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

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E3SM Energy Exascale Earth System Model

SciDAC Scientific Discovery through Advanced Computing

Motivation and Background

Project Goals

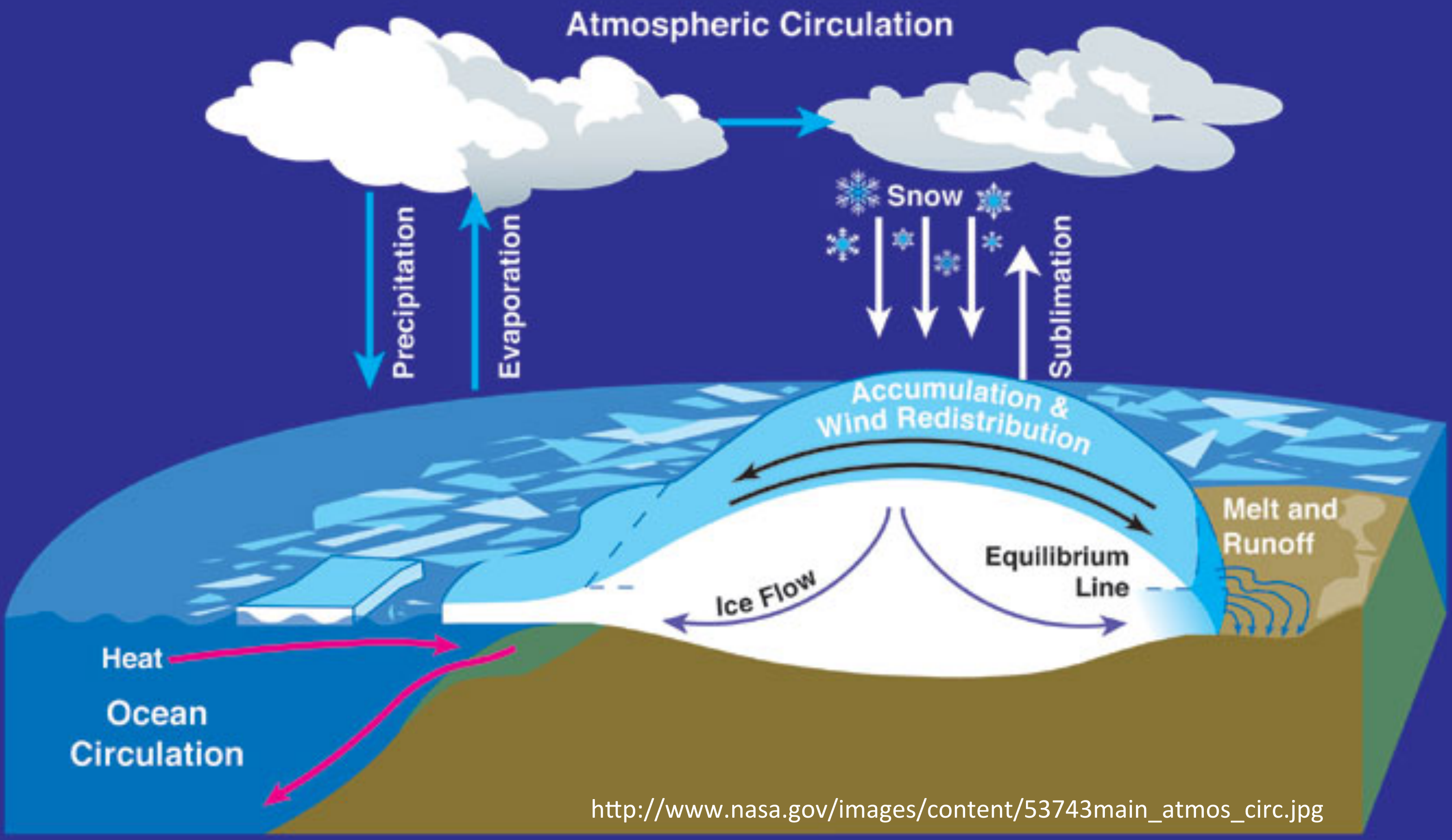
Early results

Challenges

Summary

Motivation & Background

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

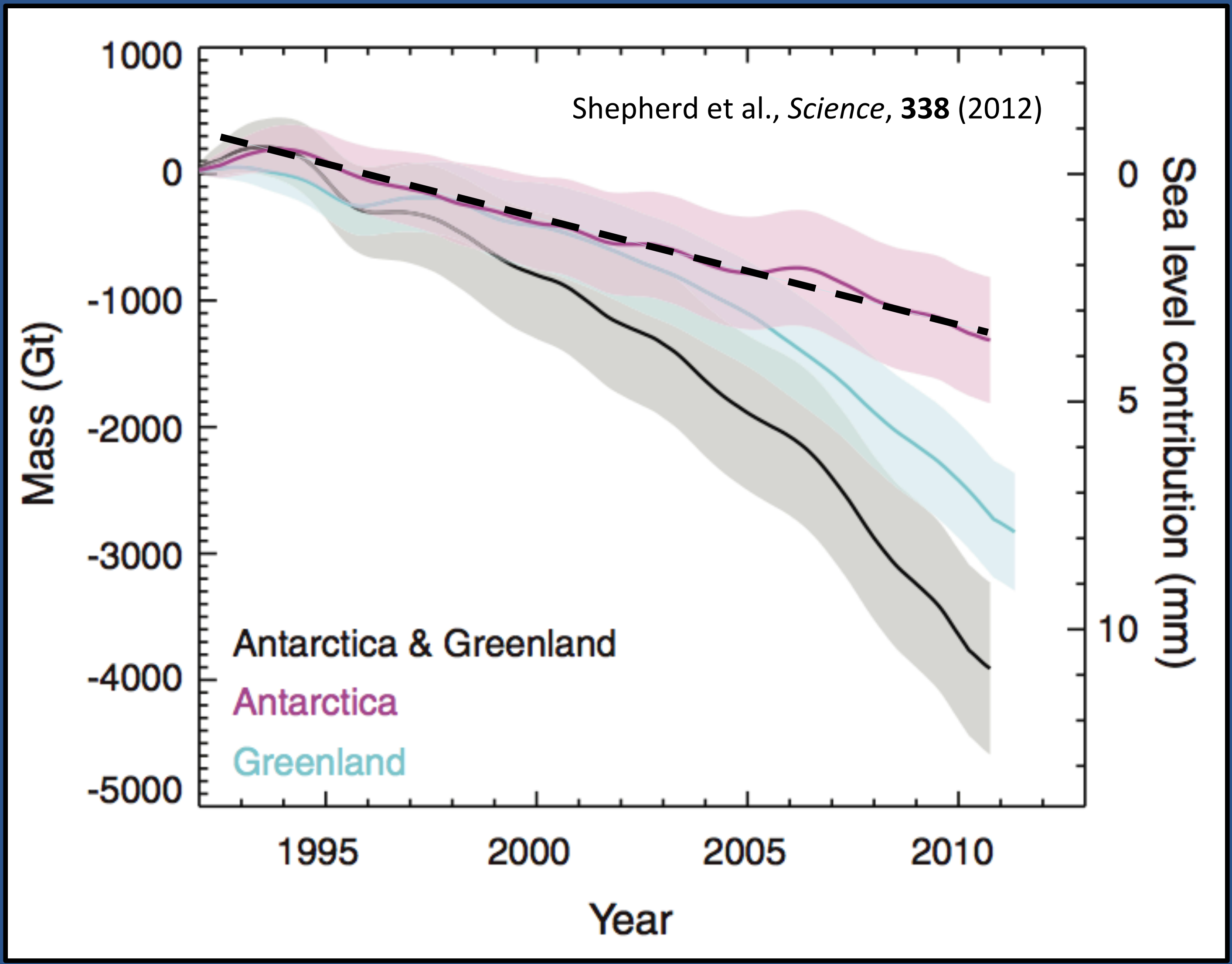


http://www.nasa.gov/images/content/53743main_atmos_circ.jpg

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

Motivation & Background

Mass loss and sea level rise (SLR) from ice sheets is accelerating



Motivation & Background

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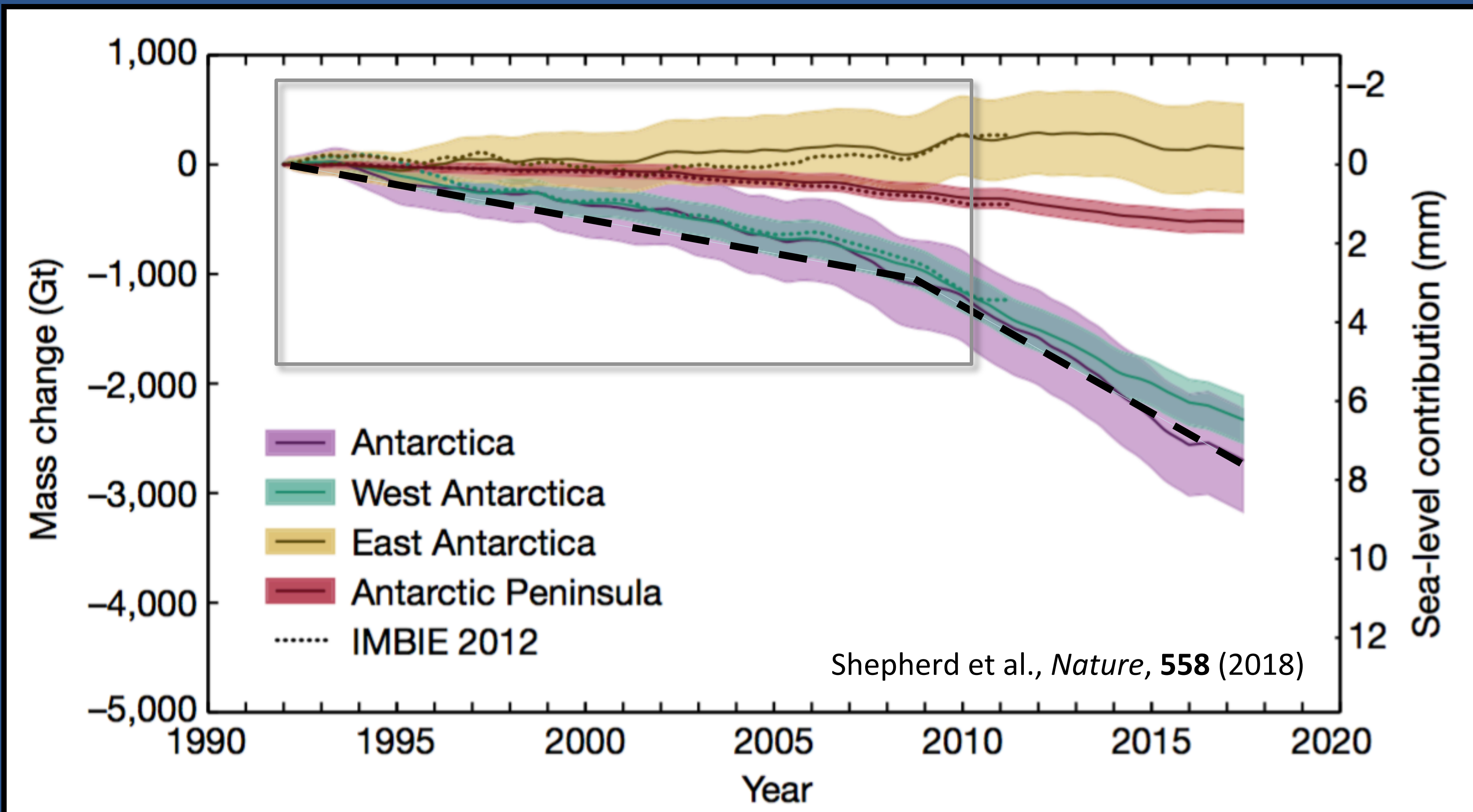
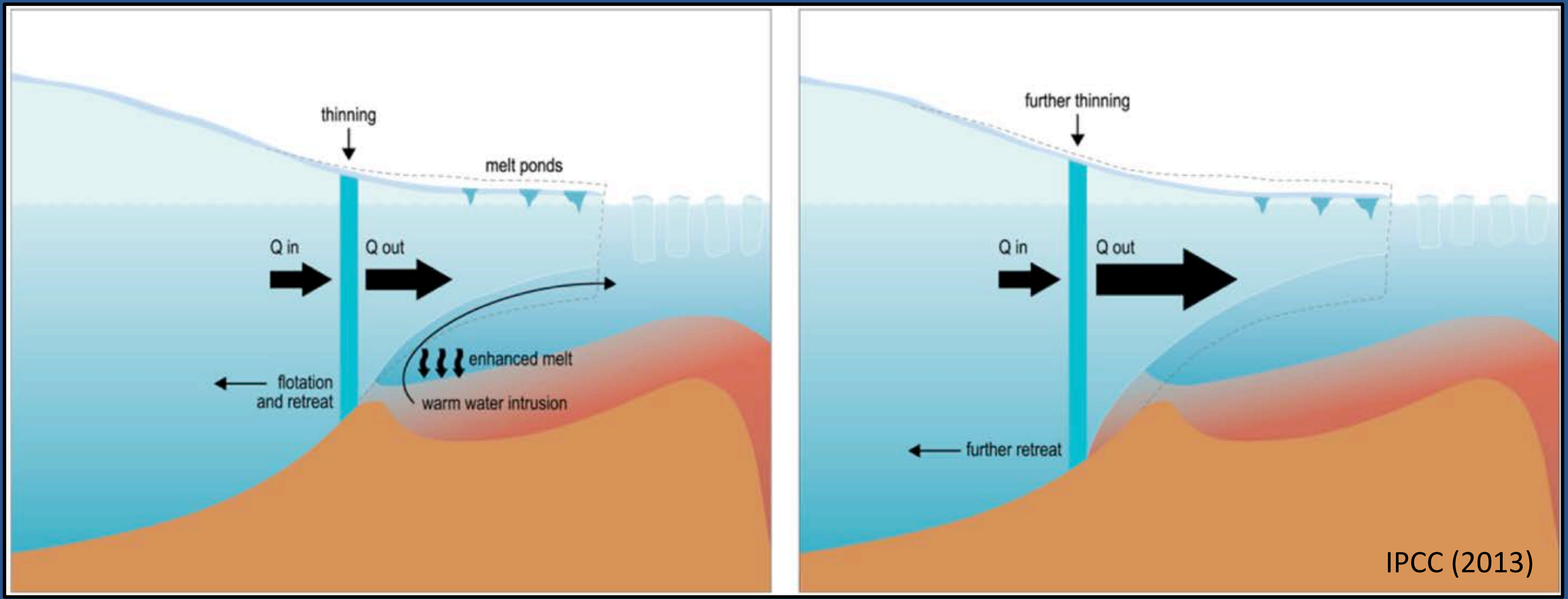


Motivation & Background

Potential rapid SLR from West Antarctica is of particular concern



- 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")

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

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

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

Project Goals

1. ISM physics
   - Subglacial hydrology
   - Damage, fracture, iceberg calving
2. ISM and ESM coupling
   - Ocean model physics
   - Coupler development
   - Solid earth model physics and coupling
3. Initial conditions for coupled ESM and ISM simulation
   - Optimization targeting coupled modeling
   - Numerical improvements to adjoint-based optimization
4. UQ / probabilistic sea-level projections
   - Bayesian calibration for high-dimensional fields
   - Dimension reduction
   - Forward propagation
   - Model structural uncertainty
5. Cross Cutting
   - Verification and Validation (V&V)
   - Performance Portability

Project Goals (this talk)

1. ISM physics
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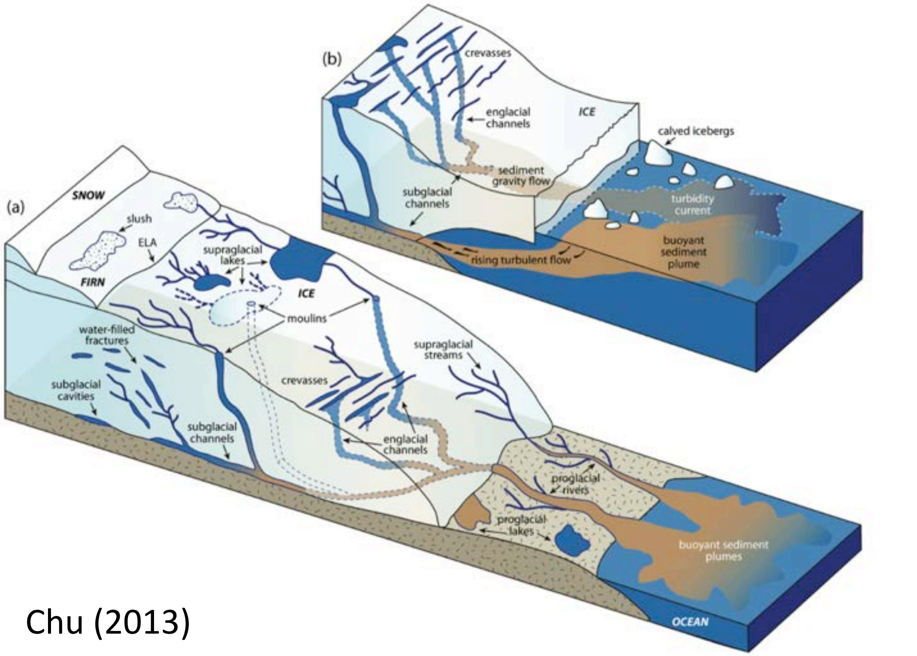
Results: subglacial hydrology

Importance:

- Ice sheet discharge to the ocean is largest in regions of rapid / free basal slip (variable on timescales of seconds to centuries)
- Basal slip controlled by spatially and temporally varying water pressure in subglacial hydrological system
- Current large-scale models treat basal properties as static (e.g., parameterized as scalar map of linear “friction” parameter)

Need:

- Explicit modeling of subglacial hydrology evolution (from external (climate) and internal (thermodynamics) processes)
- Characterization of its impact on future ice sheet evolution (and uncertainties in)

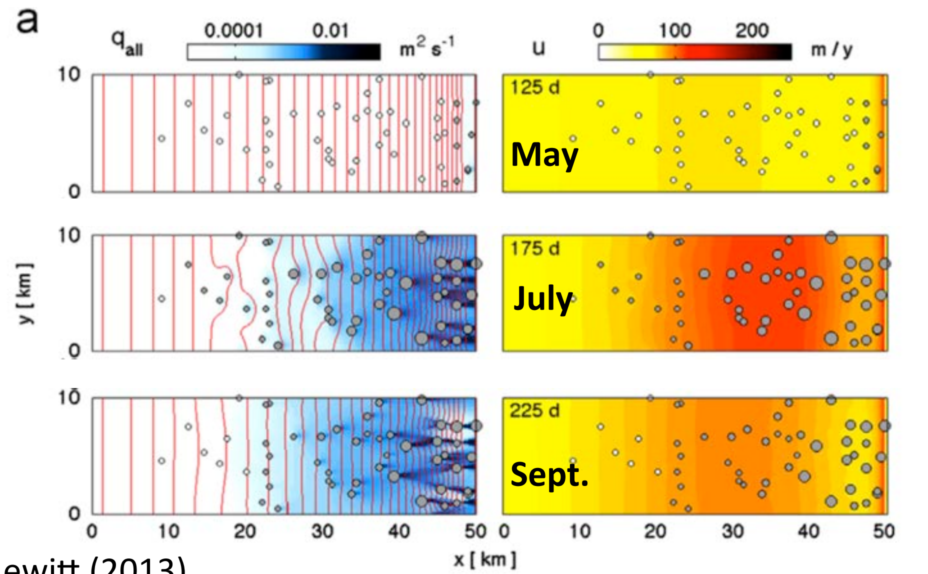


Chu (2013)

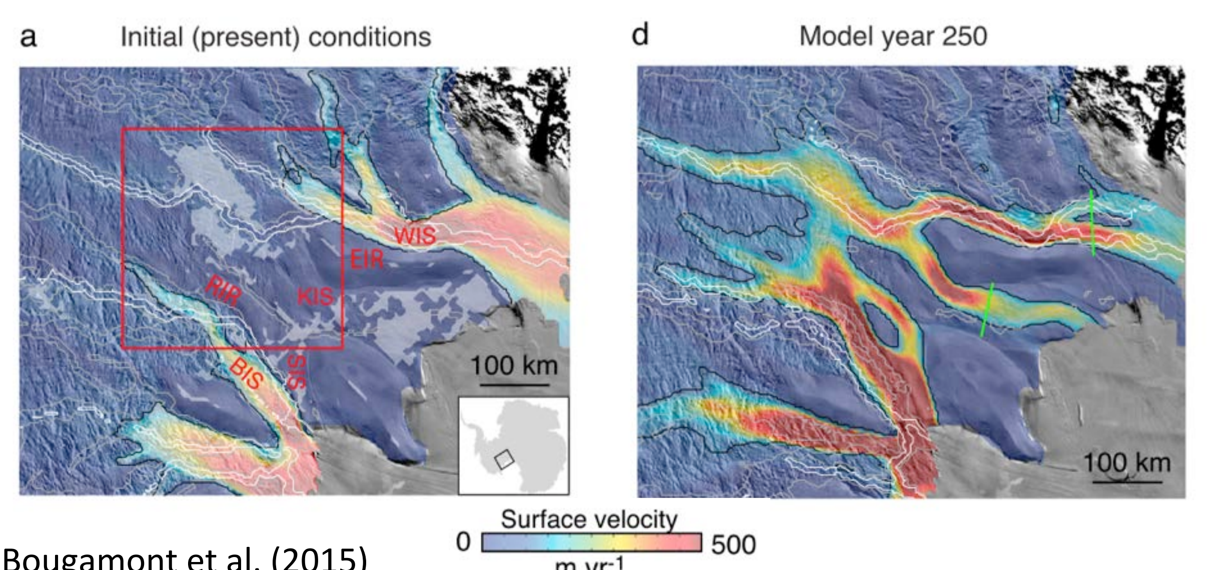
Results: subglacial hydrology

Greenland:

- ~2-10x daily and seasonal vel. changes from surface melt
- Increasing melt with warming
- Melt input to ocean at marine terminating outlet glaciers (feedbacks)



Hewitt (2013)



Bougamont et al. (2015)

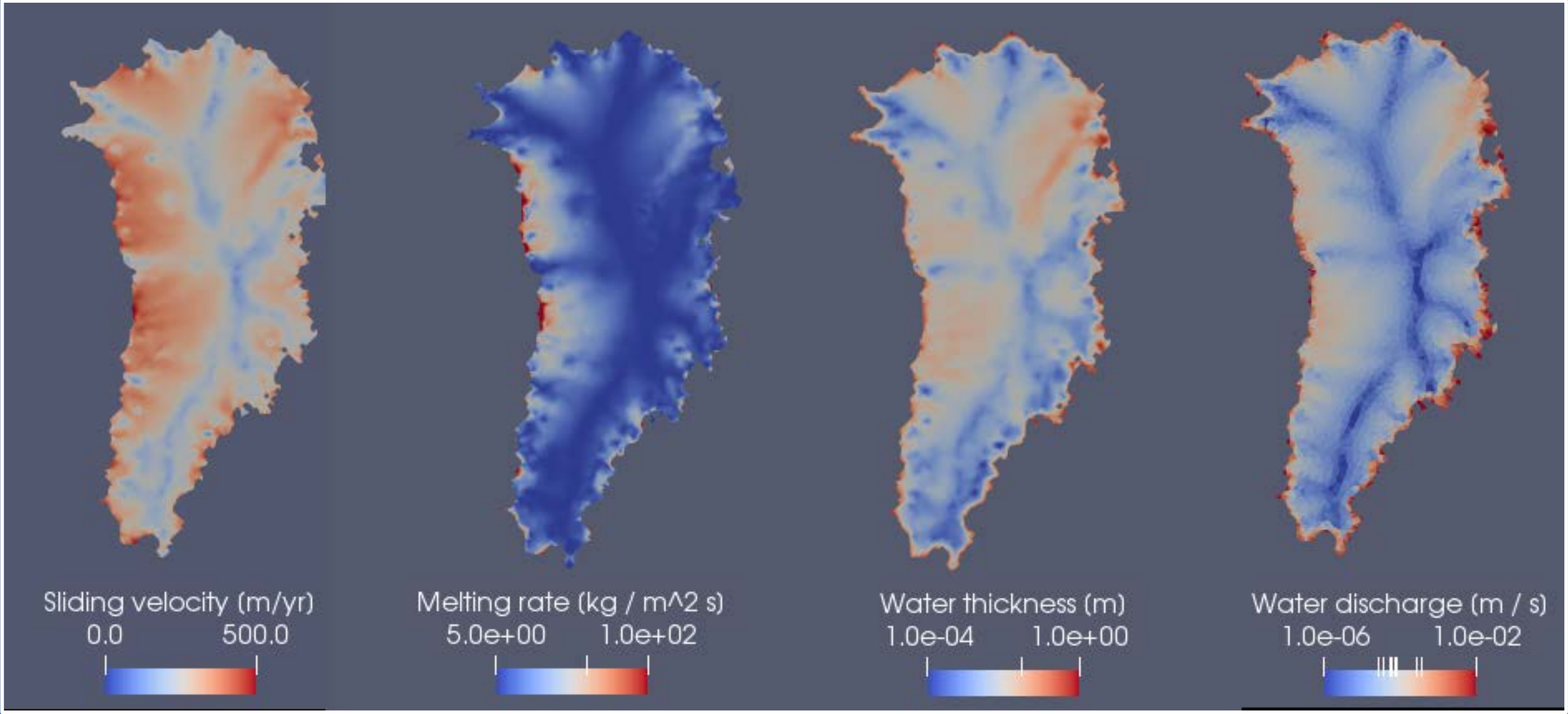
Antarctica:

- Currently little melt input from surface
- Decade-century scale flow re-arrangement from subglacial hydro.

Results: subglacial hydrology

Progress:

- working steady-state solver in Albany
- includes englacial porosity, sediment storage, nonlinear diffusion
- analytic test cases working
- run on coarse, realistic geometries with reasonable results



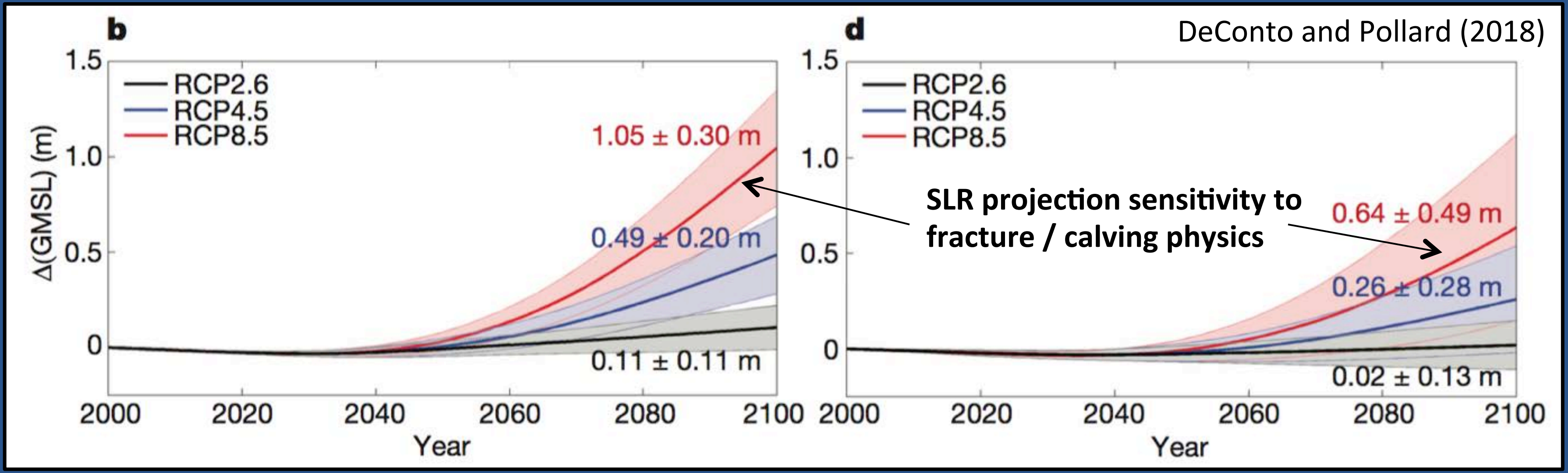
Results: damage, fracture, iceberg calving

Importance:

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

Need:

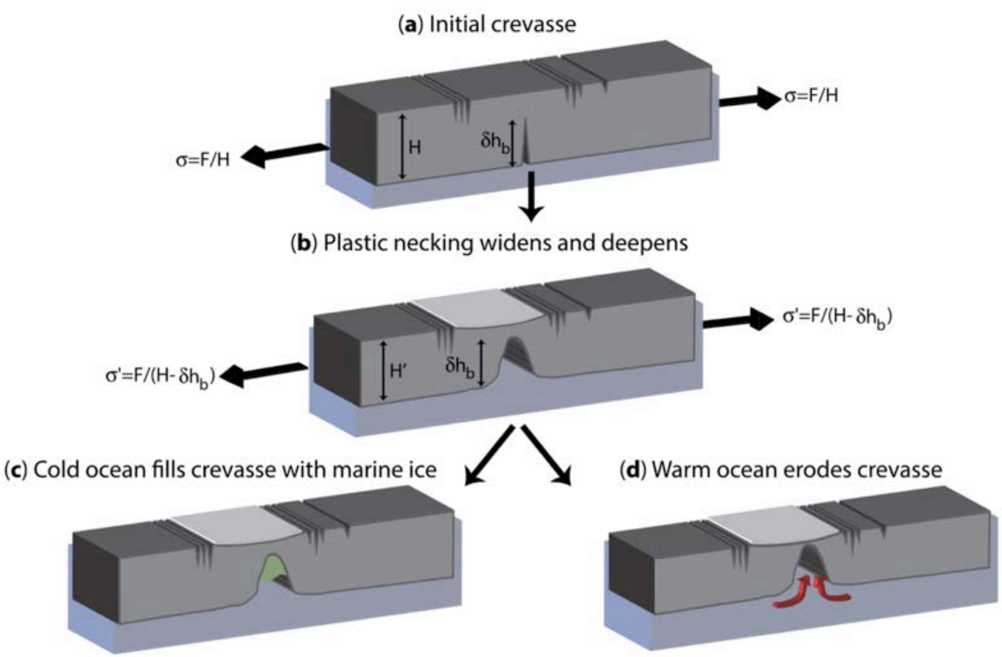
- Physics-based models of ice shelf fracture and coupling to climate
- Characterization of impact and uncertainty on ice sheet evolution

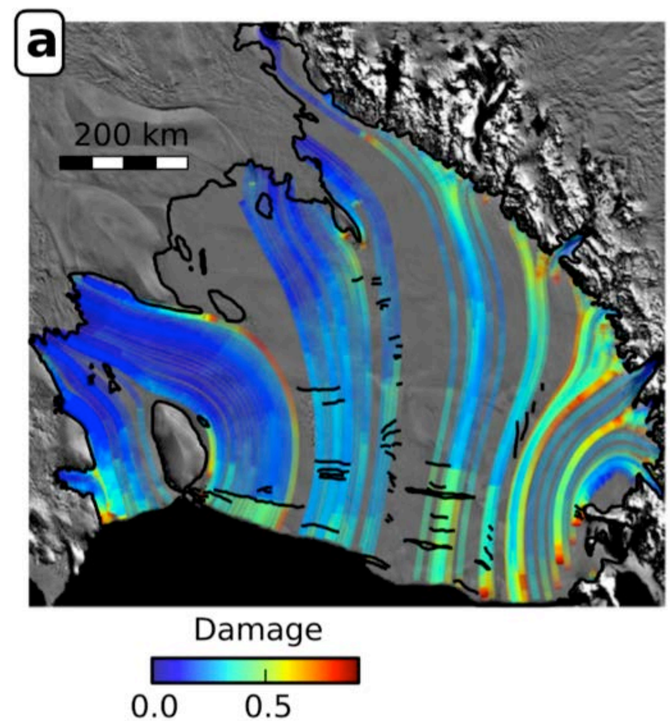


Results: damage, fracture, iceberg calving

Progress:

- parameterize sub-grid scale fracture evolution through damage mech.
- Includes “hooks” to relevant climate forcing (sfc. and basal melting)
- Prototype implementation in BISICLES

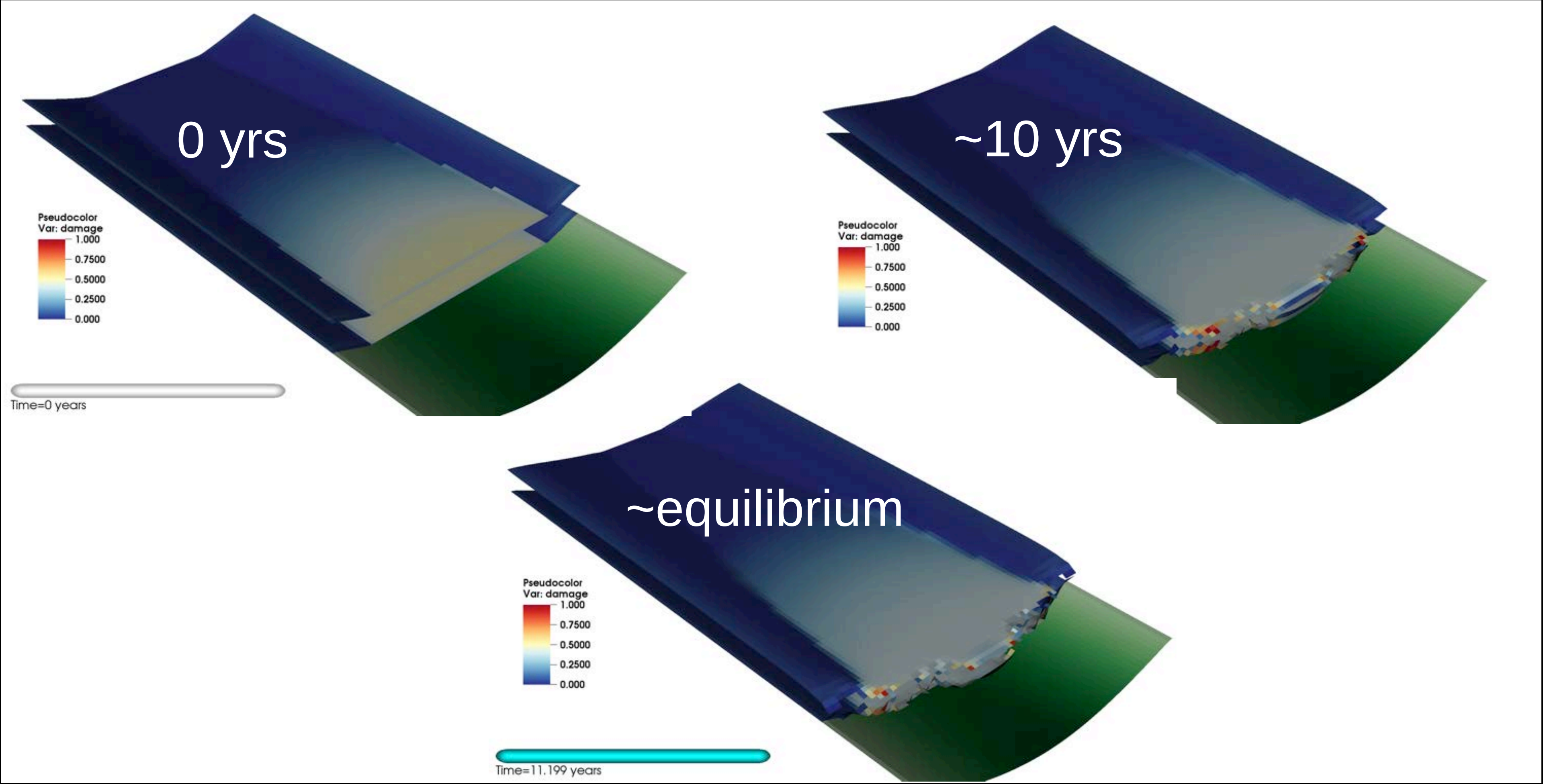




Bassis and Ma (2015)

Results: damage, fracture, iceberg calving

- Damage lower in grounded regions
- Damage higher in floating regions
- Damage at floating front leads to calving (limiting advance)



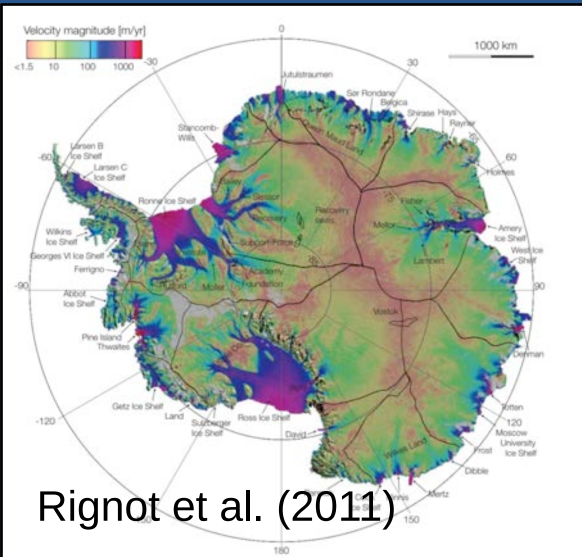
Results: Optimization and Initialization

Importance:

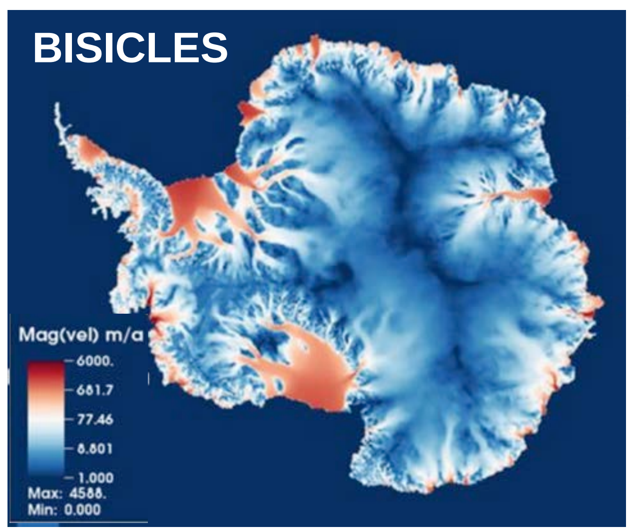
- Ice sheets have long equilibrium timescales relative to other components of the climate system (~10^3-10^5 yrs)
- Standard model initialization processes (e.g. spin-up) are not practical (too expensive; model state poor proxy for present-day)

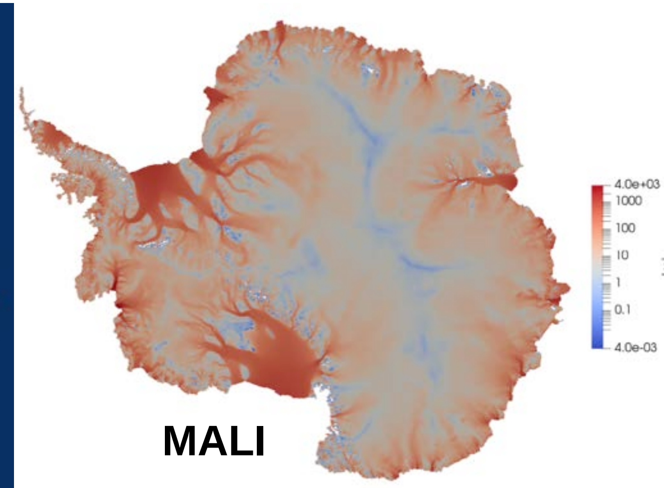
Need:

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



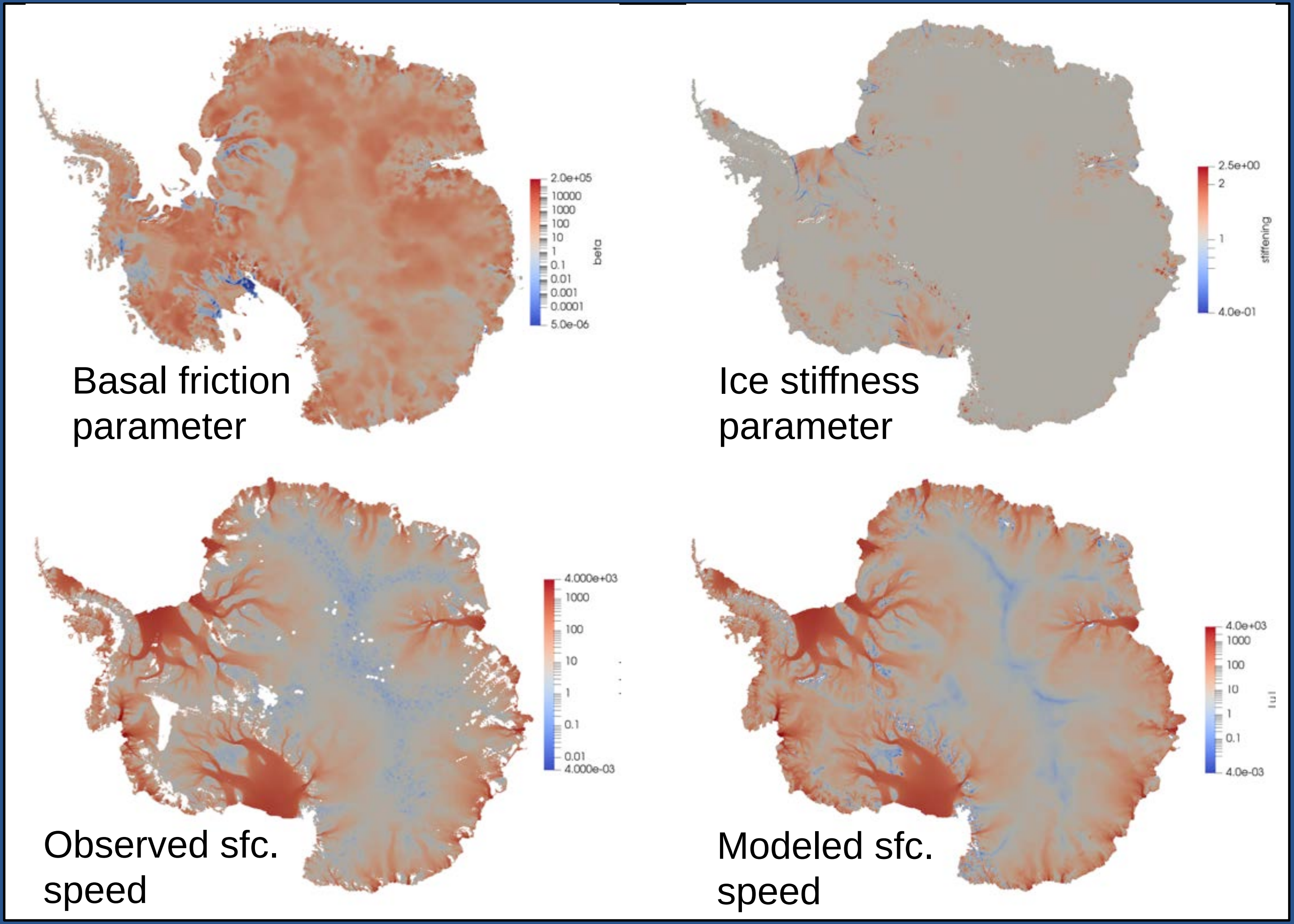
Rignot et al. (2011)





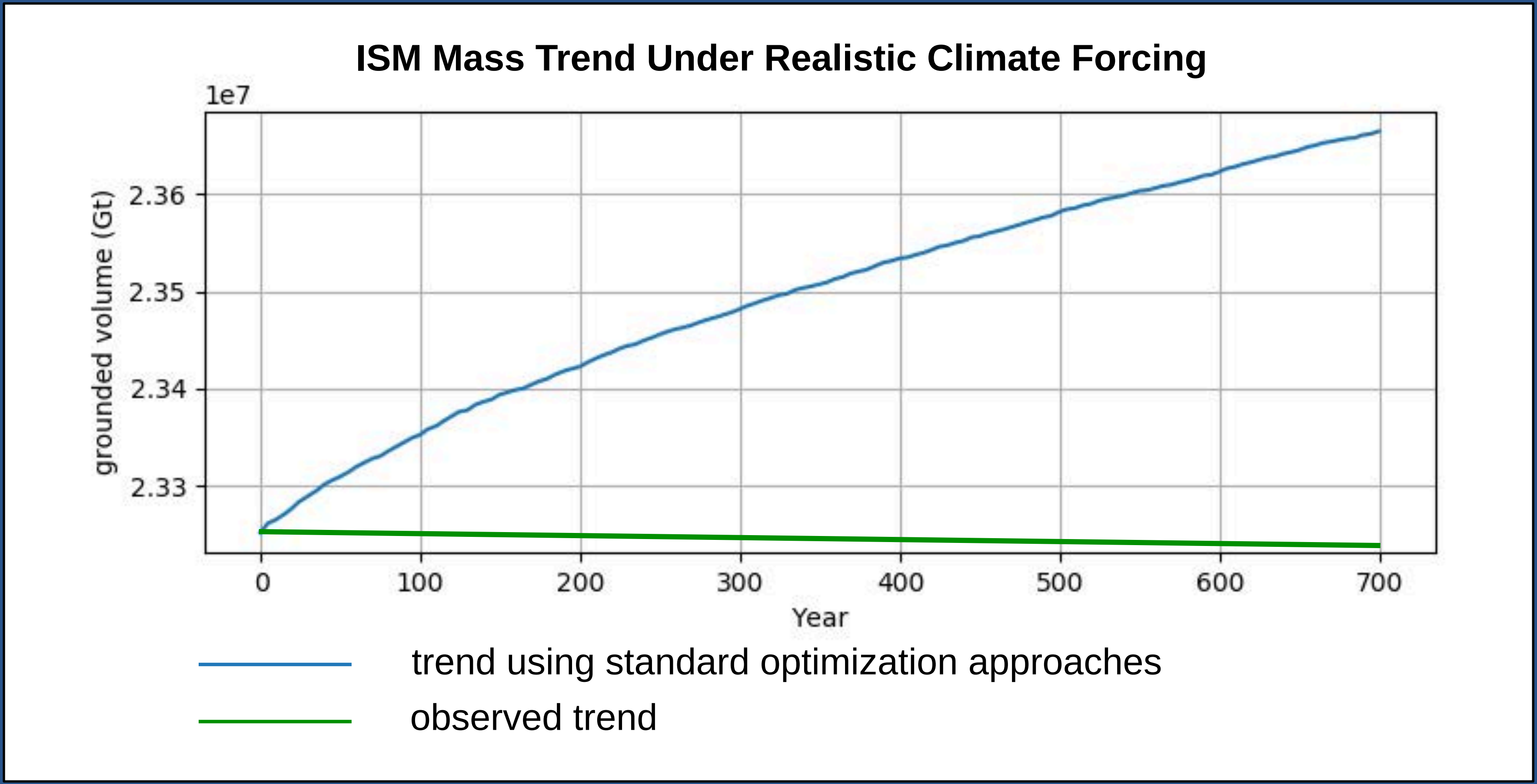
Results: Optimization and Initialization

Variable-resolution (20-1 km) Antarctic initial condition by optimizing basal friction and stiffening coefficients (2×10^6 parameters)

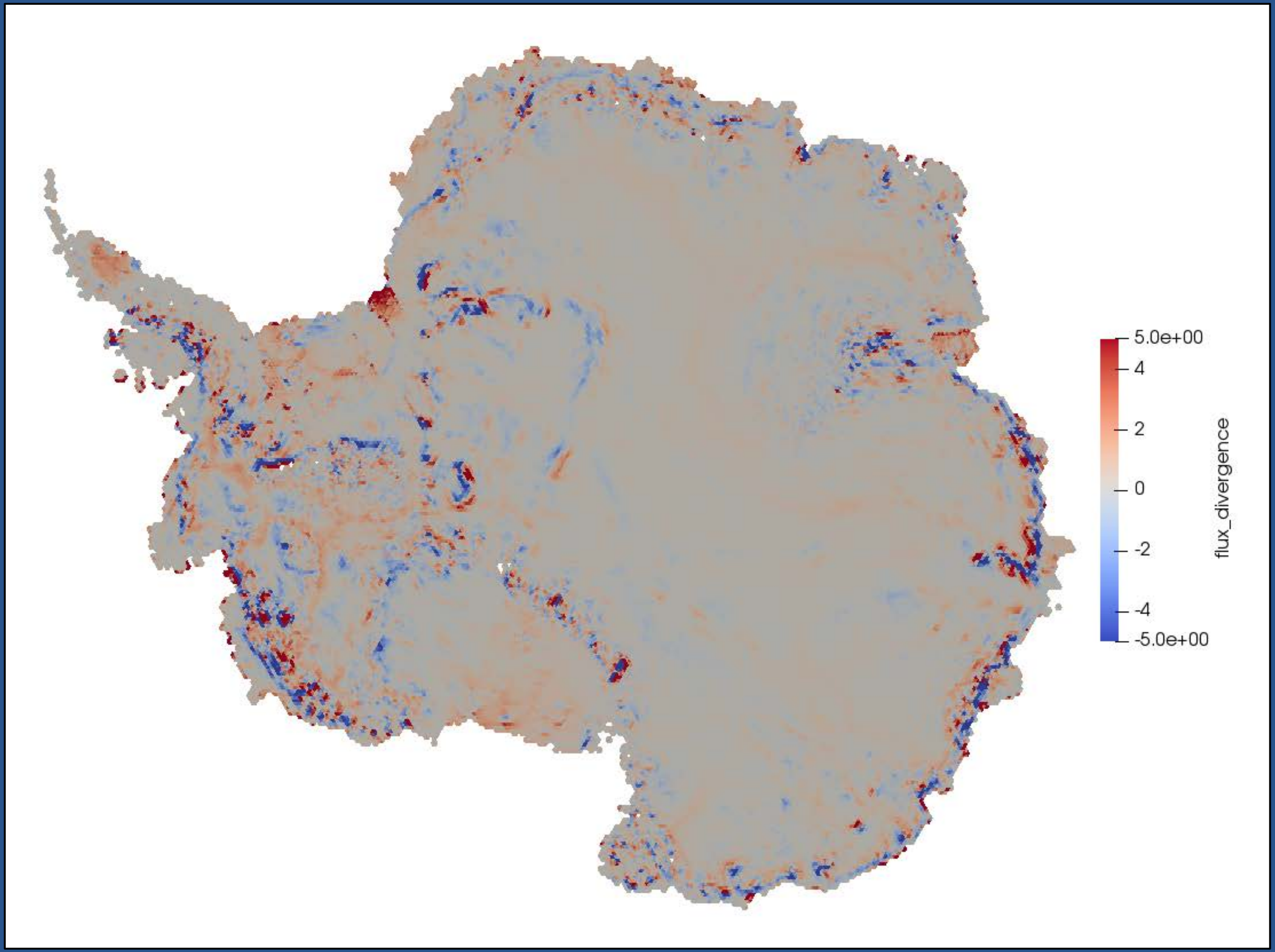


Results: Optimization and Initialization

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

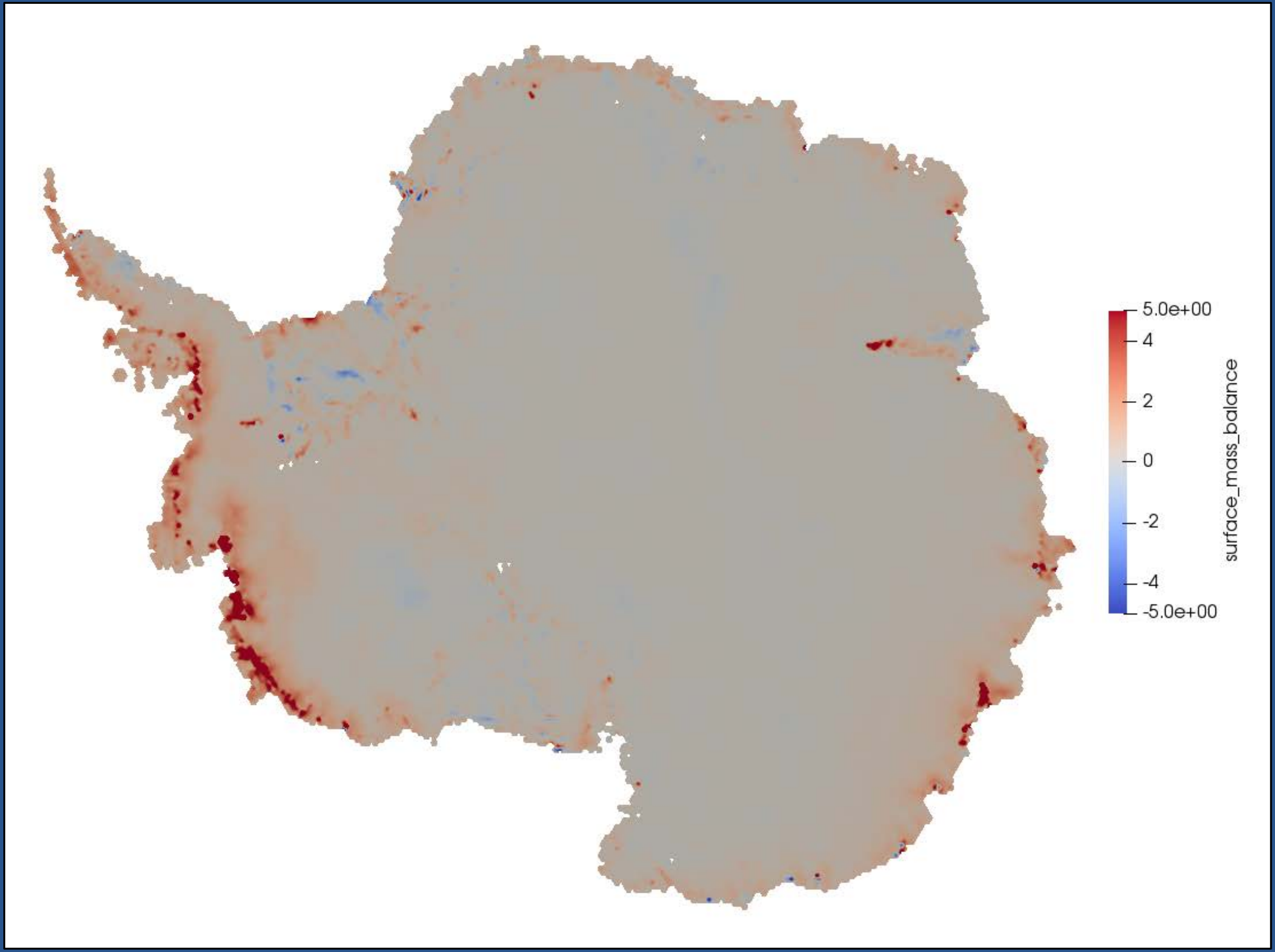


Results: Optimization and Initialization



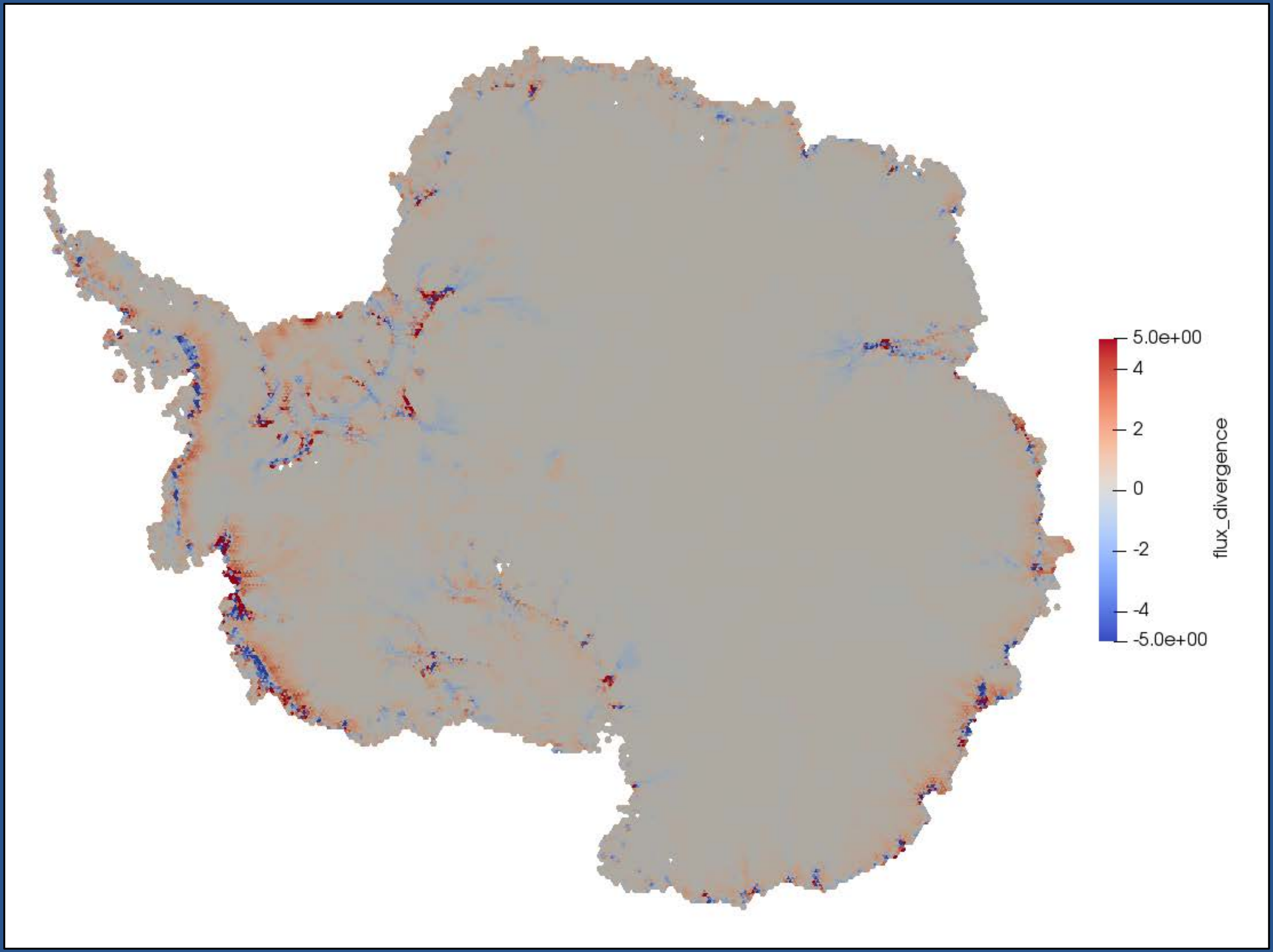
mass flux divergence (m/yr) from standard optimization

Results: Optimization and Initialization



mass balance + non-steady thickness change (m/yr)

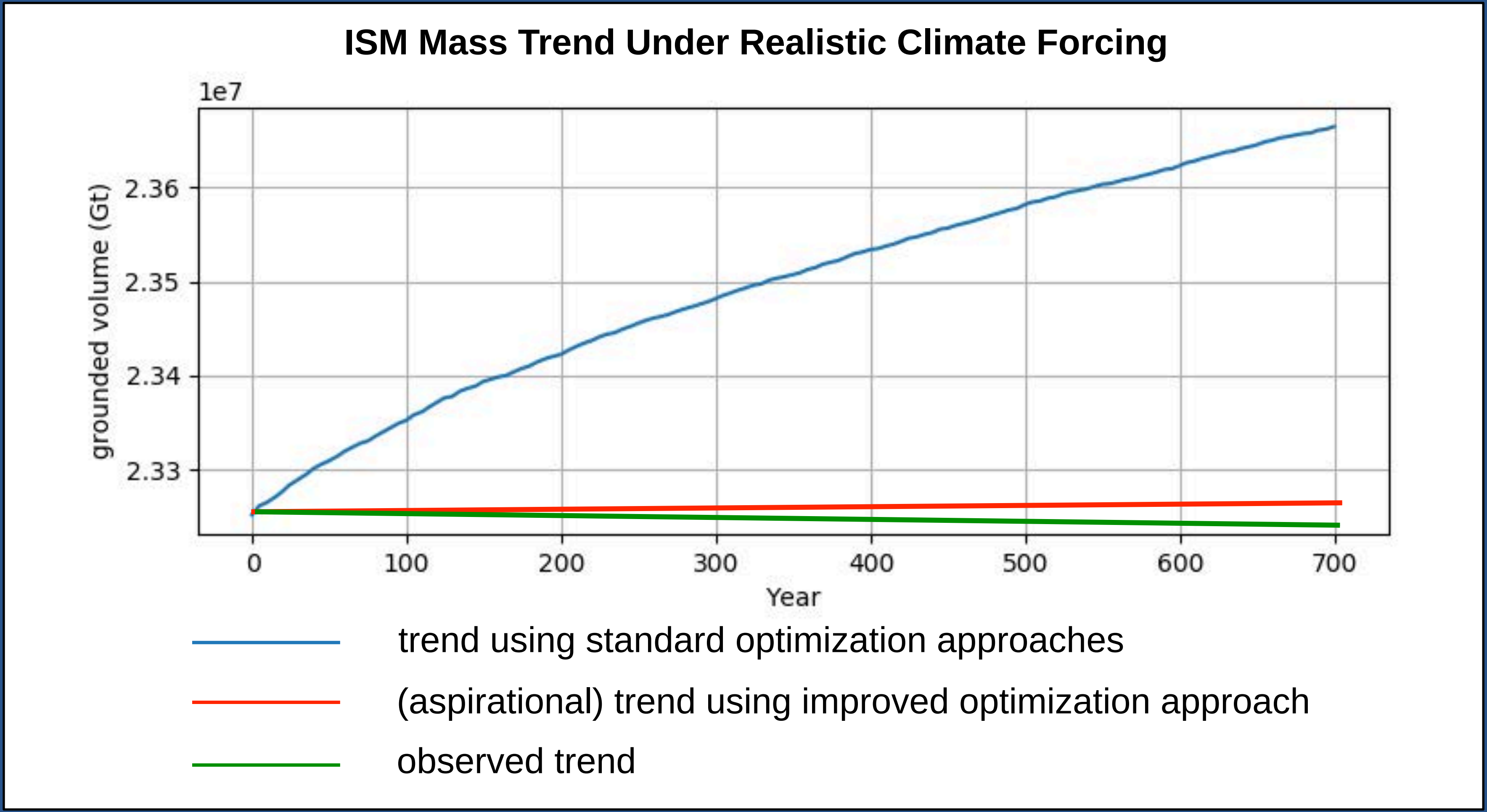
Results: Optimization and Initialization



mass flux divergence (m/yr) from optimization that 1) includes mass balance constraints and 2) allows thickness to vary within errors

Results: Optimization and Initialization

Progress: reduced, non-physical transients after optimization and when coupling to realistic climate forcing



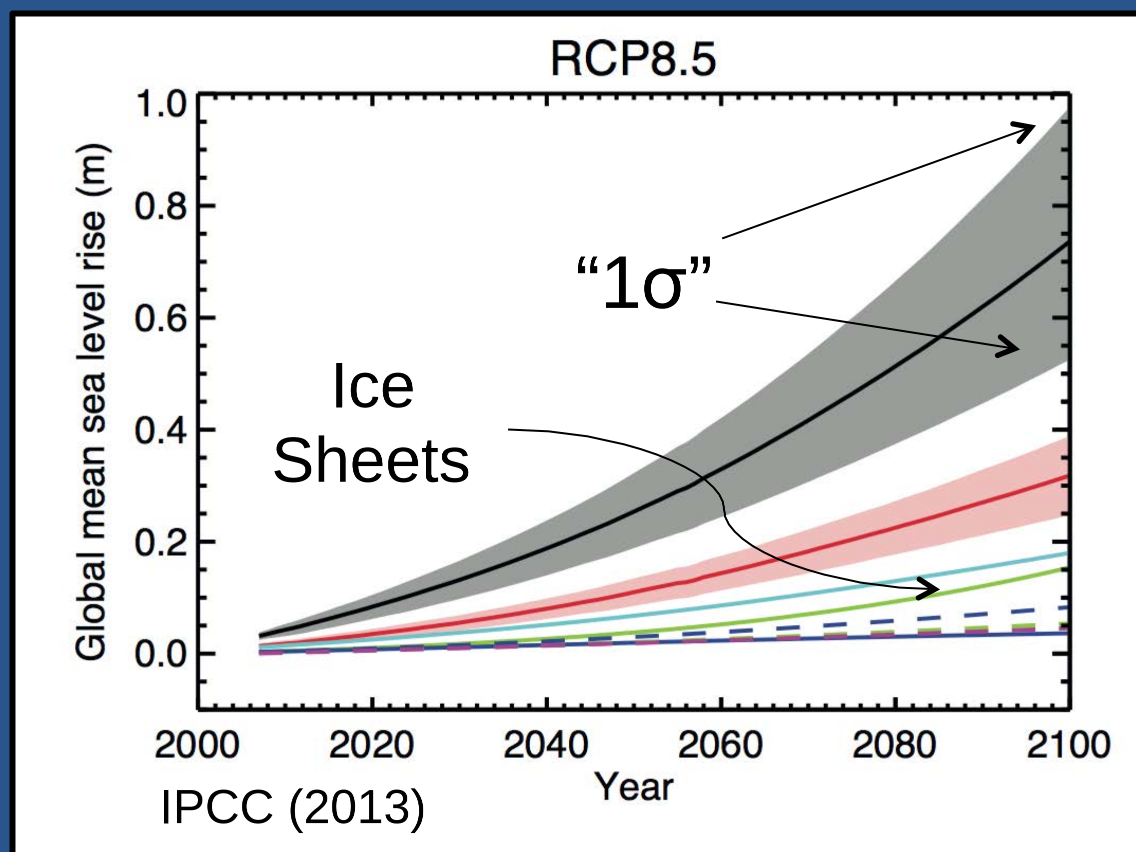
Results: Uncertainty Quantification

Importance:

- Sea level projections without confidence bounds are of limited use to policy makers and planners
- Ice sheets largest source of uncertainty w.r.t. future sea level rise
- Limited attempts at robust ISM UQ to date

Need:

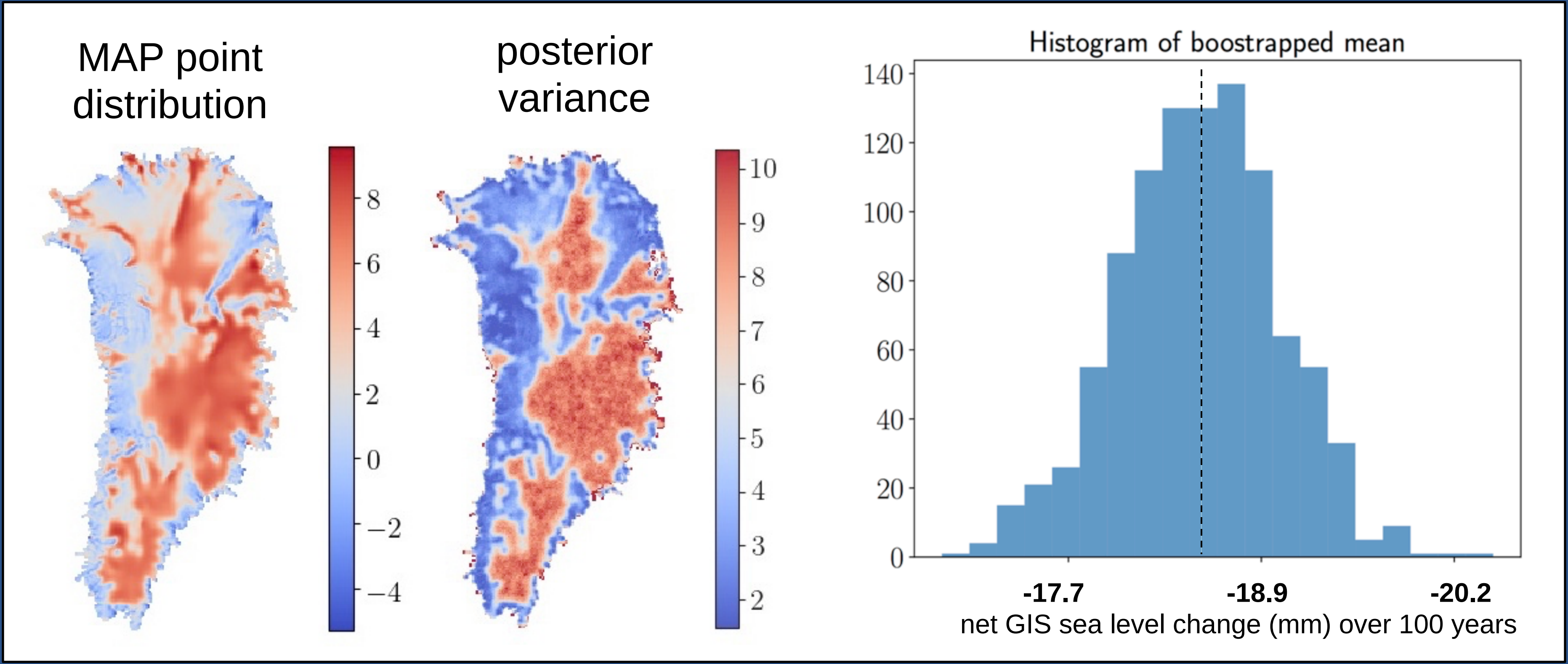
- Affordable ISM UQ methods (for both calibration and fwd propagation) that take into account high dim. optimized ISM param. fields



Results: Uncertainty Quantification

Progress – prototype "end-to-end" UQ framework:

- Leverages and extends optimization framework
- Characterize unc., assign prior for high-dim. param. fields
- Update prior with observations (calibration)
- Propagate posterior uncertainties through forward model



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- Identification / removal of icebergs and "hinged" peninsulas (lead to ill-posed problem). FASTMath solution ~1000x speed-up over Matlab prototype (similar problem and solution for BISICLES through SDAV under SciDAC3)
- Porting of MALI's *Albany/Trilinos*-based optimization code to *Tpetra* for performance portability (FASTMath)

- Improved preconditioning for fast, robust solutions of PDE-constrained optimization (FASTMath)
- Dimension reduction methods and accurate surrogate-model generation to improve efficiency of UQ framework (FASTMath)
- How best to apply new architectures / programming models to accelerate most costly parts of ice sheet model solution? Some current success on accelerating assembly; room for much larger gains in linear solve (elliptic PDE) (FASTMath)

Challenges

- Dycore computational performance “verification” achieved using Land Ice Verification and Validation toolkit with GPTL (pLIVV) under SciDAC3. Are there better performance profiling tools now available? (RAPIDS)

- Current V&V approaches require post-processing, reorganizing, regridding, reducing of model outputs. *In situ* model output processing and analysis methods (*before* writing to disk) could reduce computational (i/o) and storage costs. E3SM’s MPAS-based components aspire to this but have not yet realized it on a practical, routine basis (RAPIDS)

Summary

- Sea level rise from ice sheets continues to accelerate
- SciDAC3 developed mature, high-resolution, HPC-ready ice sheet models
- SciDAC4 effort will focus on improvements to models and modeling frameworks needed for quantifying / reducing uncertainty in sea level projections
- SciDAC and DOE's broader Earth system modeling effort are well positioned to make significant and unique contributions to sea level projection efforts

Results: Model Structural Uncertainty

Progress – testbeds for exploring structural uncertainty:

- Two high-resolution ISMs being developed under SciDAC
- Both being applied to large-scale, whole-ice-sheet simulations
- Both being coupled to E3SM
- Provides unique opportunity to start investigating how model structural uncertainty impacts sea level rise projections