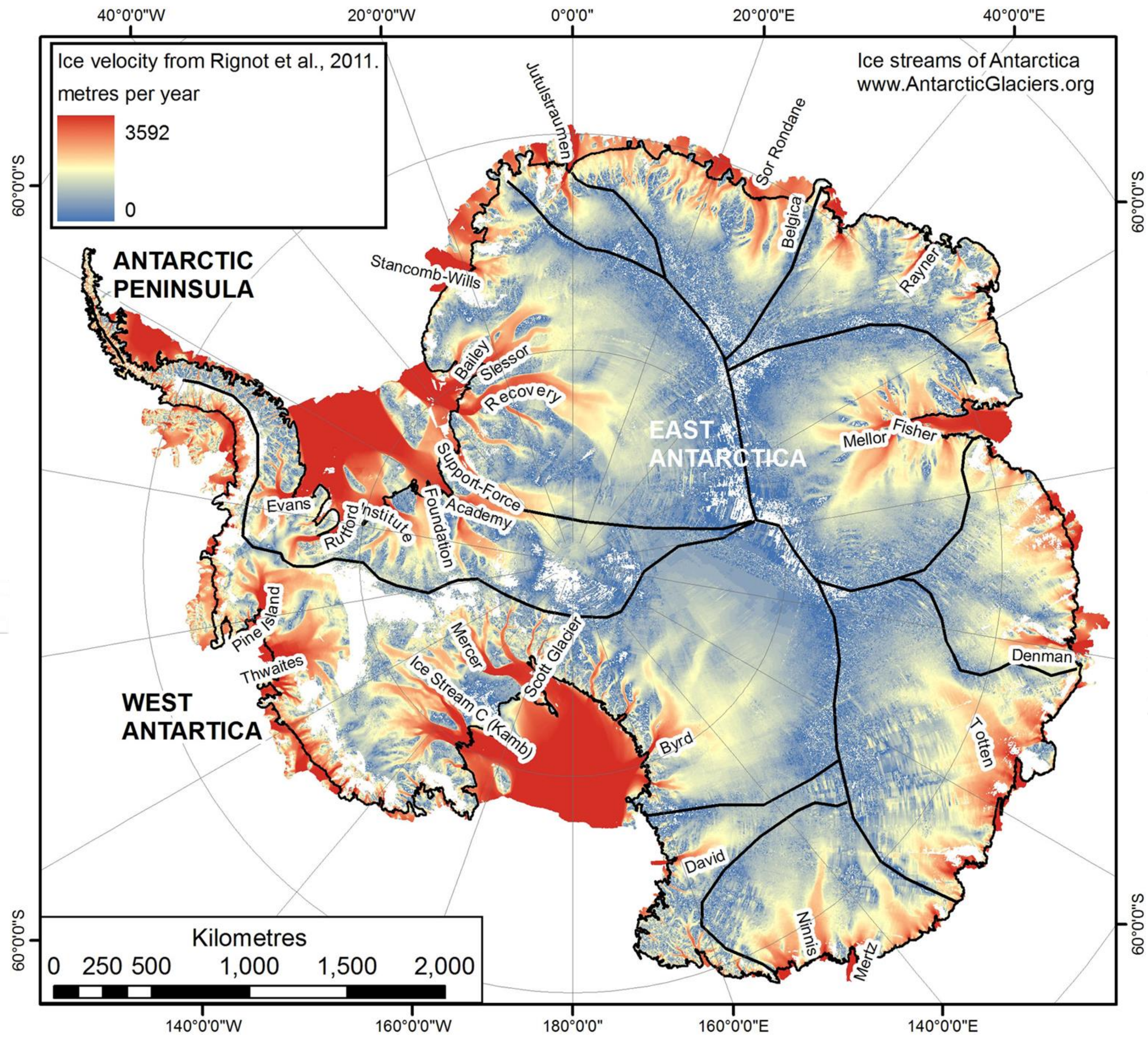

ECCO-Ice
Multi-decadal ice sheet state estimation

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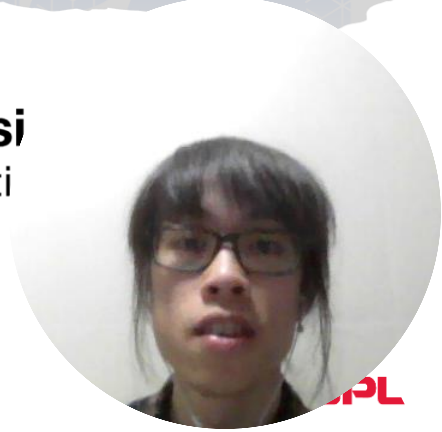
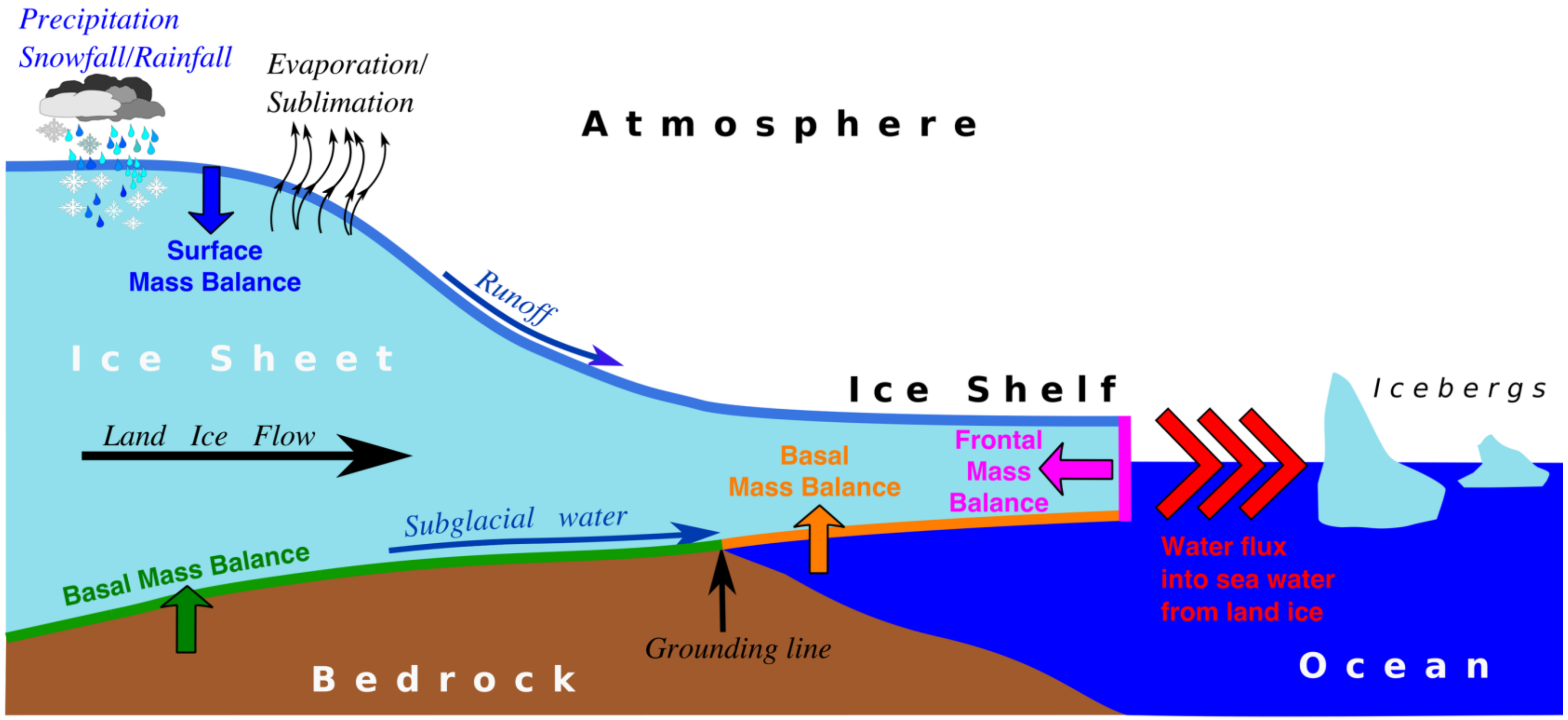


Motivation

- Improve estimates of ice/ocean interactions on multi-decadal timescales



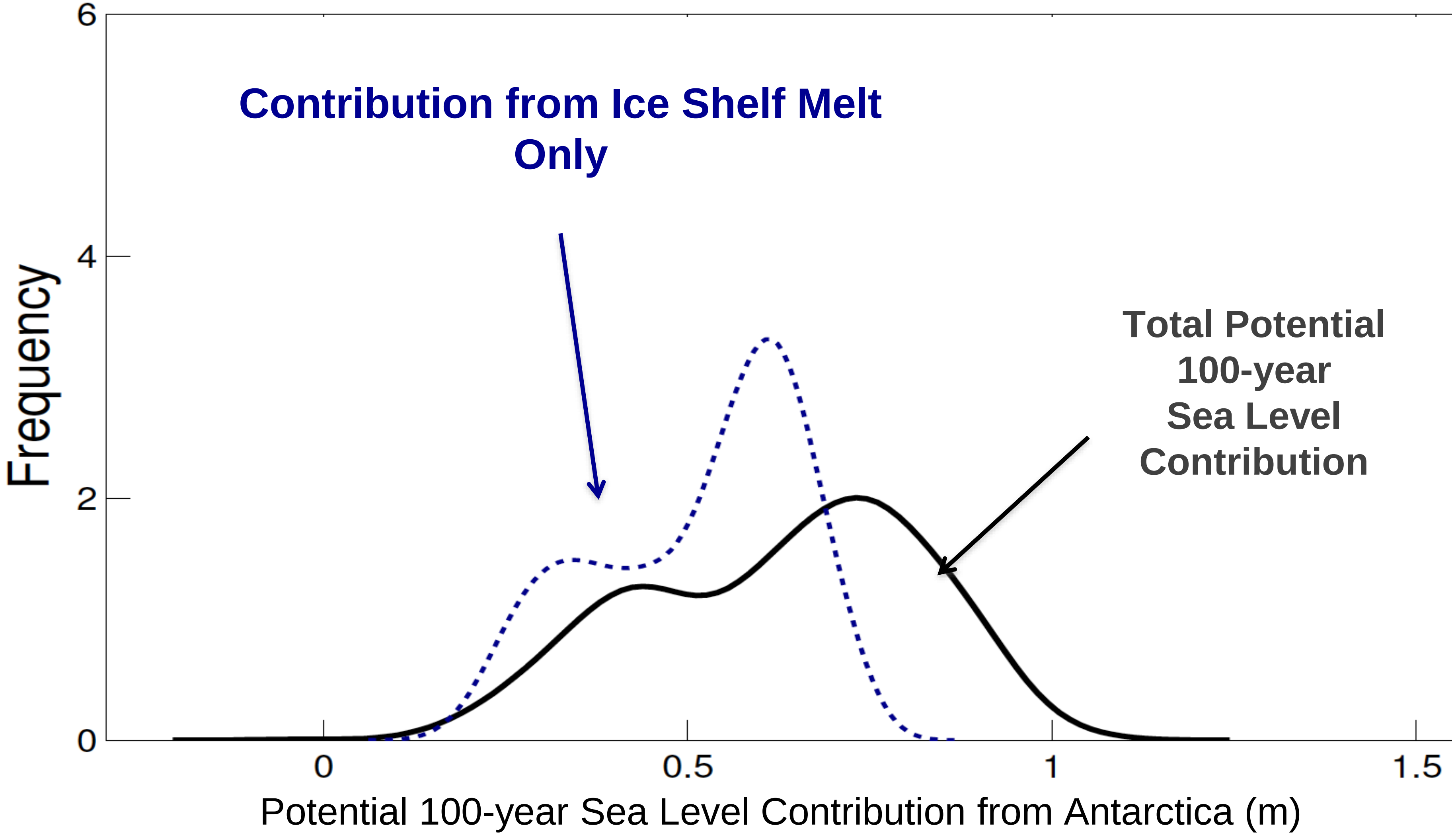
We know:

- ice elevations,
- ice surface velocities,
- ice front + grounding line
- atmosphere conditions/surf. mass fluxes
- bed geometry
- time-mean basal melt
- physics of ice dynamics
- calving fluxes

We want to know:

- ice-shelf cavity geometry
- basal friction/bed composition
- internal ice strength
- time-varying basal melt
- time-varying GL mass flux

Basal ice-shelf melt is responsible for most of the uncertainty and the complex distribution of future sea level rise associated with Antarctic Ice Sheet mass loss



Schlegel et al., 2018. Exploration of Antarctic Ice Sheet 100-year contribution to sea level rise and associated model uncertainties using the ISSM framework. Doi: 10.5194/tc-12-3511-2018

High-level question

Can we find a set of initial and boundary conditions that allow an ice sheet model to dynamically evolve in a reasonable manner over a multidecadal period?

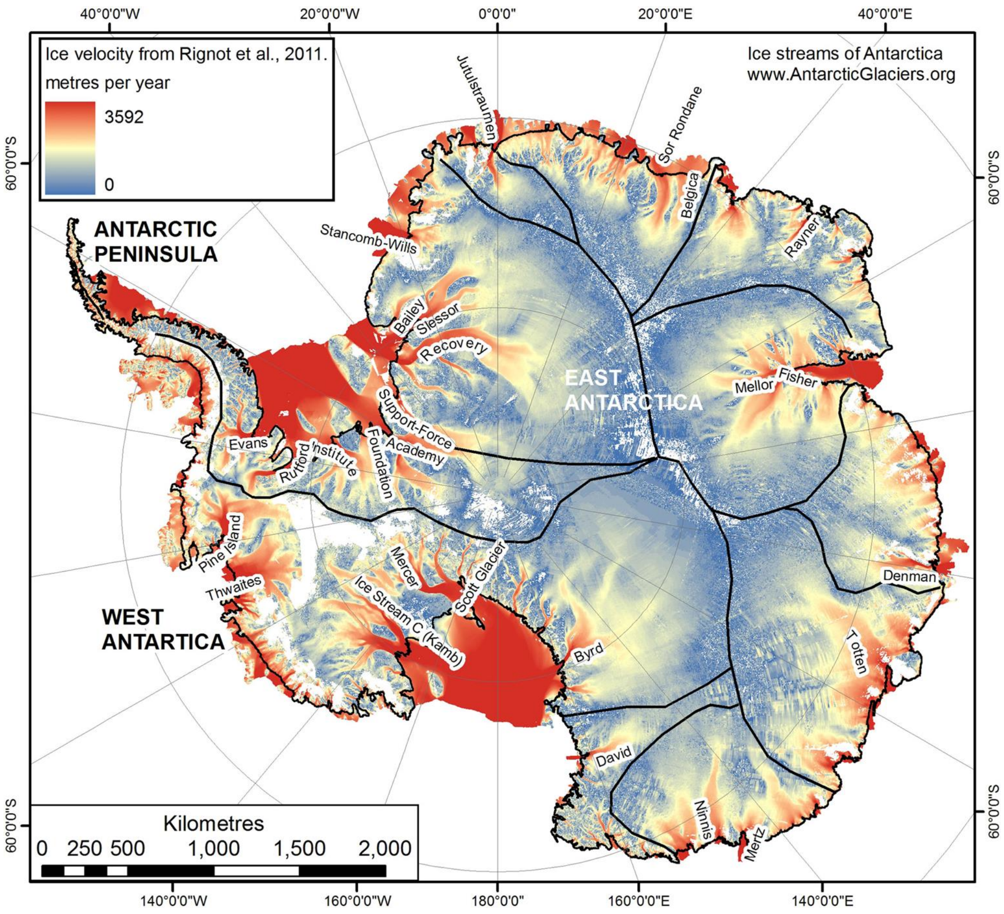
Approach so far:

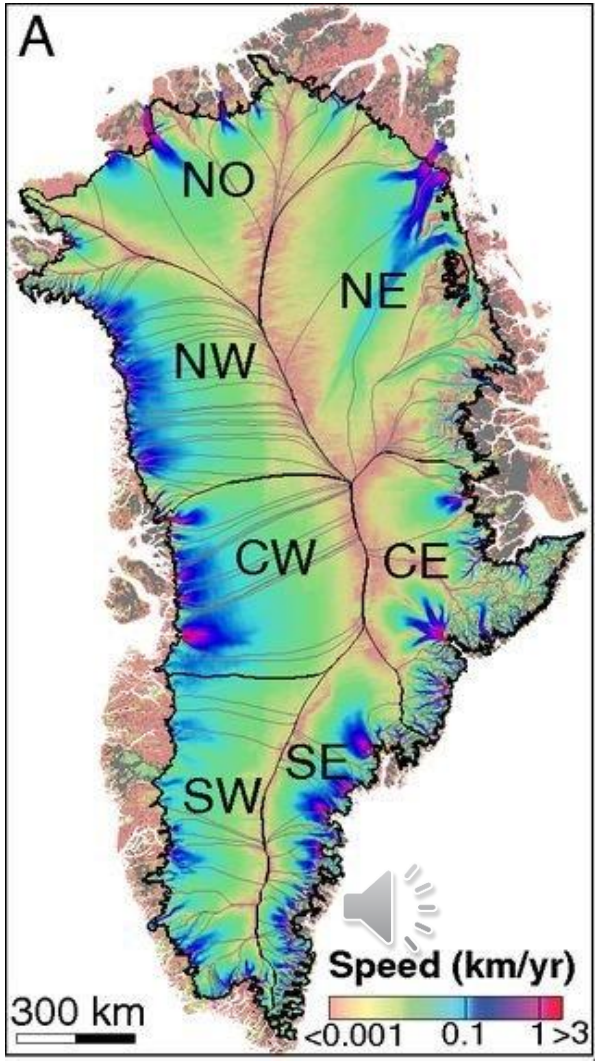
- Solve for **initial ice elevation**, **basal friction**, **internal ice strength**, and **time-varying surface mass fluxes** while specifying a time-mean ice-shelf basal melt
- Solve for **time-varying ice-shelf basal melt** while *specifying* initial ice elevation, friction, ice strength, time-varying SMB

5-year Plan

- Model: Ice-sheet and Sea-level System Model (ISSM) 4.21
- Provide 1995-(near) present ice-sheet/shelf state estimates

- Year 1-2: West Antarctica
- Year 3: East Antarctica
- Year 4-5: West Greenland
- Year 5: East Greenland





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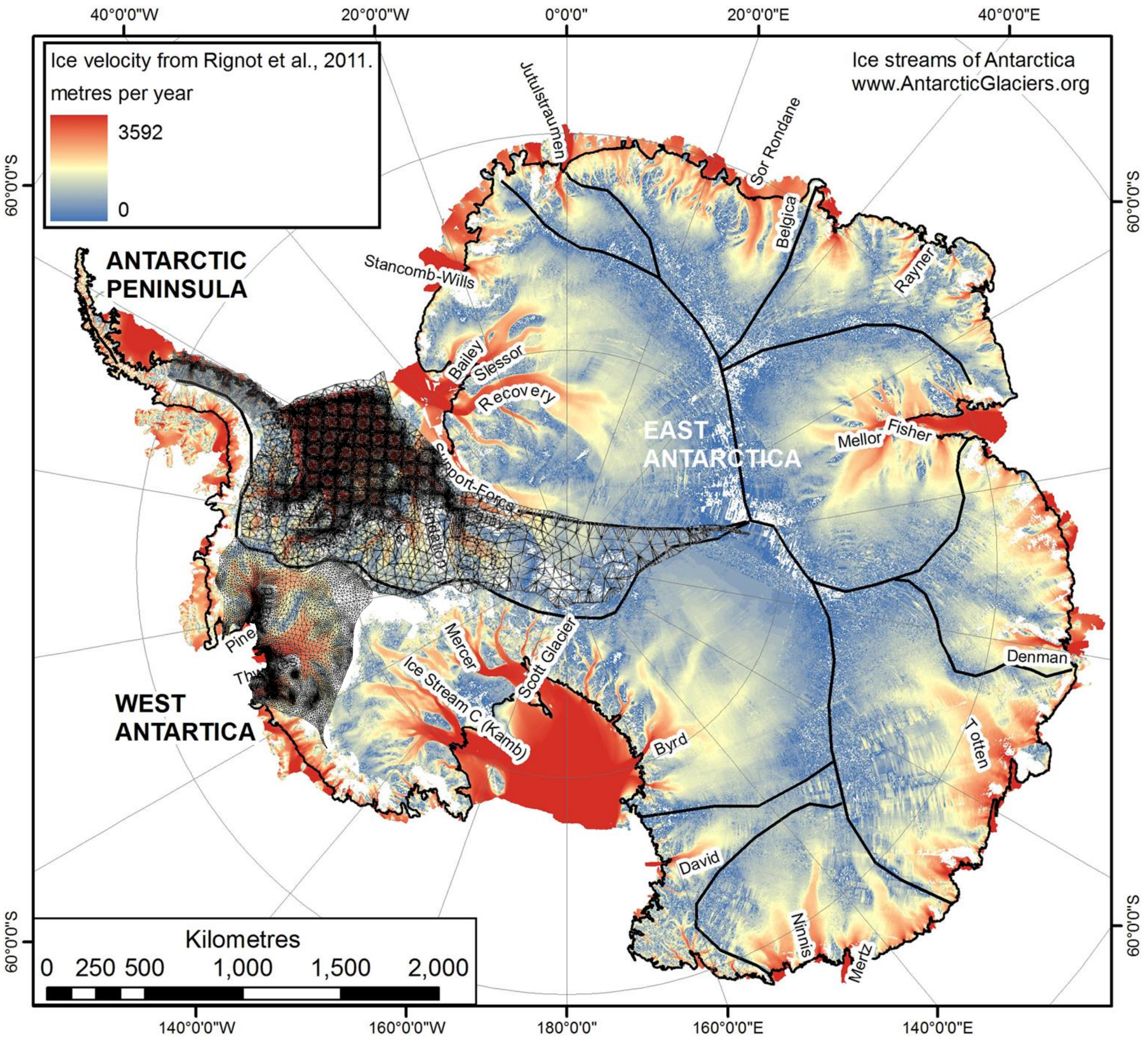
Strategy



- Divide ice sheets into dynamically-independent “ice basins”
  - Antarctica n~10
  - Greenland n~8
- Individual ice basins span multiple ice streams and ice shelves
- Separating ice basins reduces computational requirements and facilitates model development
- Current focused on 3 basins
  - Ronne
  - Larsen D
  - PIG-Thwaites

State estimation strategy

Phase 1: Initial Conditions/Spin-up

- Outputs: “first-guess” model setup: internal ice rigidity, basal friction, grounding line position
- Data inputs: bed geometry, representative ice elevation, time-mean ice-shelf basal heat flux, time-mean ice surface temperature, time-mean ice velocity

Steps:

- Assume ice sheet in equilibrium/steady state w.r.t. velocity and ice elevation
- Calculate first-guess internal ice rigidity using a 3D thermal model
- Calculate first-guess basal friction by inverting the ice stress balance equation
- Run a short model spin-up simulation to smooth out initially “noisy” input fields (ice thickness, velocity, grounding line position)

Ronne Basin Model Setup

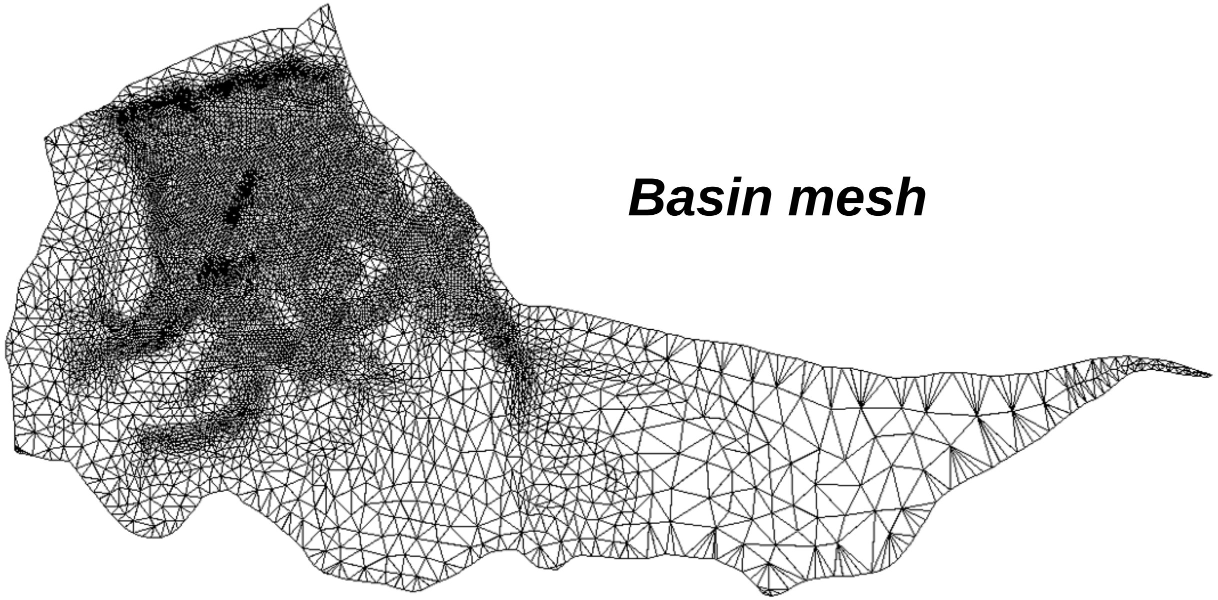
- Anisotropic mesh: 13k elements
- Spatial Resolution: 4km-40km
- Timestep: 3-month
- 1995-2018
- Dynamic grounding line
- Fixed ice-shelf front position

Computational requirement

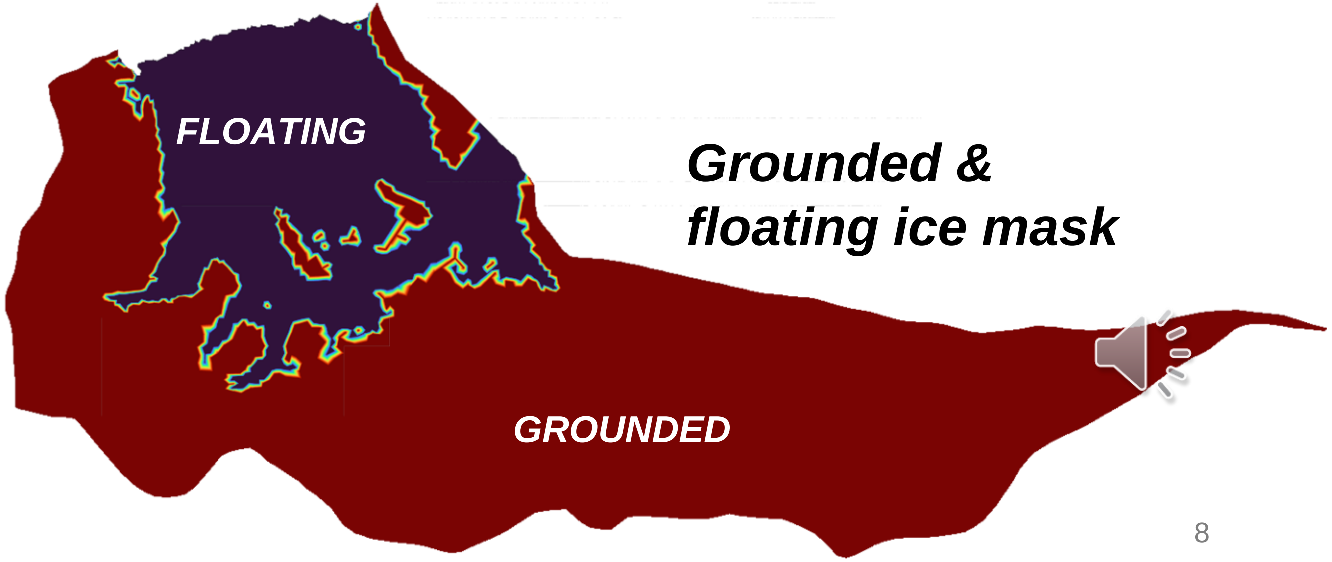
40 CPUs →

Forward simulation time: 70s

Adjoint simulation time: 800s



Basin mesh



Grounded & floating ice mask

PIG-Thwaites Basin Model Setup

- Anisotropic mesh: 19k elements
- Spatial Resolution: 2km-40km
- Timestep: 3-month
- 1995-2022
- Dynamic* grounding line
- Fixed ice-shelf front position

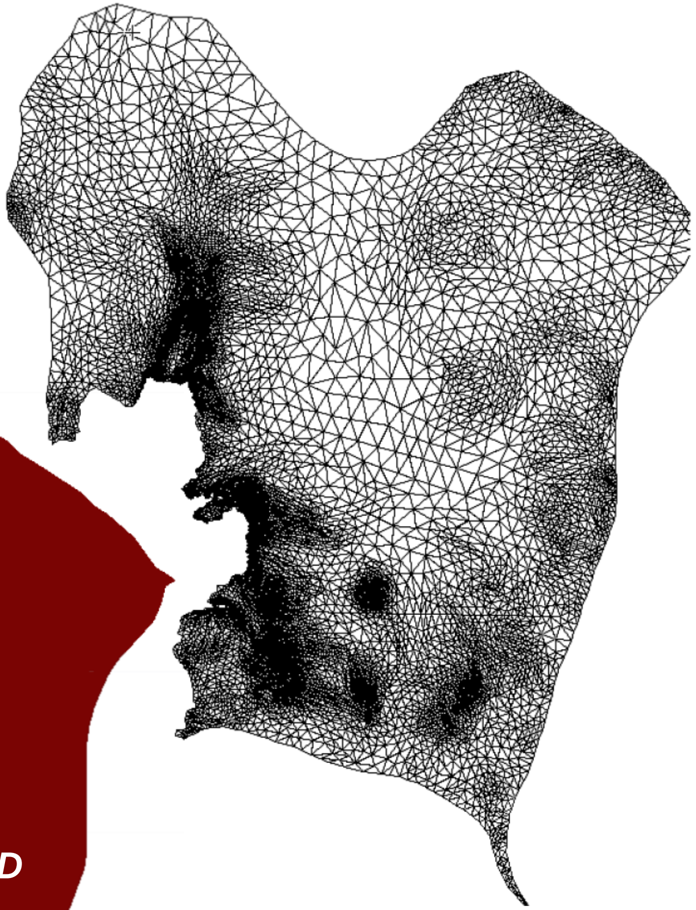
Computational requirement

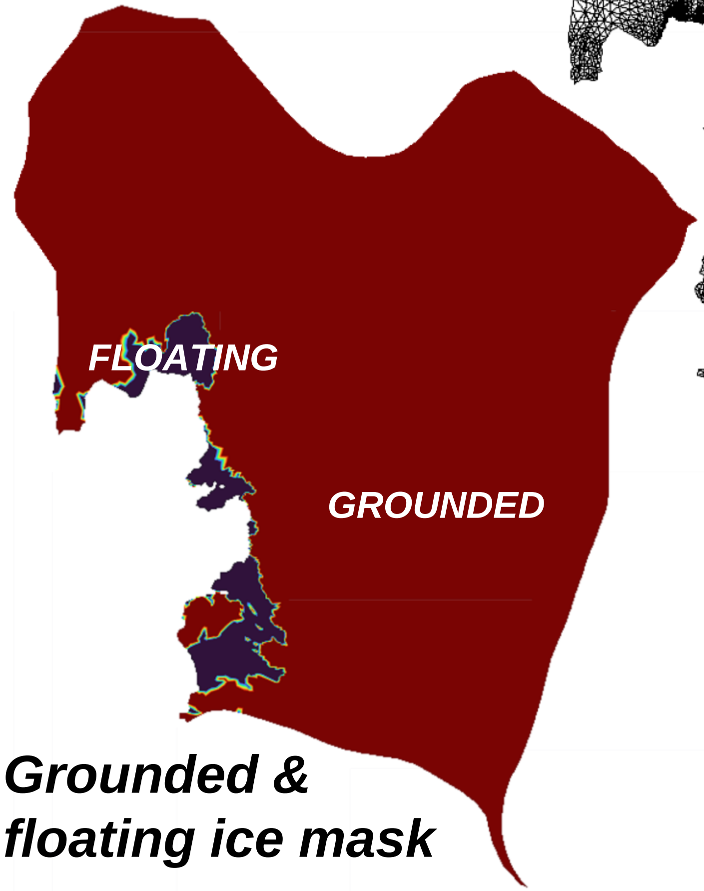
40 CPUs →

Forward simulation time: 90s

Adjoint simulation time: 1020s

Basin mesh





Grounded & floating ice mask

Larsen-D Basin Model Setup

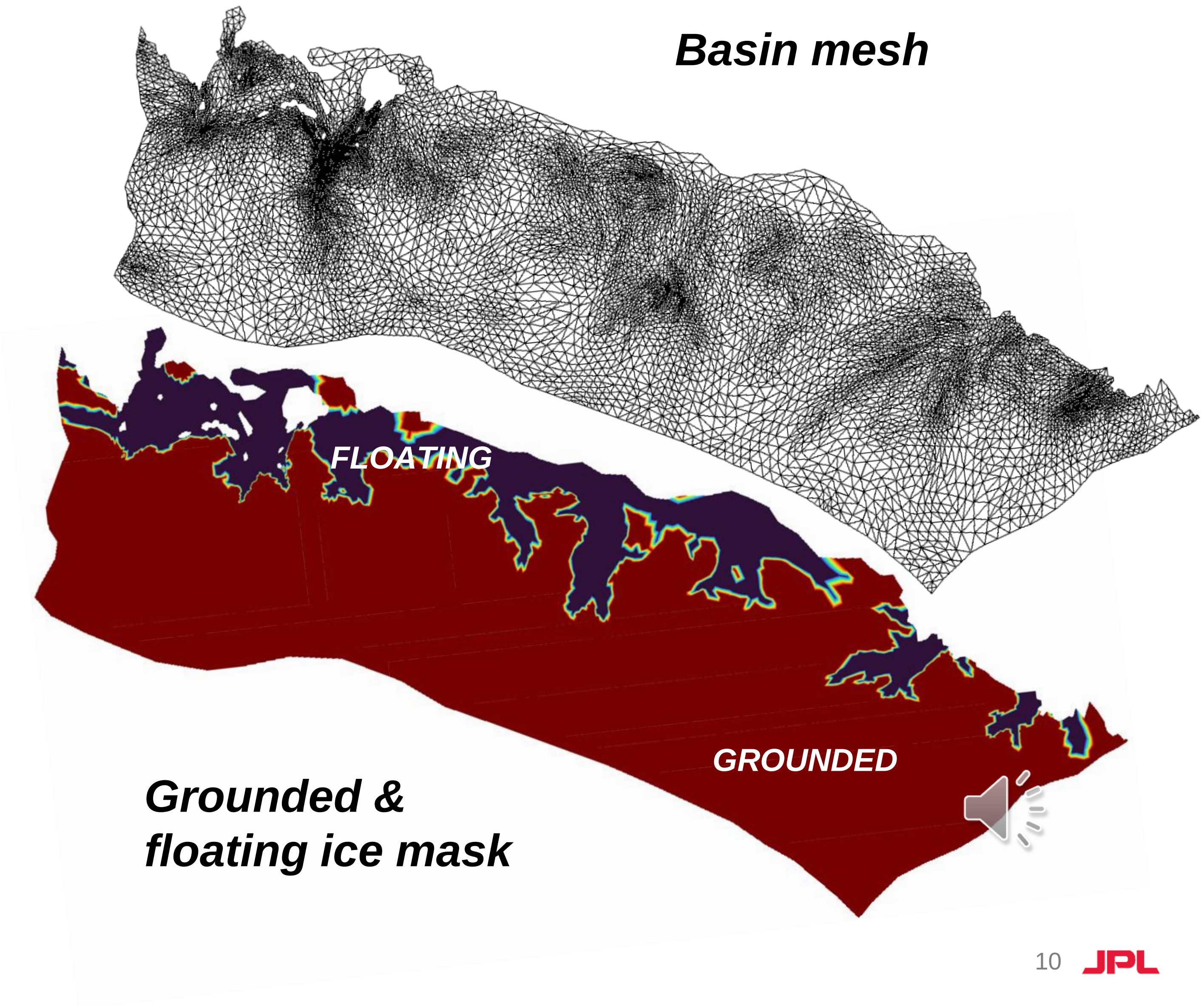
- Anisotropic mesh: 16k elements
- Spatial Resolution: 0.4km-30km
- Timestep: 3-month
- 1995-2022
- Dynamic grounding line
- Fixed ice-shelf front position

Computational requirement

40 CPUs →

Forward simulation time: 80s

Adjoint simulation time: 1260s



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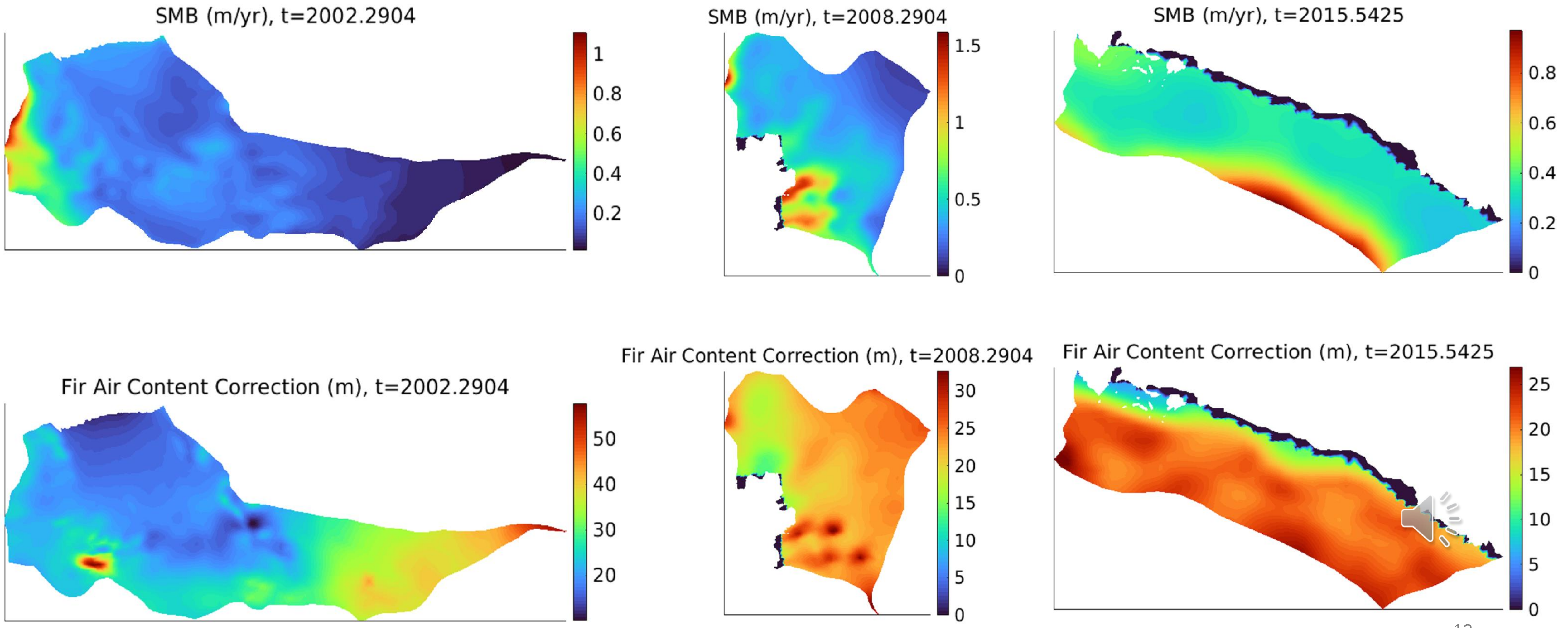
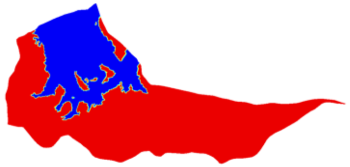
Input fields

- Ice surface temperature: MAR 3-month time-mean surface mass fluxes (Fettweis et al., 2013)
- Surface Mass Balance + Firn Air Content corrections: GEMB monthly (Schlegel et al., 2024)
- Geothermal heat flux (Maule et al., 2005)
- Bed geometry and time invariant ice-surface elevation: BedMachine v4 (Morlighem et al., 2017)
- Time varying velocity and grounded ice-surface elevation: ITS_LIVE (Gardner et al., 2023)
- Time varying floating ice-surface elevation: Adusumilli et al. (2021)
- Time invariant Basal melt: Rignot et al. (2013), Adusumilli et al. (2021), and Paolo et al. (2022)

Phase 1: Initial Conditions/Spinup

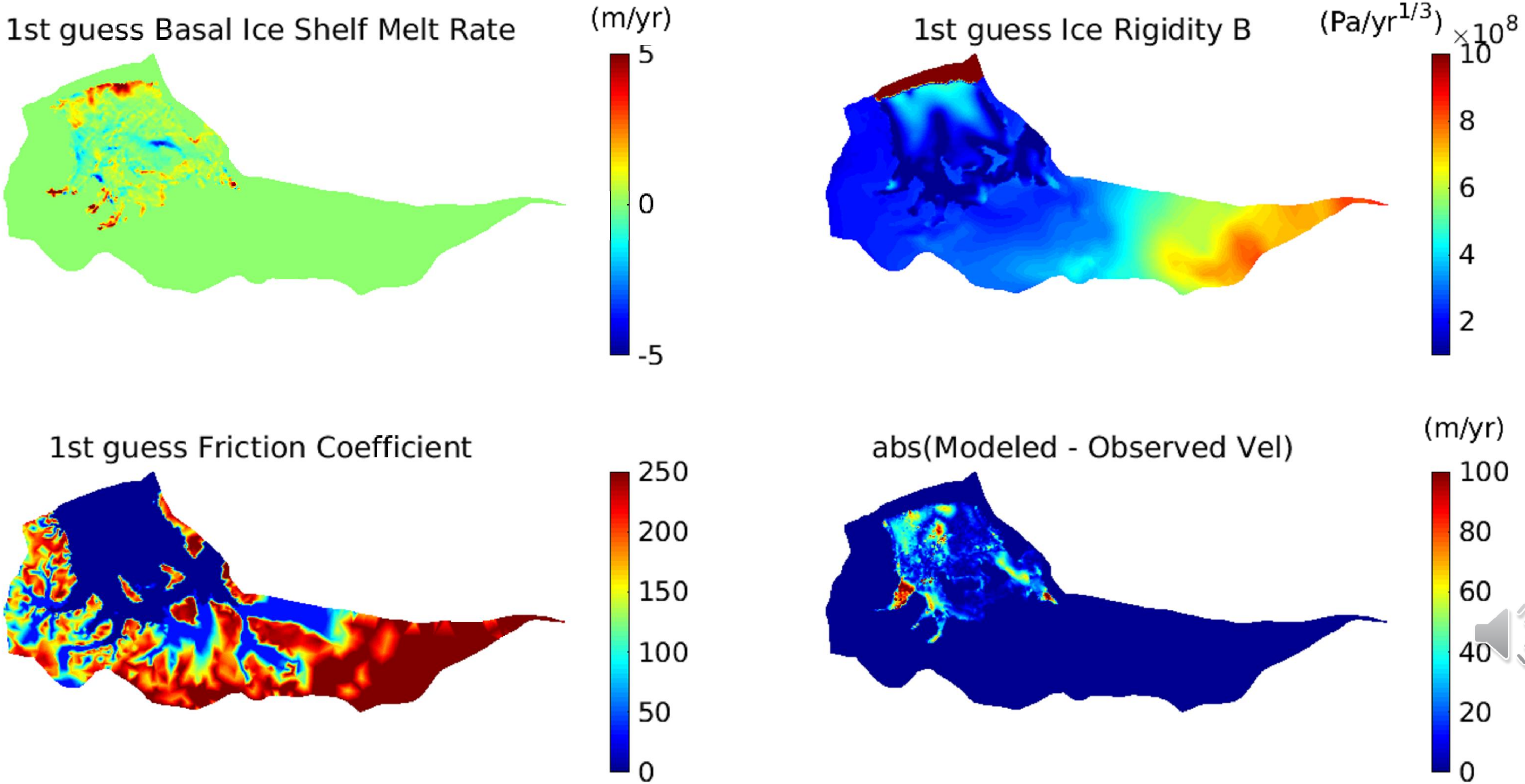
- Interpolate inputs onto mesh. SMB & FAC for Ronne, PIG/Thwaites, and LarsenD.



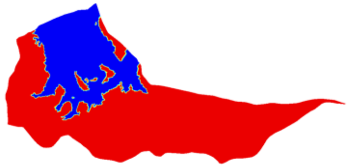


Phase 1: Initial Conditions/Spinup

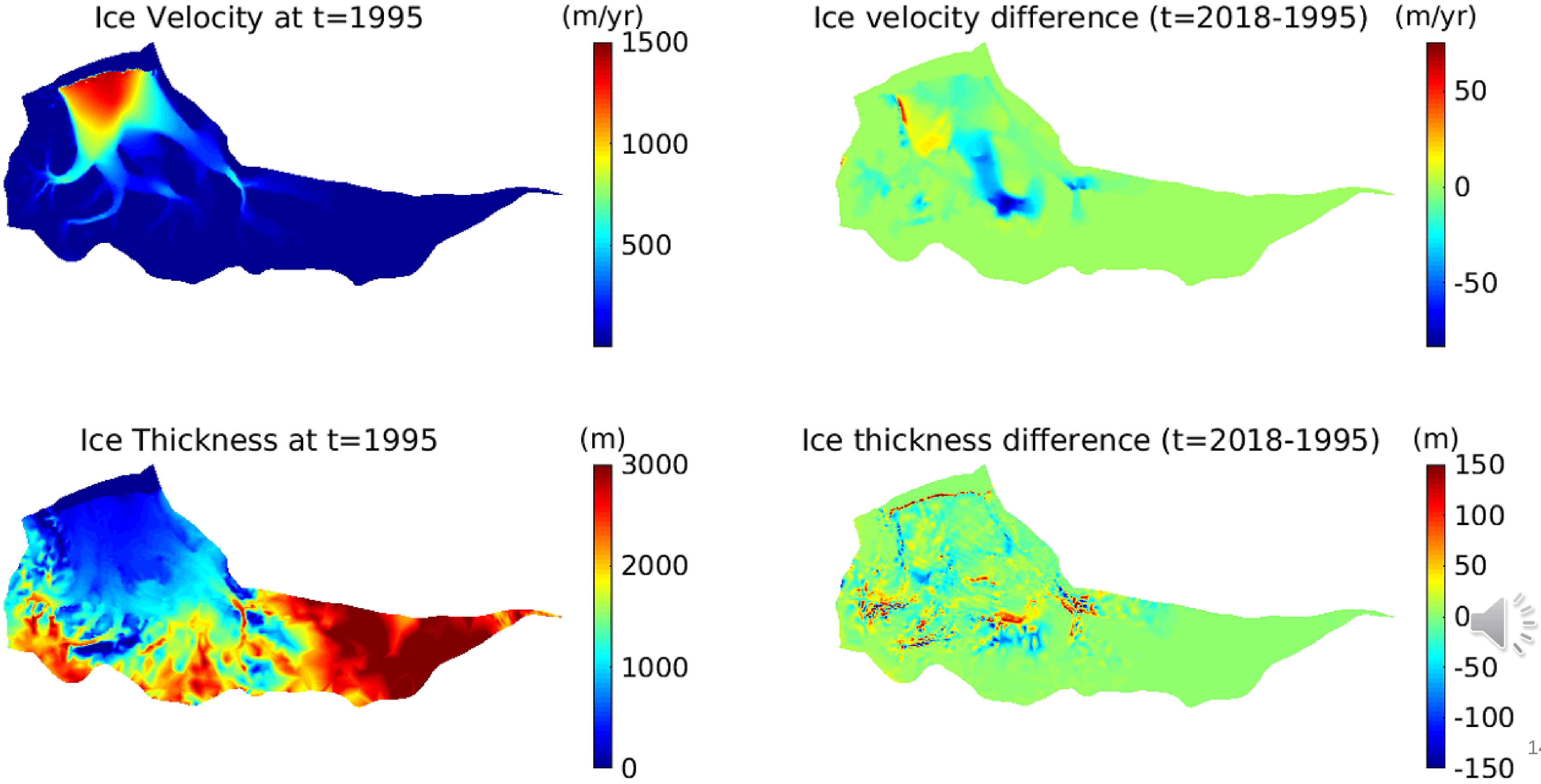
- Solve for 1995 ice rigidity & basal friction. Use Rignot for 1st guess melt rates.



Phase 1 - “Iteration 0” Transient Control Run



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



State estimation strategy

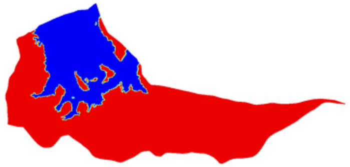
Phase 2: Adjoint estimation

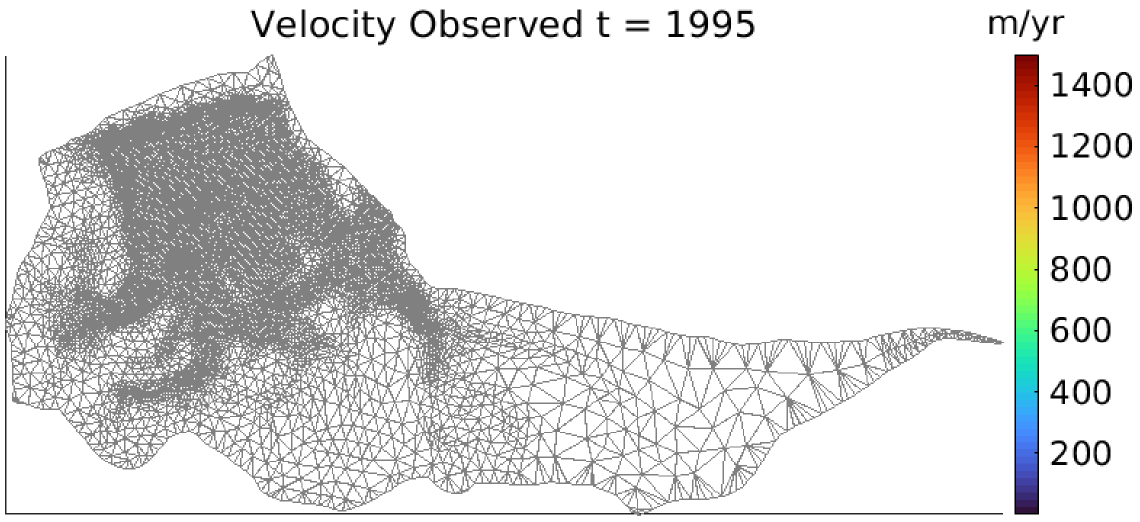
- Outputs: optimized internal ice rigidity, basal friction, time-varying ice surface elevation, ice velocity, and grounding line position
- New data inputs: time-varying ice elevation, time-varying ice velocity

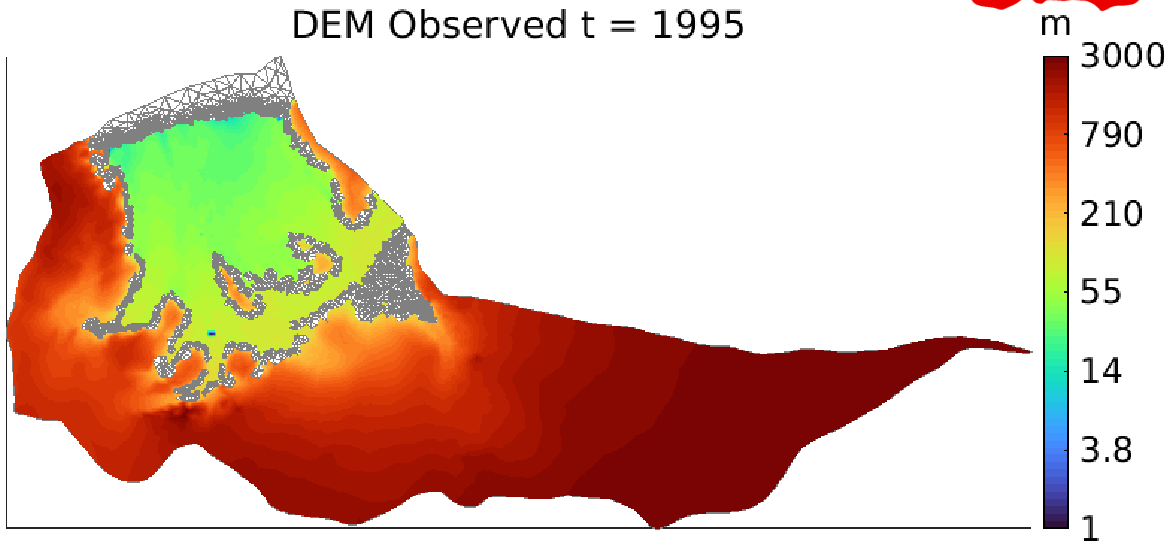
Steps:

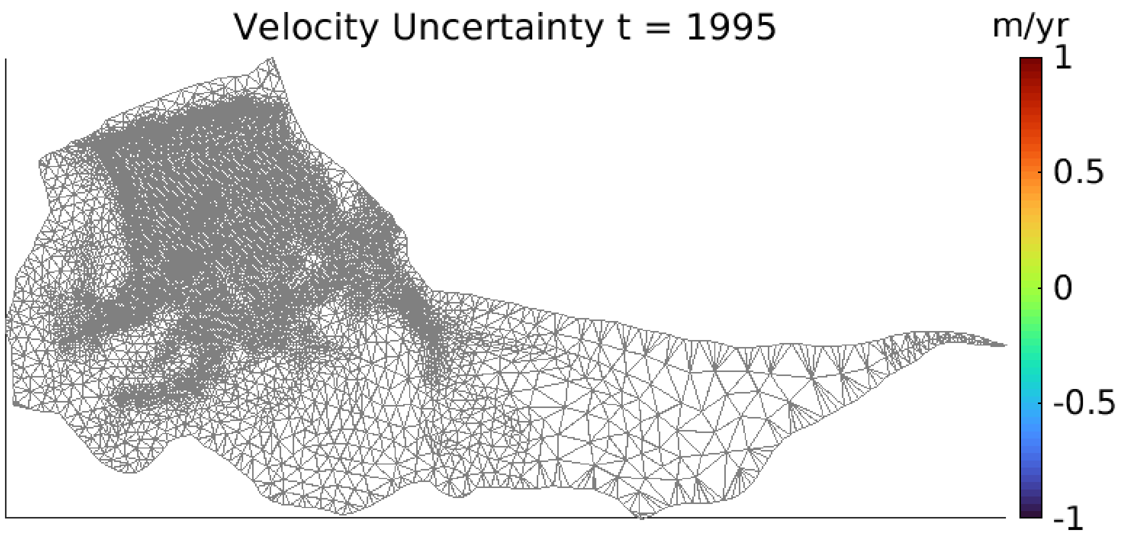
1. Formulate a model-data misfit cost function w.r.t. observed time-varying ice-surface elevation and ice velocity: weighted least squares
2. Define model control parameters: internal ice rigidity, basal friction, initial ice elevation, varying surface mass balance
3. Run a 1995-2018 transient simulation starting from the Phase 1 “spin-up” first-guess model
4. Calculate the misfit of the transient solution to the data
5. Calculate the gradients of the cost function w.r.t. control parameters
6. Use LBFGS and the gradients and to adjust the control parameters
7. Re-run the 1995-2018 transient simulation with adjusted control parameters
8. Repeat from (4) until misfits are acceptably small.

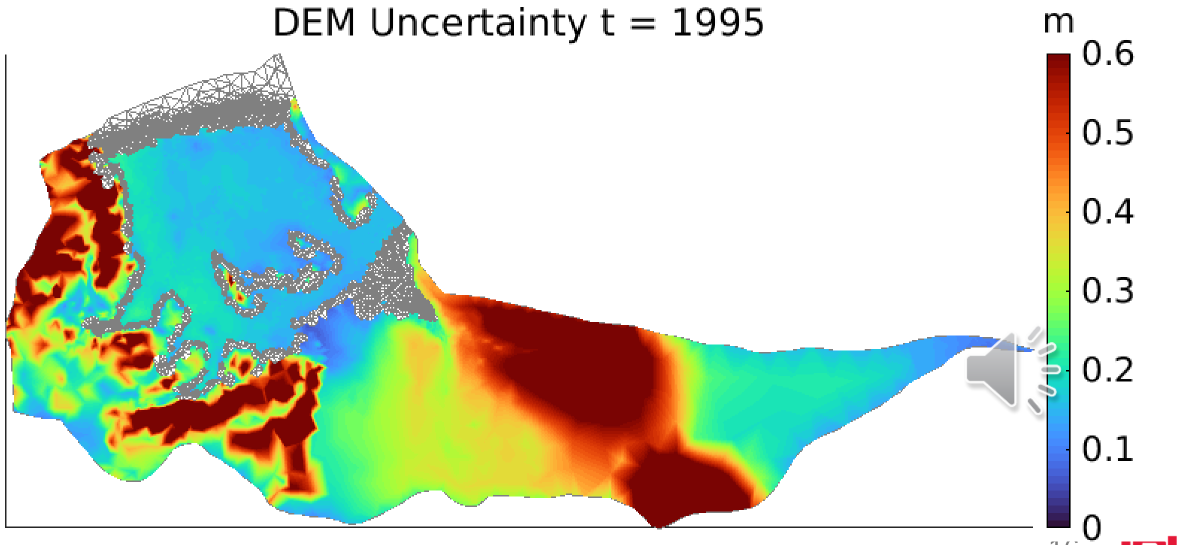
Ice Velocity and Ice Elevation observations: 1995-2018



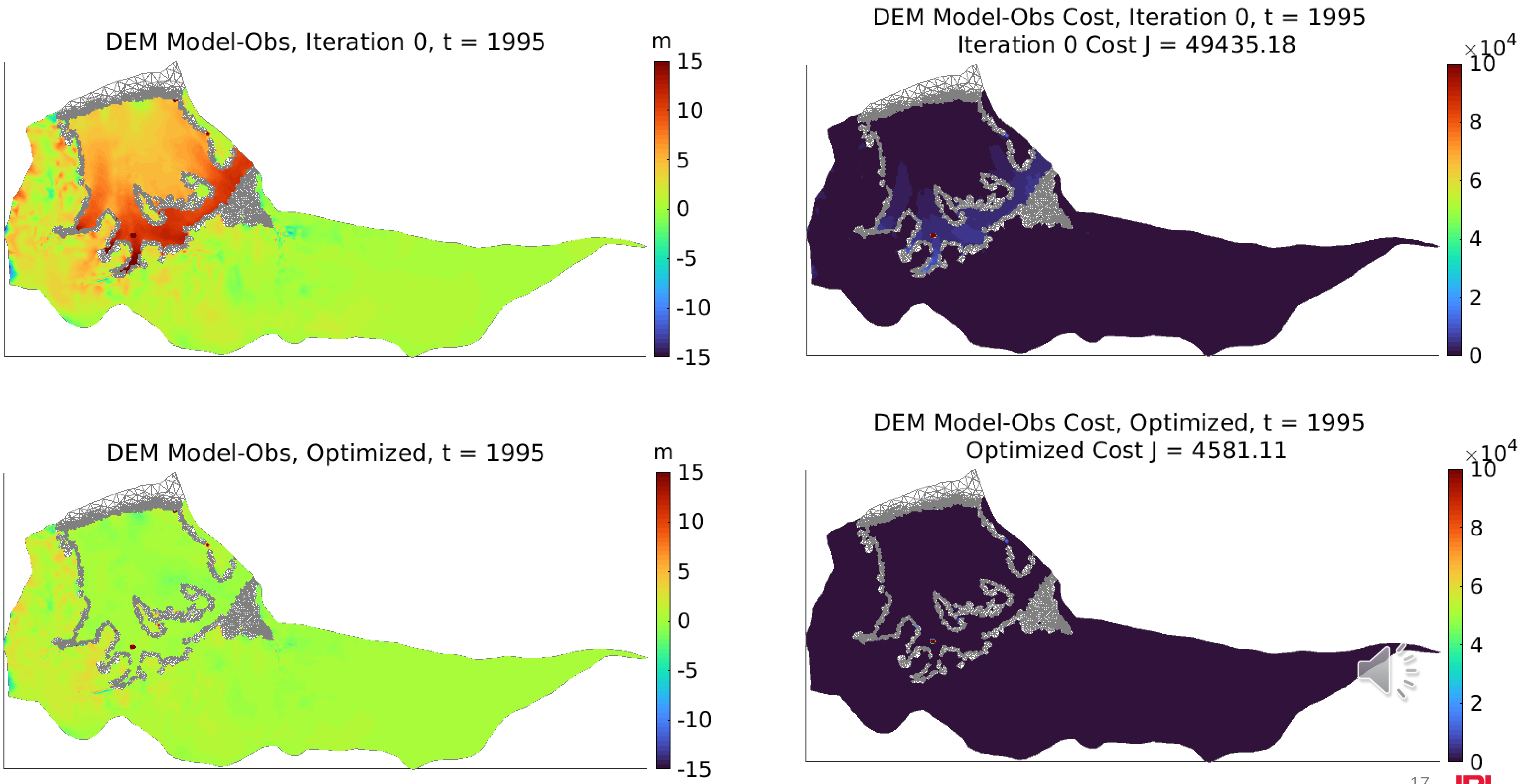






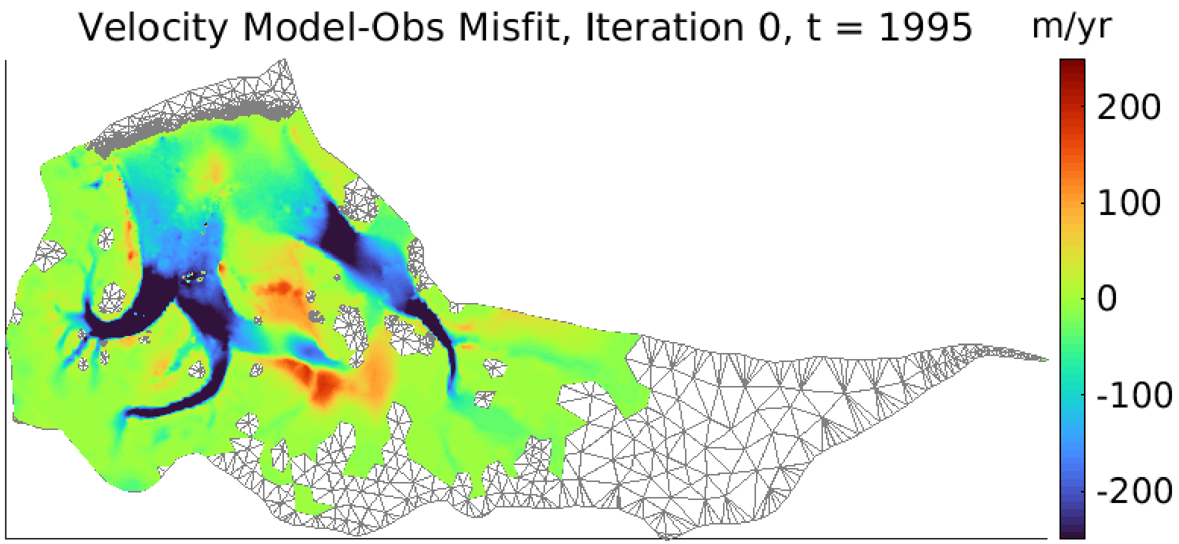


Ice Surface Elevation misfits & cost: 1995-2018

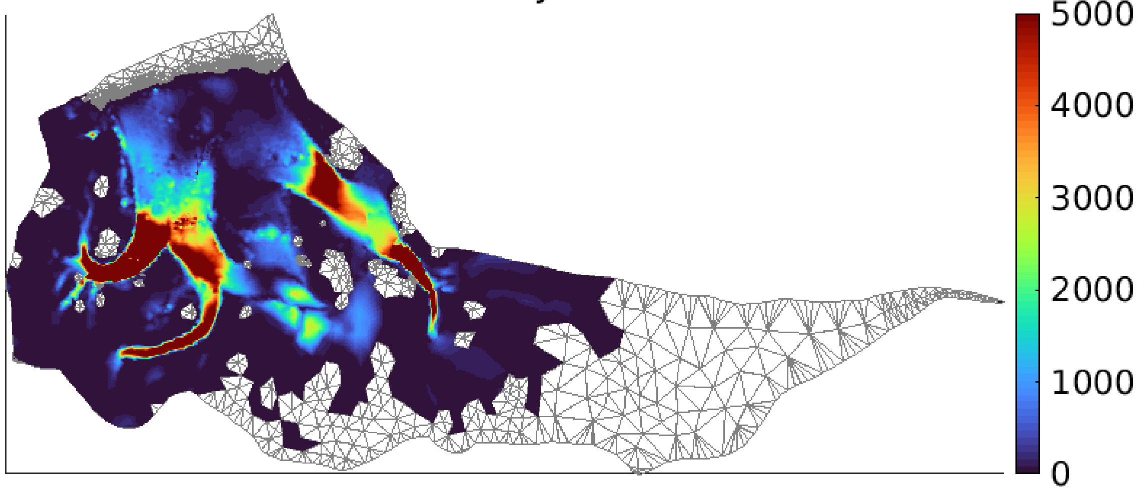


Ice Surface Velocity misfits & cost: 1995-2018

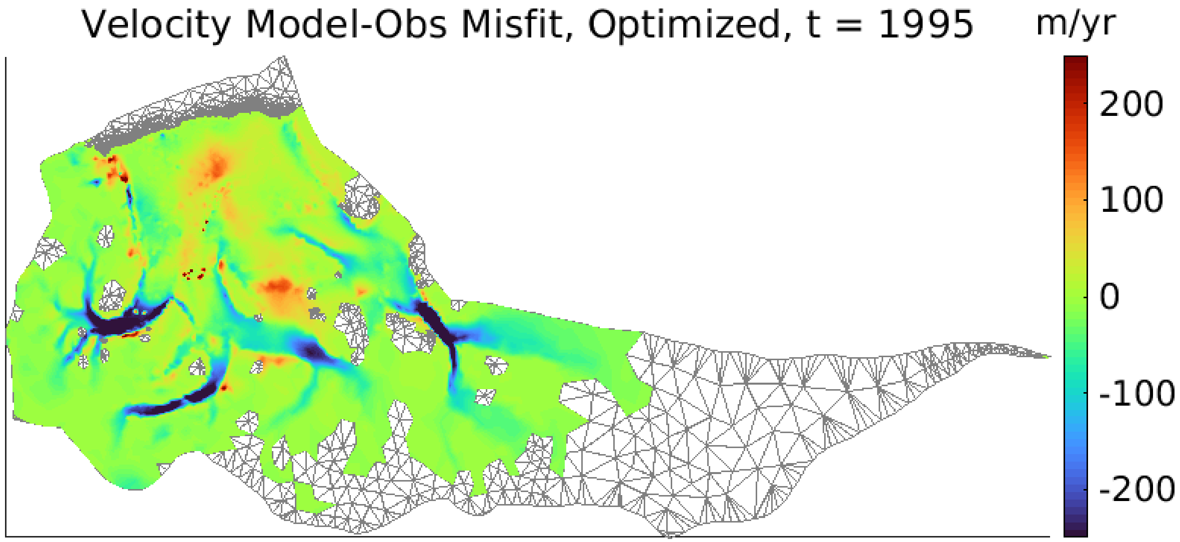
Velocity Model-Obs Misfit, Iteration 0, t = 1995



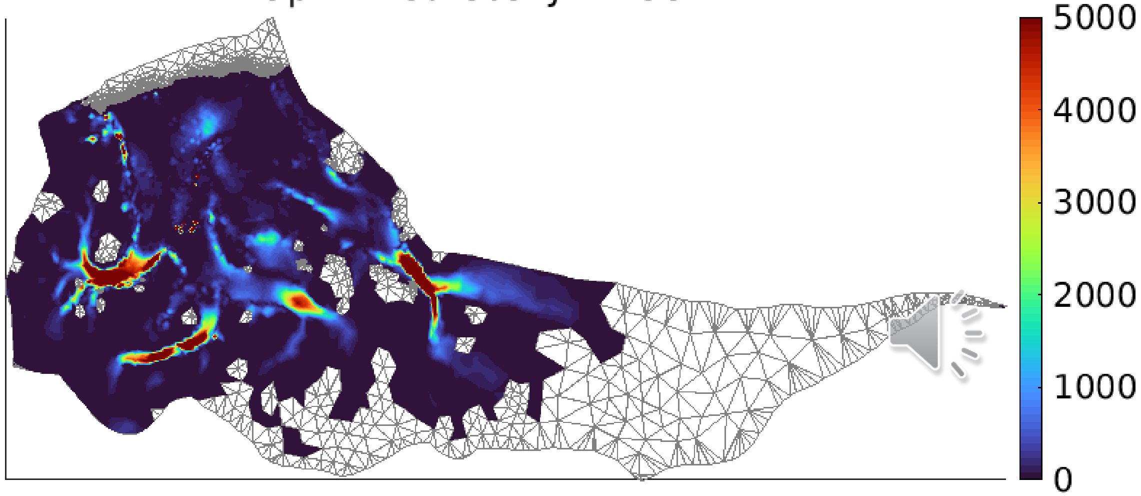
Velocity Model-Obs Cost, Iteration 0, t = 1995
Iteration 0 Cost J = 49435.18



Velocity Model-Obs Misfit, Optimized, t = 1995



Velocity Model-Obs Cost, Optimized, t = 1995
Optimized Cost J = 4581.11



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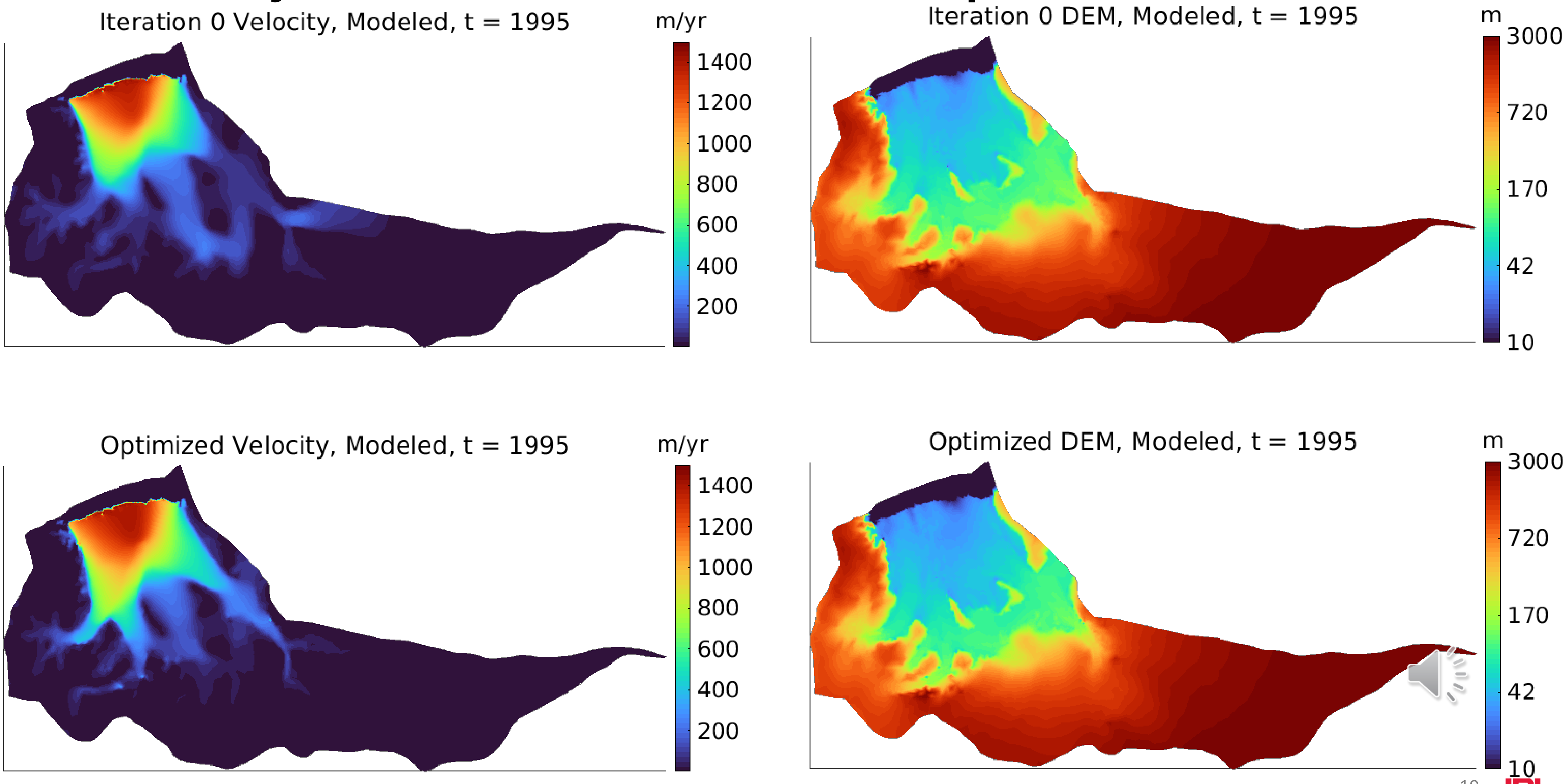
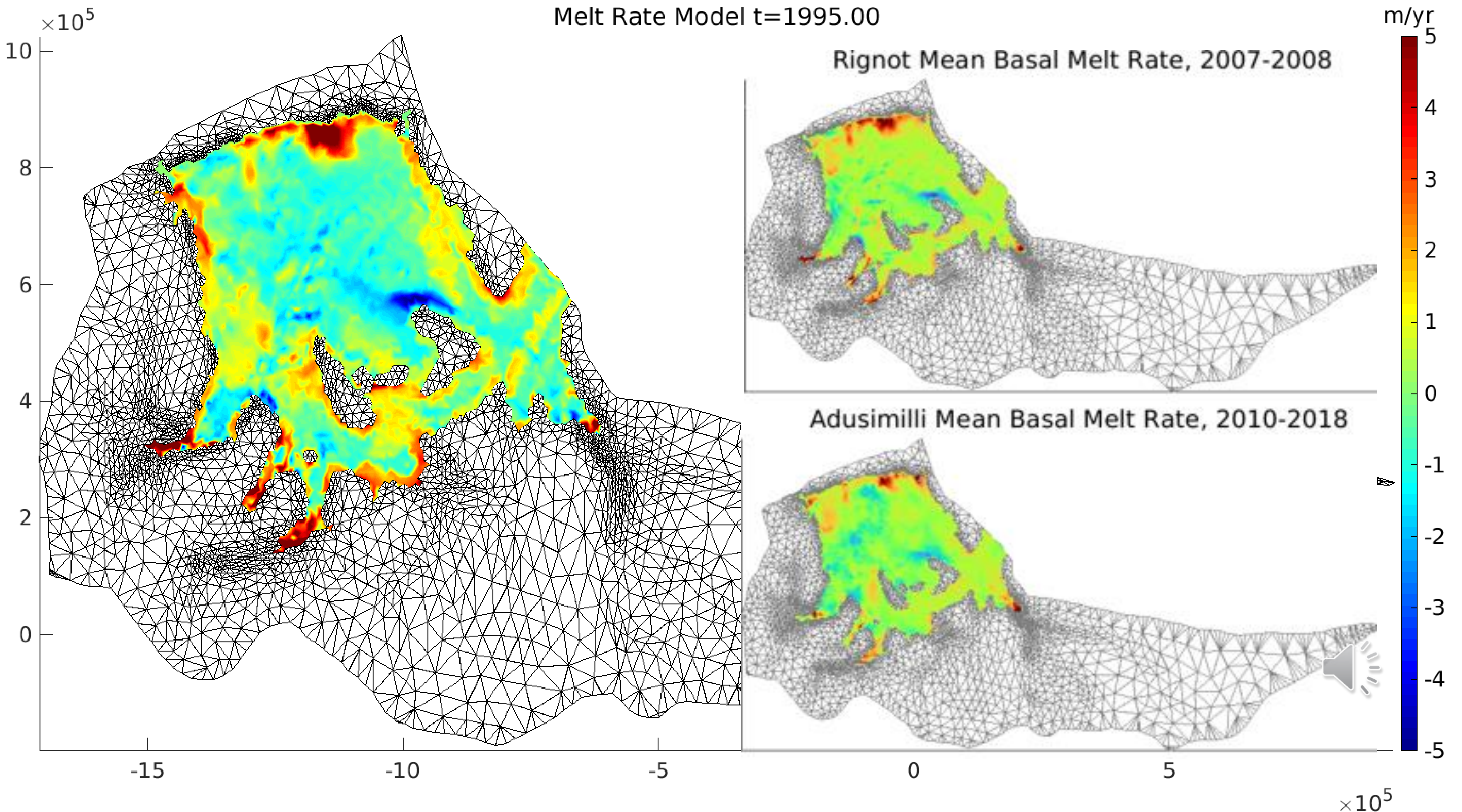
Ice Velocity and Elevation Iteration 0 vs Optimized: 1995-2018

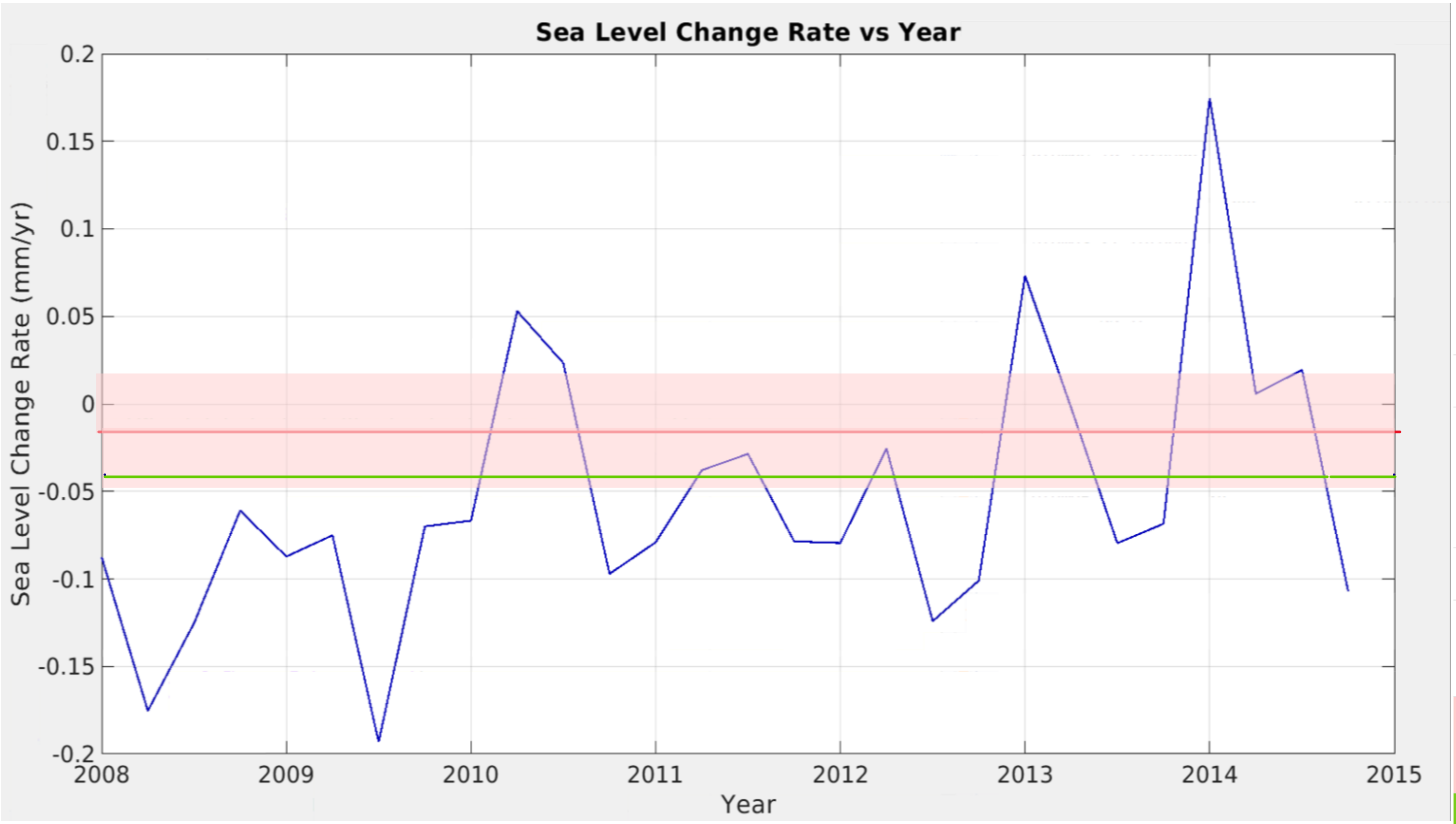


Ronne Ice Shelf Basal Melt Rate, Optimized



Can we recover sea level change?

- Compare our quarterly (blue) and mean (green) rates to GRACE-derived sea level change (red) and mass change estimates from TU Dresden
- Recovery is within range, though note difference in time ranges
- Can further constrain using discharge



Mass Change Change Rate

Source	Basin	Mass change rate [Gt/yr]	Time
TU Dresden	AIS01	7.4 ± 5.7	2002-2022
TU Dresden	AIS02	3.4 ± 4.5	2002-2022
TU Dresden	AIS01 + AIS02	10.8 ± 10.2	2002-2022
Ours	Ronne	10.087	2008-2015

Mean Sea Level Change Rate

Source	Basin	Mean Sea level change rate [mm/yr]	Time
TU Dresden	AIS01	-0.02 ± 0.02	2002-2022
TU Dresden	AIS02	-0.01 ± 0.01	2002-2022
TU Dresden	AIS01 + AIS02	-0.03 ± 0.03	2002-2022
Ours	Ronne	-0.0536	2008-2015

Current Status and Next Steps

- **Completed:**
  - Verify model spin up in Ronne, PIG-Thwaites, Larsen-D basins
- **Current status:**
  - Validation of mass flux/discharge against existing estimates
- **Next steps:**
  - Provide freshwater flux across grounding line, calving front, and other data products for use
  - Monthly timesteps, expand time series range to 1993-2022
  - Publication on data, model, and method
  - Expand to all basins in West Antarctica, East Antarctica