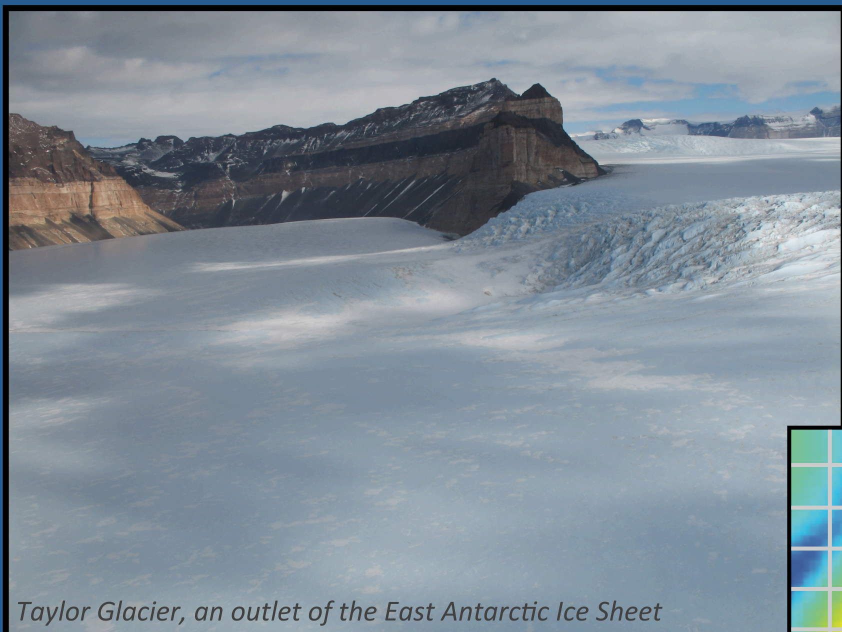
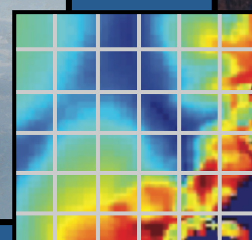
Modeling Land Ice in the Community Earth System Model



Taylor Glacier, an outlet of the East Antarctic Ice Sheet



Iceberg in Jakobshavn Icefiord, Greenland

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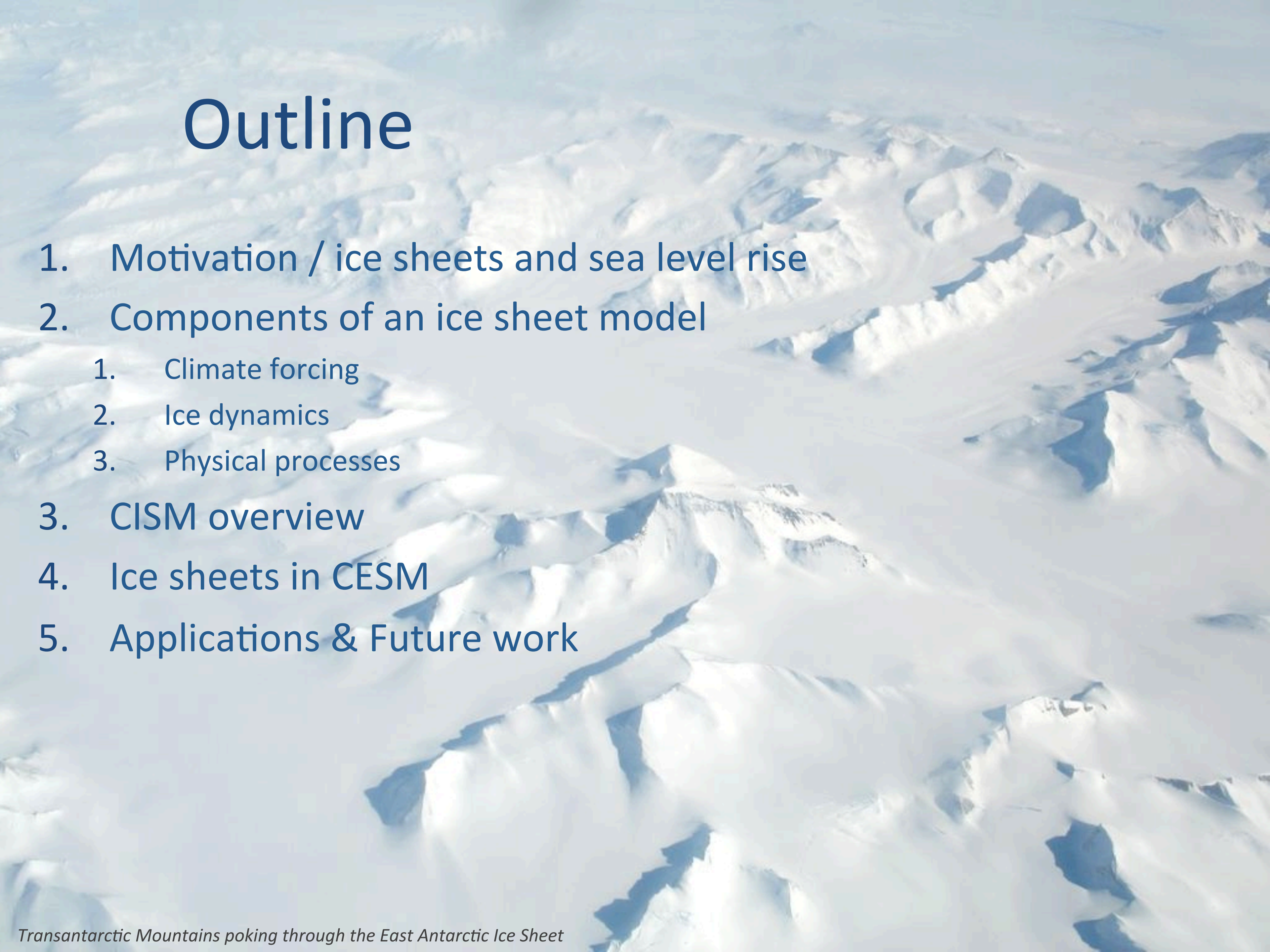
COSIM

Outline

1. Motivation / ice sheets and sea level rise
2. Components of an ice sheet model
    1. Climate forcing
    2. Ice dynamics
    3. Physical processes
3. CISM overview
4. Ice sheets in CESM
5. Applications & Future work



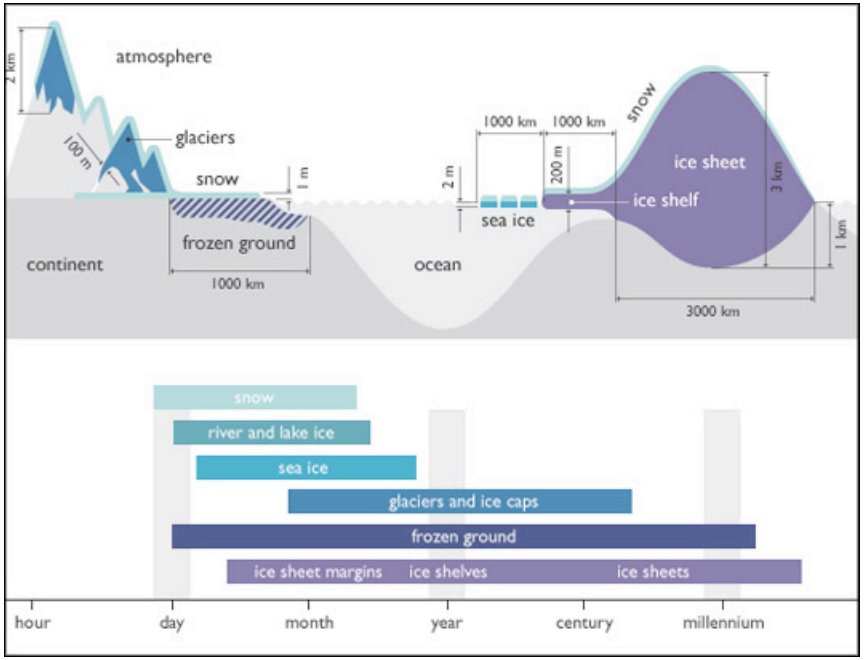
Transantarctic Mountains poking through the East Antarctic Ice Sheet

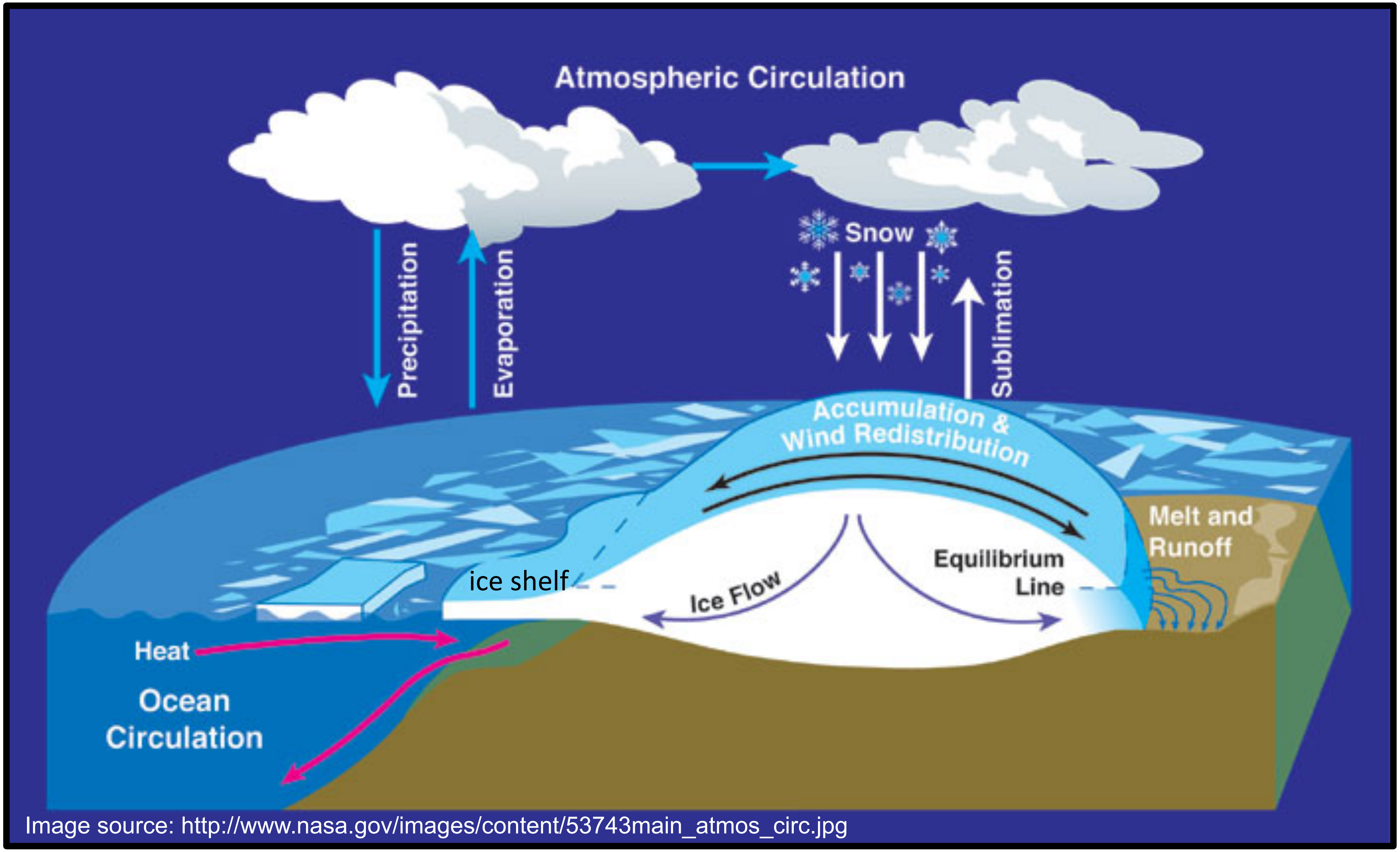
Motivation for modeling land ice

- **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 21st 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)

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; paleo Laurentide, etc.).
- 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.





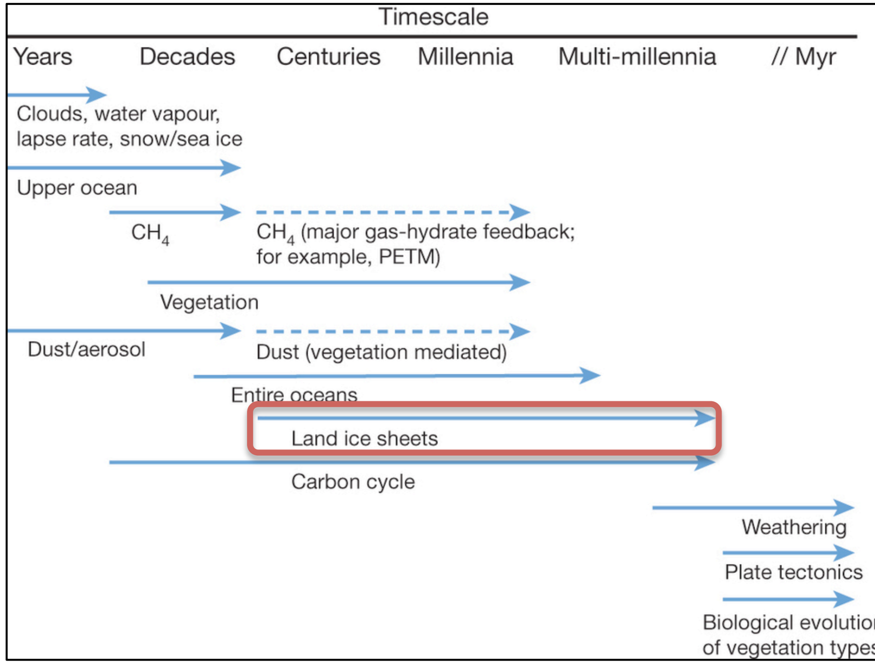
Mass Balance: Change in ice sheet mass = mass in – mass out

sea level change

snowfall

melting
sublimation
calving

Ice Sheet Temporal & Spatial Scales

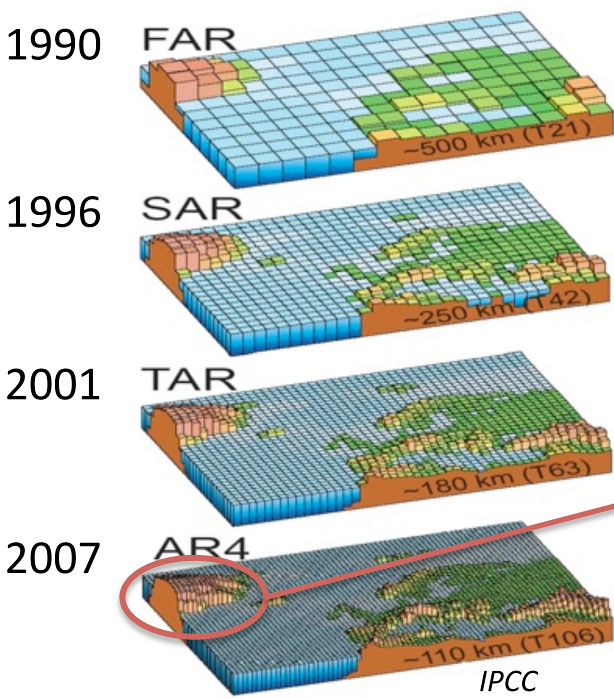


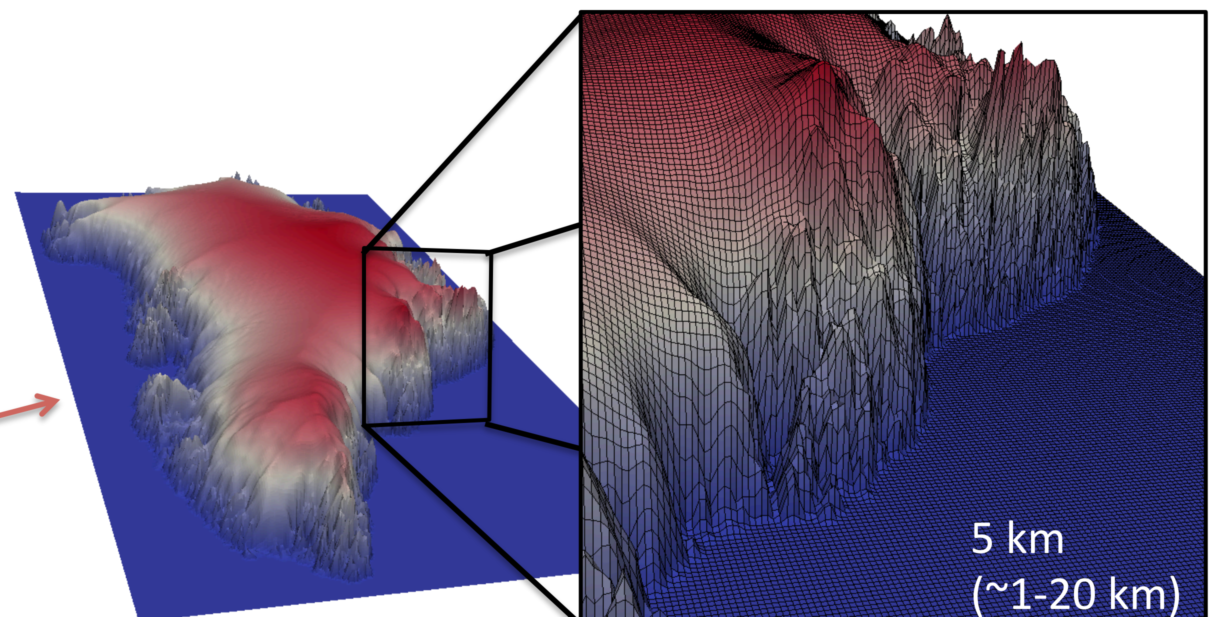
temperature equilibration:
10,000s yrs

ice sheet geometric adjustment:
1000s yrs

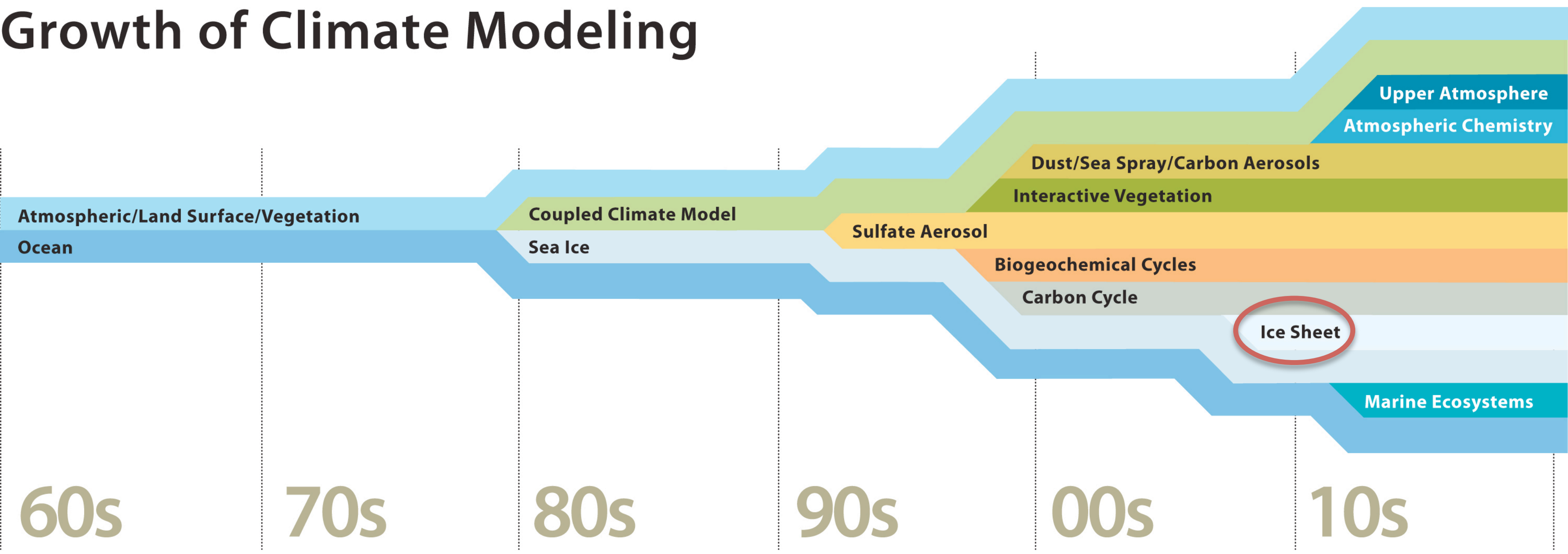
ice stream/outlet glacier adjustment:
10s to 100s yrs

ice shelf collapse:
days to 10s yrs

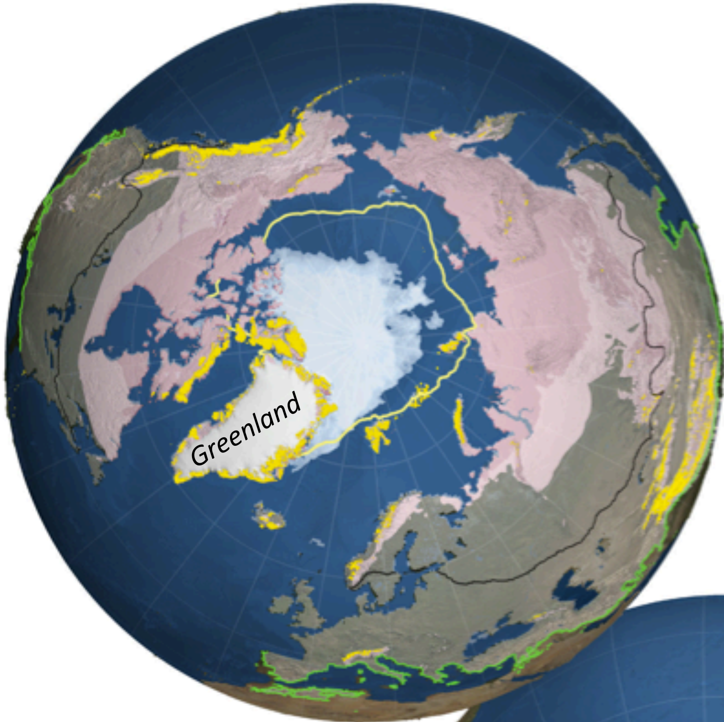




Another Ice Sheet "Temporal Scale"



UCAR

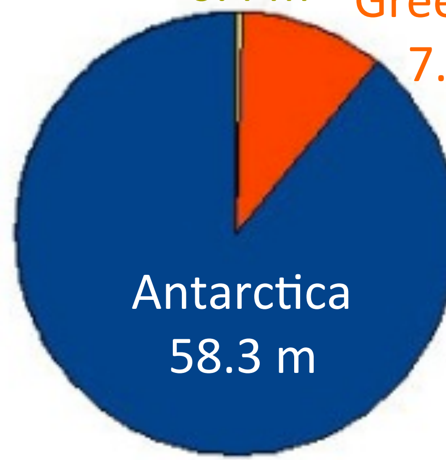


Greenland

- 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

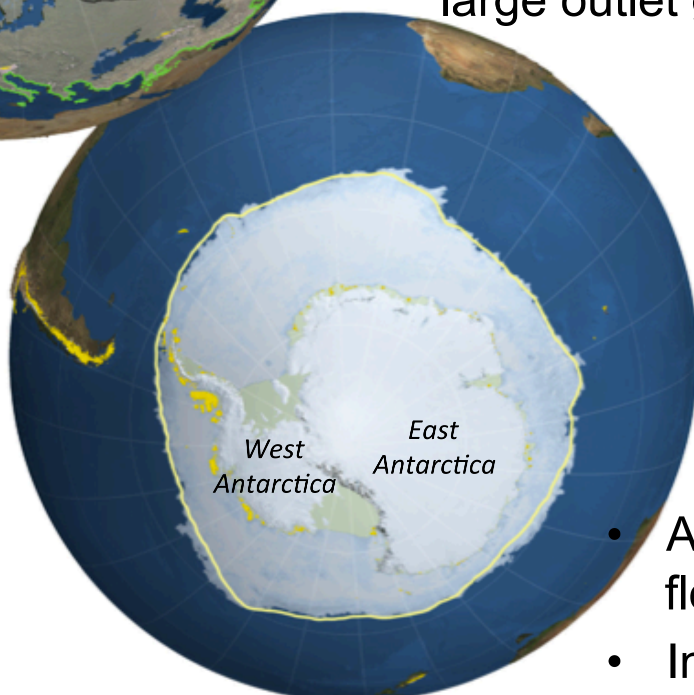
Ice Volume

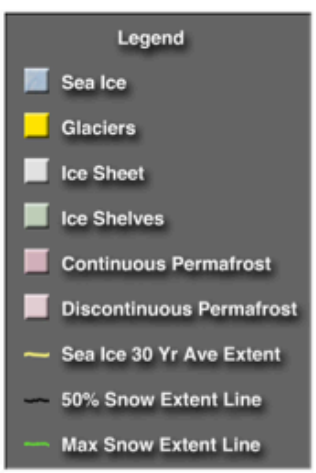
(Sea Level Equivalent)



East: 53.3 m
West: 4.3 m
Peninsula: 0.2 m

Fretwell et al. 2013
University of Oslo; http://my.opera.com/nielsol/blog/2009/03/13/melting-glaciers-contribution-to-sea-level-rise





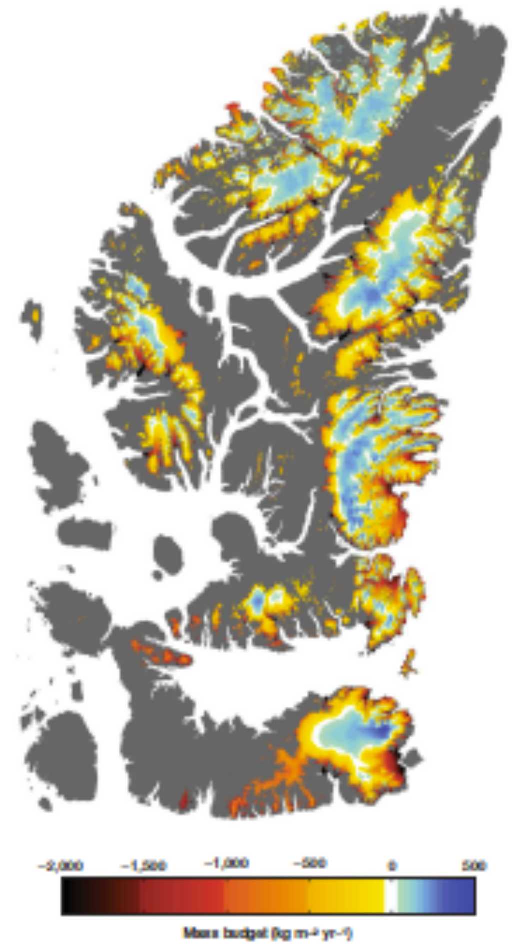
IPCC AR5

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

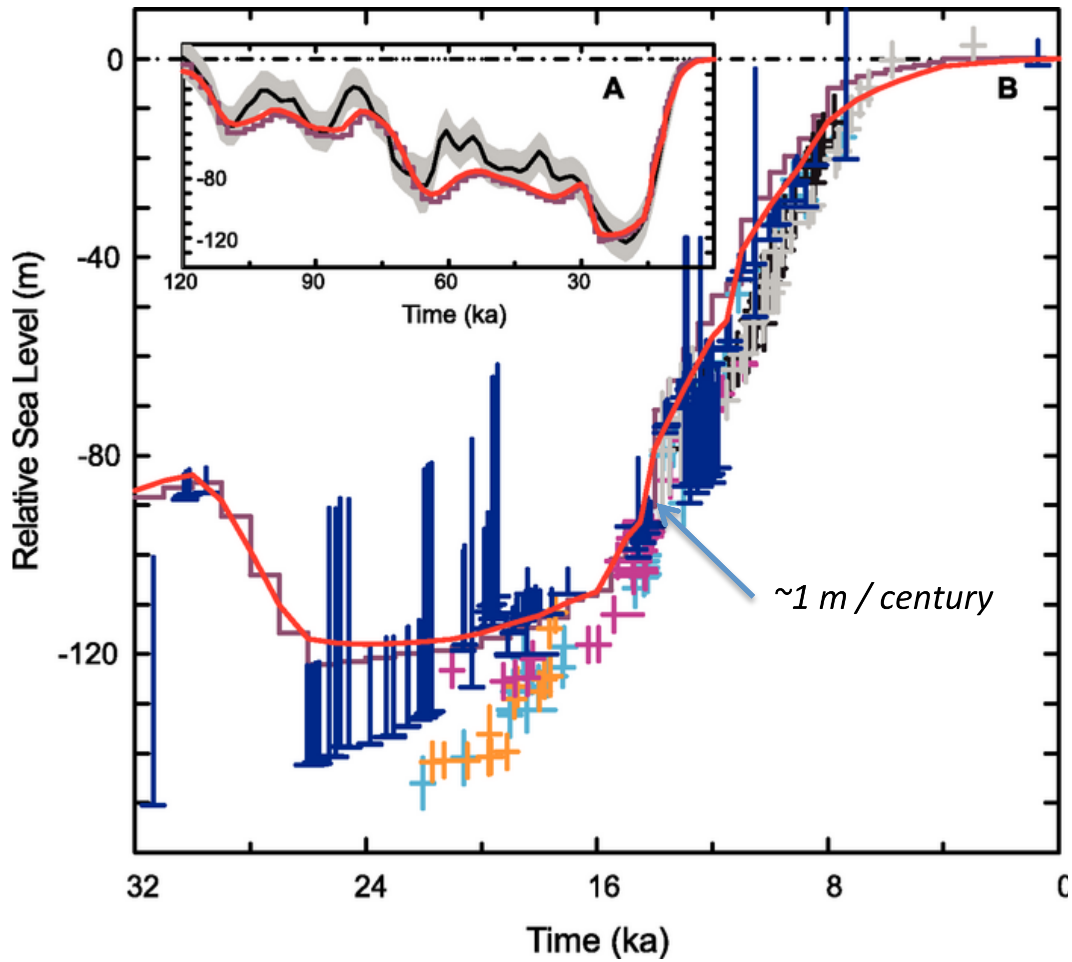
Glaciers and ice caps

- 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)

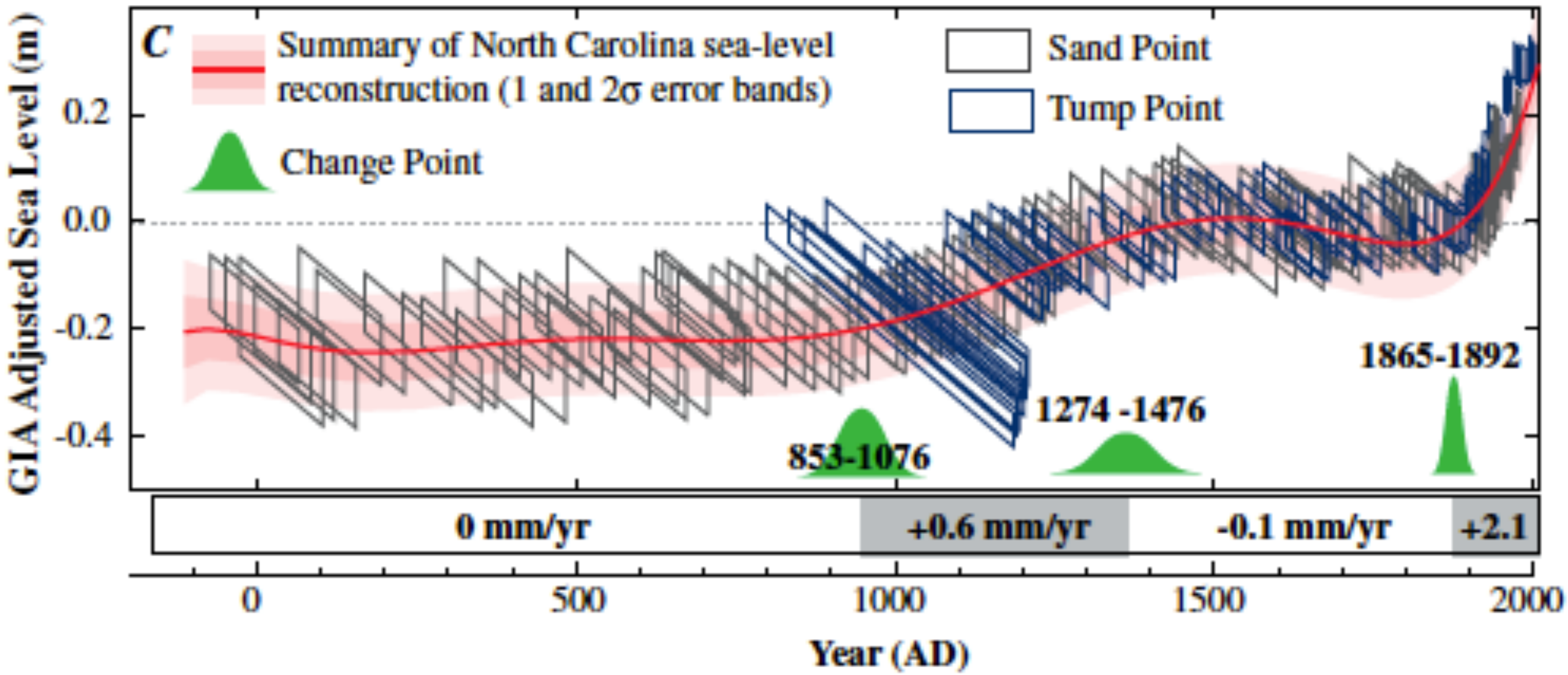
Sea-level change since the last interglacial



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).

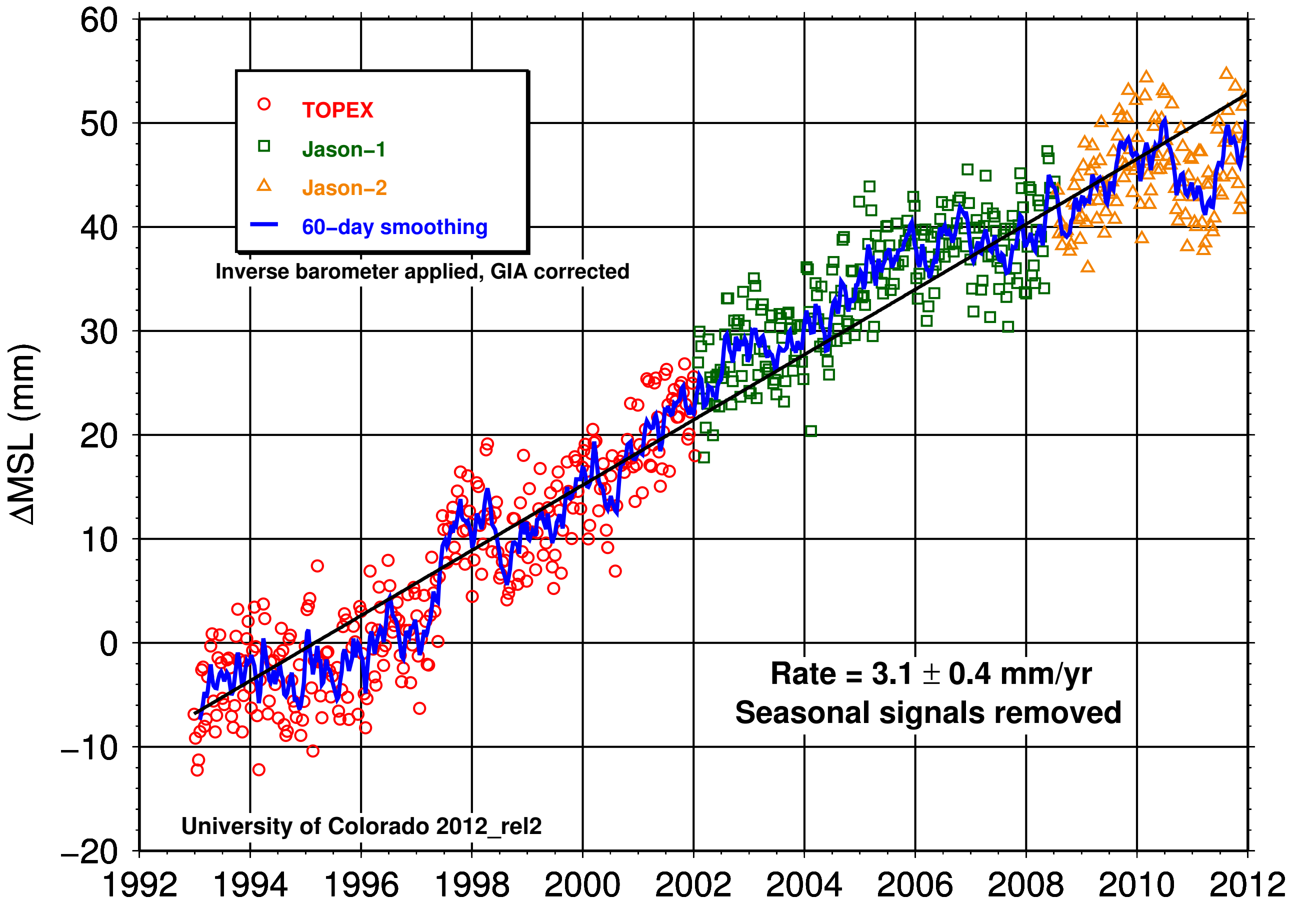
Sea-level change over the past two millennia



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

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

Sea-level rise over the past two decades



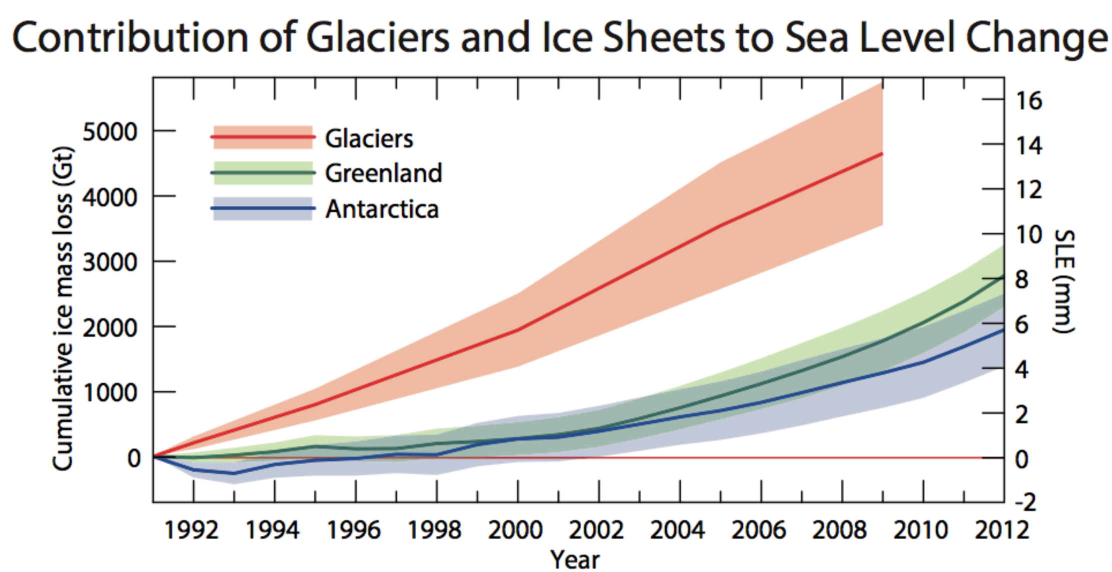
Global mean sea-level rise from satellite altimetry (Nerem et al. 2010)

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

Current global sea level budget

- **Ocean thermal expansion**: ~1 mm/yr
- **Glaciers and ice caps**: ~1 mm/yr
- **Ice sheets**: ~1 mm/yr
  - Greenland 0.7 mm/yr
  - Antarctica 0.2-0.4 mm/yr
- **Terrestrial storage**: ~0 mm/yr
  - Dam retention -0.3 mm/yr
  - Groundwater depletion 0.3 mm/yr

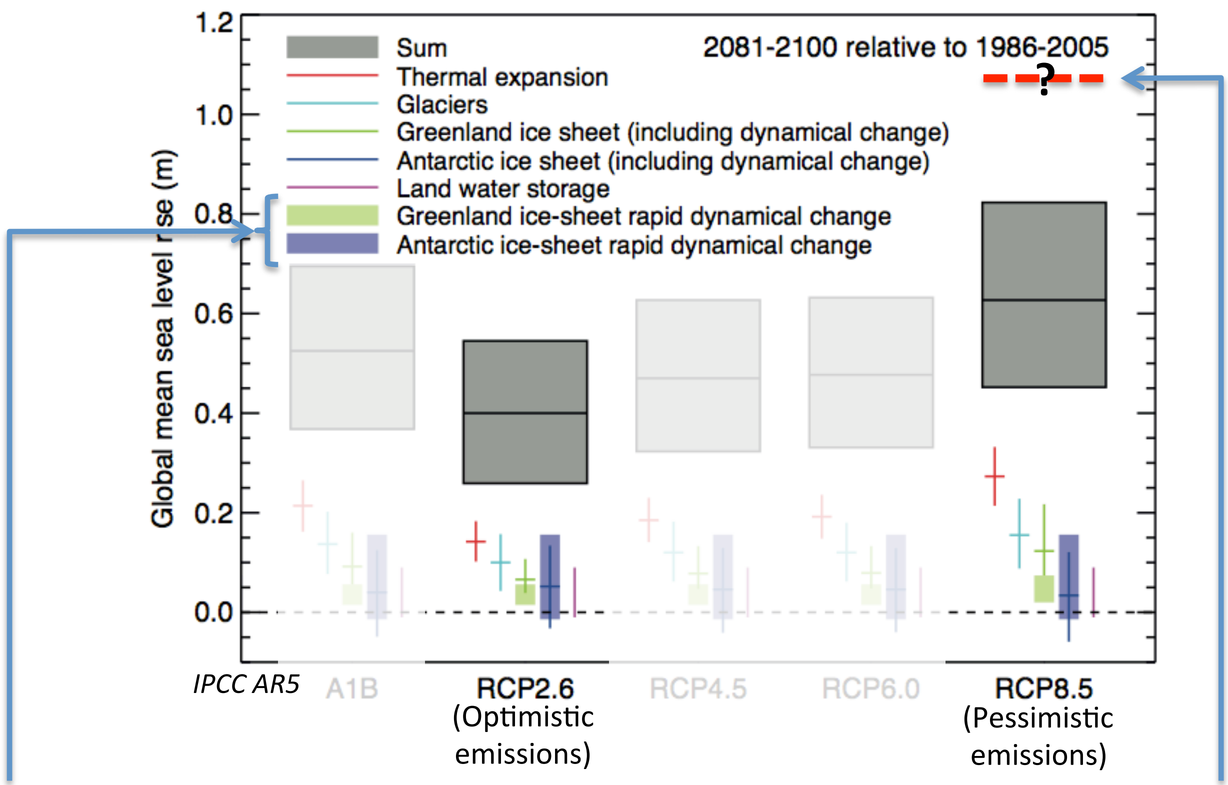
The ice sheet contribution has roughly doubled since 2000 and will likely continue to increase.



IPCC AR5 (2013)

Ice sheet "dynamics" (increased/decreased ice flux to oceans) thought to be largest future uncertainty.

21st century sea-level projections

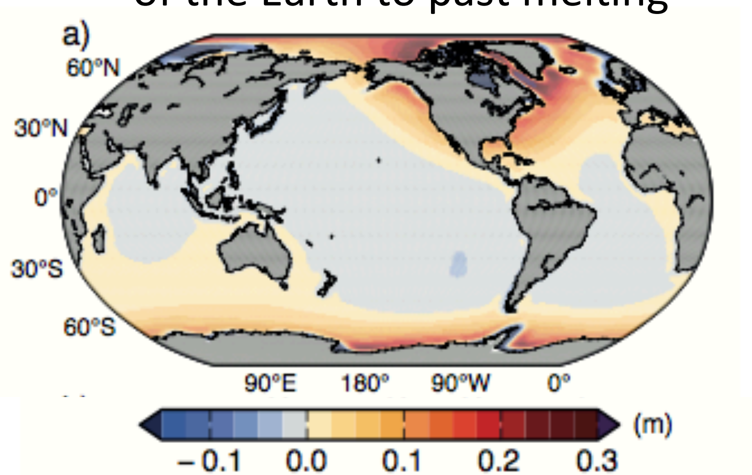


"The contributions from ice-sheet rapid dynamical change ... are treated as having uniform probability distributions, uncorrelated with the magnitude of global climate change, and as independent of scenario. ... [T]he current state of knowledge does not permit a quantitative assessment."

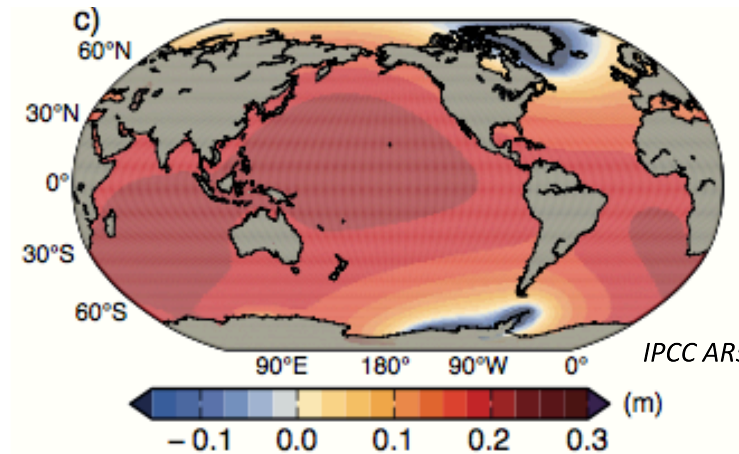
"Potential **additional** contribution [from collapse of the marine-based sectors of the Antarctic ice sheet] cannot be precisely quantified but there is *medium confidence* it would not exceed several tenths of a metre during the 21st century."

Regional variations in sea level change from ice-sheet mass loss

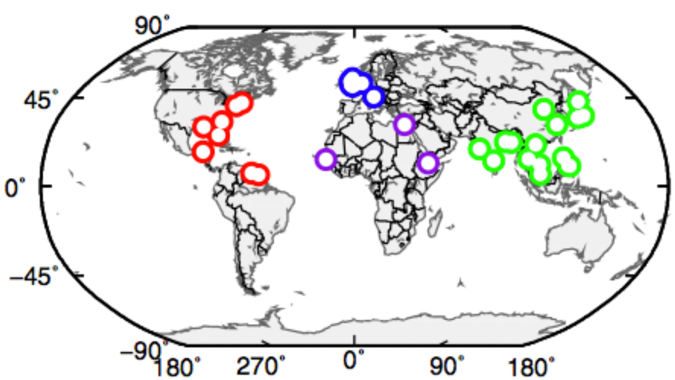
1) Ongoing glacial isostatic adjustment (GIA) of the Earth to past melting



2) Change in Earth's gravity & rotation due to mass redistribution from current melting

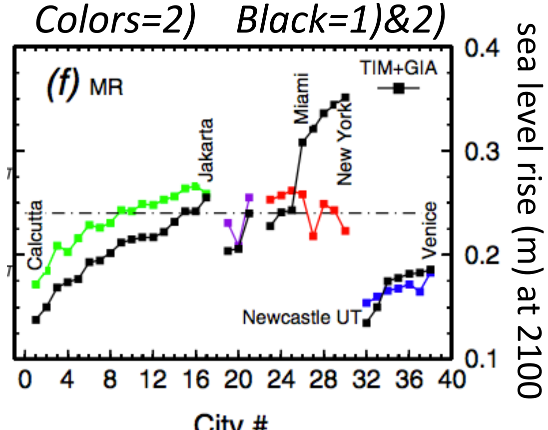


IPCC AR5



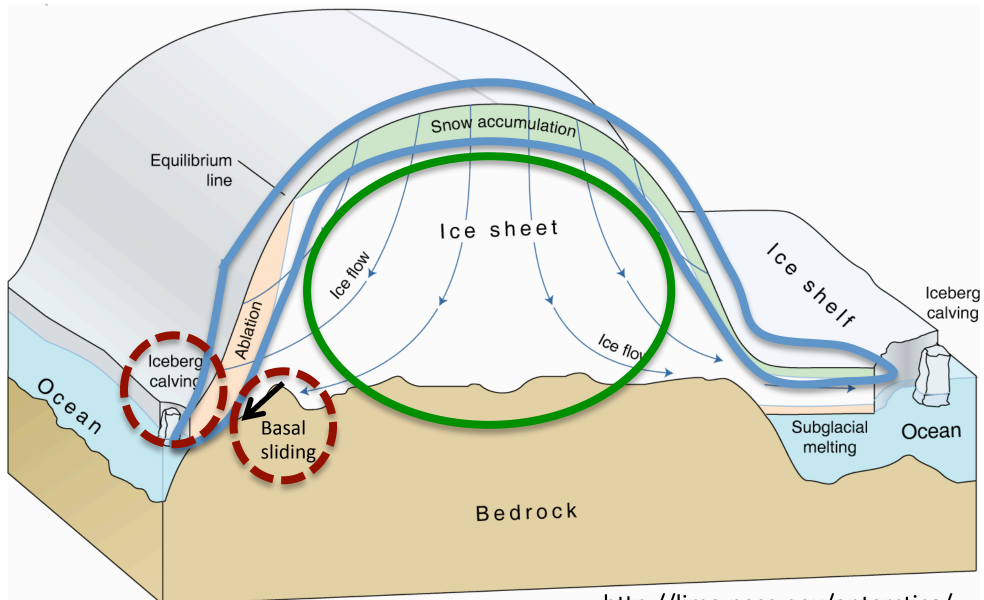
Spada et al. 2013

Colors=2)   Black=1)&2)



What is an Ice Sheet Model?

- Climate Forcing
  snowfall/melt
  ocean melting/freezing
- Dynamical Core
  Conservation of:
  - Mass
  - Momentum
  - Energy



http://lima.nasa.gov/antarctica/

- Physical Processes ("Physics")
  iceberg calving
  basal sliding
  etc., ...

Conservations Equations

Conservation of mass:

mass divergence
(from mom. bal.)

basal mass balance
(from OCN model)

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

surface mass
balance
(from LND model)

Evolves geometry in time

Conservation of energy:

diffusion

advection
(from mom. bal.)

internal energy
dissipation
(from mom. bal.)

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot \left(k \nabla T \right) - \mathbf{u} \cdot \nabla T + \tau_{ij} \dot{\varepsilon}_{ij}$$

Evolves temperature in time

Conservation of momentum:

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

Solves velocity field

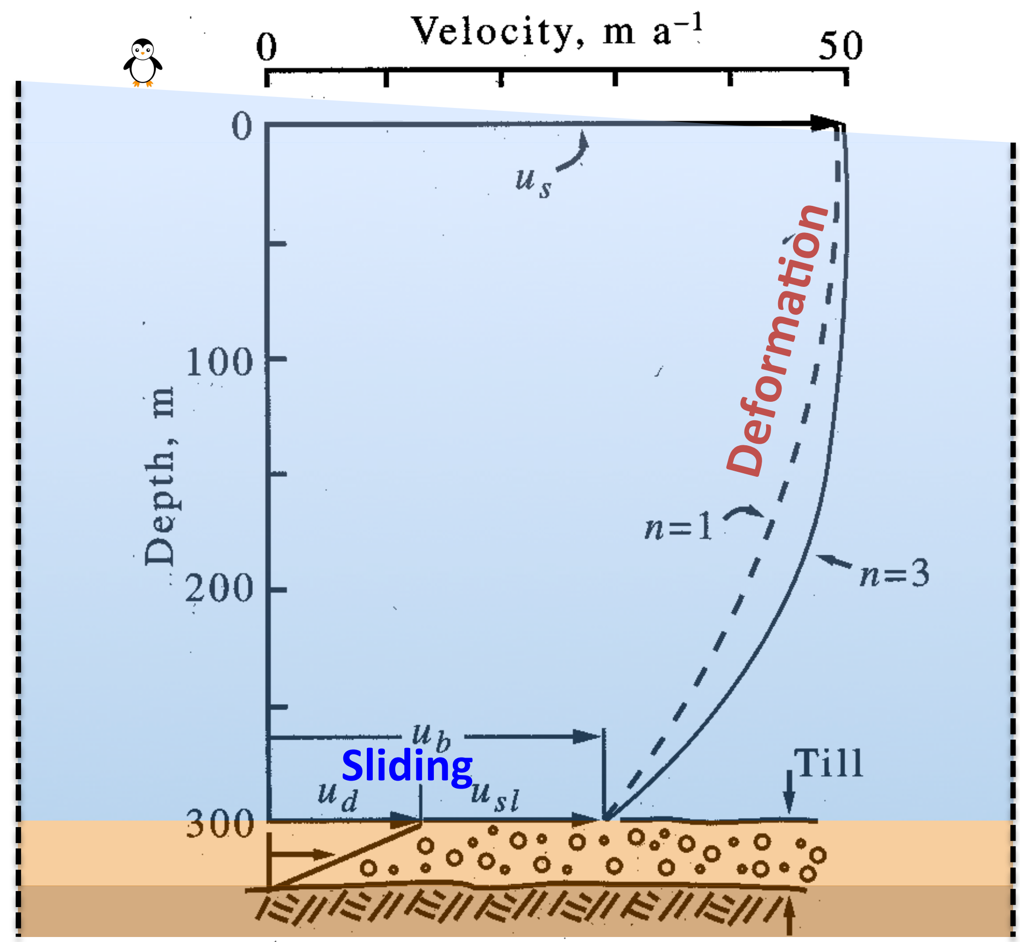
Stokes flow: Assume static balance of forces
by ignoring acceleration.
(time-independent, "diagnostic")

How Glaciers & Ice Sheets Move

- Glaciers flow downhill due to the force of gravity.

- Glaciers flow like a very viscous fluid by plastic deformation.
  (individual ice grains slip past one another)
  The viscosity is strongly dependent on ice temperature and strain rate.
  (warmer, faster-deforming ice is softer)

- When there is water at the bed, glaciers also slide over the bedrock or sediment that they lie on.
  The presence of water can increase velocity by orders of magnitude.



Modified from Hooke (1998)

Conservation of momentum – velocity solver

Ice momentum balance: Stokes flow

- incompressible
- no acceleration
- Driving and resisting stresses in global balance at every moment in time
  - velocity is time-independent ('diagnostic' output)
  - a function of geometry and BC at every point in time

$$0 = \nabla \cdot \sigma + \rho \vec{g}$$

$$\tau_{ij} = B \dot{\varepsilon}_e^{\frac{1-n}{n}} \dot{\varepsilon}_{ij}, \quad B = EB_0(T)$$ (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)

Ice Rheology: empirical Glen's flow law

- non-Newtonian: shear-thinning
- strain rate (i.e. velocities) = f(stress state, effective ice viscosity)
- viscosity = f(rate factor[T,fabric,...], strain rate)
- Solving velocity is nonlinear → fixed point iteration

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

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

$$B = EB_0(T)$$

Ice Sheet Momentum Balance: Calculation of ice velocity

Until recently, most ice sheets models used these simplified approximations of ice motion.

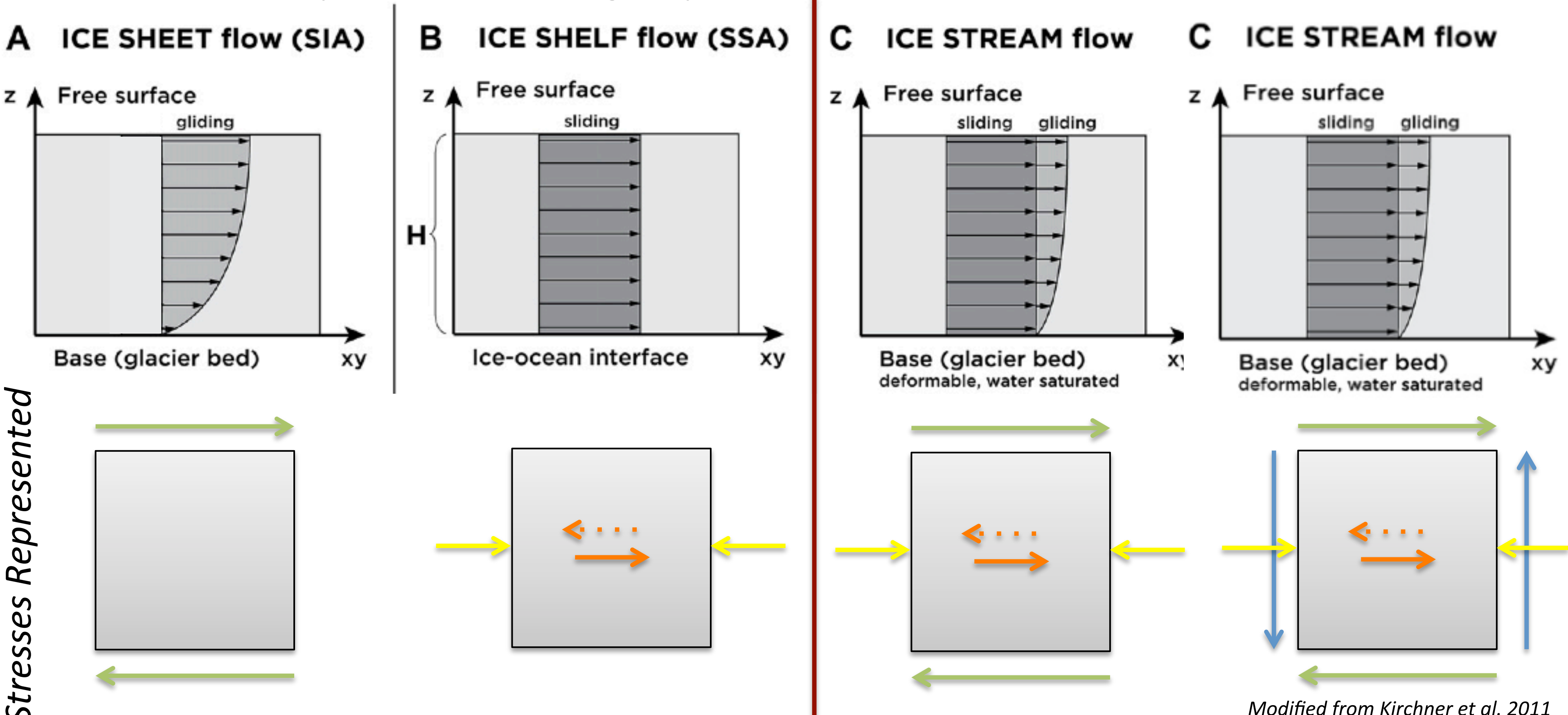
New models have begun to use more complete representations of ice motion needed to accurately model fast-flowing regions.

Shallow Ice Approximation
deformation only*

Shallow Shelf Approximation
sliding only*

First-order Stokes
deformation+sliding

Full Stokes
deformation+sliding



Modified from Kirchner et al. 2011

Boundary Conditions

top: free surface $\left(\tau_{ij} - P\delta_{ij}\right)n_j = -P_{atm}n_i = 0$

Margins:

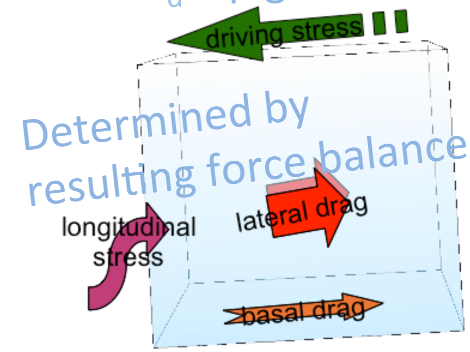
grounded - specified flux or small ice cliff

floating - stress at ice front balance by hyd. pressure

$$\left(\tau_{ij} - P\delta_{ij}\right)n_j = -P_{water}n_i$$

Set by geometry

$\tau_d = \rho\ g\ H \sin\alpha$



Set by basal B.C.

base:

(1) frozen, no slip: $u, v, w = 0$

(2) sliding w/ specified basal traction: $\tau_{bx} = Bu$

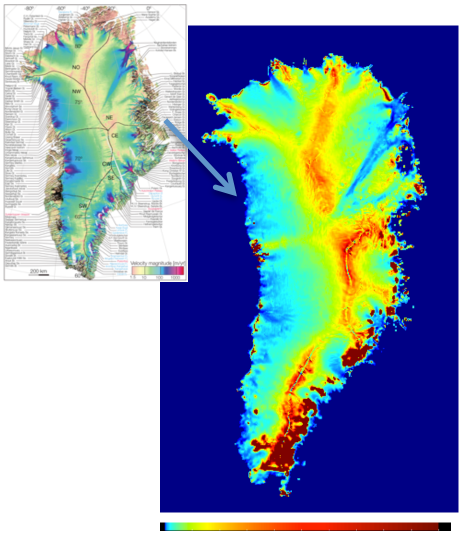
(3) sliding w/ specified basal yield stress: $\tau_{bx} = \tau_0 = B(\mathbf{u})u$

(4) Coulomb friction law with cavitation

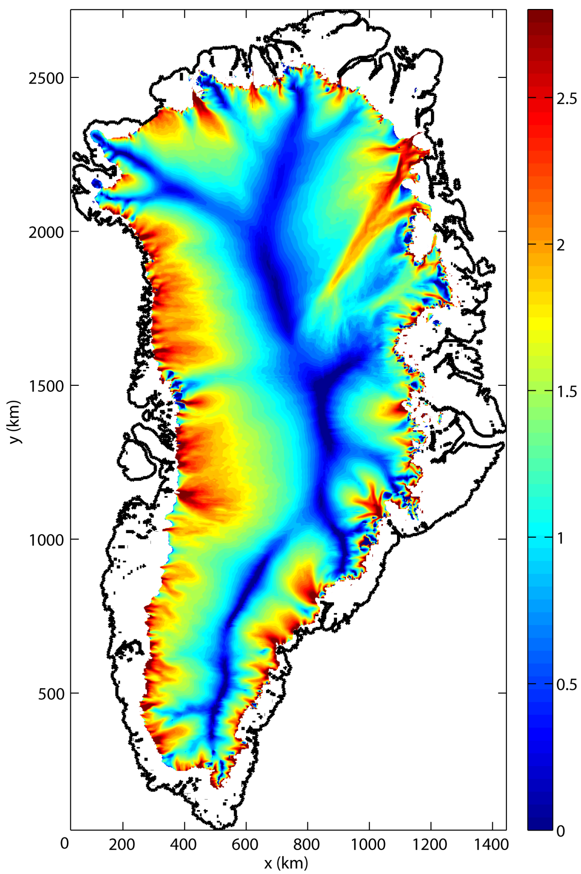
...

Basal Traction Parameter, β

Tuned from observed velocities

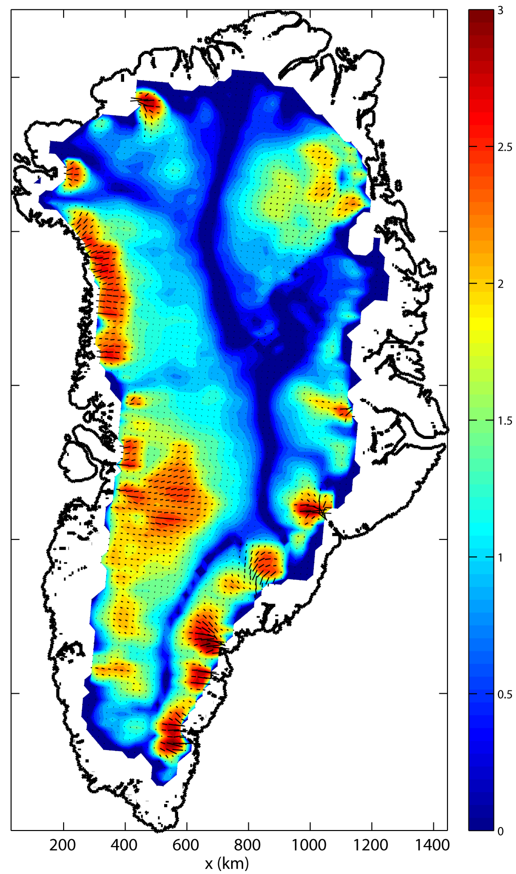


Importance of Higher-Order Dynamics

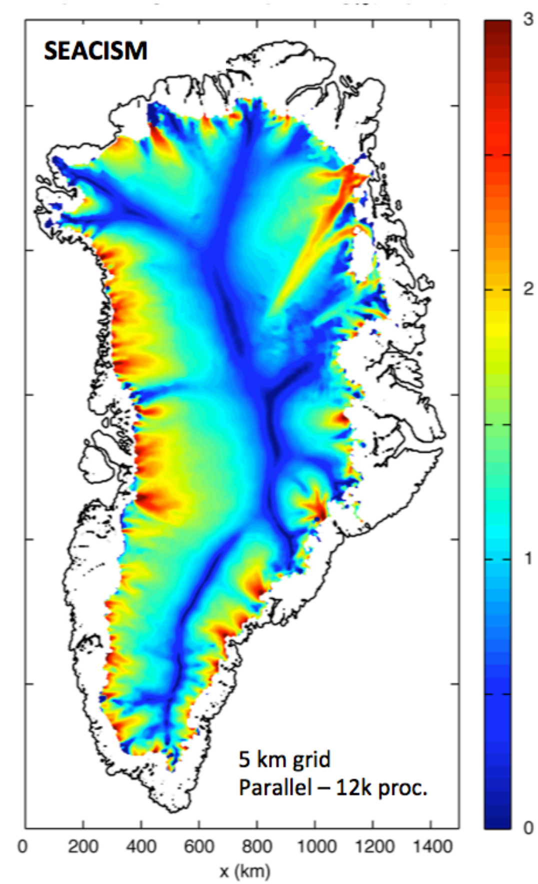


Balance Velocities
2.5 km DEM

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



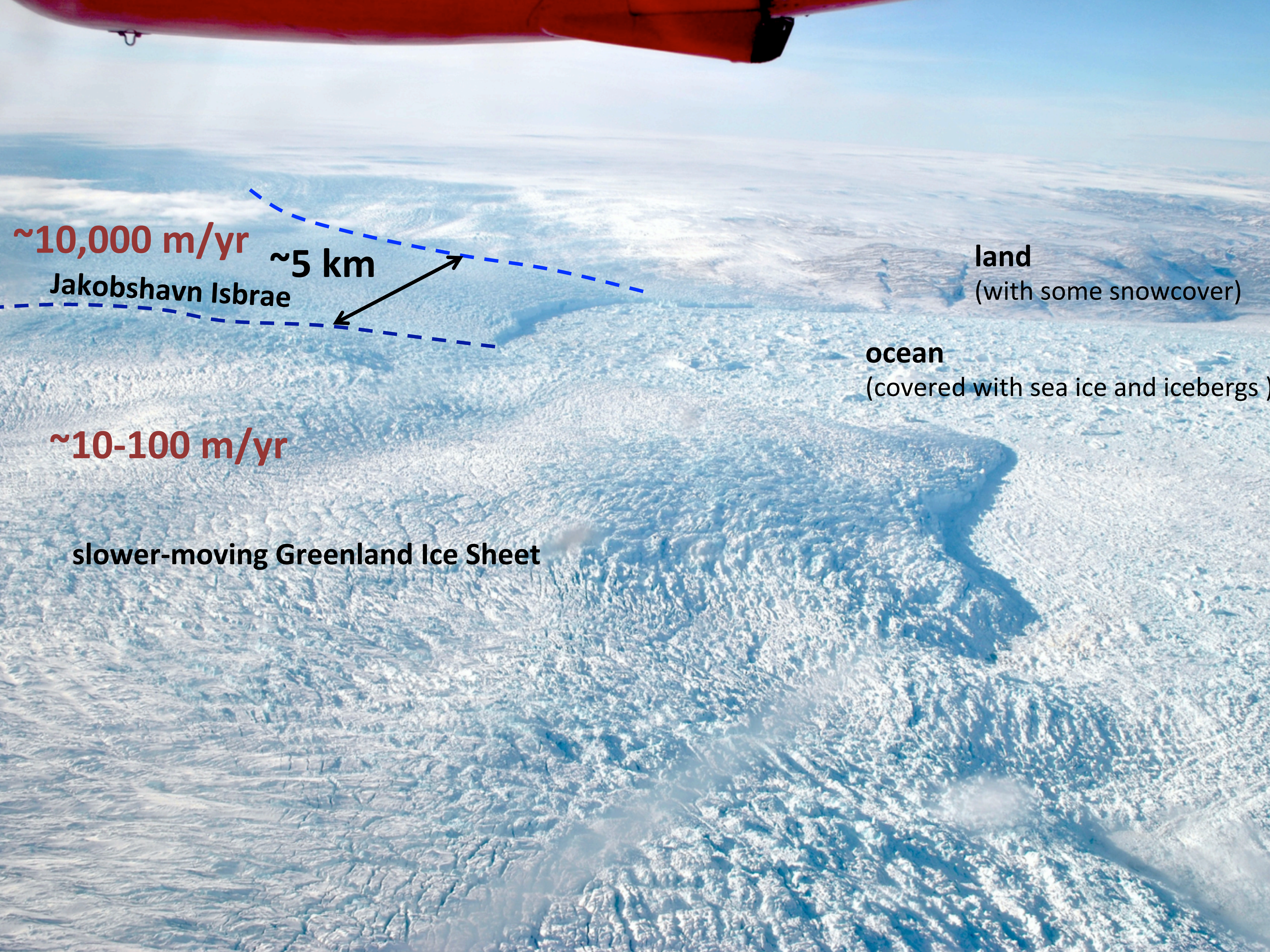
Surface Speed
0-order SIA model
CISM v1
(no sliding)
20 km DEM

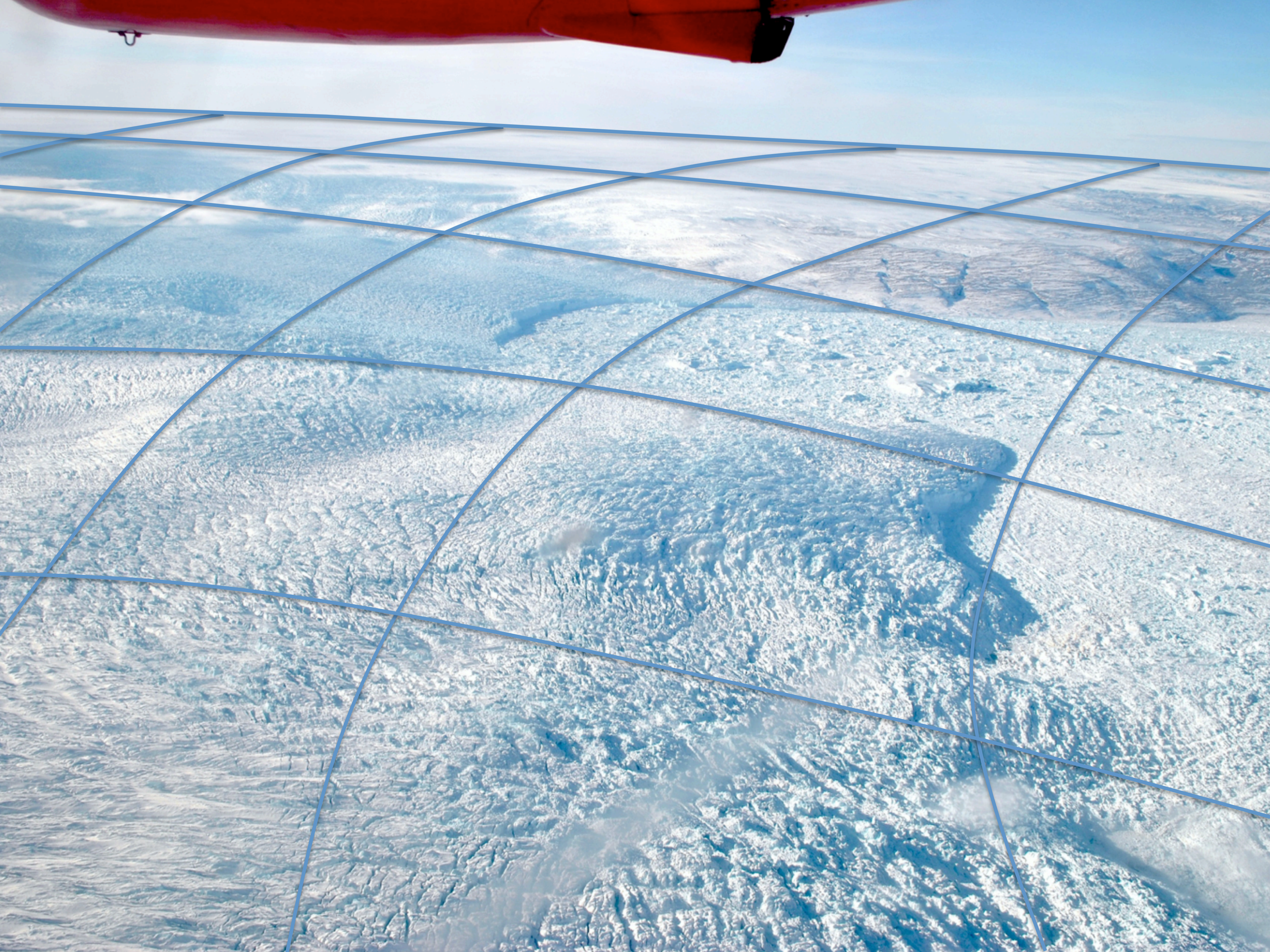


Depth-averaged speed
1-order model
CISM v2
5 km DEM
Price et al. (*PNAS*, **108**(22), 2011)

(Necessary ice sheet physics for marine ice sheets (Antarctica) but needed GLC <-> OCN coupling not ready.)


Calving front of Jakobshavn Isbrae, Greenland


~10,000 m/yr
~5 km
Jakobshavn Isbrae
land
(with some snowcover)
ocean
(covered with sea ice and icebergs)
~10-100 m/yr
slower-moving Greenland Ice Sheet



Physical Processes ("Physics")

Constitutive laws

Basal sliding submodels / parameterizations

Surface and subglacial hydrology

Iceberg calving

Isotopes and other tracers

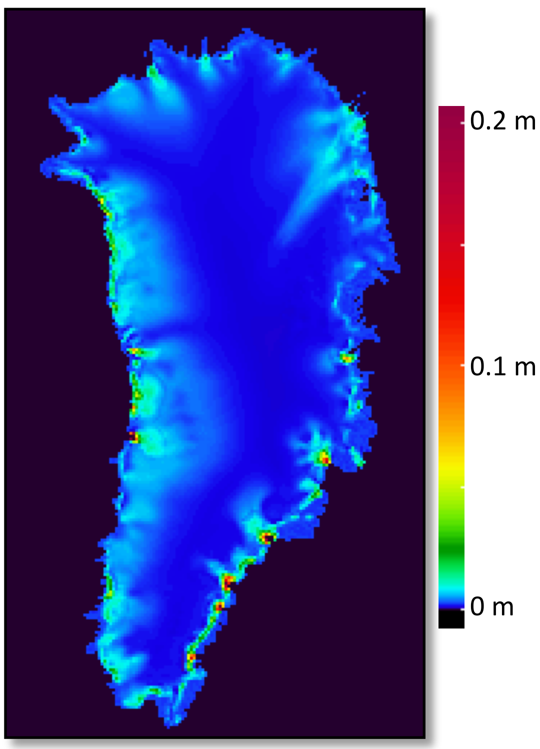
etc…

Evolutionary Subglacial Hydrology in CISM

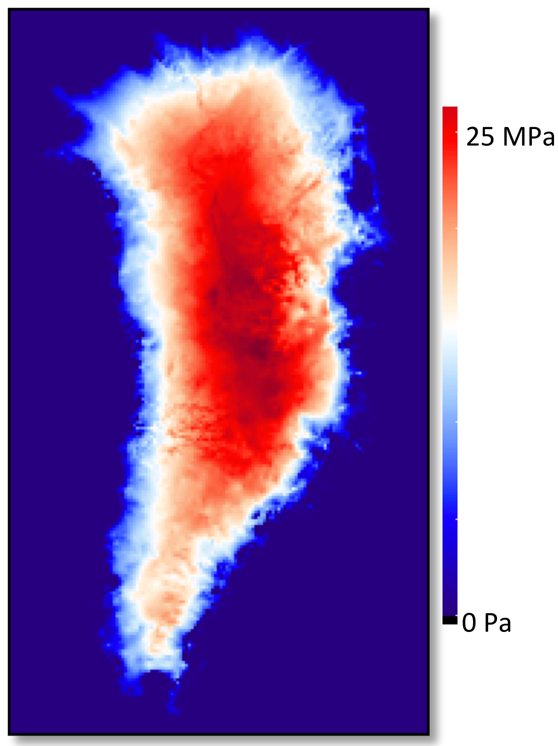
Conservative, 2d, time-dependent subglacial hydrology model, containing both distributed (macroporous film) and channelized elements[1]

Coupled to water-pressure dependent sliding law with theoretical[2] and observational[3] support

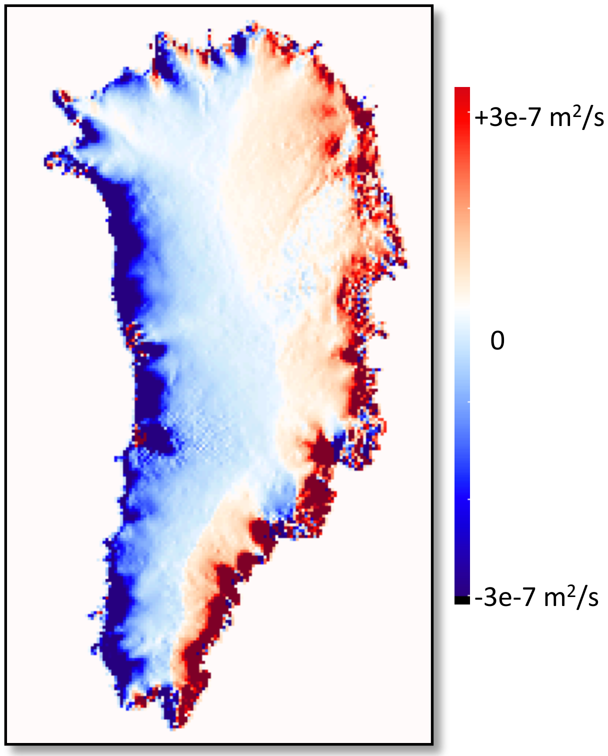
Basal water thickness



Water pressure

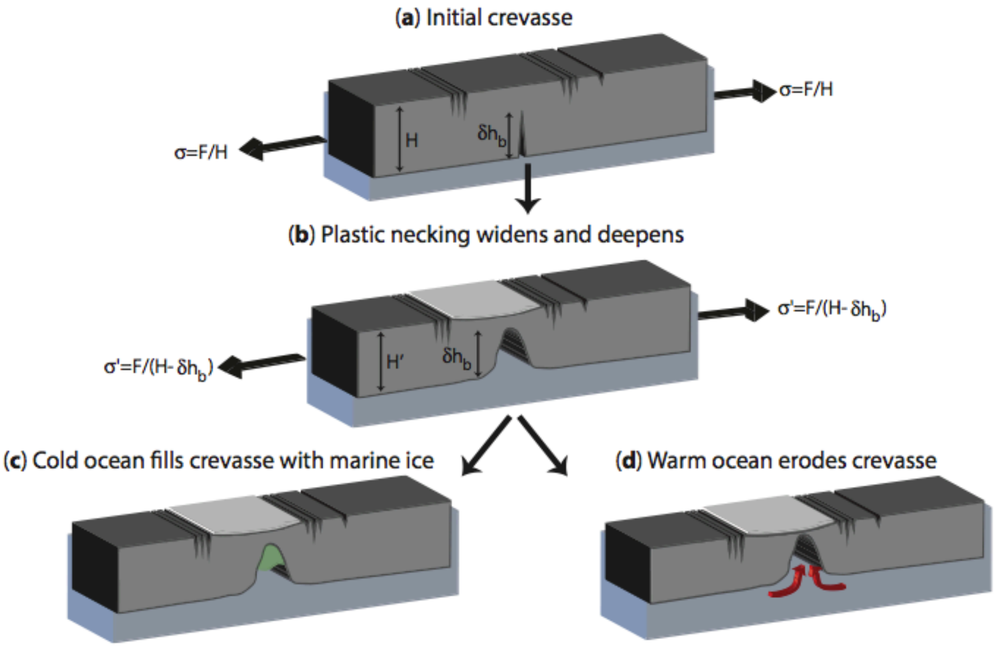


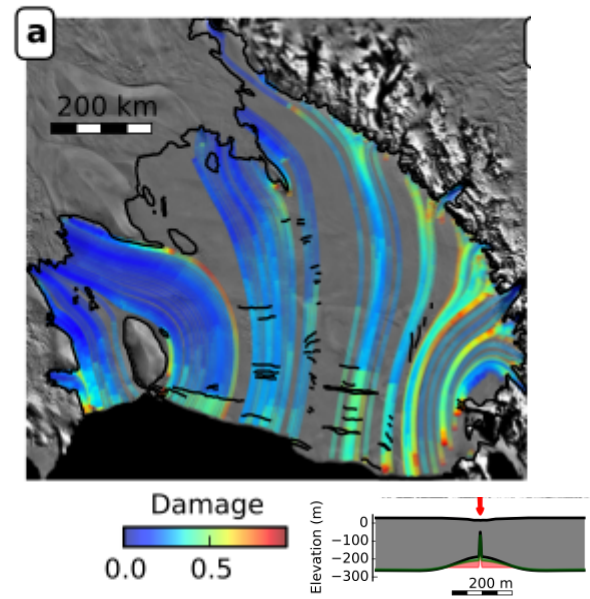
Water flux (x dir.)



[1]Hoffman & Price, 2014 JGR [2]Schoof, 2005 [3]Iverson, 2011

Damage-based calving model





Jeremy Bassis, Univ. of Michigan

Community Ice Sheet Model
http://oceans11.lanl.gov/cism/

History

- based on GLIMMER model developed largely out of University of Bristol *[SIA only]*
- Glimmer-CISM v1.6: transitional version added to CESM v1.0 (June 2010) *[SIA only]*
- Glimmer-CISM v1.9 added to CESM v1.2
- Standalone CISM v2.0 released Oct. 2014
  - SIA, SSA, FO-2d, FO-3d velocity solvers
  - parallel (scales to 10k cores)
- CISM v2.1 to be included in CESM v2

Overview

- regular mesh
- mixture of finite-difference, finite-volume, and finite-element methods
- sigma vertical coordinate

- **GLIDE – Implicit SIA solver** CISM 1.0+

Implicit Ice Sheet Evolution (SIA only)

dt =~ months for 4 km GIS

On each time step:

Evolve thickness $H_{n+1} = f(dt, H_n, H_{n+1})$

Evolve temperature (and tracers) $T_{n+1} = f(dt, T_n, u_n)$

- **GLISSADE – Explicit higher-order solver** CISM 2.0+

Explicit Ice Sheet Evolution (SIA, SSA, L1L2, DIVA, FO)

dt ~= days for 4 km GIS

On each time step:

Evolve thickness $H_{n+1} = f(dt, H_n, u_n)$

Evolve temperature (and tracers) $T_{n+1} = f(dt, T_n, u_n)$

Calculate diagnostic velocity field $u_{n+1} = f(H_{n+1}, T_{n+1}, b.c.)$

- **Shared Physics**

Lithosphere model

Geothermal heat flux model

Subglacial hydrology

...

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

- CESM 2 will include **Community Ice Sheet Model (CISM) v2.1**
  - Default configuration:
    - Greenland ice sheet on a 5 km grid
    - higher-order DIVA velocity solver (with calibrated basal friction coefficient?)
  - Legacy configuration:
    - Greenland ice sheet on a 4 km grid
    - SIA solver
- 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.

Ice sheets in CESM

CESM 1.2+

Land -> Ice sheet (10 classes)

- Surface mass balance
- Surface temperature

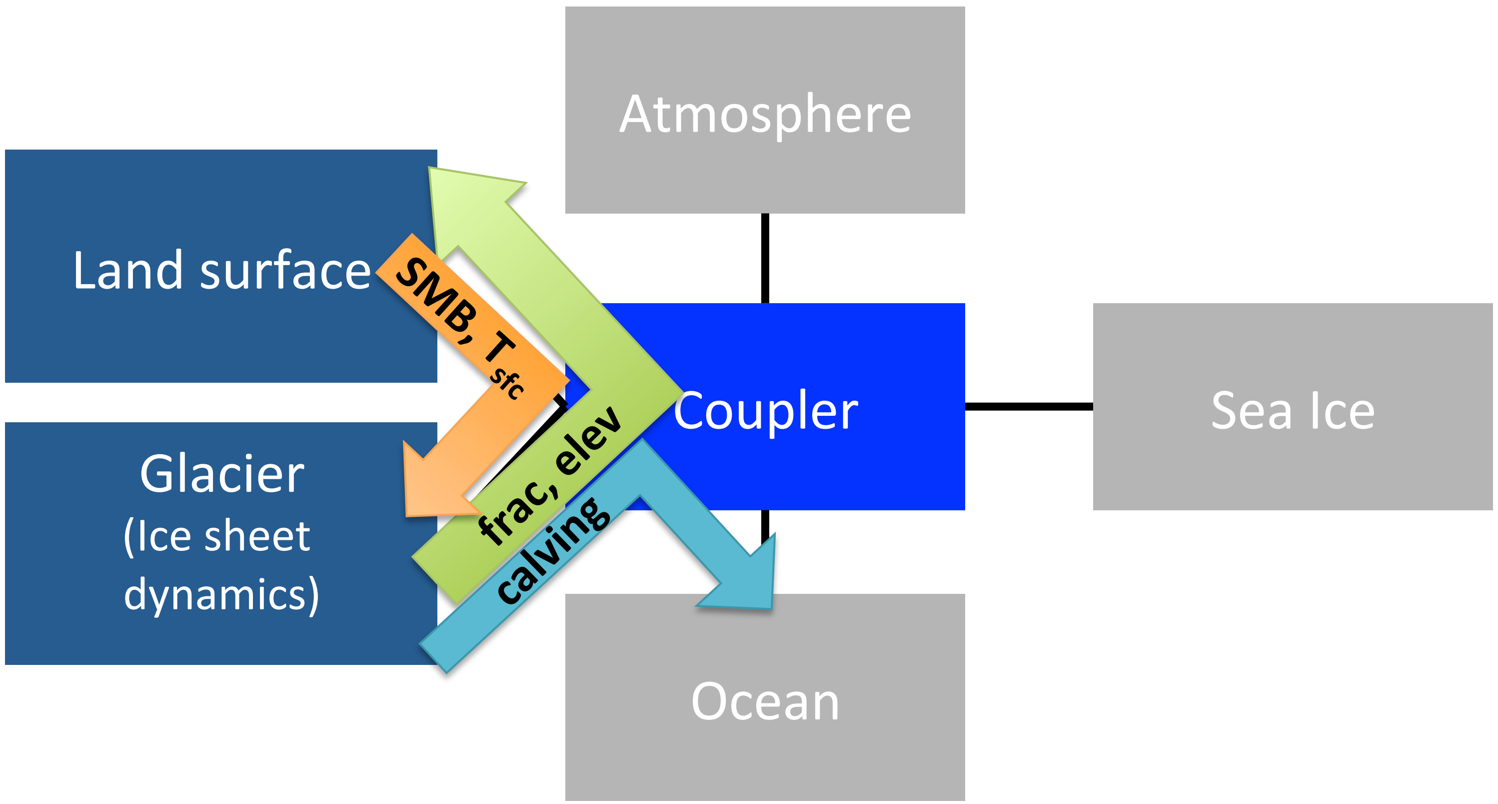
CESM 2

Ice sheet -> Land (10 classes)

- Ice fraction and elevation

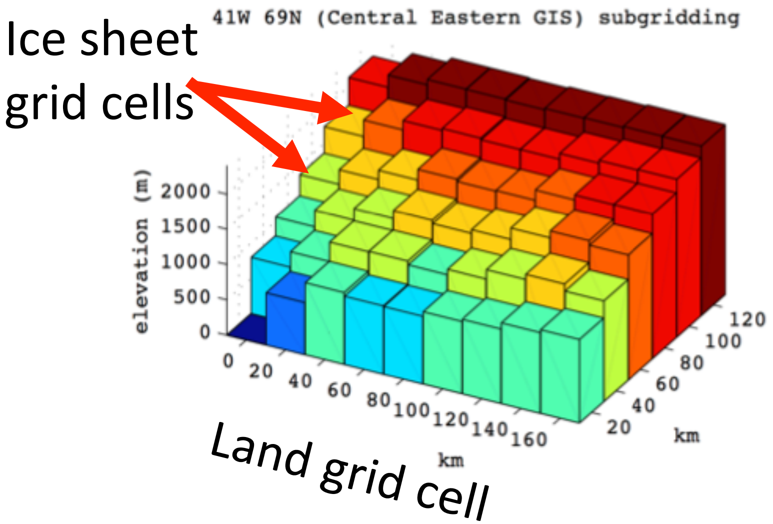
Ice sheet -> Ocean

- Calving fluxes



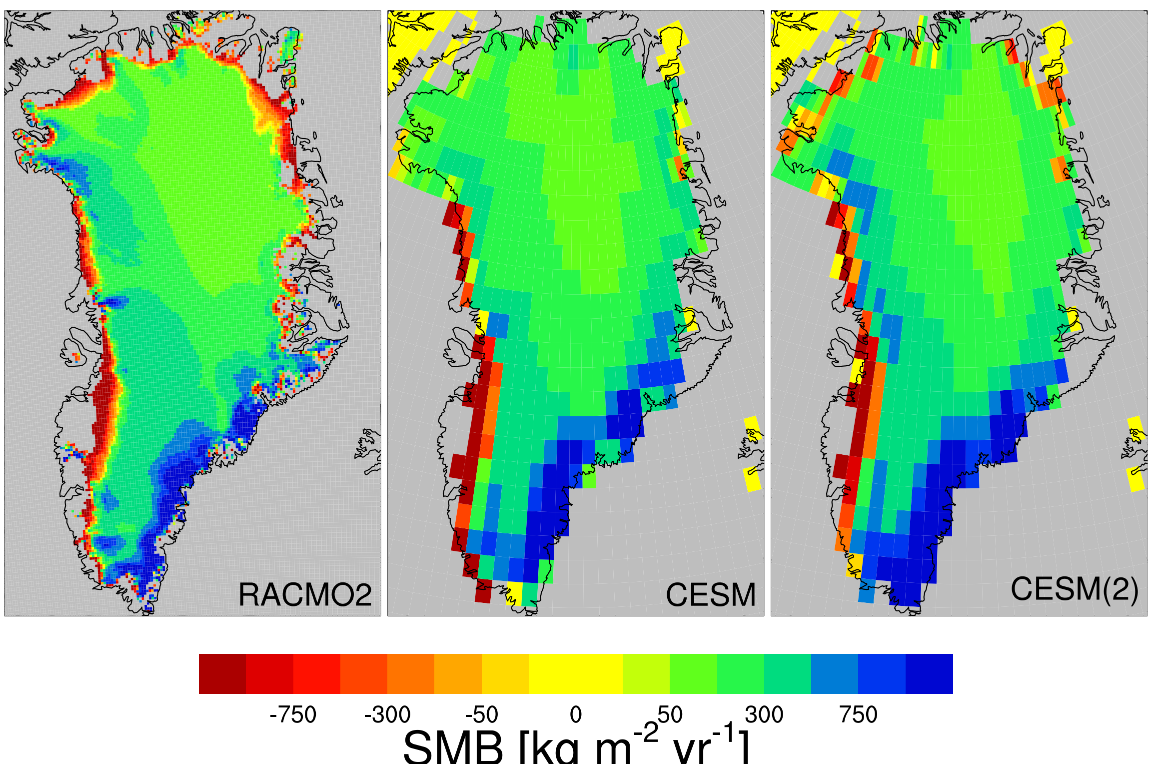
Ice sheet surface mass balance in CESM

- 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



Greenland SMB in CESM

- CESM computes Greenland's SMB in multiple elevation classes, using simple temperature downscaling.
- Result are generally good, but are sensitive to biases in radiation and snow physics. Model improvements can degrade the SMB by removing canceling biases.

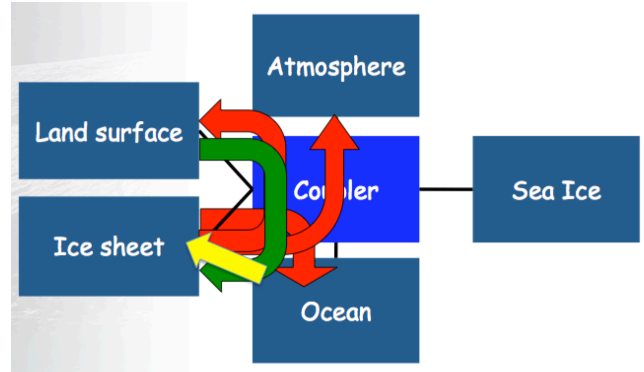


Greenland surface mass balance simulated in RACMO2, CESM1, and a beta version of CESM2 (courtesy of Jan Lenaerts)

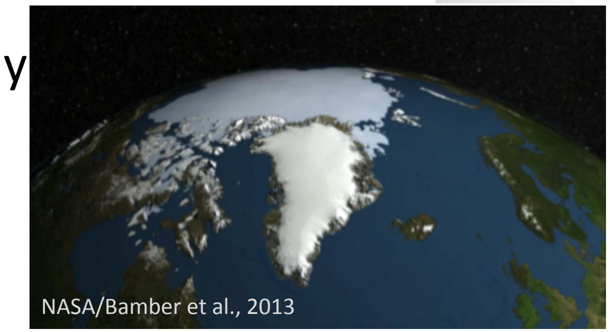
Changes to Land Ice in CESM2

CESM1.0	CESM2.0
One-way coupling	Two-way coupling
Serial, shallow ice approximation	Parallel, higher-order
No way to run standalone CISM	TG compset for running standalone CISM
1-m snow pack in CLM	10-m snow pack in CLM
Only 3 land/atm resolutions supported	All land/atm resolutions supported
SMB only computed in runs done by LIWG	SMB computed in all runs

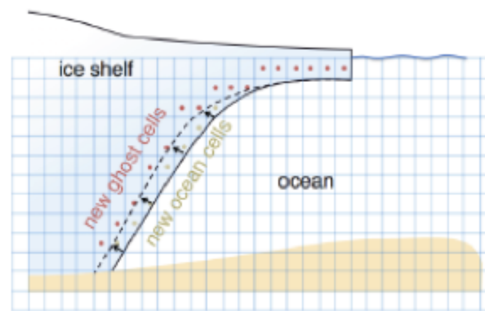
What's Missing:
GLC coupling in CESM 2



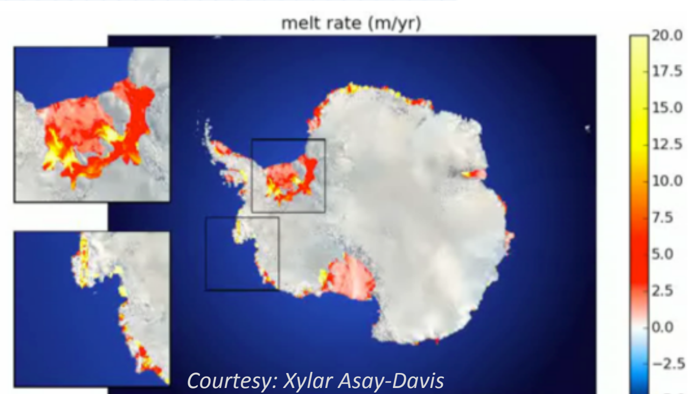
- GLC -> ATM
  (changing surface topography)
  (Available using scripts and restarts)



- GLC -> OCN/ICE
  (ice shelf draft)



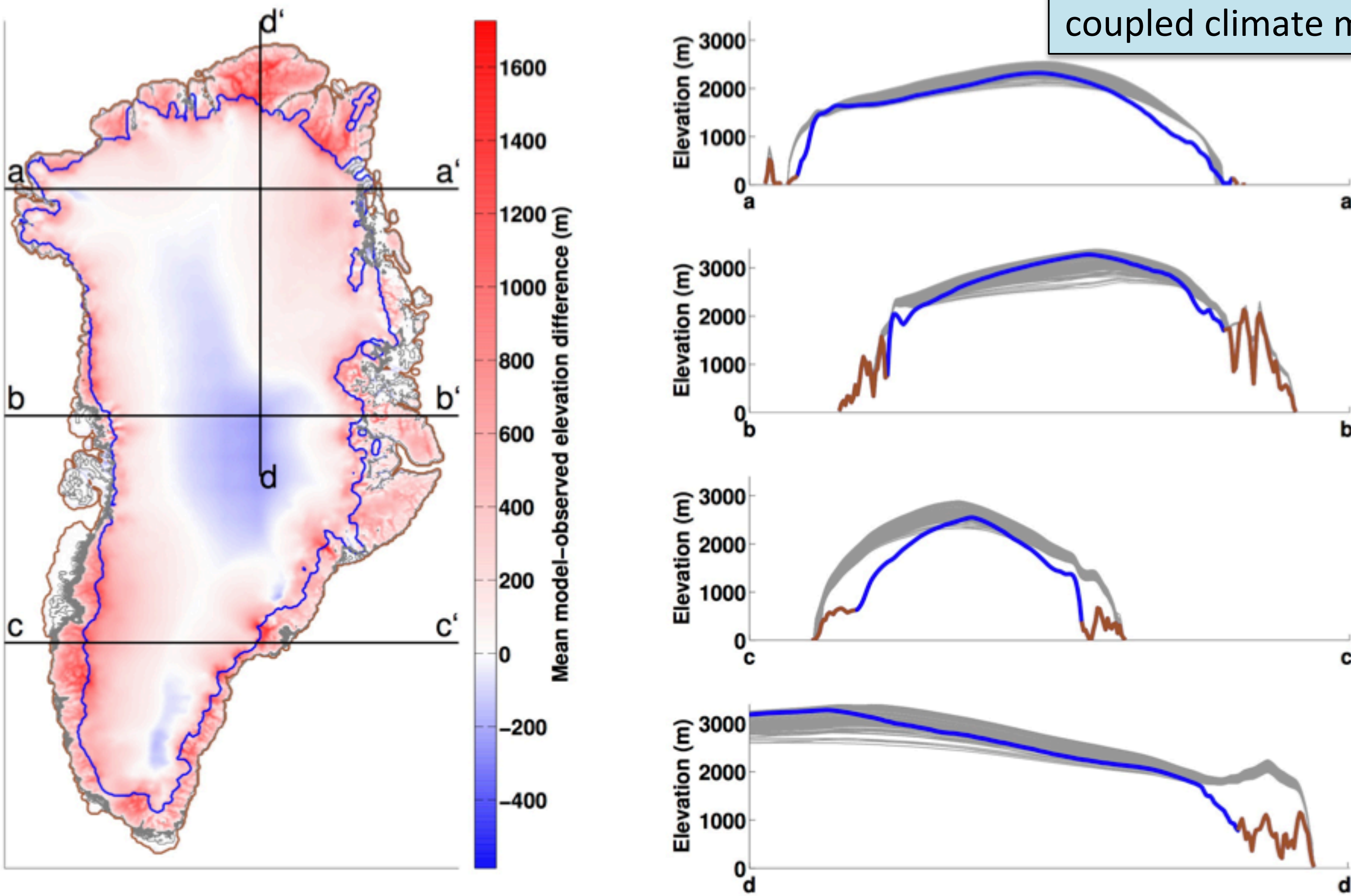
- OCN -> GLC
  (subshelf mass and heat fluxes)



Needed for Antarctica simulation

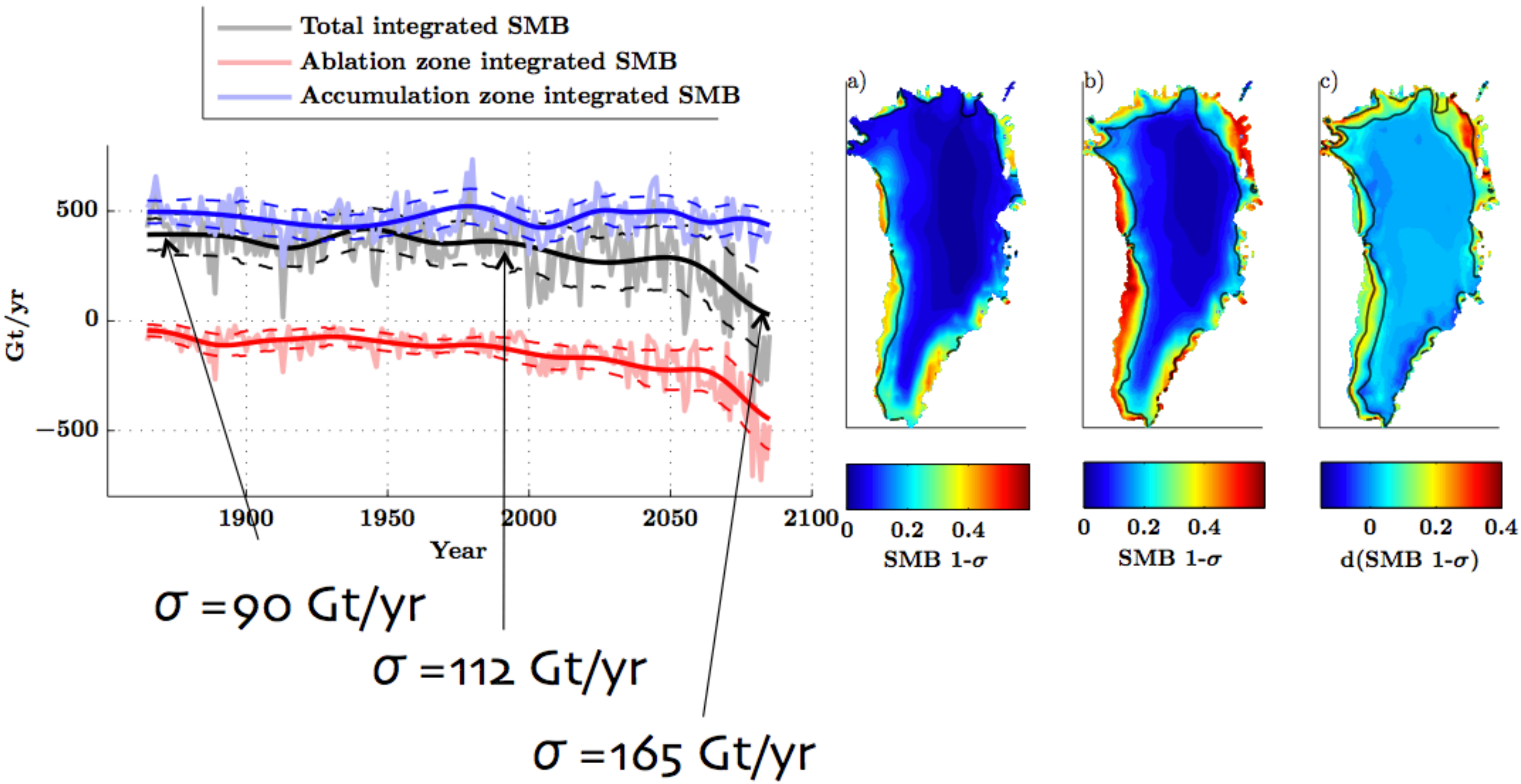
Preindustrial CISM GrIS steady-state perturbed-physics ensemble

Free-running ice sheet may differ from reality in a coupled climate model!



Lipscomb et al. 2013

Future GrIS SMB variability



Fyke et al. 2014b

Quantifying effects of Greenland freshwater fluxes to ocean

Lenaerts et al. (2015) *GRL*

Runoff and iceberg discharge projections (no ice sheet model)

↓

CESM

↓

Regional cooling due to slight AMOC weakening

FWF prescribed because no climate model could do this experiment!

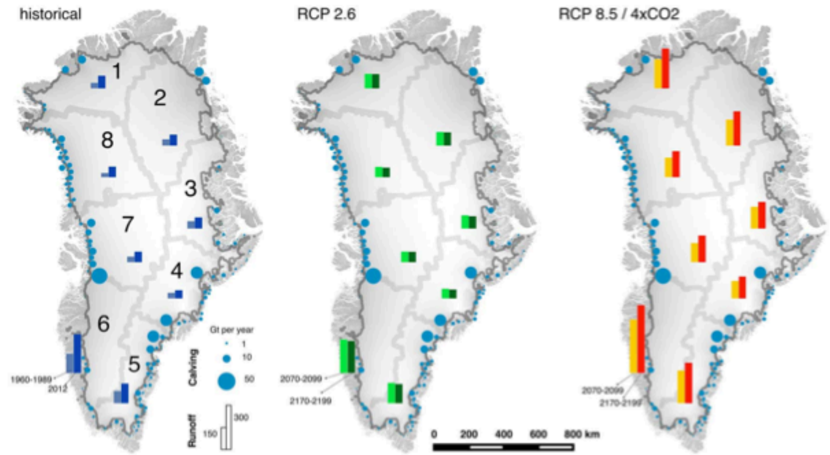


Figure 1. (left) Reconstruction and future evolution of GrIS runoff (bars) and glacier discharge (circles): (middle) RCP2.6 and (right) RCP8.5/4 × CO_2. The background on the maps shows the basin and ice sheet delineation (grey lines) and the Greenland continental extent derived from the Greenland Ice Mapping Project (GIMP) data set [*Howat et al.*, 2014].

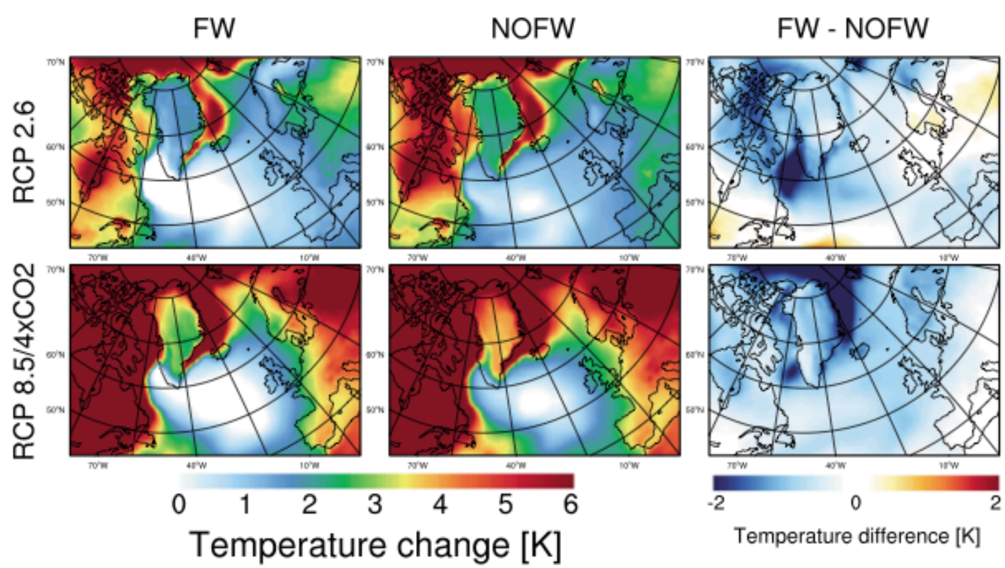


Figure 4. (left and middle columns) Two meter air temperature change (K) between 1960–1989 (period 1 in Figure 3a) and 2070–2099 (period 3 in Figure 3a) for the four future simulations and (right) the differences between FWF and NOFWF for both scenarios.

...but no ice sheet model, no coupling back to FWF.

CESM Land Ice Working Group

Leadership

- Co-chairs: Miren Vizcaino (Delft)
  William Lipscomb (Los Alamos), outgoing
  Jan Lenaerts (Utrecht, soon to be CU), incoming
- Science liaison: Jeremy Fyke (Los Alamos)
- Software liaison: William Sacks (NCAR)

LIWG info

- Web site: http://www.cesm.ucar.edu/working_groups/Land+Ice/
- Email list: http://mailman.cgd.ucar.edu/mailman/listinfo/ccsm-liwg

Meetings

winter (Boulder, CO)
June annual CESM meeting (Breckenridge, CO)

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- Biological and Environmental Research (BER)
- Advanced Scientific Computing Research (ASCR)
- Scientific Discovery through Advanced Computing (SciDAC; BER + ASCR)

Collaborative model development at:
DOE National Labs:
Los Alamos*, Berkeley, Oak Ridge, Sandia
Academic Institutions:
NCAR#, Florida State, MIT, South Carolina, Texas

* Steve Price, Bill Lipscomb, Matt Hoffman, Jeremy Fyke
# Bill Sacks

Community Ice Sheet Model

http://oceans11.lanl.gov/cism/

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