Modeling land ice in the Community Earth System Model

- Motivation for simulating ice sheets in Earth-system models
- Ice sheet basics and ice-sheet/climate coupling
- Current/upcoming state of ice sheets in CESM1.2/1.3
- Recent CESM ice sheet science

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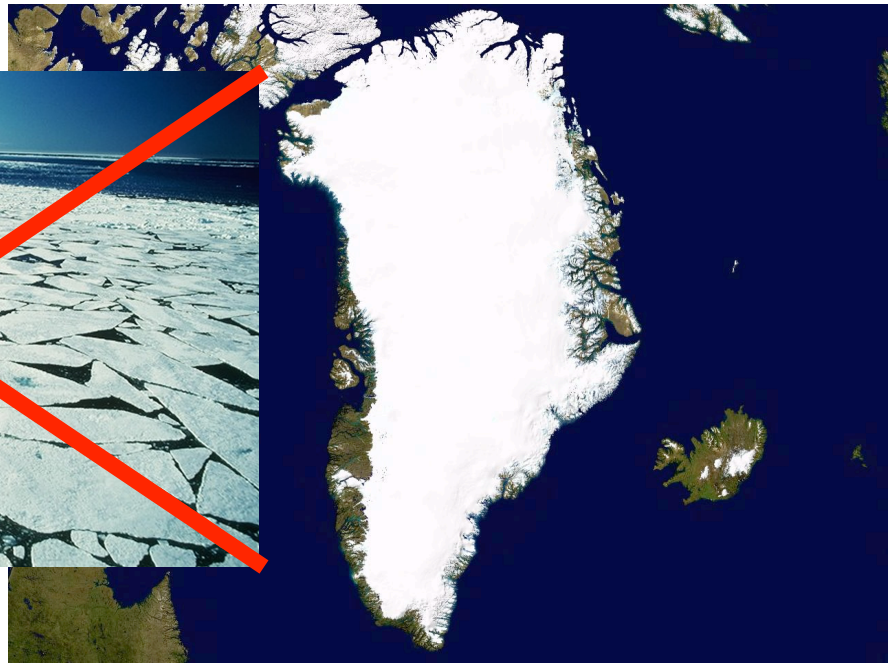
Why model coupled ice-sheet/climate?

- Understand effects of climate change on ice sheets
- Understand effects of ice sheet change on climate
- Understand feedbacks between ice sheets & climate
- Understand past climate change
- Predict future ice sheet loss and sea level rise

What is land ice?

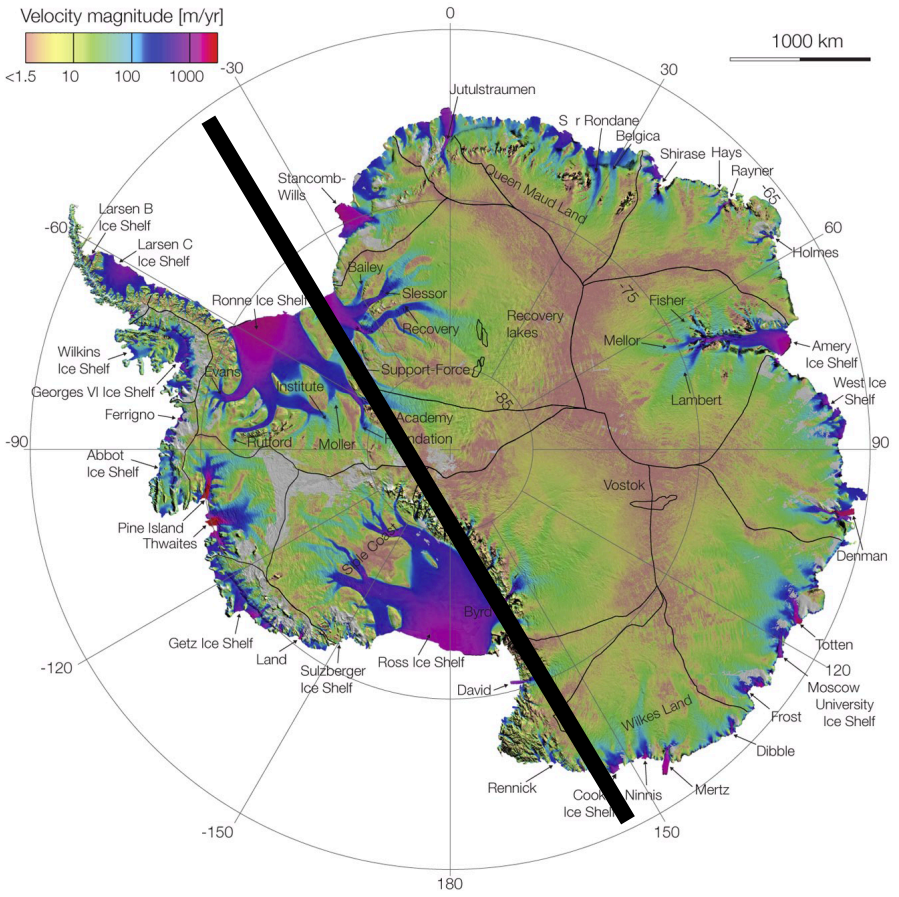
glaciers

ice caps



Antarctica (AIS)

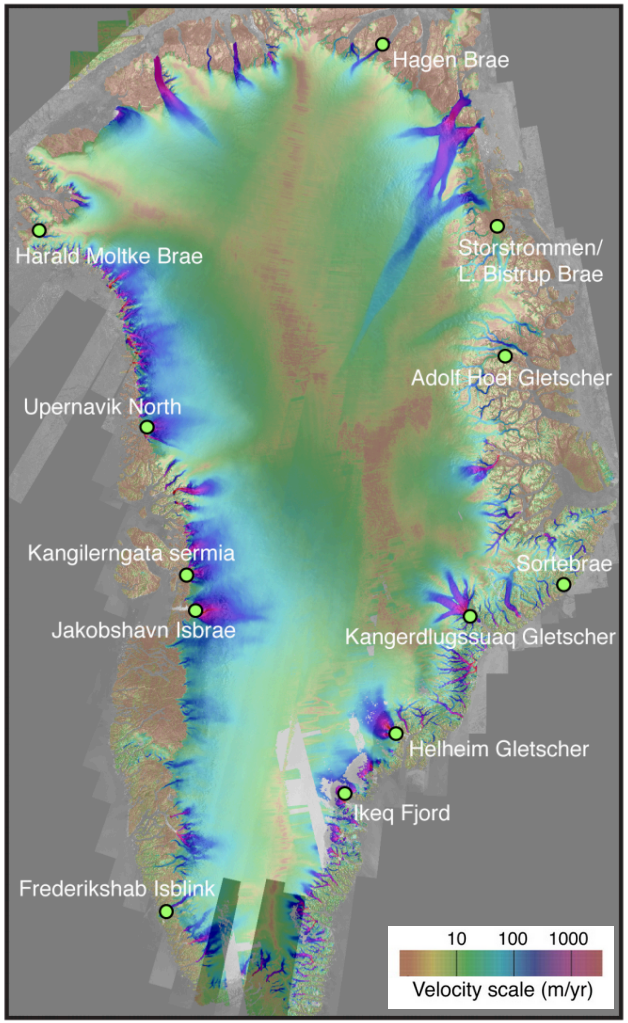
- **60 m** sea-level equivalent (~**5 m** in marine-grounded parts of West Antarctica)
- Accumulation mostly balanced by ice flow into ocean
- Increasing mass loss (~**150 Gt/yr**)



Antarctic ice flow speed
(Rignot et al. 2011)

Greenland (GrIS)

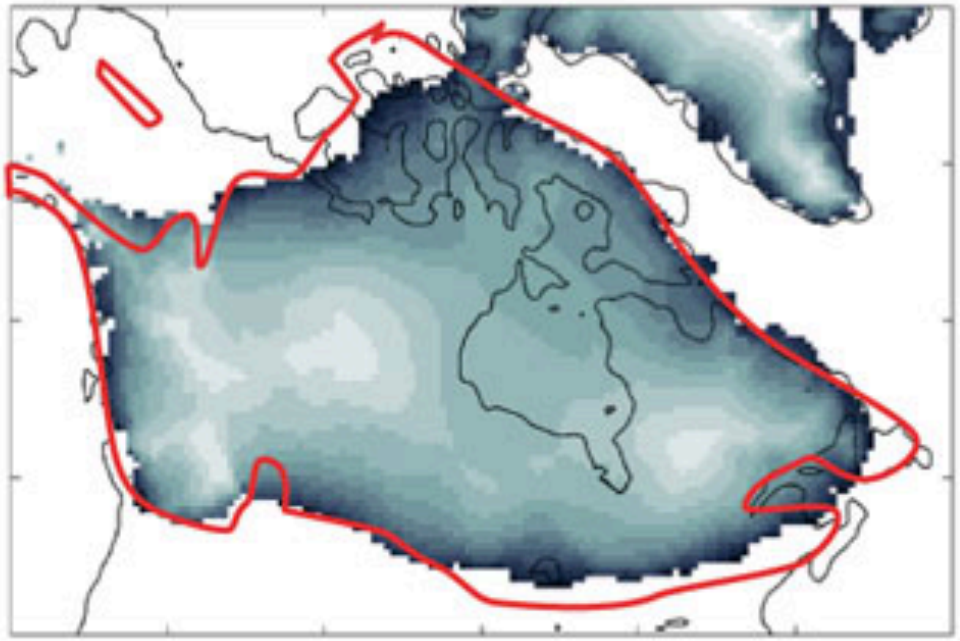
- 7 m sea-level equivalent
- Accumulation balanced by surface runoff and ice flow into ocean (~50/50)
- Increasing mass loss (~200 Gt/yr) since late 1990s



Greenland flow speed
(Moon et al. 2012)

Paleo ice sheets

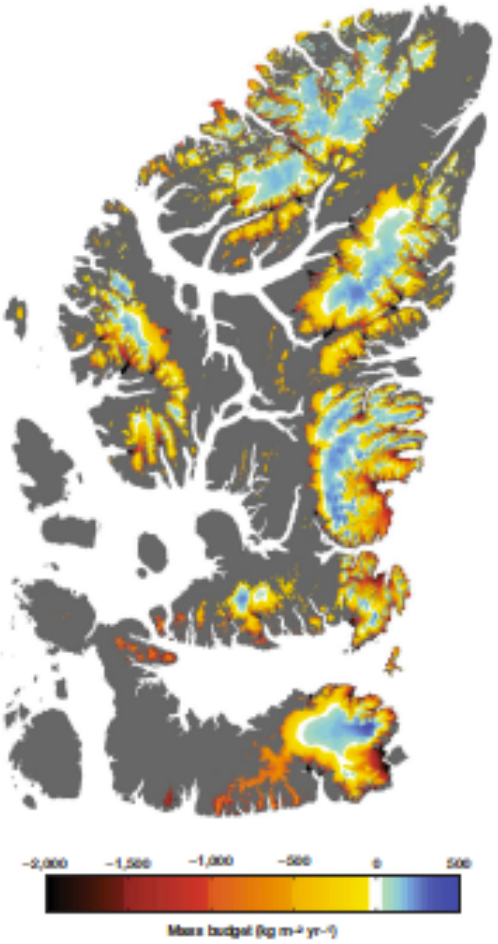
- Past glacial periods contained ice sheets that stored ~120m of sea level equivalent on land



Modelled/reconstructed LGM Laurentide Ice Sheet
(Gregoire et al. 2012)

Glaciers and ice caps

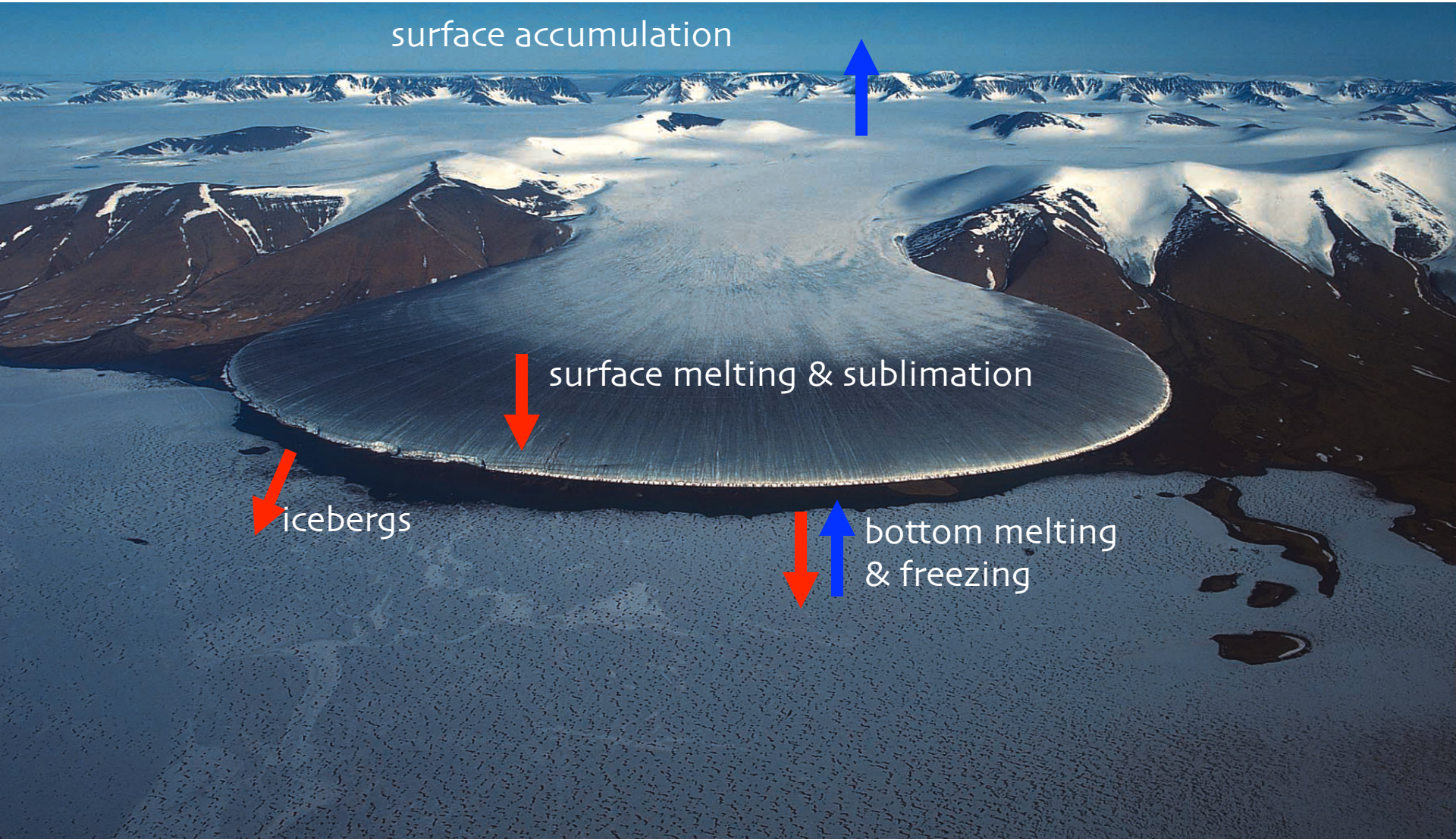
- 200,000+ glaciers and ice caps
  Only **0.6 m** sea-level equivalent (Radic & Hock 2010), but short response times
- Most glaciers are out of balance with the climate and retreating



Surface mass balance, Canadian Archipelago, 2003–2009
(Gardner et al. 2011)

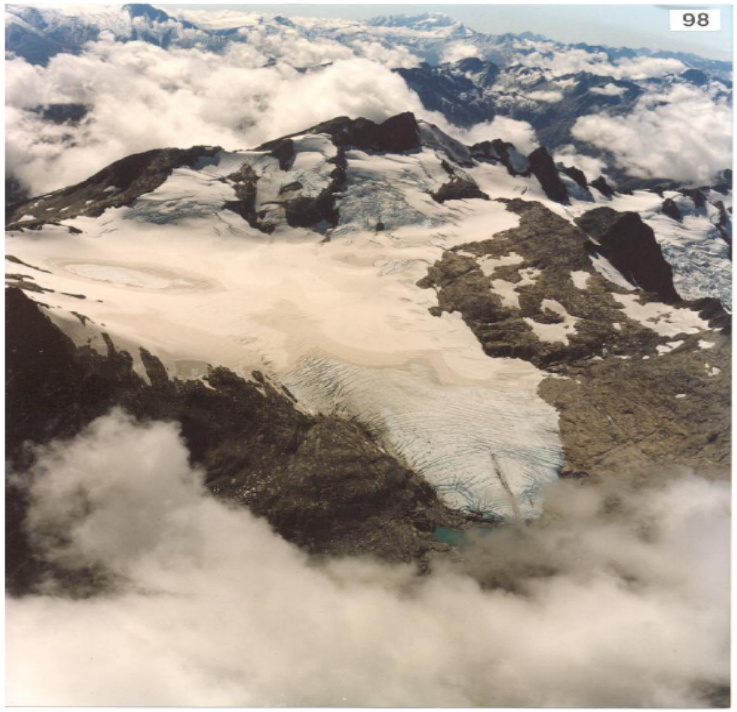
Ice sheet basics: mass balance and dynamics

Mass balance



Mass balance

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



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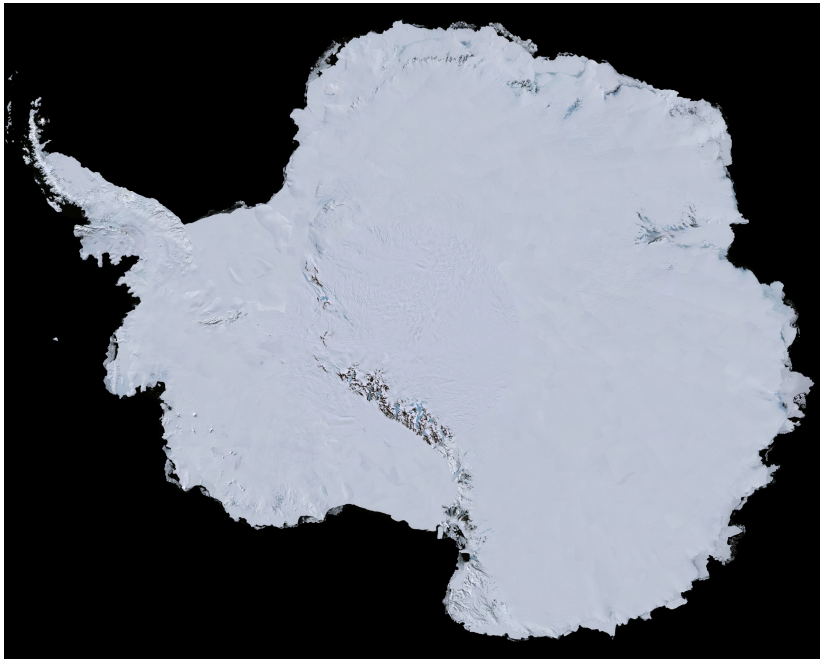
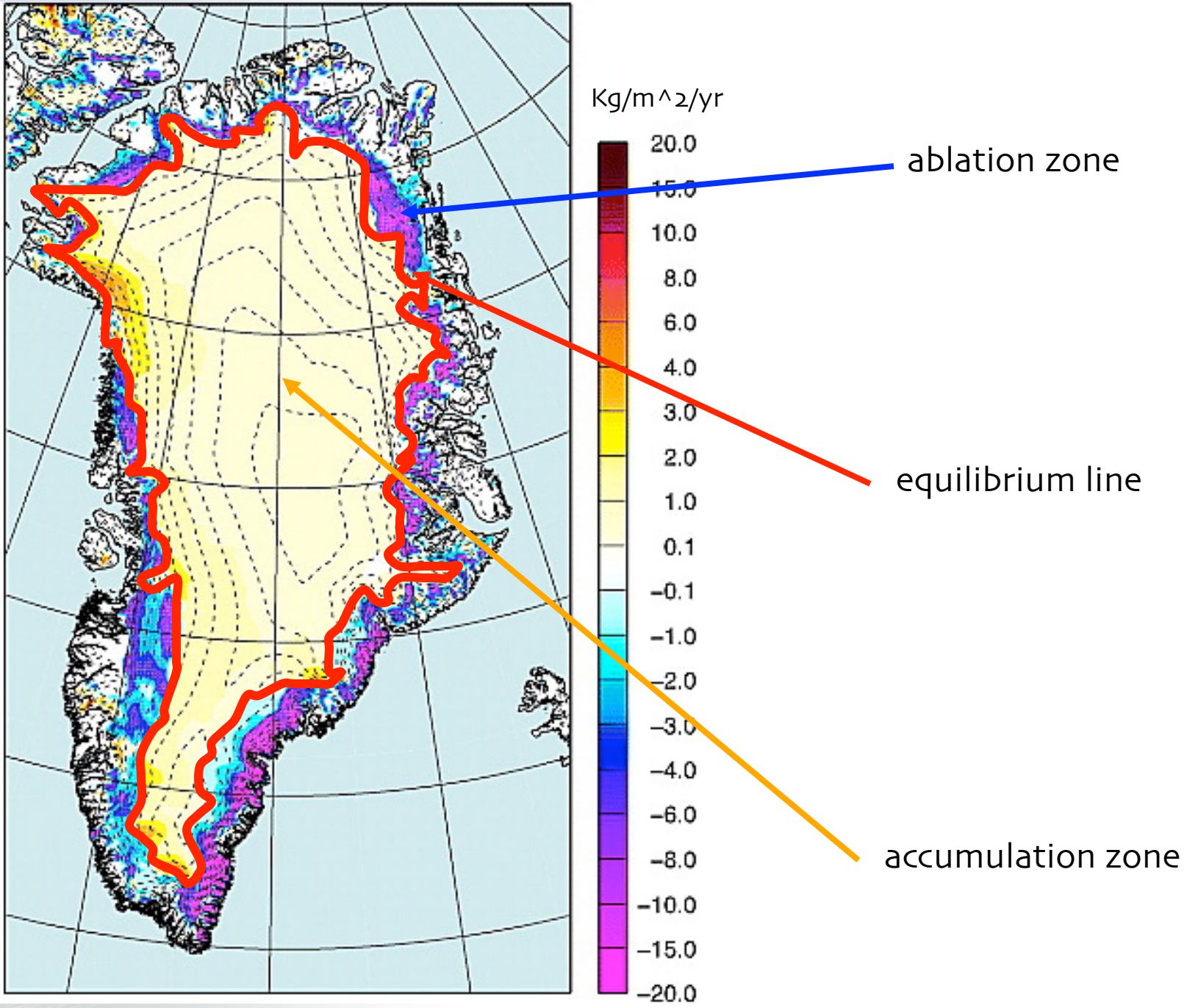
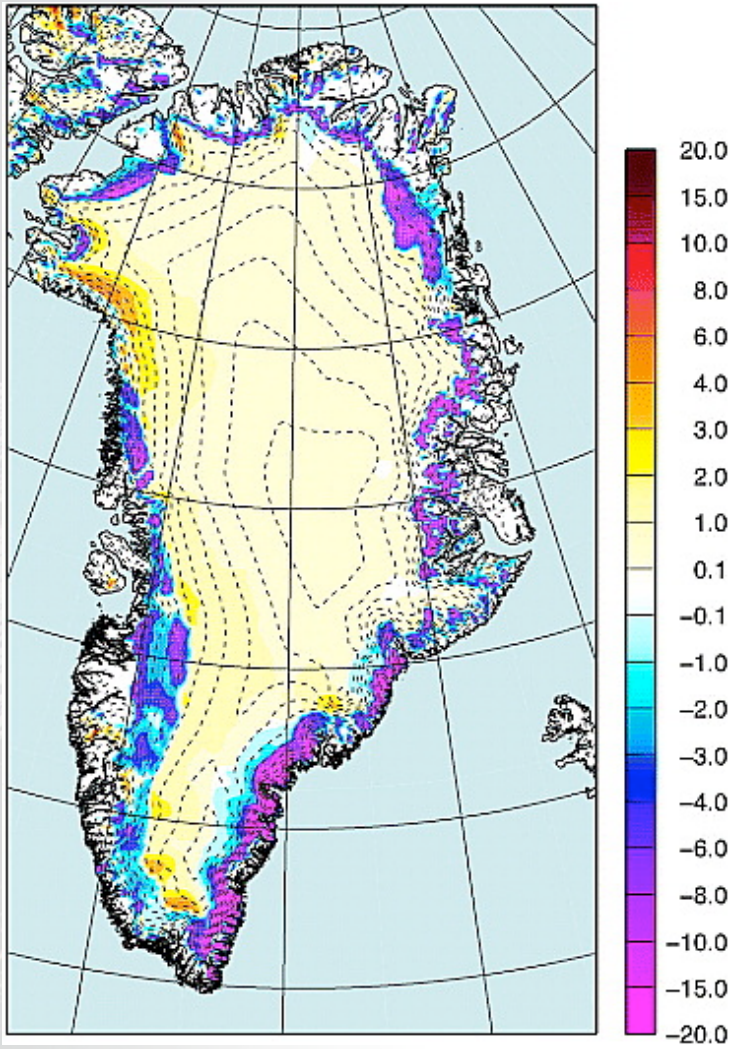


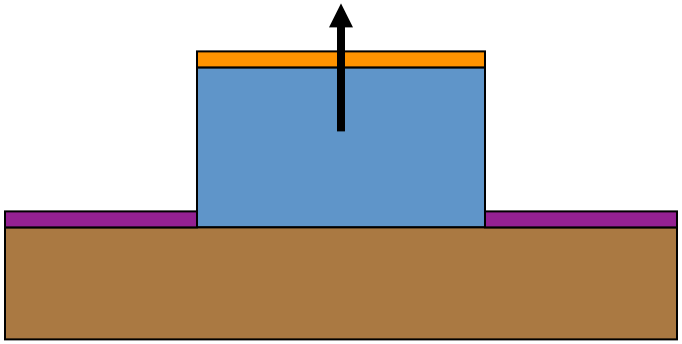


Ettema et al. (2009)

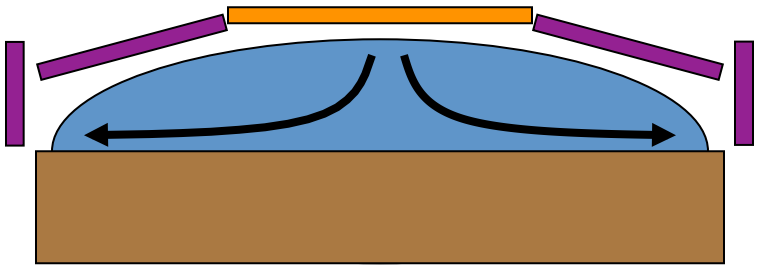
Ice dynamics

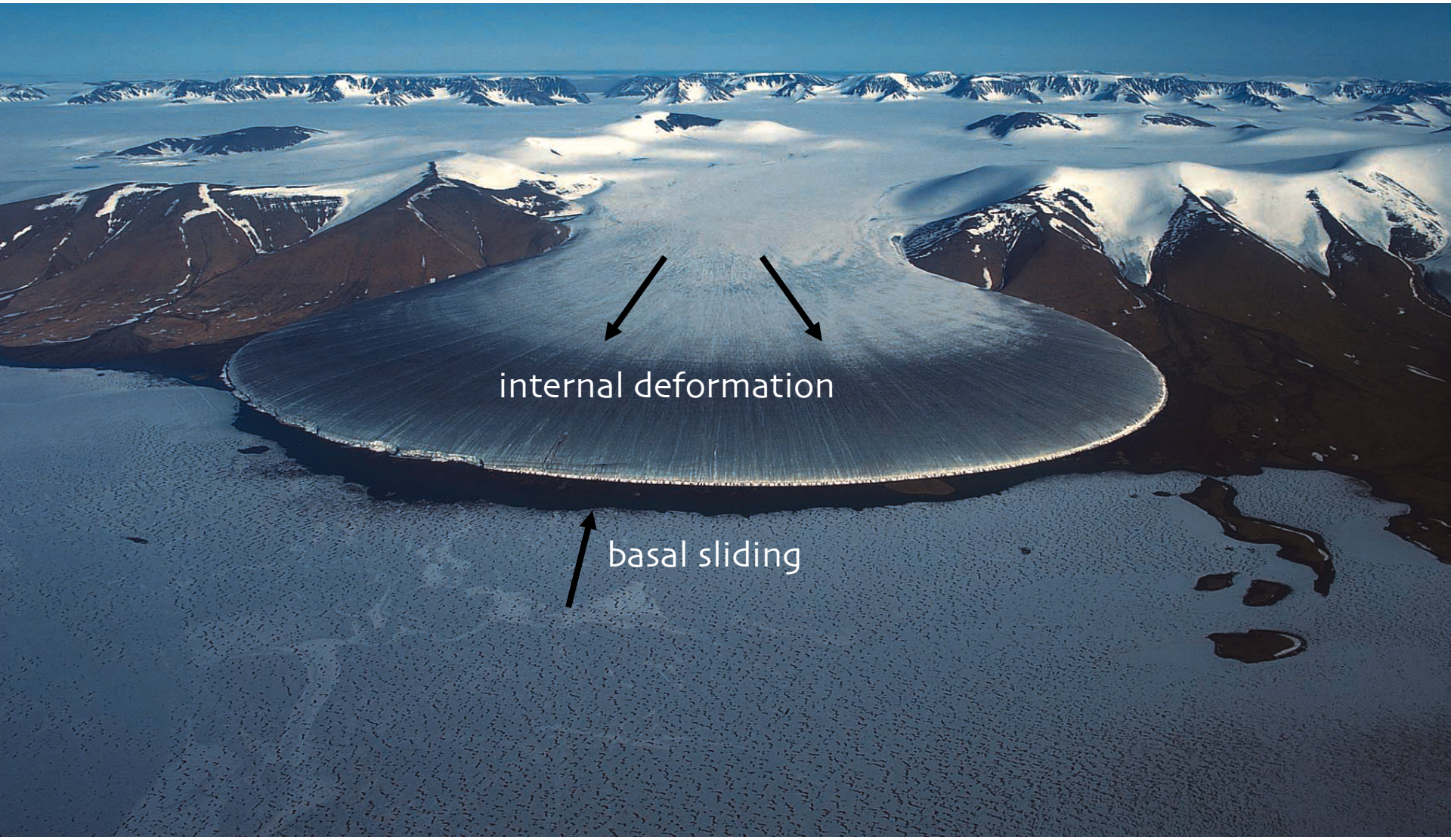


if ice were completely undeformable:



In reality:




internal deformation
basal sliding

Coupled conservation equations

Conservation of Momentum:

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

internal stress

gravity

Conservation of Energy:

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

diffusion

advection

internal energy

Conservation of Mass:

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

mass divergence

mass balance

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

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

Modeled physics

- Constitutive models:
  translate stress tensor to stress-induced velocity

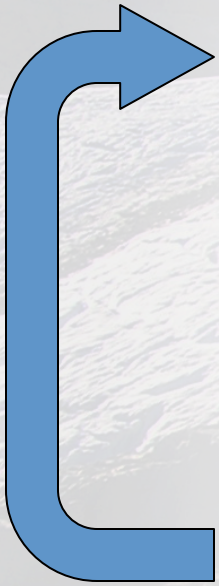
- Basal sliding:
  relates of basal slip to temperature, bed roughness, basal water pressure

- Surface and subglacial hydrology:
  determines basal water pressure (important for sliding, above)

- Iceberg calving:
  determines mass loss at ocean boundary

What do we mean by ice-sheet/climate coupling?

As ice sheets evolve, they interact with the surrounding climate; interactions generate *feedbacks*.

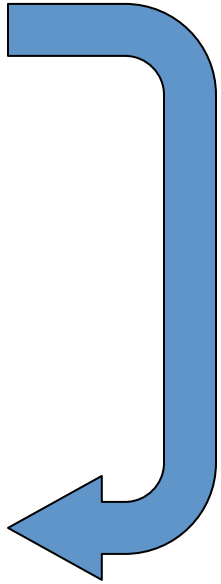


Climate passes:

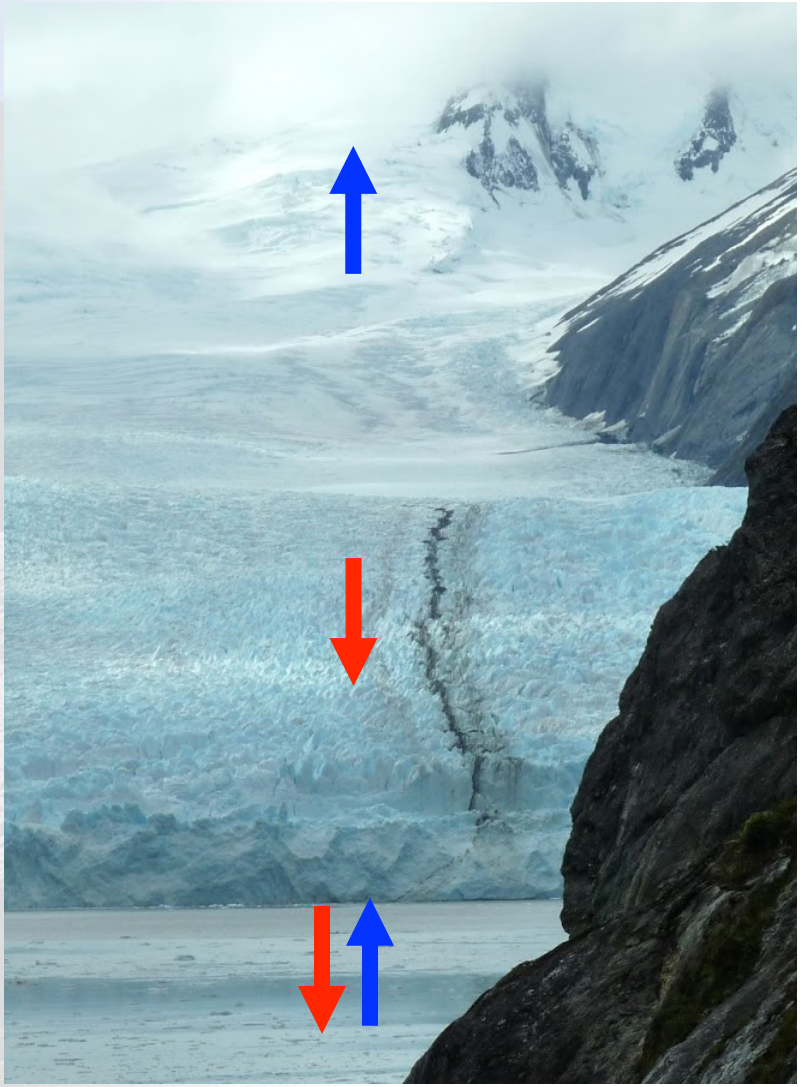
- Surface mass balance (SMB)
- Submarine melt rates
- Boundary temperatures

Ice sheet passes:

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



Climate passes: mass fluxes



surface accumulation

surface melt/sublimation

sub-shelf melting

(/freeze-on)

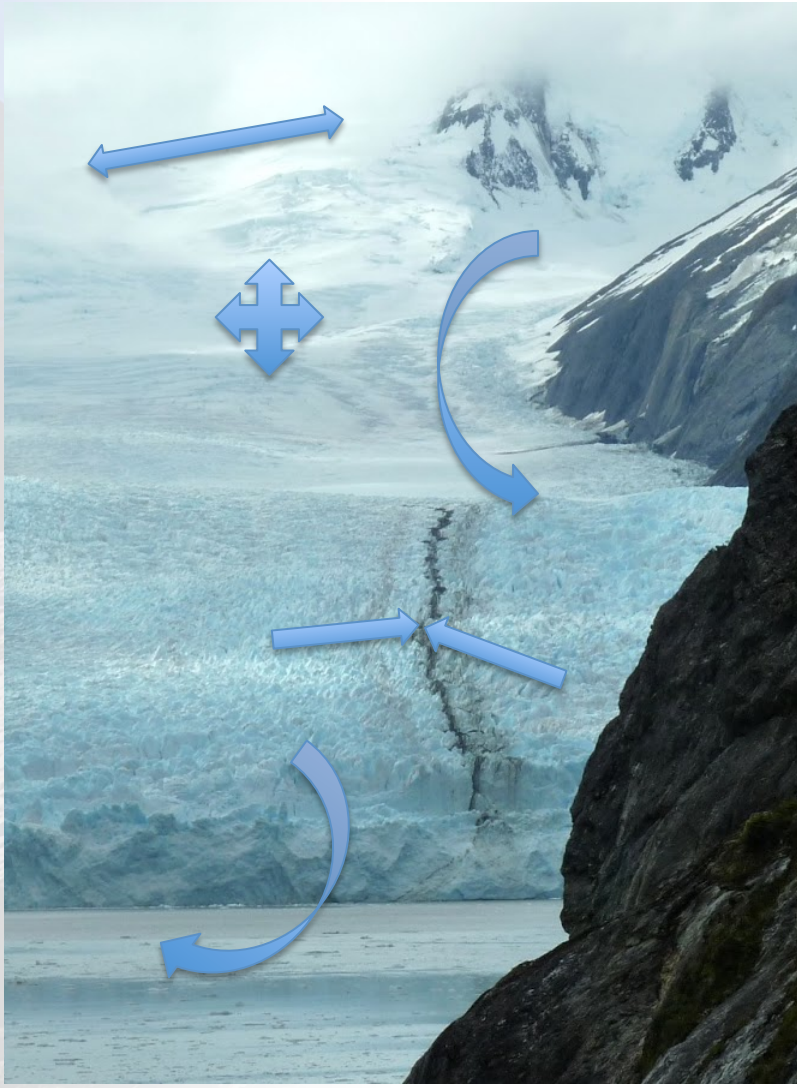
Climate passes: temperature boundary condition

cold (stiff ice)

S. Price archives

warm (not so stiff ice, maybe more/less basal sliding?)

M. Hoffman archives



Ice sheet model accepts climate-derived boundary condition forcing and moves ice.

Ice sheet passes: solid ice discharge (calving)

ice discharge

oceanic heat extraction

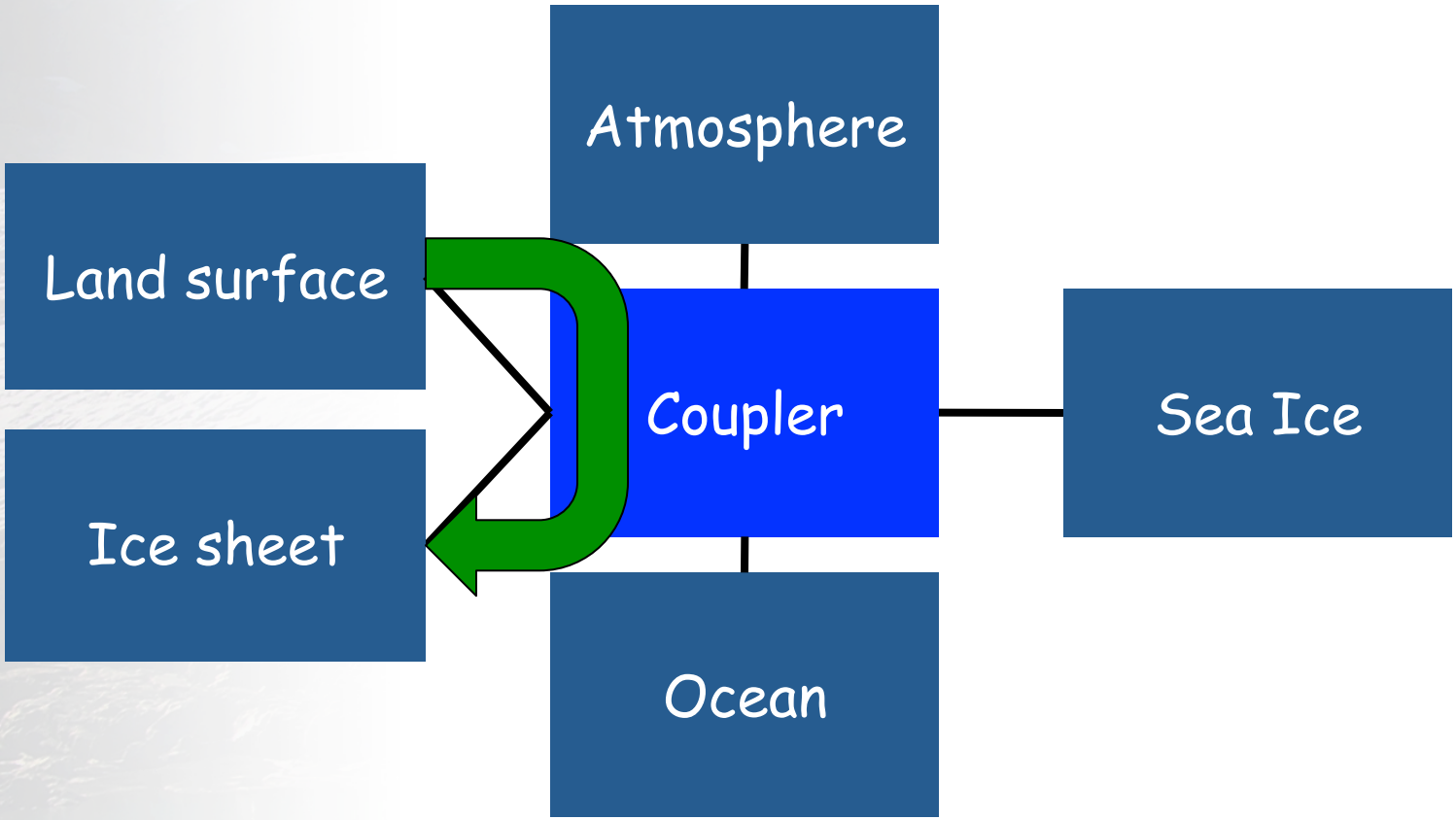
Ice sheet passes: elevation

NASA/Bamber et al., 2013

Ice sheet passes: ice extent

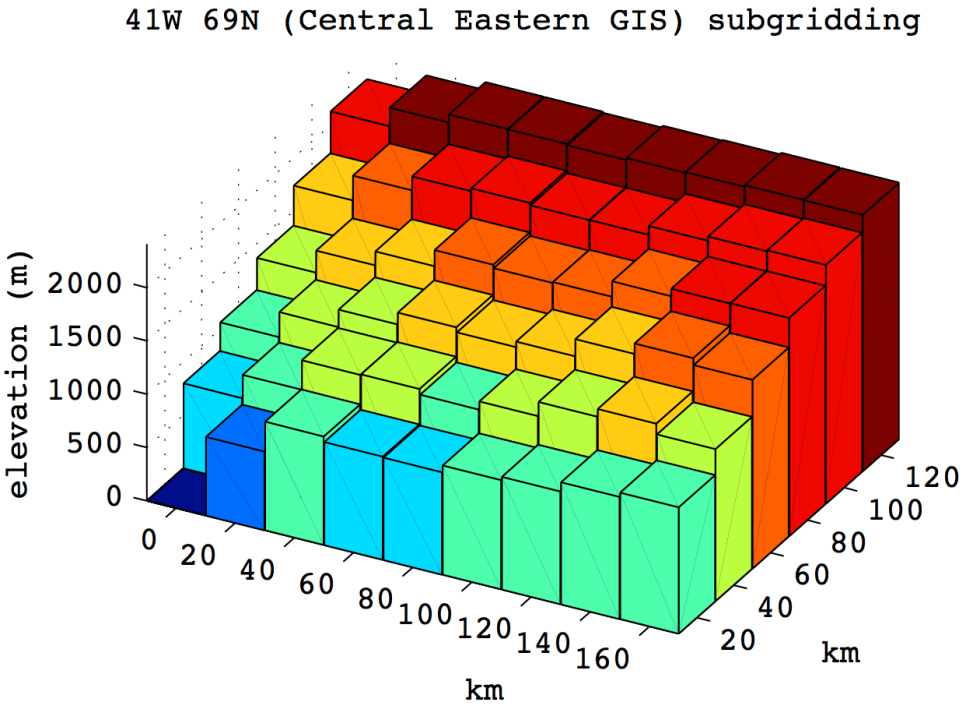
- Ice sheet retreat replaces ice sheet area with bare land area (ice loss)
- Ice sheet advance replaces bare land area with ice sheet area
- In-situ ice sheet growth from perennial snow accumulation

Coupling of ice sheets in CESM 1.2



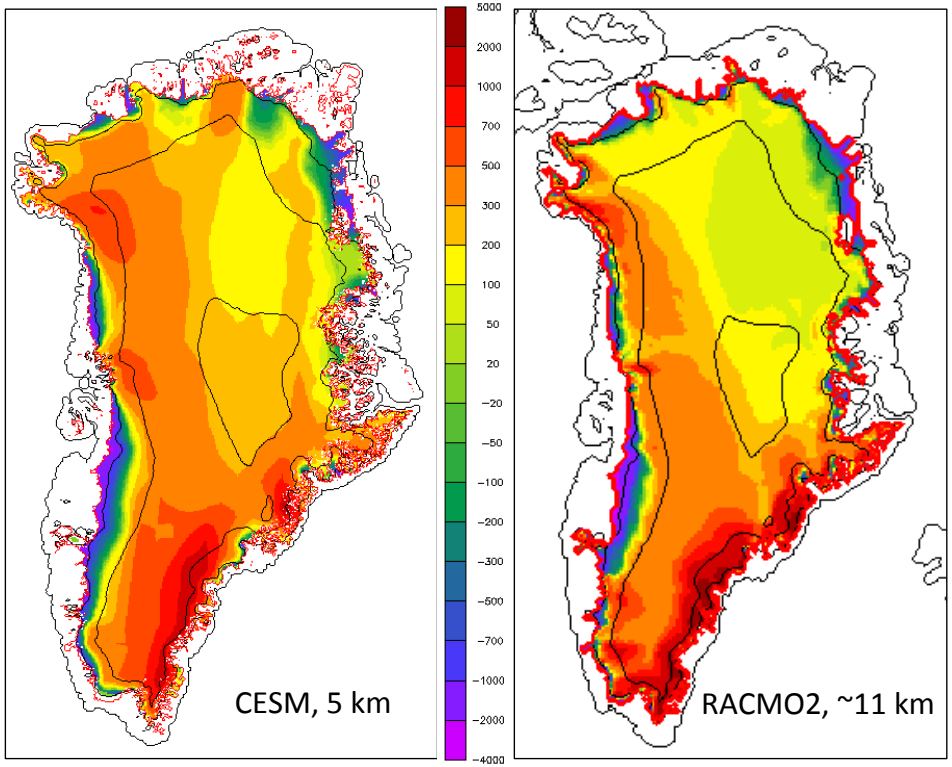
Ice sheet surface mass balance in CESM

- CESM computes the SMB/ surface ice temperature in the land model (CLM) on a coarse (~100 km) grid on several elevations
  - Energetic consistency
  - Surface albedo changes feed back on the atmosphere



CAM4-based CESM GrIS comparison with RACMO ('state of the art' regional model)

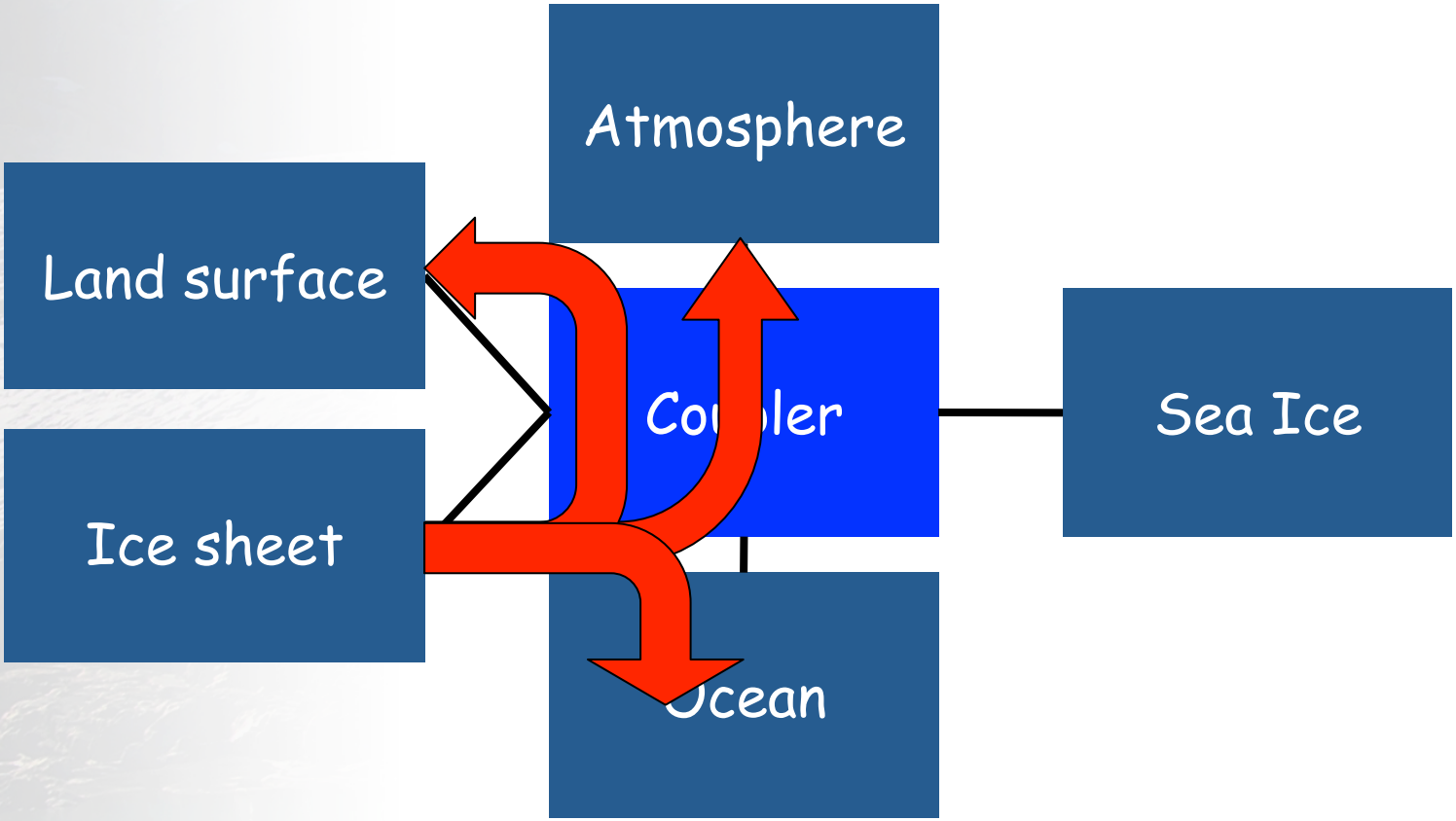
	CESM	RACMO2
SMB (Gt/yr)	359 ± 120	376 ± 117



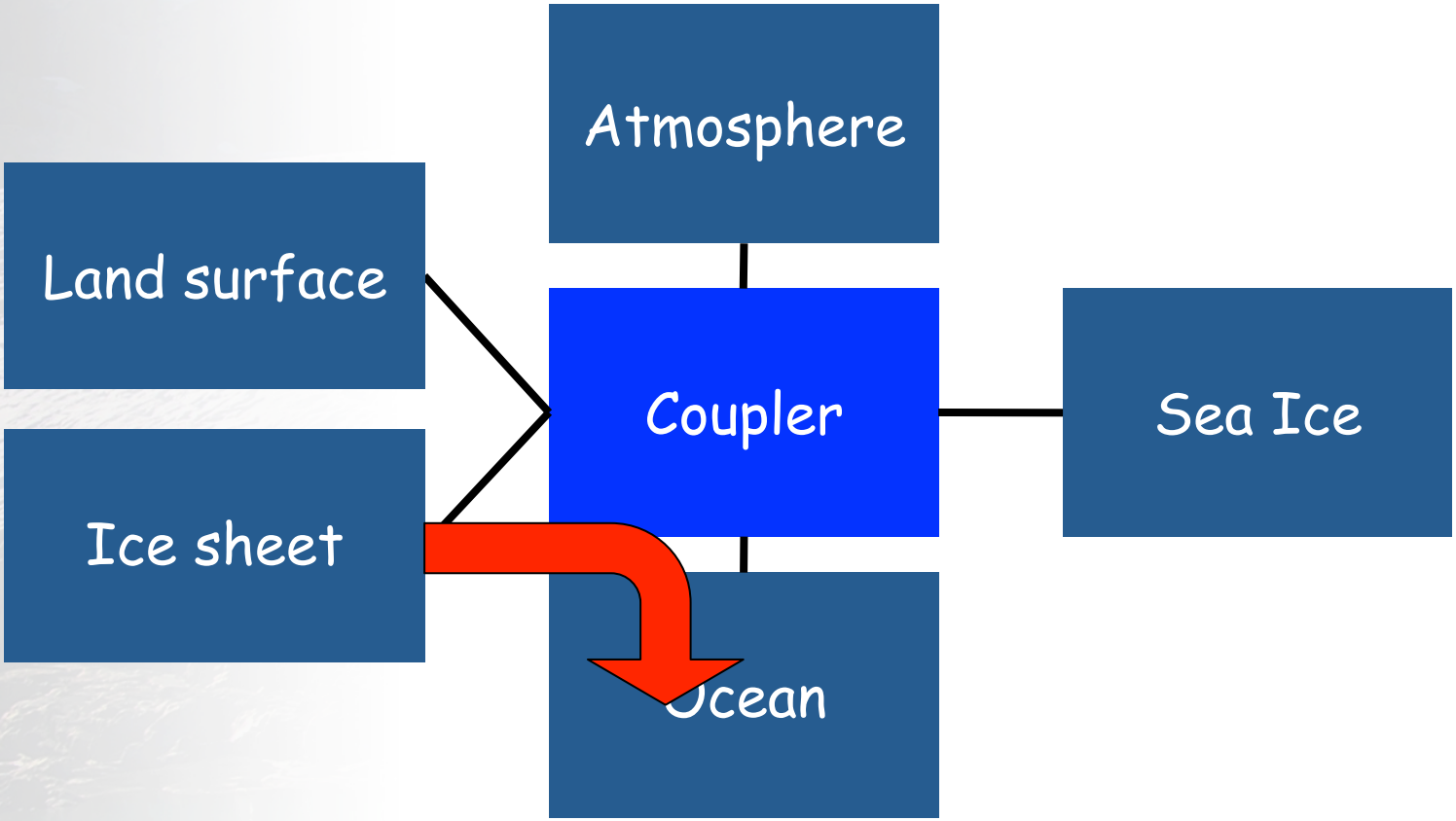
- Good match in ablation zones
- Accumulation is overestimated in the interior and underestimated in the southeast (smoother orography in CESM)

Vizcaino et al 2013

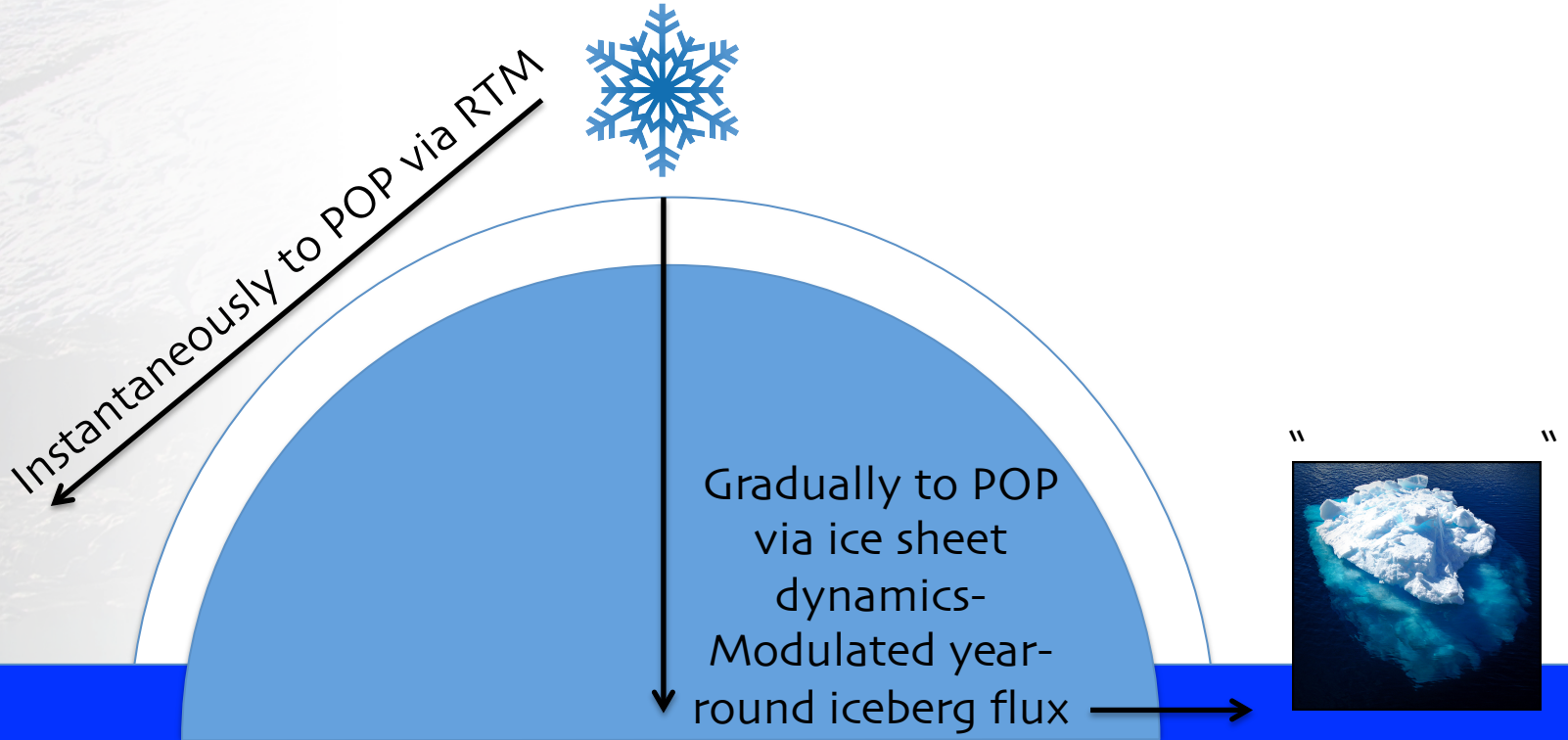
Additional coupling in CESM 1.2+



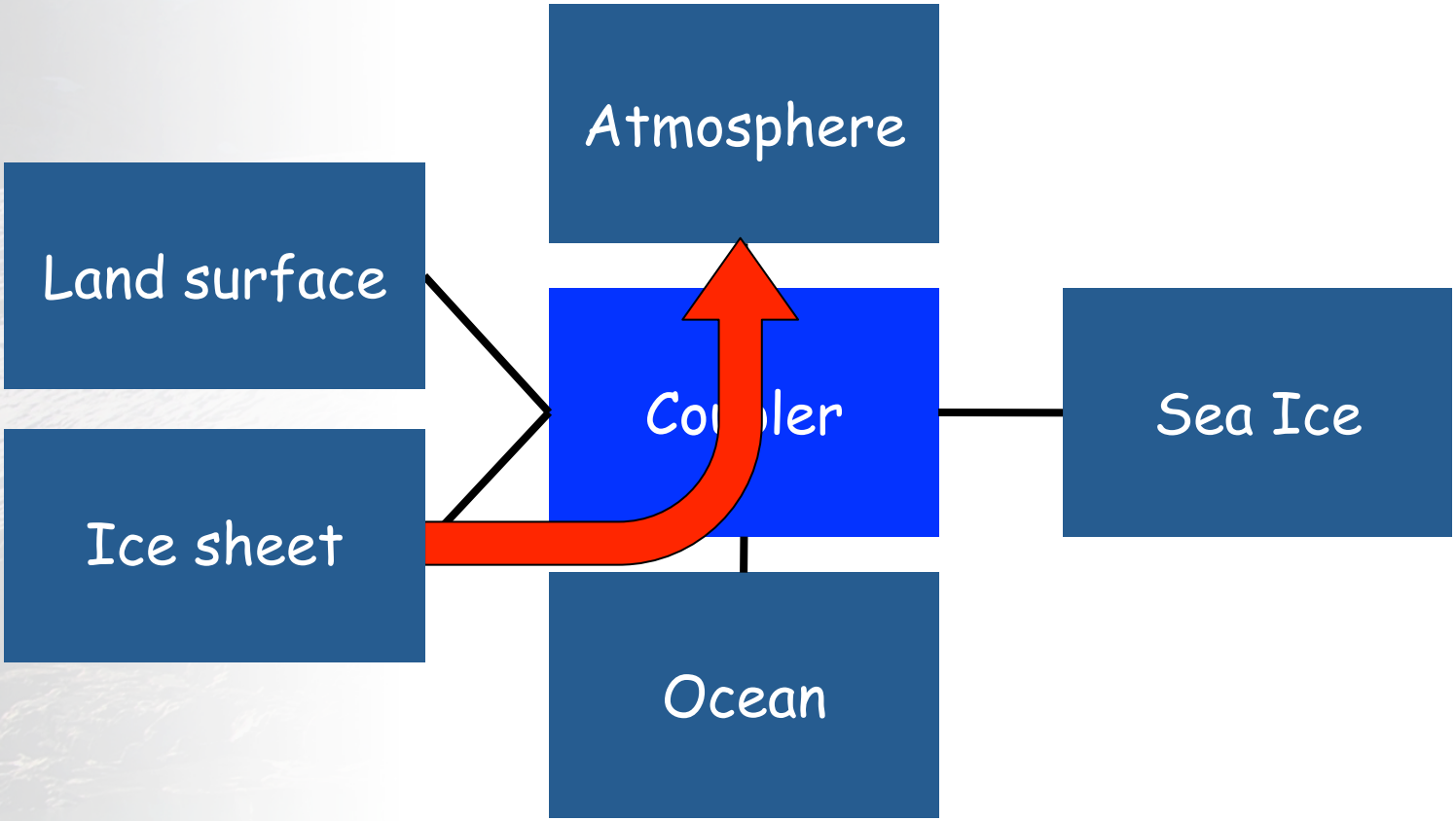
Additional coupling in CESM 1.2+



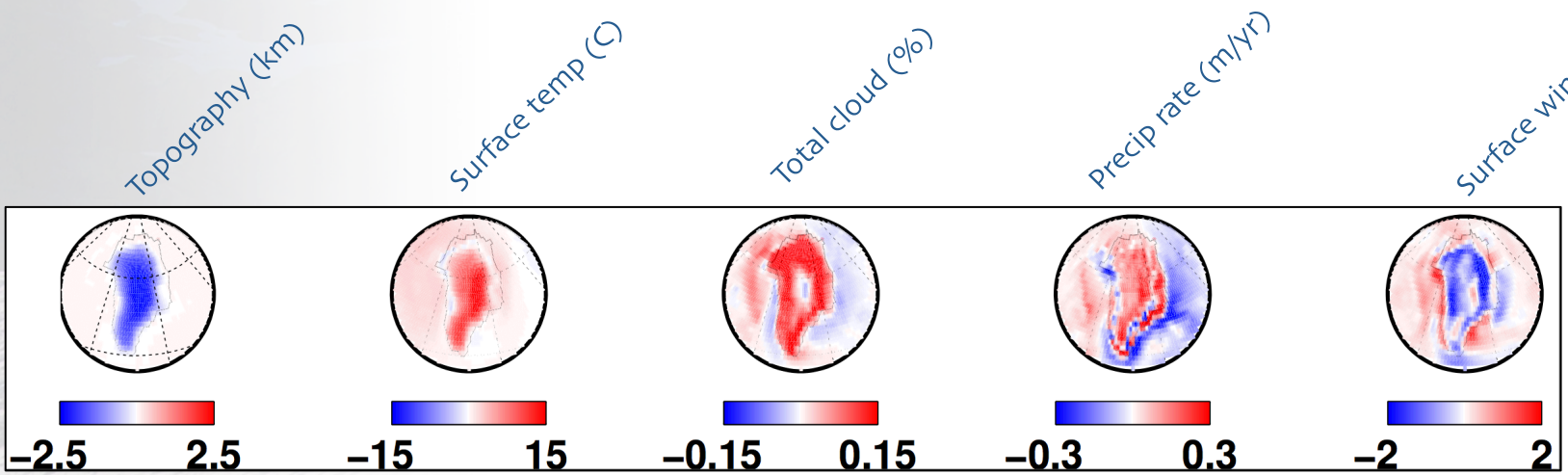
- Solid ice routing replaces snow-capping scheme over ice sheets
- Excess snow sent to CISM, which in turn determines solid ice discharge flux (|*excess snow -> CISM*|~=|*CISM discharge flux*|, *at given coupling interval*)
- Could alleviate excess simulated wintertime frazil ice growth

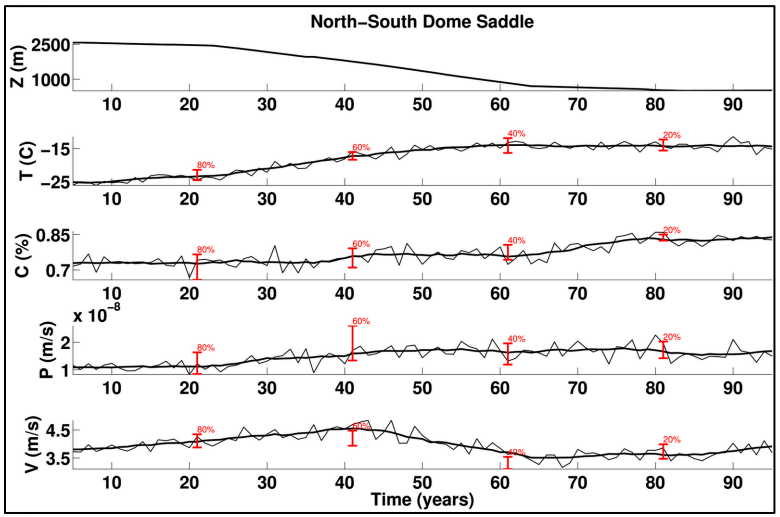


Additional coupling in CESM 1.2+

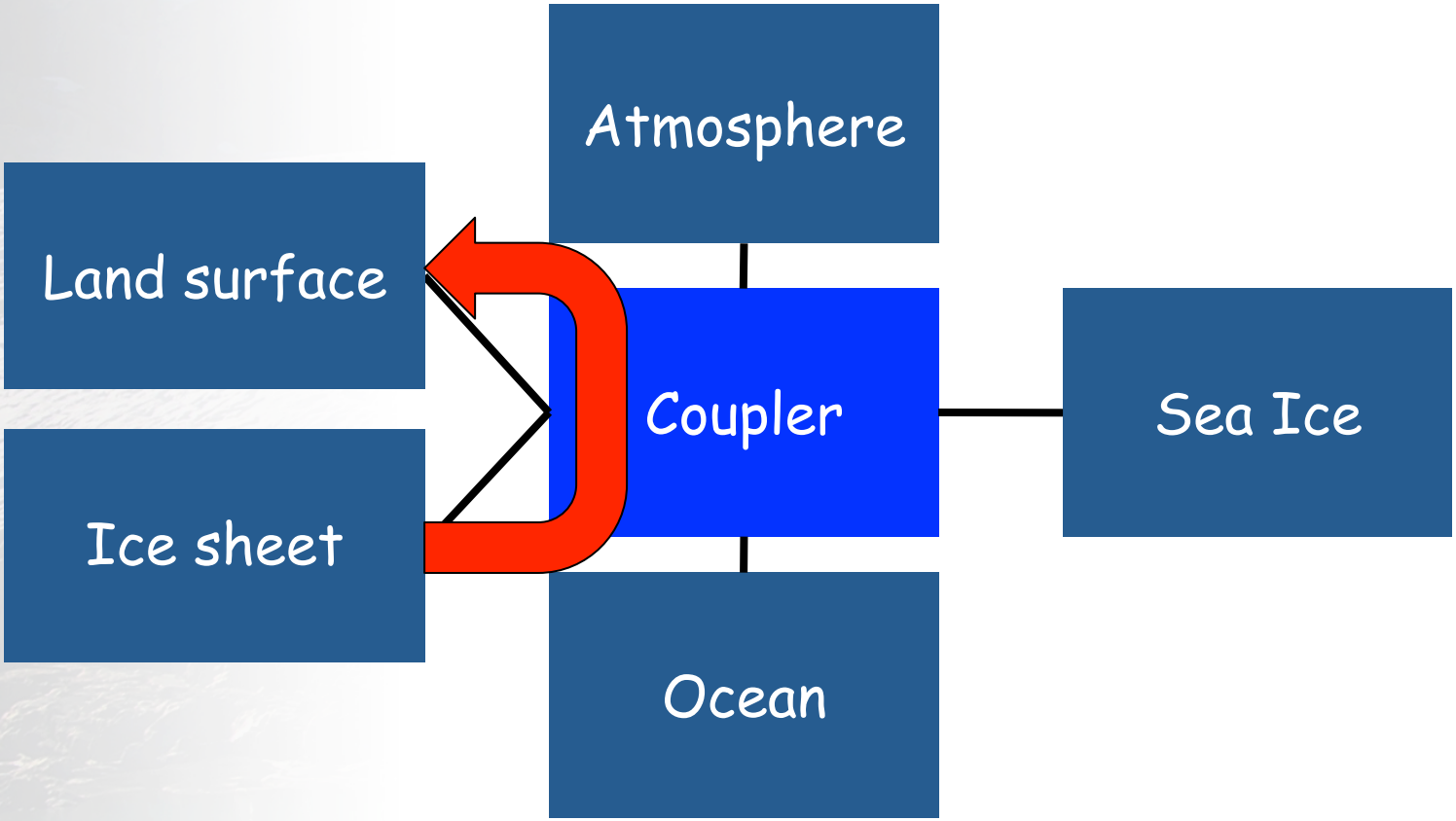


- Script-based approach regenerates global CAM topography at every coupled model resubmission point (~1 year)
- Time series trends from 100-year transient GrIS simulation bracketed by snapshot simulations -> coupling successful

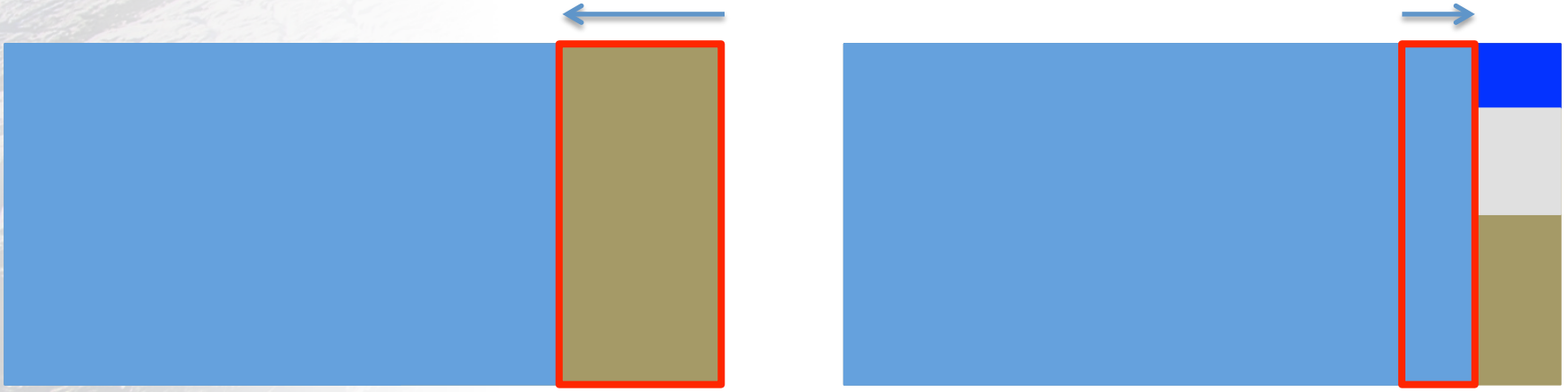


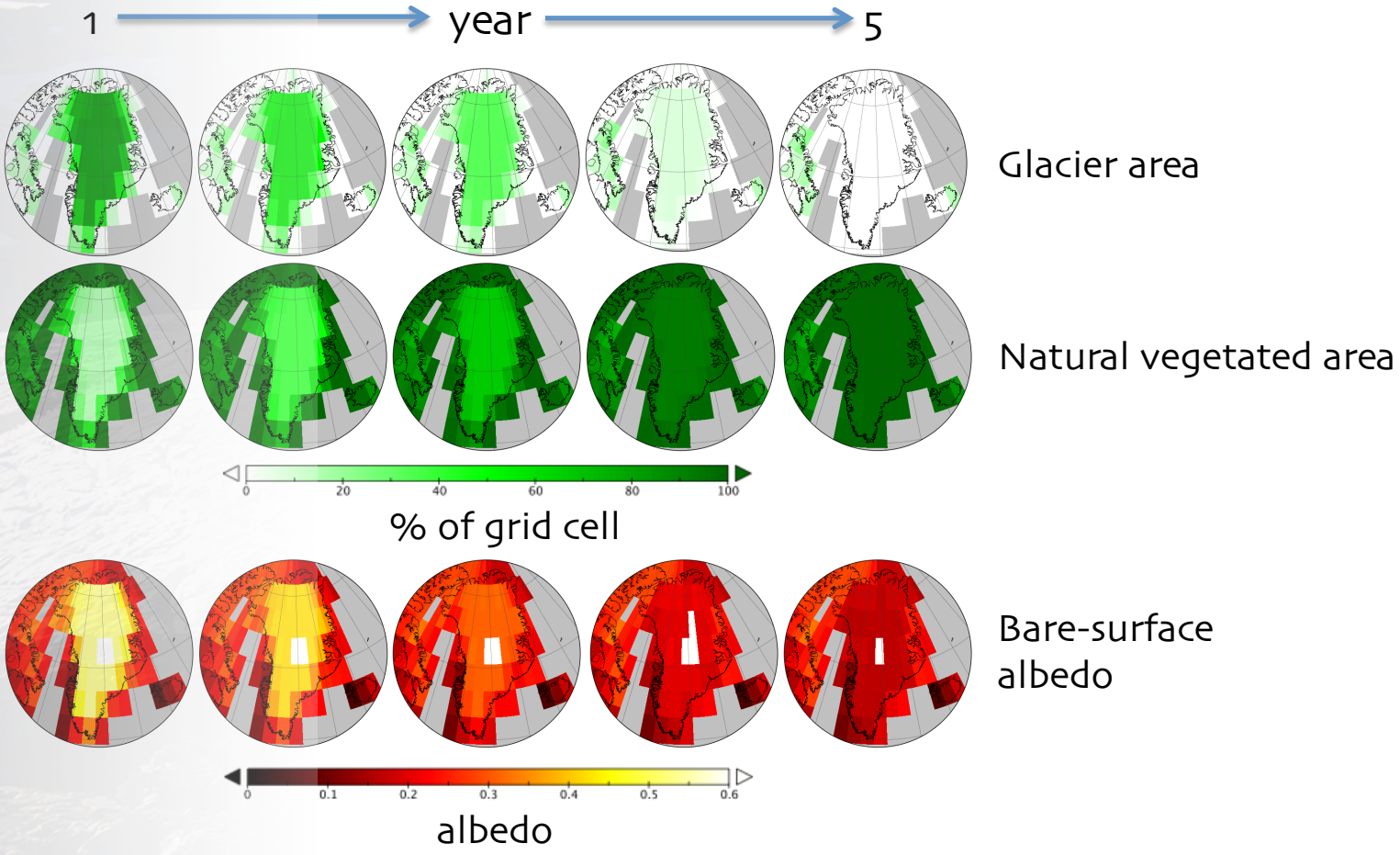


Additional coupling in CESM 1.2+

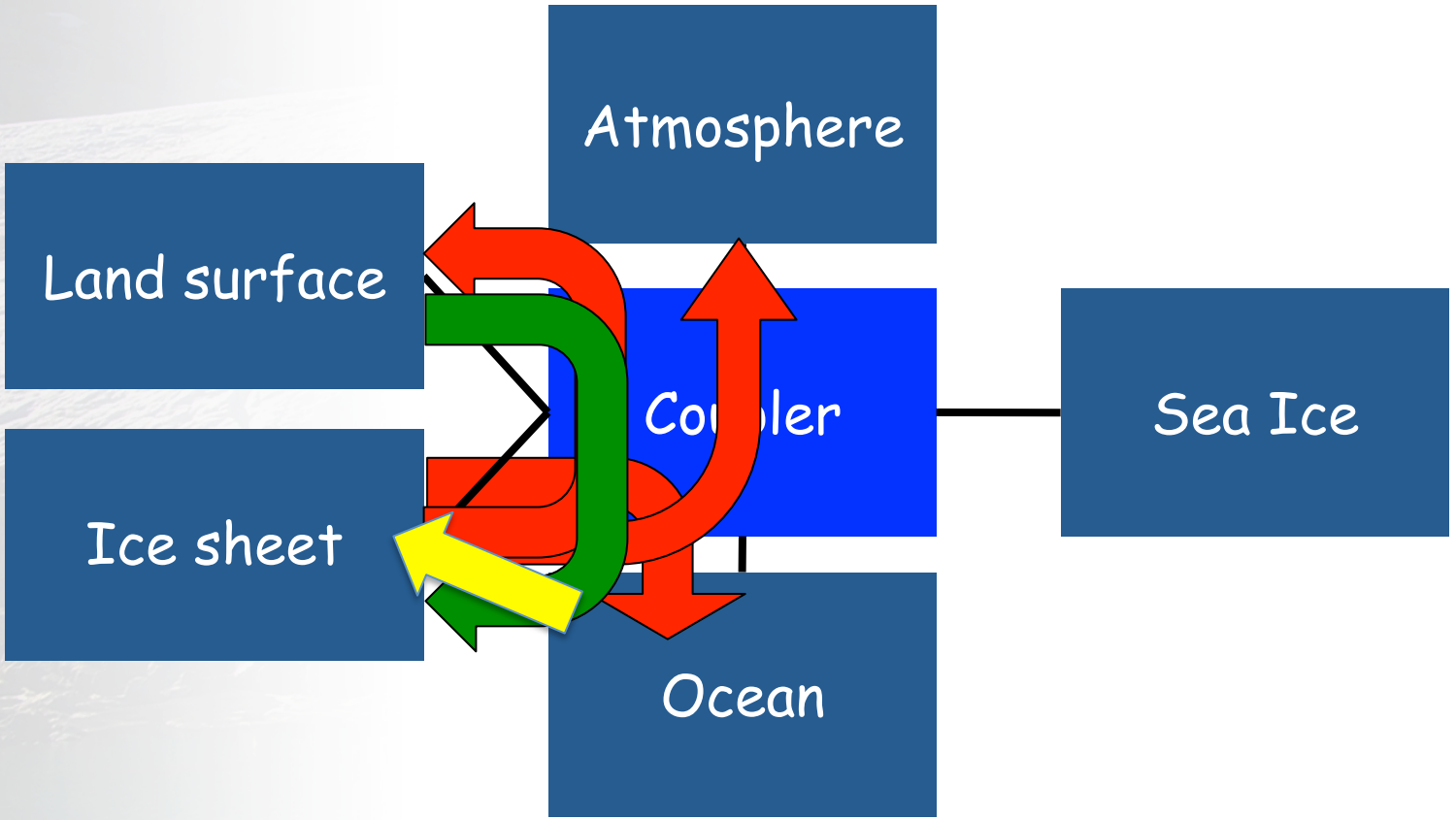


- ***CLM refactoring carried out to allow runtime land unit changes***
- CISM ice area/ice/bare land elevations now passed to CLM
- Initialization of new glacier/vegetated areas achieved via use of virtual (zero-area) land columns



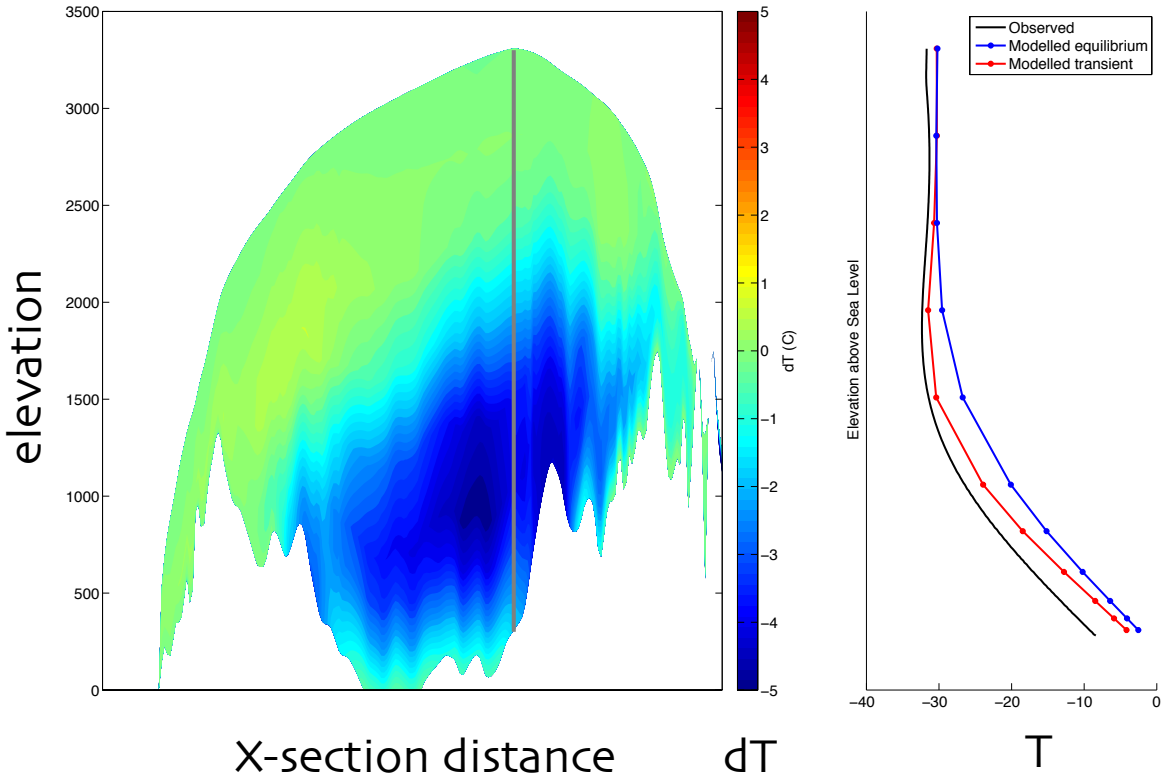

1
year
5
Glacier area
Natural vegetated area
0
20
40
60
80
100
% of grid cell
Bare-surface albedo
0
0.1
0.2
0.3
0.4
0.5
0.6
albedo

- Current 2-way coupling undergoing testing
- Planned release in CESM1.3 (2015)
- Allows for coupled simulation of primarily terrestrial ice sheets (*GrIS is current focus*)
- Lack of ocean->ice forcing: no coupled Antarctic simulations



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

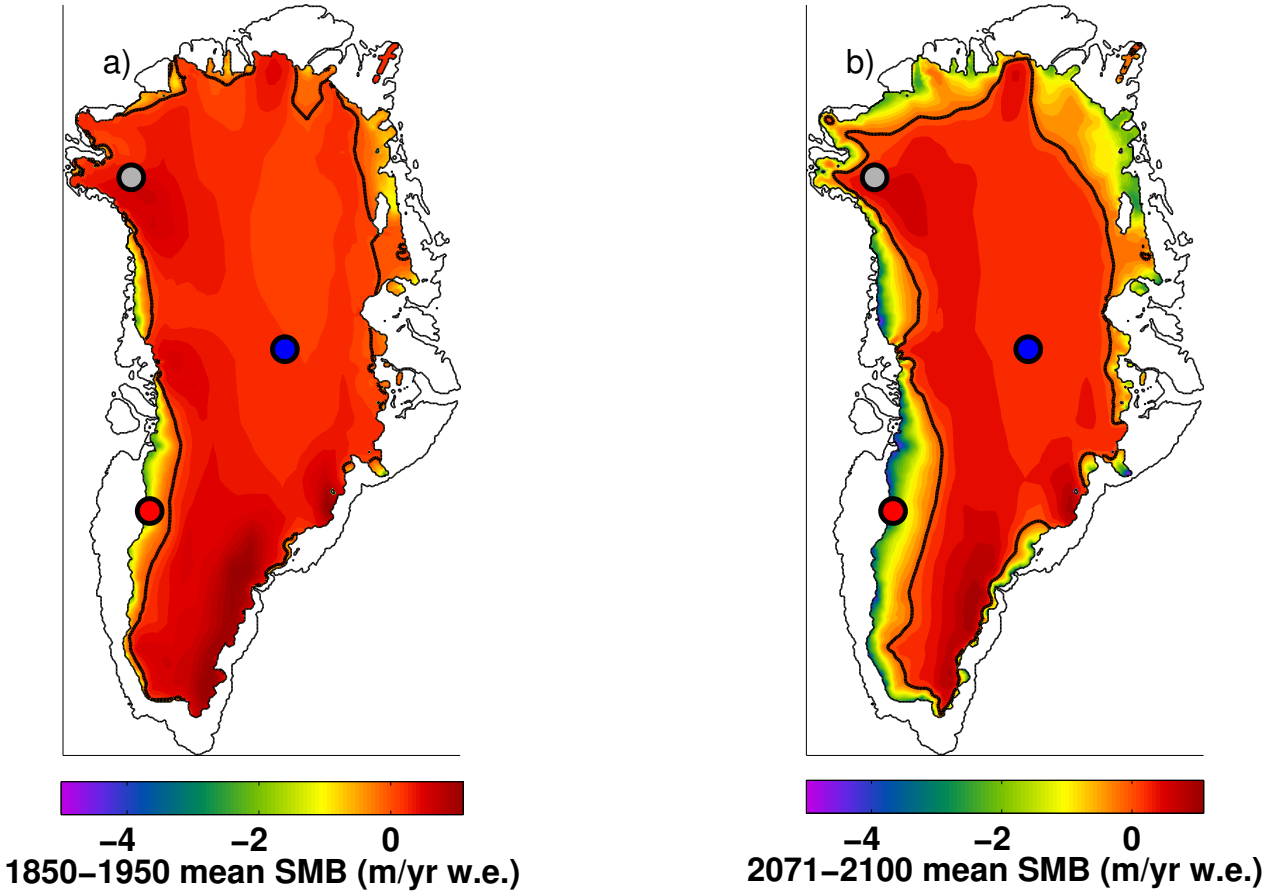


Fyke et al. 2014a

Recent science results with CESM…

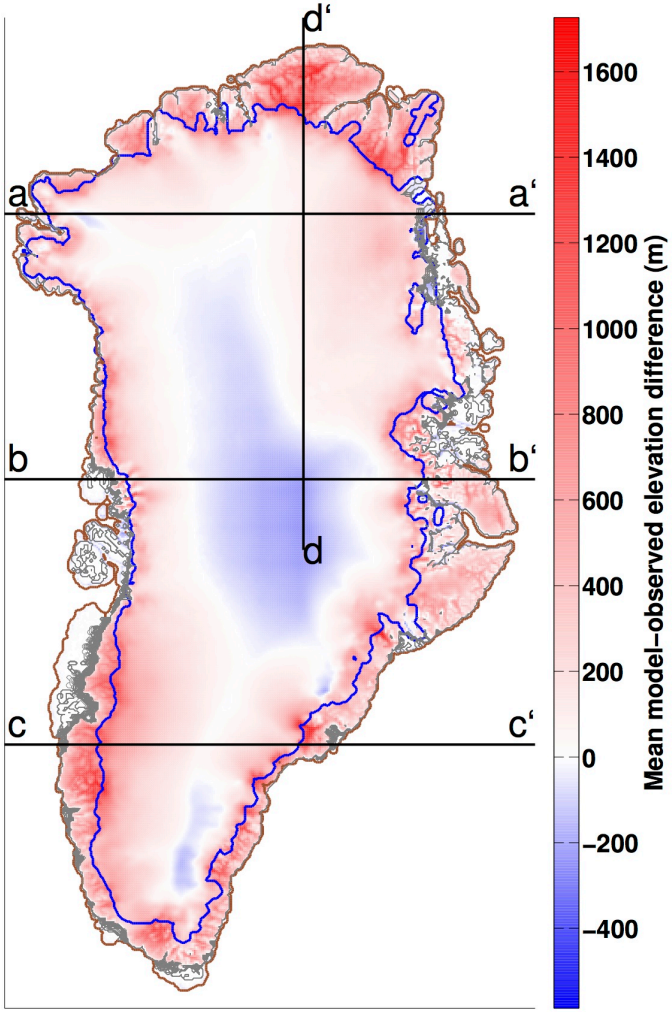
CESM GrIS surface mass balance

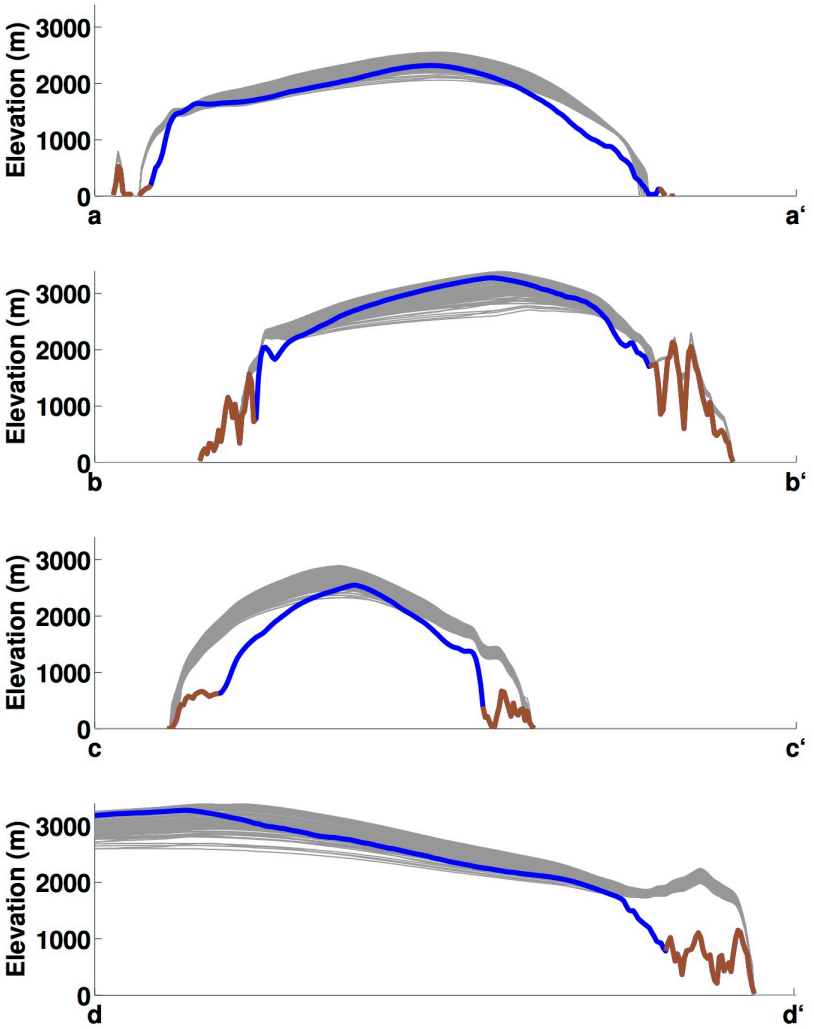
	20th-century (1980-1999)	RCP8.5 (2080-2099)
SMB (Gt/yr)	372 ± 100	-78 ± 143



Vizcaino et al. 2013 + 2014

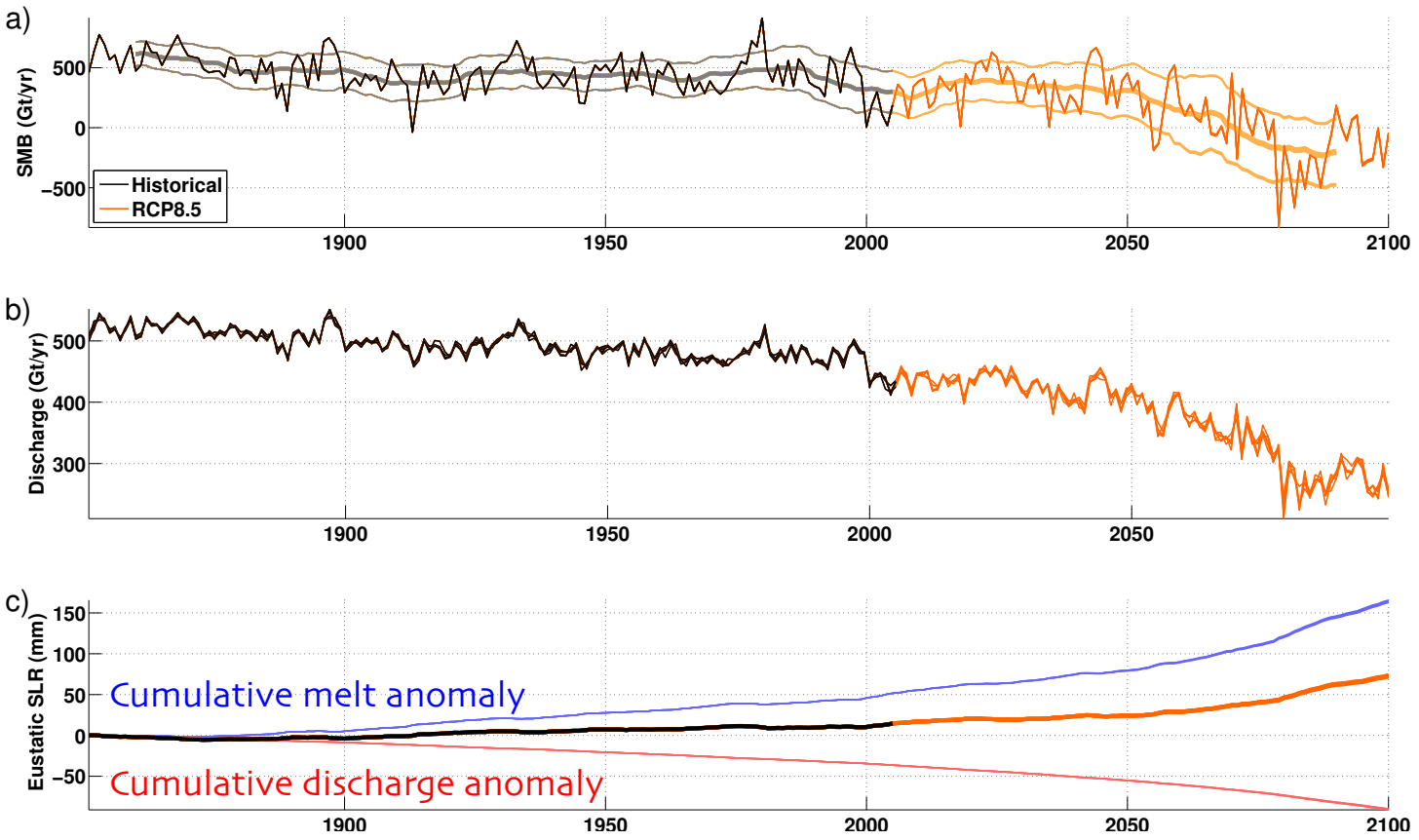
Preindustrial CISM GrIS steady-state perturbed-physics ensemble





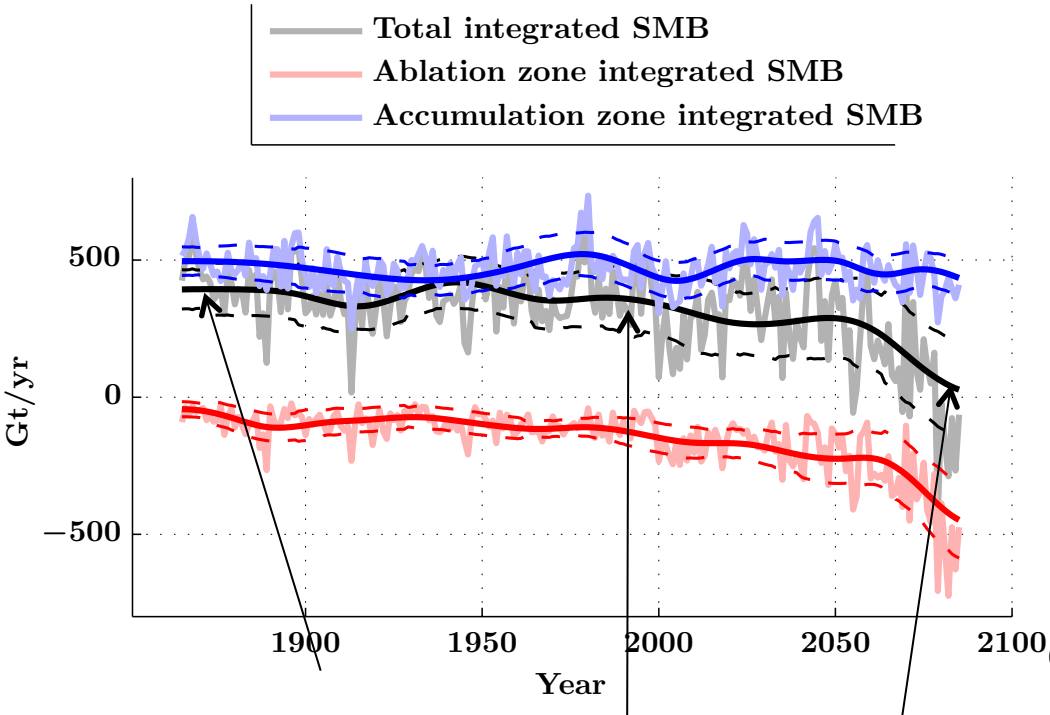
Lipscomb et al. 2013

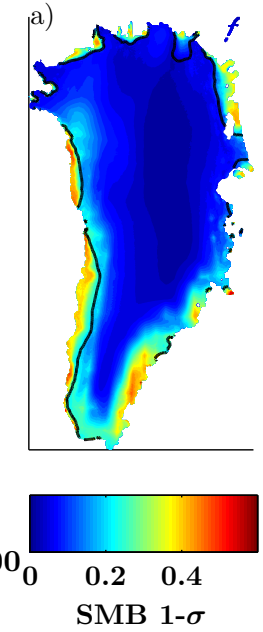
RCP8.5 GrIS sea level rise contribution

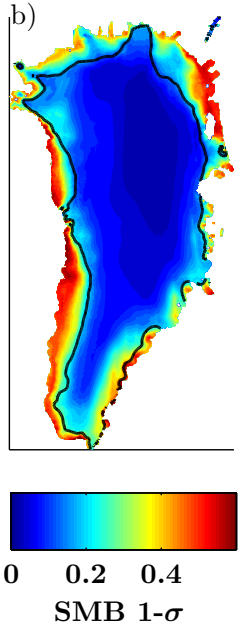


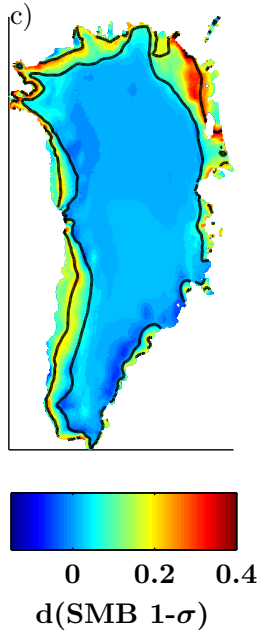
Lipscomb et al. 2013

Future GrIS SMB variability









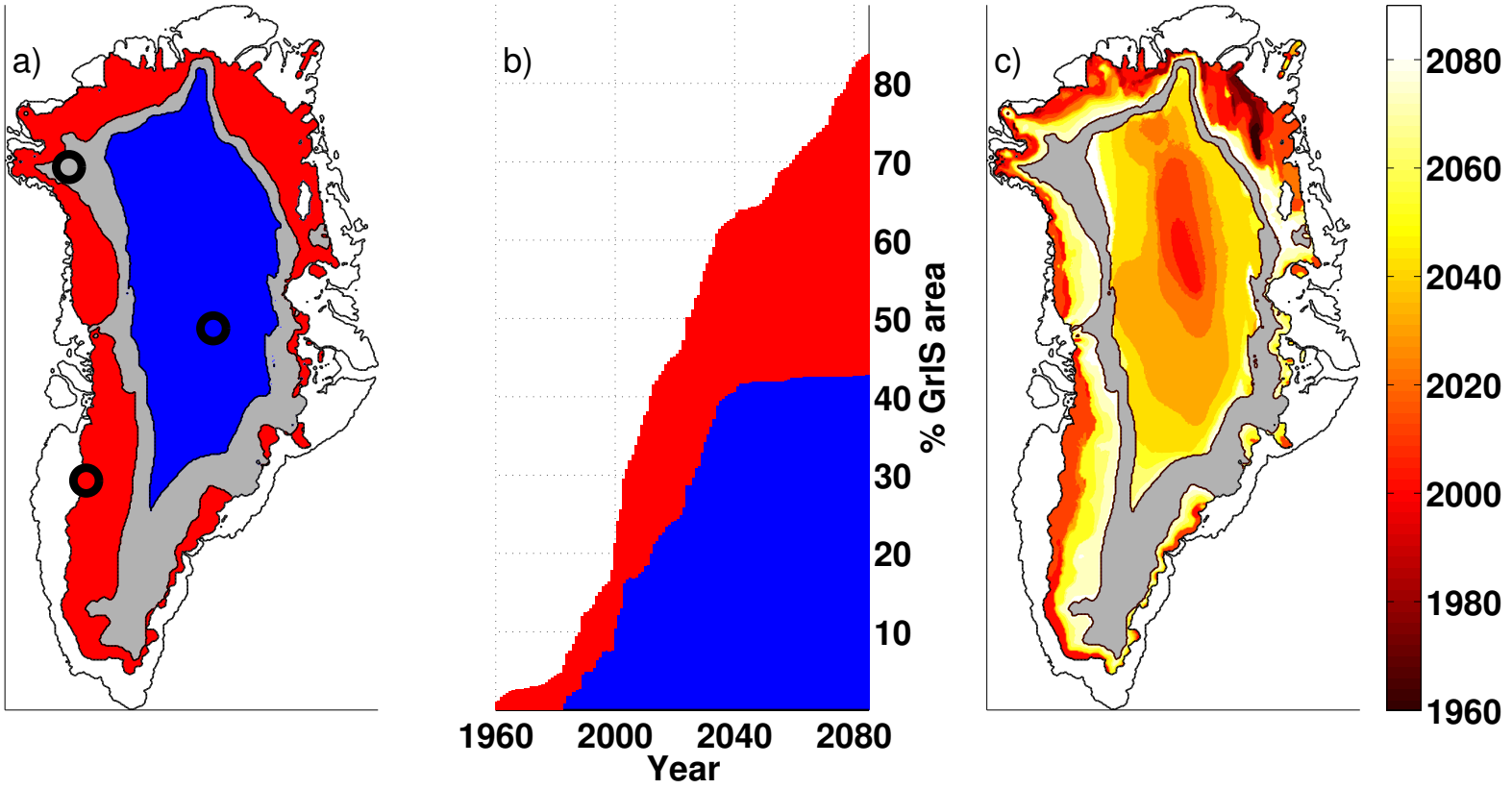
σ =90 Gt/yr

σ =112 Gt/yr

σ =165 Gt/yr

Fyke et al. 2014b

Anthropogenic GrIS SMB signal emergence



Fyke et al. 2014c

Summary…

- There is clear motivation for studying ice sheets as part of the coupled climate system!
- Current 2-way ice-sheet/climate coupling in CESM complete, undergoing initial testing
- Recent CESM-based land ice results highlights 'low-hanging-fruit' status of coupled ice-sheet/climate science
- We encourage interested parties to consider:
  - *two-way coupled model testing and development*
  - *initial two-way coupled simulations (when model released)*