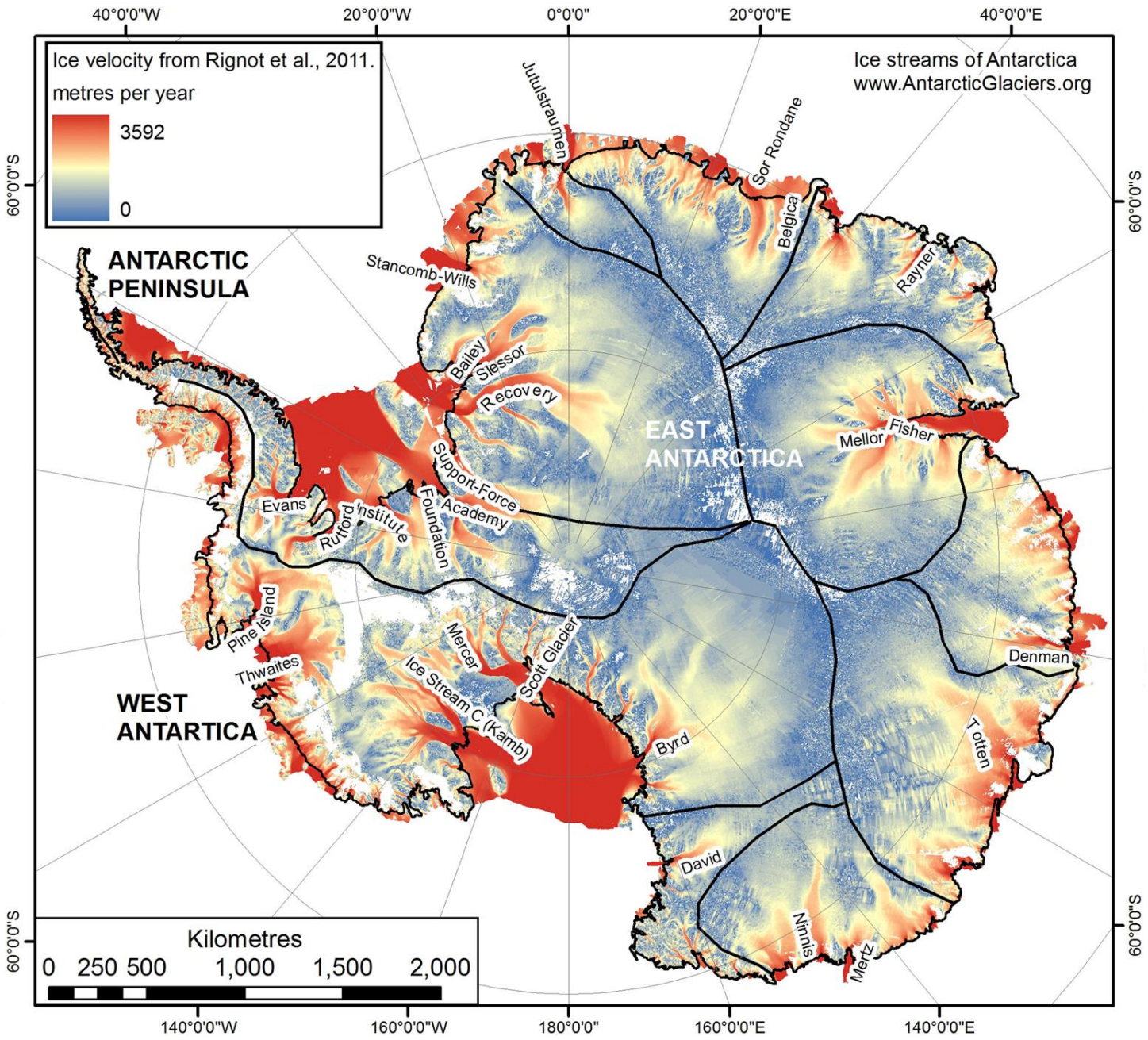

Ice Sheet State Estimation using ISSM

2023 ECCO Annual Meeting Update

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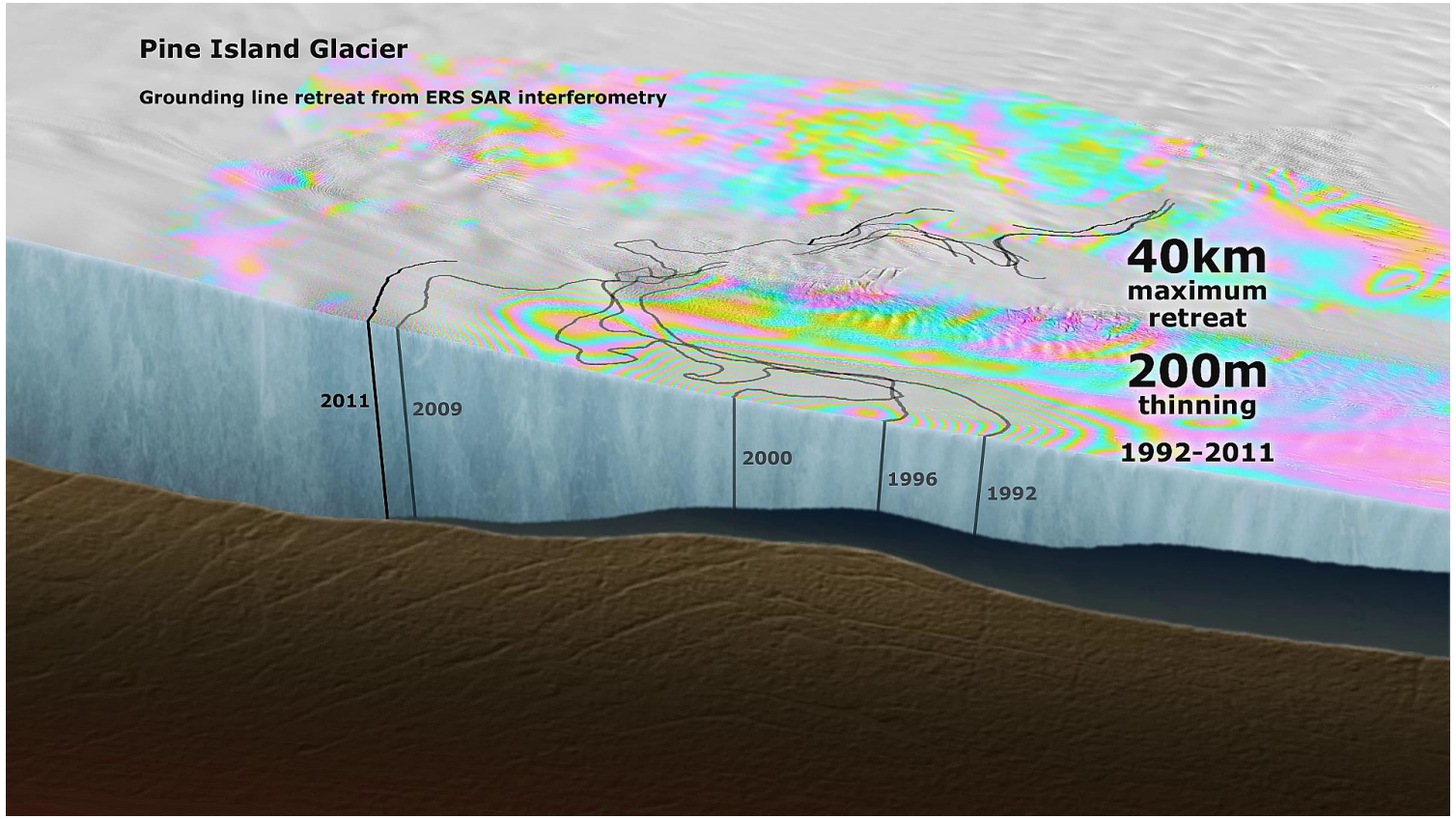
California Institute of Technology

Motivation

- Improve estimates of ice/ocean interactions on multi-decadal timescales
- Provide ECCO ocean model time-varying fields:
  - grounding line position
  - ice mass flux across grounding line
  - ice shelf/glacier geometry
  - iceberg calving fluxes
  - basal melt rate



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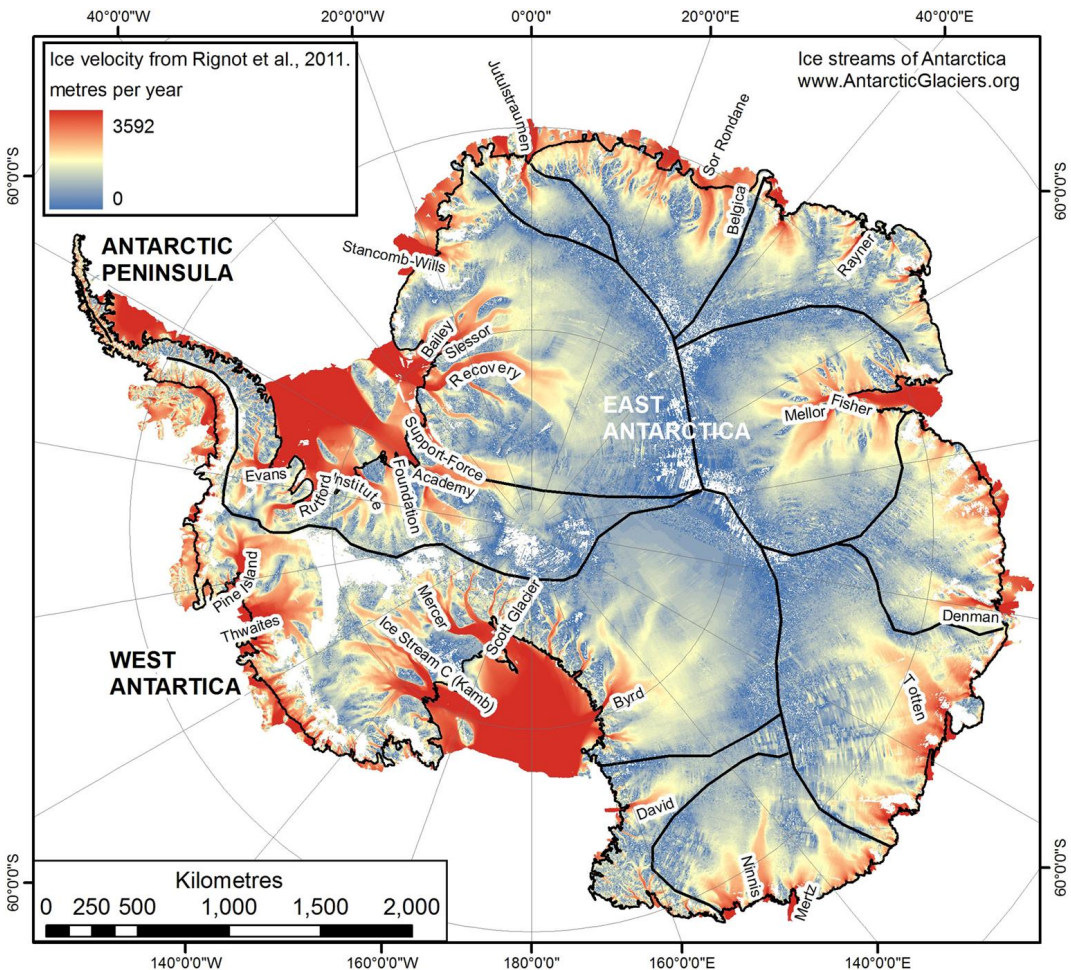
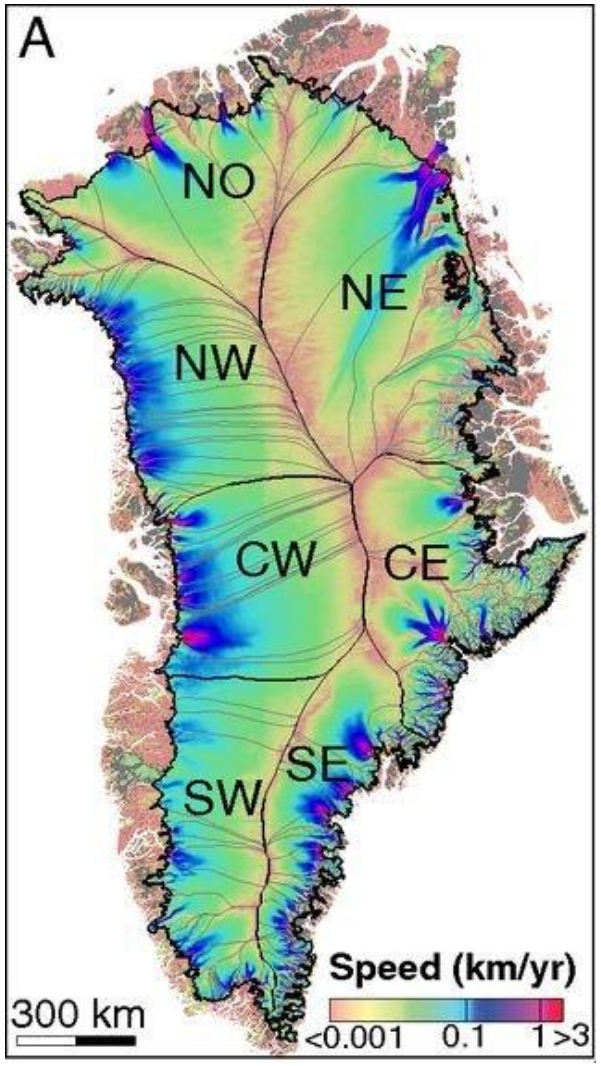
5-year Plan

- Model: Ice-sheet and Sea-level System Model (ISSM) 4.21
- Provide 1995-(near) present ice-sheet/shelf state estimates
- Year 1: West Antarctica
- Year 2: East Antarctica
- Year 3 & 4: West Greenland
- Year 4 & 5: East Greenland

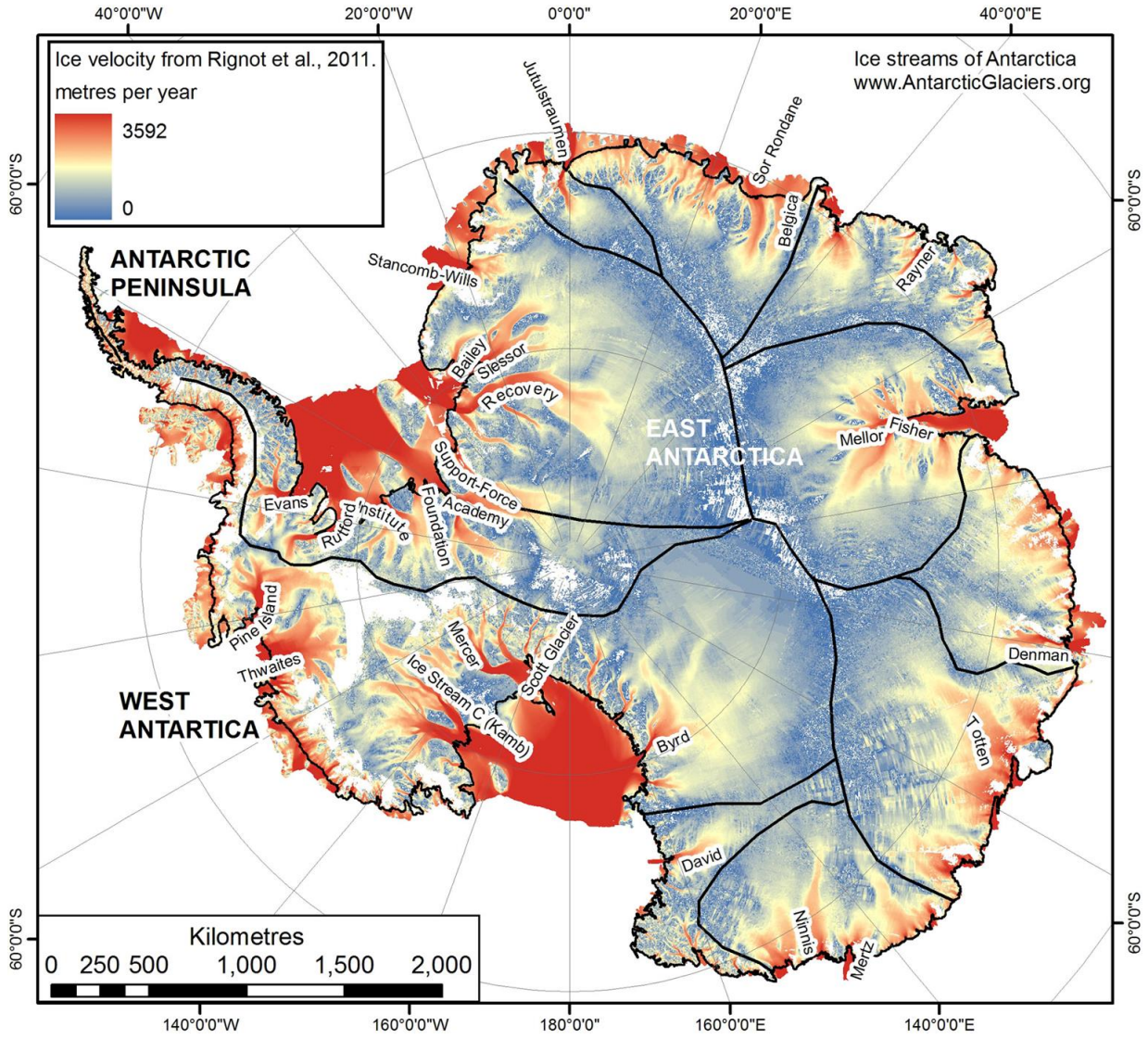




State estimation strategy

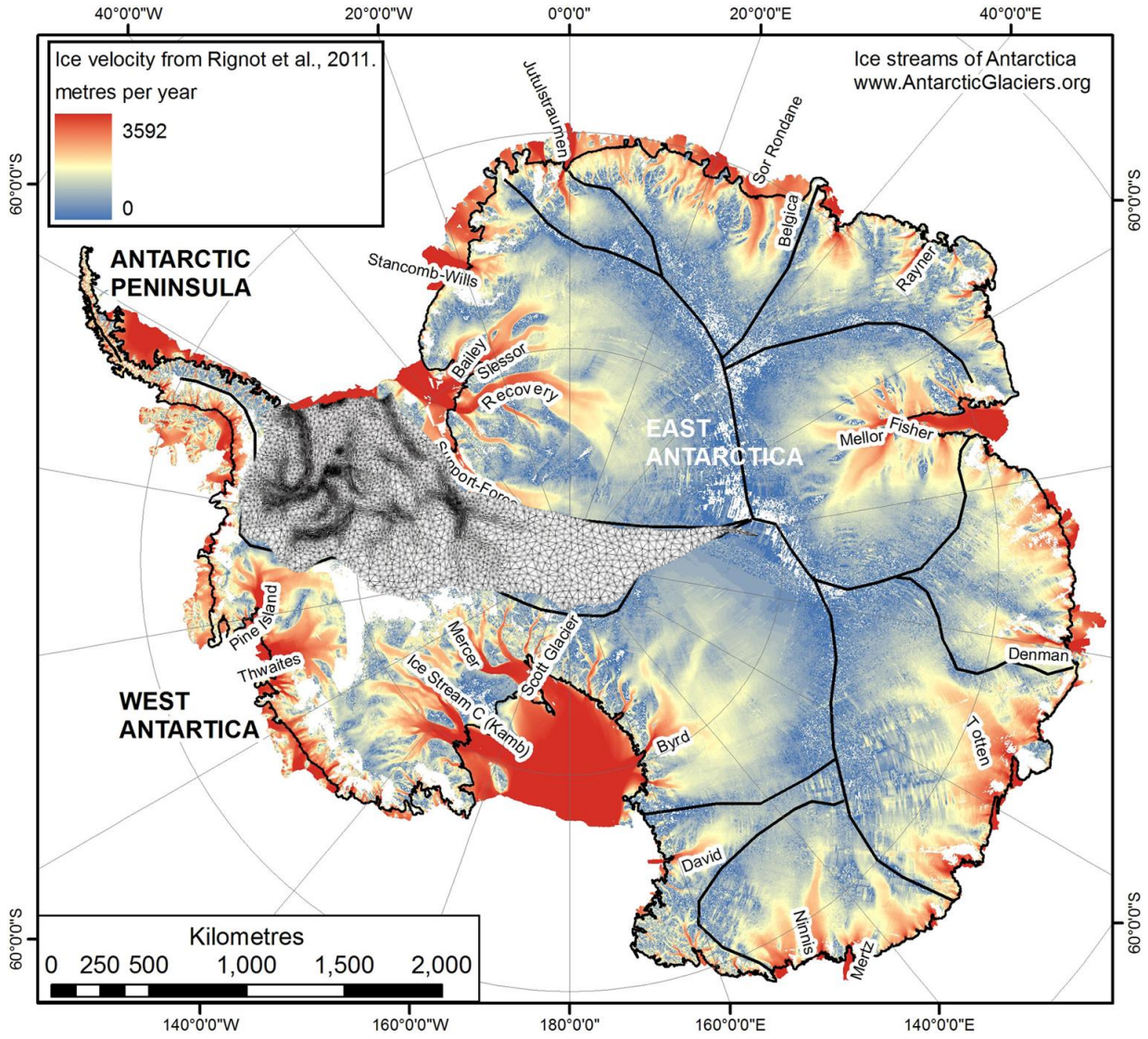
- **Phase 1: Initial Conditions/Spin-up**
  - Inputs: bed geometry, ice elevation
  - Make a first-guess velocity field from ice stress balance (assume steady state)
  - From first-guess velocity, infer internal ice temperature and rigidity
  - Invert for basal friction by constraining to an observed “mean” velocity field
  - Run a short simulation to smooth initially “noisy” input fields (ice thickness, velocity, grounding line position)
- **Phase 2: Adjoint Estimation**
  - 1995-present transient simulations
  - Forcing: ice surface mass balance (snow + surface melt), basal shelf melt, geothermal heating, ice-shelf calving front position
  - Observational constraints: time-varying ice elevation and surface velocity
  - Model control parameters: time-varying basal melt rate, time-invariant ice rigidity,& time-invariant basal friction

Phase 1: Model Spin-up



- Models are split by ice basin
- Basins represent “watershed” catchments that are taken as decoupled
- Computational constraints lead to solving basins independently
- Smaller basins can be combined, larger ones can be split up
- Total for Antarctica ~10
- Total for Greenland ~8

Phase 1: Model Spinup



- Models are split by ice basin
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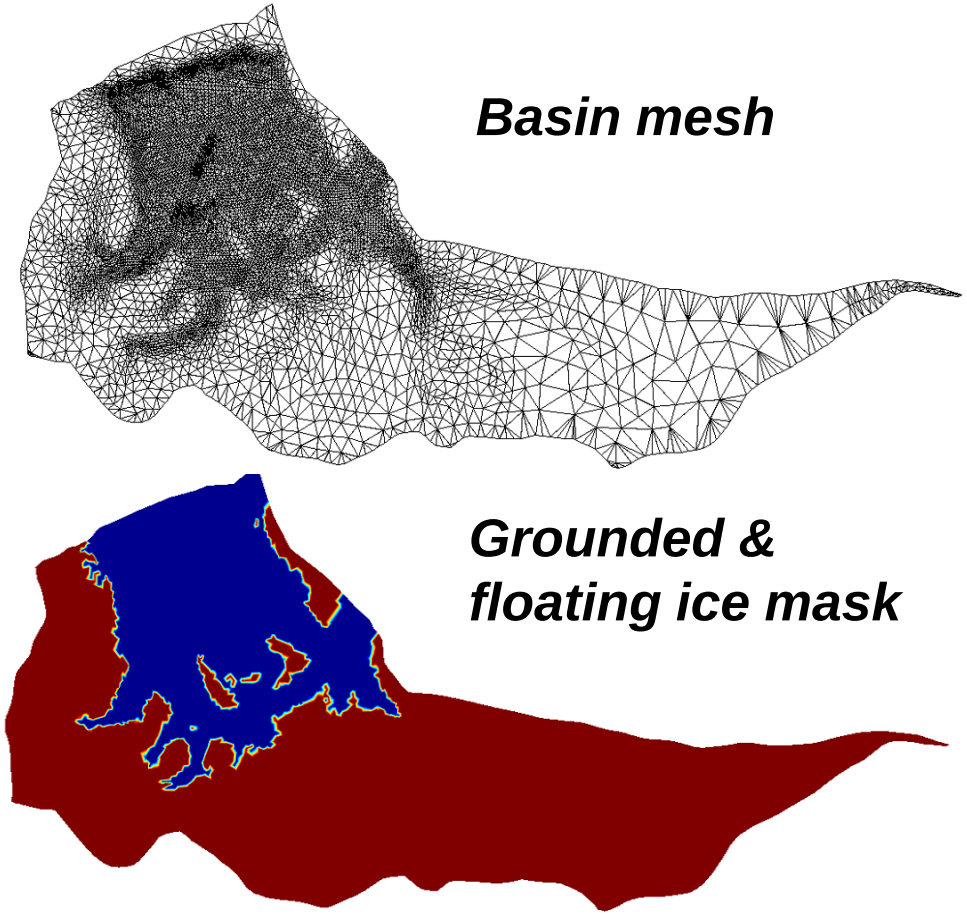
- Computational constraints lead to solving basins independently
- Smaller basins can be combined, larger ones can be split up
- Total for Antarctica ~10
- Total for Greenland ~8
- Begin Phase 1 with Ronne basin

Phase 1: Model Spinup

- Anisotropic mesh generation, followed by parameterization
- Resolution: 1km-40km, 13k elements
- Timesteps: 3 month timesteps for 23 years
- CPU usage: ~22 CPUs
- Forward Simulation time: 90 seconds
- Adjoint Simulation time: 16 minutes

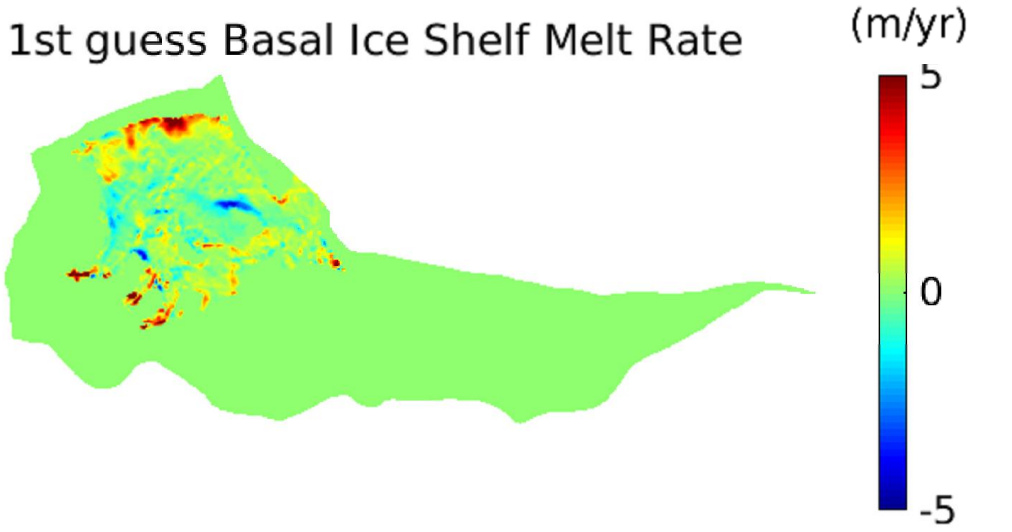


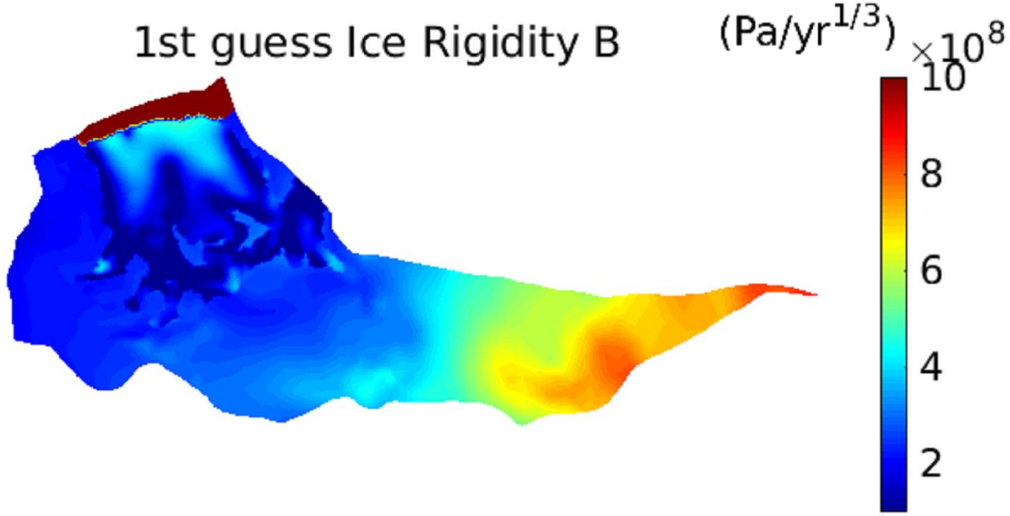
Basin mesh

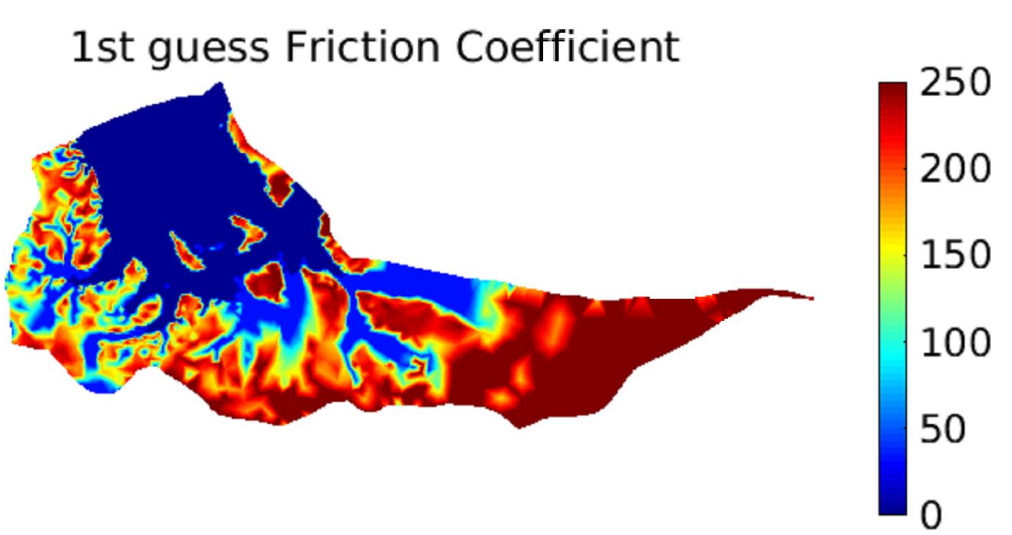
Grounded & floating ice mask

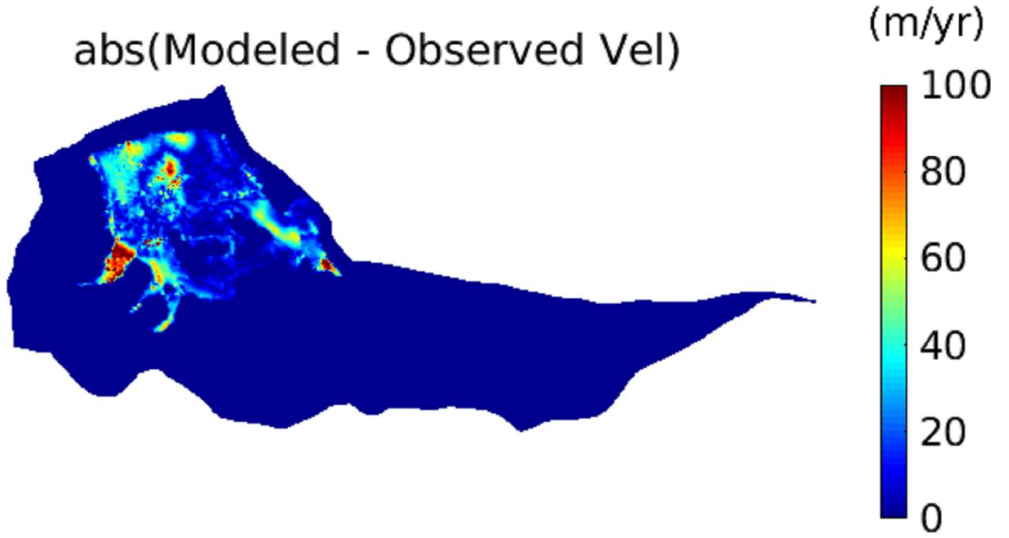
Phase 1: Initial Conditions/Spinup

- Solve for 1995 ice rigidity & basal friction. Use Rignot for 1st guess melt rates.



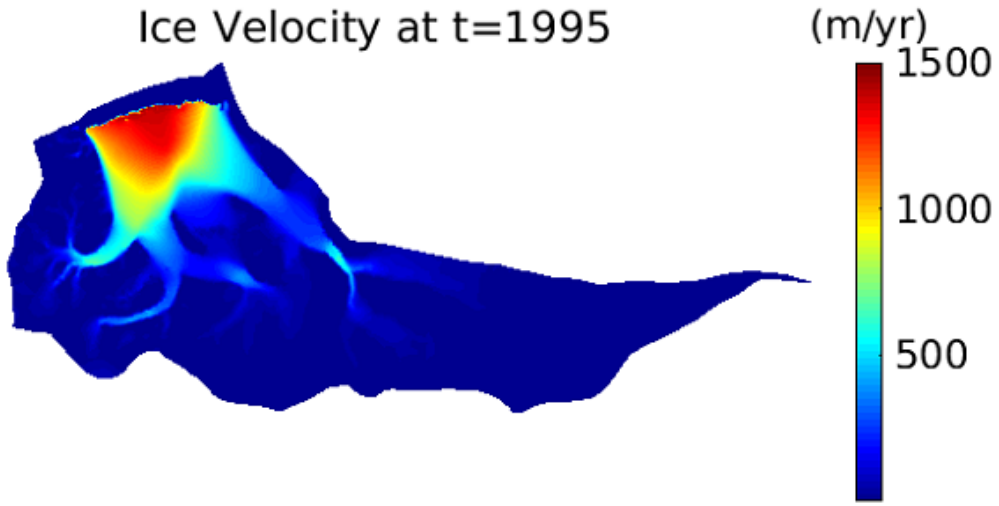


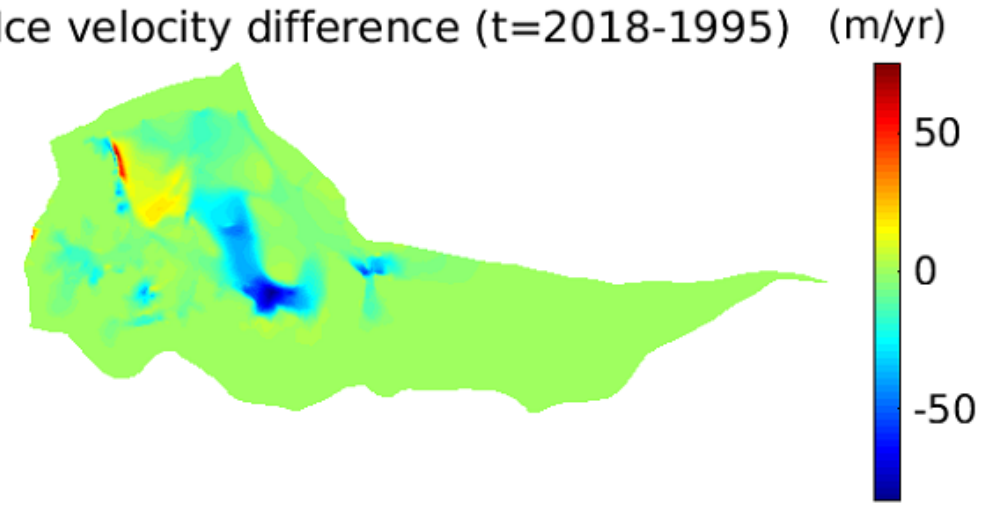


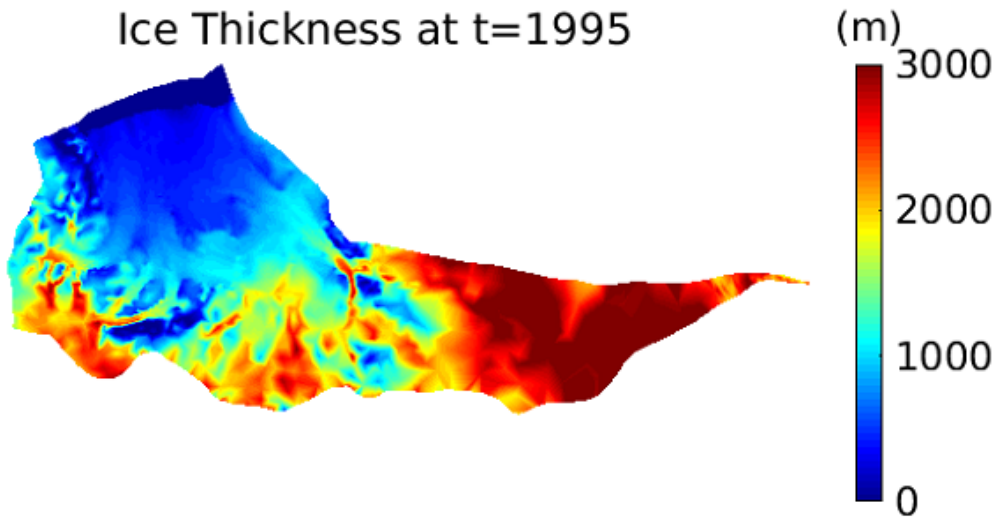


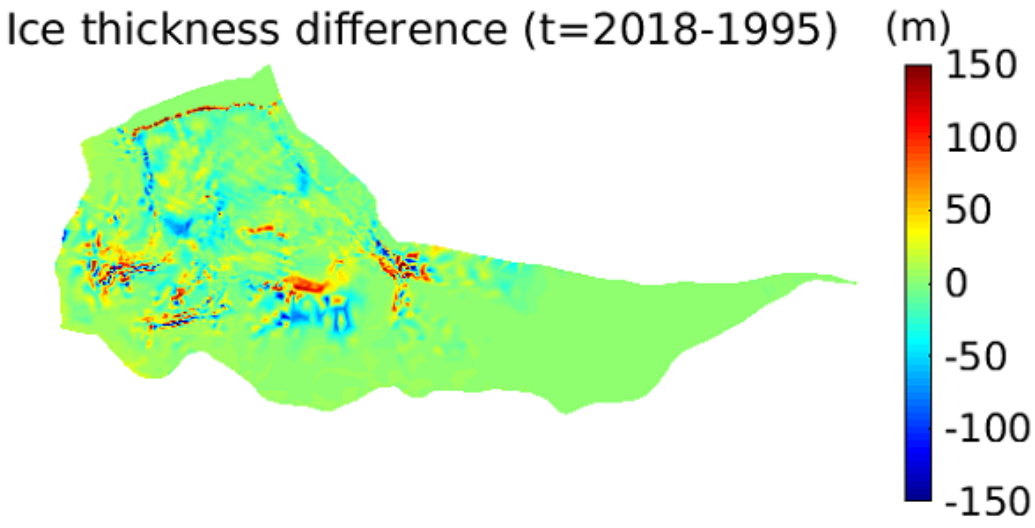
Phase 1 - “Iteration 0” Transient Control Run

- Perform transient control run (“Iteration 0”), 23 year forward simulation









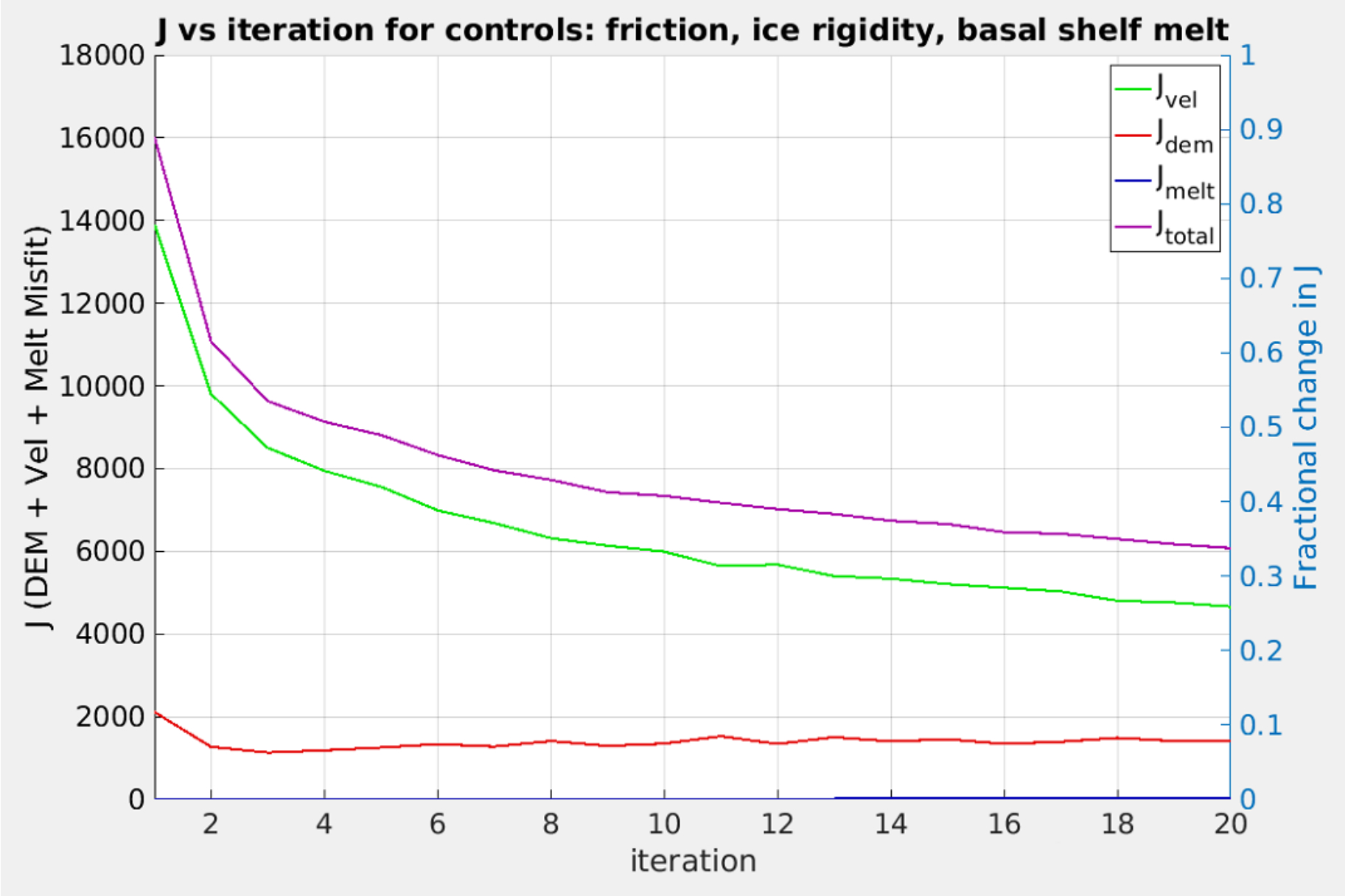
Phase 2: Adjoint Runs & Cost Function Formulation

- Use adjoint of ISSM to perform state estimate w/ simultaneous inversion for observed basal friction, ice rigidity, and basal ice shelf melting rate
- Describe our cost function in terms of Wunsch and Heimbach (2006):

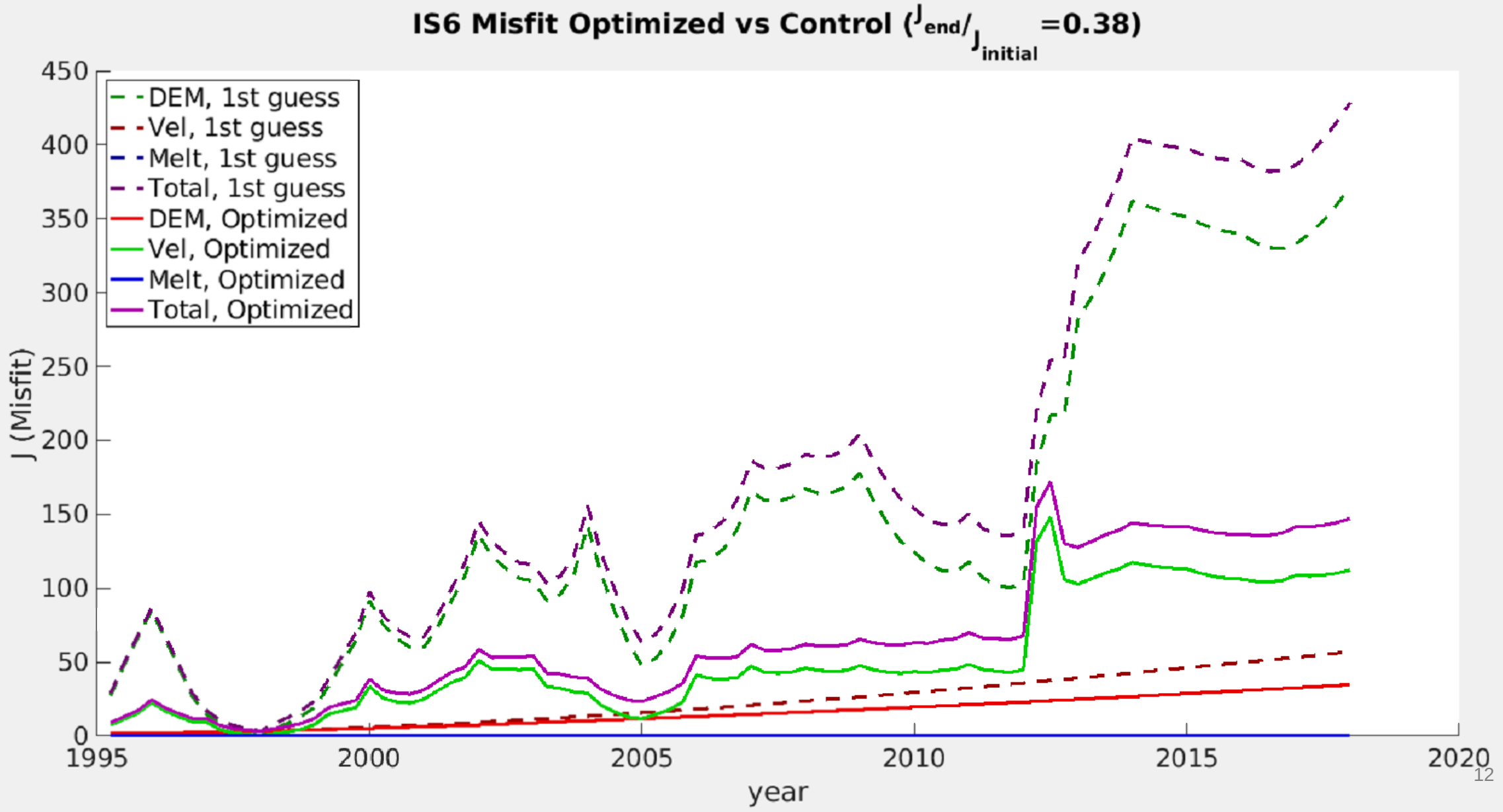
$$
\begin{aligned}
J = & \sum_{t=1}^{t_f} [\mathbf{y}(t) - \mathbf{E}(t)\mathbf{x}(t)]^{\mathrm{T}} \mathbf{R}(t)^{-1} [\mathbf{y}(t) - \mathbf{E}(t)\mathbf{x}(t)] \\
& + 0 * [\mathbf{x}_0 - \mathbf{x}(0)]^{\mathrm{T}} \mathbf{P}(0)^{-1} [\mathbf{x}_0 - \mathbf{x}(0)] \\
& + 0 * \sum_{t=0}^{t_f - 1} \mathbf{u}(t)^{\mathrm{T}} \mathbf{Q}(t)^{-1} \mathbf{u}(t),
\end{aligned}
$$

- For our optimization problem, y = time-varying velocity and time-varying ice surface elevation; E=mapping; R = uncertainties
- Currently using zero weights for initial condition penalty (2nd term) and control adjustment penalty (3rd term), to be added in the future

Phase 2 - Adjoint Runs - Optimization

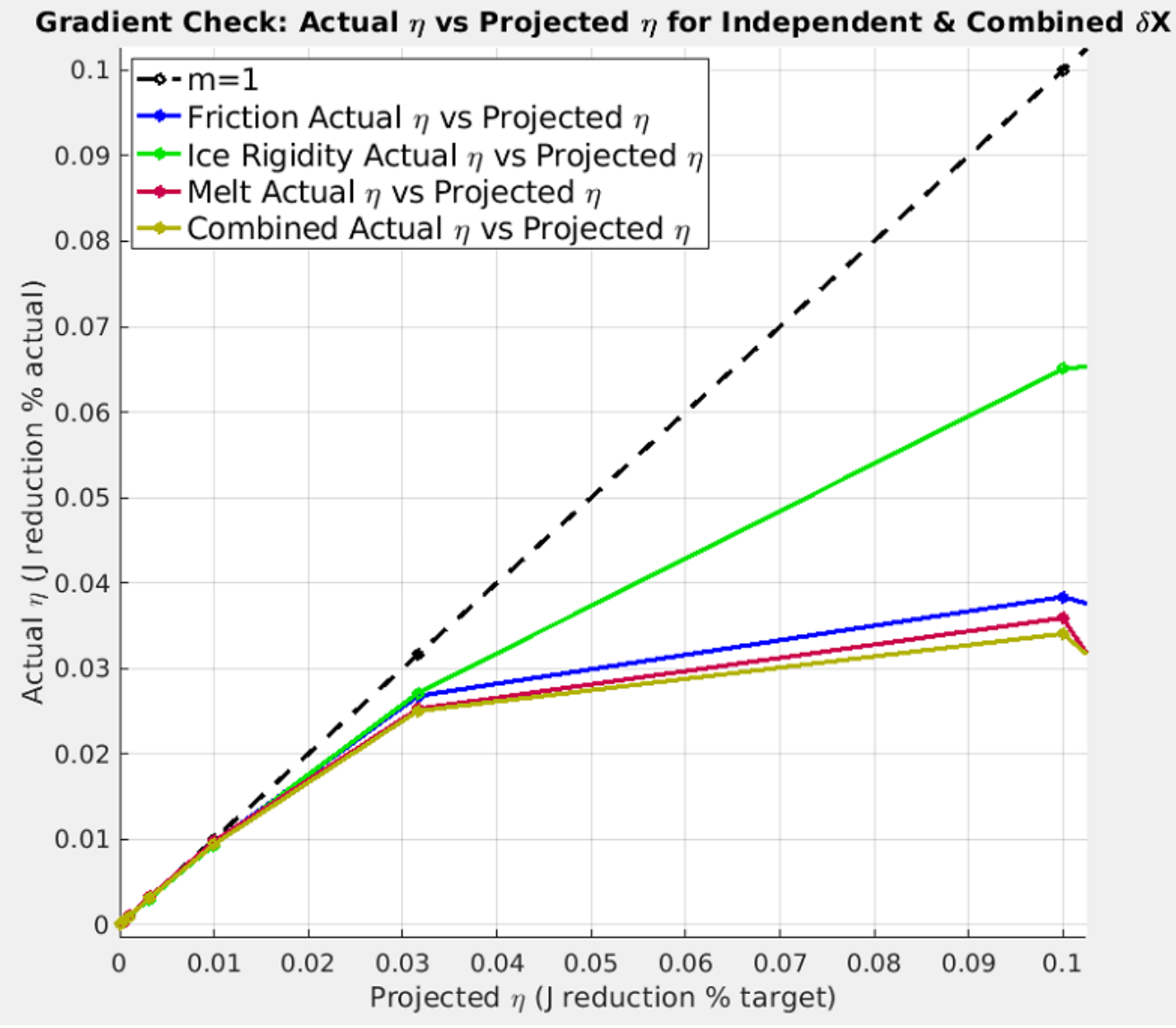


Phase 2 - Adjoint Runs - Optimization

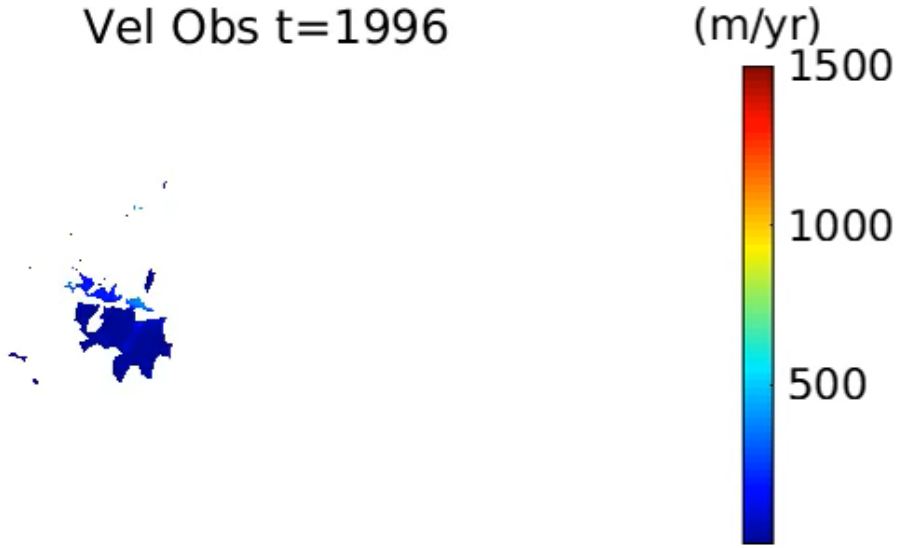


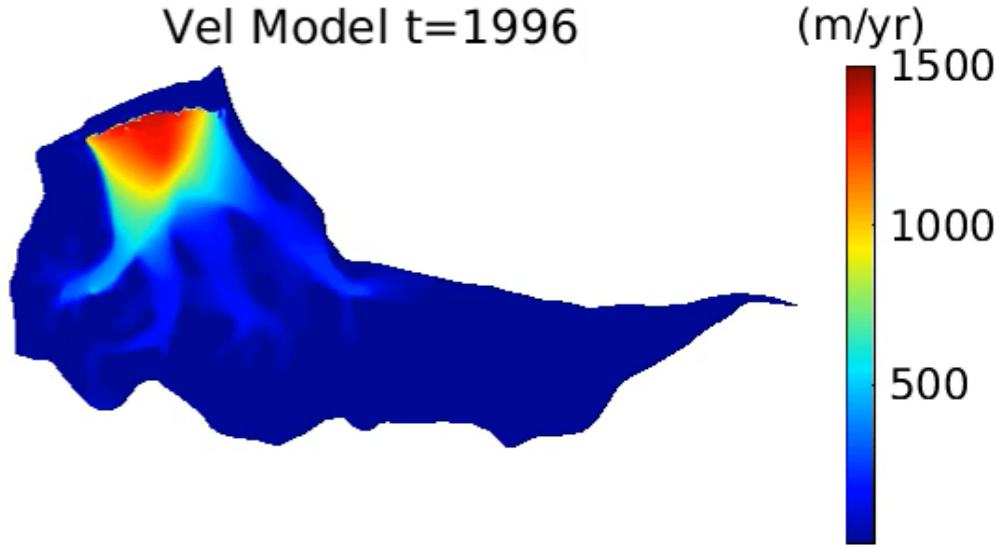
Phase 2 - Adjoint Runs - Gradient Check

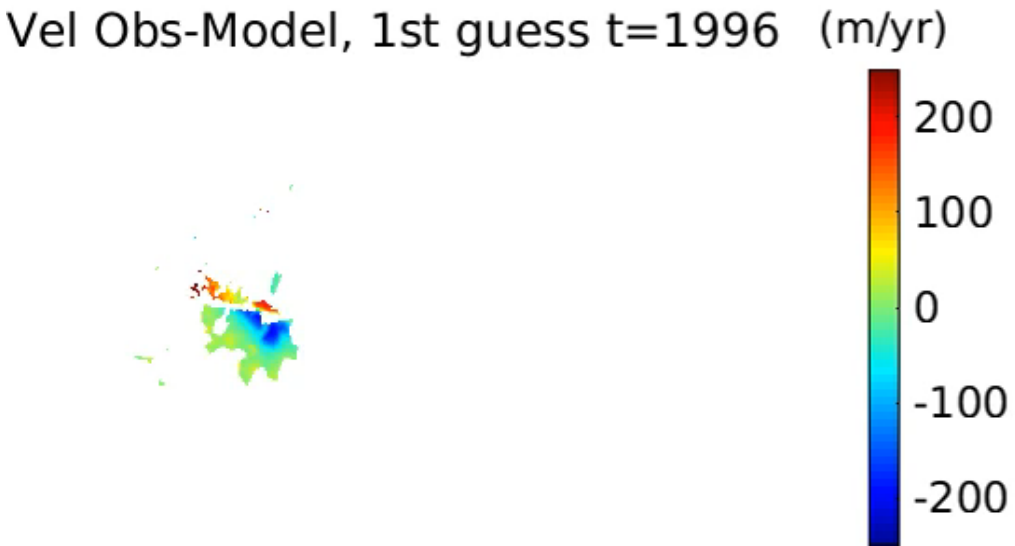
- Ensure validity/linearity of gradients from ISSM-AD for small step sizes/**η**

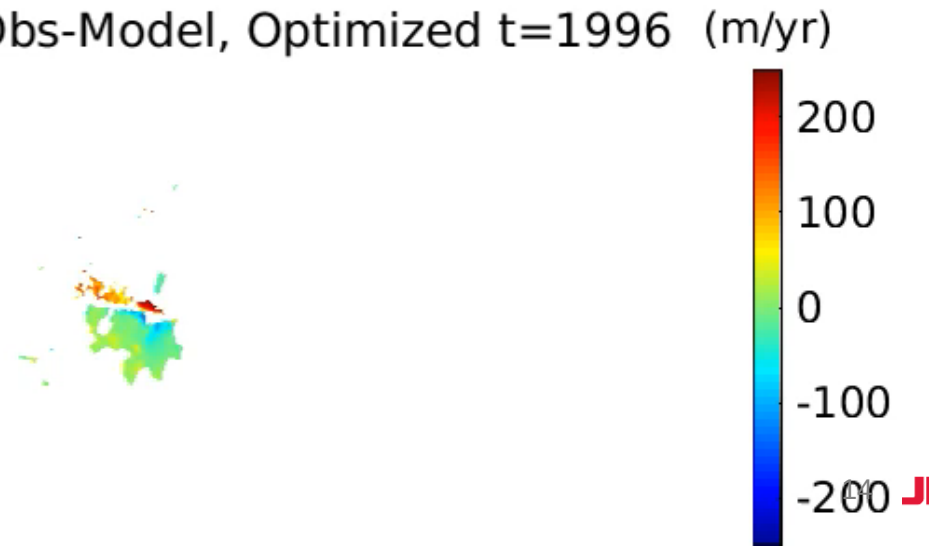


ECCO ISSM – Model Consistency Check & Outputs

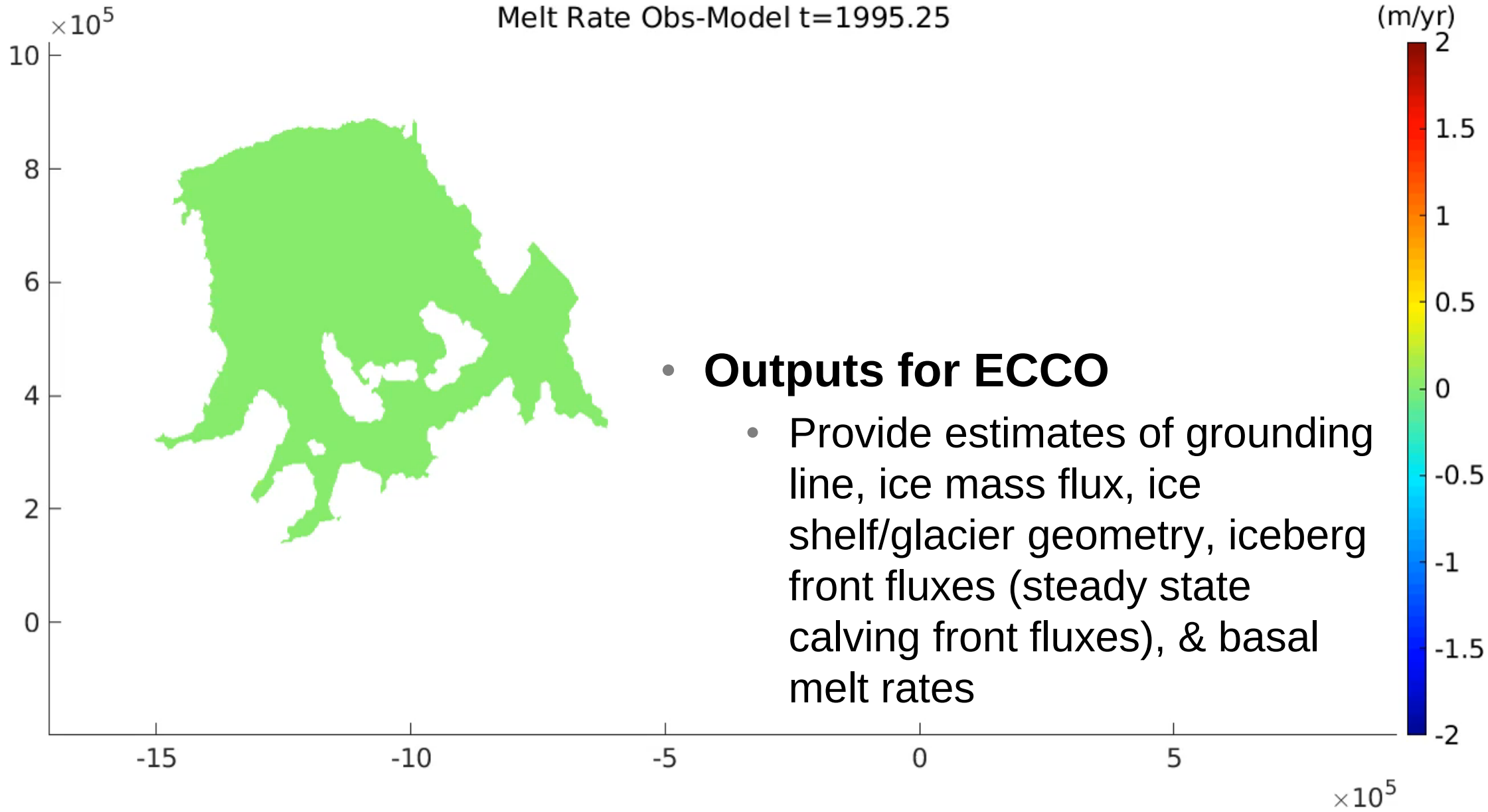








ECCO ISSM – Model Consistency Check & Outputs



- **Outputs for ECCO**
  - Provide estimates of grounding line, ice mass flux, ice shelf/glacier geometry, iceberg front fluxes (steady state calving front fluxes), & basal melt rates

ECCO ISSM – Current Status and Next Steps

- **Completed:**
  - Verify model spin up in Ronne basin
- **Current status:**
  - Phase 2 - Estimation using transient forward/adjoint runs
- **Next steps:**
  - Monthly timesteps, expand time series range
  - Increase spatial resolution around grounding line/trouble spots
  - Refine model/consistency checks (shear softening, cyclic spin-up, GL)
  - Expand to other basins in West Antarctica