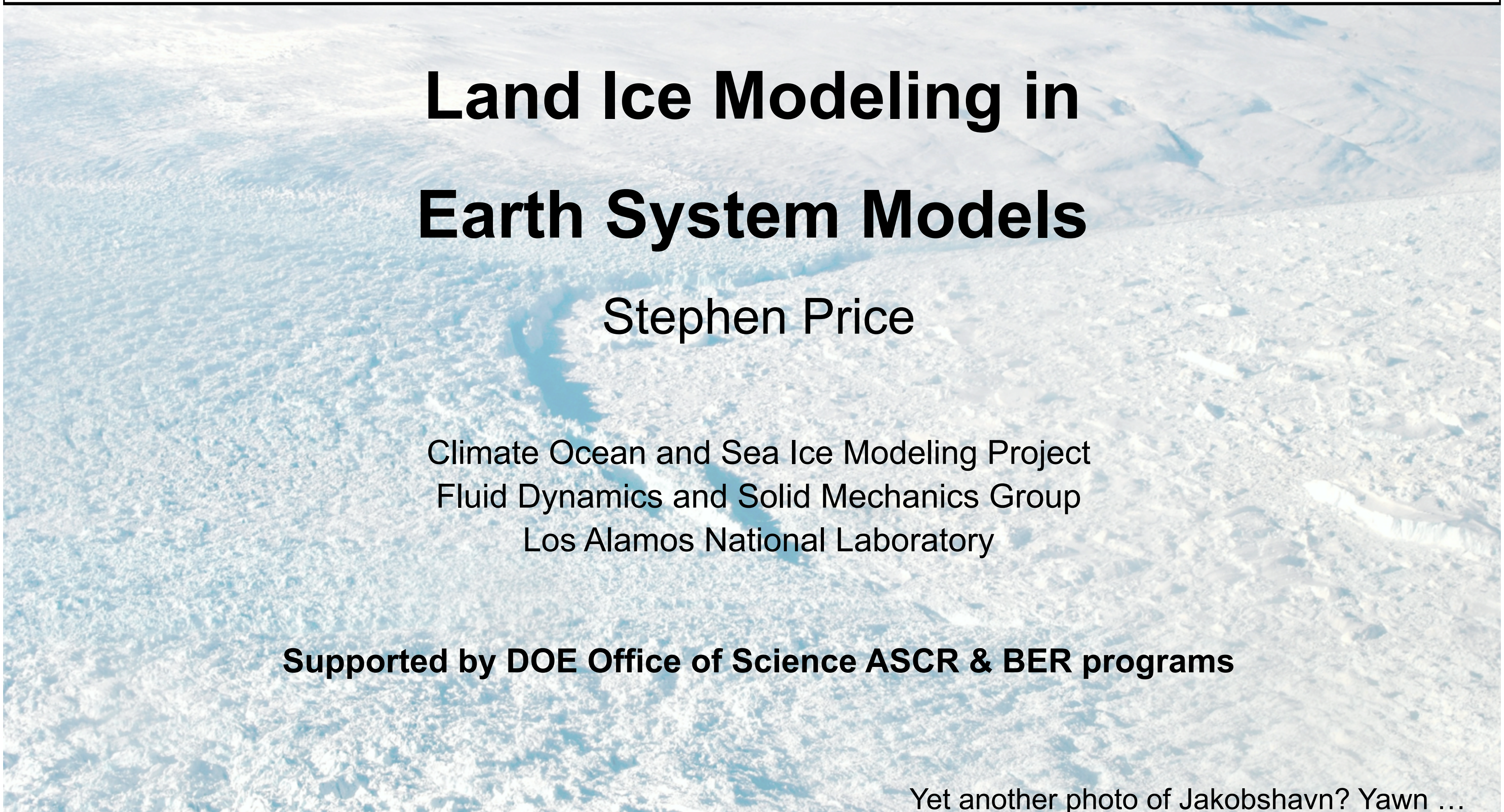


Land Ice Modeling in Earth System Models

Stephen Price

Climate Ocean and Sea Ice Modeling Project
Fluid Dynamics and Solid Mechanics Group
Los Alamos National Laboratory

Supported by DOE Office of Science ASCR & BER programs

Yet another photo of Jakobshavn? Yawn …

Los Alamos NATIONAL LABORATORY EST. 1943

U.S. DEPARTMENT OF ENERGY Office of Science

Climate, Ocean, and Sea Ice Modeling Project

presentation goals & caveats

ice sheet & atmos. / land model coupling

ice sheet & ocean model coupling

glacier & ice cap coupling to ESMs

coupled land ice & ESM initialization

summary

presentation goals & caveats

ice sheet & atmos. / land model coupling

ice sheet & ocean model coupling

glacier & ice cap coupling to ESMs

coupled land ice & ESM initialization

summary

Goals & Caveats

- provide overview of challenges associated with, and state of, efforts to couple models of land ice with Earth Systems Models (ESMs)

Goals & Caveats

- provide overview of challenges associated with, and state of, efforts to couple models of land ice with Earth Systems Models (ESM)

- … or, how do large-scale, (ideally) predictive ESM capabilities square with the discussions this week?

*“Have you coupled processes **X** and **Y**?”*

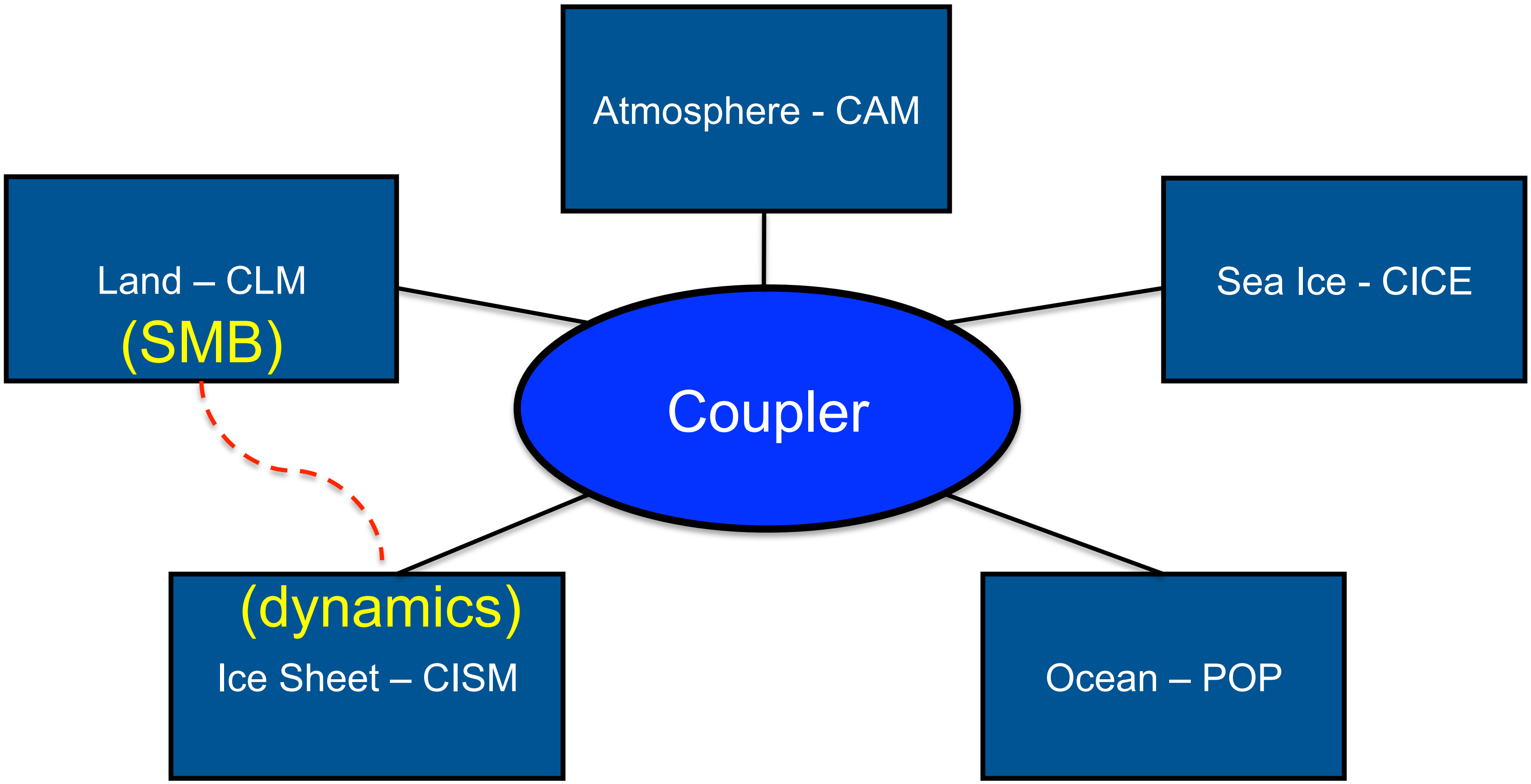
Goals & Caveats

- Caveats:
  - perspective is largely through past 5 yrs of work on coupling land ice models to the Community Earth System Model (CESM)
  - related efforts with similar and different challenges (and successes) are ongoing elsewhere (e.g., GFDL, NASA GISS/GSFC, various in U.K. and E.U.)
  - Many things are covered in passing or not at all (e.g. calving, melange, sea ice)

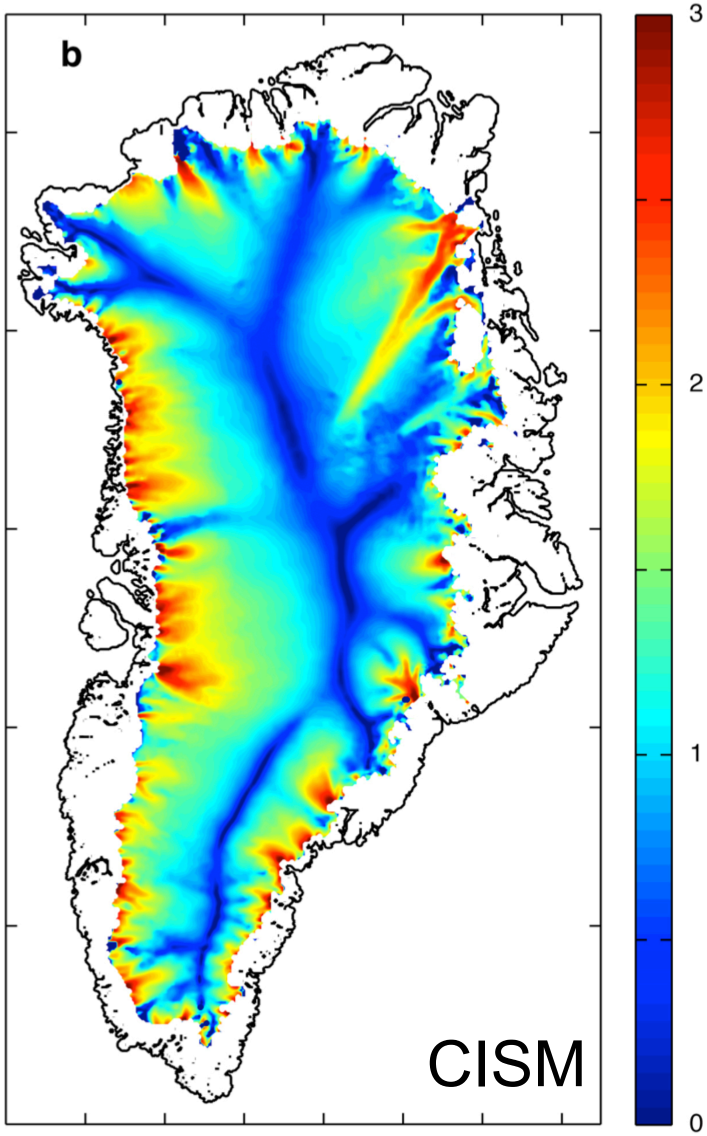
Community Earth System Model

- CESM consists (largely) of:
  - Atmosphere model (CAM)
  - Land model (CLM)
  - Ocean model (POP)
  - Sea ice model (CICE)
  - Land ice model(s) (CISM)

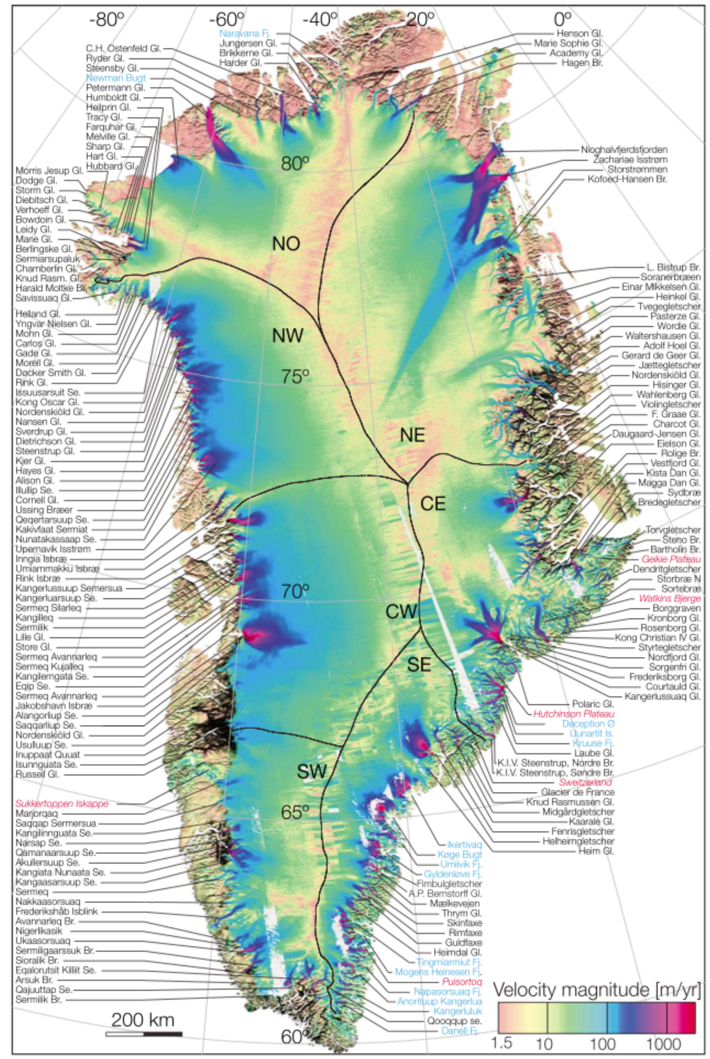
CESM Component Coupling:
Hub (coupler) and Spokes (component models)



Greenland: Models vs. Observations

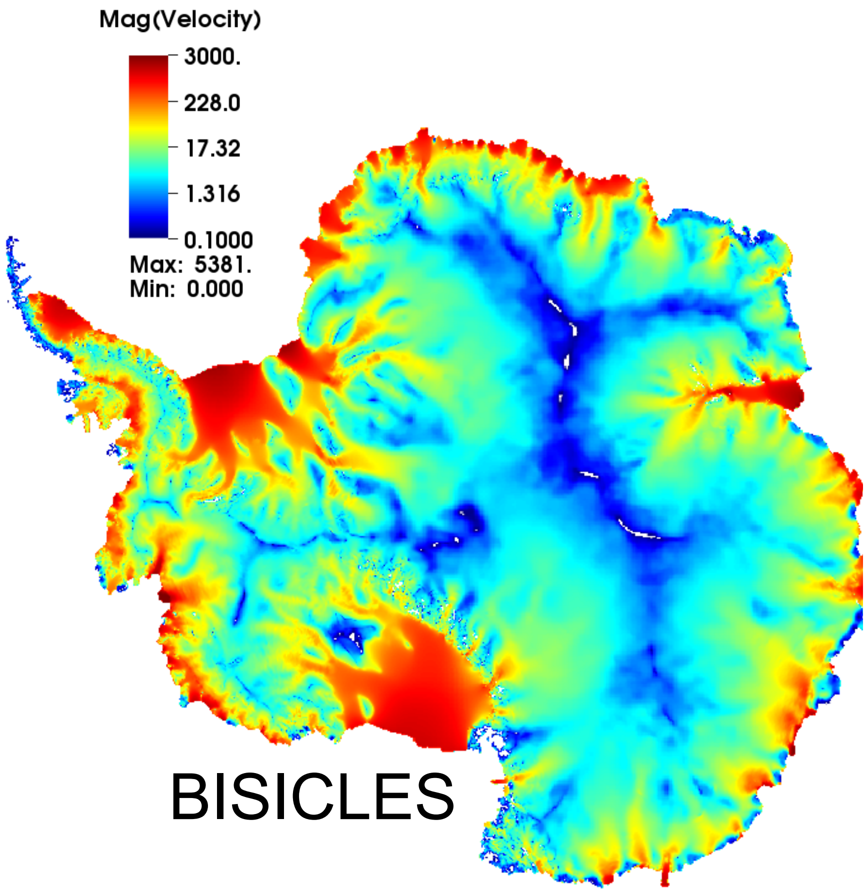


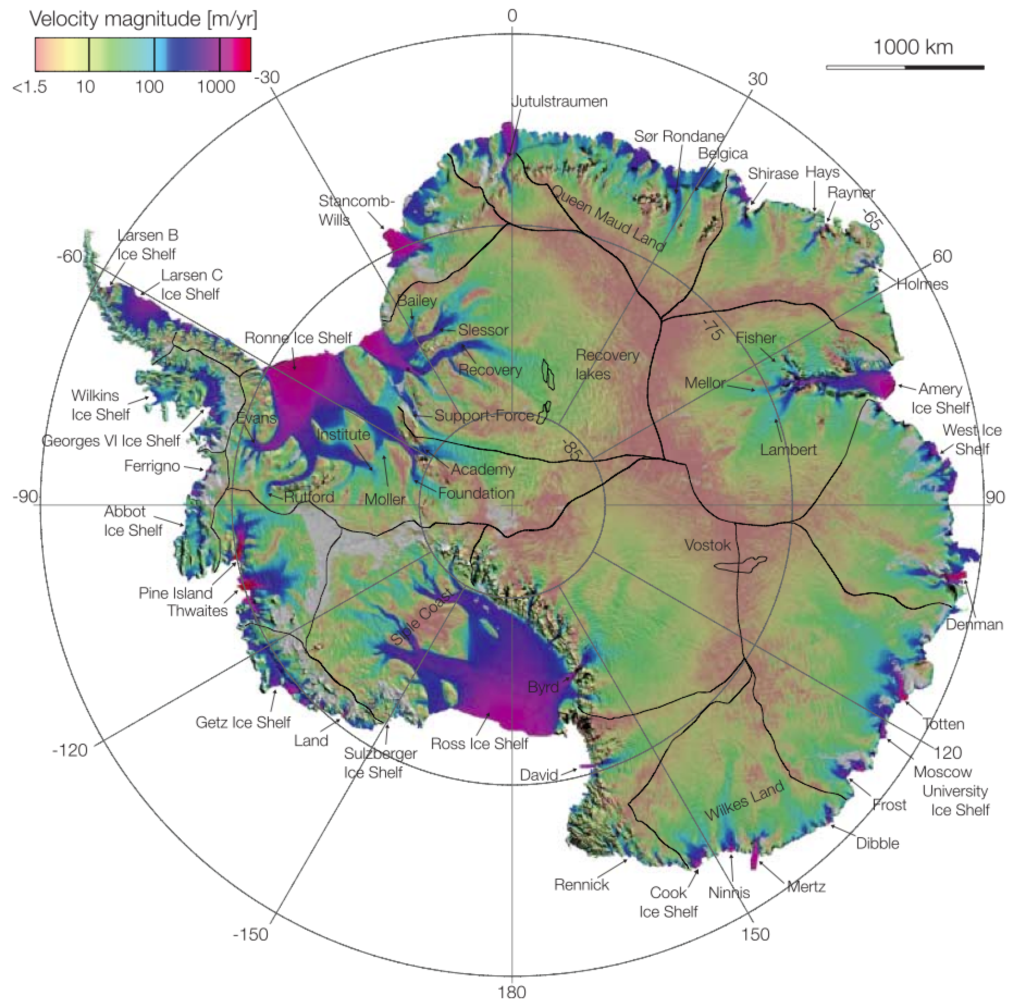
Price et al. (*PNAS*, **108**(22), 2011)



Rignot & Mouginot, *GRL*, **39** (2012)

Antarctica: Models vs. Observations





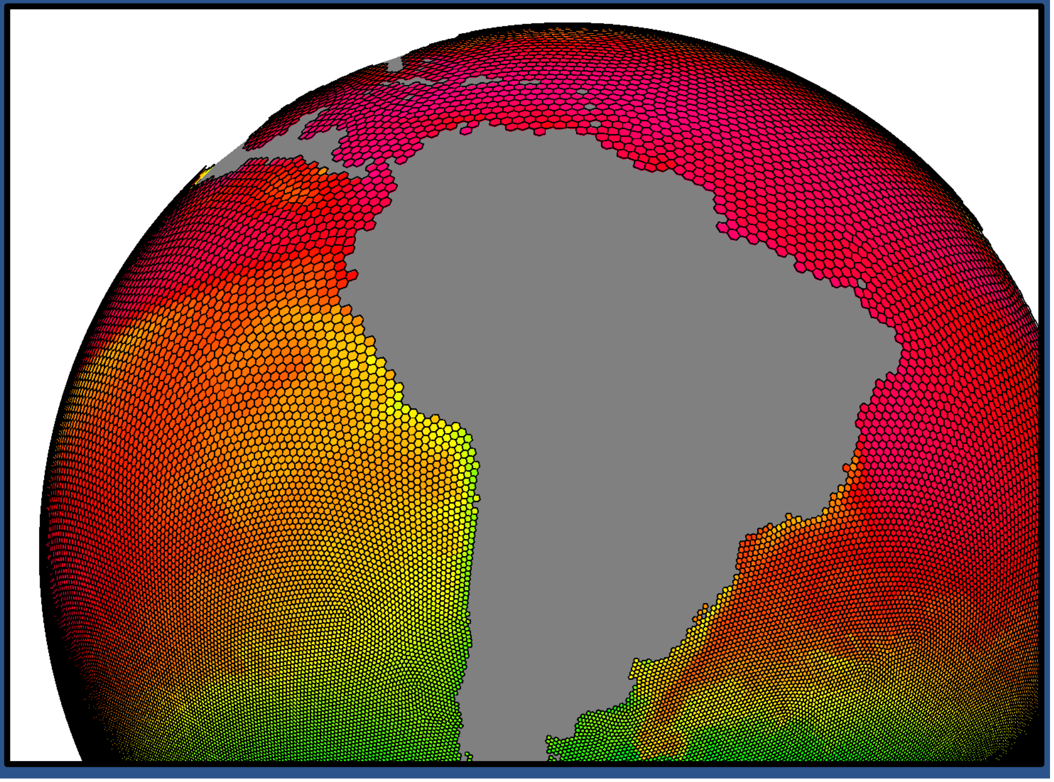
(courtesy of D. Martin & S. Cornford)

Rignot et al., *Science*, **333** (2011)

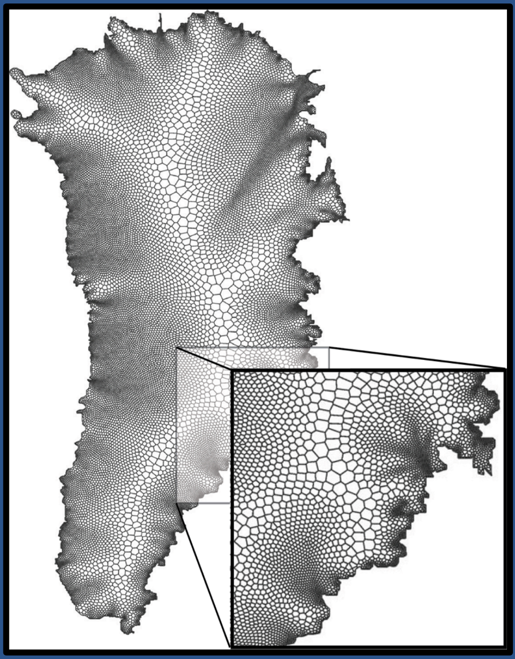
Model for Prediction Across Scales (MPAS)

- Spherical Centroidal Voronoi Tesselations (SCVT); unstructured mesh framework for var. res. climate model components
- Atmos., ocean, land, sea ice & ice sheet components under devel.
- Enhance grid using arbitrary density function
- Shared framework (LANL-NCAR M^3)
- Beta release (ocean) this year

var. res. global mesh:
120 - 30 km in S. Ocean



var. res. Greenland ice sheet mesh: 65 - 2 km



presentation goals & caveats

ice sheet & atmos. / land model coupling

ice sheet & ocean model coupling

glacier & ice cap coupling to ESMs

coupled land ice & ESM initialization

summary

Ice Sheet & Atmos. / Land Coupling

Important processes & feedbacks to capture

1) Conservation of energy & mass (heat & moisture fluxes)

   a) Freshwater flux betweeen ice sheet & ocean (SMB)

2) Impact of changing ice sheet geometry on:

   a) SMB – “free” using standard SMB downscaling schemes[1] (~5-10%)

   b) Atmos. circulation – “difficult”; currently requires restart of atmos. model using new (filtered?) surface topog[2] (~5-10%)

   c) Albedo – conceptually simple using “dynamic land units” (changing land types in time), but not standard in large-scale ESMs (?)

[1] Edwards et al., TCD, 2013a, 2013b (*Ice2Sea*) [2] J. Fyke / M. Vizcaino (pers. comm.)

Ice Sheet & Atmos. / Land Coupling

Important processes & feedbacks to capture

1) Conservation of energy & mass (heat & moisture fluxes)
   a) Freshwater flux betweeen ice sheet & ocean (SMB)
2) Impact of changing ice sheet geometry on:
   a) SMB – “free” using standard SMB downscaling schemes
   b) Atmos. circulation – “difficult”; currently requires restart of atmos. model using new (filtered?) surface topog.
   c) Albedo – conceptually simple using “dynamic land units” (changing land types in time), but not standard in large-scale ESMs

Importance to GRISO:

1. SMB is 0-order control on ice sheet geom. & vel. (& more so in future when margin does not contact ocean?)
2. SMB is 0-order control on GIS freshwater flux to ocean (important for fjord circulation & transfer of heat from ocean to fjords)

SMB Downscaling

Use snowpack & energy balance model (EBM) in land model (CLM)

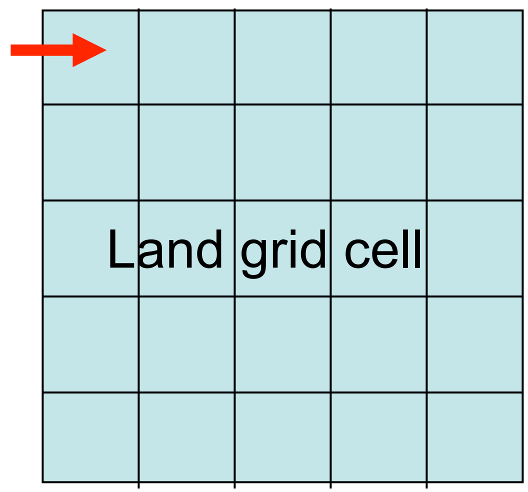
Precipitation on coarse atmos grid (~100 km) downscaled to fine (<=5km) ice sheet grid using lapse rate and hi-res DEM

Compute SMB in ~10 elevation classes from hi-res grid

- Avoid code duplication
- Better than PDD scheme (e.g., energetic consistency)
- Cost savings (~1/10 as many columns)
- “Dynamic land units” (in devel) – allow for albedo feedbacks

SMB Downscaling

Ice sheet grid cell (5 x 5 km)



(100 x 100 km)

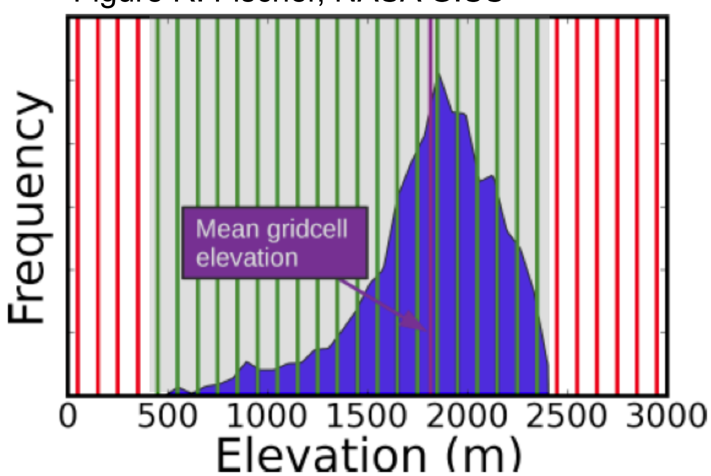
Ice sheet → Land (10 classes)

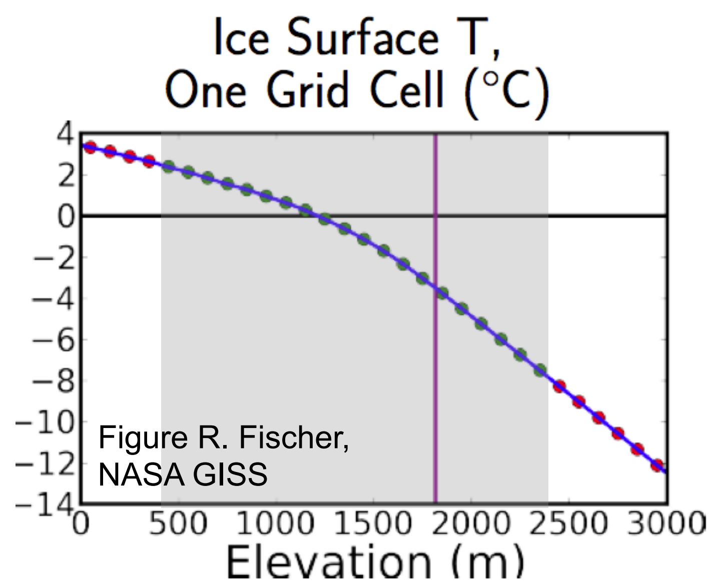
- Ice fraction and elevation
- Runoff and calving fluxes
- Heat flux to surface

Land → Ice sheet (10 classes)

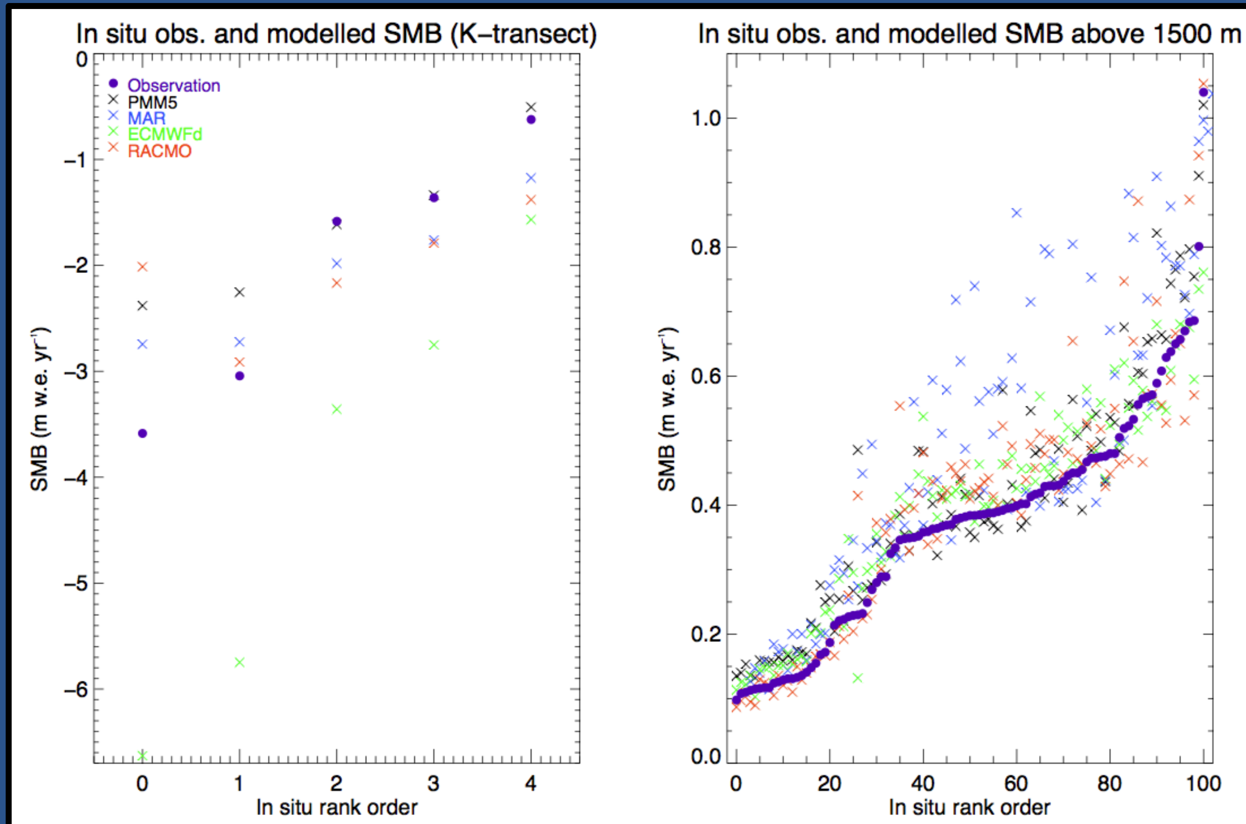
- Surface mass balance
- Surface elevation
- Surface temperature

Figure R. Fischer, NASA GISS

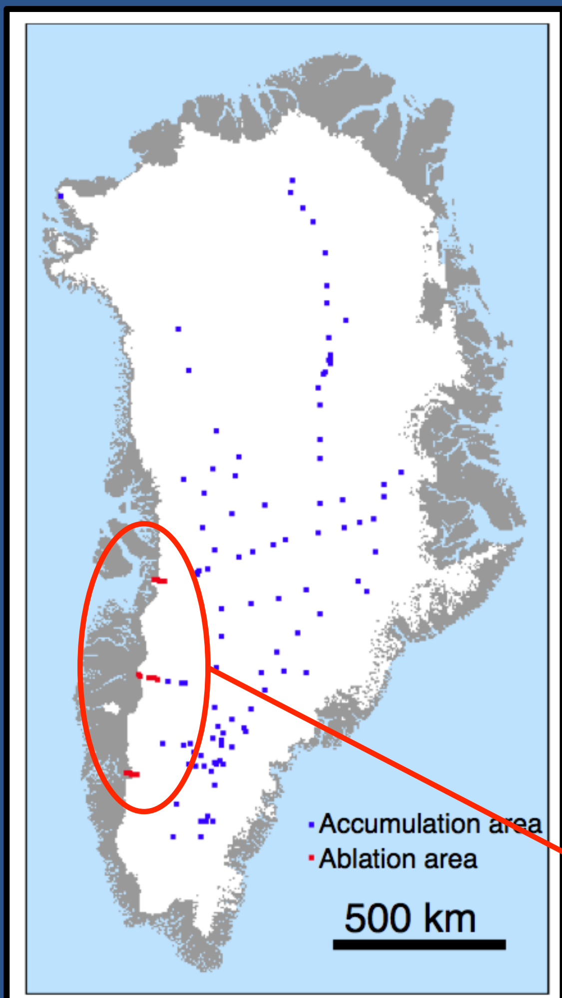




Surface Mass Balance Models



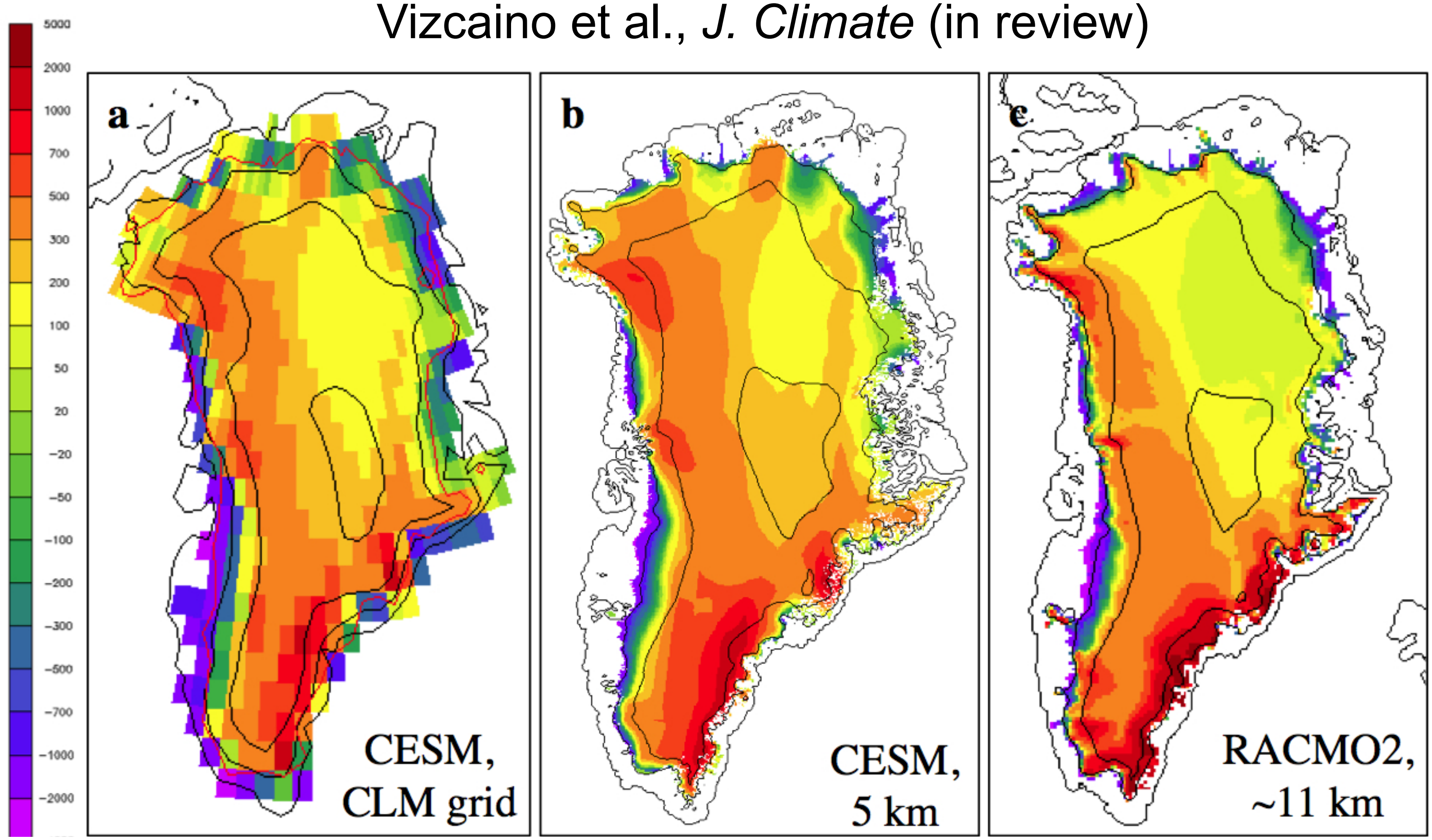
Vernon et al., *TC*, **7** (2013)



Note relative lack of observations in ablation zone

CESM vs. RACMO SMB (5 km res)

Vizcaino et al., *J. Climate* (in review)

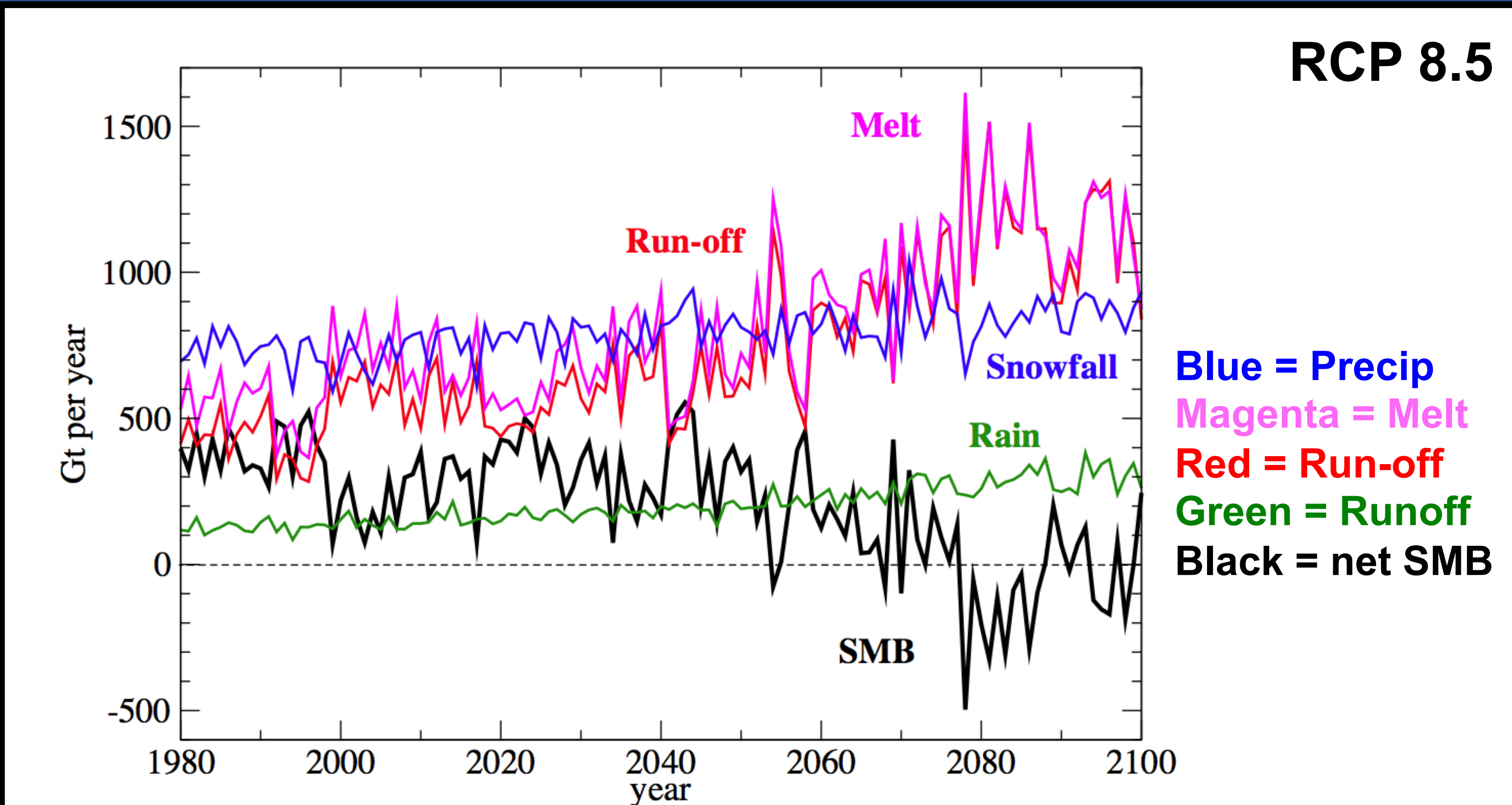


Take RACMO as the “true” SMB

Current downscaling scheme gives reasonable comparison

Underestimation of accum. in steep coastal regions

CESM SMB (Gt/yr): 1980-2100



Vizcaino et al., *J. Climate* (in review)

- Precipitation increases slightly over time
- Melt and runoff increase more
- SMB is persistently <= 0 after ~2070

Ice Sheet & Atmos. / Land Coupling

Missing / poorly captured / in need of improvement:

1) 2-way coupling (geom. effect on atmos.) non-standard and clunky (offline filtering / creating of new topog; restarts)

2) Precip. downscaling non-standard (is it feasible at all?)

3) Downscaling scheme does not capture important orographic effects (in reality, not all cells at same elev. will have same SMB)

4) Coupling of land ice liquid / solid freshwater flux to ocean non-standard

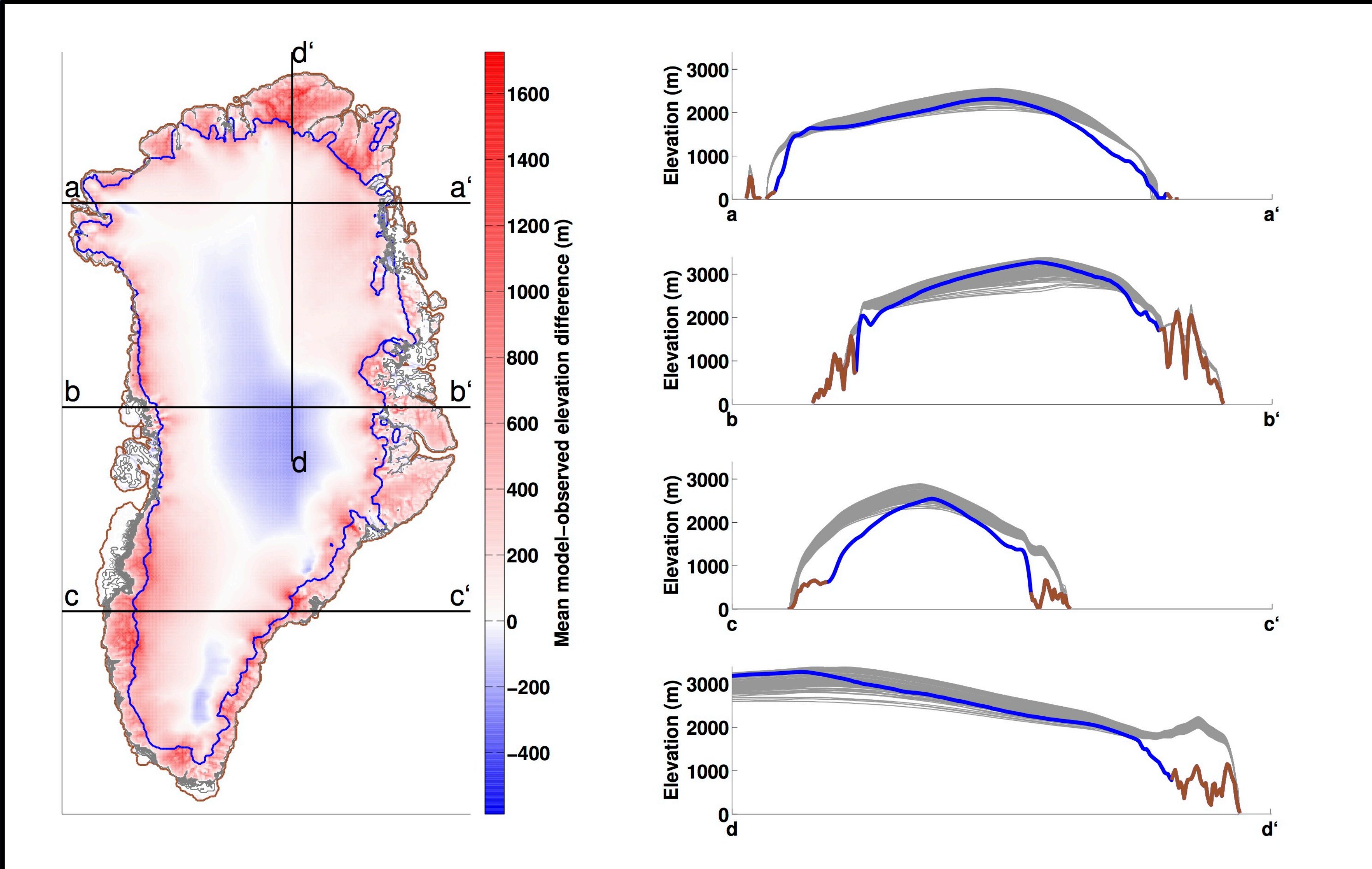
5) Subglacial hydrology models non-standard (incorrect location & lagging of melt water input to ocean); Supra- & en-glacial models non-standard

6) Albedo effects from changing land types non-standard ("dynamic land units", snow/ice → rock))

7) SMB biases, difficult to diagnose & remove, can cause very large biases in land ice geometry & evolution

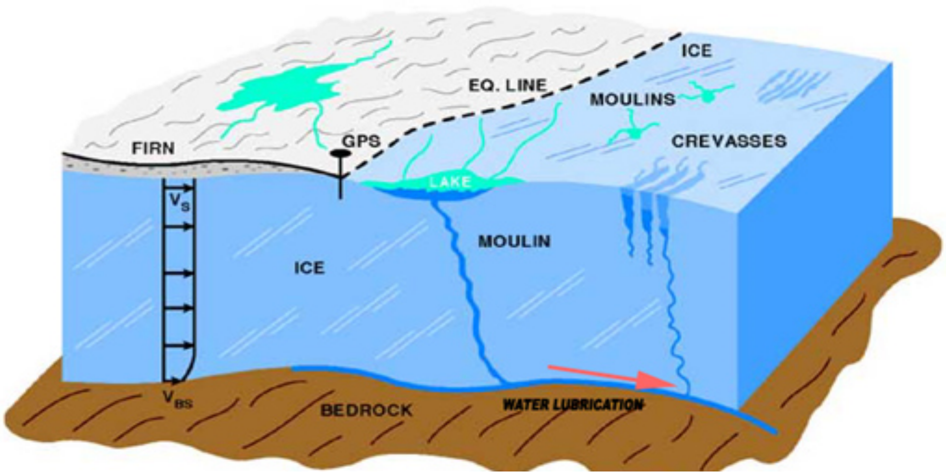
Many of these are currently being tackled (1,4,5,6,7) &/or become less important w/ hi-res (var-res) models (2,3,7?)

SMB Biases: CISM-CESM GIS Initial Condition



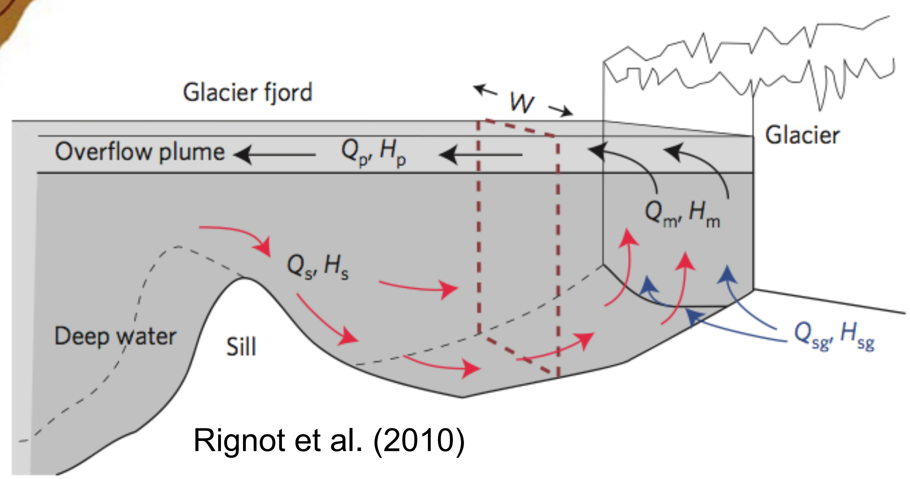
Subglacial Hydrology
(simplistic, big picture)

Subglacial hydrology is a strong control on basal sliding (& thus ice discharge to ocean)



Zwally et al. (2002)

Subglacial hydrology is important to circulation within Greenland fjords



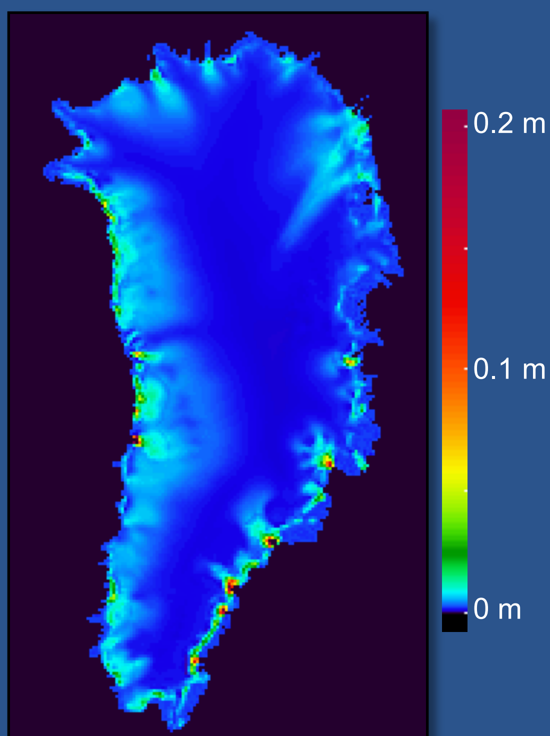
Rignot et al. (2010)

Evolutionary Subglacial Hydrology in CISM

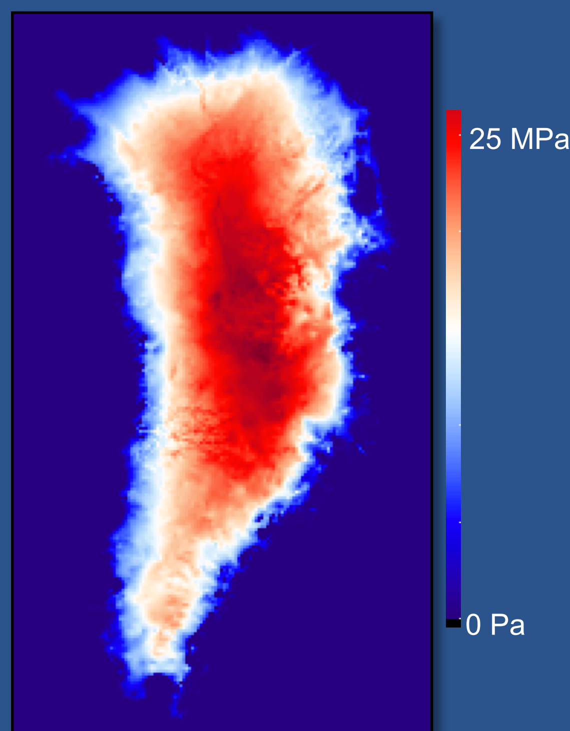
Conservative, 2d, time-dependent subglacial hydrology model, containing both distributed (macroporous film) and channelized elements[1]

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

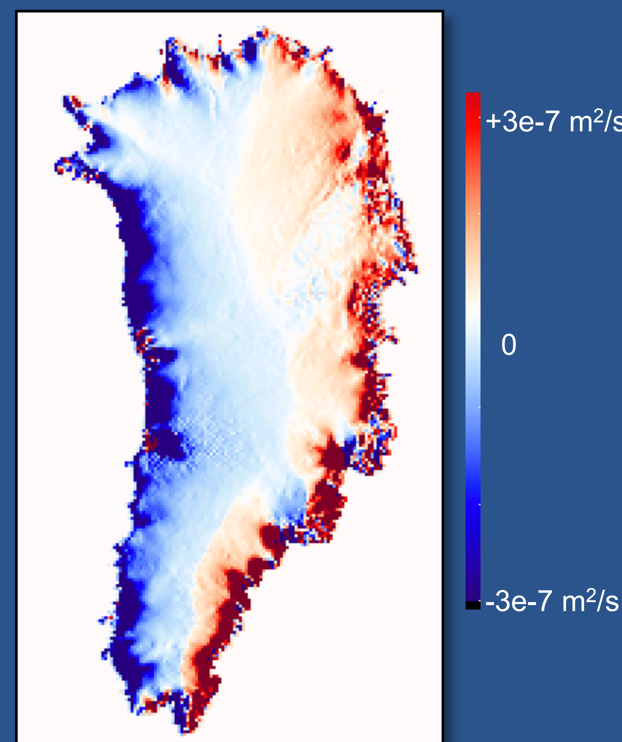
Basal water thickness



Water pressure



Water flux (x dir.)



[1]Hoffman et al., AGU 2012 (after Creyts, Flowers, Hewitt, Schoof, Werder) [2]Schoof, 2005 [3]Iverson, 2011

presentation goals & caveats

ice sheet & atmos. / land model coupling

ice sheet & ocean model coupling

glacier & ice cap coupling to ESMs

coupled land ice & ESM initialization

summary

Ice Sheet & Ocean Coupling

Important processes & feedbacks to capture

1) Conservation of energy & mass between ice sheet & ocean
   a) solid / liquid water & sensible / latent heat fluxes TO ocean
   b) solid / liquid water & sensible / latent heat fluxes FROM ocean
2) Atmos. & ocean coupling
   a) Warm / cool / moisture laden air mass advection to GIS
3) Freshwater effects on (local & regional) ocean circulation
4) Formation, advection, melting of sea ice (orphaned here)
5) Changes in sea level (eustatic + steric + circulation)

Ice Sheet & Ocean Coupling

Important processes & feedbacks to capture

1) Conservation of energy & mass between ice sheet & ocean
   a) solid / liquid water & sensible / latent heat fluxes TO ocean
   b) solid / liquid water & sensible / latent heat fluxes FROM ocean
2) Atmos. & ocean coupling
   a) Warm / cool / moisture laden air mass advection to GIS
3) Freshwater effects on (local & regional) ocean circulation
4) Formation, advection, melting of sea ice
5) Changes in sea level (eustatic + steric + circulation)

Importance to GRISO:

1. Ocean heat content affect on marine outlet dynamics
2. Freshwater flux affecting local (fjord) and regional ocean circulation (& sea ice formation?)

Ice Sheet & Ocean Coupling: Implementation

Ice Sheet Model: fairly trivial code alterations

Ocean Model (POP):

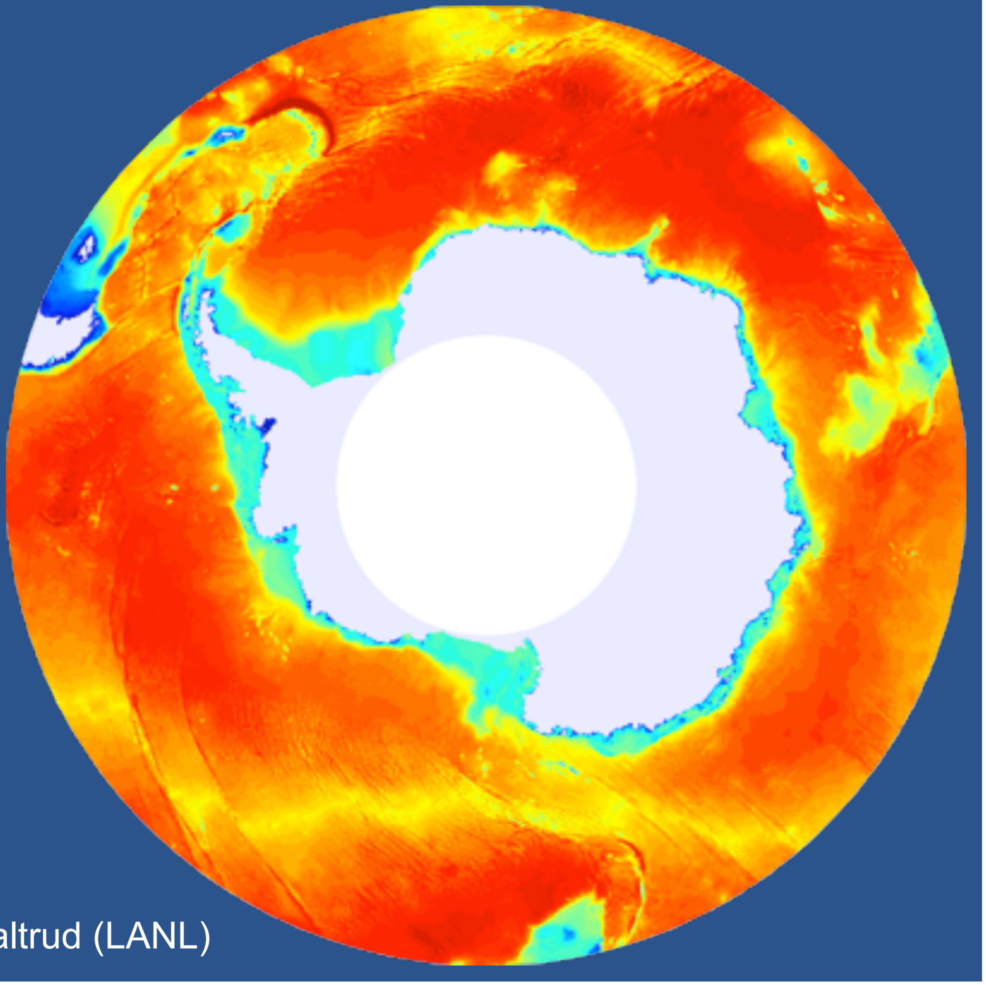
- 3d, primitive equations on the sphere, **hydrostat**. & Boussinesqe approx.
- Eularian grid in vert., depth as vert. coord. (“z coord.”)
- Fixed volume: mean sea-level = fixed!
- Many tedious & fiddly changes for sub-shelf circulation

Ocean Model (MPAS)

- Largely the same equations
- ALE, z* vert. coord., pressure forcing at sfc
- NOT fixed volume
- Sub-shelf circulation apparently trivial (so far)

New Ocean Model Grid

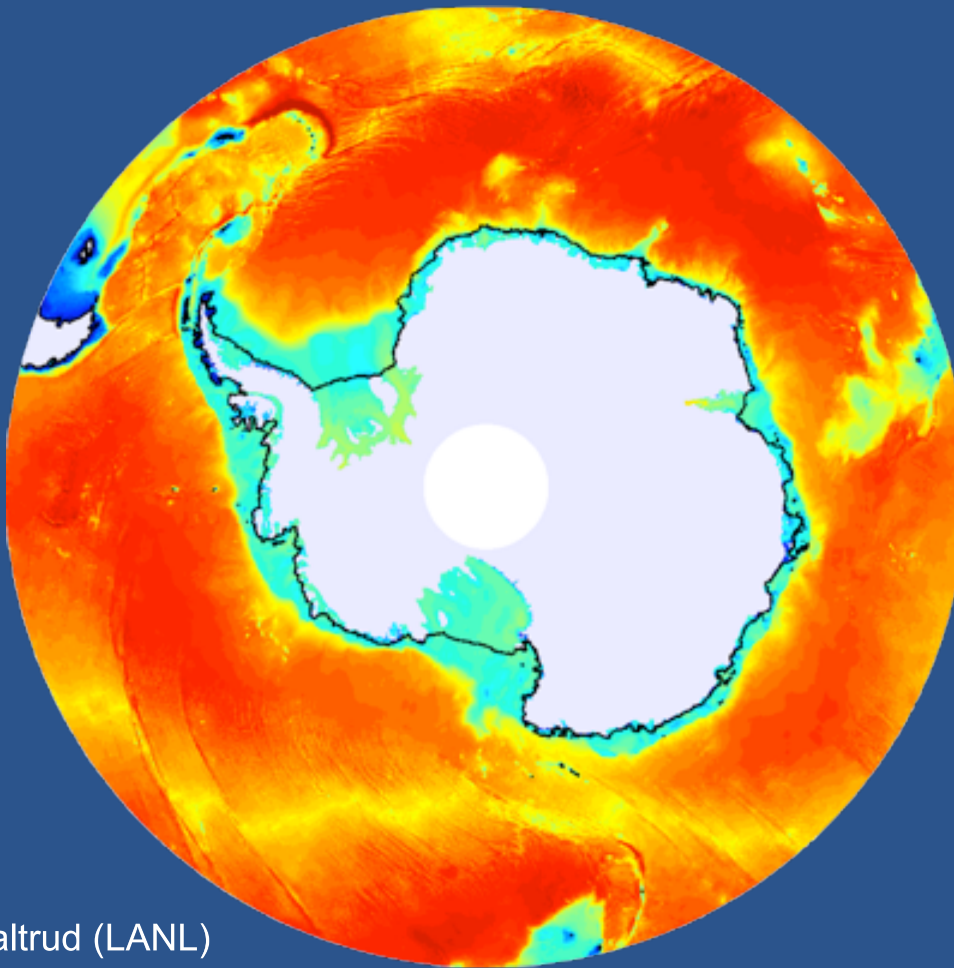
- Existing POP grid: No cavities under ice shelves



Figures courtesy of X. Asay-Davis (LANL / PIK) & M. Maltrud (LANL)

New Ocean Model Grid

- Existing POP grid: No cavities under ice shelves
- New POP grid: Ice shelves replace by open ocean
- Bathymetry from RTOPO-1 data set (Timmermann et al. 2010)



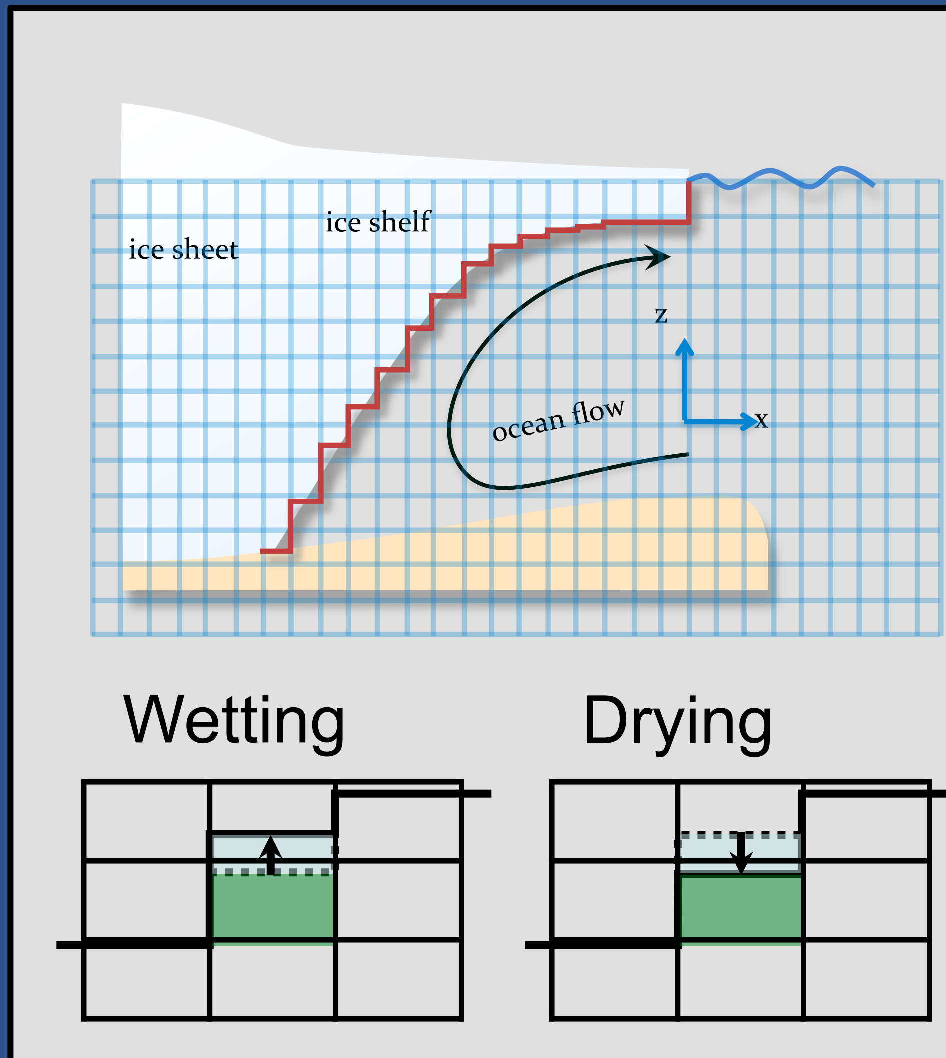
Figures courtesy of X. Asay-Davis (LANL / PIK) & M. Maltrud (LANL)

Coupling Ice Sheet Model to Ocean Model

Current - Partial Cells Method

- Interface represented by a stair-step & “partial top cells”
- Vertical (but not horizontal) heat and freshwater fluxes at interface ($L >> H$)
- Moving interface means that grid cells are added or removed from the ocean over time (“wetting”/ “drying”)

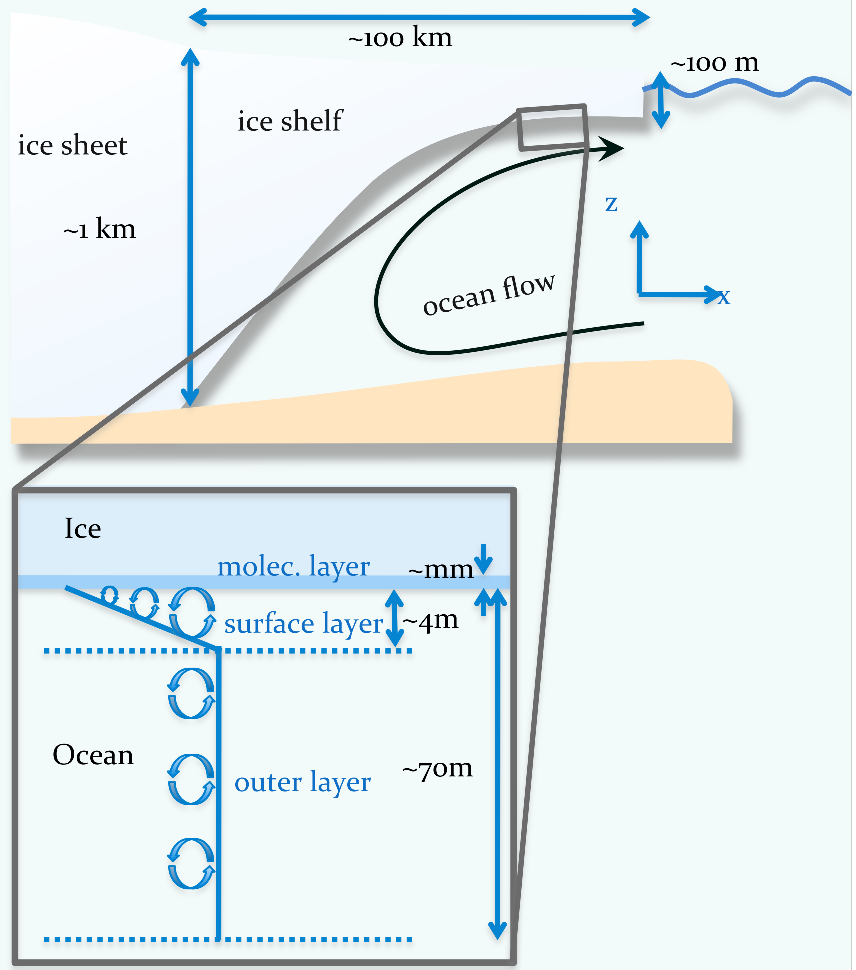
Future – Immersed Bndry Method (maybe)



Figures courtesy of X. Asay-Davis (LANL / PIK)

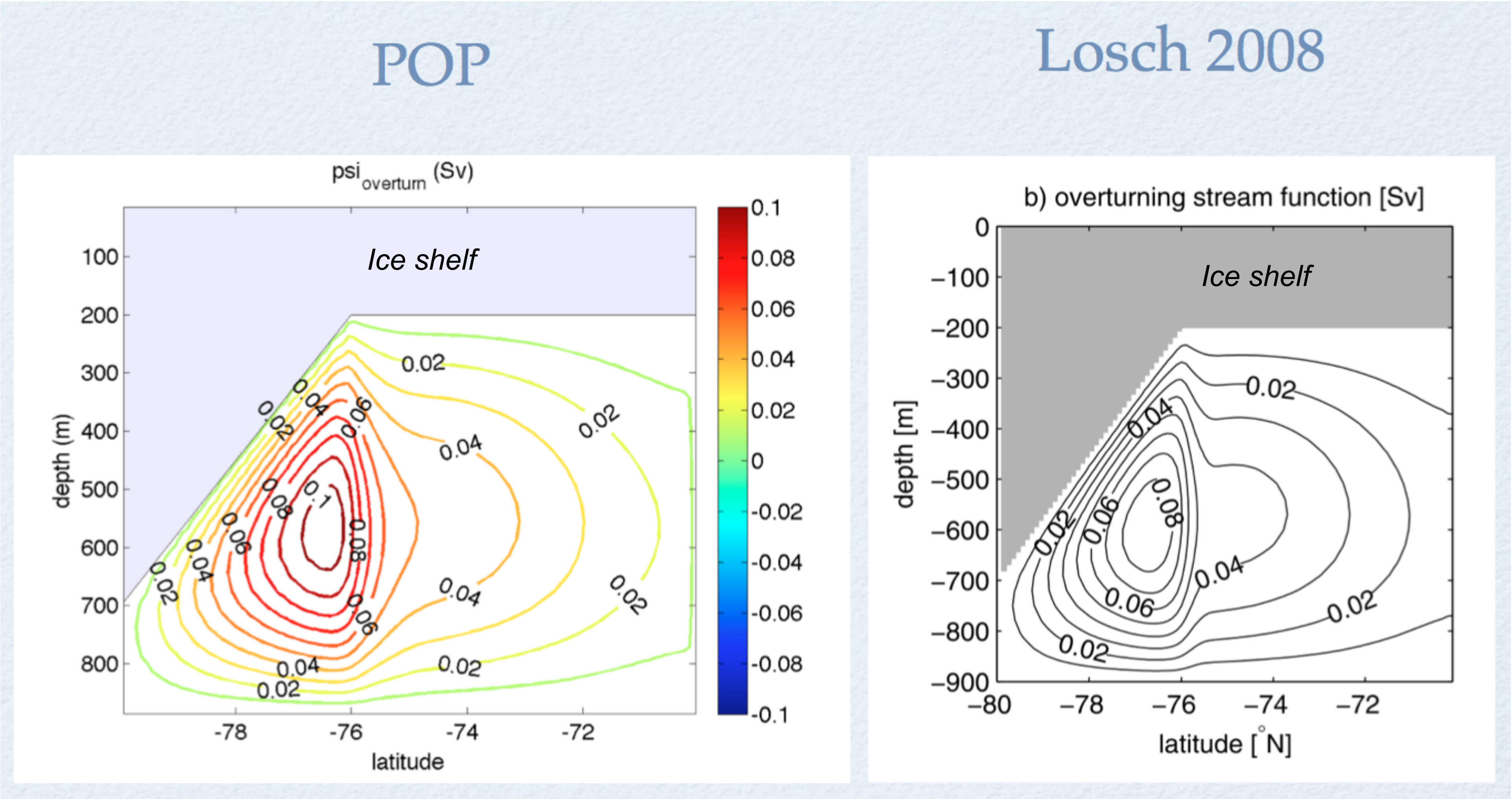
Boundary Layer Physics
heat, salt, momentum and mass transport

- *few* observations under ice shelves
- use boundary layer theory validated for **sea ice** (McPhee 2008)
- includes stabilizing effect of **stratification**, very important for rapid melting
- Implemented in POP, not yet in MPAS-Ocean



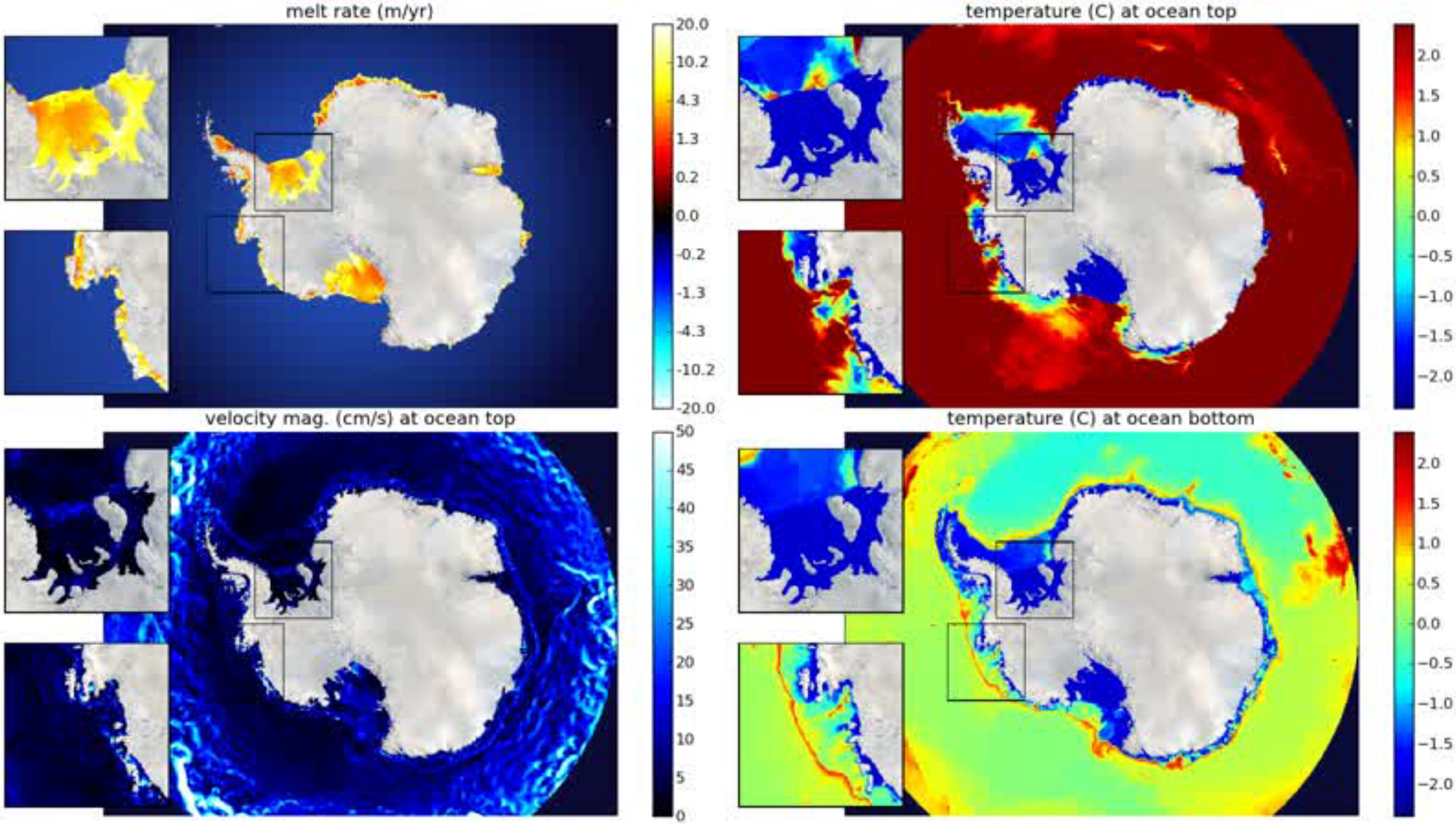
Slide courtesy of Xylar Asay-Davis (LANL / PIK)

Coupling CISM to ocean circulation model



Figures courtesy of X. Asay-Davis (LANL / PIK)

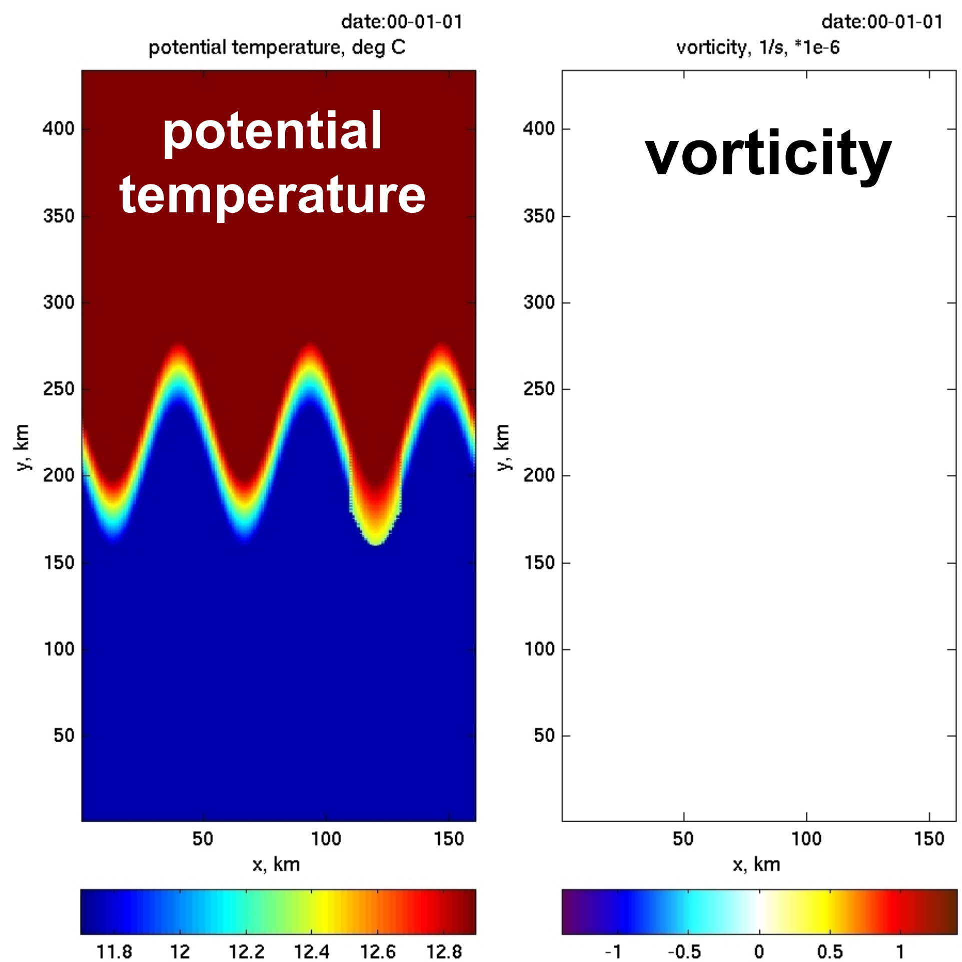
Ice-Ocean Coupling: Antarctica / S. Ocean Simulation

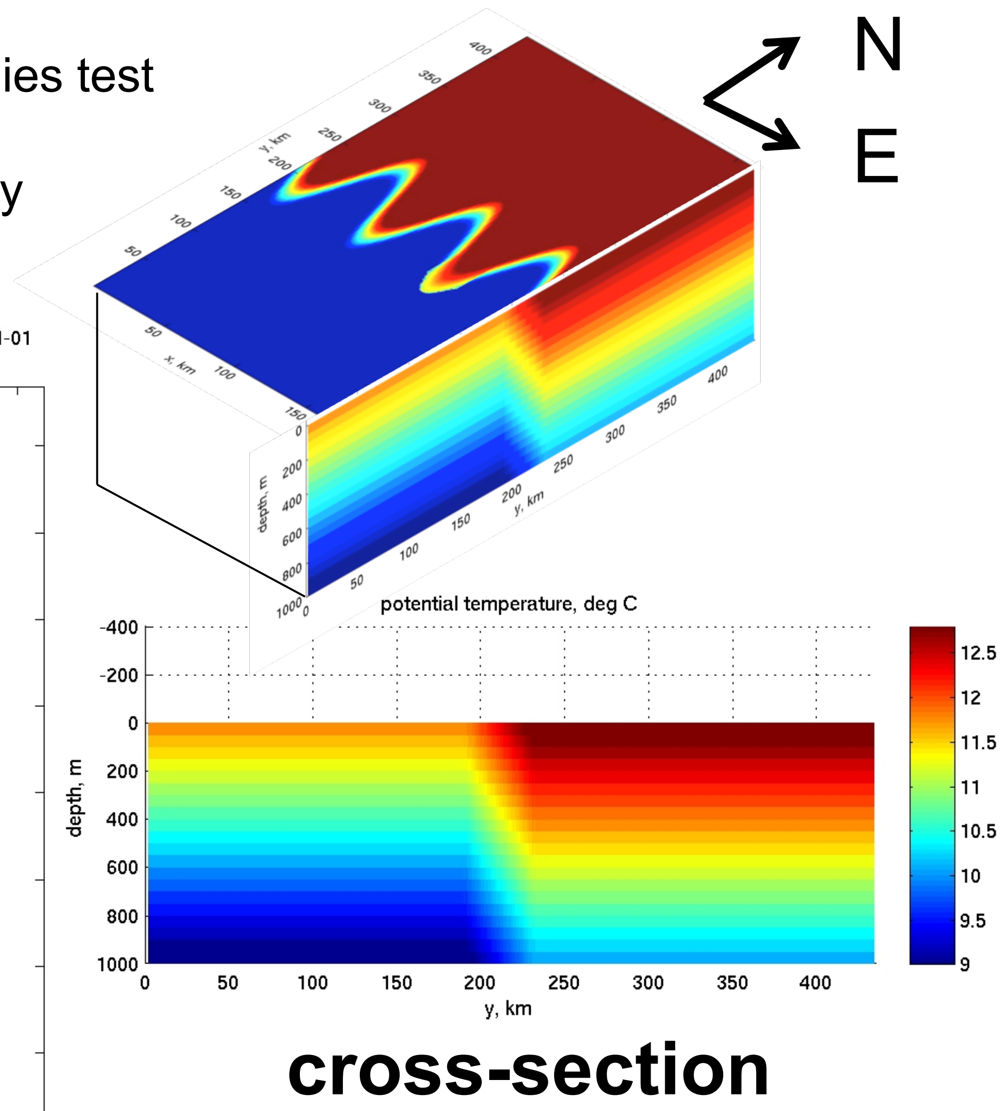


Simulations and figures courtesy of X. Asay-Davis (LANL / PIK)

MPAS-Ocean: Ice Shelf & Ocean Coupling

- Test domain: Baroclinic instab. / eddies test case from Ilicak et al. 2012.
  1 km res. grid, 20 50m layers, zonally periodic

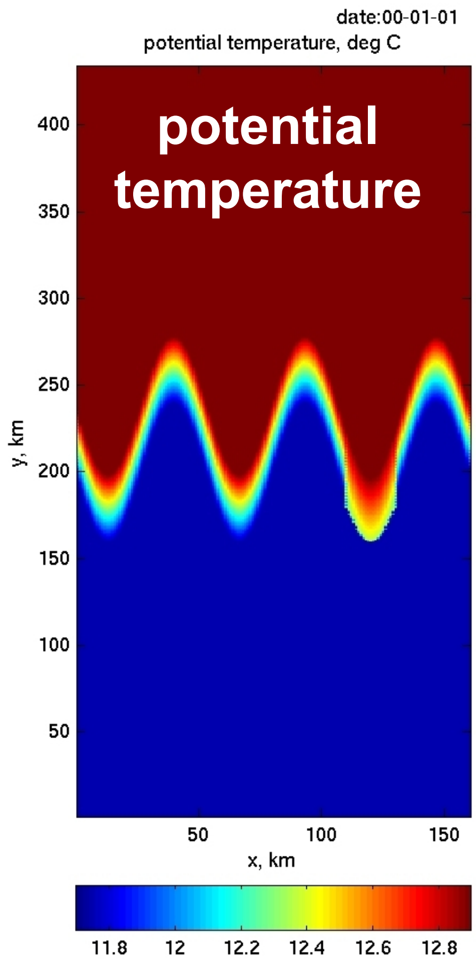


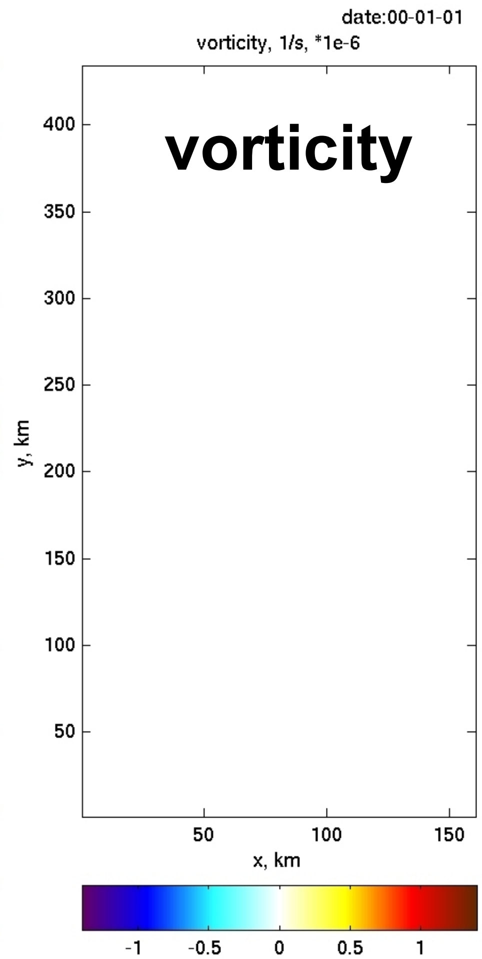


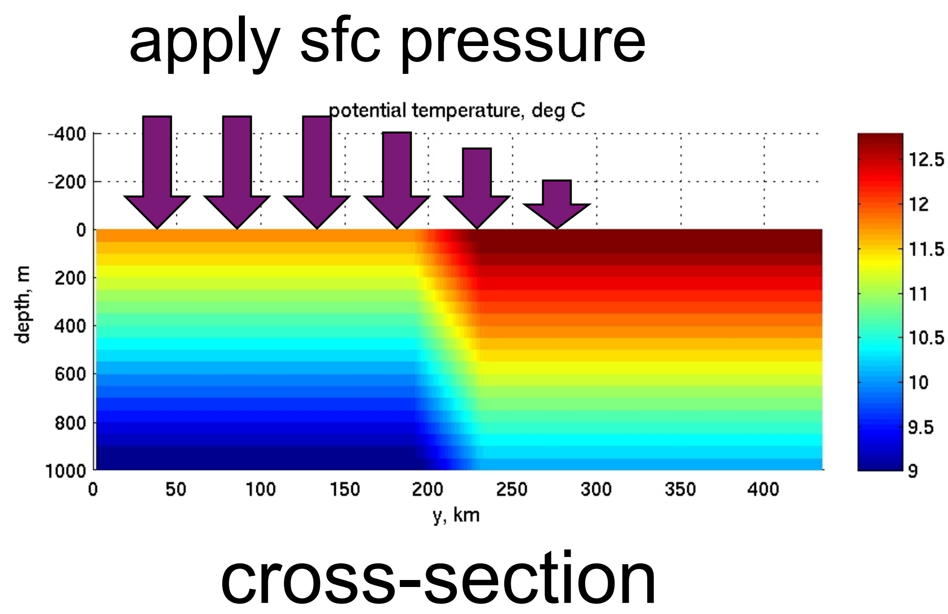
Slide courtesy of Mark Petersen (LANL)

MPAS-Ocean: Ice Shelf & Ocean Coupling

- Apply surface pressure, increasing in time, to southern portion.
- Vertical coordinate is z*; all layers compress proportionally.
- This is meant as a proof of concept to test robustness of the vertical coordinate, and not as a realistic land ice test.



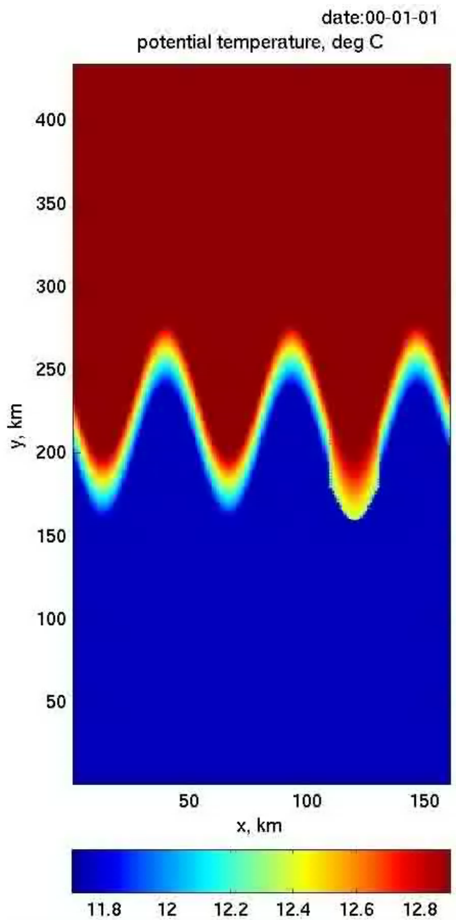


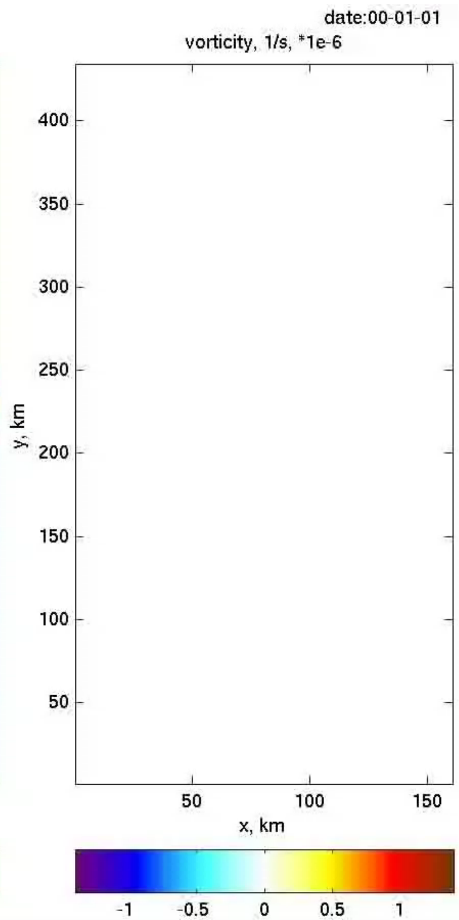


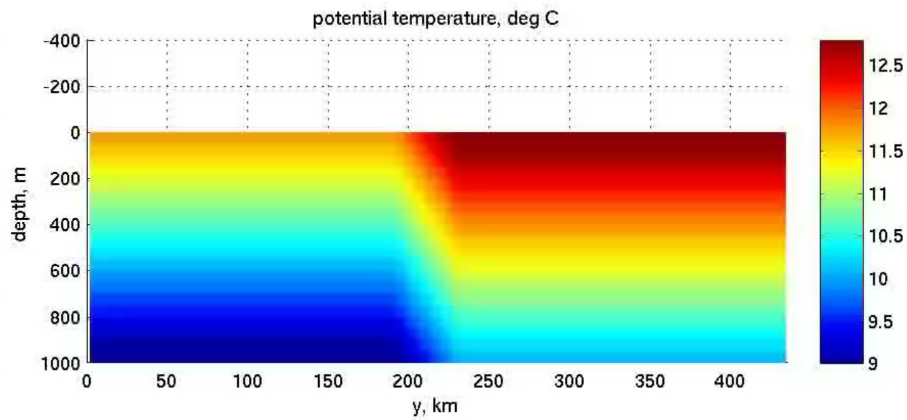
Slide courtesy of Mark Petersen (LANL)

MPAS-Ocean: Ice Shelf & Ocean Coupling

- Apply surface pressure, increasing in time, to southern portion.
- Vertical coordinate is ALE, so all layers compress proportionally.
- This is meant as a proof of concept to test robustness of the vertical coordinate, and not as a realistic land ice test.







Slide courtesy of Mark Petersen (LANL)

Ice Sheet & Ocean Coupling

Missing / poorly captured / in need of improvement:

1) Hydrostatic models adequate? New mixing params. to go from non-hydrostatic fjord models to global-scale ocean models?

2) Adequate understanding / treatment of boundary layer physics?

3) Fjord / outlet resolution in ice sheet and ocean models: var. / hi-res. ocean models require "scale aware" parameters

4) Hi-res. models require hi-res. ice thickness and bathymetry (extreme outlet gl. sensitivity to small unc. in geom., e.g. E. Enderlin work)

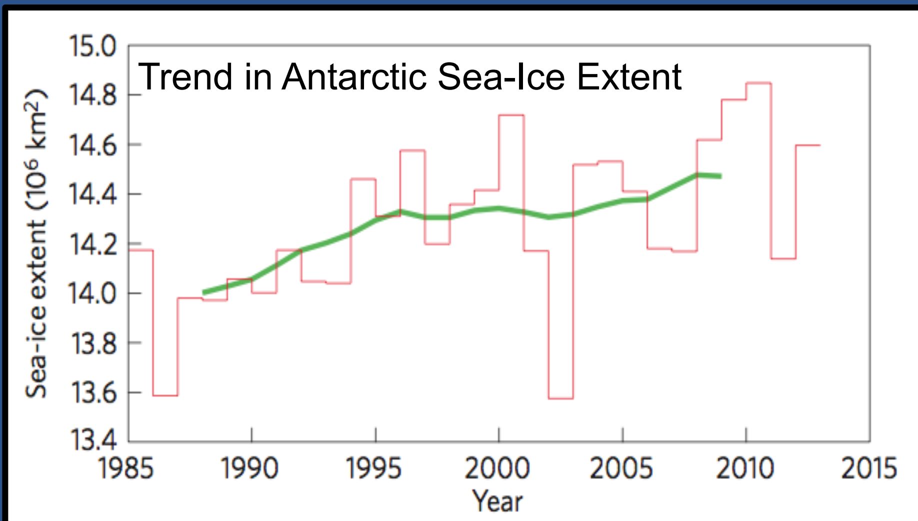
5) For low-res, global models, large marginal fresh-water inputs can lead to negative salinities – fixed by going to hi-res?

6) Need more obs for validation of modeled submarine melt

7) Icebergs: 50% and 99% of freshwater flux to oceans in GIS and Ant., respectively. Thermodynamic and mechanical effects currently ignored in most ocean / sea-ice models.

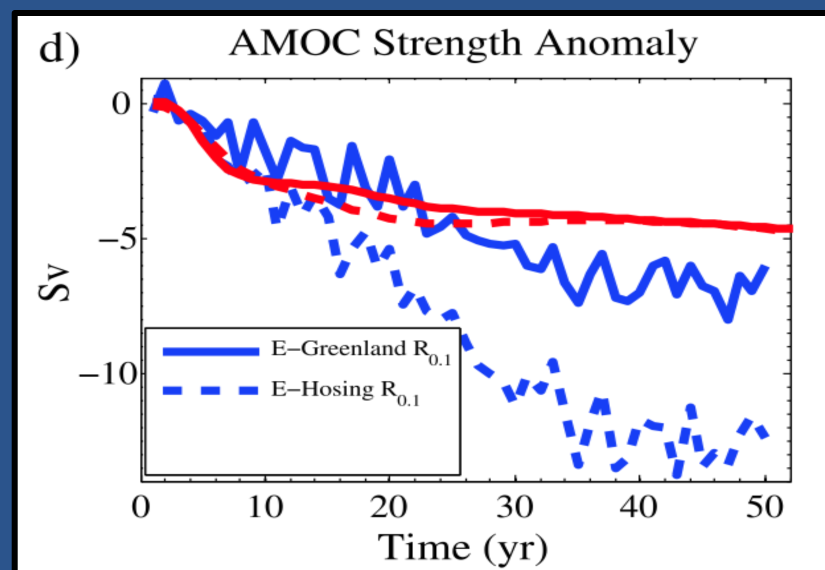
Ice Sheet & Ocean Coupling

Bintanja et al., *Nat Geos.* (2013)



Recent trends in Ant. sea-ice extent better explained when accounting for freshwater flux from iceberg discharge

AMOC “hosing” experiments: much less sensitive when using realistic spatial distribution of freshwater around GIS margin



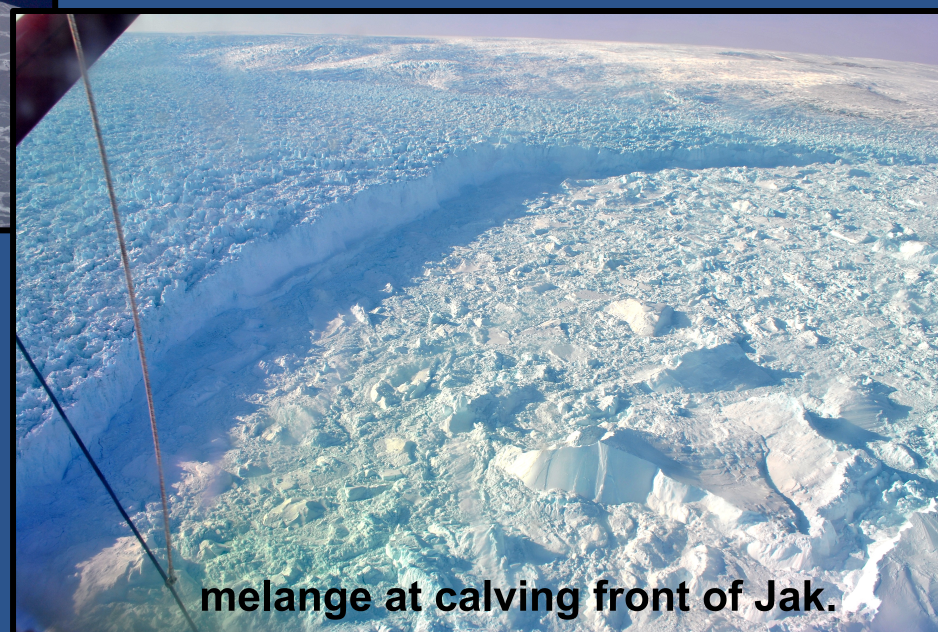
Weijer et al., *GRL* (2012)

Ice Sheet / Ocean / Sea Ice Coupling

Thermal and mechanical effects
of icebergs on sea ice and ocean

Tabular iceberg opening sea-ice lead
… new ice forming in lee

Ocean and sea-ice evolution
influence melange properties



melange at calving front of Jak.

presentation goals & caveats

ice sheet & atmos. / land model coupling

ice sheet & ocean model coupling

glacier & ice cap coupling to ESMs

coupled land ice & ESM initialization

summary

Sastrugi, Jakobshavn Isbrae catchment, Greenlar

G&IC Coupling to ESMs

Important processes / feedbacks & relevance to GRISO have been discussed already (e.g., solid / liquid freshwater flux to oceans, albedo effects on larger ice sheet, etc.)

Current Approaches:

- predict SMB as already discussed
- RGI and volume-area scaling for initial condition (on V&A)
- Evolve G&IC in time using SMB evolution and V&A scaling

Issues:

- SMB biases even more problematic for smaller ice masses
- Large no. of tidewater glaciers – how to treat statistically?

presentation goals & caveats

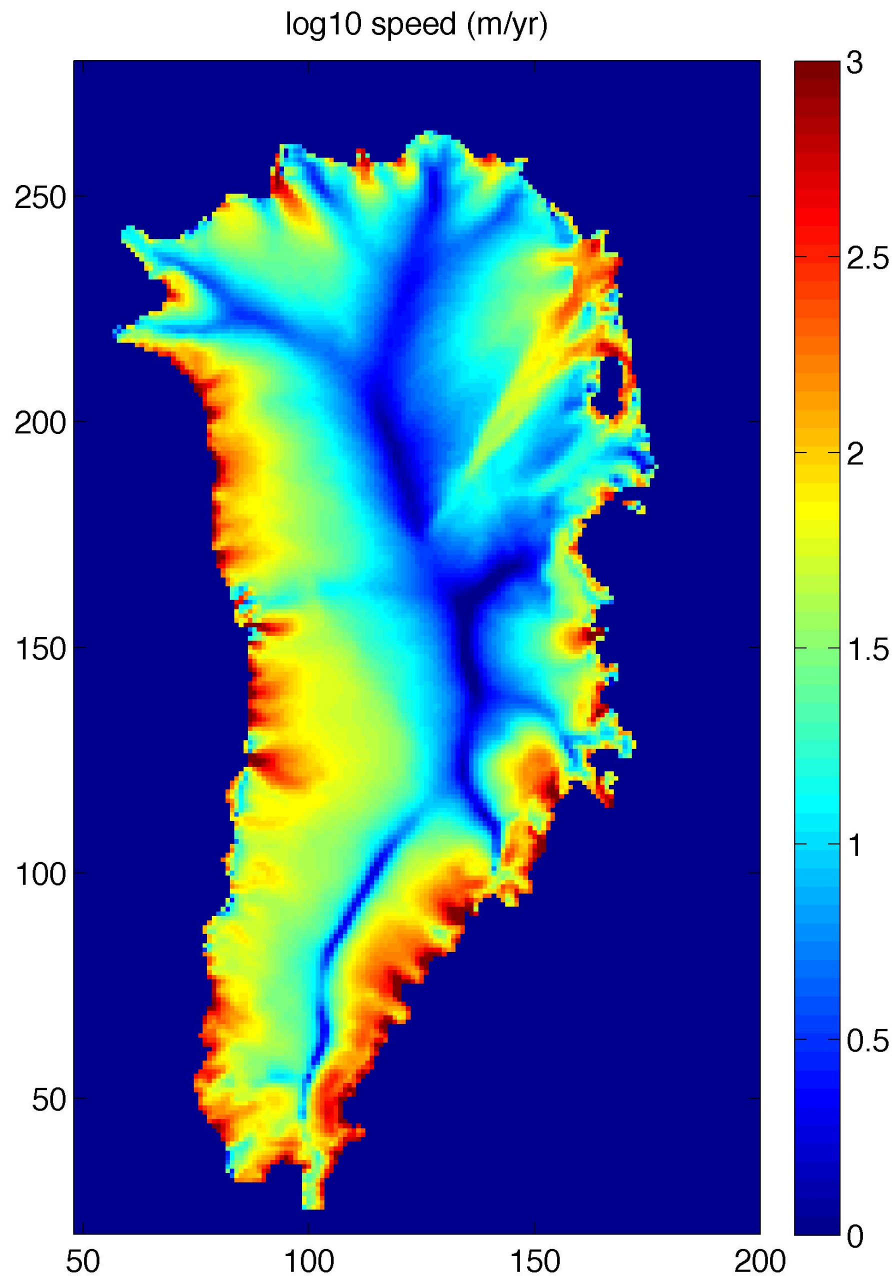
ice sheet & atmos. / land model coupling

ice sheet & ocean model coupling

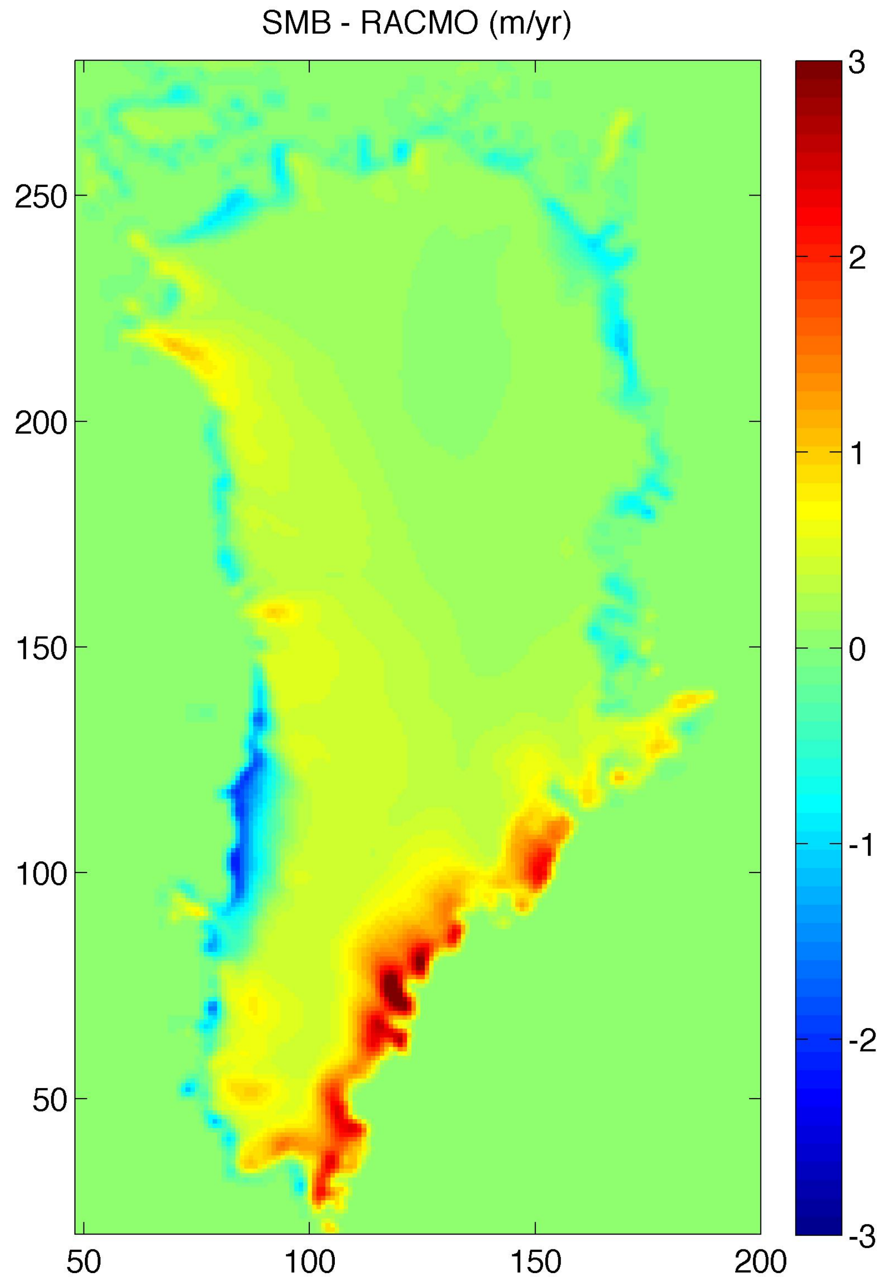
glacier & ice cap coupling to ESMs

coupled land ice & ESM initialization

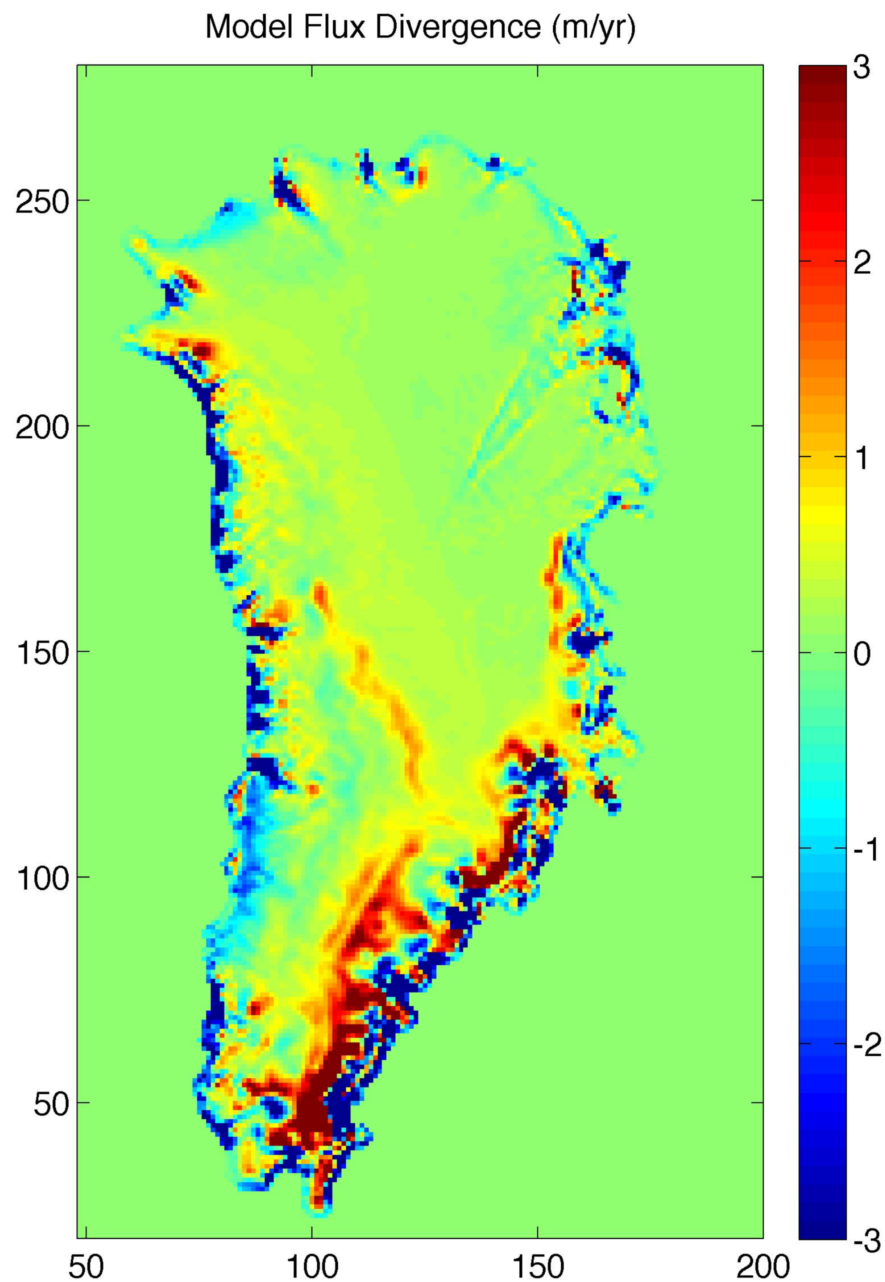
summary



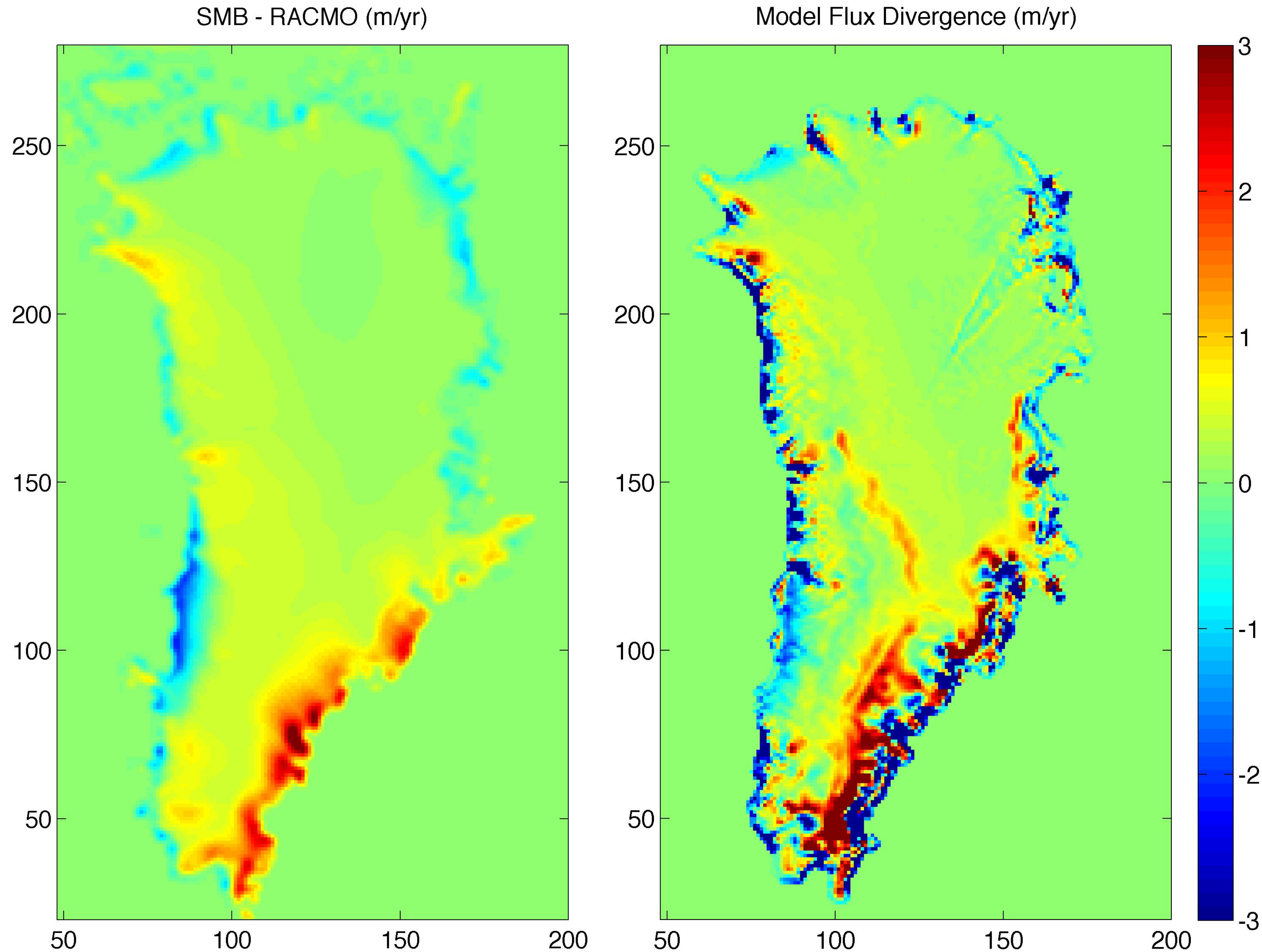
SS init. cond. for GIS (10 km res; tuned to bal vels)



SMB from ESM (here, RACMO)

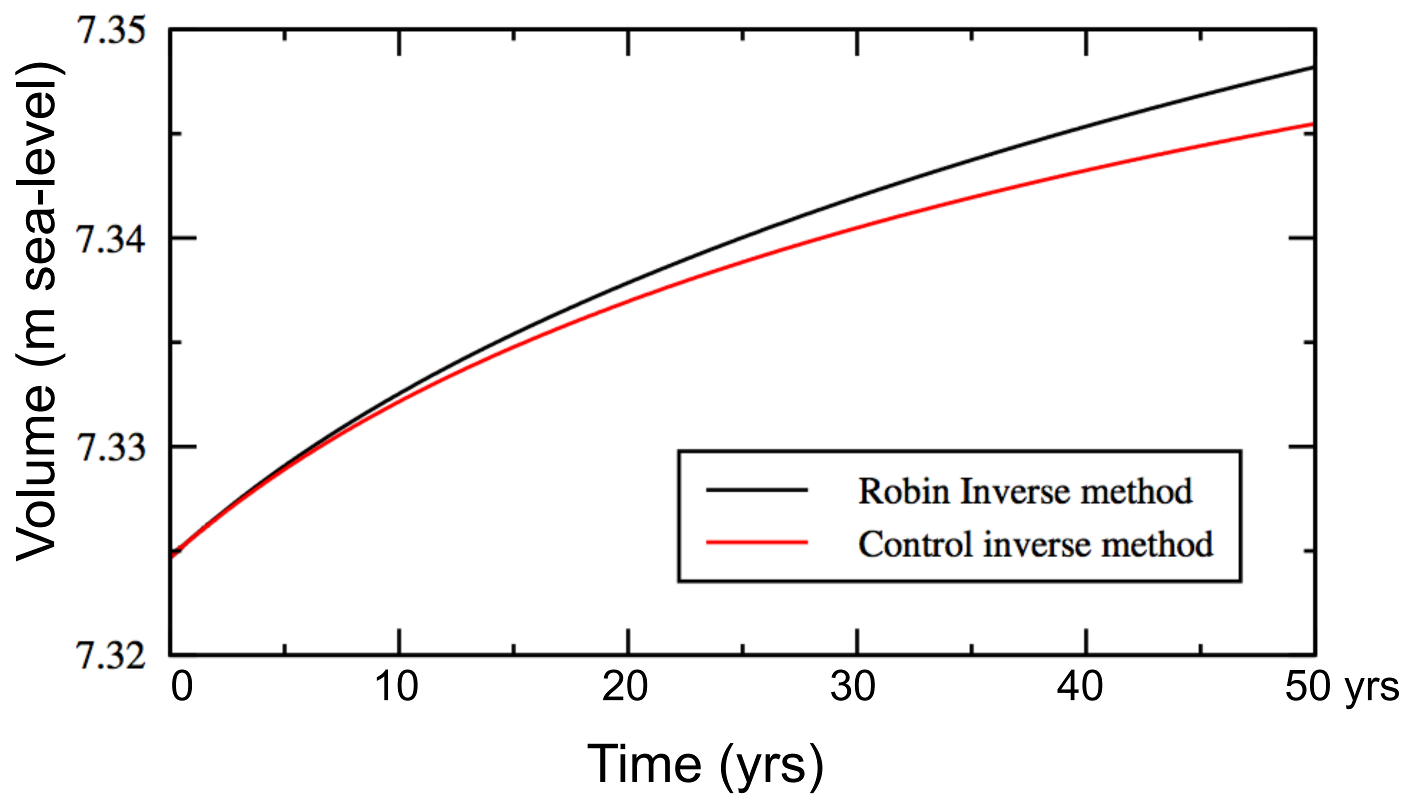


- div[flux] = SMB needed for SS upon coupling to ESM

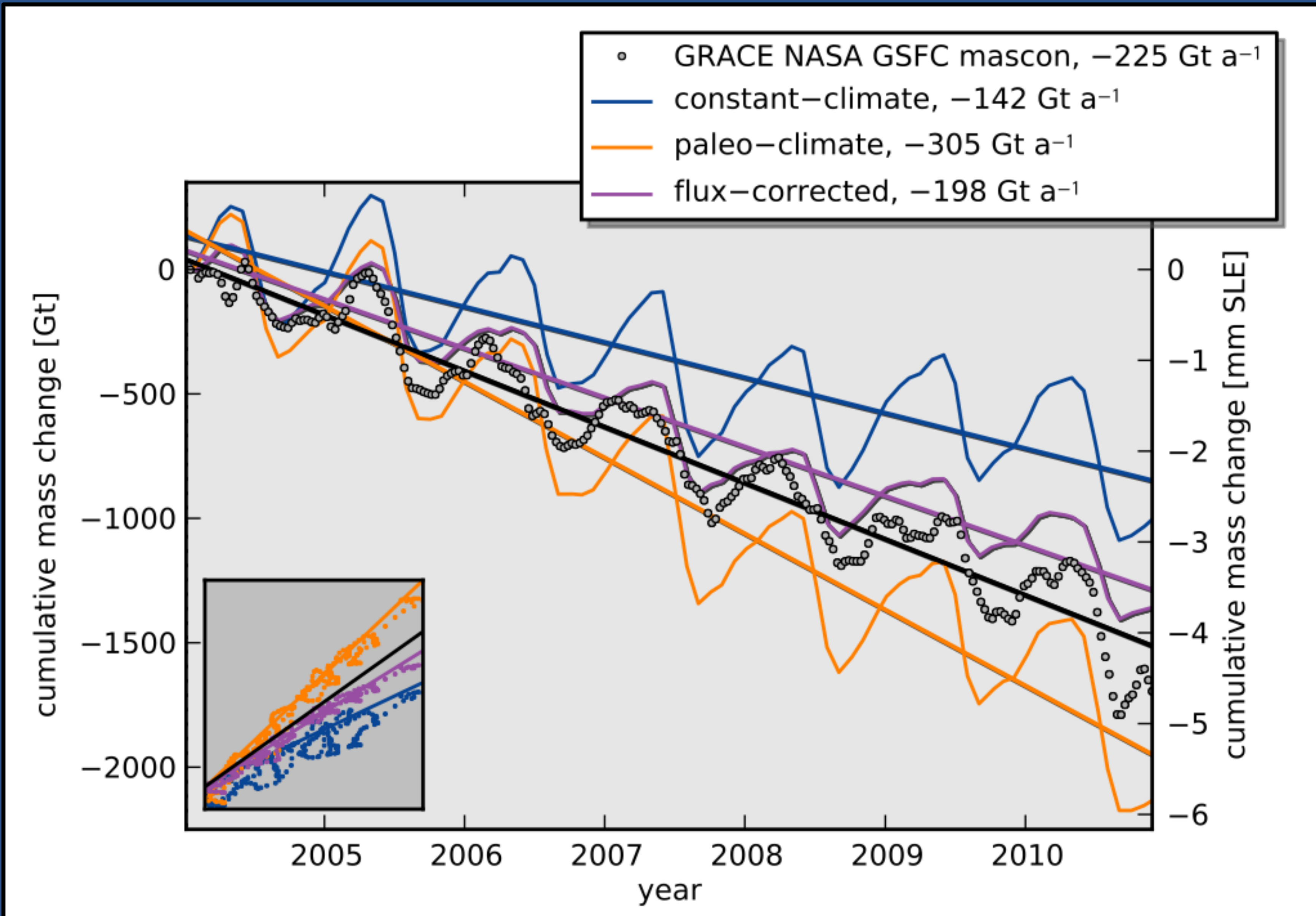


Target (left) and “compensatory” SMB (right)

When the coupling to SMB field is turned "on", ice sheet does this …



Gillet-Chaulet et al., *TC* (2012)



Aschwanden et al., *TC* (2013)

Coupled Land Ice & ESM Initialization

Problem:

Method 1: Can tune model to fit observations of modern vels and shape …

… but then ESM SMB is NOT in equilb. w/ ice sheet

Method 2: Can "spin-up" model to (try and) include ~10^4-10^5 yr transients (e.g., temperature), and possibly even capture realistic modern mass trends …

… but no (easy) way to constrain to also fit today's vels and shape

Coupled Land Ice & ESM Initialization

* Solution:

Use method 1 with …

- *ad hoc* additional tuning of sliding coeff. and ice thickness to minimize difference between model flux divergence and ESM SMB (should be ~0)

- Formal PDE-constrained optimization used during initialization process

* For now, assume quasi-equilibrium initial (1850) conditions

Coupled Land Ice & ESM Initialization

Optimization Problem:
find β that minimizes the functional $\mathcal{J}$

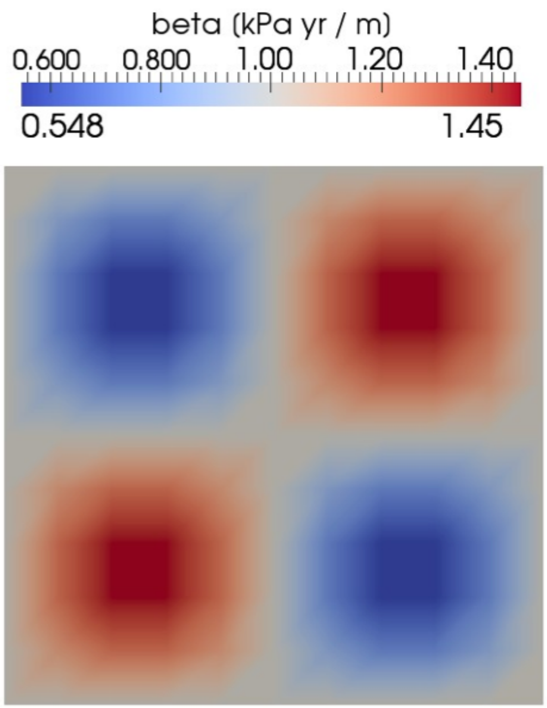
$$
\begin{aligned}
\mathcal{J}_1(\beta, H) = \quad & \tfrac{1}{2}\alpha_d \int_\Gamma |\mathrm{div}(\boldsymbol{U} H) - \tau_s|^2 \, ds + && \text{(SMB mismatch)} \\
& \tfrac{1}{2}\alpha_v \int_{\Gamma_{top}} |\mathbf{u} - \mathbf{u}^{obs}|^2 \, ds + && \text{(surface velocity mismatch)} \\
& \tfrac{1}{2}\alpha_H \int_\Gamma |H - H^{obs}|^2 \, ds + && \text{(observed thickness mismatch)} \\
& \mathcal{R}(\beta) + \mathcal{R}(H) && \text{(regularizations).}
\end{aligned}
$$

such that the ice sheet model equations (FO or Stokes) are satisfied

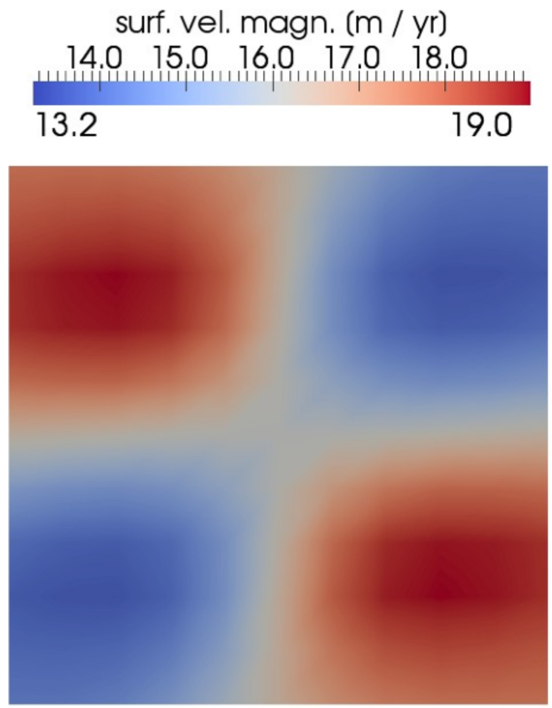
$\boldsymbol{U}$: computed depth averaged velocity
H: ice thickness
β: basal sliding friction coefficient
τ_s: SMB
$\mathcal{R}(\beta)$ regularization term

** Heavy lifting by Georg Stadler (UT) & Mauro Perego (SNL)

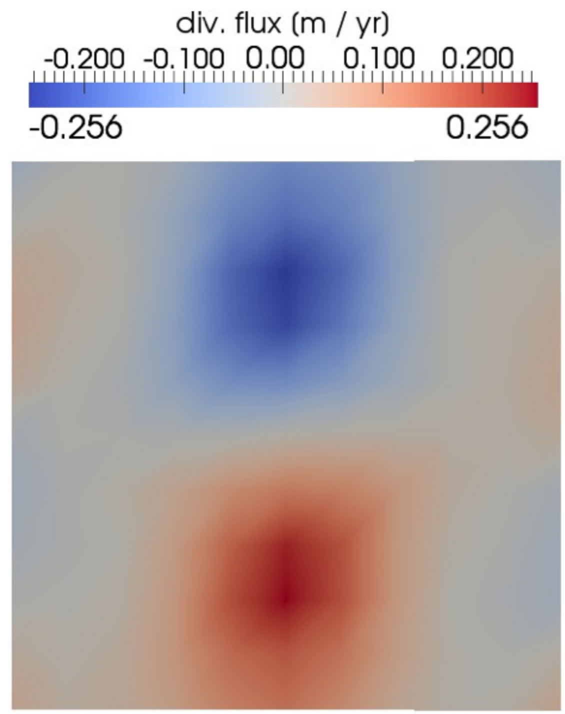
Coupled Land Ice & ESM Initialization



sliding coeff.



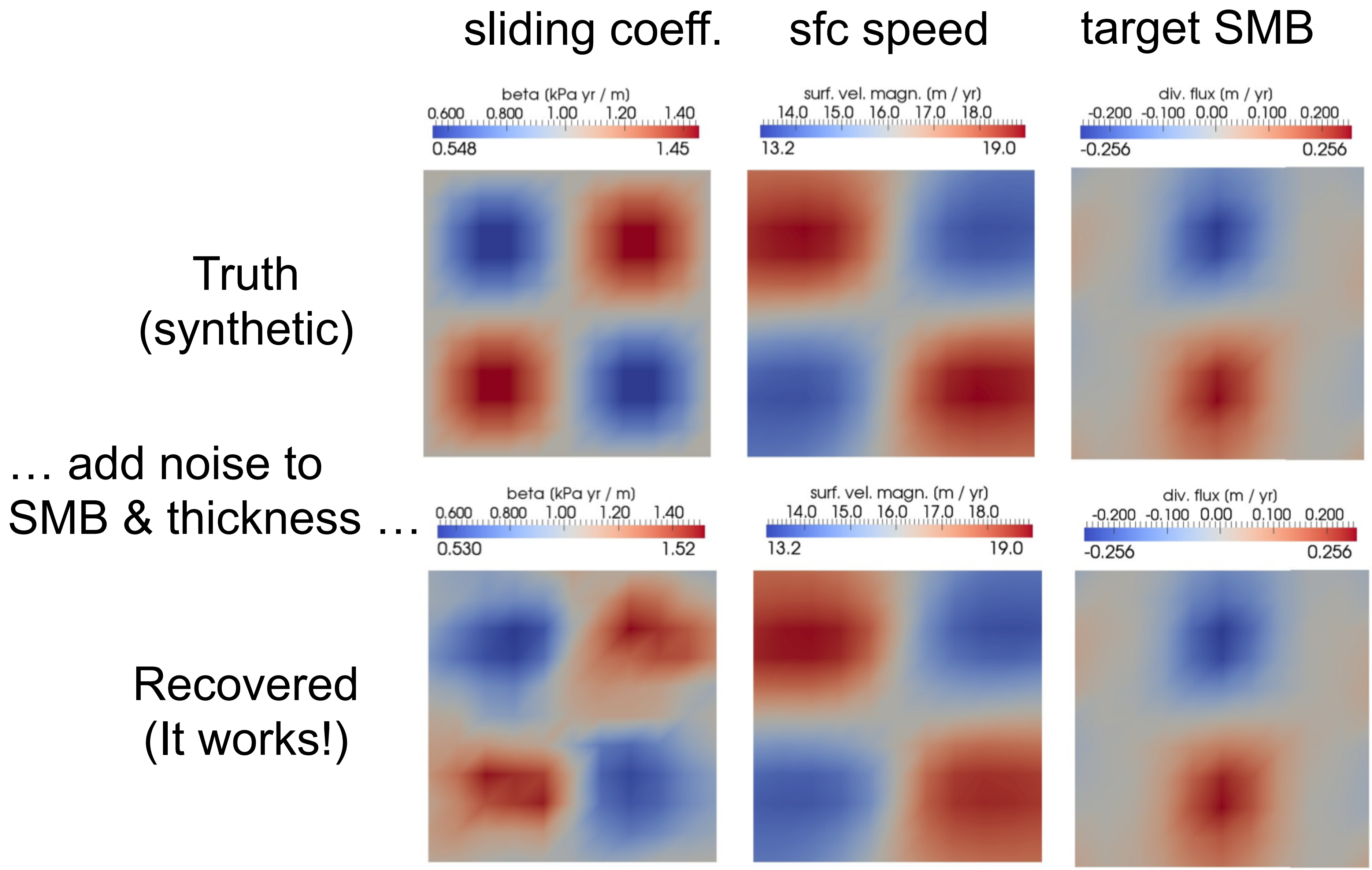
sfc speed



target SMB

Figures from Mauro Perego (SNL)

Coupled Land Ice & ESM Initialization



Figures from Mauro Perego (SNL)

presentation goals & caveats

ice sheet & atmos. / land model coupling

ice sheet & ocean model coupling

glacier & ice cap coupling to ESMs

coupled land ice & ESM initialization

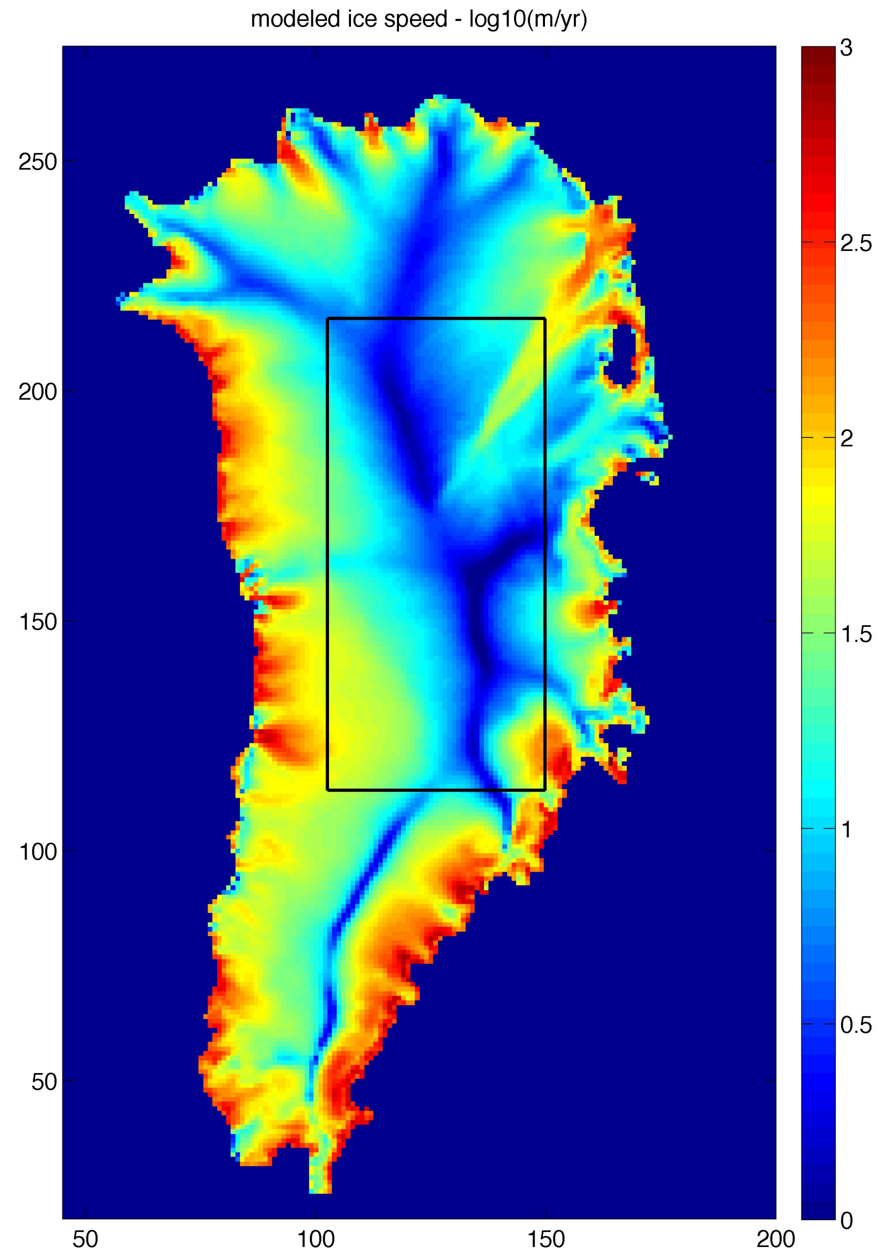
summary

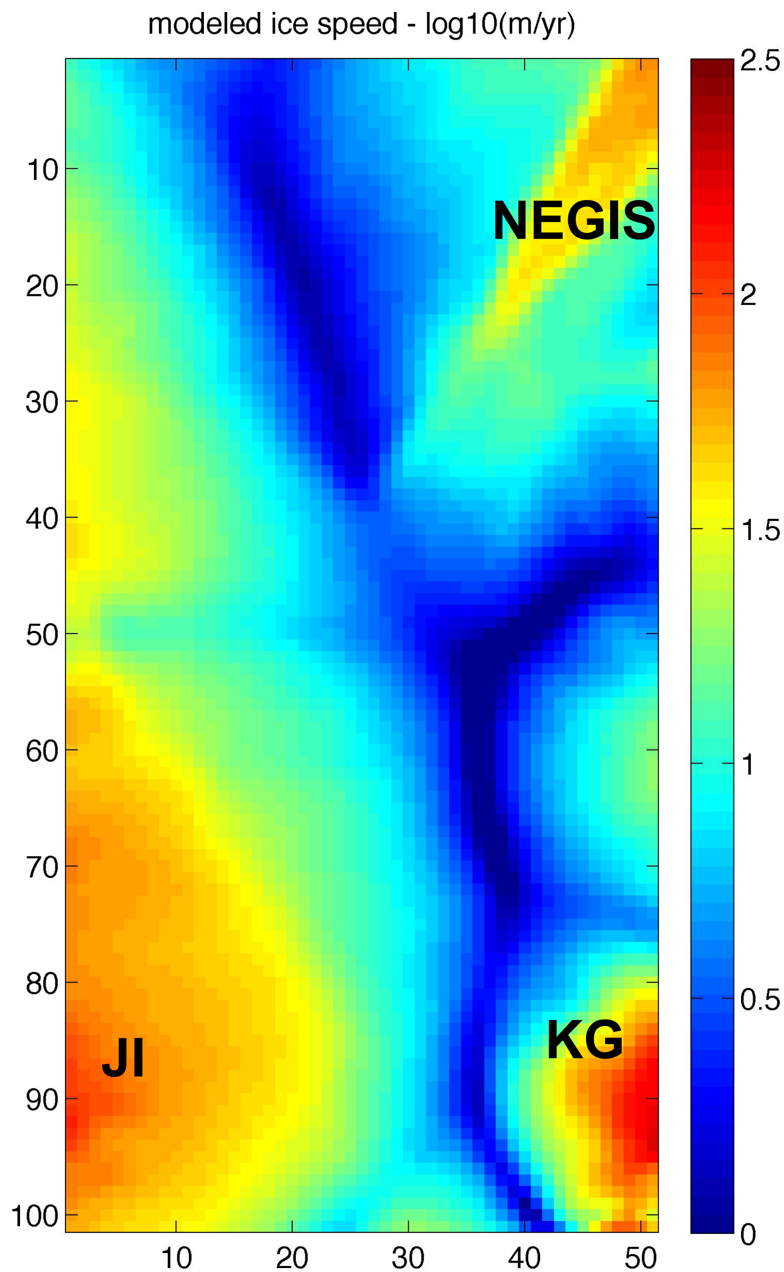
Summary

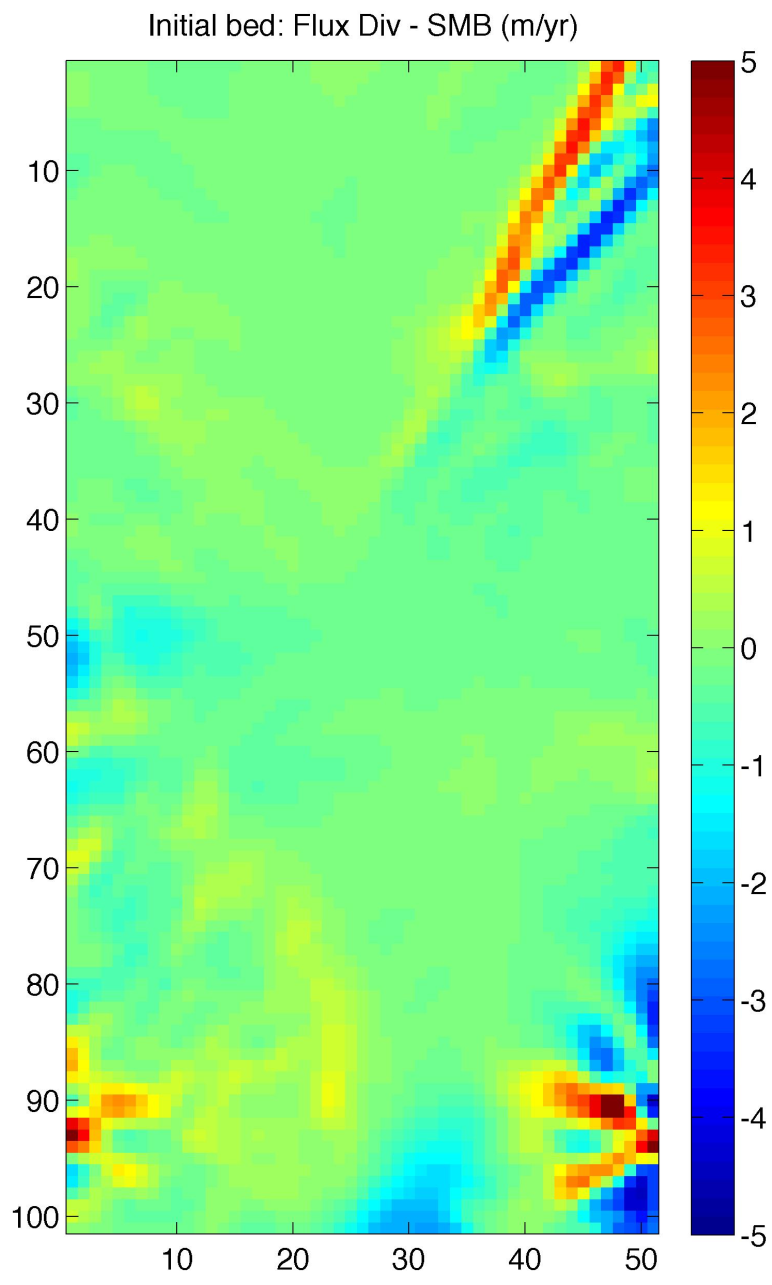
- ESM and ice sheet modeling communities are making good progress on coupling
- Still lots left to do (much of it unglamorous: software-level)
- New hi-res / var-res models in devel. May “fix” many current shortcomings (?)
- Plenty of new work to do coming up with suitable params. of process-scale models (e.g. non-hydrostat processes)

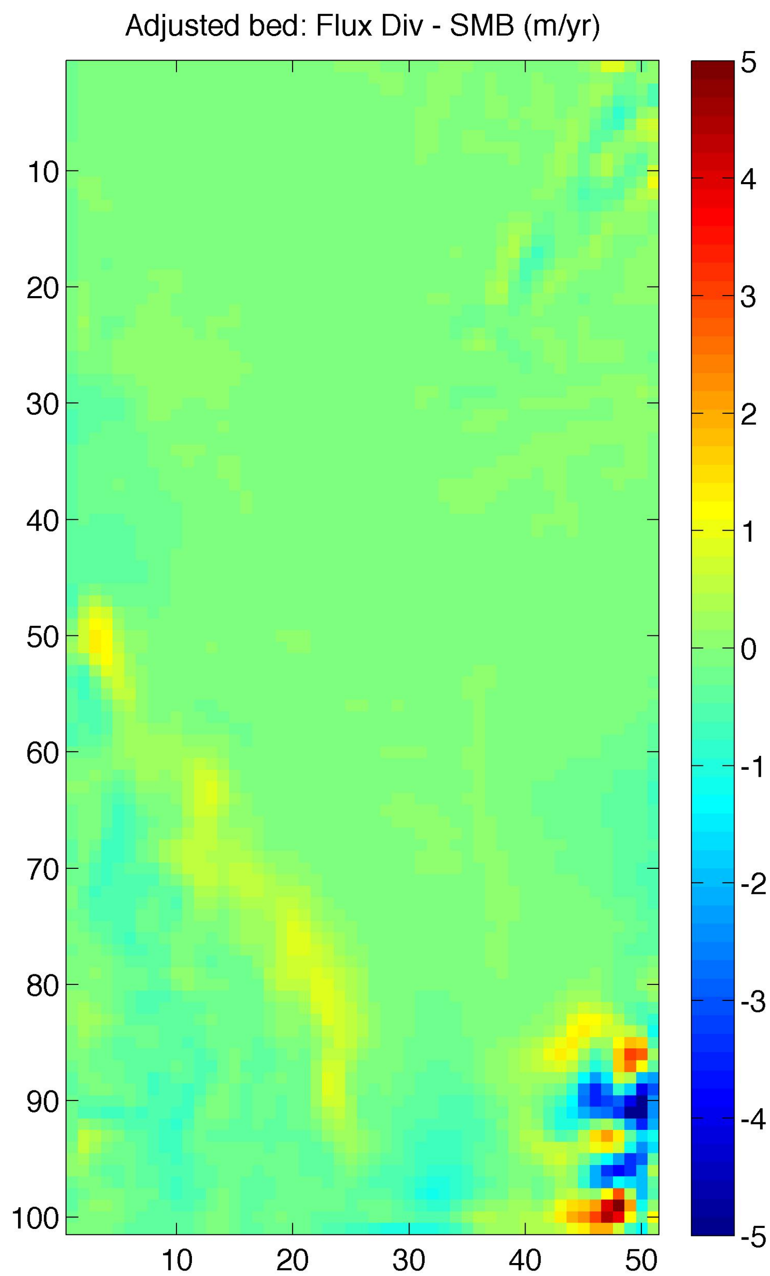
Questions:

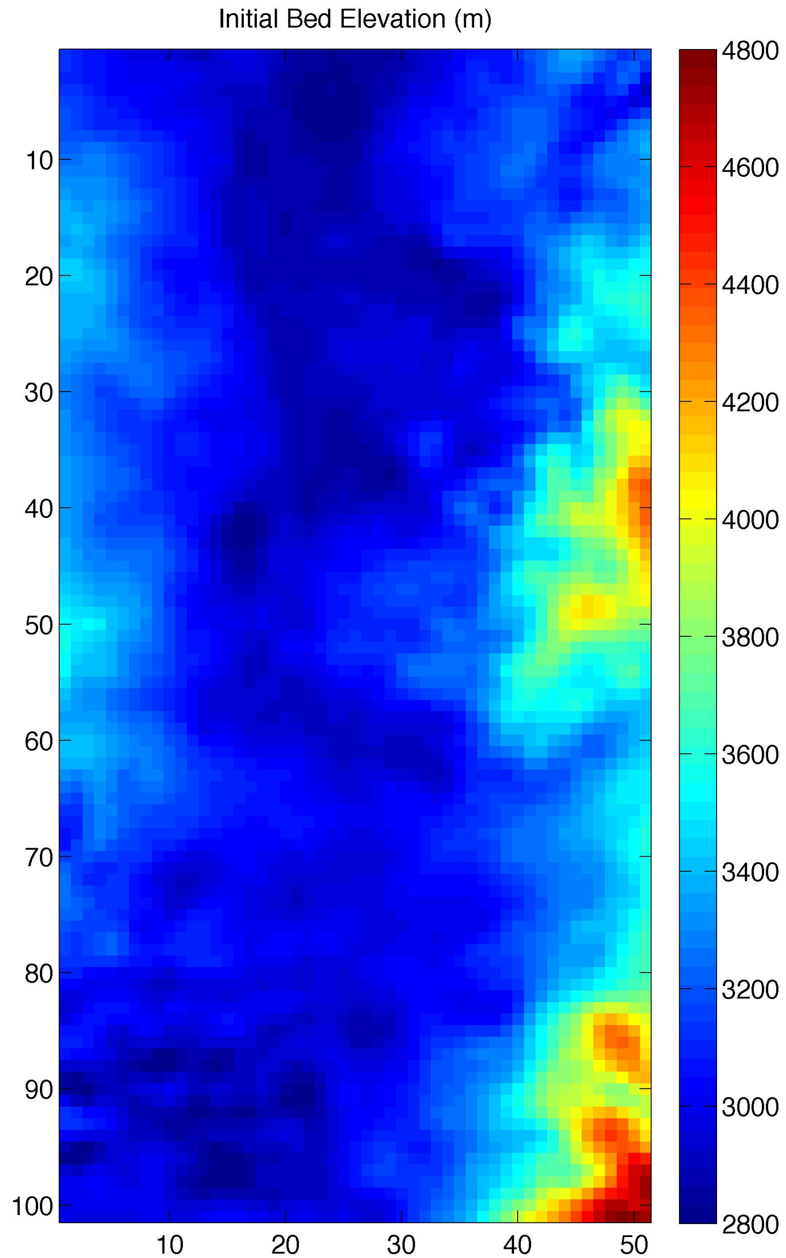
- Are we adequately engaging sea-ice community?
- Are we using CMIP4 / 5 archives to our advantage (e.g. Yin et. al, *Nat. Geosc.*, 2011)?

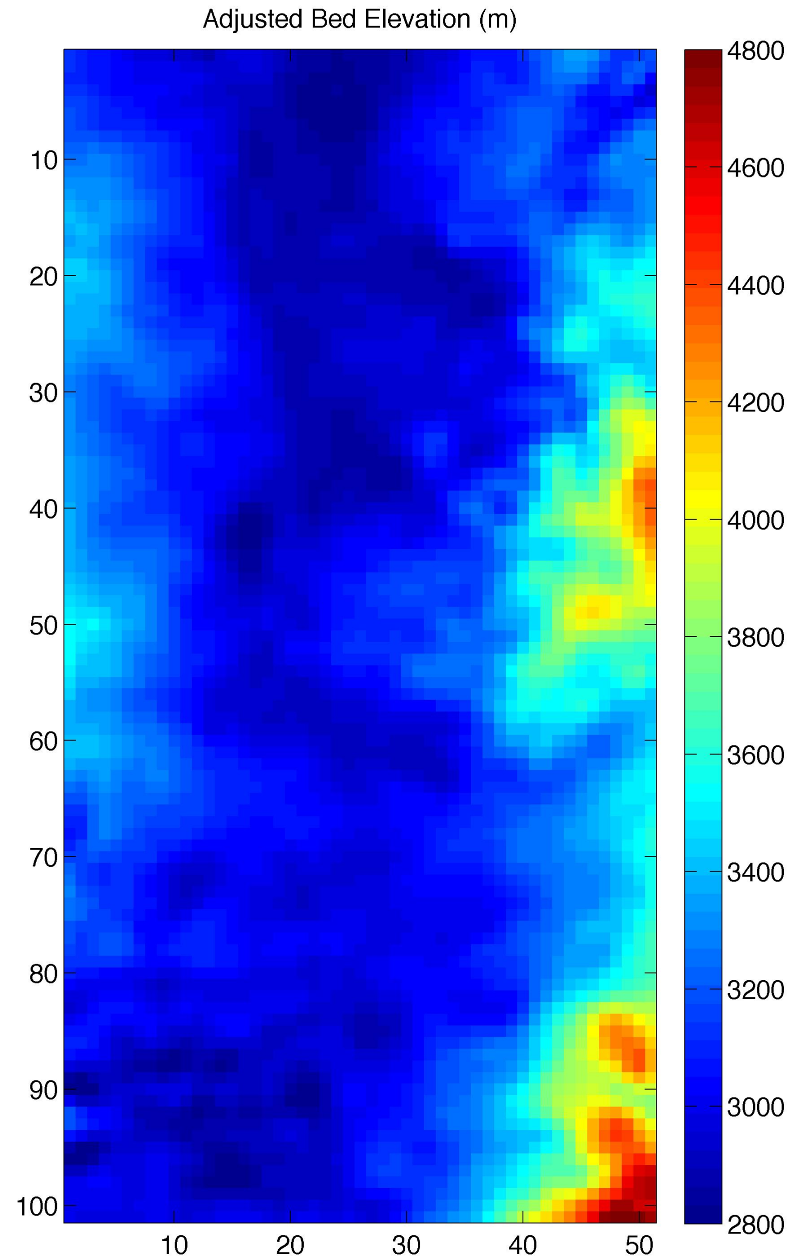

modeled ice speed - log10(m/yr)
250
200
150
100
50
50
100
150
200
3
2.5
2
1.5
1
0.5
0

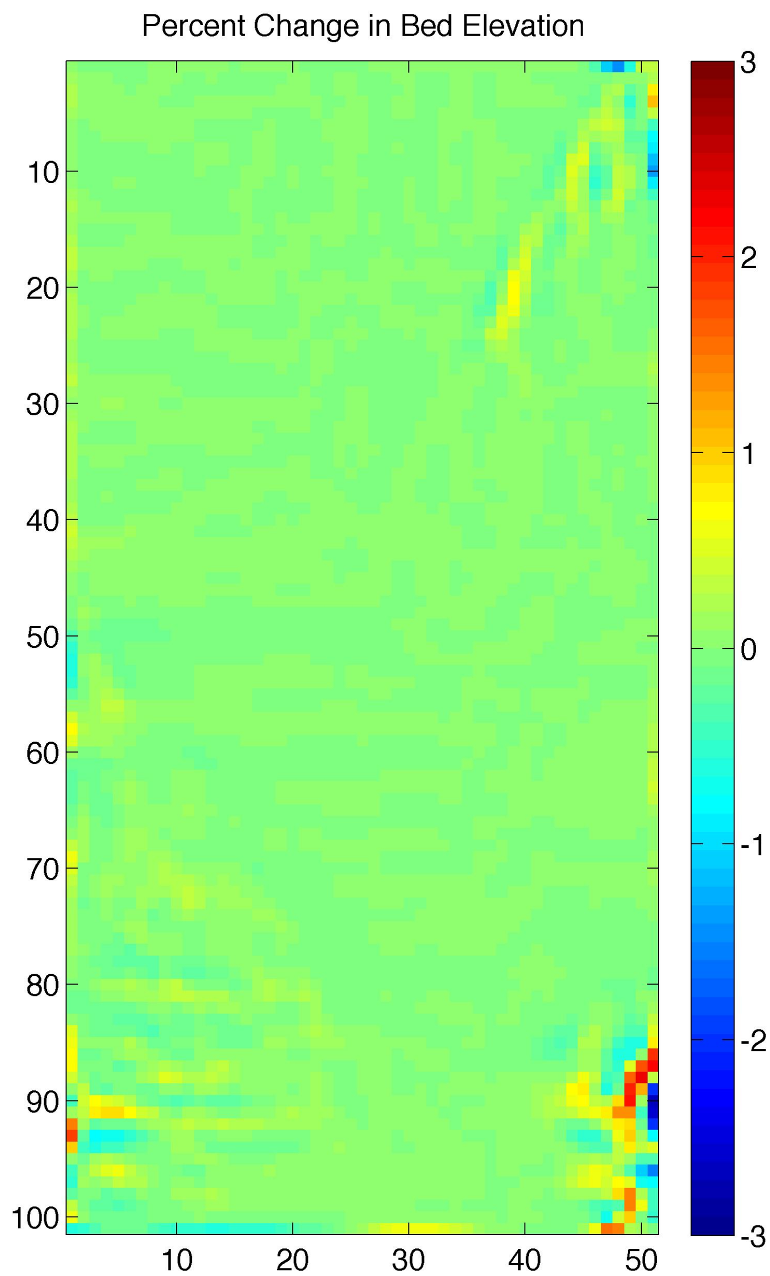

modeled ice speed - log10(m/yr)
NEGIS
KG
JI
10
20
30
40
50
60
70
80
90
100
10
20
30
40
50
2.5
2
1.5
1
0.5
0


Initial bed: Flux Div - SMB (m/yr)
10
20
30
40
50
60
70
80
90
100
10
20
30
40
50
5
4
3
2
1
0
-1
-2
-3
-4
-5


Adjusted bed: Flux Div - SMB (m/yr)
10
20
30
40
50
60
70
80
90
100
10
20
30
40
50
5
4
3
2
1
0
-1
-2
-3
-4
-5


Initial Bed Elevation (m)
10
20
30
40
50
60
70
80
90
100
10
20
30
40
50
4800
4600
4400
4200
4000
3800
3600
3400
3200
3000
2800

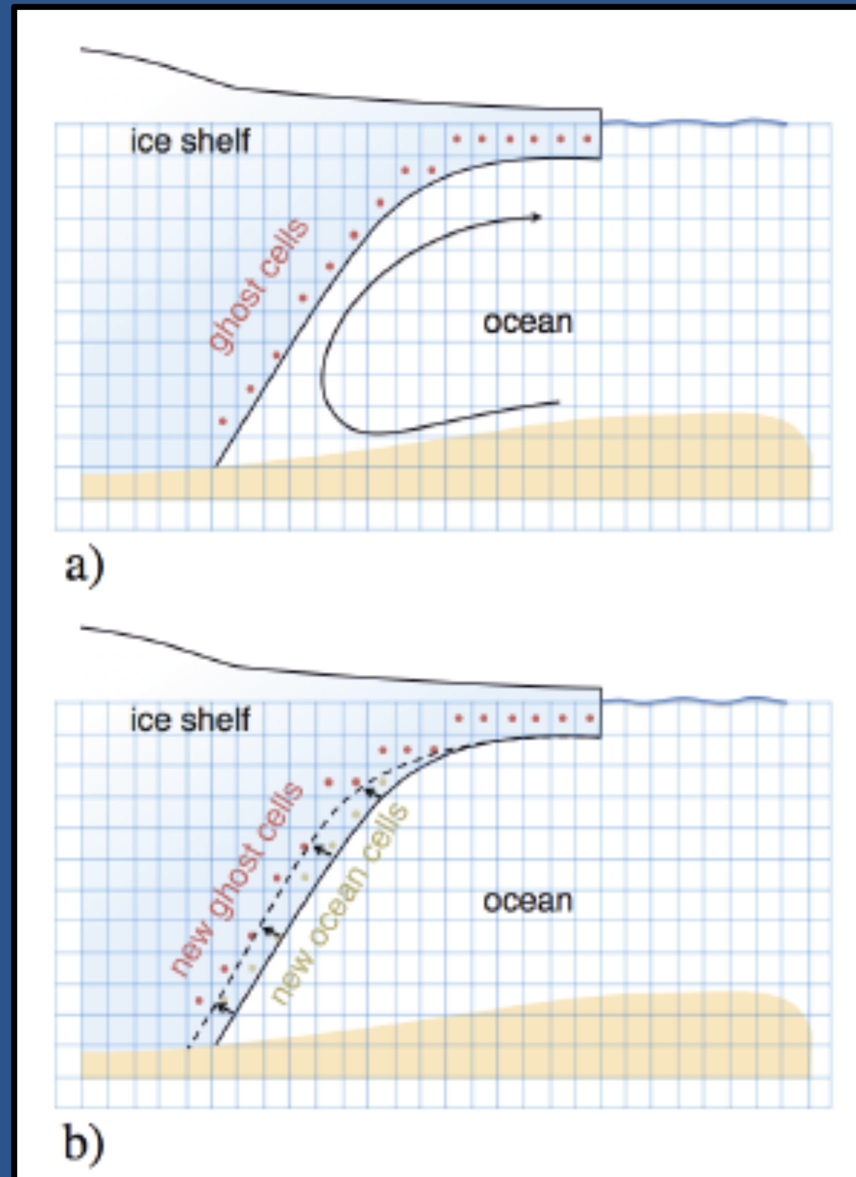

Adjusted Bed Elevation (m)
10
20
30
40
50
60
70
80
90
100
10
20
30
40
50
4800
4600
4400
4200
4000
3800
3600
3400
3200
3000
2800



Percent Change in Bed Elevation
10
20
30
40
50
60
70
80
90
100
10
20
30
40
50
3
2
1
0
-1
-2
-3

Future: Moving Boundaries using IBMs

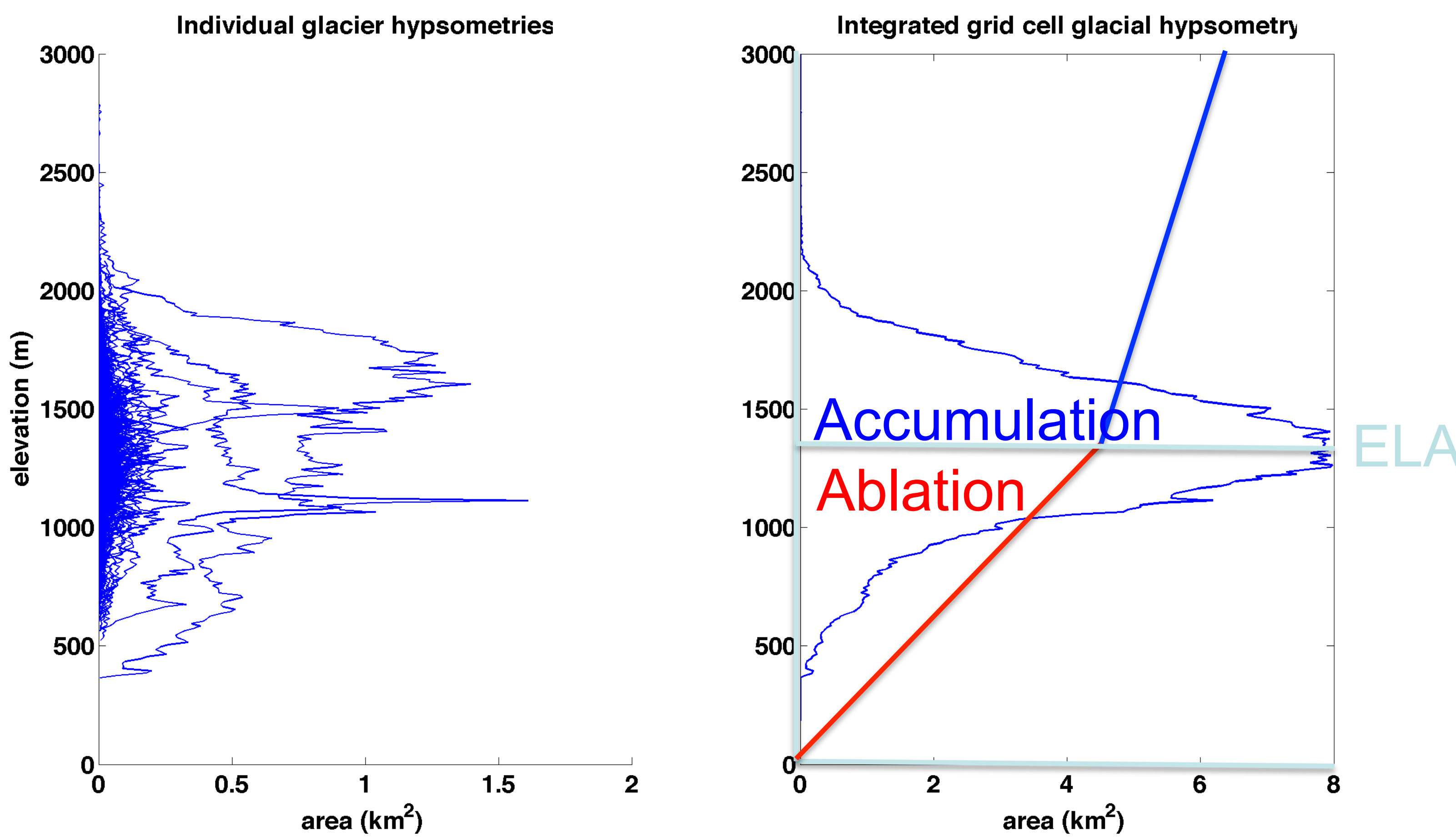
- *Immersed Boundary Method*
  - includes ghost cells adjacent to boundary
  - implicit representation of sloped interface geometry
  - as ice sheet retreats, ghost cells become new ocean cells
  - no partial cells, so never have infinitesimally thin cells



Figures courtesy of X. Asay-Davis (LANL / PIK)

CESM non-GIS surface mass balance evaluation

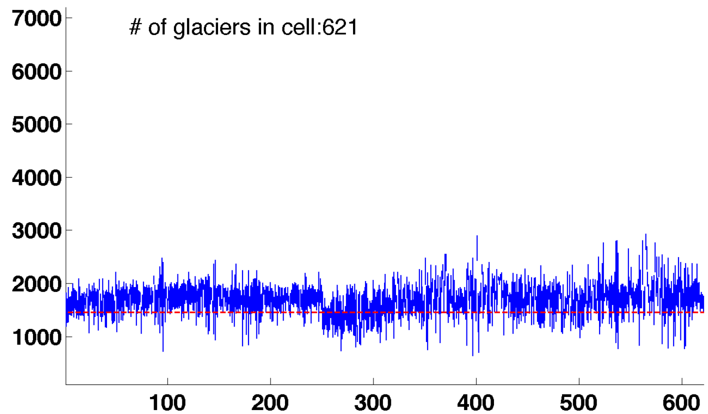
- Empirically, observed ELA occurs where accumulation area=0.57*total area [Bahr et al., 2009]

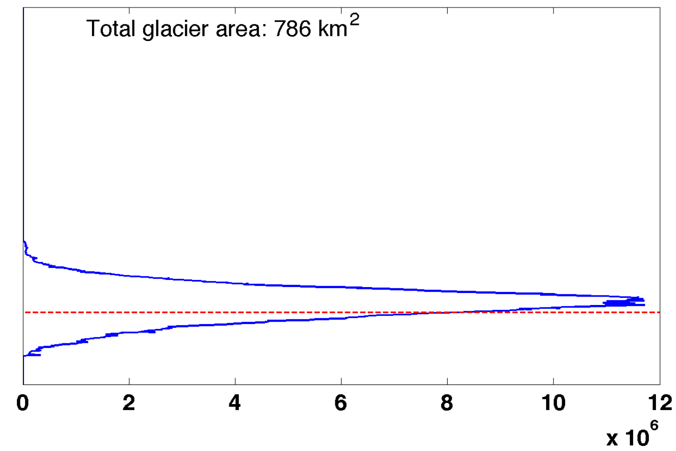


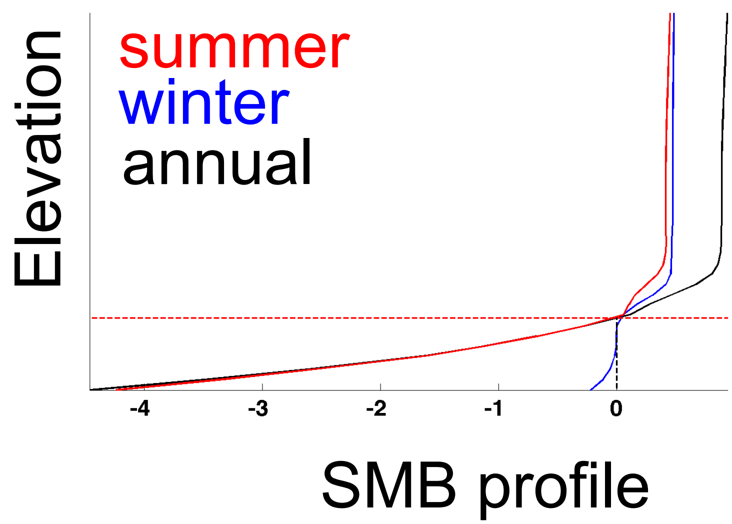
CESM non-GIS surface mass balance evaluation

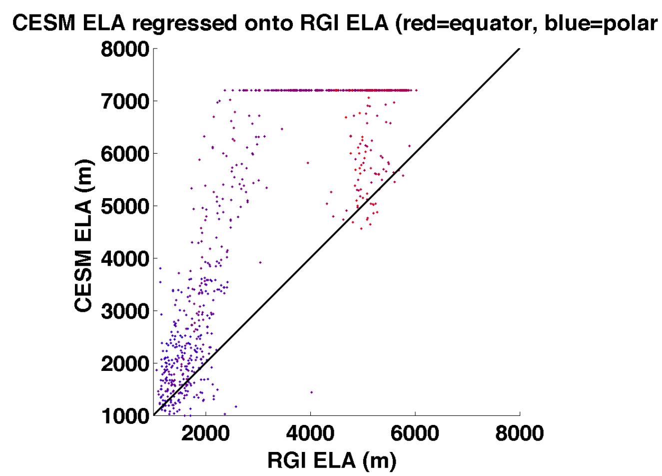
- Simulated SMB fields can be compared against RGI-derived hypsometry
- ELA (line of net 0 ice gain/loss) useful as a composite indicator of T/P conditions: gives a glaciologically-relevant, global-coverage metric of climate model performance: vertical ELA bias

CESM non-GIS surface mass balance evaluation







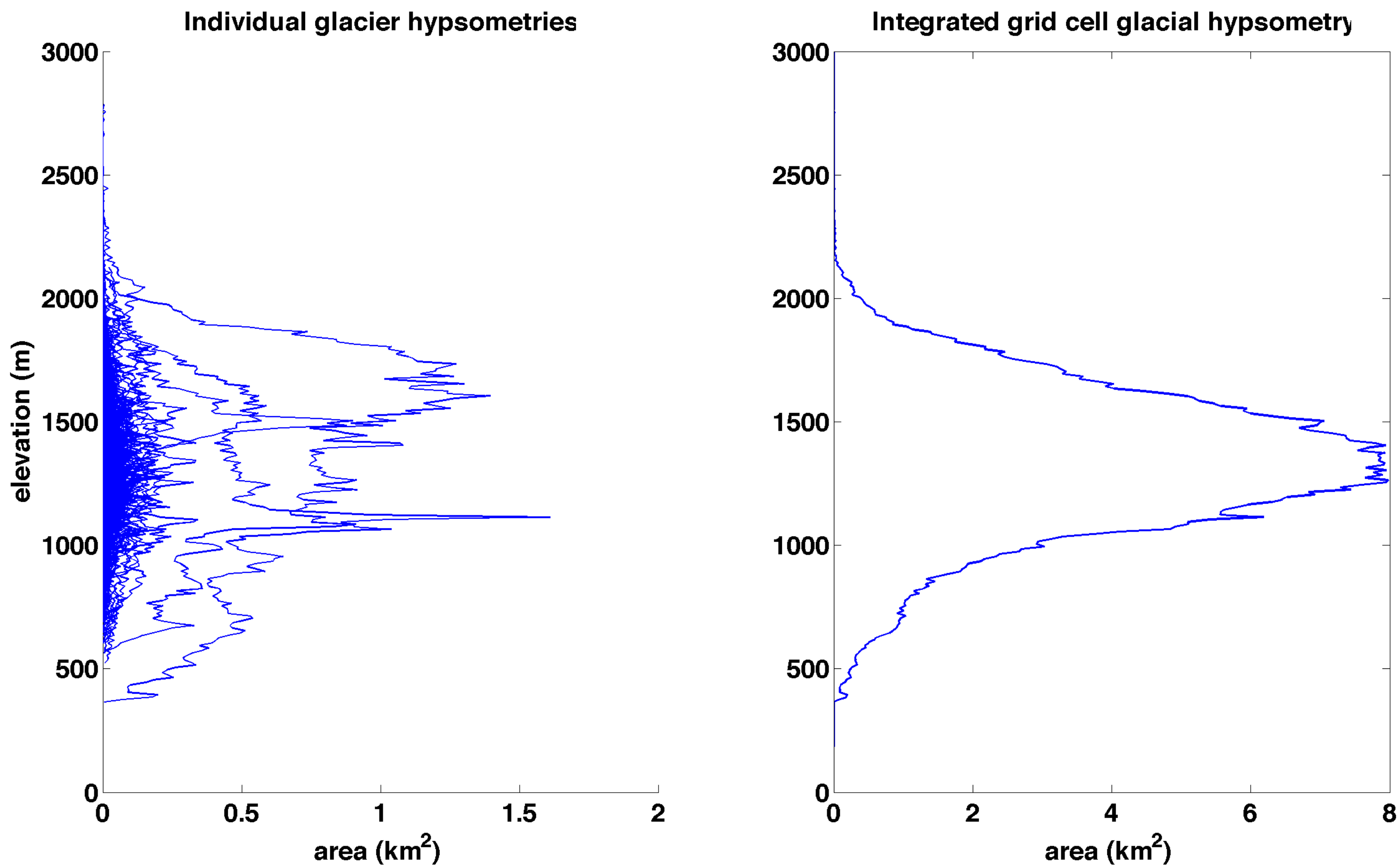


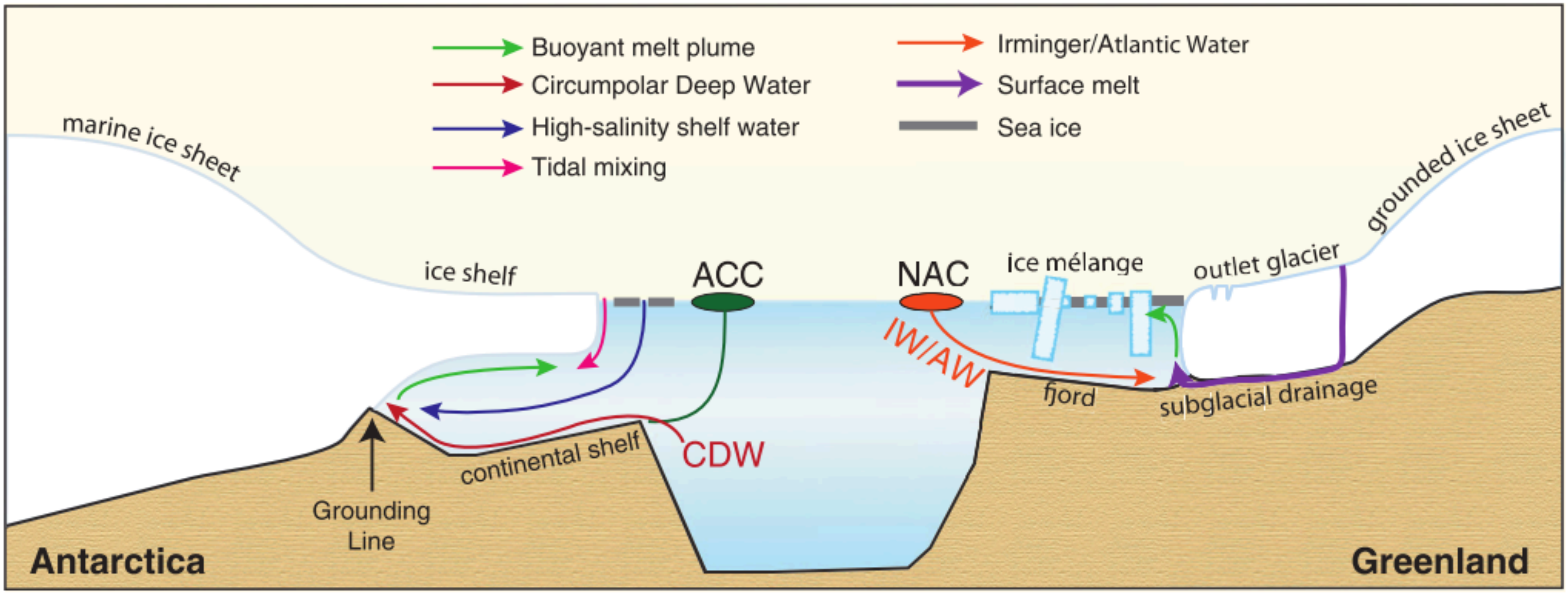
Ocean Model features needed for ice shelf simulations

- Sub-shelf circulation
  - Ocean surface is not sea level
  - Vertical walls
  - Changing upper surface elevation
- Mass and tracer fluxes at ice-ocean interface
- Boundary-layer physics (working in POP)
- Sea ice model (in early stages of development)
- Coupling to Land Ice Model

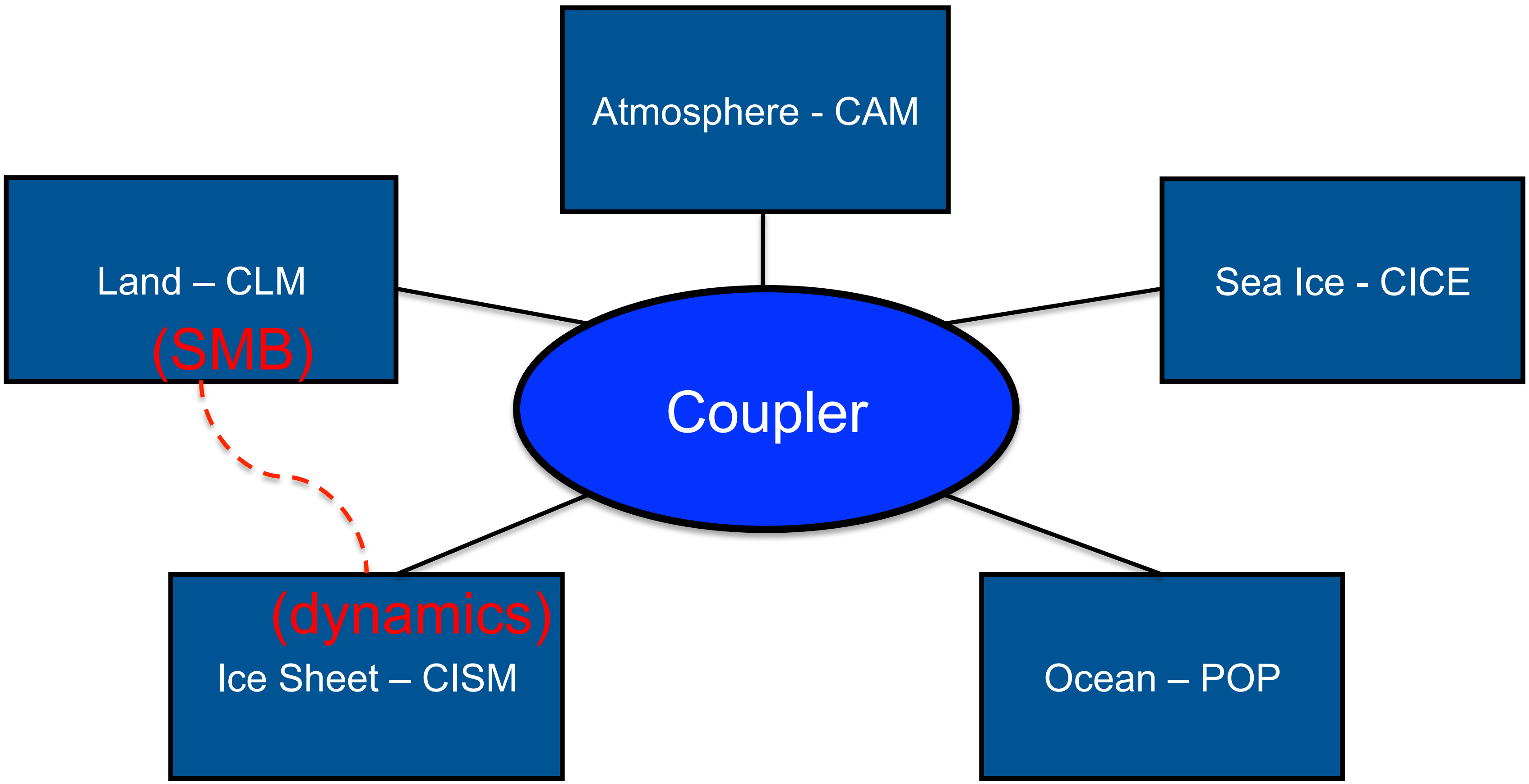
CESM non-GIS surface mass balance evaluation

- Issue: how to evaluate CESM non-ice-sheet SMB, given extreme sparsity of SMB observations?




Buoyant melt plume
Circumpolar Deep Water
High-salinity shelf water
Tidal mixing
Irminger/Atlantic Water
Surface melt
Sea ice
marine ice sheet
ice shelf
ACC
NAC
ice mélange
outlet glacier
grounded ice sheet
IW/AW
fjord
subglacial drainage
CDW
continental shelf
Grounding Line
Antarctica
Greenland

Coupling CISM to CESM Atmos. / Land



Coupling: Surface Mass Balance

Four models compared for 1960-2008 using ECMWF reanalysis (Polar MM5, RACMO, MAR, ECMWF-downscale)

Net SMB agrees to within 34%

Variation relative to component means:

42% (runoff), 20% (precip), melt (38%), refreeze (83%)

Less agreement regionally

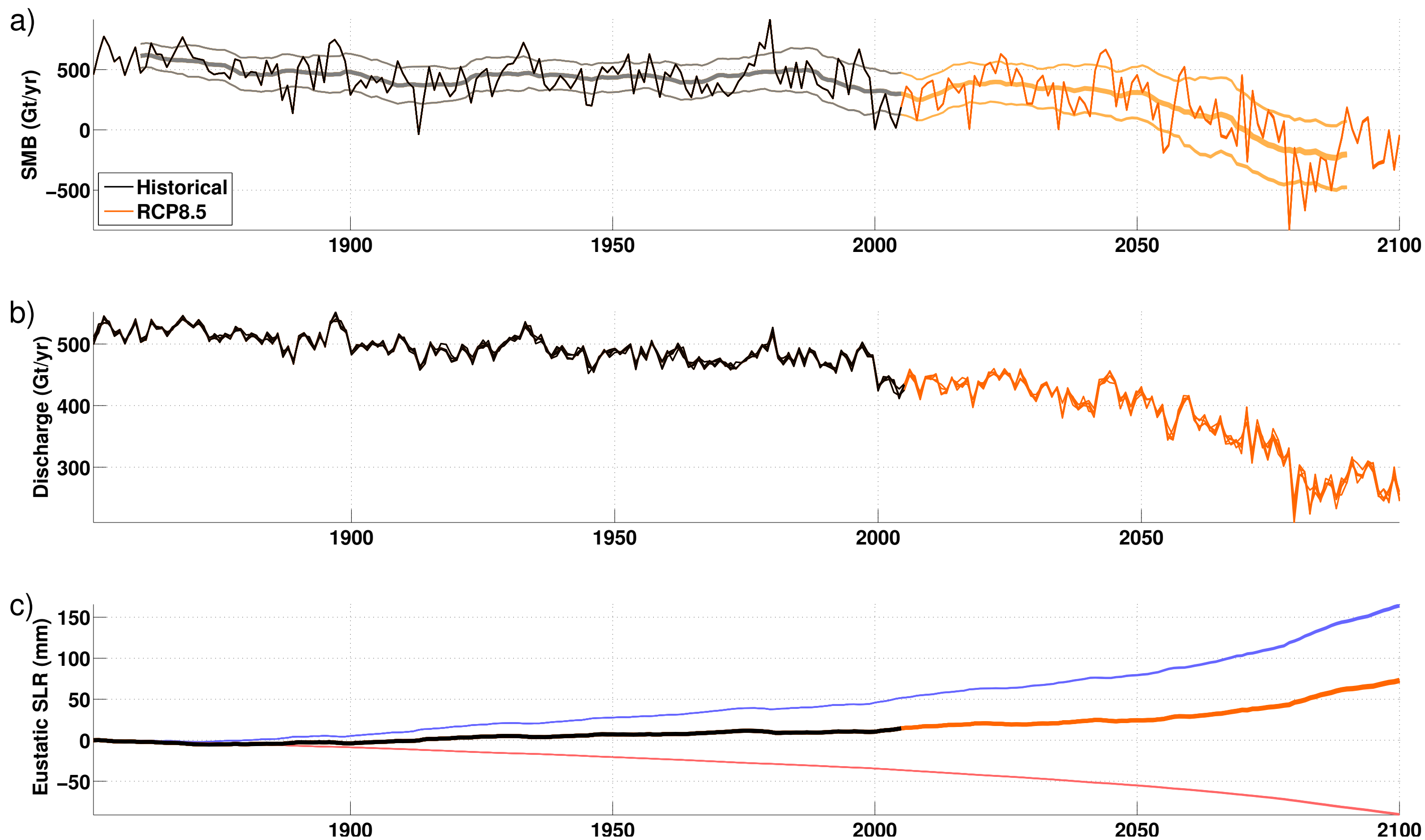
Compared w/ obs., better agreement for accum. than ablation zone (higher uncertainty in modeled ablation processes)

Use of a single, common ice sheet mask crucial for comparing model and data

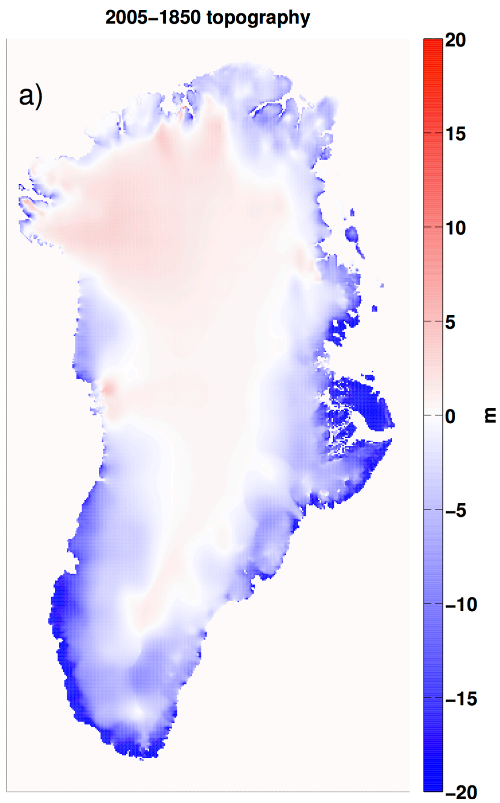
Vernon et al., *TCD*, **6** (2012)

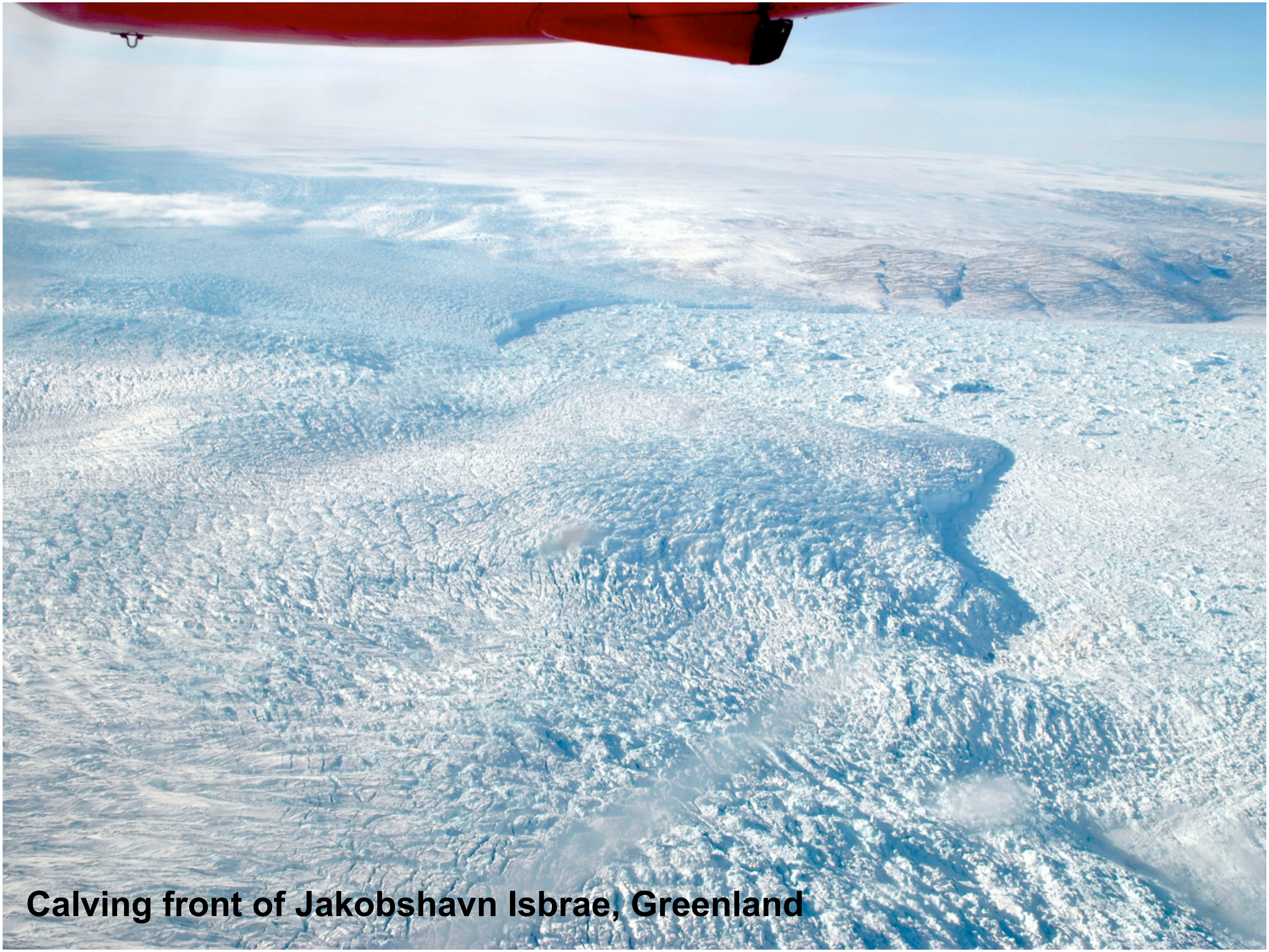
RCP8.5 GIS sea level rise contribution predictions (Lipscomb et al., in press)

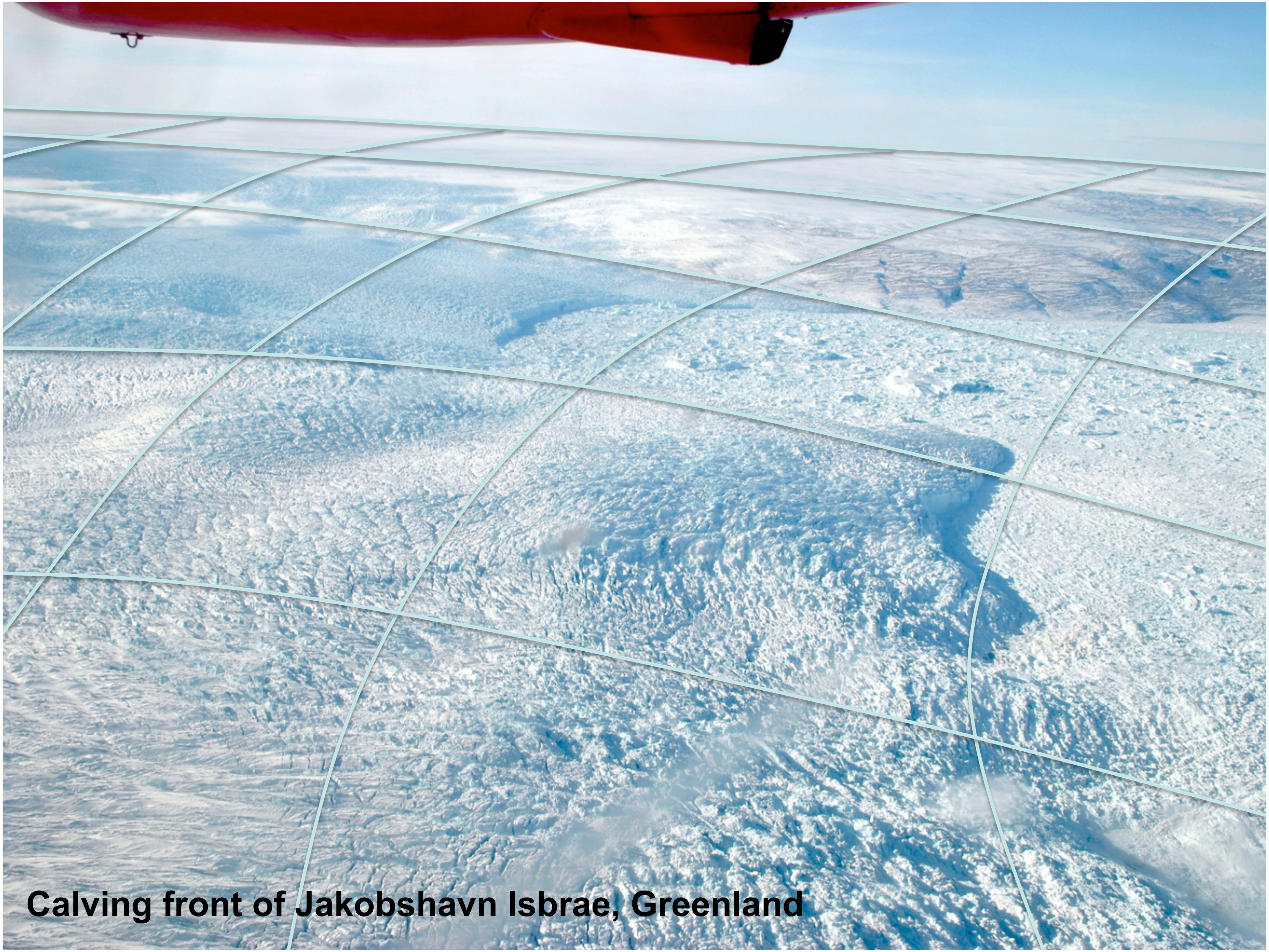
- Best initial GIS configurations generate 7.3 cm of eustatic sea level rise (SLR) 1850-2100



RCP8.5 GIS sea level rise contribution predictions



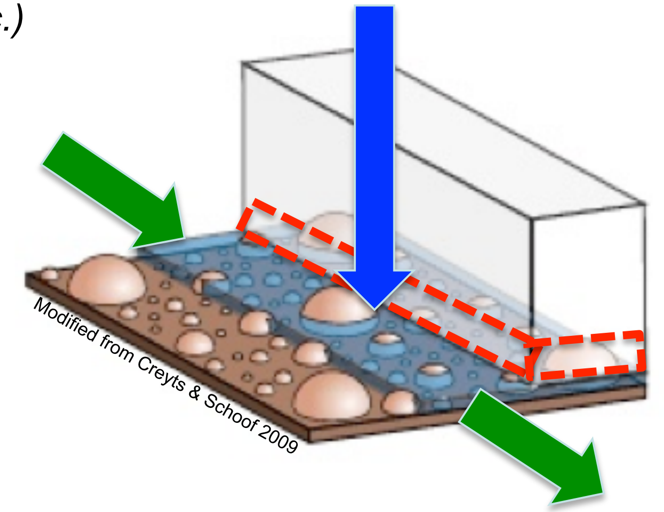

Calving front of Jakobshavn Isbrae, Greenland


Calving front of Jakobshavn Isbrae, Greenland

Distributed Flow Model

sheet flow, e.g. linked cavities

(e.g. Hewitt 2011, J.Glac.)



1) Mass conservation of w

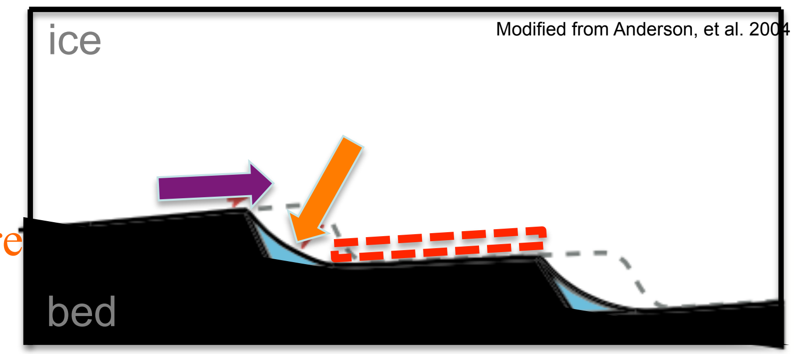
$$\frac{\partial h}{\partial t} + \nabla \cdot \mathbf{q} = \frac{m}{\rho_w} + \omega$$

Flux divergence | Basal melt | Water input from surface

2) Evolution of subglacial cavities

$$\frac{\partial h}{\partial t} = V_O - V_C = \left(\frac{m}{\rho_i} + |\mathbf{u_b}|\frac{h_r - h}{l_r}\right) - \left(\frac{hN}{\eta_i}\right)$$

Melt opening | Sliding over bumps | Creep closure of ice



A Darcy style flow law

$$\mathbf{q} = -\frac{k_0 h^3}{\eta_w}\nabla\phi$$

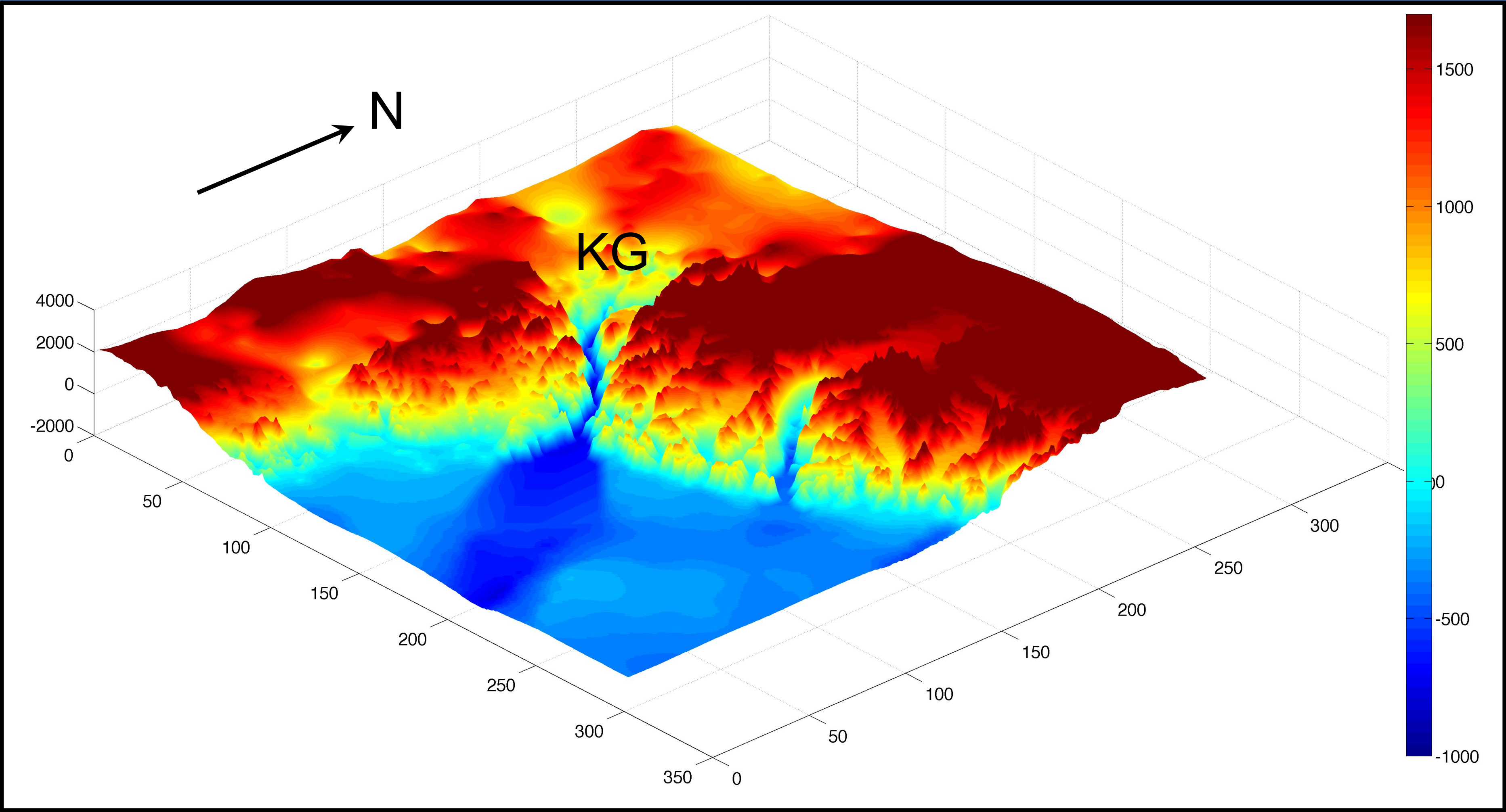
Heat from passive sources

(heat from water flow neglected)

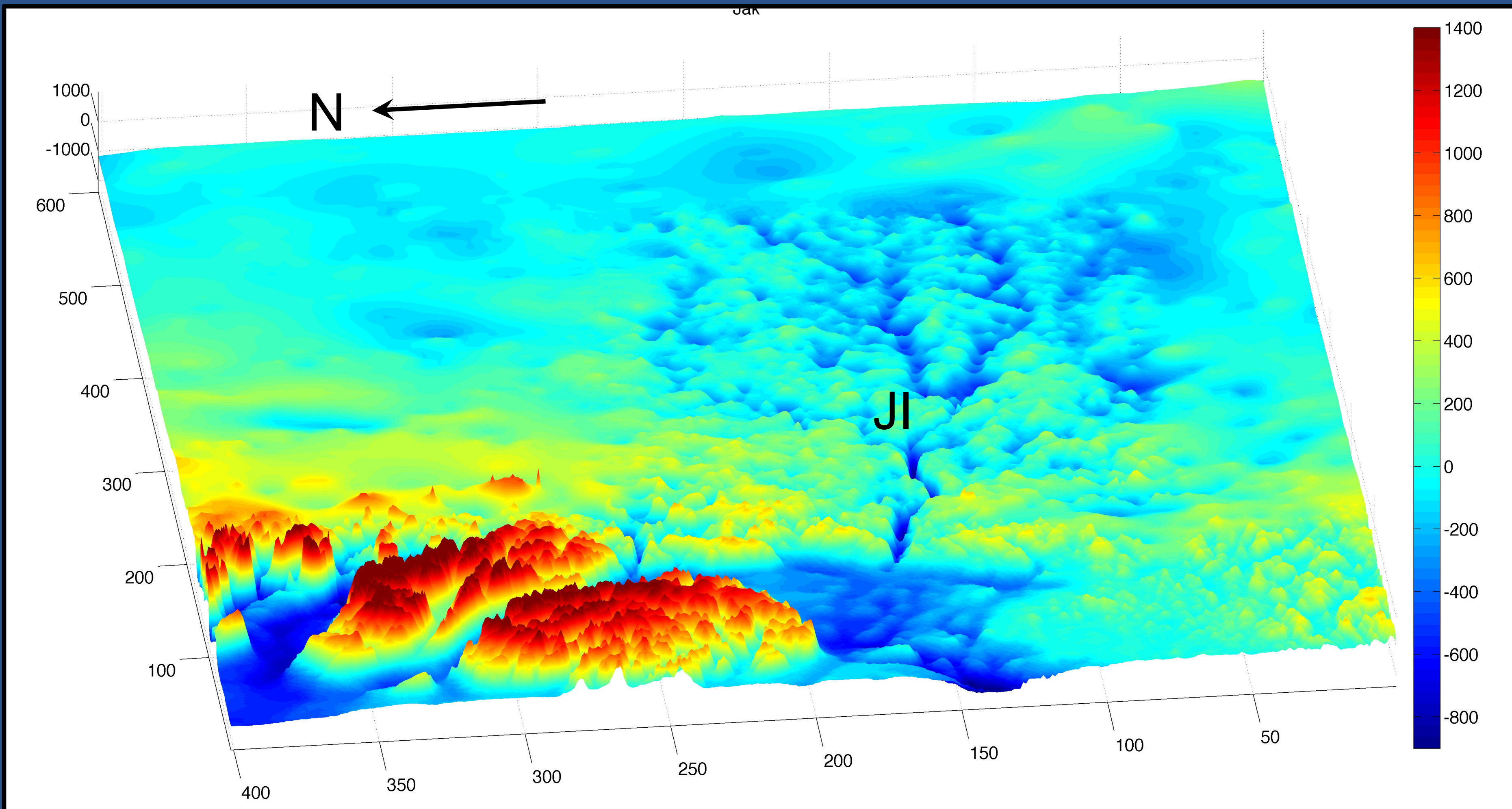
$$mL = G + \mathbf{u_b} \cdot \tau_\mathbf{b} - \cancel{\mathbf{q} \cdot \nabla\phi}$$

Model output: sheet thickness, water pressure, water flux, etc.

Kanger. Glacier Bed and Offshore Topography



Jak. Isbræ Bed and Offshore Topography



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

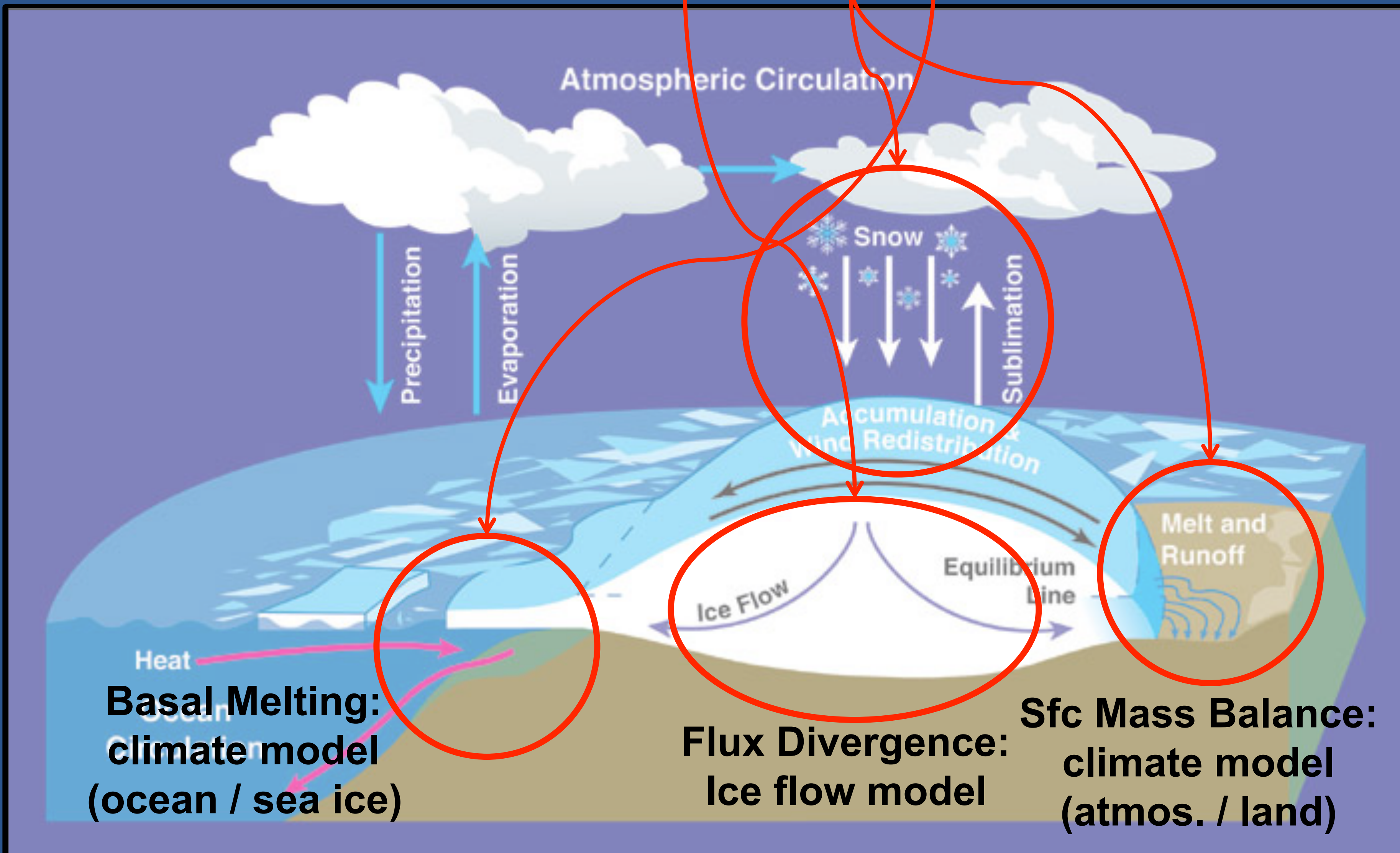
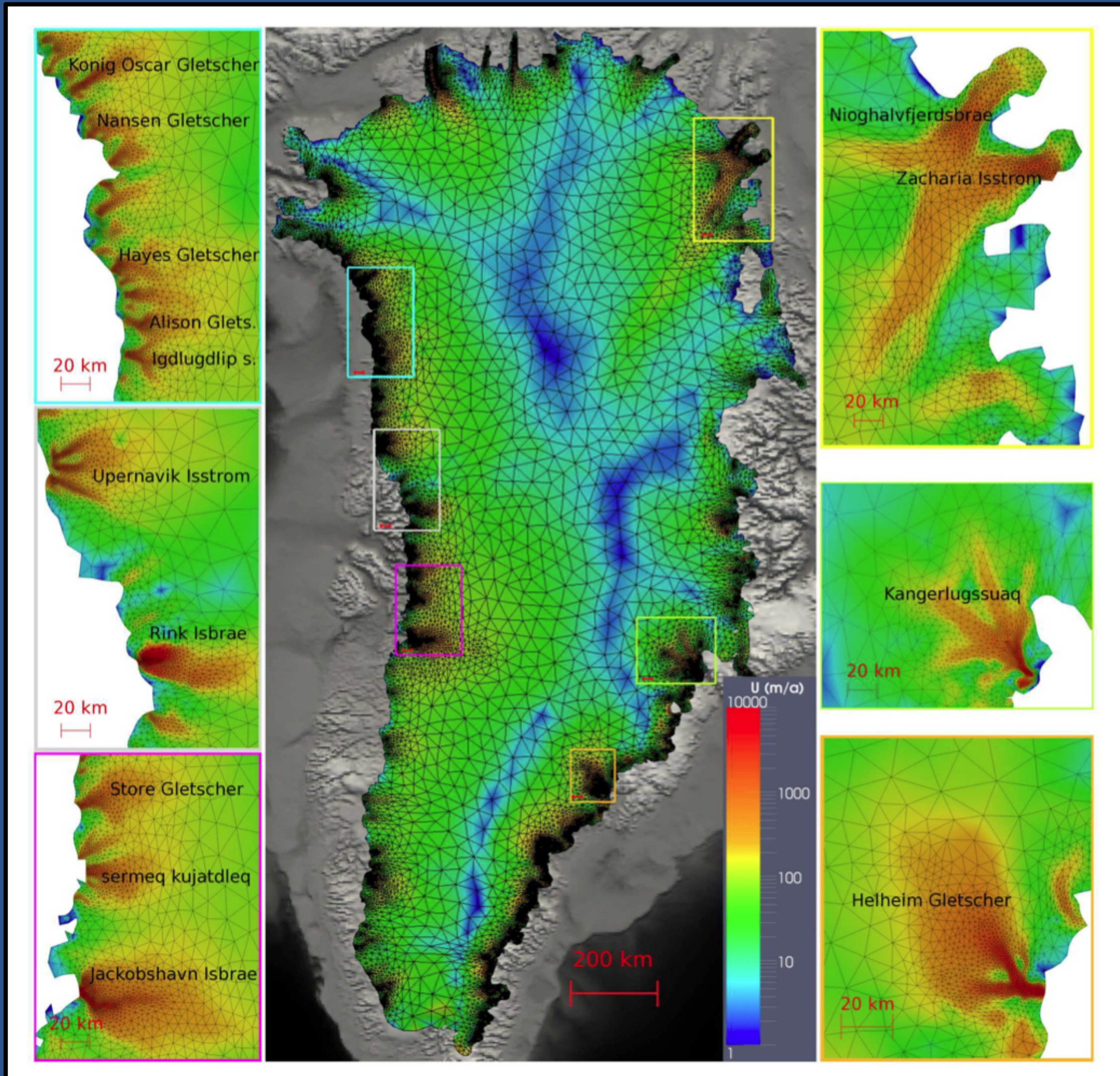


Image source: http://www.nasa.gov/images/content/53743main_atmos_circ.jpg

New Hi-Res Data Will Require Refined / Unstructured Grids



Gillet-Chaulet
et al., *TCD* (2012)

Community Earth System Model

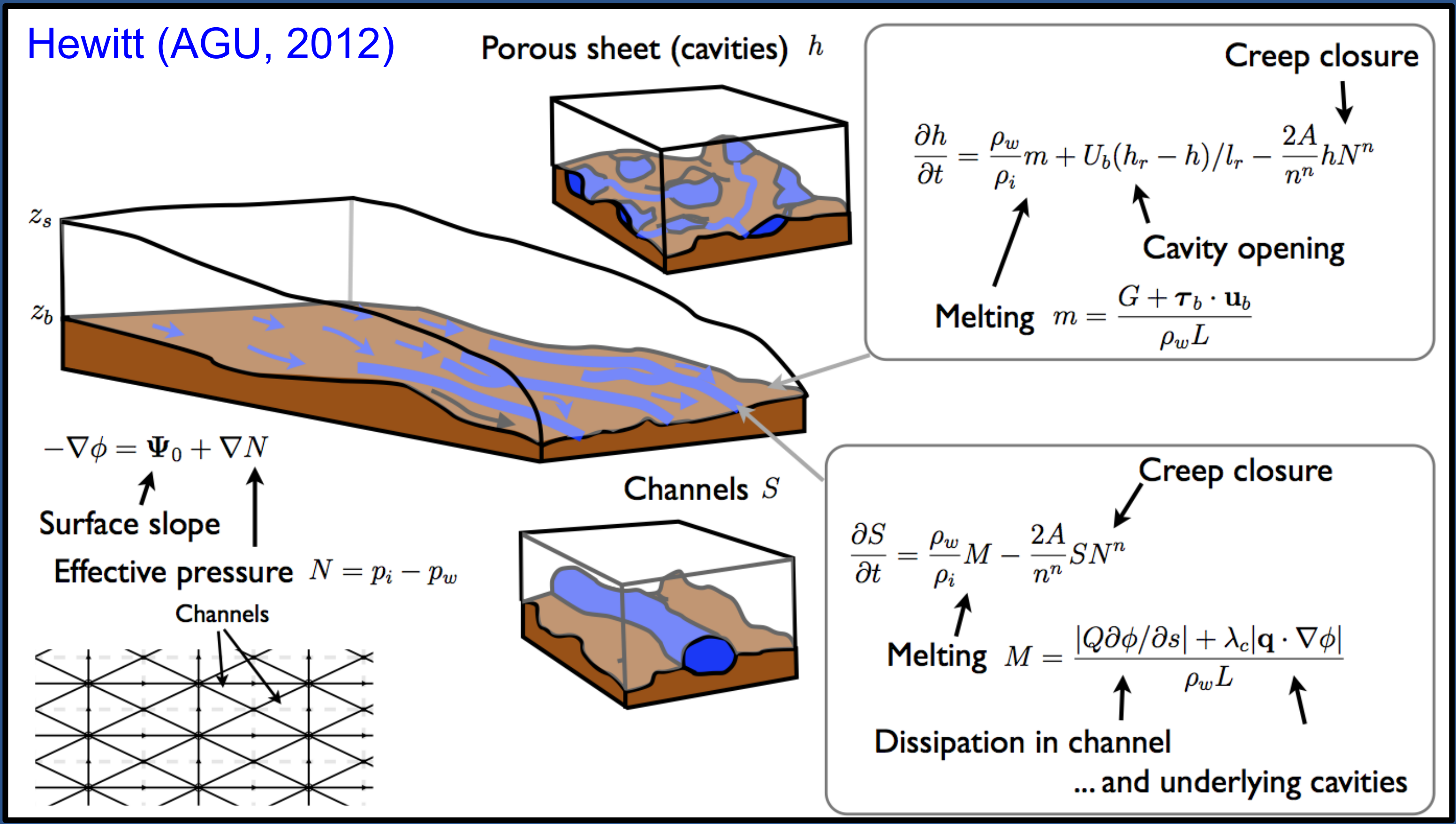
- CESM consists (largely) of:
  - Atmosphere model (CAM)
  - Land model (CLM)
  - Ocean model (POP)
  - Sea ice model (CICE)
  - Land ice model(s) (CISM)
    - 3d, regular / structured grid, SIA, FDM[1] (current)
    - "   " 1st-order ("Blatter-Pattyn"), FDM[2,3] (summer / fall 2013)
    - 2d, depth-integrated, block-structured AMR, "L1L2", FVM[4] (early 2014?)
    - 3d, unstructured, var-res (MPAS), SIA→Stokes, FEM[5,6] (2014?)

[1]Rutt et al., 2009 [2]Price et al., 2011 [3]Lemeiux et al., 2011 [4]Cornford et al., 2012 [5]Perego et al., 2012 [6]Leng et al., 2012

Evolutionary Subglacial Hydrology in CISM

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

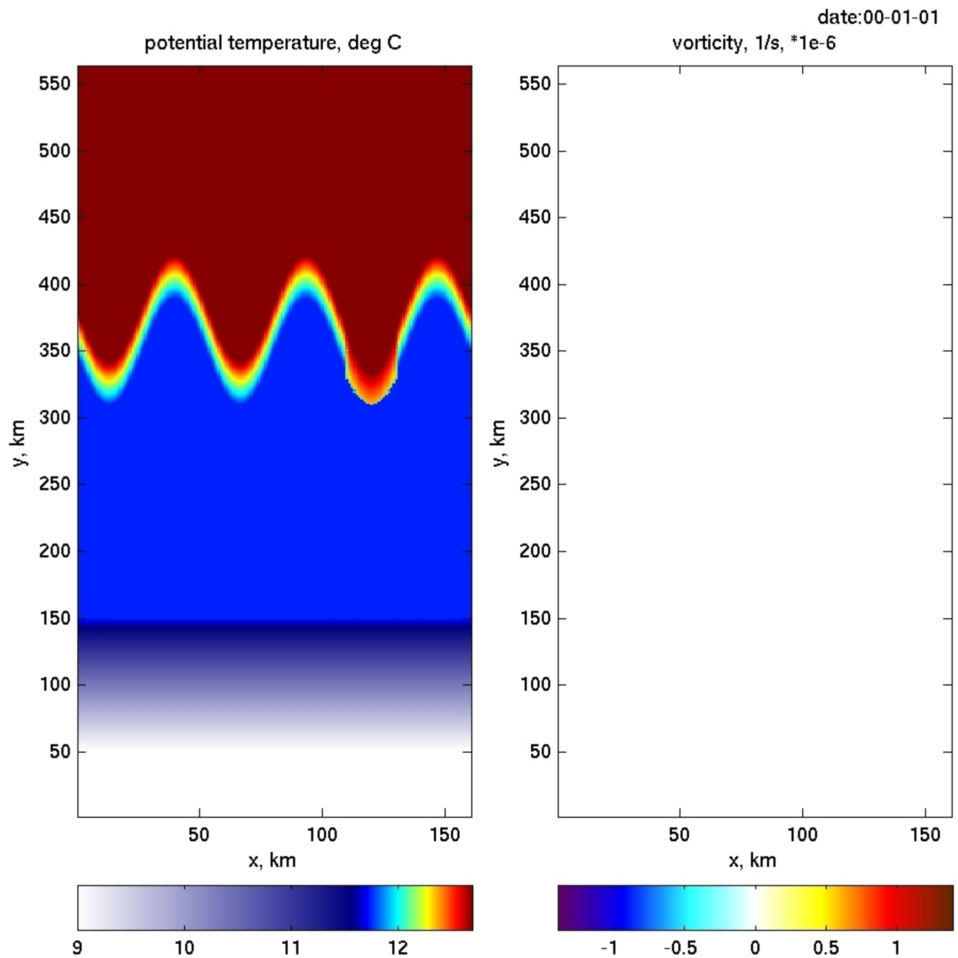
Coupled to water-pressure dependent sliding law with theoretical[2] and observational[3] support

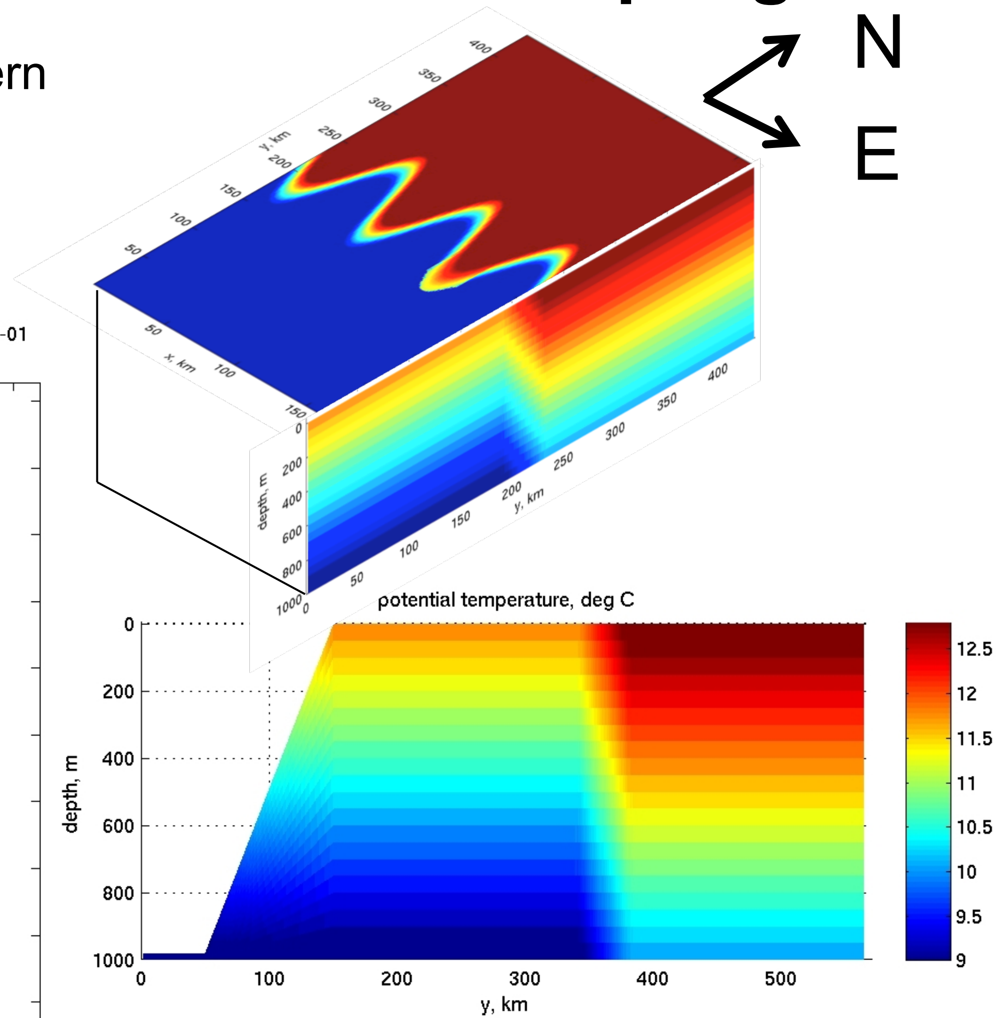


[1]Hoffman et al., AGU 2012 (after Creyts, Flowers, Hewitt, Schoof, Werder) [2]Schoof, 2005 [3]Iverson, 2011

MPAS-Ocean: Ice Shelf & Ocean Coupling

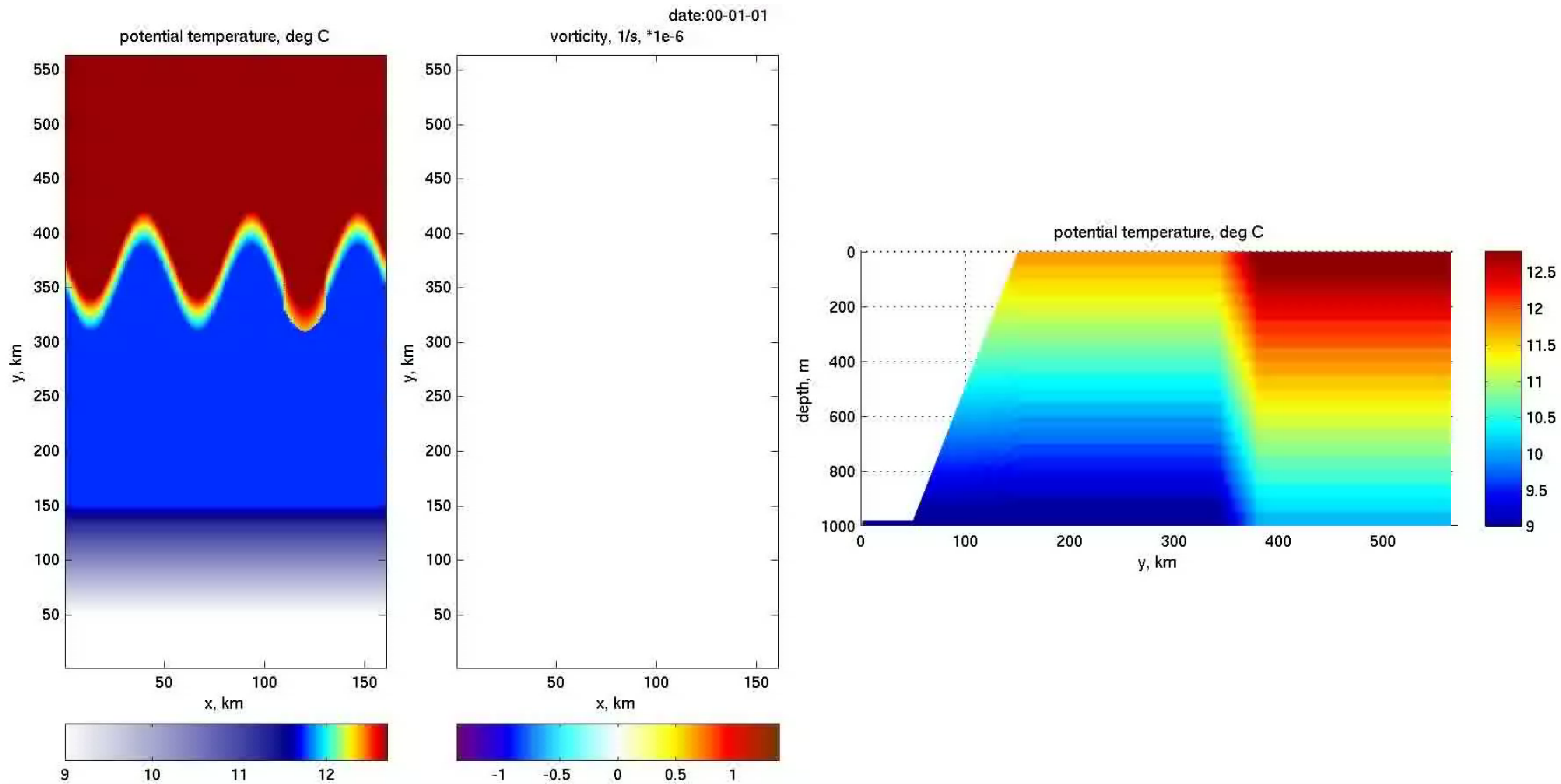
- Surface pressure applied to southern 150km, constant in time.
- Baroclinic instability in northern portion.





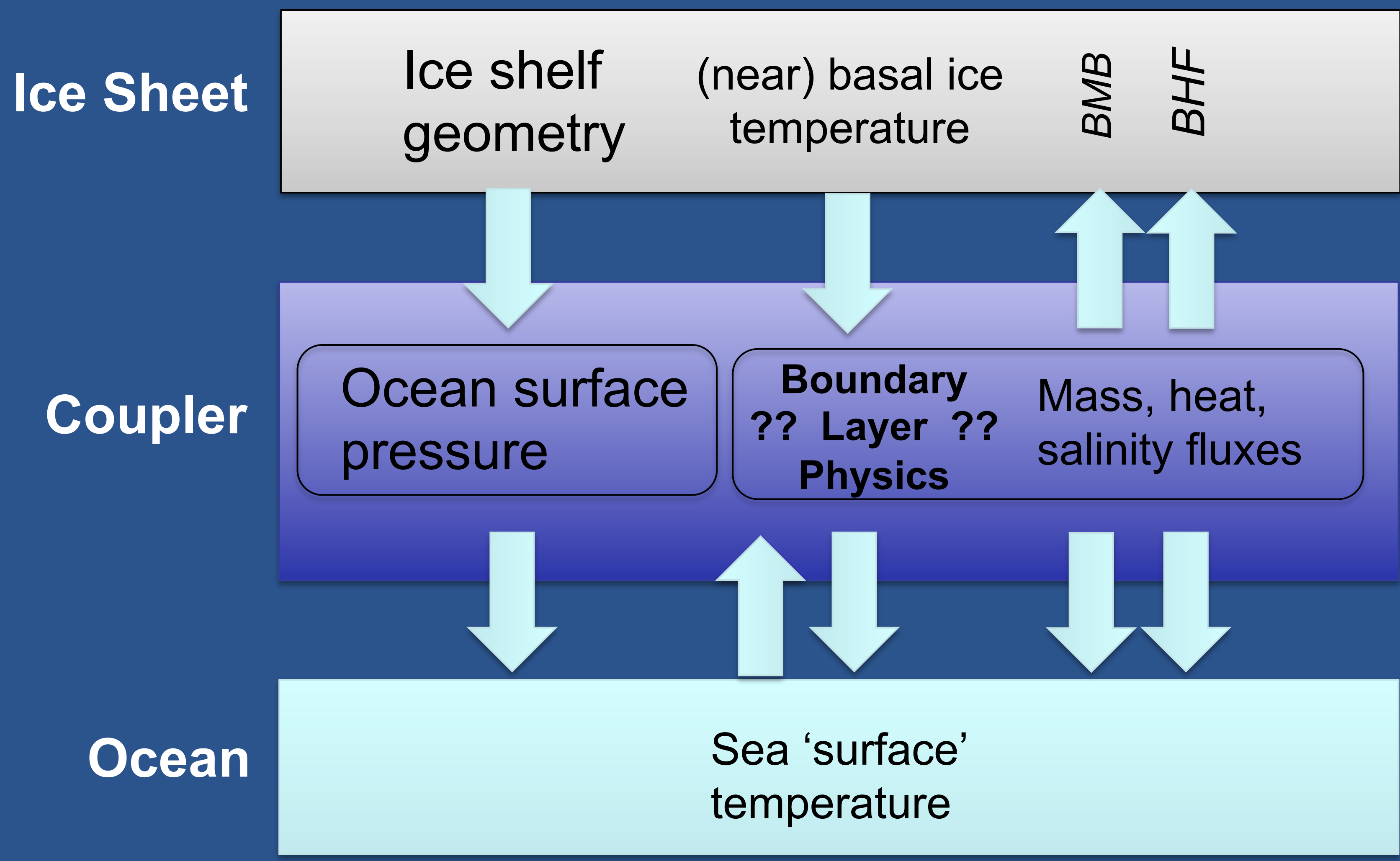
Slide courtesy of Mark Petersen (LANL)

- Surface pressure applied to southern 150km, constant in time.
- Baroclinic instability in northern portion.

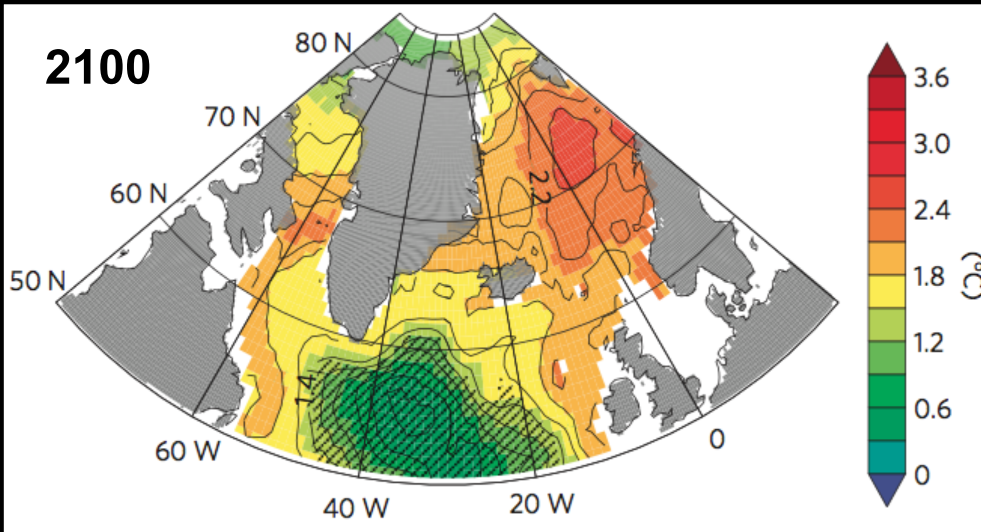


Slide courtesy of Mark Petersen (LANL)

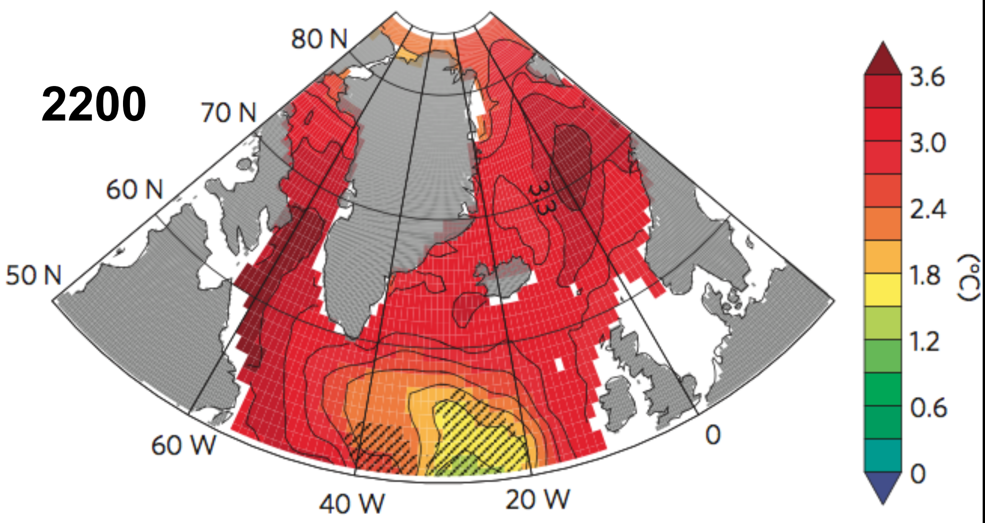
Coupling (offline) of Ice Sheet & Ocean



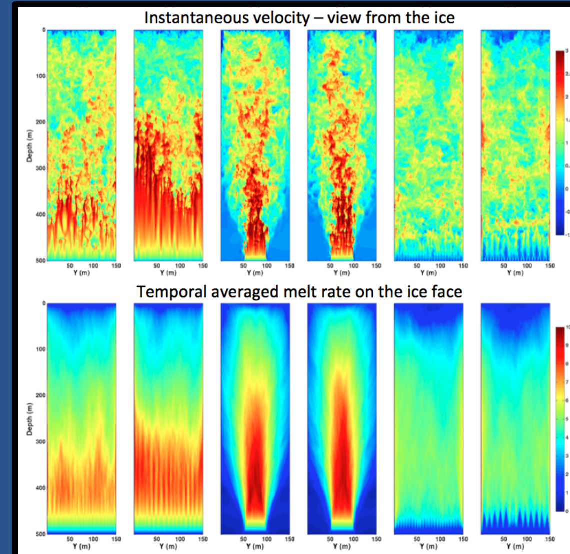
Ice Sheet & Ocean Coupling: Challenges



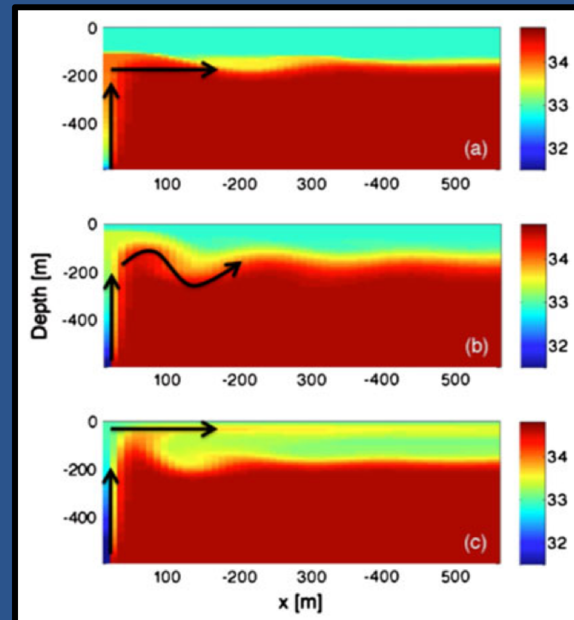
Yin et al., *Nat. Geosc.* (2011)



Warming at depths of 200-500 m (Yin et al. *Nat. Geosc.* 2011)

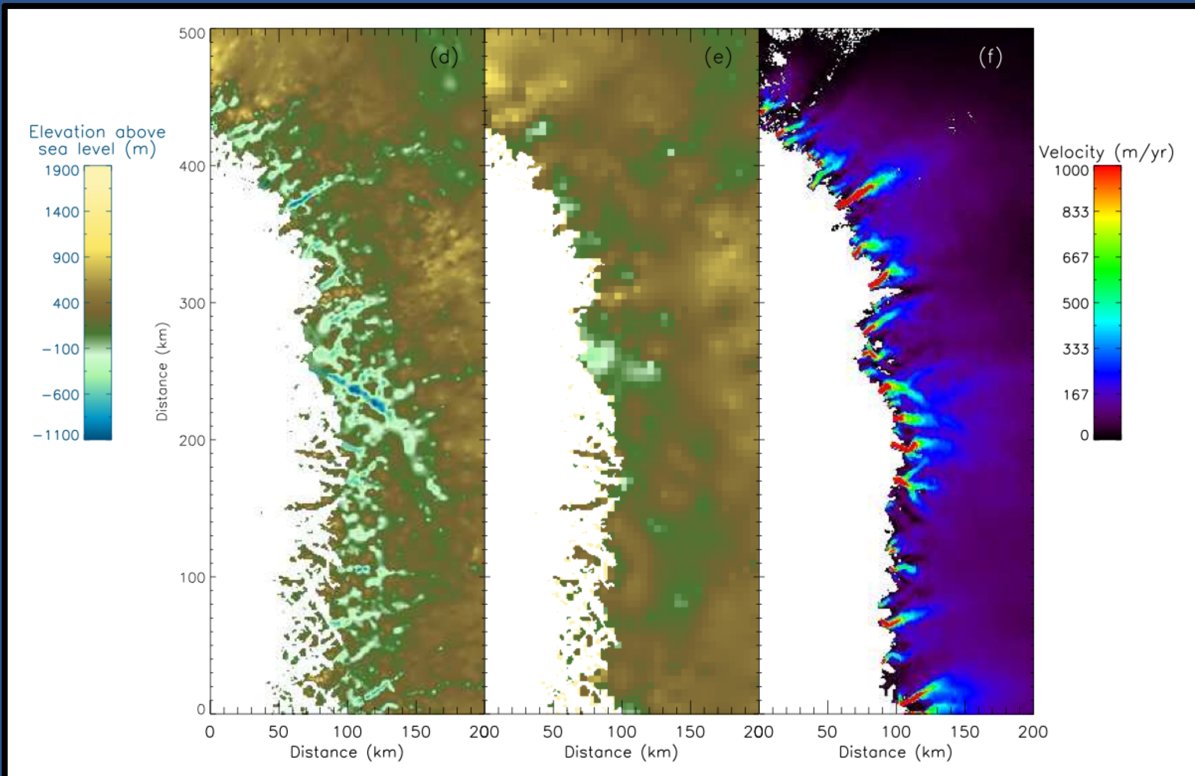


Y. Xu et al. *AGU* (2007)

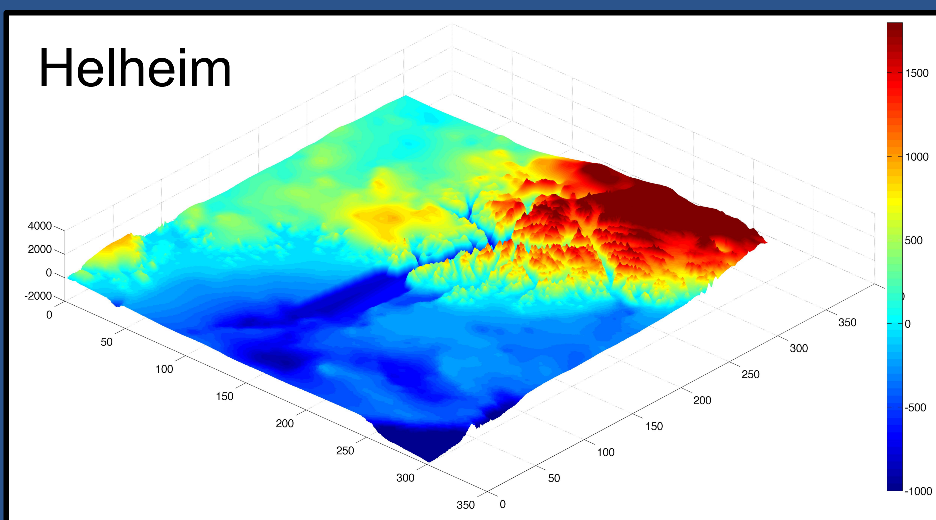


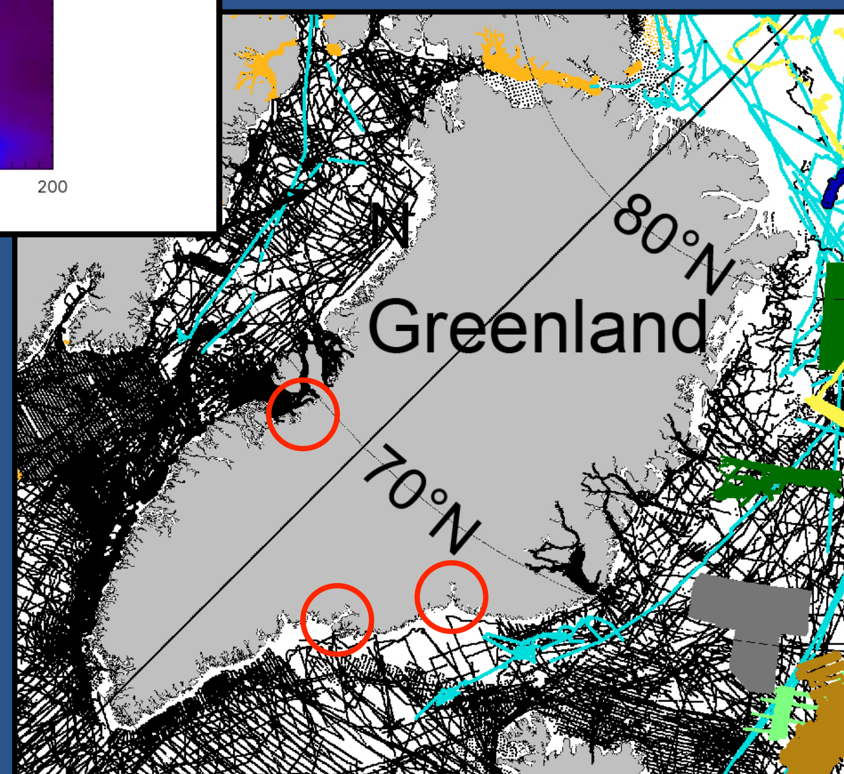
Sciascia et al. *JGR* (2013)

Assume perfect models … when will we have adequate topography (bed & bathym.) data?



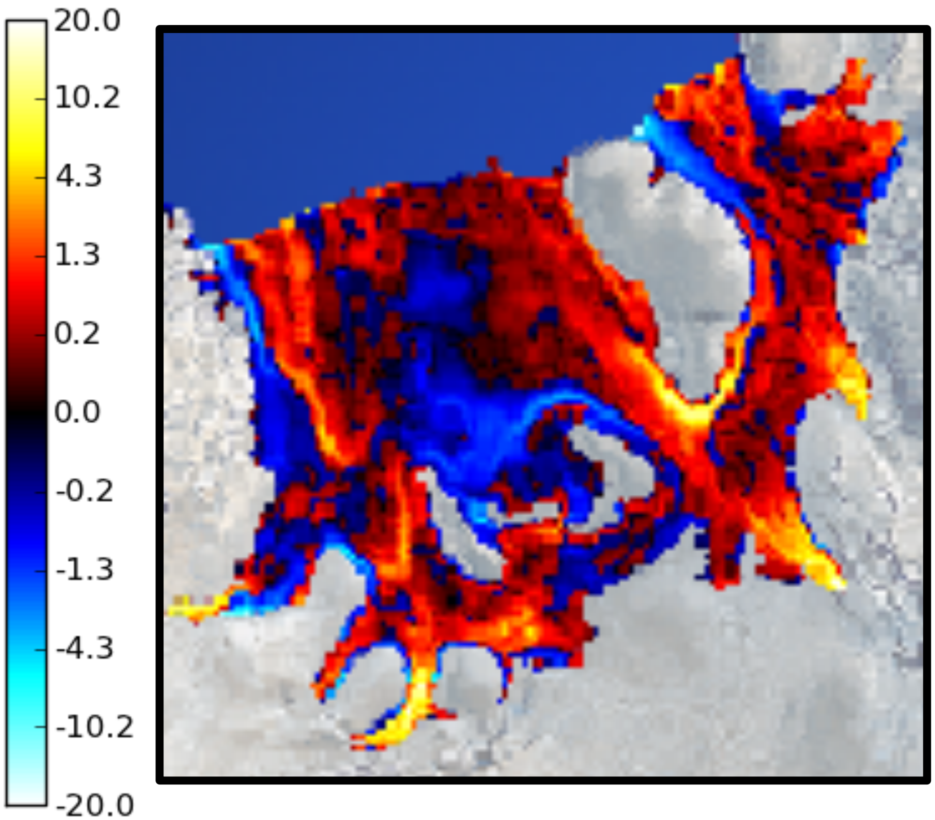
Bamber et al. *TC*, **7** (2013)

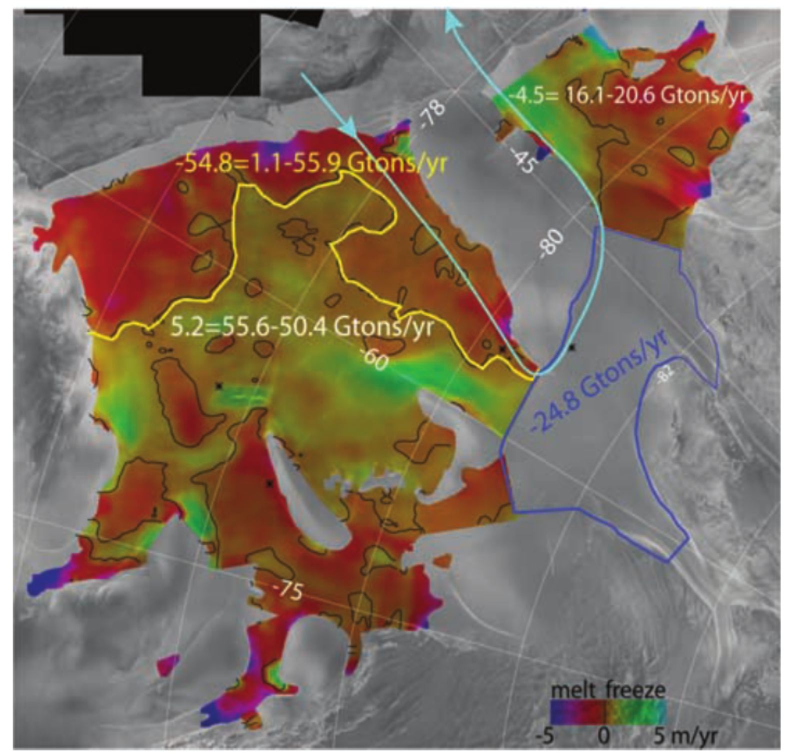




Jakobsson et al., *GRL*, **35**, 2008 (& 2012)

Ice-Ocean Coupling:
Antarctica / S. Ocean Simulation

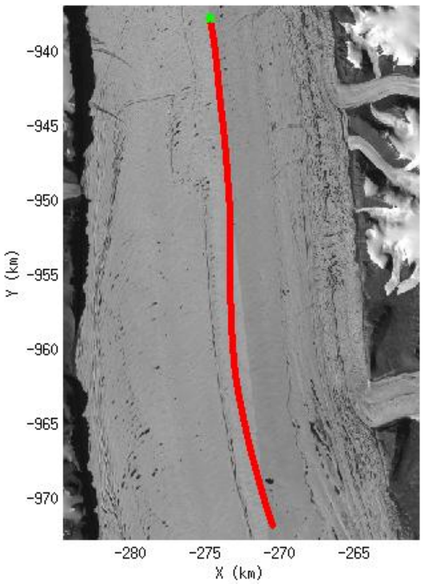




Joughin and Padman (2003)

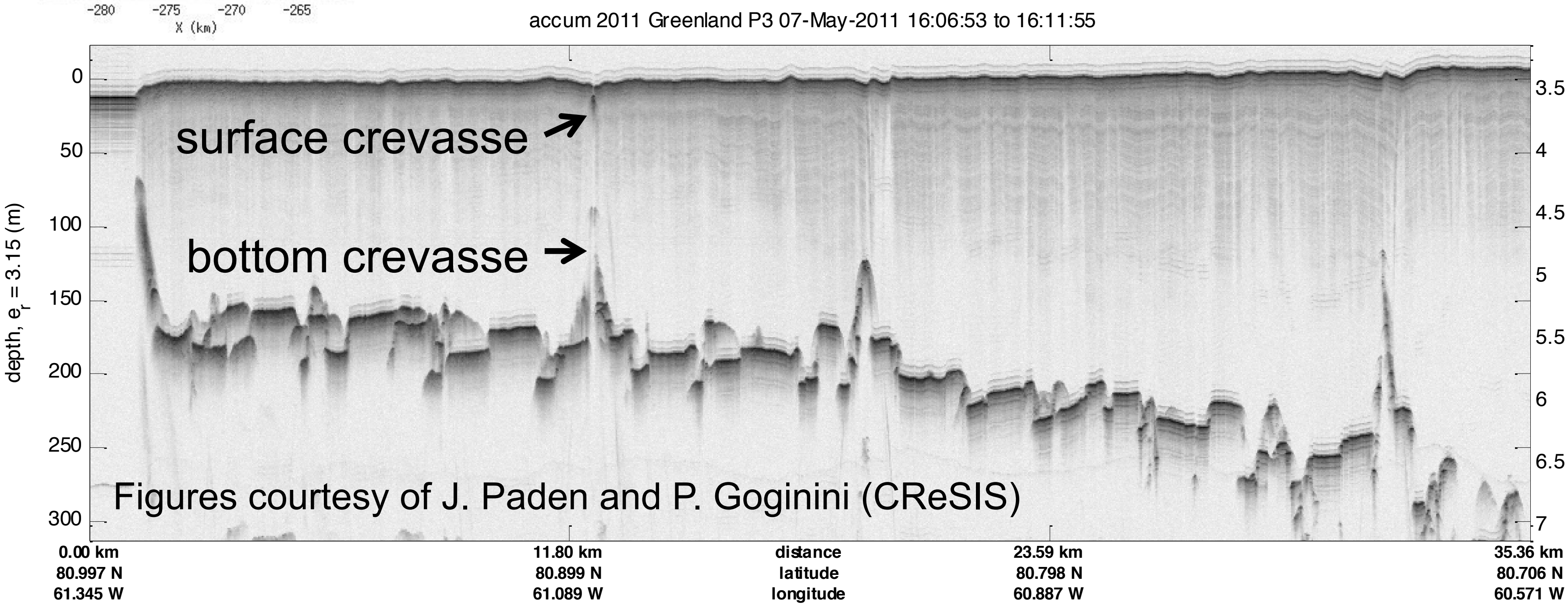
Simulations and figures courtesy of X. Asay-Davis (LANL / PIK)

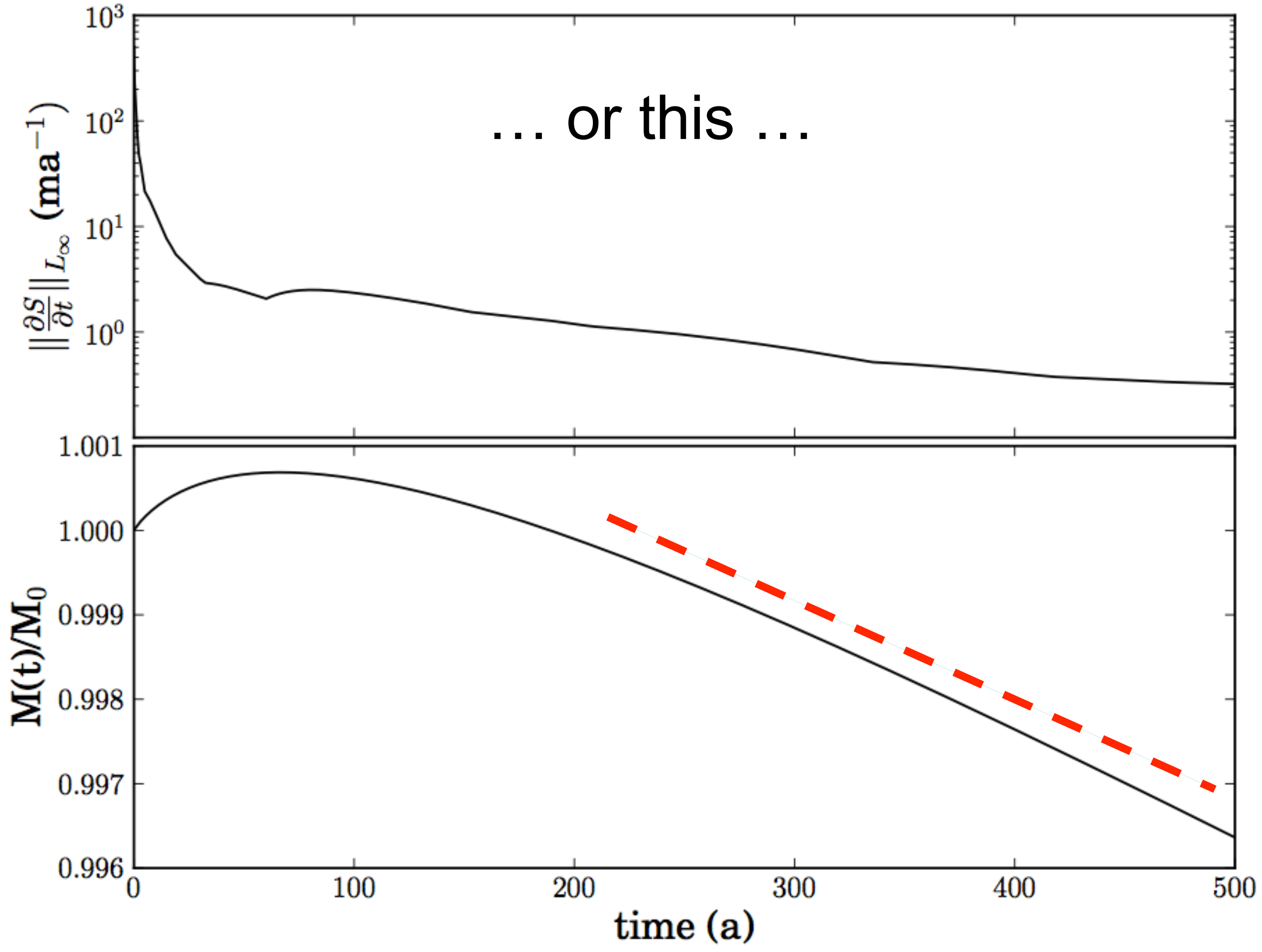
Measuring Submarine Melt Rates Using Phase-Sens. Airborne Radar



Petermann Glacier

(pre-July 16, 2012 break)





Brinkerhoff et al., *TCD* (2013)

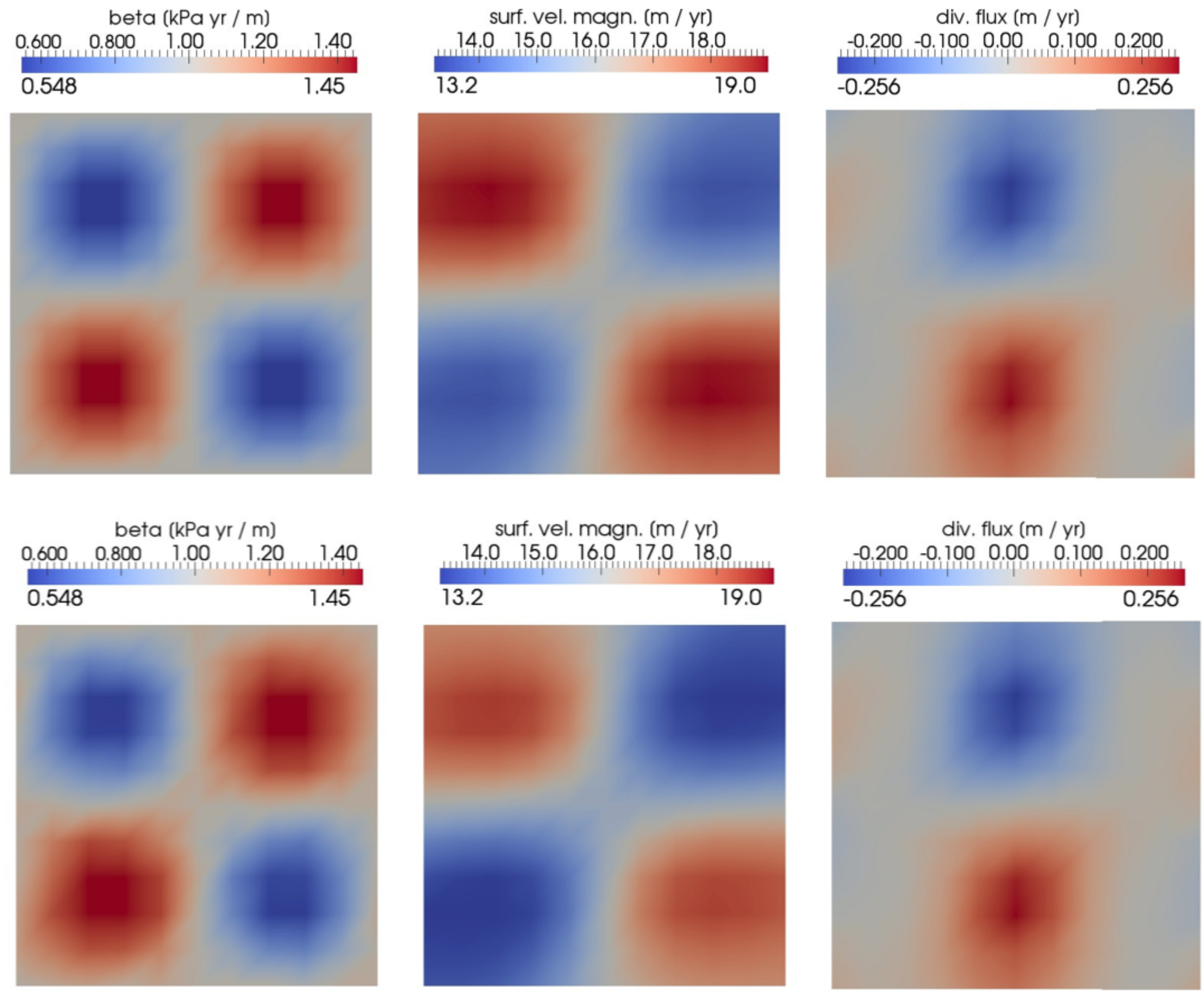
Coupled Land Ice & ESM Initialization

sliding coeff. | sfc speed | target SMB

Truth (synthetic)

… add noise to SMB …

Recovered (It works!)



Figures from Mauro Perego (SNL)