Probabilistic Sea Level Projections from Ice Sheet and Earth System Models (ProSPect)

Stephen Price[1] and Esmond Ng[2]

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U.S. DEPARTMENT OF
ENERGY
Office of Science

E3SM
Energy Exascale
Earth System Model

SciDAC
Scientific Discovery
through
Advanced Computing

Motivation and Background

Project Goals

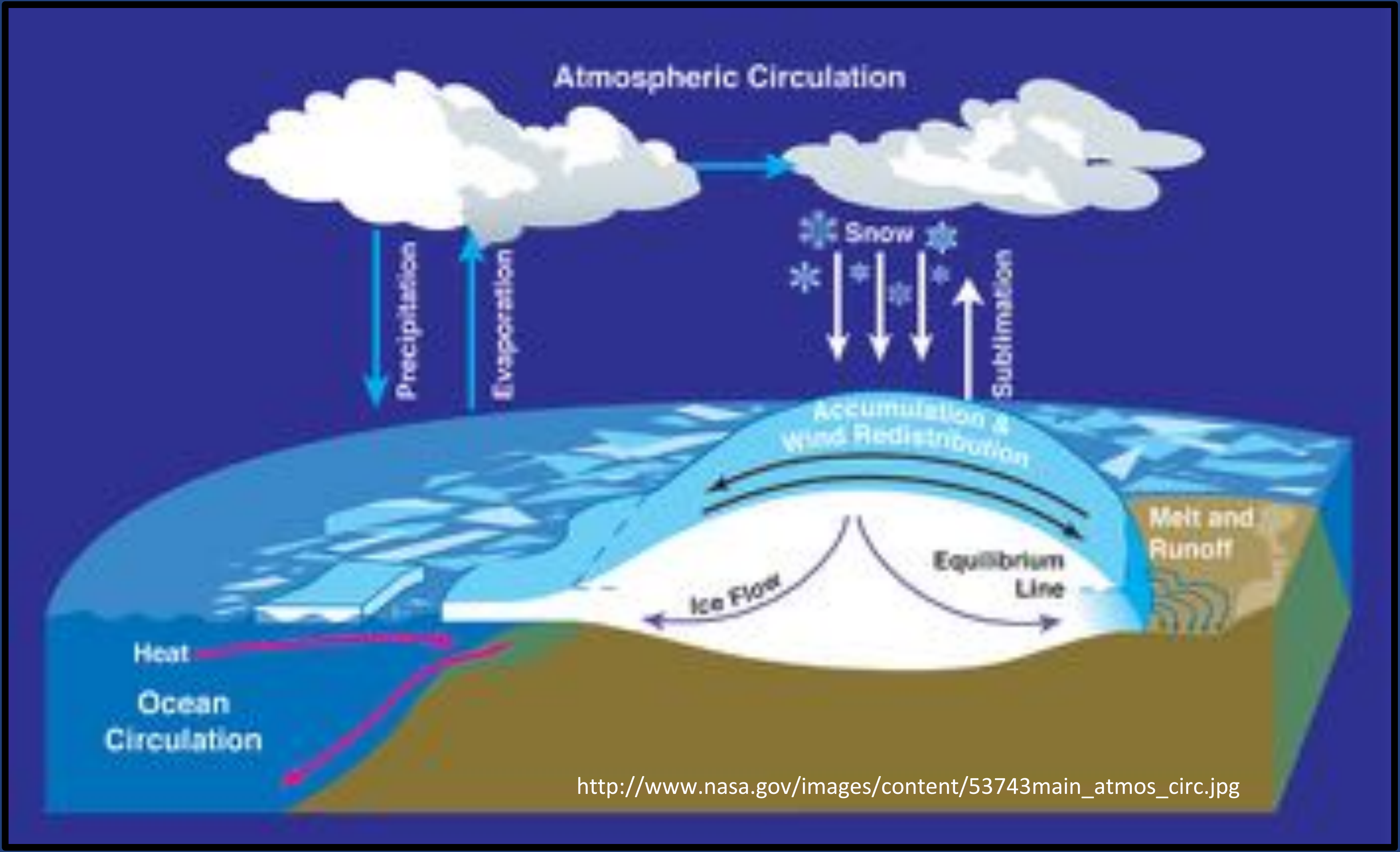
Highlights

Progress

Summary

Motivation & Background

Ice sheets are a source (or sink) for global sea level

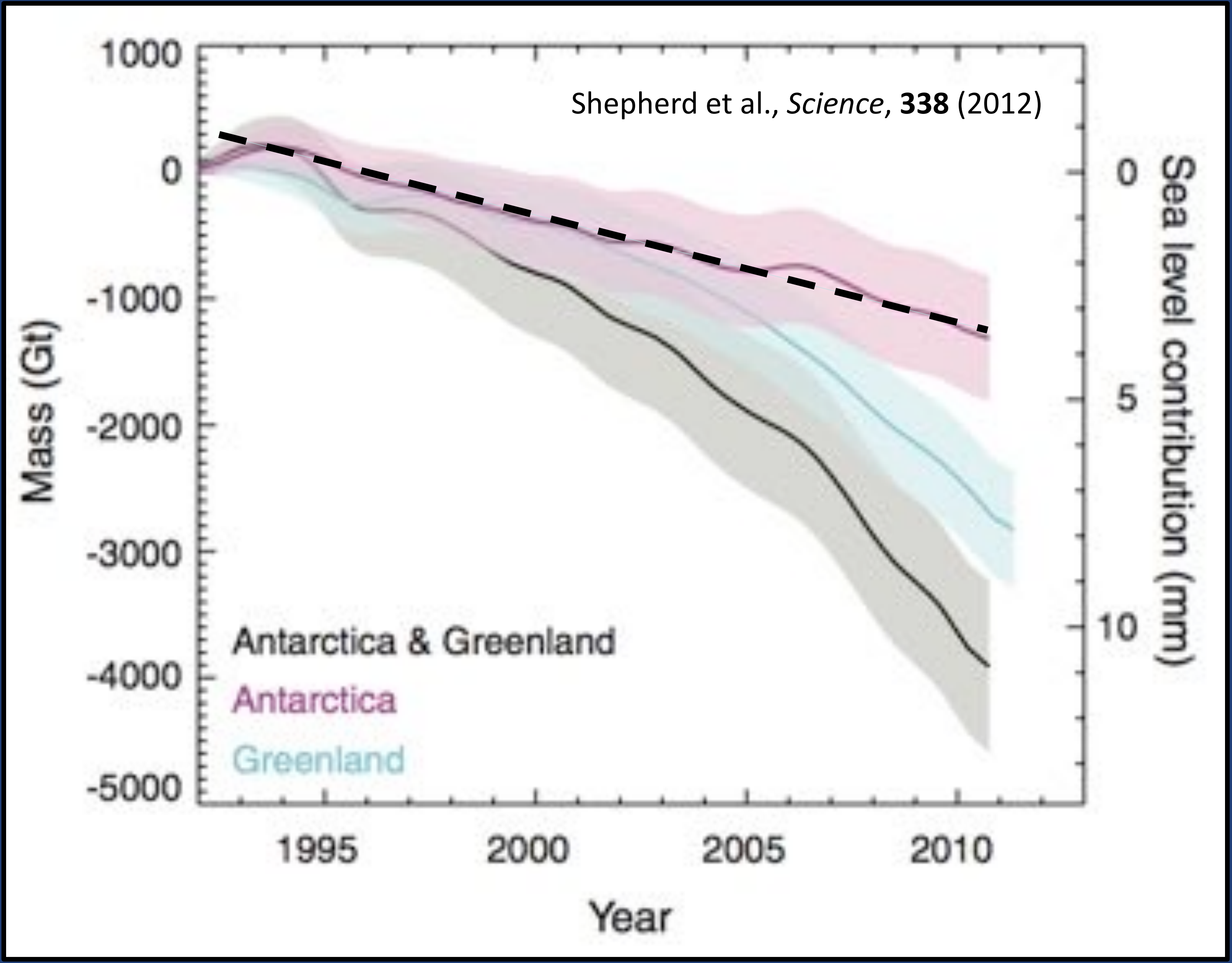


http://www.nasa.gov/images/content/53743main_atmos_circ.jpg

Mass Balance: ice sheet mass change = mass in – mass out
(sea level change) *(snowfall)* *(melt, calving)*

Motivation & Background

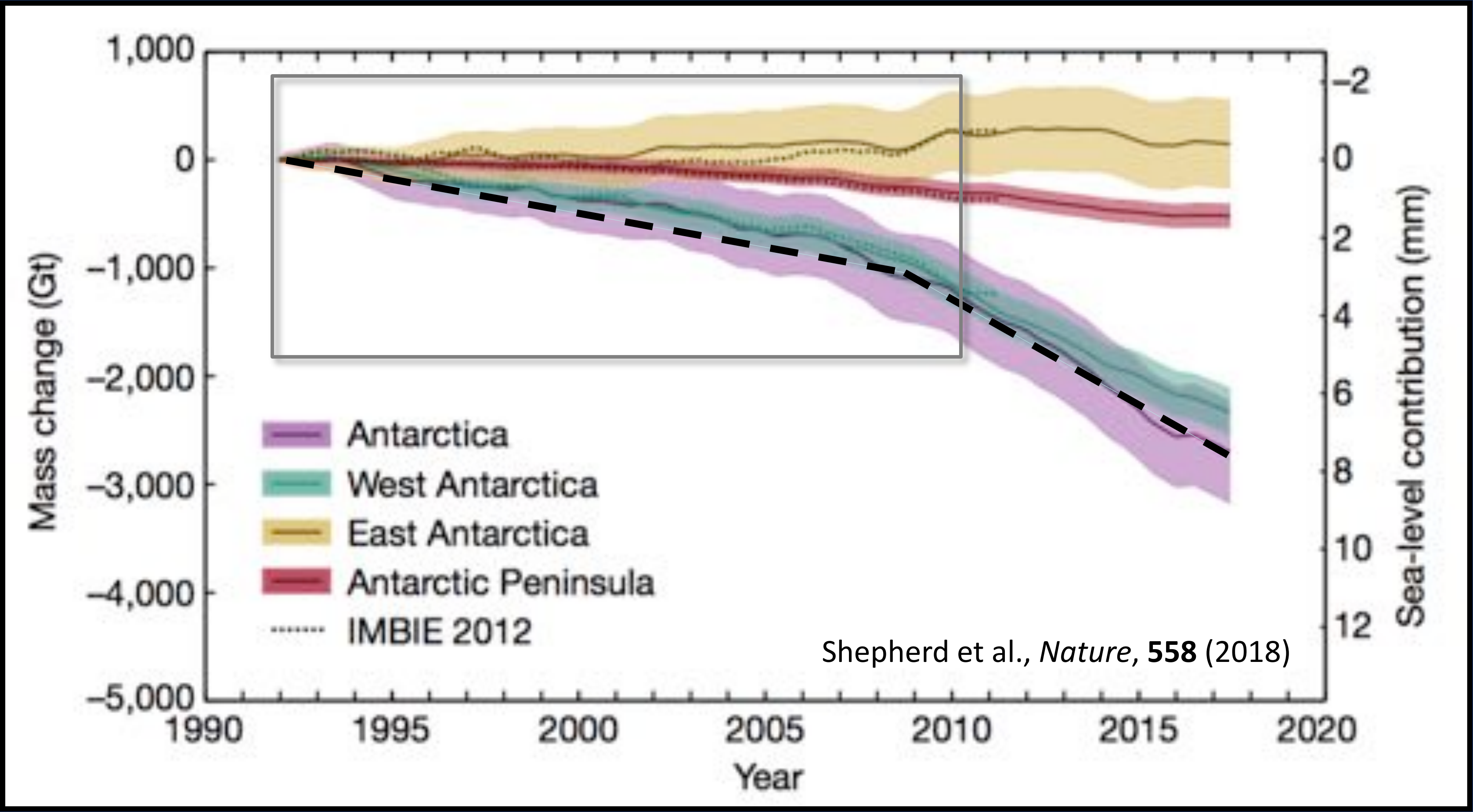
Mass loss from ice sheets is accelerating (along with sea level rise)



Shepherd et al., *Science*, **338** (2012)

Motivation & Background

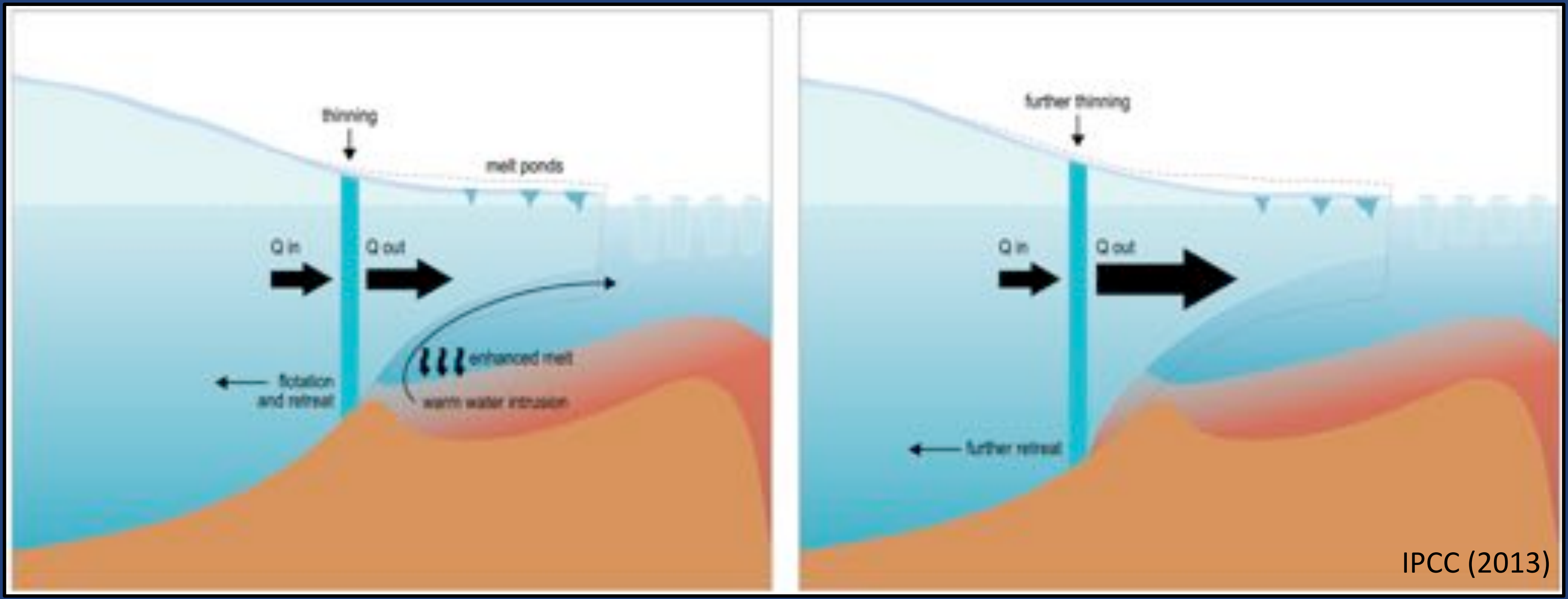
Mass loss from ice sheets is accelerating (along with sea level rise)



Shepherd et al., *Nature*, **558** (2018)

Motivation & Background

The West Antarctic Ice Sheet (WAIS) is of particular concern



IPCC (2013)

- changes in ocean circulation allow warm water to access ice shelf cavities, increasing submarine melt rates and ice shelf thinning
- ice shelf thinning decreases their ability to restrict the flux of ice from inland
- increased flux leads to retreat of the boundary between the ice sheet and shelves (the “grounding line”), which further increases ice flux and thinning, leading to further retreat (the “marine ice sheet instability”)
- future mass loss from WAIS is largest uncertainty w.r.t. future sea level projections

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ProSPect will address limitations to DOE ice sheet models (ISMs) and E3SM that prevent their application towards accurate sea-level projections. Specific focus areas include:

1. currently missing or inadequate ISM physics
2. partial or missing coupling between E3SM and ISMs
3. ISM initialization methods for coupled E3SM+ISM simulations
4. uncertainty propagation for probabilistic sea-level projections

ProSPect builds on two ice sheet models – BISICLES and MALI – developed under the SciDAC3 *PISCESS* project.

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Highlights: *ProSPect* All-Hands Meeting

SNL, Jan. 24-25, 2019

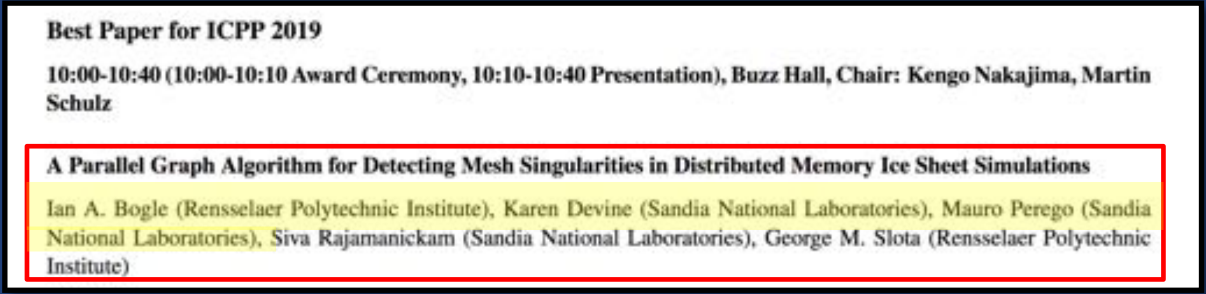
Goals:

- updates on progress & challenges from lab & project leads
- Identify where we are on or ahead of schedule
- Identify where we are behind schedule (and discuss mitigation)
- improve connections between sub-project focus areas

Highlights: Project Output

- papers:
  - 8 published, 4 accepted, 4 in review
  - 4 in prep. (2 via external leads)
  - ~2/3 of all papers include both ASCR & BER authors
- 45 presentations (~2 per month)
- 2 mature, publicly released, HPC ice sheet models (partially) coupled to E3SM (BISICLES, MALI)
- LIVVkit 2.1.6 V&V software (used by CESM, ISMIP6)
- contributions to 8 MIPS (leadership on 4)
- leadership on exp. design & param. devel. for ISMIP6

Highlights: Visibility



Best Paper for ICPP 2019

10:00-10:40 (10:00-10:10 Award Ceremony, 10:10-10:40 Presentation), Buzz Hall, Chair: Kengo Nakajima, Martin Schulz

A Parallel Graph Algorithm for Detecting Mesh Singularities in Distributed Memory Ice Sheet Simulations

Ian A. Bogle (Rensselaer Polytechnic Institute), Karen Devine (Sandia National Laboratories), Mauro Perego (Sandia National Laboratories), Siva Rajamanickam (Sandia National Laboratories), George M. Slota (Rensselaer Polytechnic Institute)

SNL student awarded best paper at ICPP 2019 for ice sheet model devel. work

The Cryosphere, 13, 1547–1564, 2019
https://doi.org/10.5194/tc-13-1547-2019
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The Cryosphere
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EGU

Regional grid refinement in an Earth system model: impacts on the simulated Greenland surface mass balance

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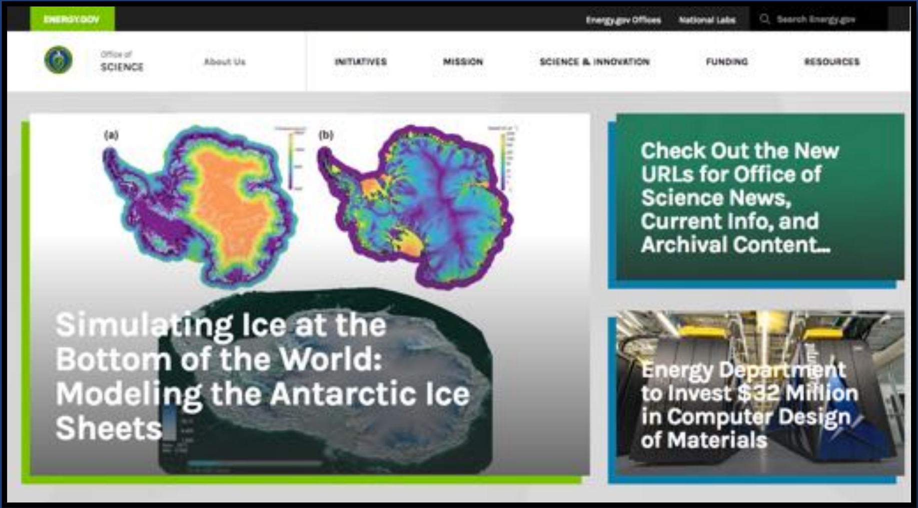
[5]Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder CO, USA

LIVVkit used by CESM Land Ice Working Group

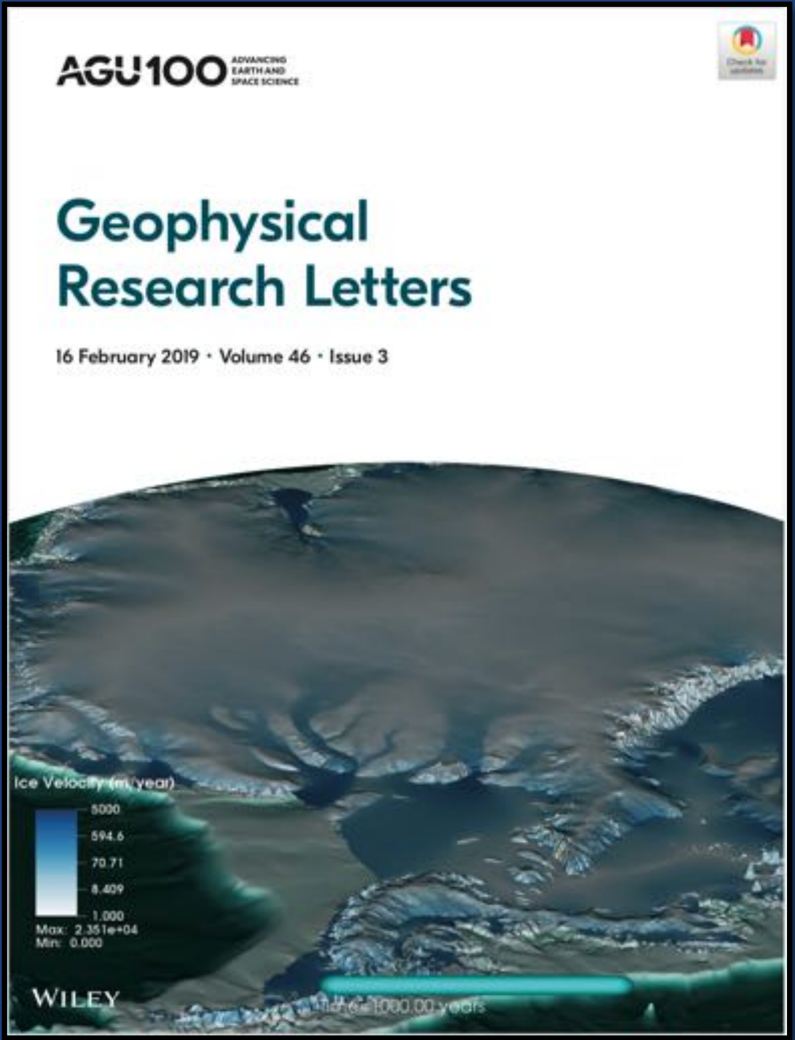


Simulating Ice at the Bottom of the World: Modeling the Antarctic Ice Sheets

Check Out the New URLs for Office of Science News, Current Info, and Archival Content...

Energy Department to Invest $32 Million in Computer Design of Materials

ice sheet modeling efforts featured on DOE BER homepage



Geophysical Research Letters

16 February 2019 · Volume 46 · Issue 3

BISICLES cover graphic for *Geophys. Res. Lett.*

Motivation and Background

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Progress: damage, fracture, iceberg calving

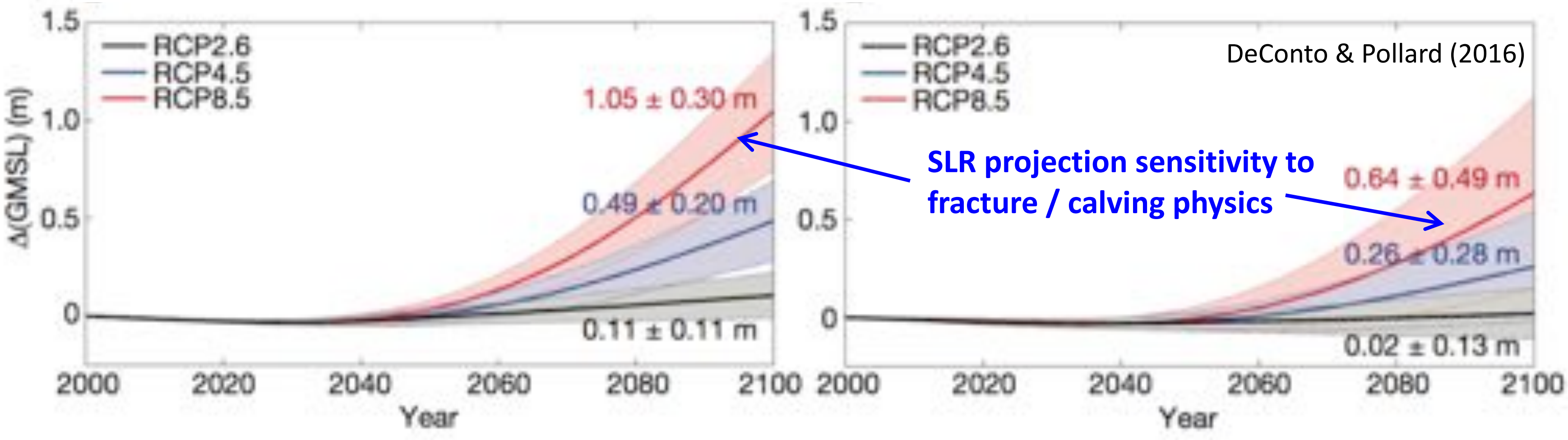
Importance:

- Ice shelves limit ("buttress") ice sheet flux to the ocean
- ice shelf thinning & iceberg calving reduce buttressing
- Ice shelf integrity is a function of fracturing (in turn a function of climate forcing), which is poorly understood & modeled

Need:

- Physics-based models of ice shelf fracture & its coupling to climate
- Characterization of impact & uncertainty on ice sheet evolution

Modeled Antarctic contribution to future sea-level rise



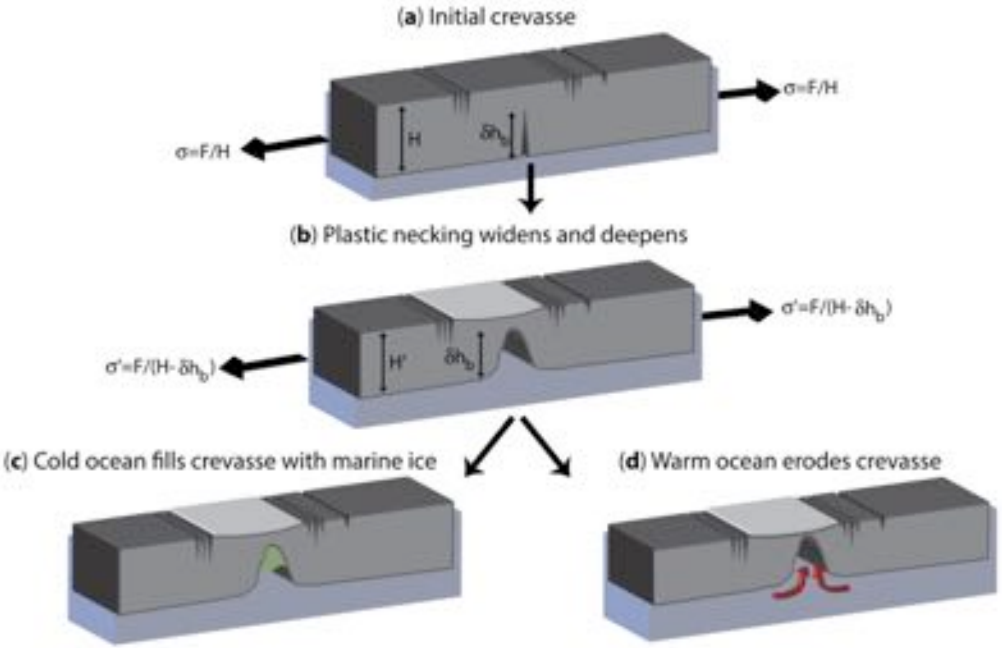
DeConto & Pollard (2016)

SLR projection sensitivity to fracture / calving physics

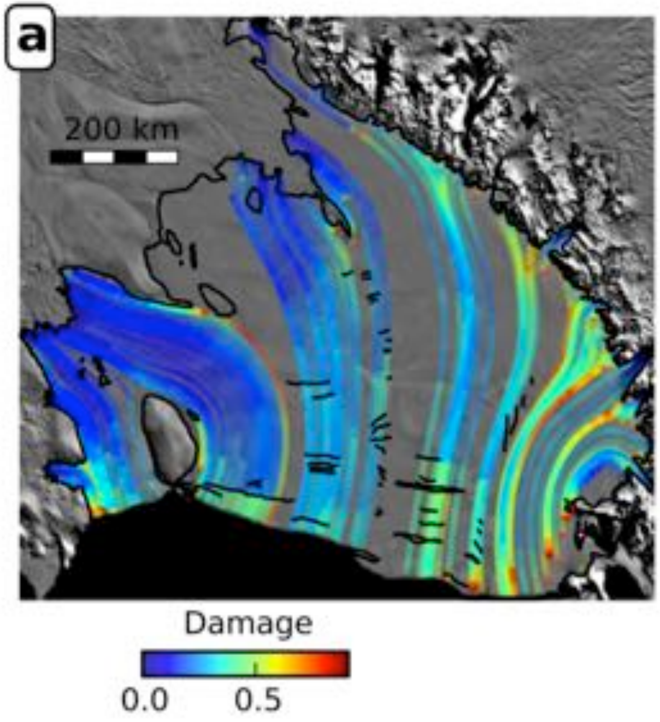
Progress: damage, fracture, iceberg calving

Approach:

- parameterize sub-grid scale fracture evolution through damage mech.
- Includes “hooks” to relevant climate forcing (surf. and basal melting)
- mature implementation in BISICLES; prototype implementation in MALI



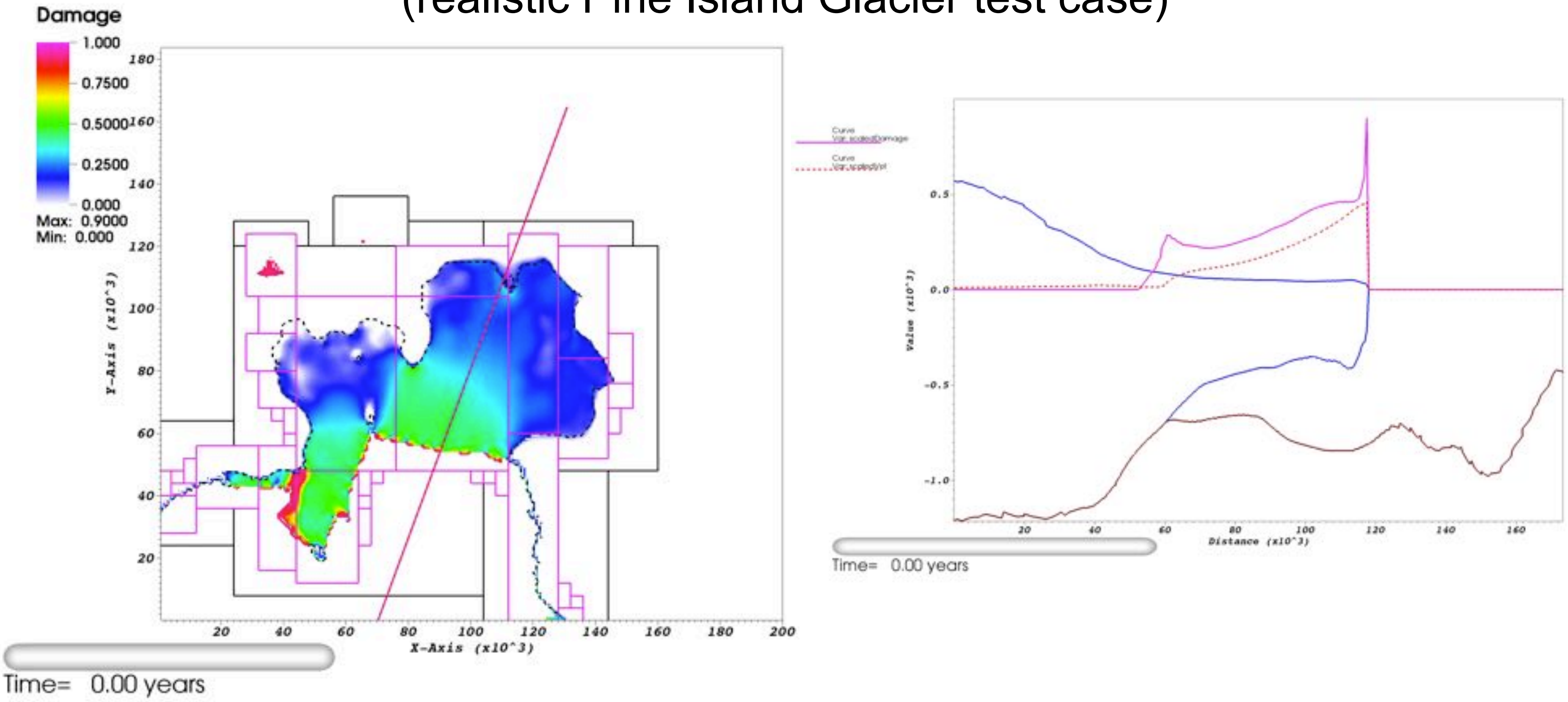
Bassis and Ma (2015)



Progress: damage, fracture, iceberg calving

BISICLES: relatively mature implementation of damage evolution

Damage evolution and advection in BISICLES
(realistic Pine Island Glacier test case)

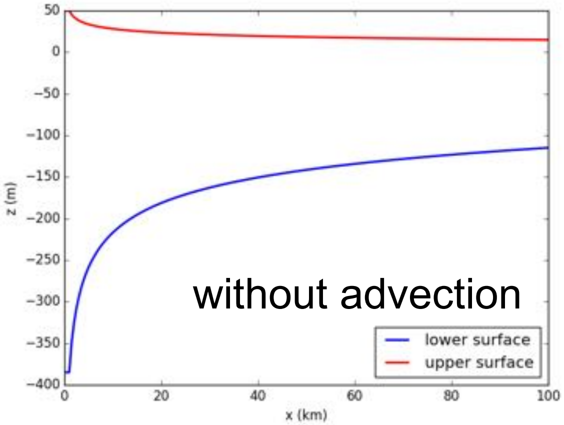


Progress: damage, fracture, iceberg calving

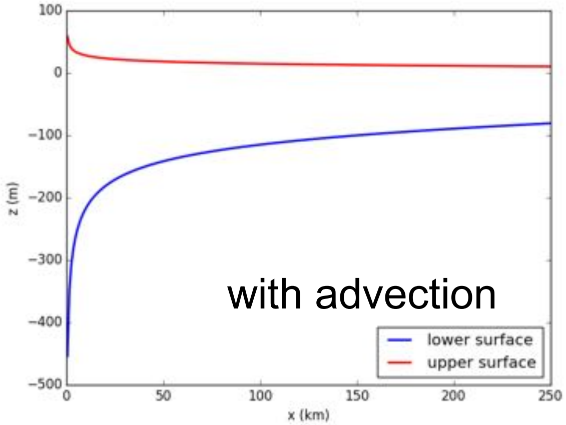
MALI:

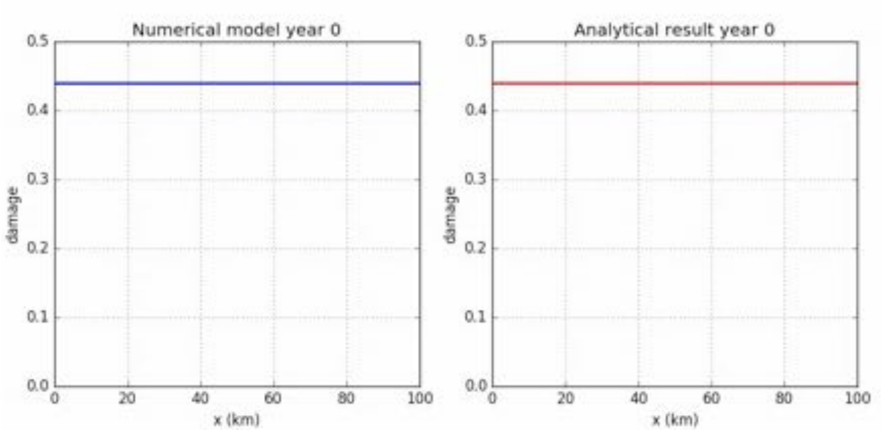
- initial damage evolution implemented
- being tested in analytical and idealized test case

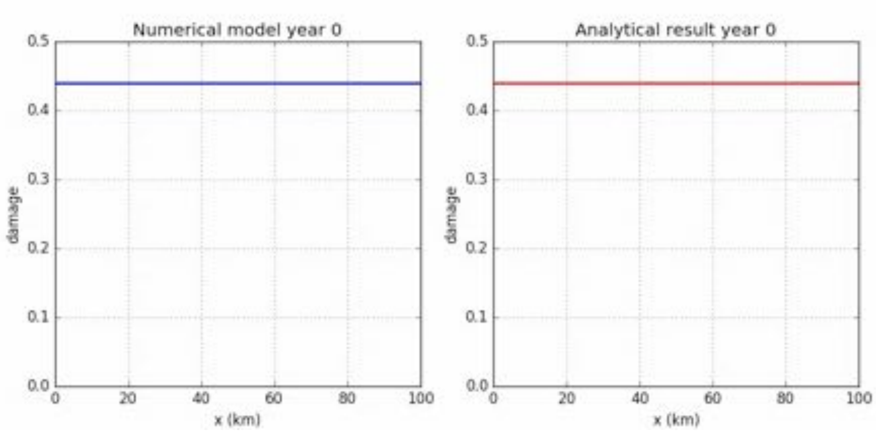
modeled damage in MALI vs. 1D analytic test cases


without advection

Analytic test cases from Whitcomb et al. (2019)


with advection





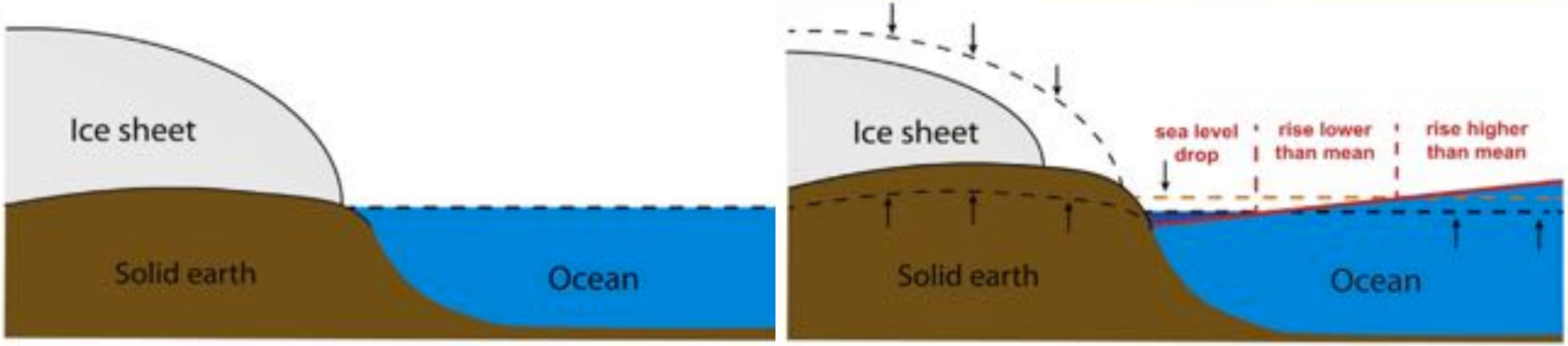
Progress: solid earth physics & coupling

Importance:

- solid earth responses to ice sheet mass loss result in significant *negative* feedbacks w.r.t. additional mass loss (and sea-level rise)
- currently unaccounted for in many models (including ours)

Need:

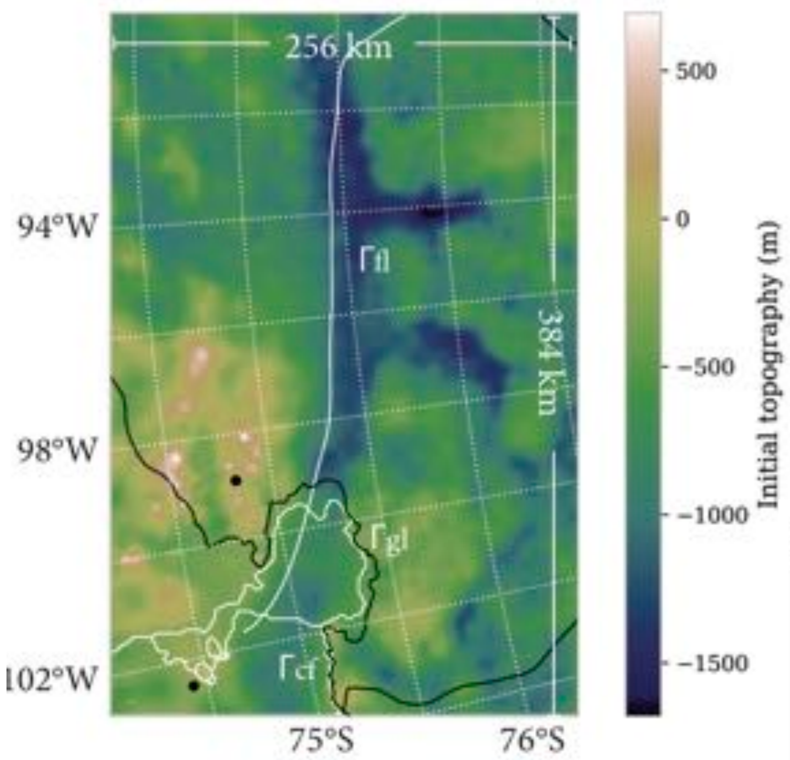
- appropriate models of solid earth response to ice sheet mass change
- coupling to allow for joint ice sheet & solid earth evolution

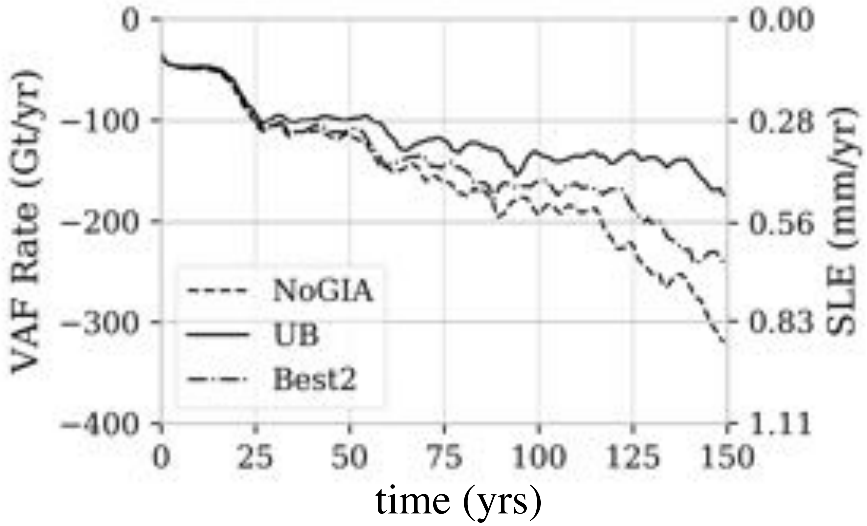


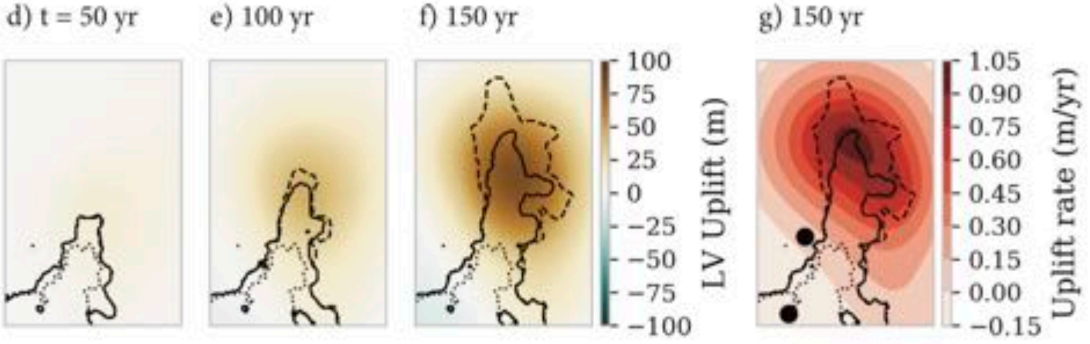
De Boer et al. (*QSR*, 2018)

Progress: solid earth physics & coupling

- BISICLES ice sheet model coupled to viscoelastic solid earth model
- Explore impact of low mantle viscosities on Pine Island Glacier (WAIS)
- Simulations of PIG retreat indicate that sea-level rise reductions of ~30-50% are possible depending on actual mantle viscosities



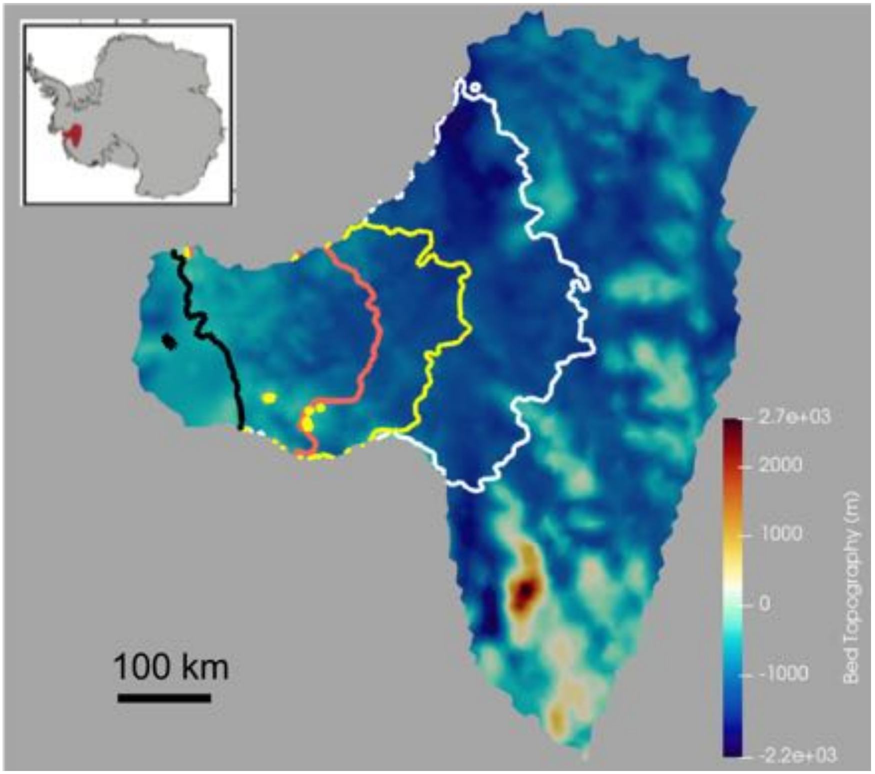




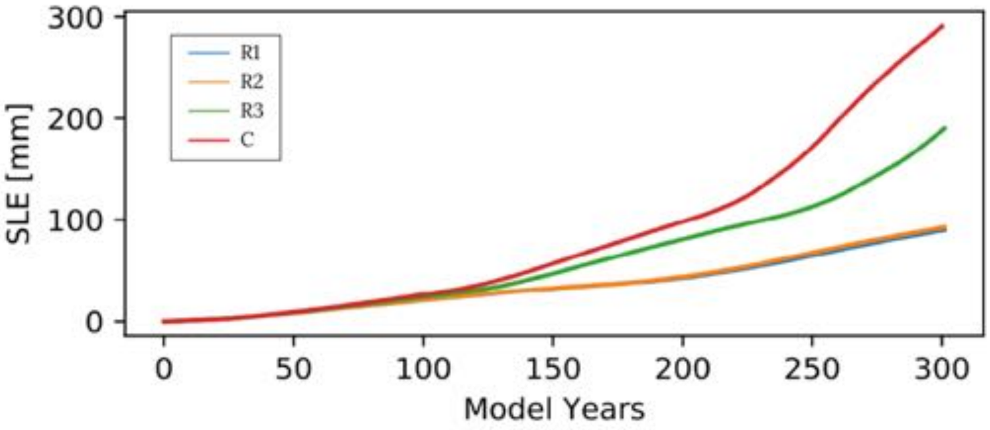
Kachuck et al. (*GRL*, submitted)

Progress: solid earth physics & coupling

- Application to Thwaites Glacier (WAIS) show similar sensitivity to PIG sims.
- Results demonstrate strong sensitivity to:
  - mantle viscosity
  - lithospheric thickness
  - ice sheet & solid earth model coupling interval
- Next: MALI & BISCLES applied to Thwaites + Pine Island glaciers



Left: Grounding line location after 300 years of retreat for no solid earth coupling (white), annual coupling (red), and coupling every ~30 years (yellow).



Above: Cumulative sea level (mm) without solid earth coupling (red) and for low (blue) and mid-range (orange) mantle viscosities. Low viscosity mantle and thick lithosphere results are shown in green.

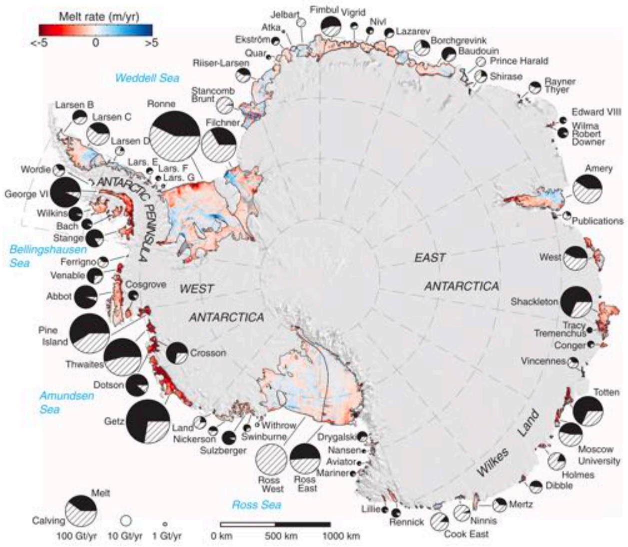
Progress: Ice Sheet & ESM coupling

Ice sheets evolve due to forcing from atmosphere & ocean:

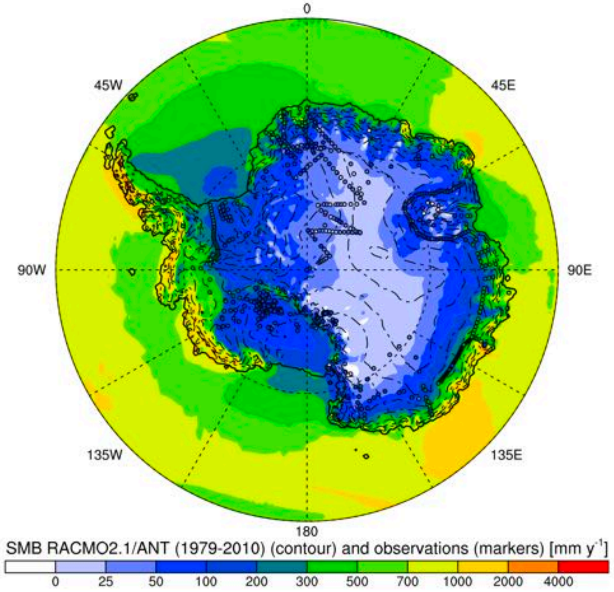
- snowfall - melting - sublimation = surface mass balance (SMB)
- sub-ice shelf freezing - melting = basal mass balance (BMB)

Greenland & Antarctica have different sensitivities to each:

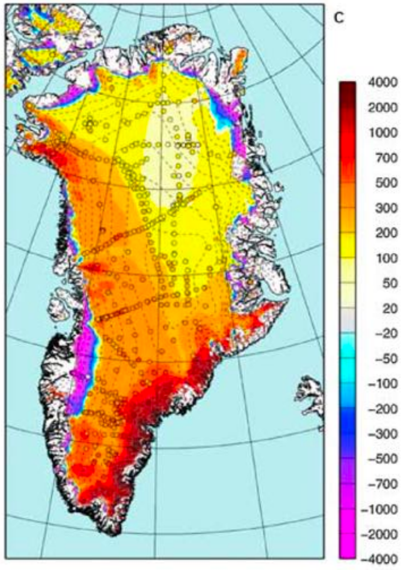
- Greenland mass loss – primarily surface melting
- Antarctic mass loss – approx. equal parts submarine melting and iceberg calving



Antarctic BMB (Rignot, 2013)



Antarctic SMB (Lenaerts, 2012)



Greenland SMB (Ettema, 2009)

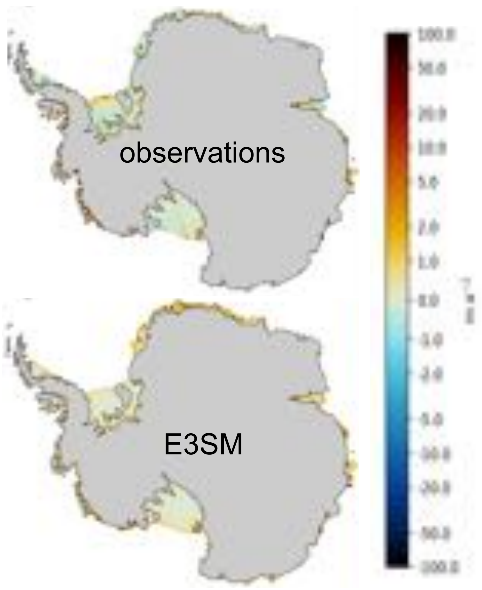
Progress: Ice Sheet & ESM coupling

Testing, validating, and improving SMB & BMB in E3SM is ongoing:

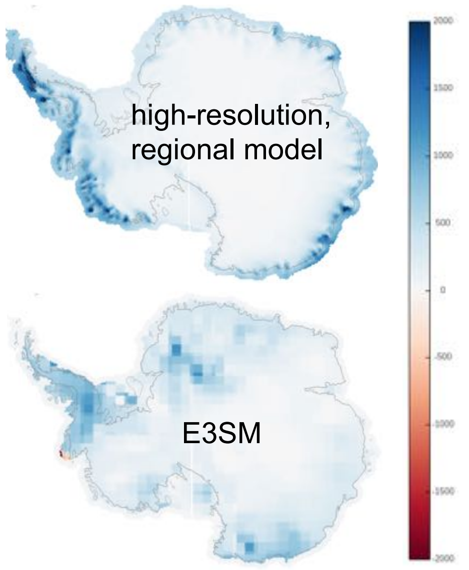
- **SMB**: ProSPect (improve snowpack model, test & validate SMB) + E3SM (identify & improve biases in E3SM atmosphere model)
- **BMB**: E3SM (initial work on coupling of heat & freshwater fluxes to non-dynamic ice sheets; validation of submarine melt rates; bias identification & improvement)

Coupling with E3SM:

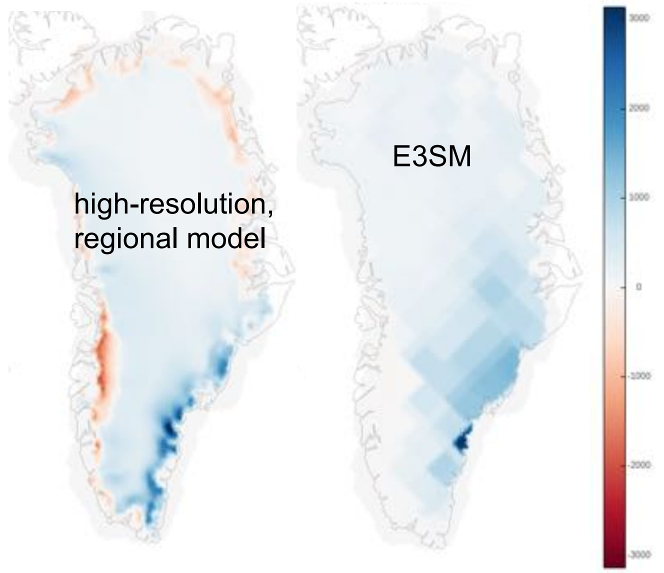
- SMB calculated & passed to coupler for Greenland & Antarctica (ProSPect)
- BMB calculated & passed to coupler for Antarctica (E3SM + ProSPect)
- applying BMB requires ocean model & coupler devel. (ProSPect)



Antarctic BMB



Antarctic SMB



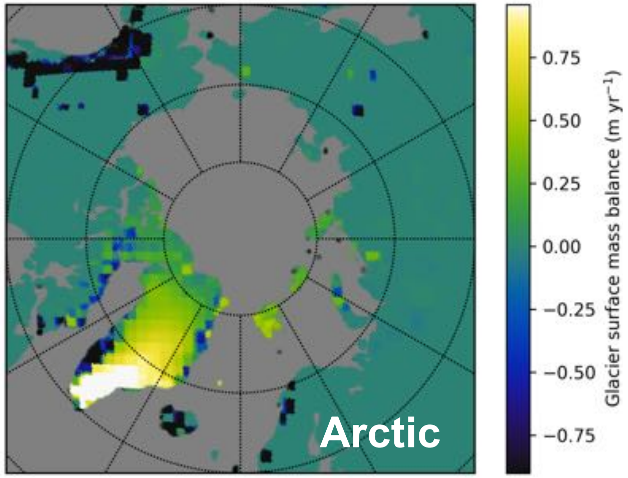
Greenland SMB

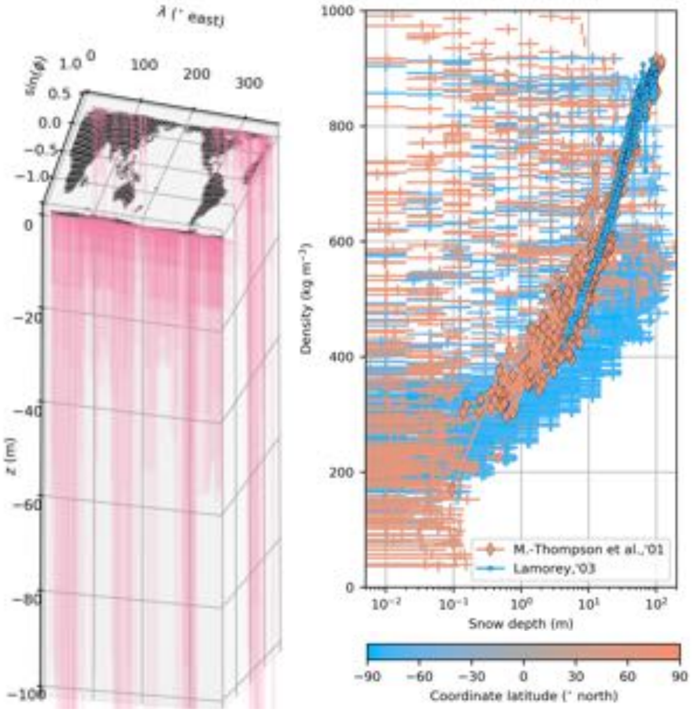
Progress: Ice Sheet & ESM coupling

Improving SMB: snowpack model development

- ice sheets have snowpack depths up to ~100's m ("firn")
- default, maximum snowpack model depth in E3SM is << 100 m
- deeper snowpack on ice sheets required for simulating accurate SMB …
- … requires new model development, testing, & validation

Below: N. and S. hemisphere glacier surface mass balance (m of w.e./yr) calculated in Oct. of year 10 in standalone (improved) snowpack model simulation. Accumulation zones are yellow-white and ablation zones (melting) are blue-black.



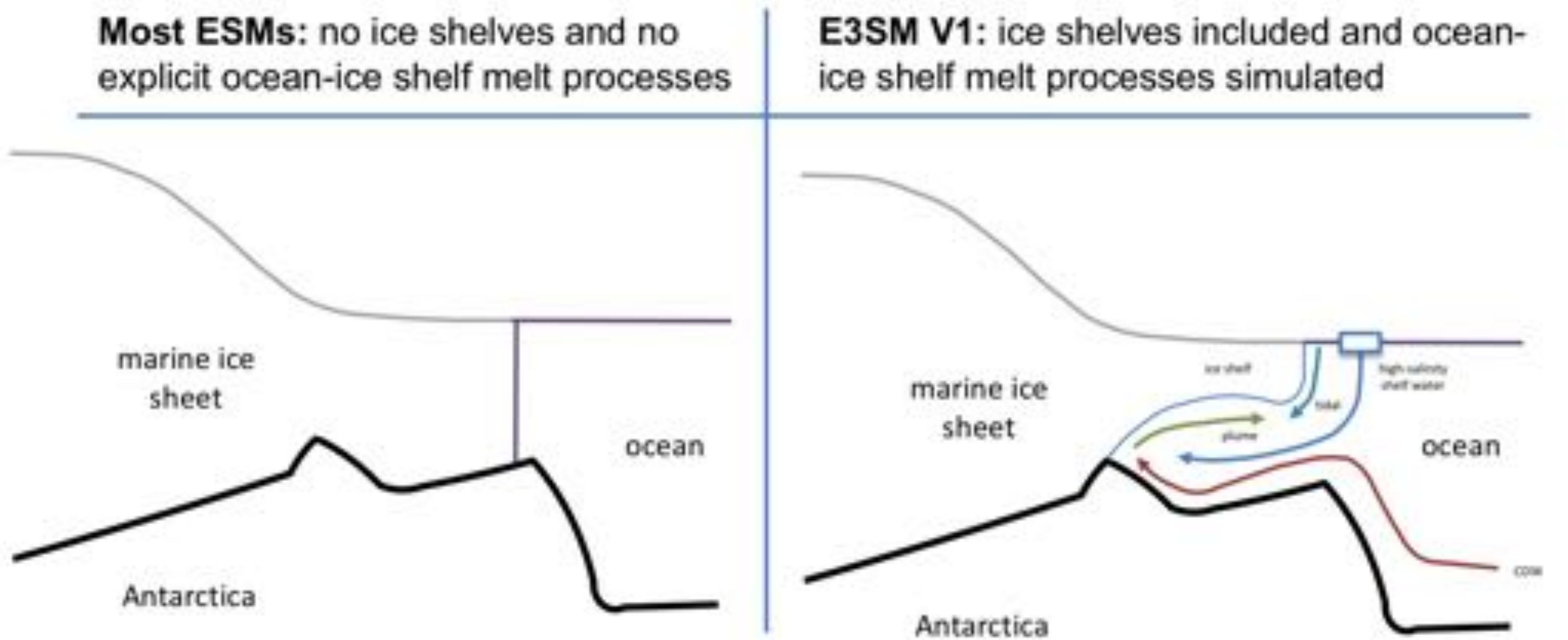


Right: Modeled snowpack accumulation and densification using observationally-based atmospheric forcing (Viovy, 2019). Snowpack thicknesses are integrated from accumulated snowfall and compaction over a 100 year spin up (refreezing of rain and melt-water, sublimation, & vapor deposition are included. Modeled densities vs. depths show at right vs. measured density profiles from Antarctica and Greenland.

Progress: Ice Sheet & ESM coupling

Ice sheet & Ocean model coupling (dynamic ice sheets in E3SM):

- lateral & lower ice sheet boundaries are currently fixed in E3SM
- ocean interactions requires these to be allowed to expand or contract in time
  - ocean model development: capability for "wetting-and-drying" needed
  - coupler development: ice sheet "footprint" must be allowed to change in time



Most ESMs: no ice shelves and no explicit ocean-ice shelf melt processes

E3SM V1: ice shelves included and ocean-ice shelf melt processes simulated

Progress: Ice Sheet & ESM coupling

Ice sheet & Ocean model coupling (dynamic ice sheets in E3SM):

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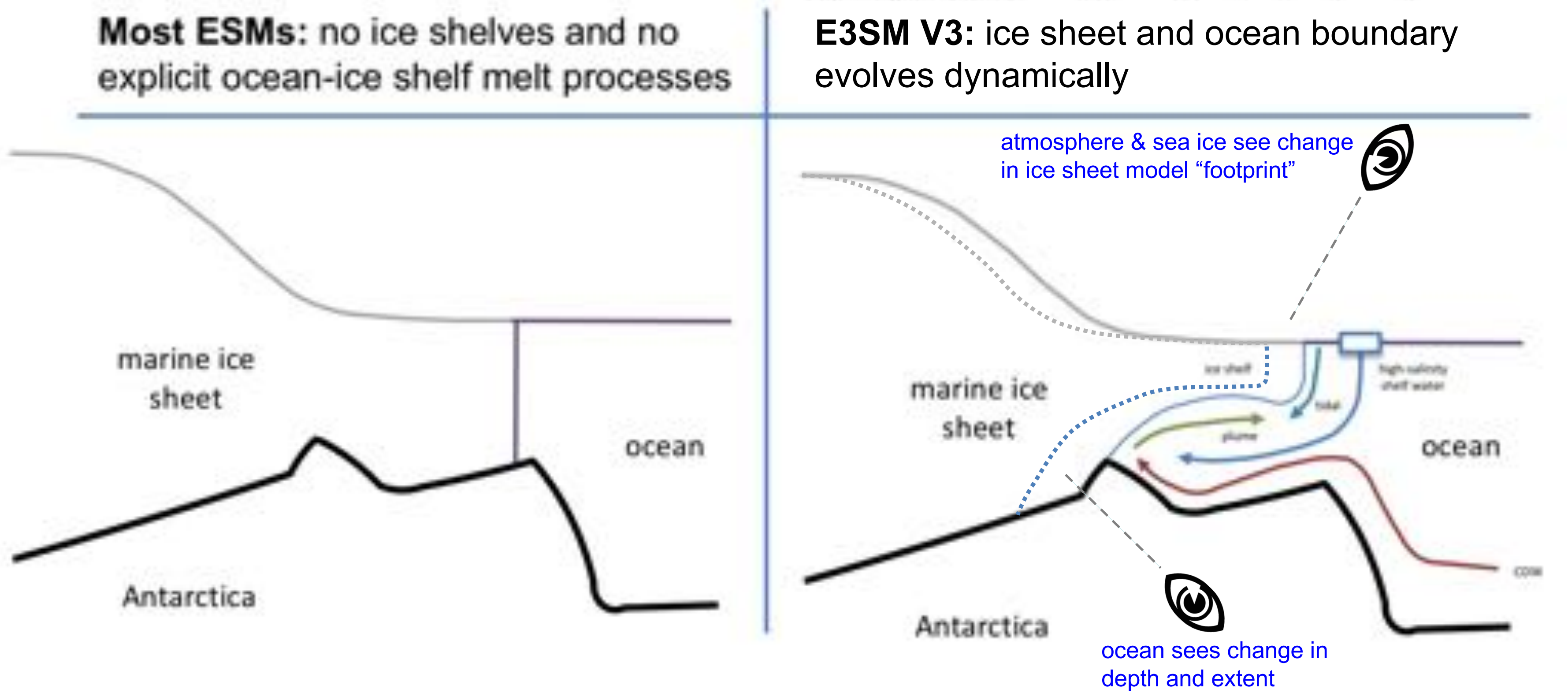


Most ESMs: no ice shelves and no explicit ocean-ice shelf melt processes

E3SM V3: ice sheet and ocean boundary evolves dynamically

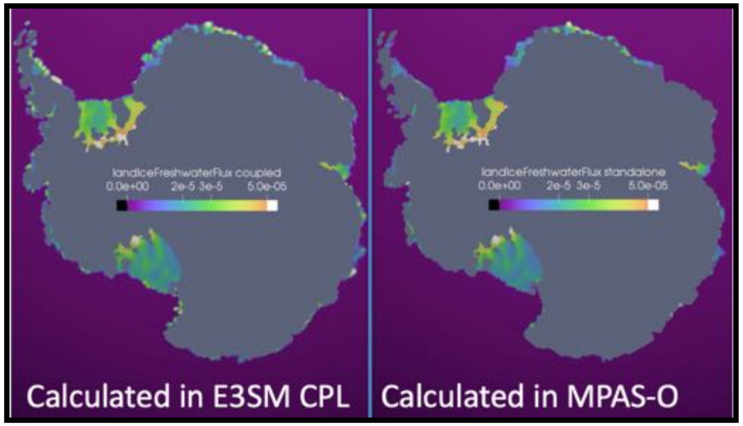
atmosphere & sea ice see change in ice sheet model “footprint”

ocean sees change in depth and extent

Progress: Ice Sheet & ESM coupling

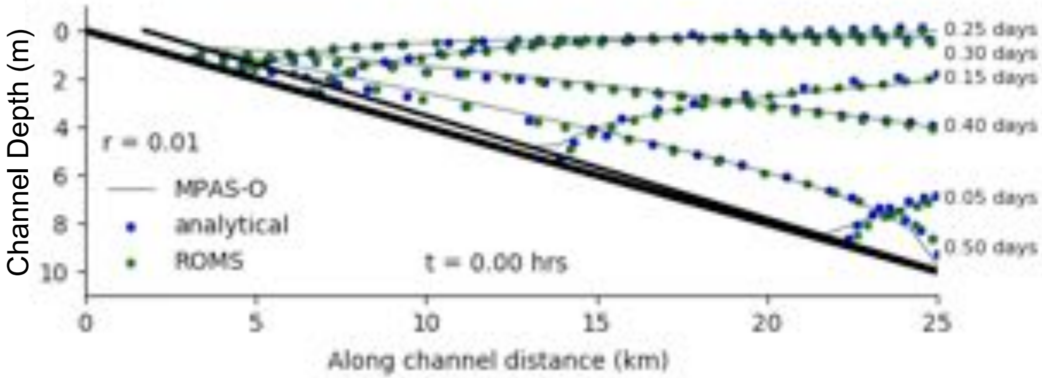
Ice sheet & Ocean model coupling (dynamic ice sheets in E3SM):

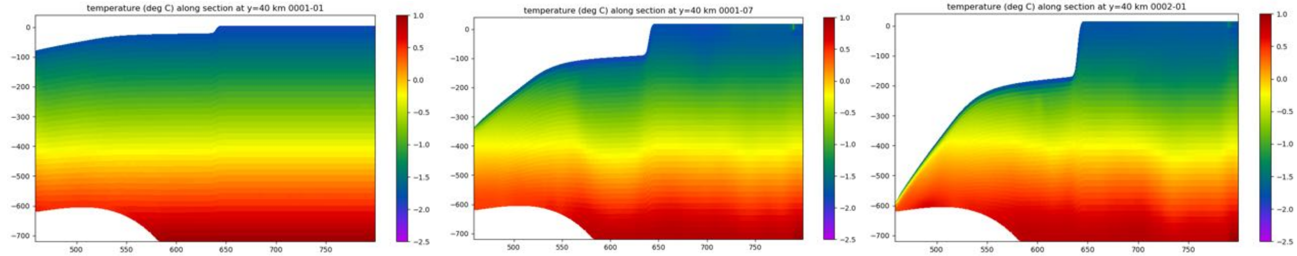
- heat & freshwater fluxes (melting/freezing) need to be exchanged between ice sheet & ocean model components in E3SM (model & coupler modifications)
- lateral and lower boundaries of ocean/ice sheet need to expand or contract in time
  - ocean model development: capability for “wetting-and-drying” needed
  - coupler development: ice sheet “footprint” must be allowed to change in time



Above: Verification of correct freshwater fluxes passed between ocean & ice sheet via coupler

Below: Analytic test case for testing wetting-and-drying in ocean model for idealized coastal (inundation) application.





Left: MISOMIP idealized test case for testing (1) higher-order pressure gradient, (2) stability of ocean model in highly-tilted layers, (3) wetting-and-drying.

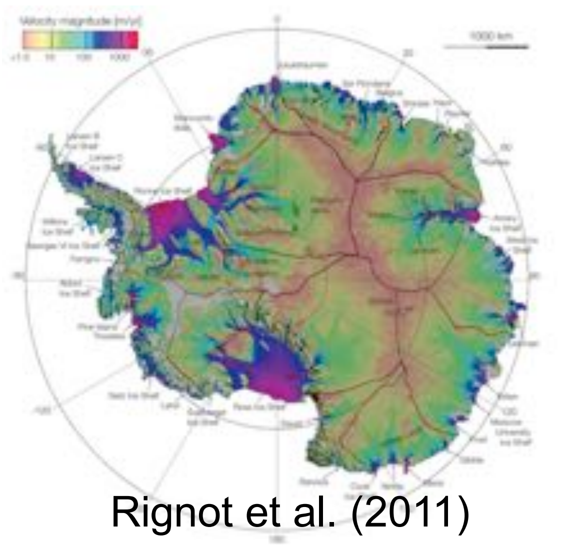
Progress: Optimization and Initialization

Importance:

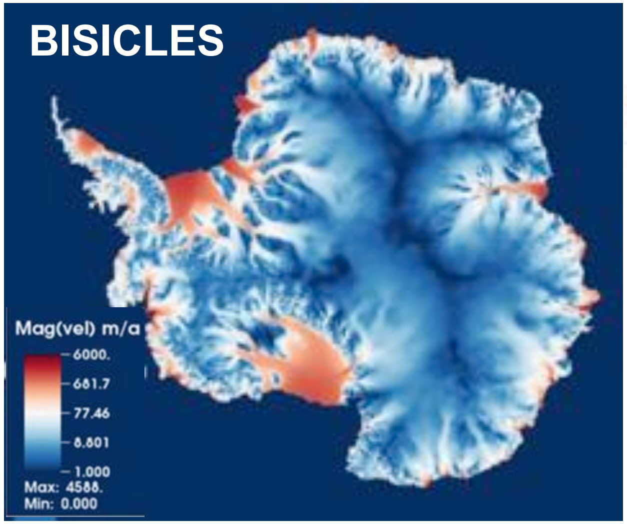
- Ice sheets have long equilibrium timescales relative to other components of the climate system (~10^3-10^5 yrs)
- Standard model initialization processes (e.g. spin-up) are not practical (too expensive; model state poor proxy for present-day)

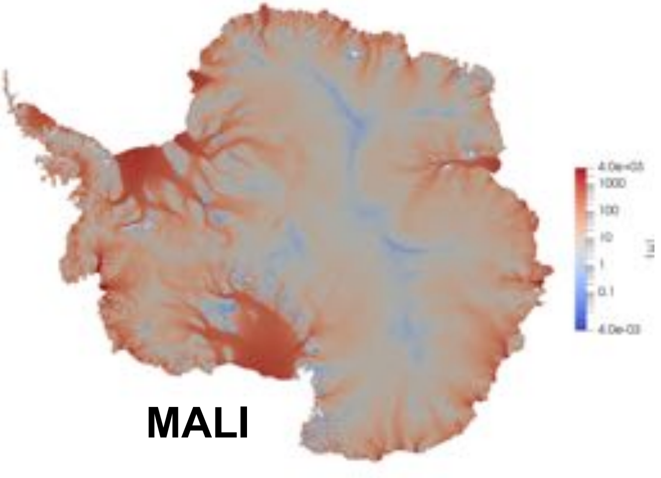
Need 1:

- Formal PDE-constrained optimization methods providing a model state that is a good representation of present-day observations



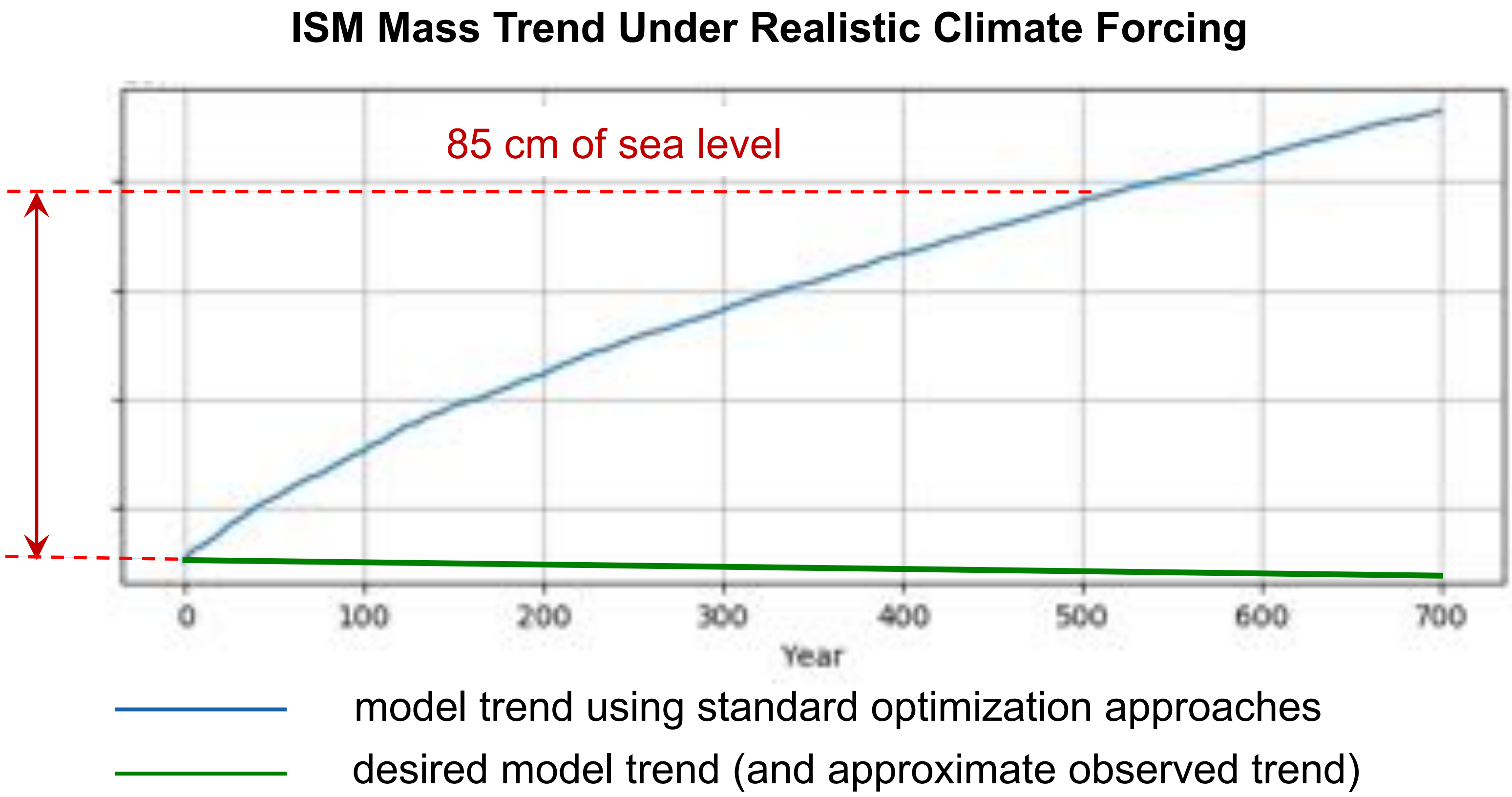
Rignot et al. (2011)





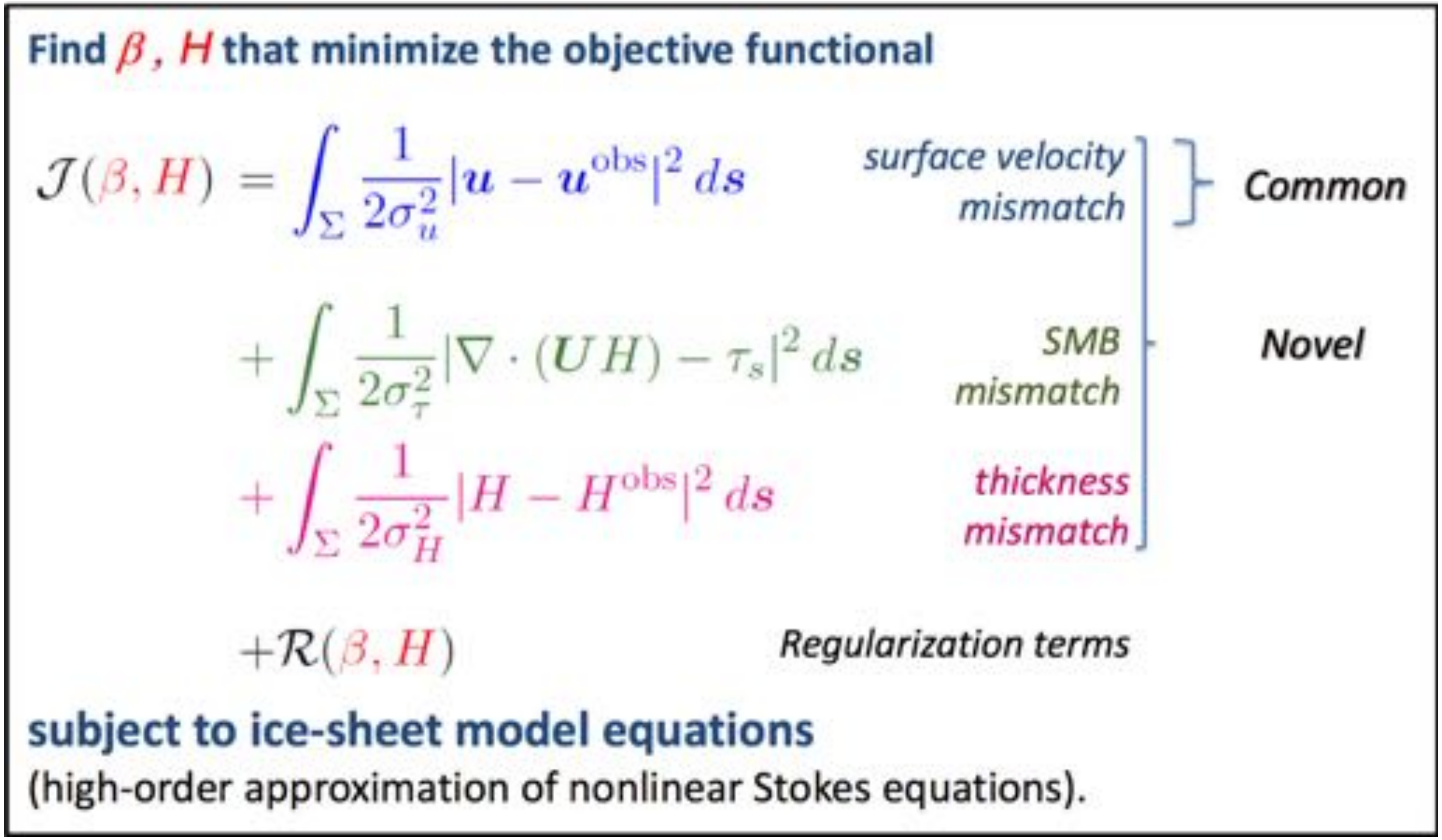
Progress: Optimization and Initialization

Need 2: Realistic, observationally-constrained *trends* in ISM initial condition when coupled to realistic climate forcing (e.g., from climate model), requires a broader, more flexible *data assimilation capability*


ISM Mass Trend Under Realistic Climate Forcing

Progress: Optimization and Initialization

Need 2: Realistic, observationally-constrained *trends* in ISM initial condition when coupled to realistic climate forcing (e.g., from climate model), requires a broader, more flexible *data assimilation capability*



Find β , H that minimize the objective functional

$$\mathcal{J}(\beta, H) = \int_\Sigma \frac{1}{2\sigma_u^2}|\boldsymbol{u}-\boldsymbol{u}^{\mathrm{obs}}|^2\,ds$$

surface velocity mismatch

$$+\int_\Sigma \frac{1}{2\sigma_\tau^2}|\nabla\cdot(\boldsymbol{U}H)-\tau_s|^2\,ds$$

SMB mismatch

$$+\int_\Sigma \frac{1}{2\sigma_H^2}|H-H^{\mathrm{obs}}|^2\,ds$$

thickness mismatch

$$+\mathcal{R}(\beta, H)$$

Regularization terms

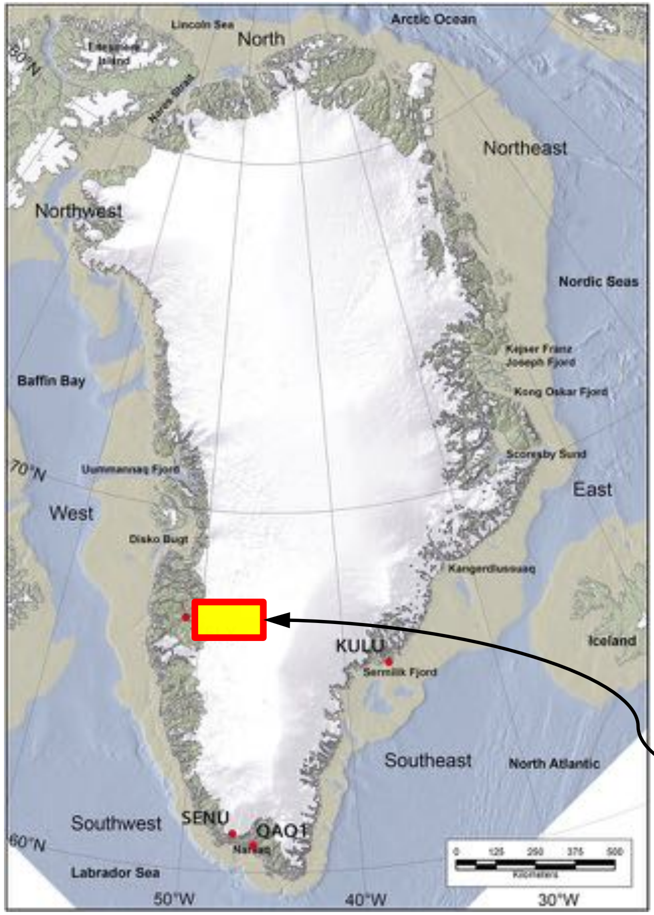
subject to ice-sheet model equations

(high-order approximation of nonlinear Stokes equations).

Perego et al. (*JGR*,2014)

Progress: Optimization and Initialization

Need 2: Realistic, observationally-constrained *trends* in ISM initial condition when coupled to realistic climate forcing (e.g., from climate model), requires *broad data assimilation capability*



Find β, H that minimize the objective functional

$$\mathcal{J}(\beta, H) = \int_\Sigma \frac{1}{2\sigma_u^2}|\boldsymbol{u} - \boldsymbol{u}^{\text{obs}}|^2\,ds$$

surface velocity mismatch } **Common**

$$+ \int_\Sigma \frac{1}{2\sigma_\tau^2}|\nabla \cdot (\boldsymbol{U}H) - \tau_s|^2\,ds$$

SMB mismatch

$$+ \int_\Sigma \frac{1}{2\sigma_H^2}|H - H^{\text{obs}}|^2\,ds$$

thickness mismatch

} **Novel**

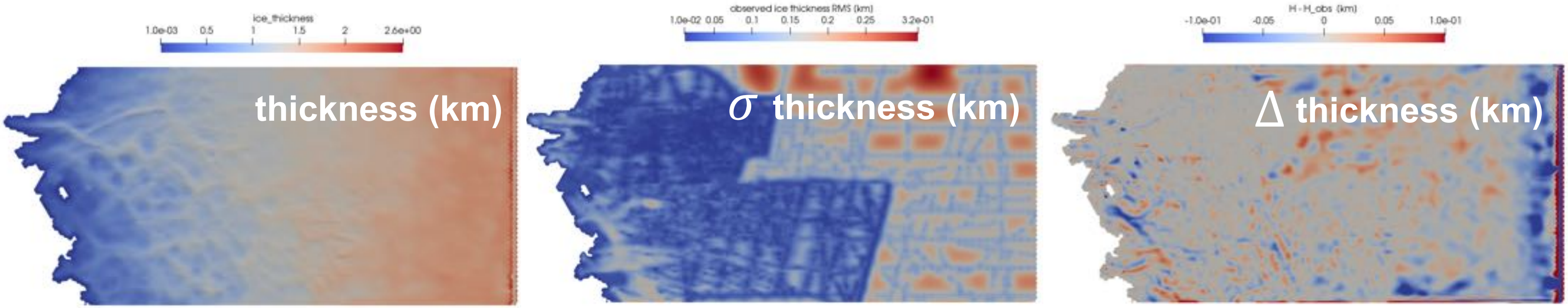
$$+\mathcal{R}(\beta, H)$$

Regularization terms

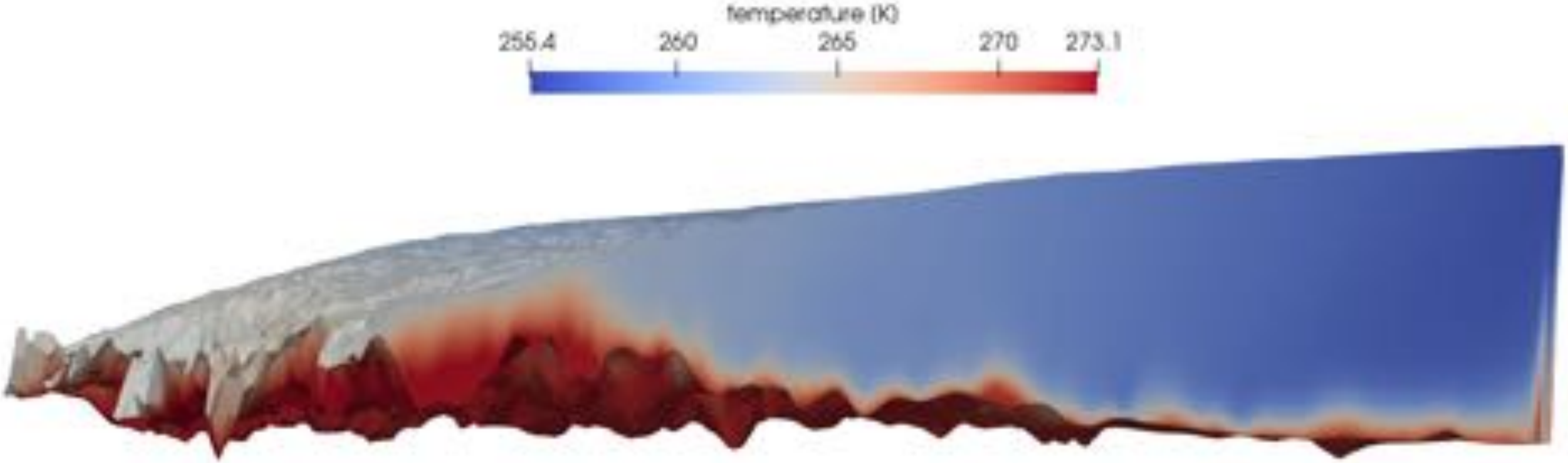
subject to ice-sheet model equations
(high-order approximation of nonlinear Stokes equations).

{ ***apply and test in a small area of Greenland margin where there are lots of data and simple boundary conditions***

Progress: Optimization and Initialization



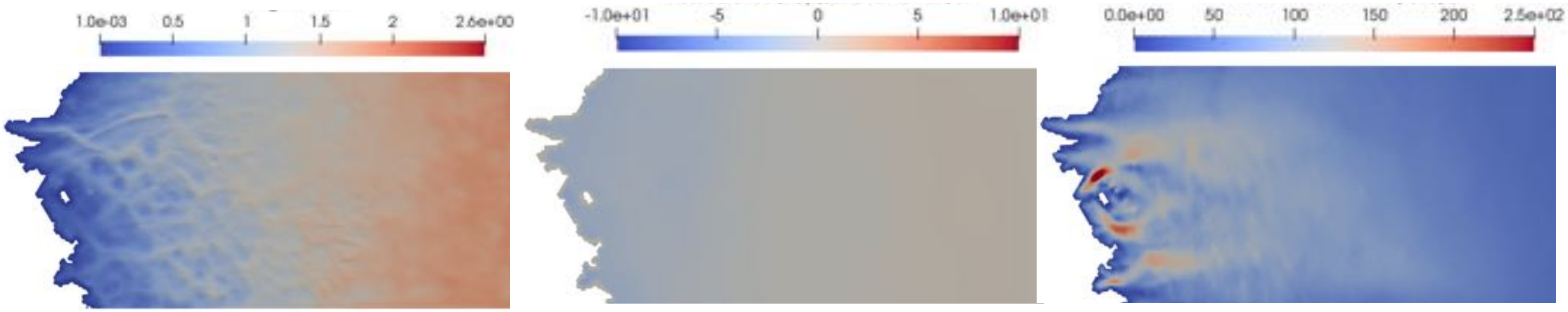
Novelty 1: Ice thickness is allowed to vary during the optimization (but constrained by observational uncertainties) to provide another (powerful!) degree of freedom.



Novelty 2: Ice temperature, a strong control on rheology, is simultaneously optimized to be consistent with ice dynamics (via enthalpy solution).

Progress: Optimization and Initialization

Inputs
(observations)

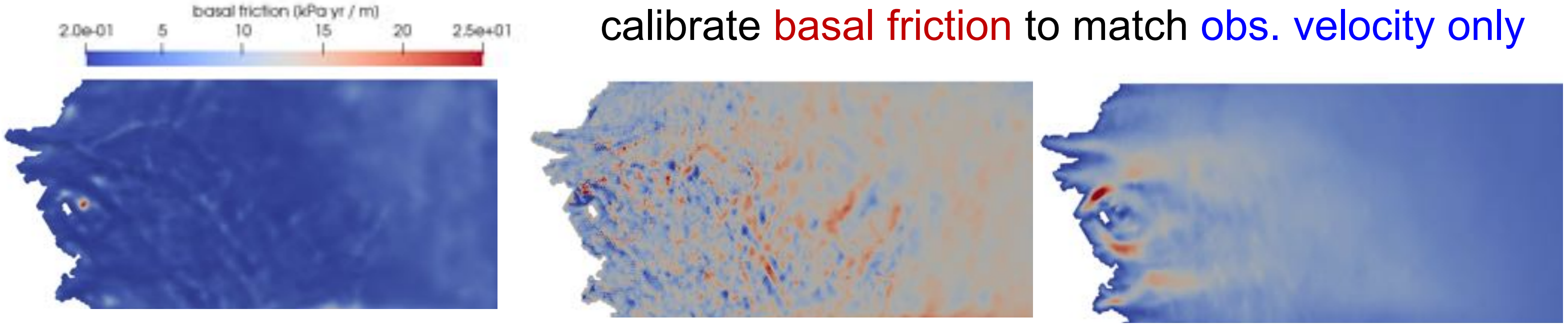


thickness (km) | mass balance + tendencies (m/yr) | surface velocity (m/yr)

Outputs
(model optim.)

calibrate basal friction to match obs. velocity only

basic



calibrate basal friction and thickness to match obs. velocity and tendencies)

improved

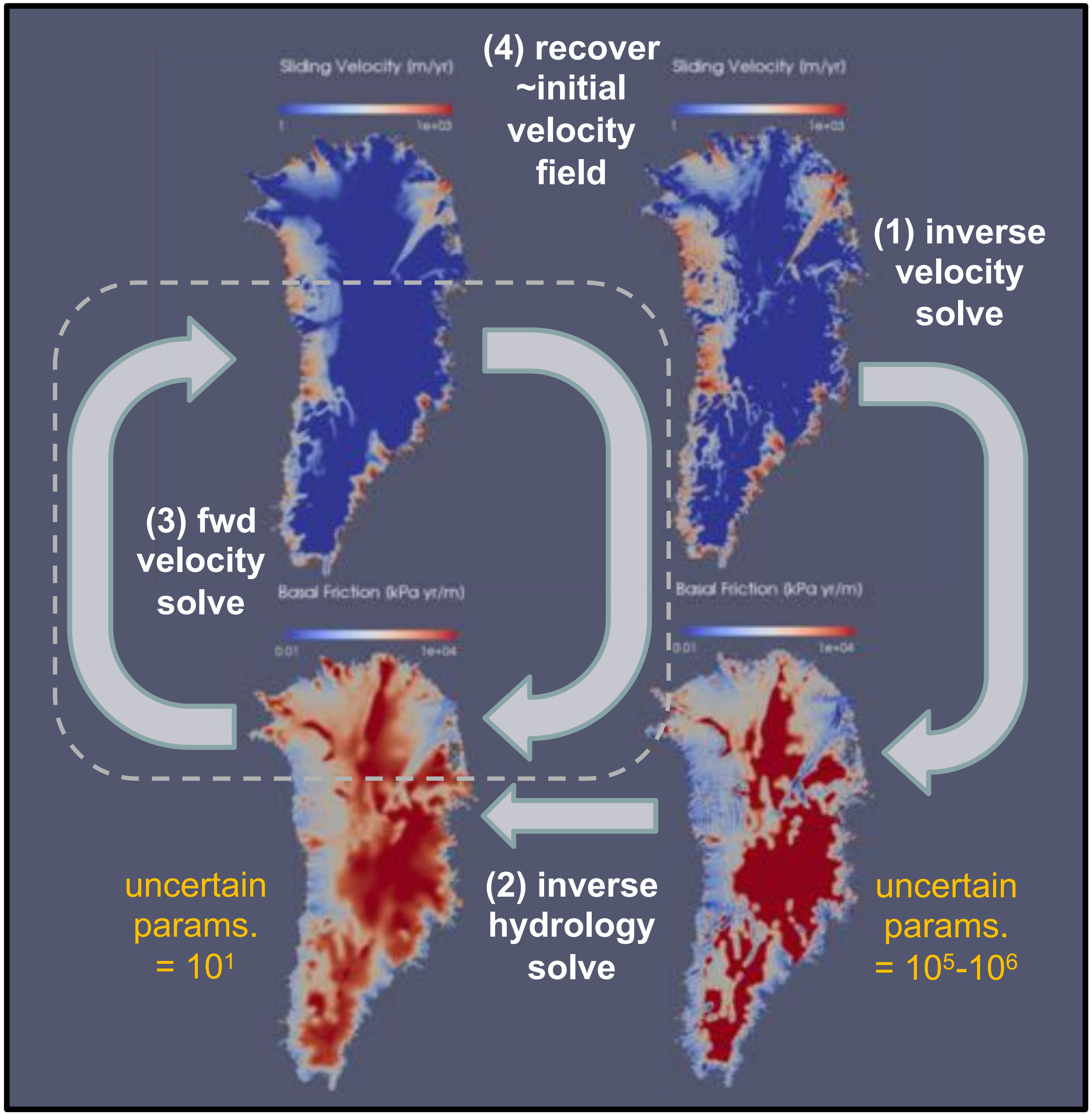
basal friction (kPa yr /m) | flux divergence (m/yr) | surface velocity (m/yr)

Progress: Subglacial Hydrology + Optimization + Uncertainty Quantification

1. invert obs. vels. for basal friction params.
2. invert hydro. & sliding model params. from friction field params.
3. from optimal hydro. & sliding params., fwd solve for sliding vel.
4. approx. consistency in initial and secondary optimized sliding fields

Significance:

Potential for reduction in uncertain param. fields from order ~10^5-10^6 to ~10^1, with potential for very large UQ cost savings



(4) recover ~initial velocity field

(1) inverse velocity solve

(3) fwd velocity solve

(2) inverse hydrology solve

uncertain params. = 10^1

uncertain params. = 10^5-10^6

Impact of SciDAC Institutes

FASTMath:

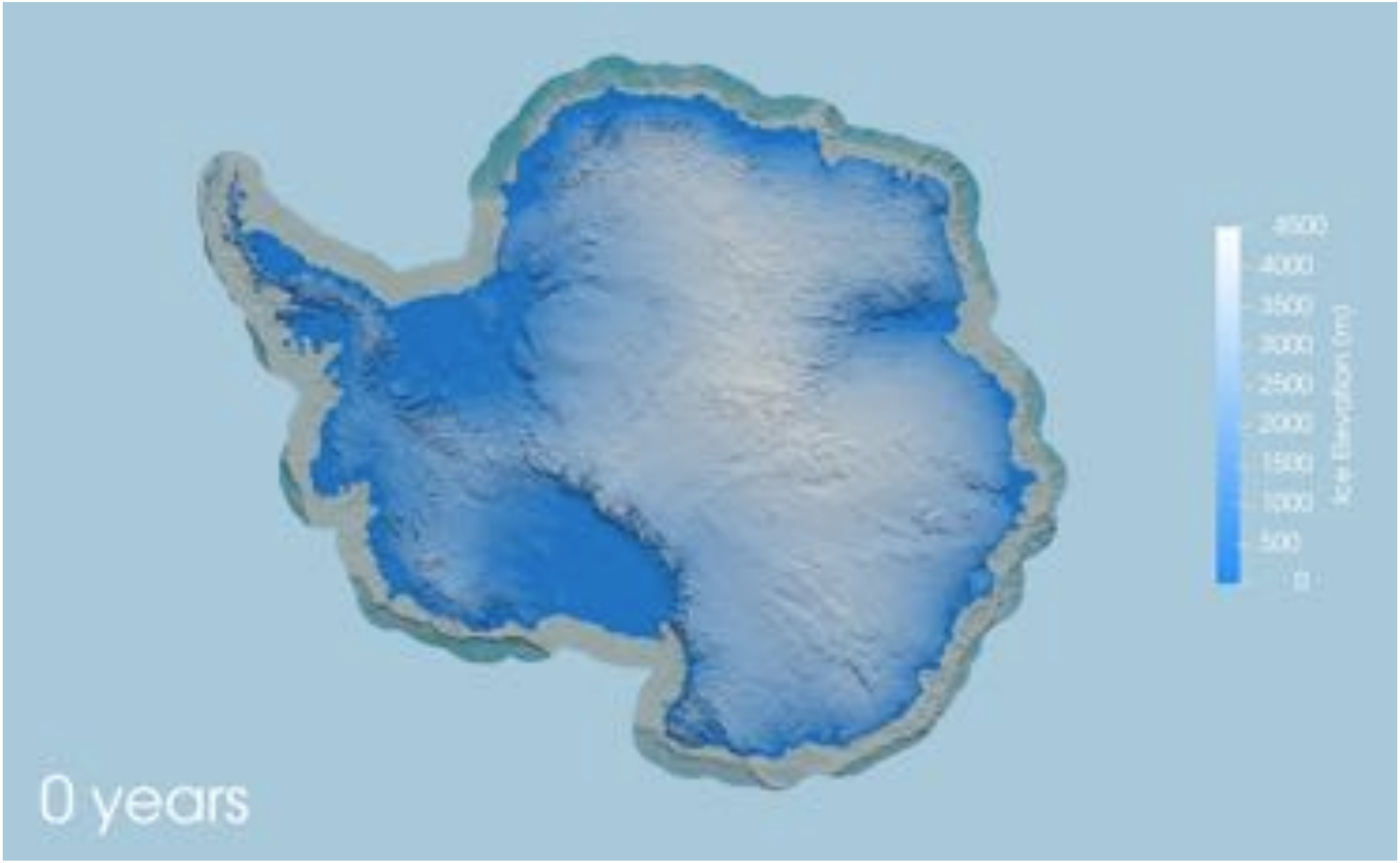
- Improve speed/robustness of velocity solve (ML precond. in *Muelu*)
- Infrastructure for improved optimization in (*Trilinos ROL*)
- Parallel Island / hinge detection & removal for FEM ice sheet mesh
- Ice sheets target application for *Trilinos* FROSCH[1] solver
- Improved speed/robustness of velocity solve (AMB in *PETSc*)
- Embedded-boundary discretization for grounding lines & calving fronts

RAPIDS:

- *Paraview* & *VisIT* used as primary visualization and quick analysis tools
- Ongoing:
  - Generating high-end ice sheet model visualizations & narratives for communicating complex climate science to general public (targeting SC 2019)
  - Exploring methods for visualizing large-scale simulation performance

[1] FROSCH = Fast and Robust Overlapping Schwarz solver)

RAPIDS: Ice Sheet Model Visualization



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Summary

- Sea level rise from ice sheets continues to accelerate
- SciDAC3 developed mature, high-resolution, HPC-ready ice sheet models
- SciDAC4 effort is focusing on additional model improvements, ESM coupling, and maturation of optimization and UQ frameworks
- SciDAC and DOE’s broader ESM effort are well positioned to make significant and unique contributions to sea level projection efforts