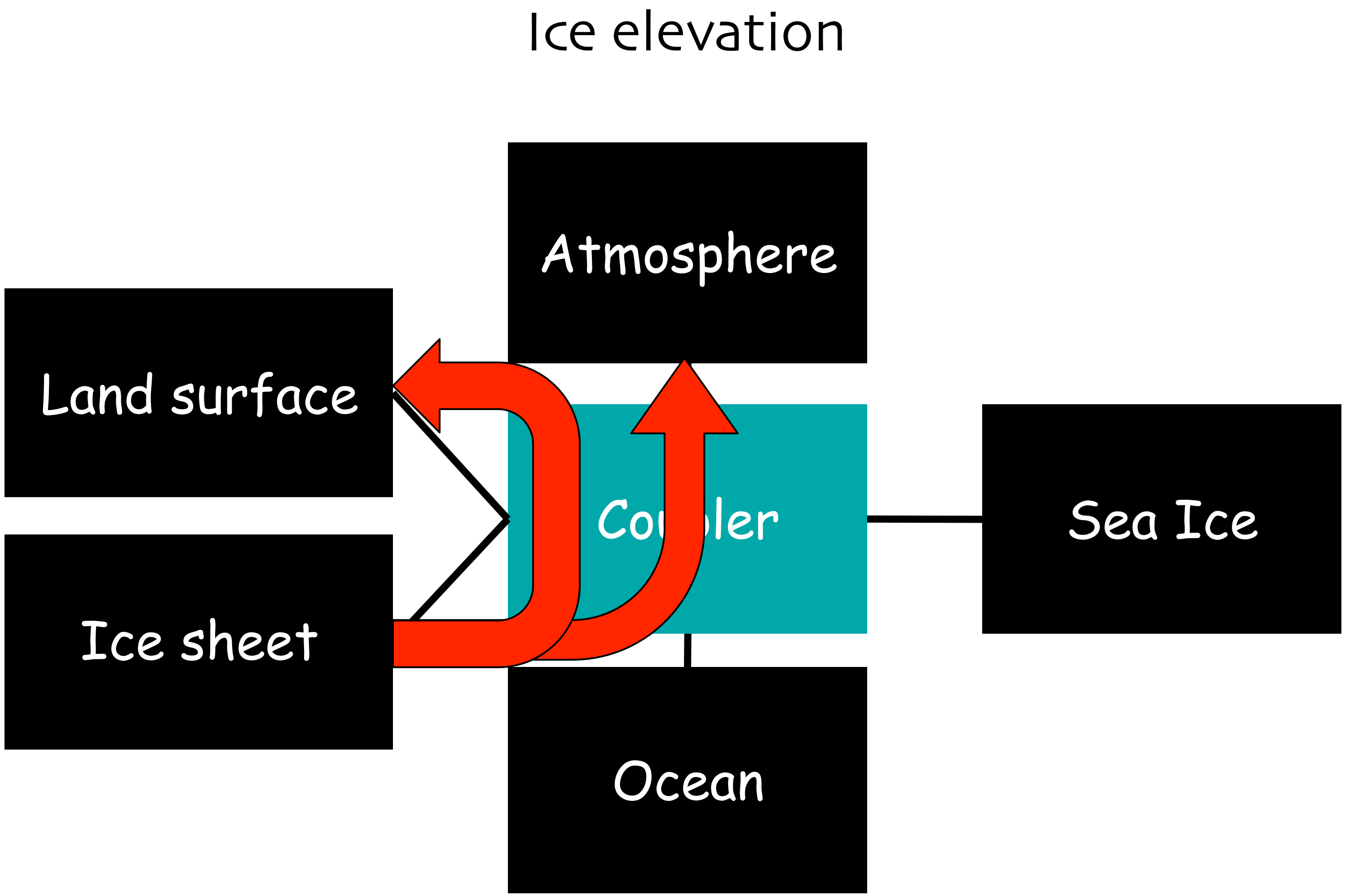
- Good match in ablation zones
- Accumulation is overestimated in the interior and underestimated in the southeast (smoother orography in CESM)

Vizcaino et al, 2013

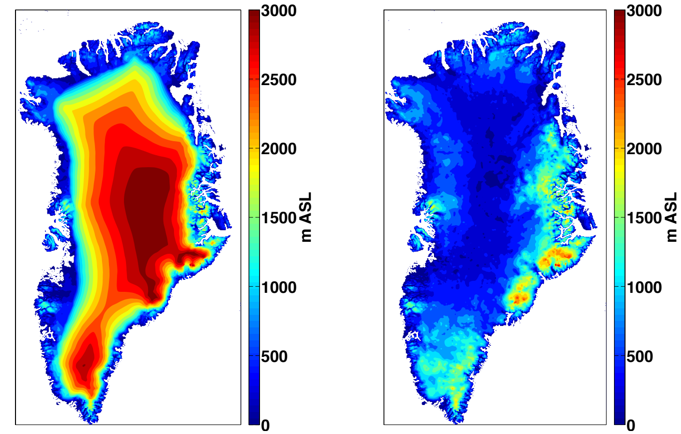
Preindustrial CISM Greenland steady-state perturbed-physics ensemble

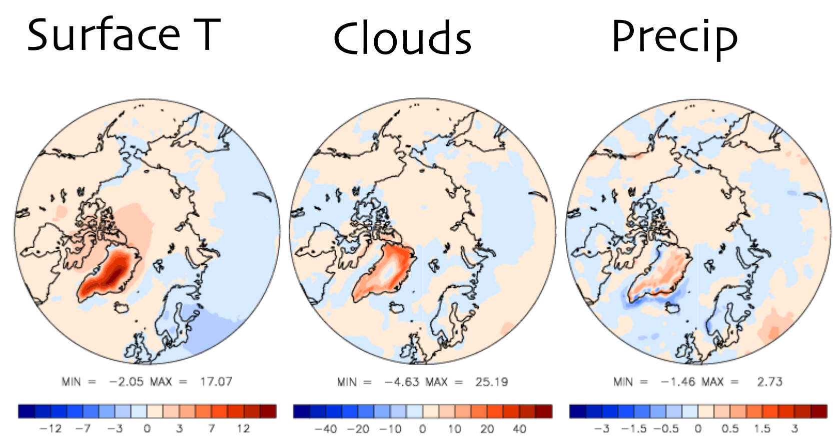


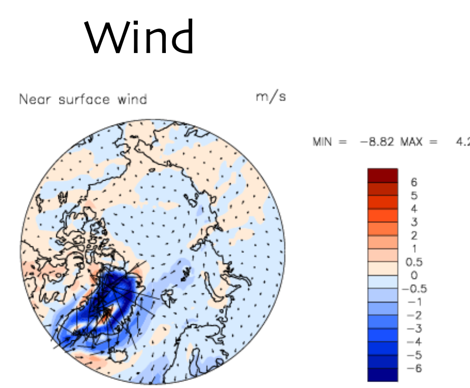
coupling of ice sheets in CESM 1.3



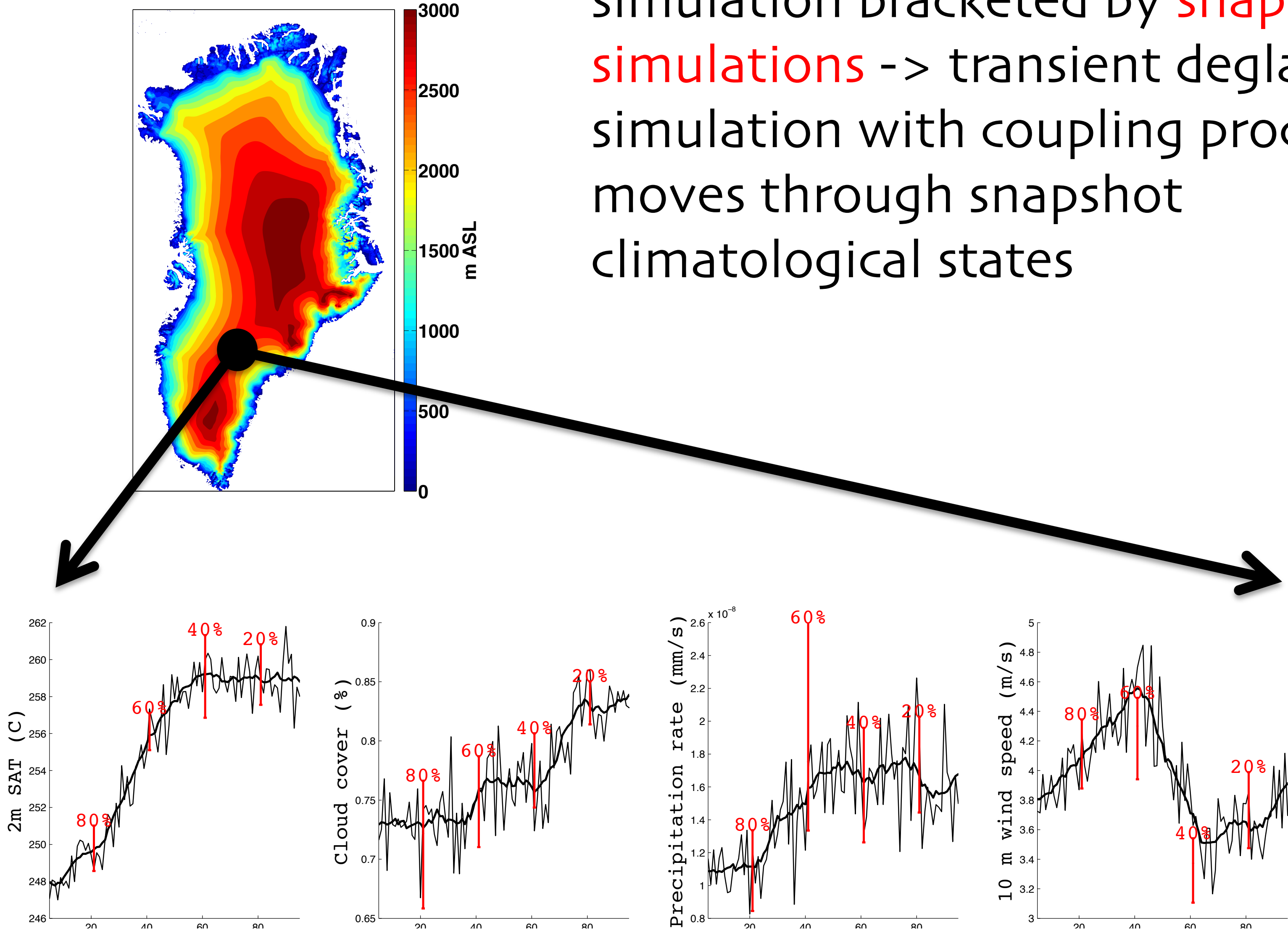
- Script-based coupling approach merges high-resolution ice sheet model topography into raw GTOPO-30 dataset, regenerates CAM topography and surface roughness fields in restart file.
- Script called during initialization of simulations and once/year resubmission step





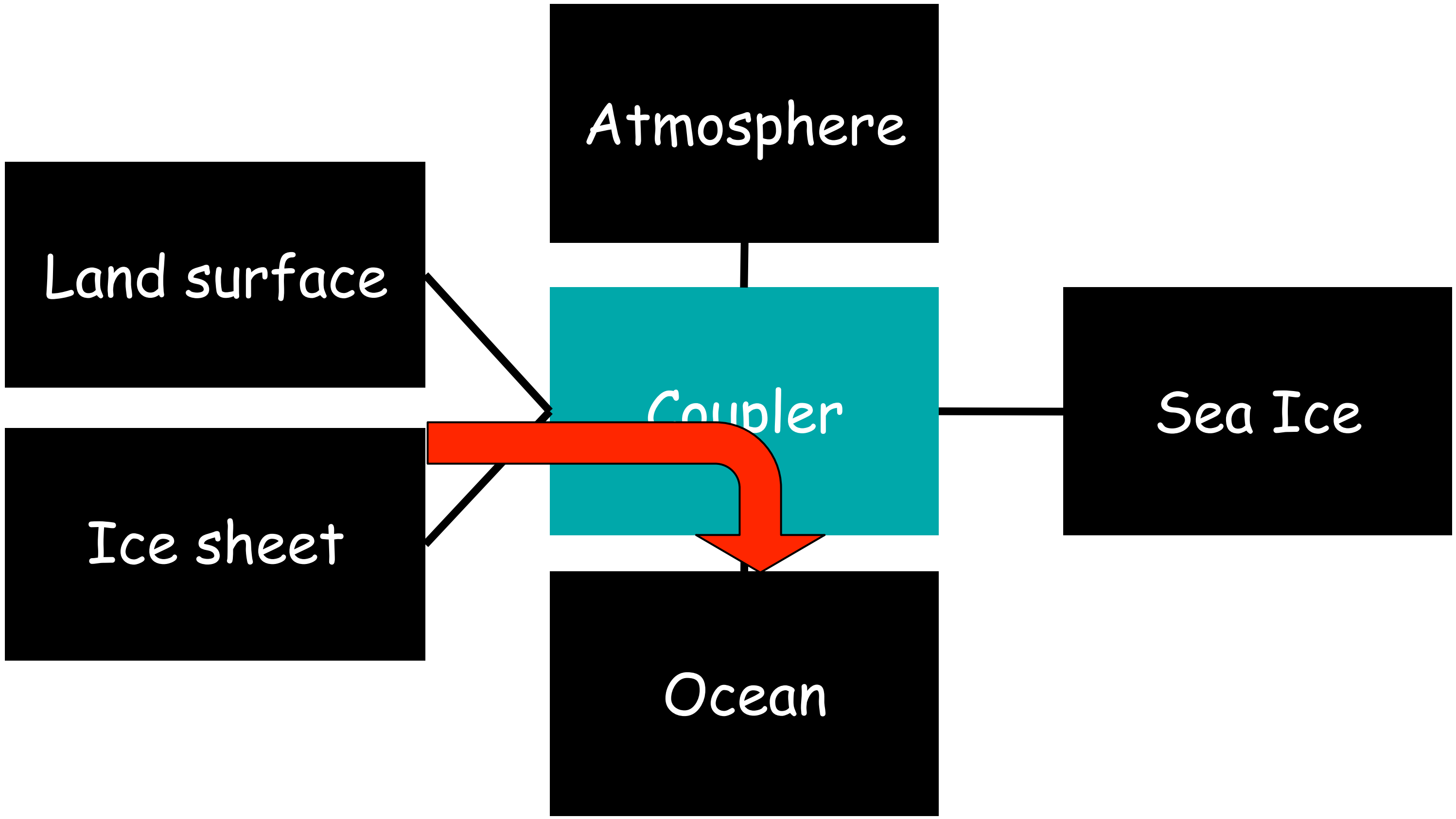


- Time series trends from transient simulation bracketed by snapshot simulations -> transient deglacial simulation with coupling procedure moves through snapshot climatological states



coupling of ice sheets in CESM 1.3

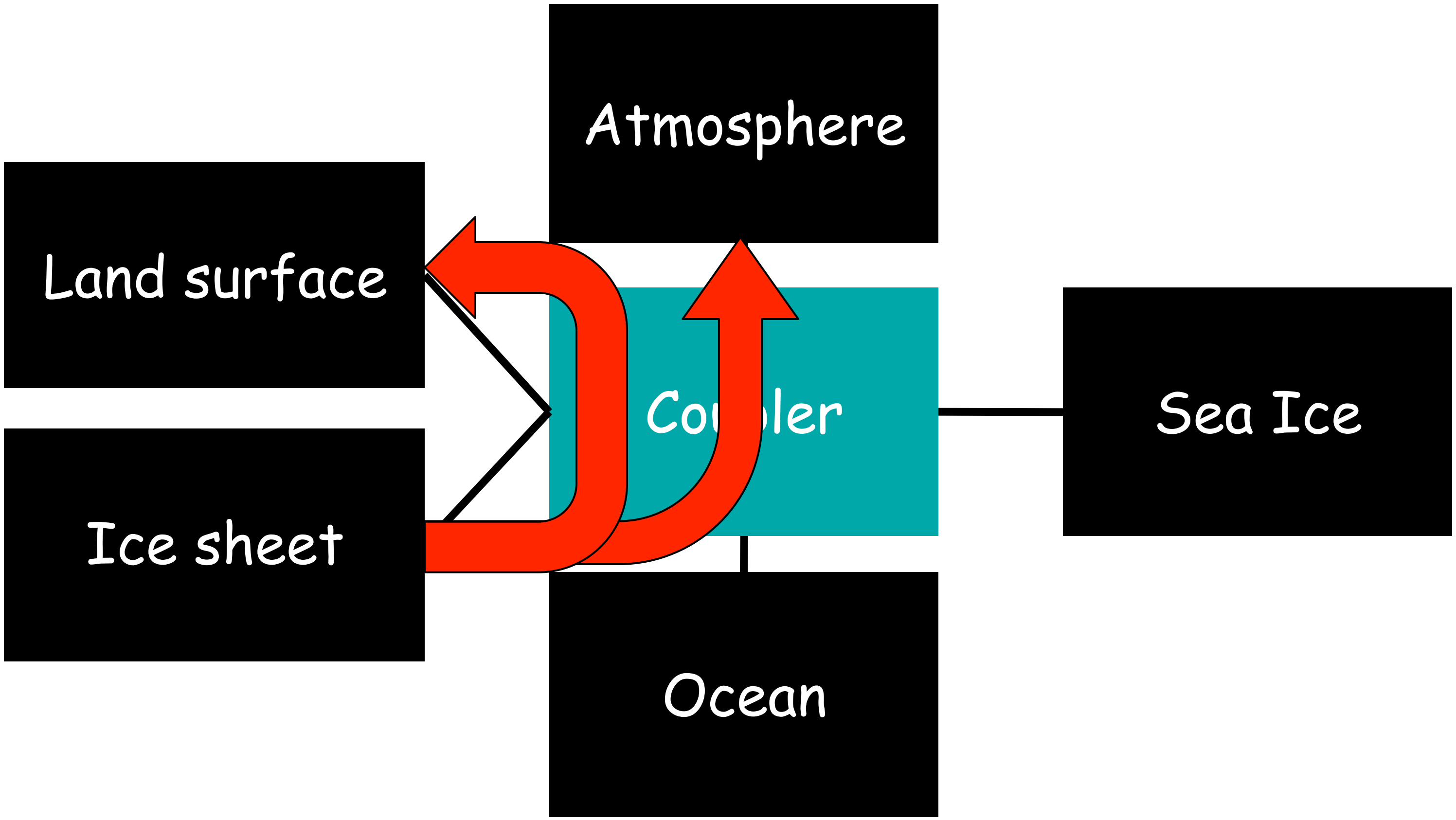
Meltwater runoff and iceberg discharge



- Two (of three) ways for land ice H_2O to reach the ocean: via surface melt, and via iceberg discharge
- Surface melt calculated in CLM, routed to ocean via river transport model
- Iceberg discharge: two routing options under development to route calved ice mass from CISM to ocean:
  1. freshwater flux (and negative heat flux) to static distribution of ocean grid cells using nearest-neighbour routing
  2. Explicitly to dynamic/thermodynamic iceberg model (nested in the CICE sea ice model, Hunke and Comeau, [2011])

coupling of ice sheets in CESM **1.3**

Land ice areal distribution changes

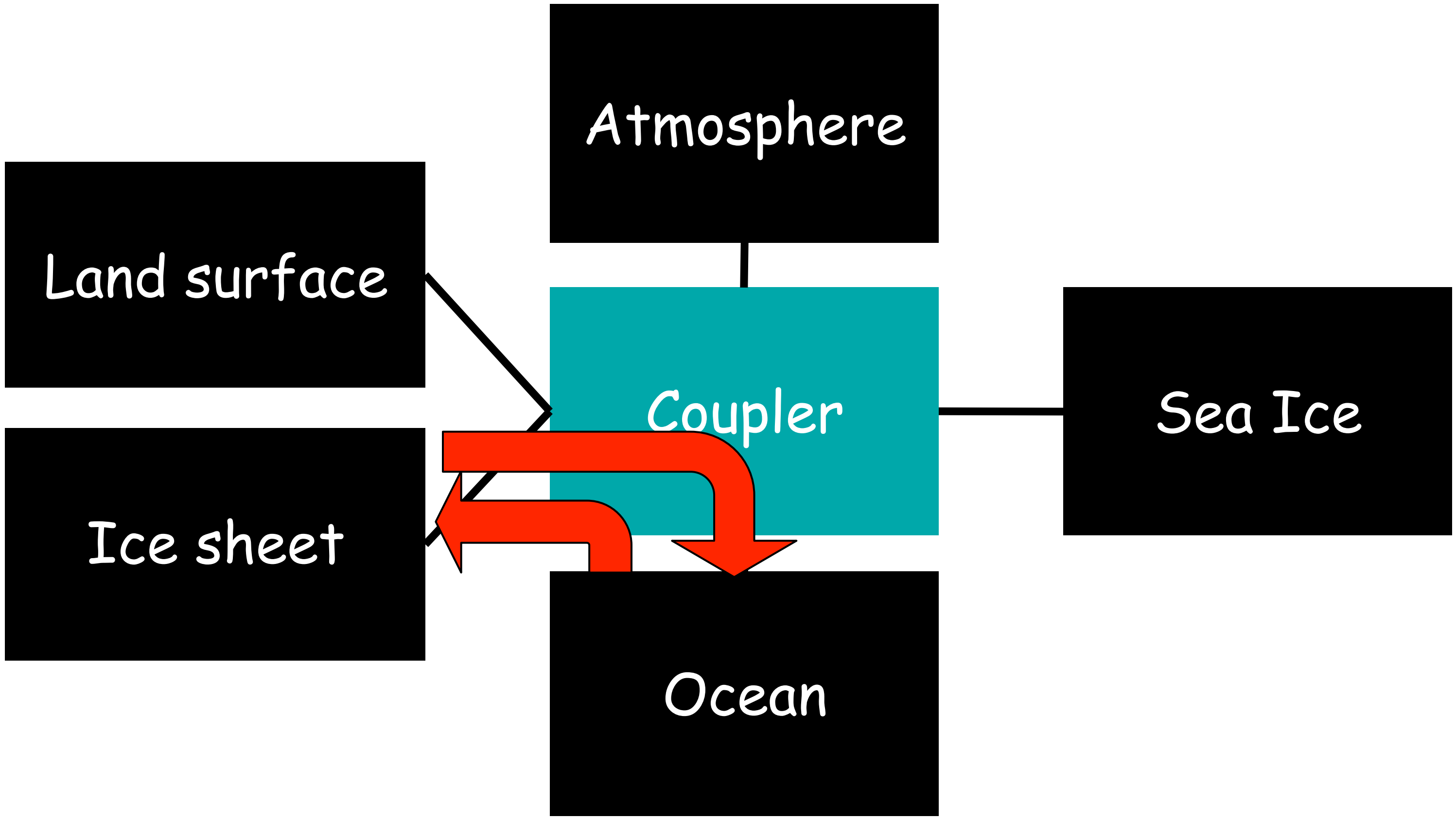


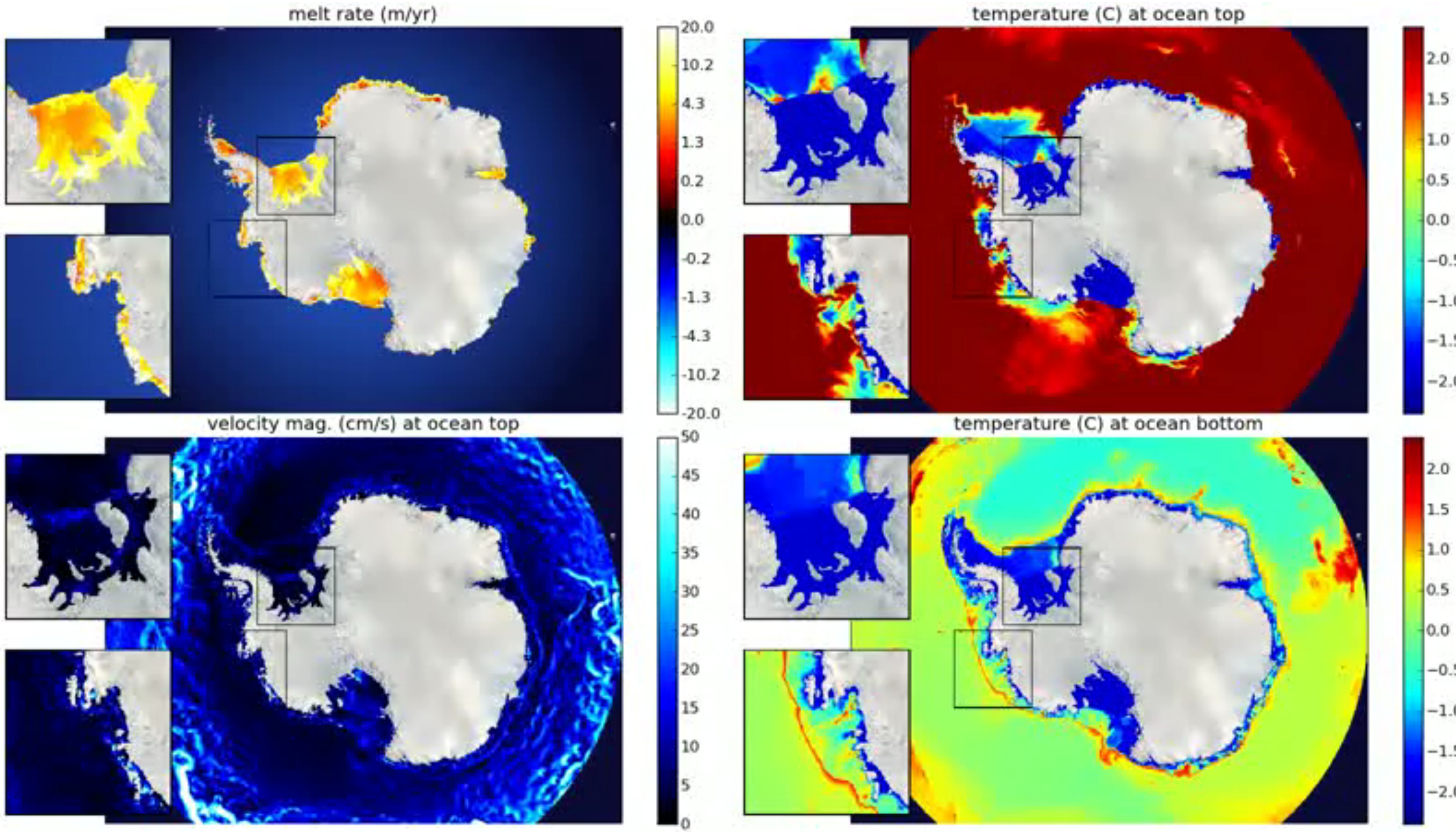
- Ice sheet areal extent influences:
  - Surface roughness
  - Land hydrology
  - Bare-land albedo
  - Dynamic vegetation
- Development ongoing to make CLM landunits ‘dynamic’, so changes to ice sheet areal extent are mirrored in CLM and CAM boundary conditions

Mix et al., 2001

coupling of ice sheets in CESM 1.+

Sub-shelf melting

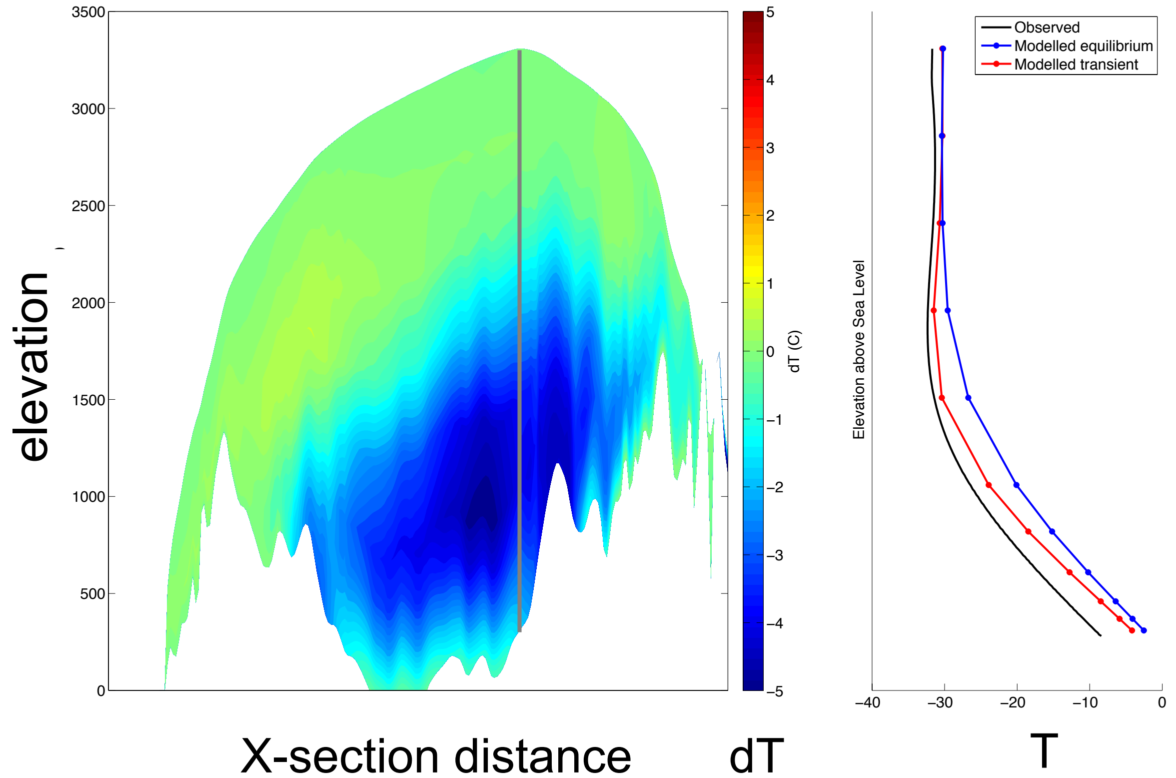




animation courtesy Xylar Asay-Davis

ice sheet spin-up

- CESM-and-climate-consistent 122,000 year spin up completed through last glacial cycle
- Forced with GRIP $\delta^{18}O$-interpolated SMB, end-members from CCSM4 LGM/mid-Holocene/preindustrial IG simulations



Fyke et al, 2013, in review

Science output with CESM/CISM

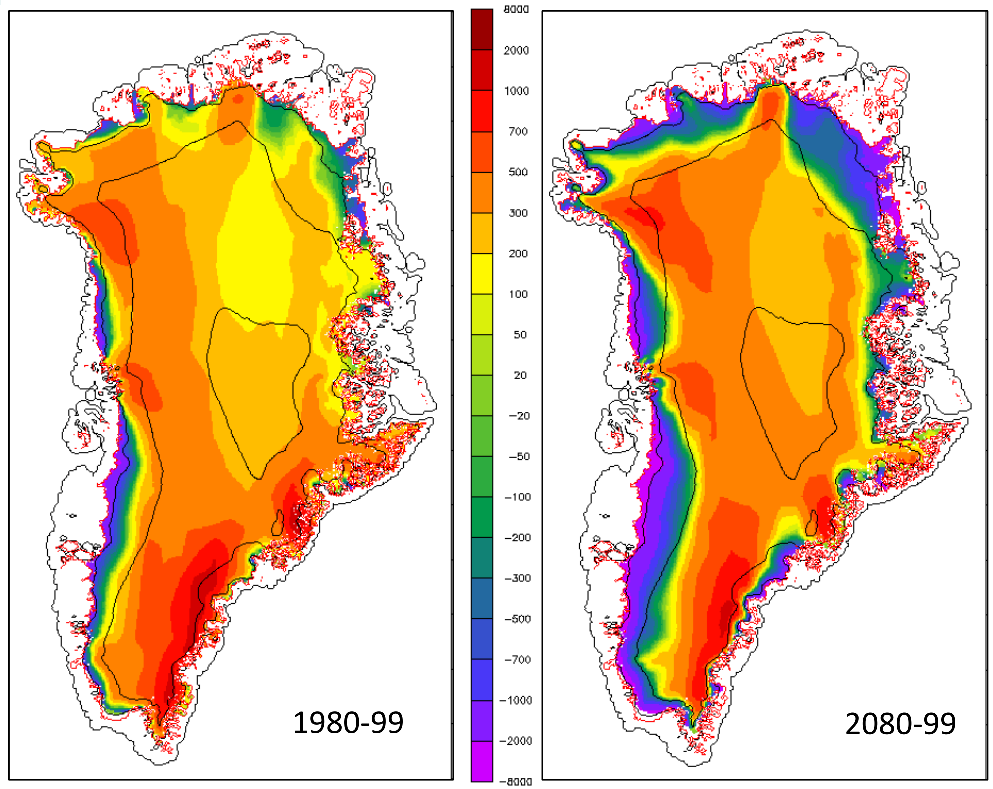
CESM Greenland surface mass balance

	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

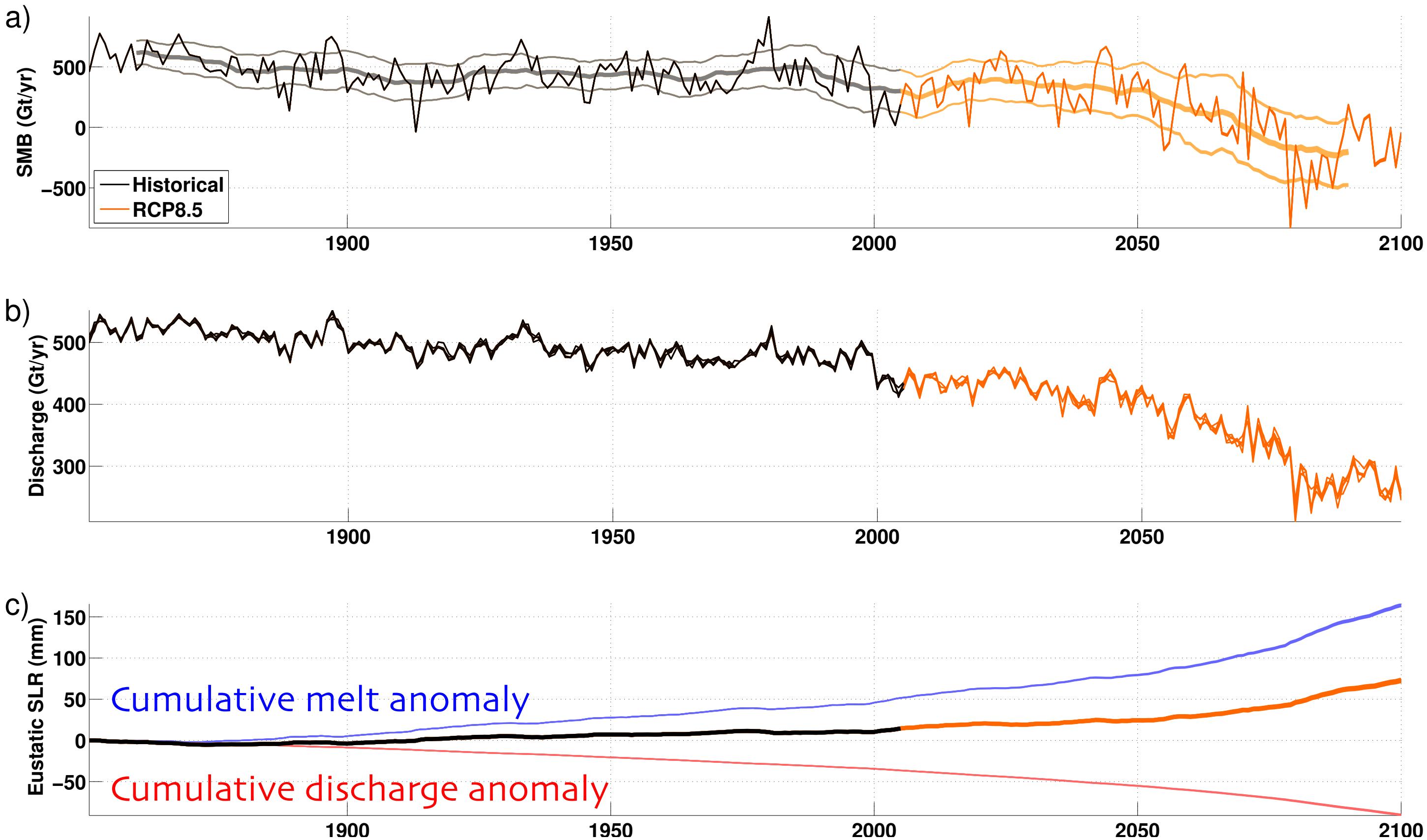


- For RCP8.5, precipitation increases, but melt and runoff increase more.
- Warming is greatest in north (less sea ice), least in southeast (weaker MOC).
- Average SMB is negative by 2100, implying long-term decay of ice sheet.

Vizcaino et al., in review

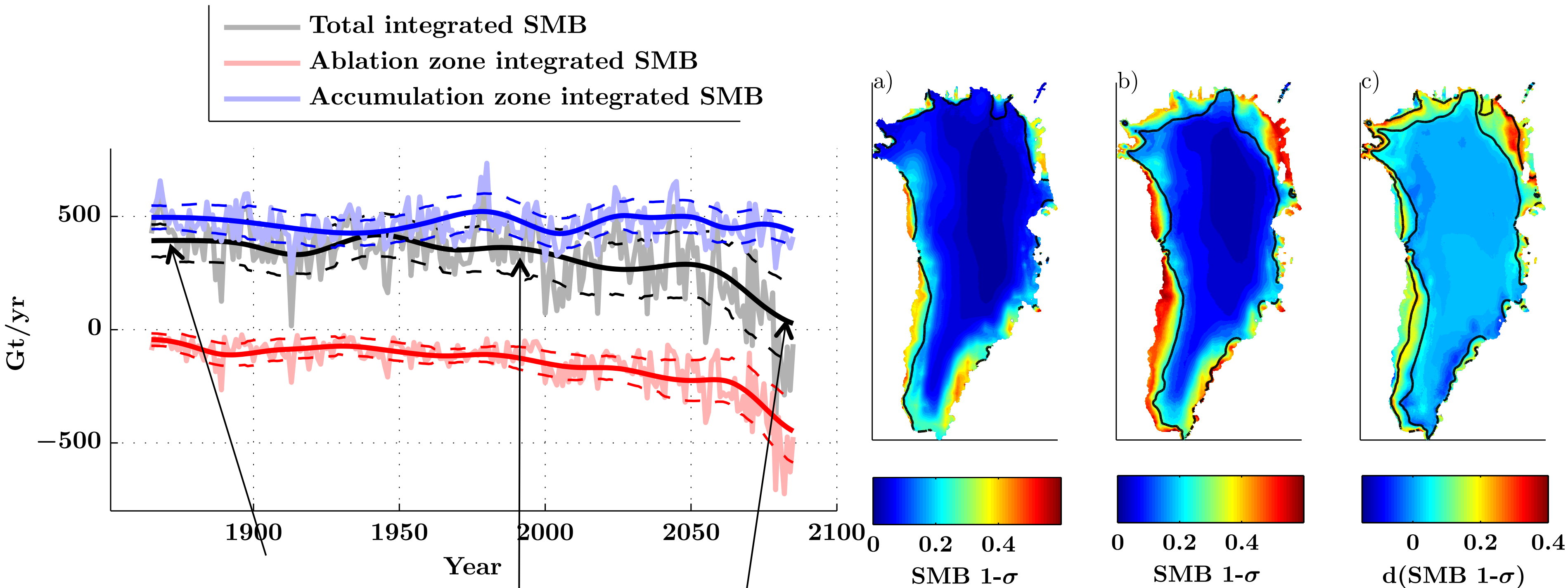
CESM RCP8.5 GIS sea level rise contribution

- CESM generates 7.6 cm of SLR, with strong dampening due to negative dynamic feedback



Lipscomb et al., 2013

CESM future GIS SMB variability



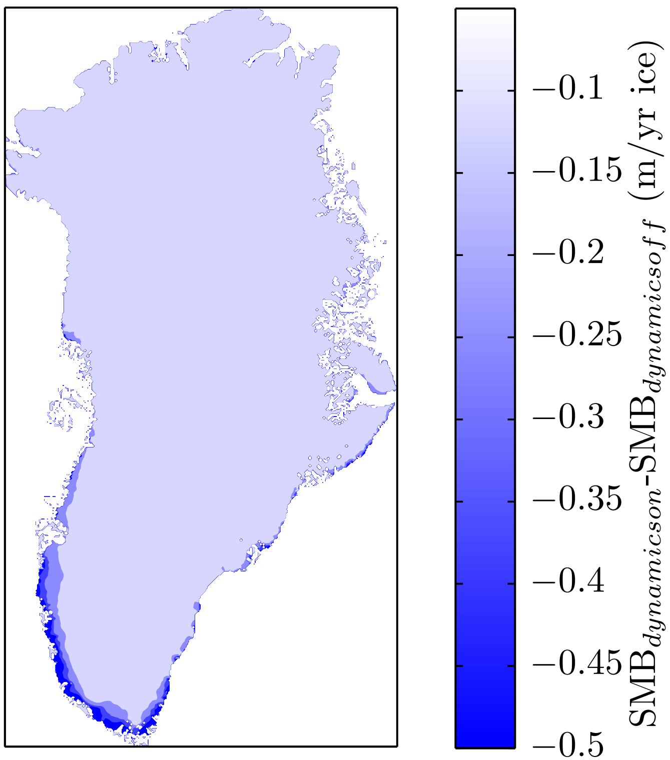
σ =90 Gt/yr

σ =112 Gt/yr

σ =165 Gt/yr

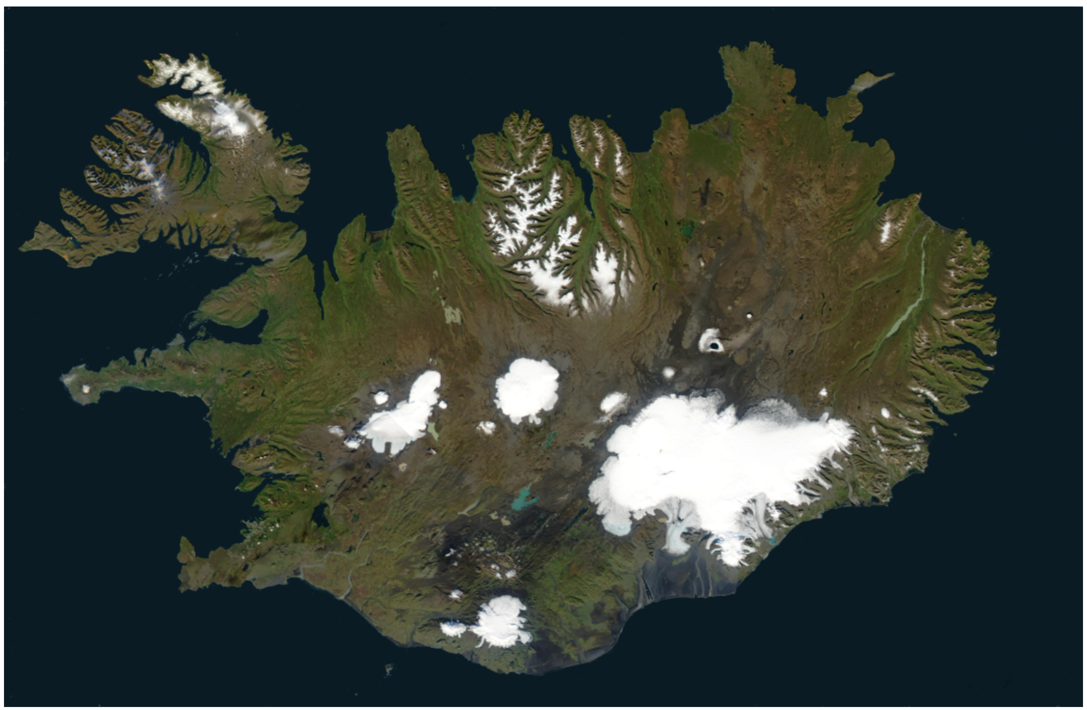
CESM-CISM ice-sheet/climate feedbacks

- Surface mass balance in ablation zone 7% more negative when height-surface mass balance feedback resolved
- Height-surface mass balance feedback impacts GIS SMB even over IPCC timescales



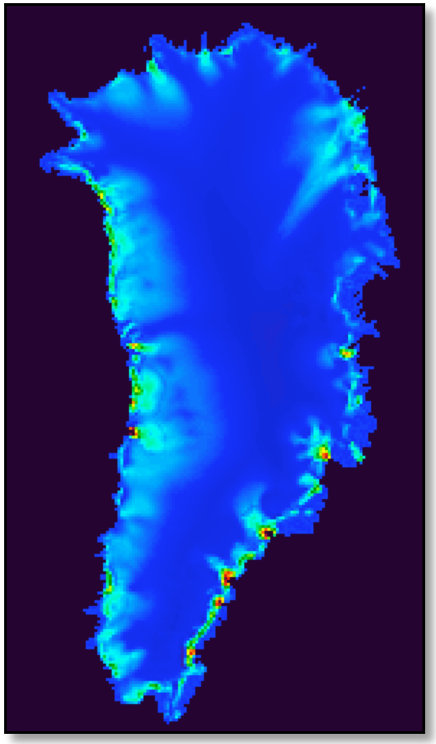
ongoing development

1. Statistical model of glaciers and ice caps in CESM
2. Hydrology-sliding coupling
3. Higher-order ice sheet models

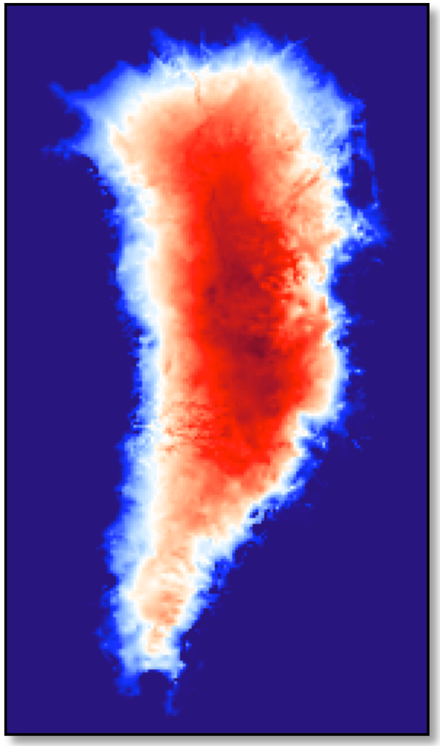


ongoing development

1. Improved models of glaciers and ice caps in CESM
2. Hydrology-sliding coupling
3. Higher-order ice sheet models



Basal water thickness



Water pressure

figures courtesy
M. Hoffman

ongoing development

1. Improved models of glaciers and ice caps in CESM
2. Hydrology-sliding coupling
3. Higher-order, variable resolution ice sheet models

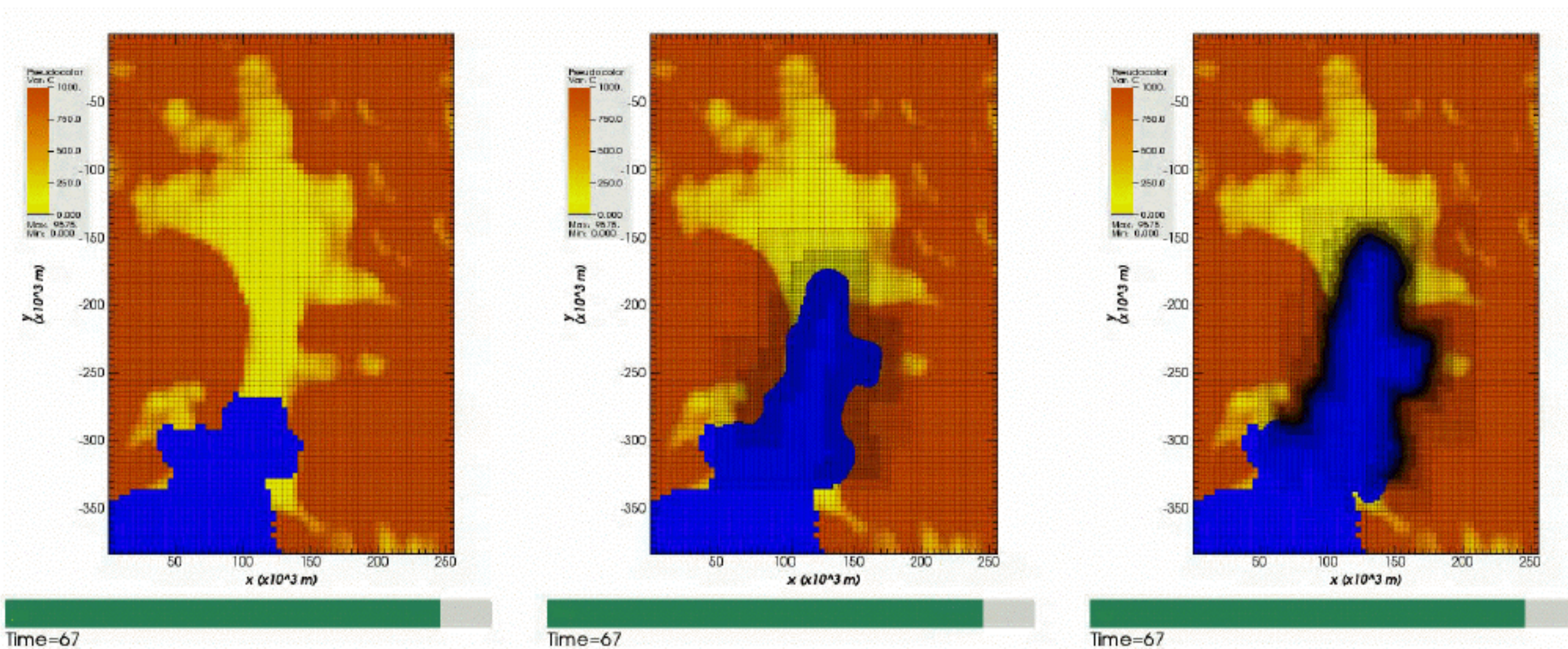


figure courtesy of S. Cornford and D. Martin

CESM Land Ice Working Group

Leadership

- *Co-chairs*: William Lipscomb/Steve Price (LANL), Jesse Johnson (U. Montana)
- *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


Thank you !