Toward Simulations of Coupled, Antarctic, Ice-Ocean Evolution Using BISICLES and POP2x

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(Applying BISICLES to Realistic Problems)

Joint work with:

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- Steve Price (LANL)
- Mat Maltrud (LANL)
- Doug Ranken (LANL)
- Stephen Cornford (Bristol)
- Mark Adams (LBNL-FASTMath)
- Esmond Ng (LBNL)

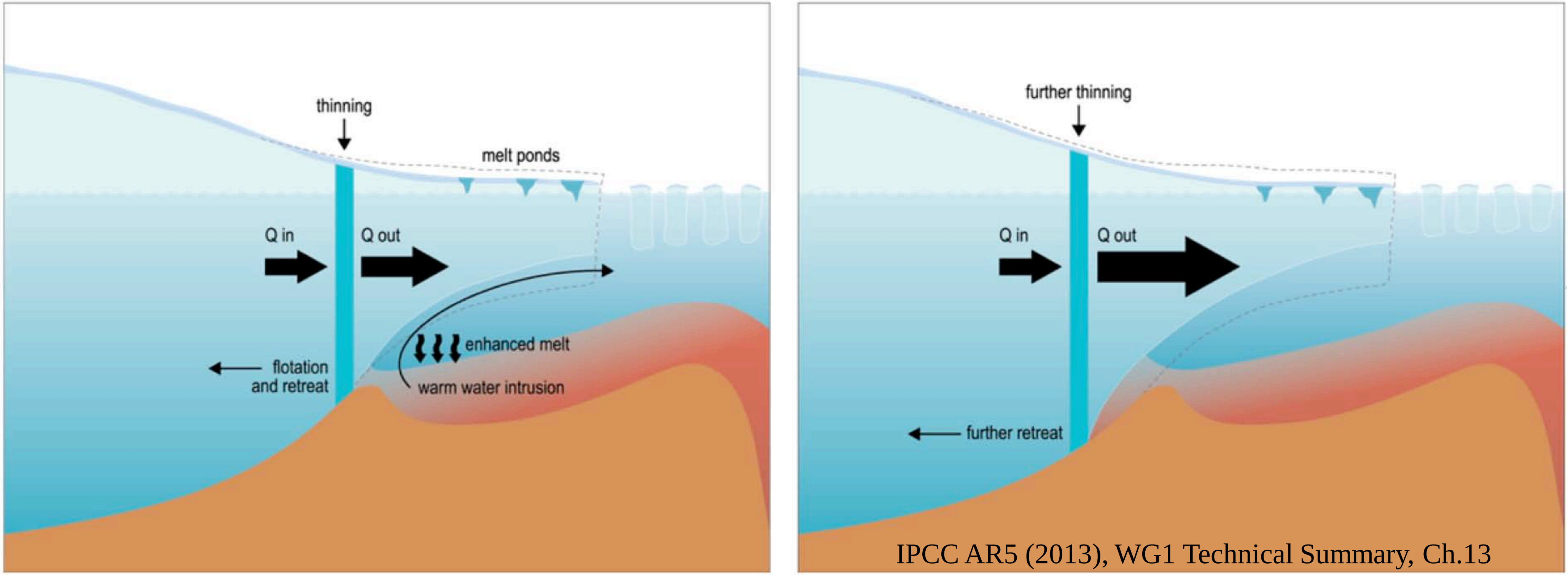
Motivation: Projecting future Sea Level Rise

- Potentially large Antarctic contributions to SLR resulting from marine ice sheet instability, particularly from WAIS.

- Climate driver: subshelf melting from warm(ing) ocean water intrusion into subshelf cavities.

- Paleorecord implies that WAIS has deglaciated in the past.

Motivation: Future Sea Level Rise (SLR)



IPCC AR5 (2013), WG1 Technical Summary, Ch.13

Observations and modeling argue for the importance of ice-ocean interactions in causing changes in submarine melt rates, with consequent dynamic ice sheet response, including grounding line retreat and increased mass flux to the oceans.[1, 2]

[1]Joughin & Alley (*Nat. Geosc.*, **4**, 2011) [2] Straneo et al. (*BAMS*, **94**, 2013)

Previous Work (mainly Antarctic)

Previous work exploring coupled ice-ocean evolution:

- idealized, stand-alone ocean modeling
- idealized, stand-along ice sheet modeling
- realistic, low / high res., stand-alone ocean modeling
- realistic, low / high res., stand-alone ice sheet modeling
- idealized, fully coupled ice-ocean modeling

Our Goal: realistic, high resolution, fully coupled ice-ocean modeling

Grosfeld et al. (1997); Holland & Jenkins (2001); Walker et al. (2007,2008); Losch (2008); Holland et al. (2008); Thoma et al. (2008); Pollard et al. (2009); Joughin et al. (2010); Yin et al. (2011); Cornford et al. (2012); Mueller et al. (2012); Schodlok et al. (2012); Heimbach & Losch (2012); Goldberg et al. (2012a,b); Gladish et al. (2012); Little et al. (2012); Hellmer et al. (2012); Timmerman et al. (2013); Kushara et al. (2013); Sergienko et al. (2013a,b); Parizek et al. (2013); Wilson (2013); Robinson (2013) … plus many more.

Models:

- ❑ **Ocean Circulation Model: POP2x**

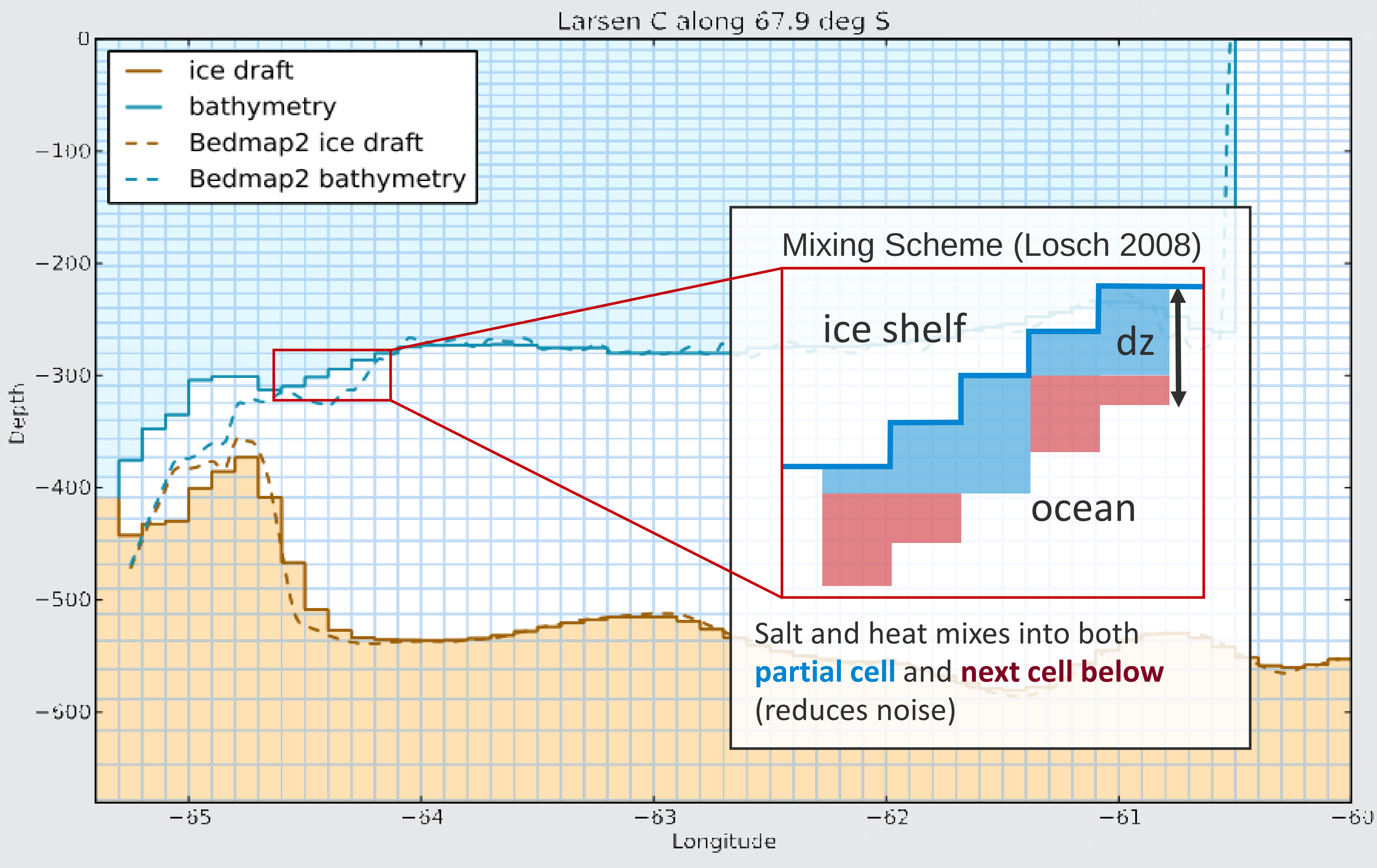
- ❑ **Ice Sheet: BISICLES (CISM-BISICLES)**

Ocean Model: POP2x

- POP2 = **P**arallel **O**cean **P**rogram version 2 (hydrostatic, Boussinesq, primitive equations)[1]
- z-level vertical coordinate, partial bottom cells
- "x" = eXtended to include ice shelf cavity circulation using partial top cells[2]
- sub-shelf mixed layer thickness = dz (vert. mixing scheme[2], not physics based)
- For idealized experiments[2], sub-shelf circulation in POP2x compares very well with previously published results

[1]Smith et al., (2010); [2]Losch (2008)

Modeling ice shelves in POP



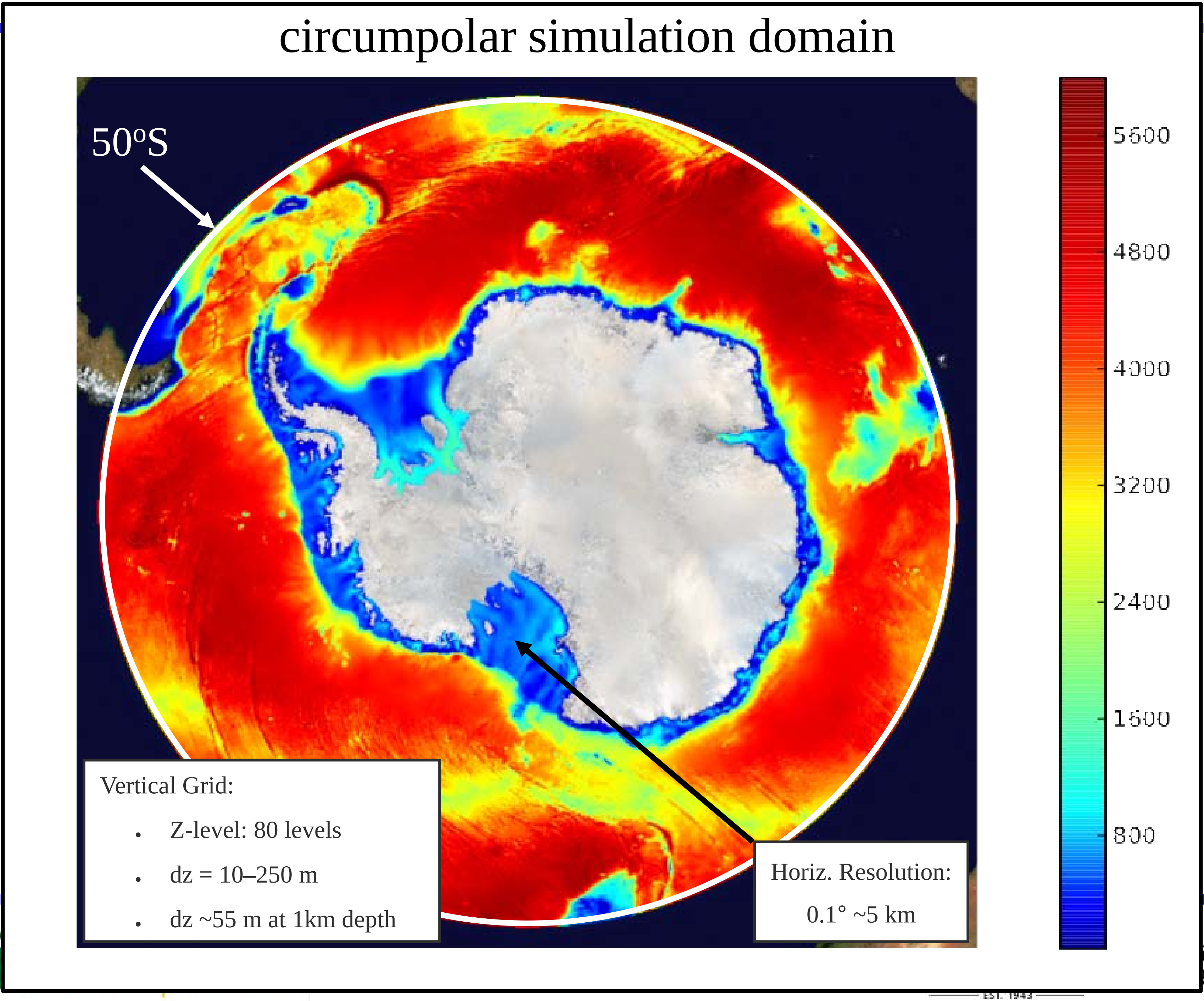
POP2x: Southern Ocean experiments

Experimental Setup:

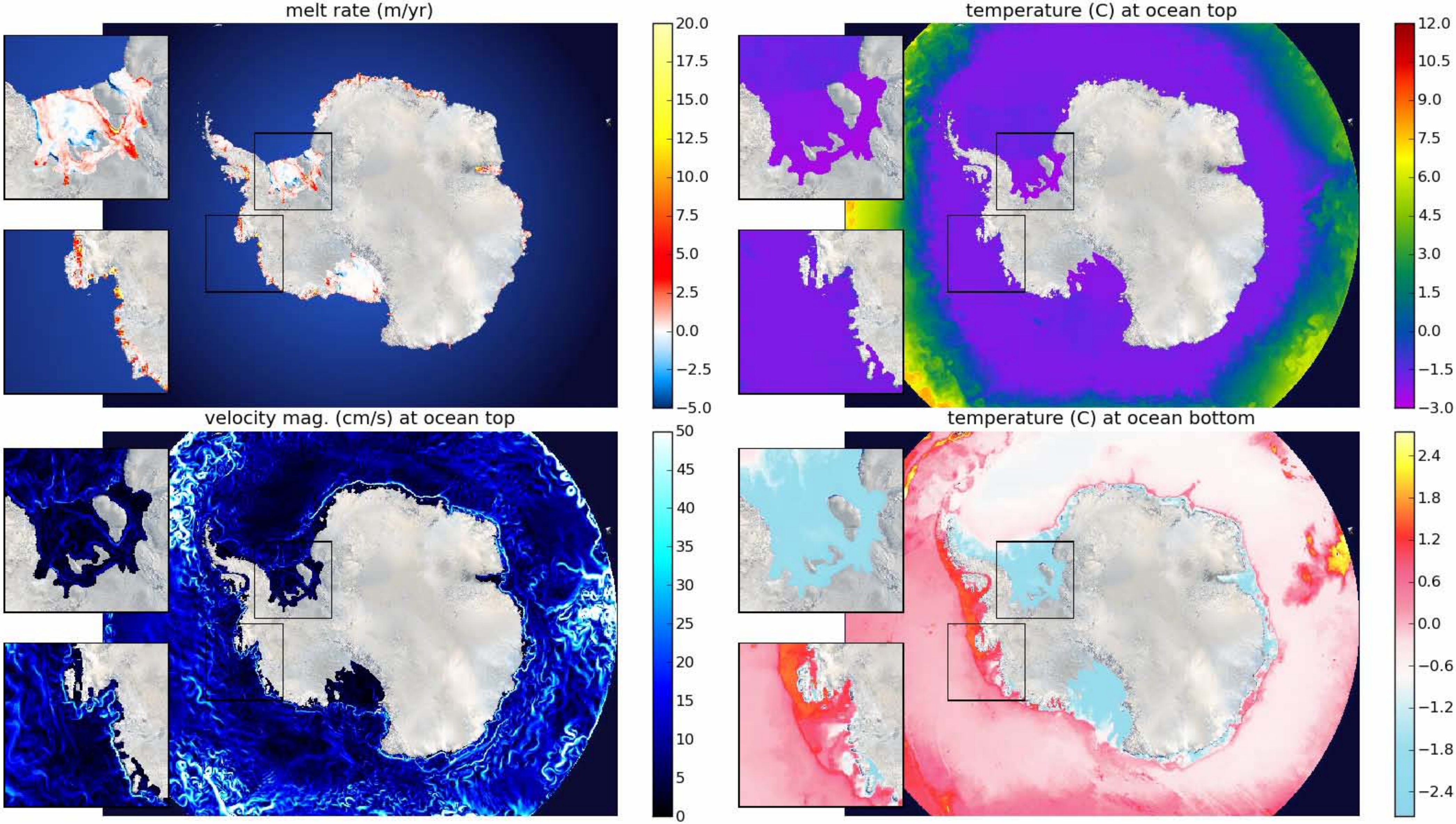
- hi-res (eddying) ocean model with circulation under static ice shelves (**POP2x**)
- regional southern ocean domain (50-90 deg. south)
- ~5 km horiz. res. near ice shelves of interest
- "Normal Year"[1] forcing with monthly restoring to WOA data at northern boundaries
- bathymetry and ice draft from Bedmap2 [2]

[1]Large and Yeager (2008); [2]Fretwell et al. (2013)

POP2x: realistic experiments (uncoupled)



POP2x: realistic experiments (uncoupled)



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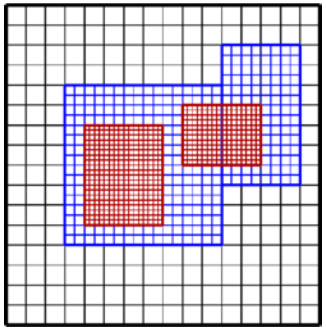
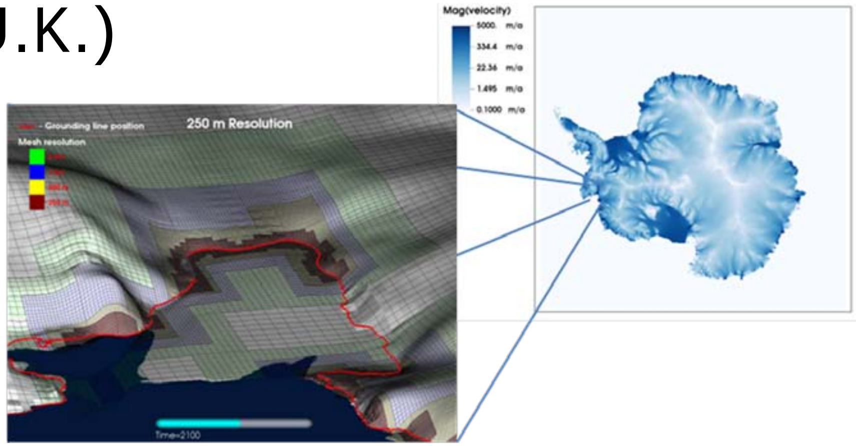
BISICLES Ice Sheet Model

- DOE SciDAC-funded project to develop a scalable adaptive mesh refinement (AMR) ice sheet model/dycore
  - Local refinement of computational mesh to improve accuracy
- Chombo AMR framework supports block-structured AMR
  - Support for AMR discretizations
  - Scalable solvers
  - Developed at LBNL
  - DOE ASCR supported (FASTMath)



- Collaboration with LANL and Bristol (U.K.)
- Variant of the "L1L2" model.
- Alternate dycore interface to CISM
- Linked to Petsc linear solver package for improved solver robustness and performance.



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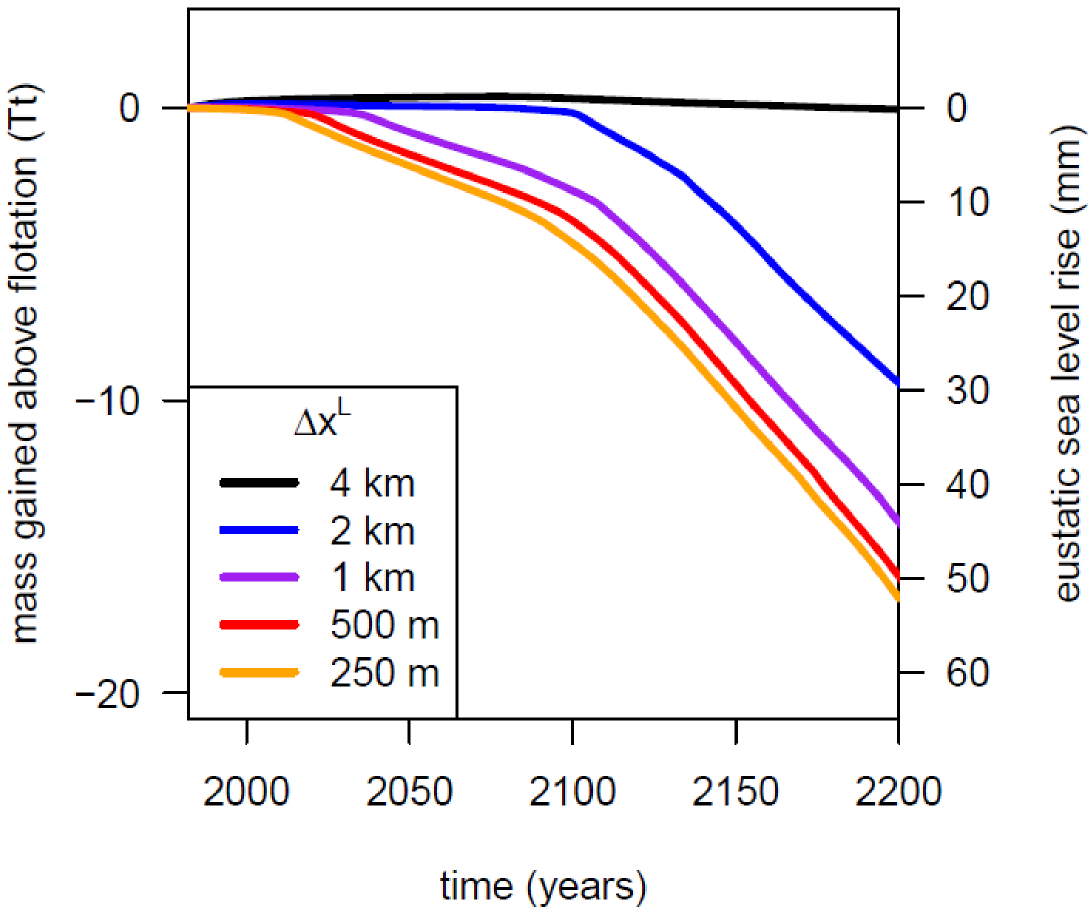
Ice2Sea Amundsen Sea Results

- SLR contribution from Ice2Sea simulation of Amundsen Sea w/ warming ocean forcing.
- Need at least 2 km resolution to get any measurable contribution to SLR.
- Appears to converge at first-order in Δx

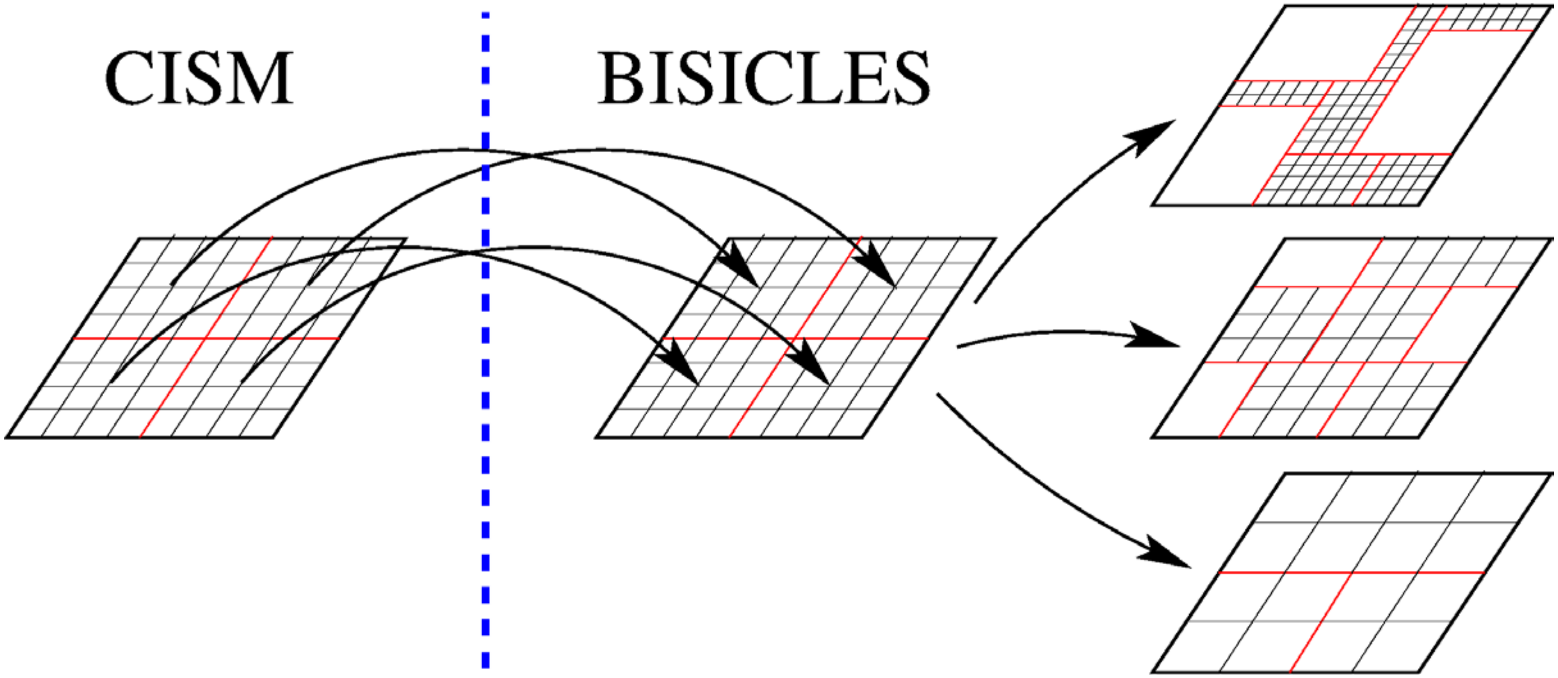
SLR vs. year, Amundsen Sea Sector

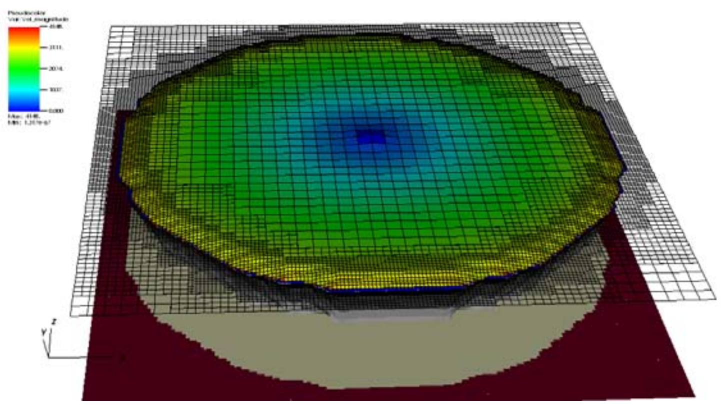


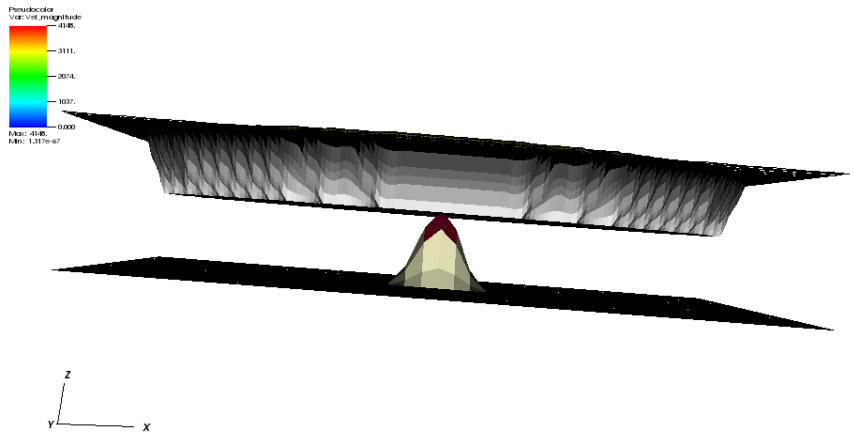
Community Ice Sheet model (CISM)/BISICLES

- CISM (F90) to BISICLES (C++)
- General API design for coupling alternate dynamical cores into CISM
- Moderately complex build process (working to streamline)
- CISM owns “main”, problem setup, coupler to ESMs, other physics (like isostasy, hydrology, etc)
- CISM hands control to BISICLES, which evolves the ice sheet
- BISICLES passes fields like thickness, velocity back to CISM
- I/O: Both CISM NetCDF and BISICLES/Chombo HDF5
- (includes checkpoint-restart)

CISM/BISICLES coupling (cont)

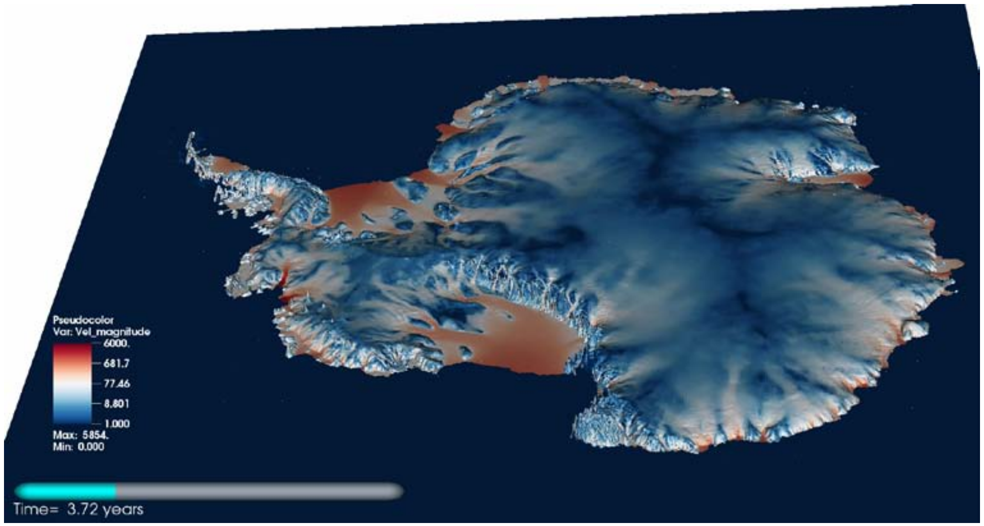


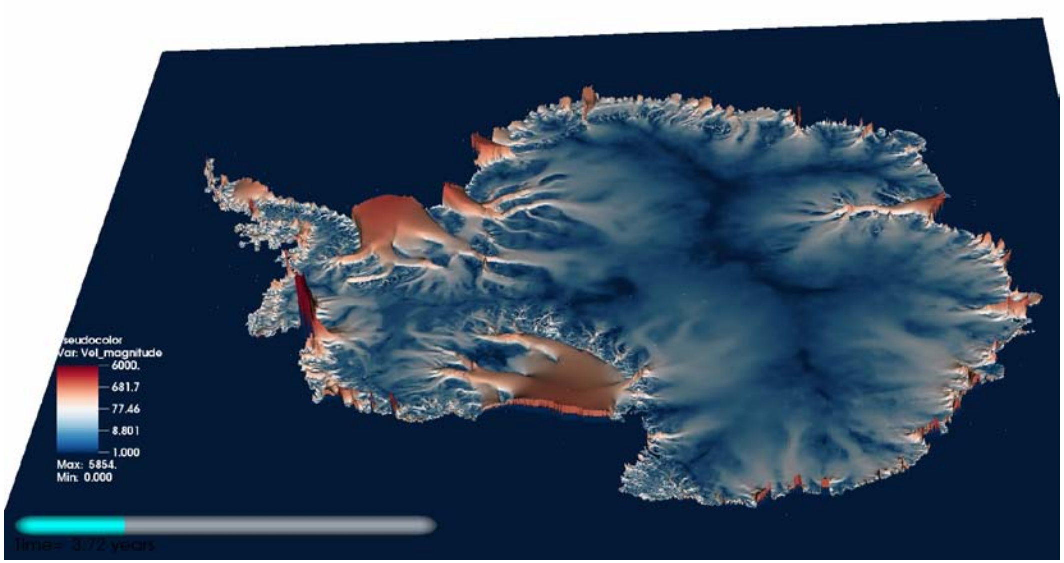




BISICLES Standalone: Antarctica Steady-State

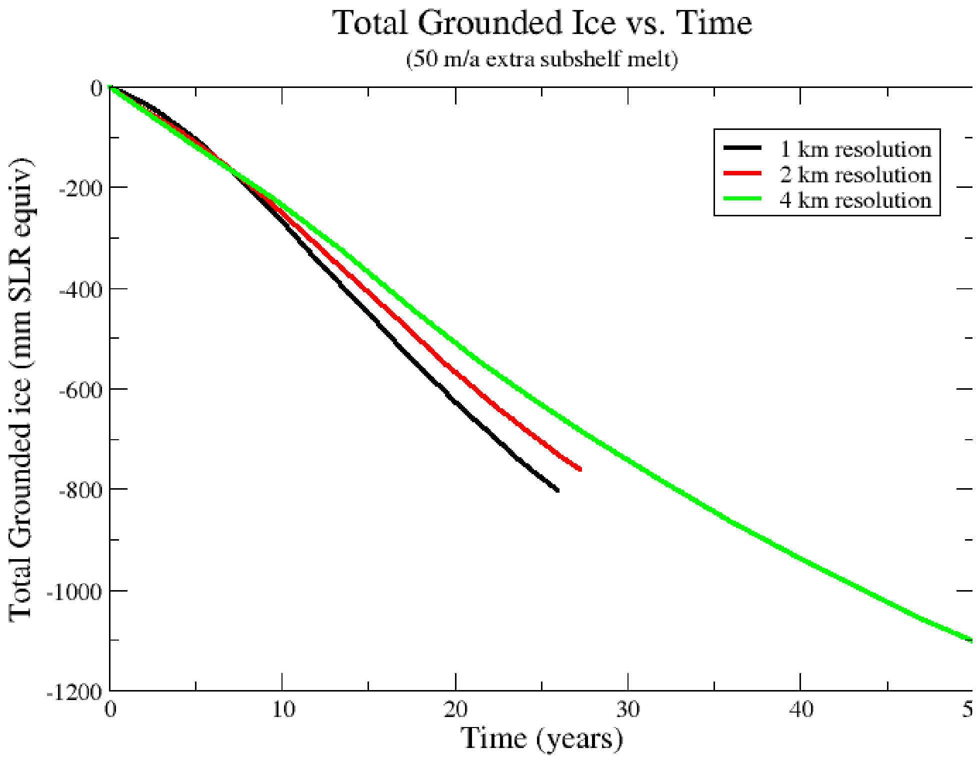
- BedMap2 (2013) Topography, thickness,
- Rignot (2011) Velocities
- Temperature field from Pattyn (SIA)
- Subshelf melt rates from POP2x
- Synthetic SMB to maintain balance.
- 1 km resolution

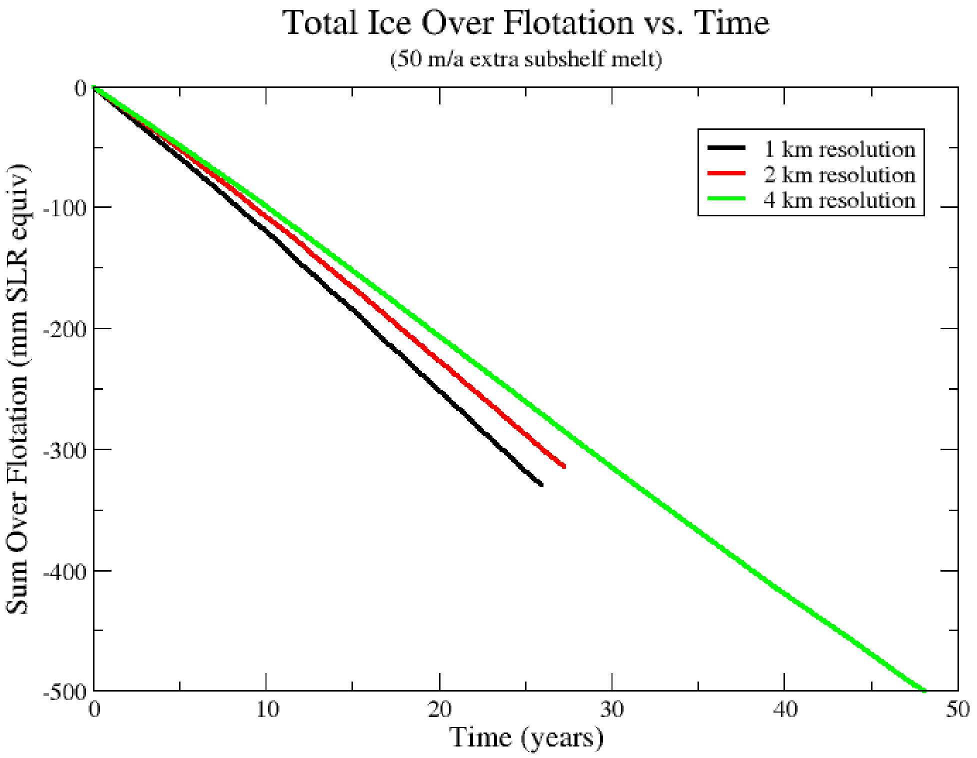




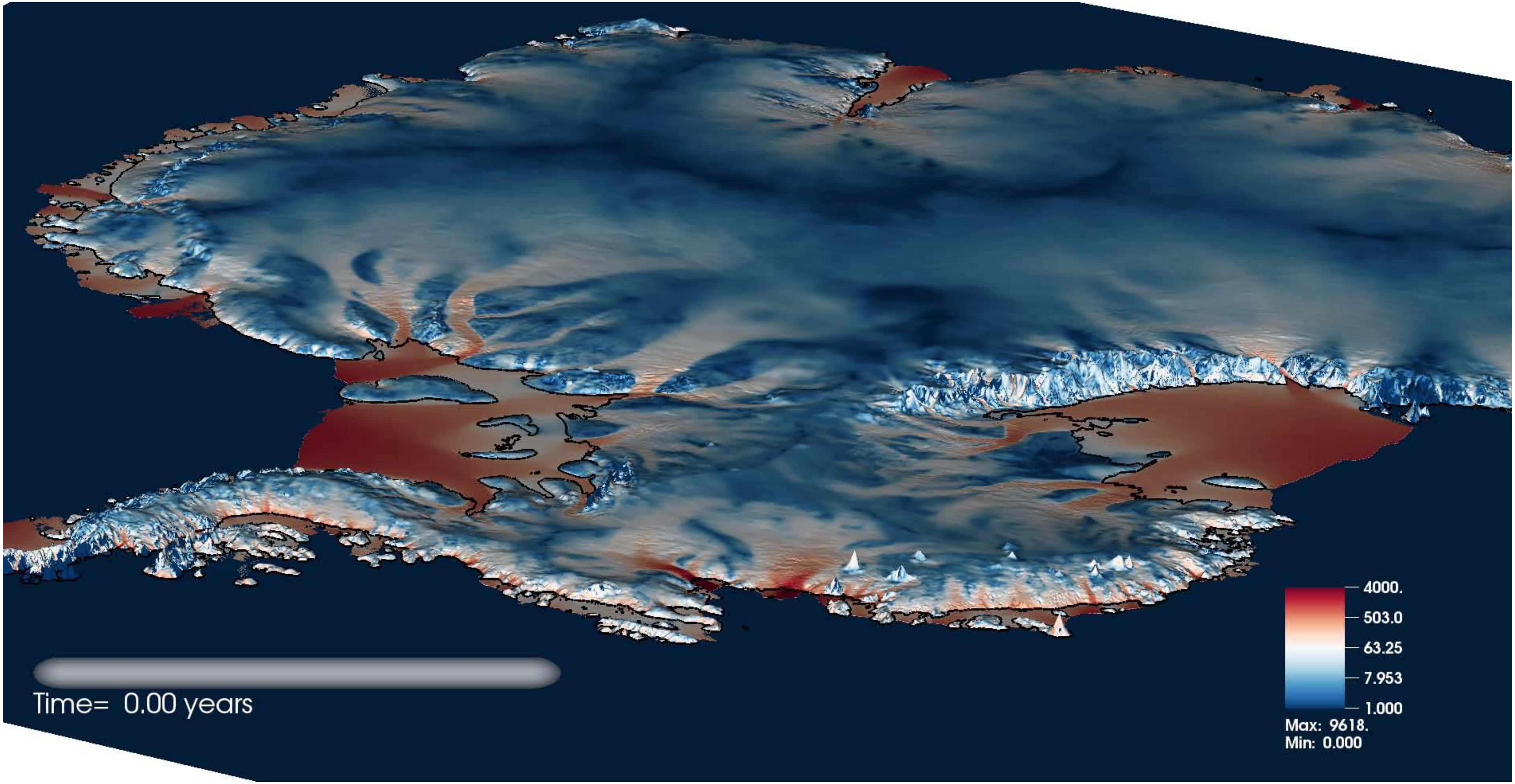
BISICLES Standalone: Extreme Melting

- Perturb with additional 50 m/a subshelf melting





BISICLES Standalone: Extreme melting



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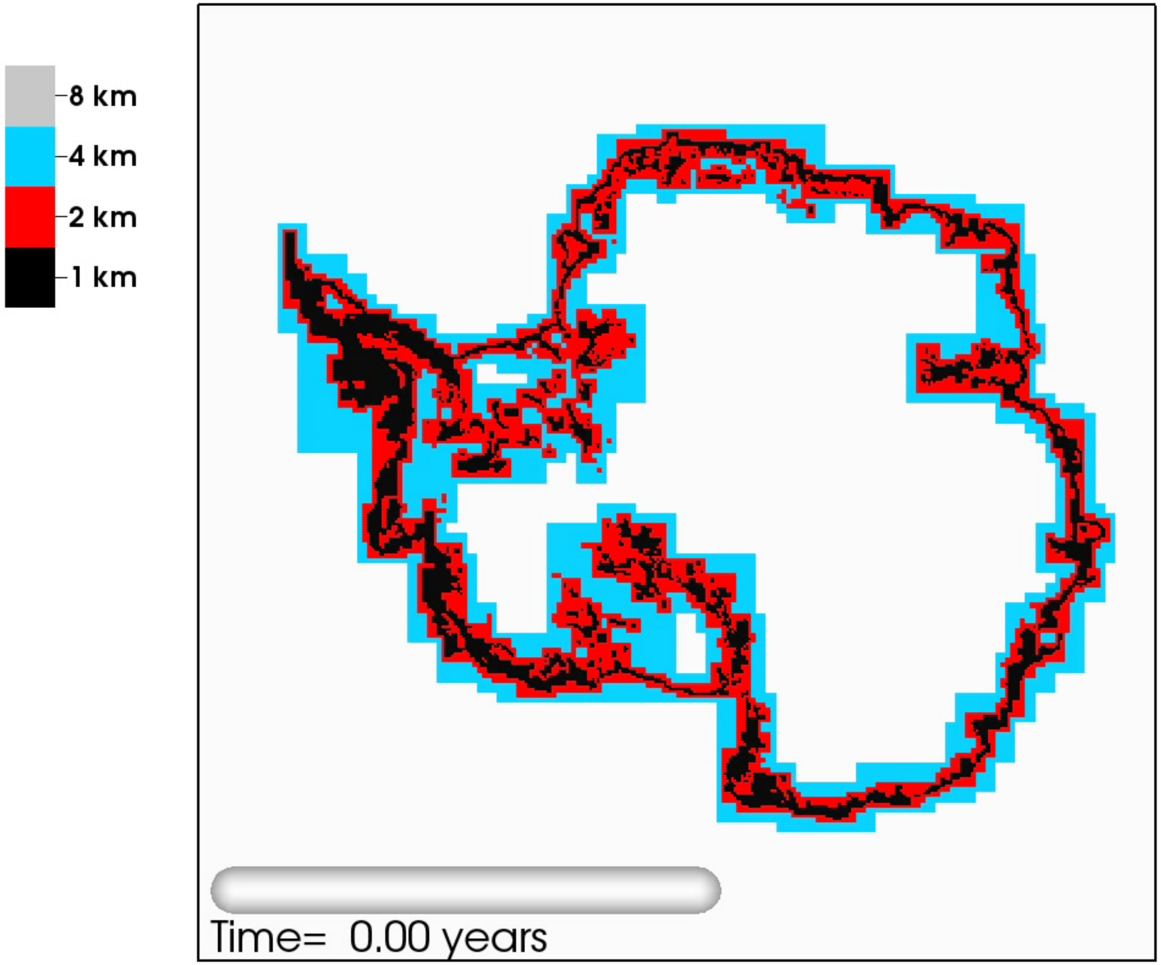


Coupling: Asynchronous-offline

Assumes that relevant $dt_{ice\_sheet} >> dt_{ocean}$ such that sub-shelf circulation is always in quasi-equilib. with ice sheet forcing

Coupling time step ~ ice sheet evolution time step

BISICLES → POP2x:

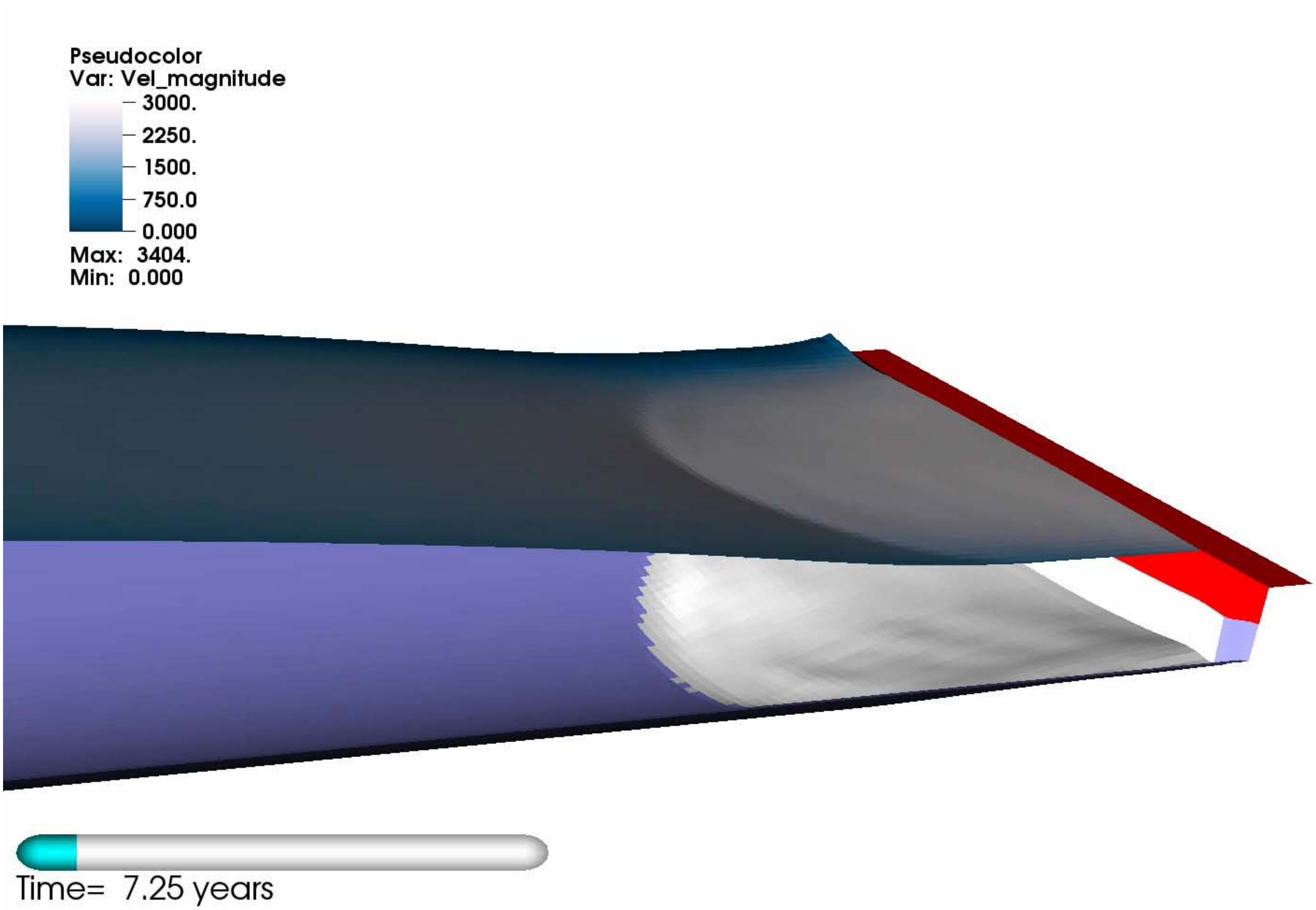
- ice draft
- basal temperatures
- grounding line location

POP2x → BISICLES:

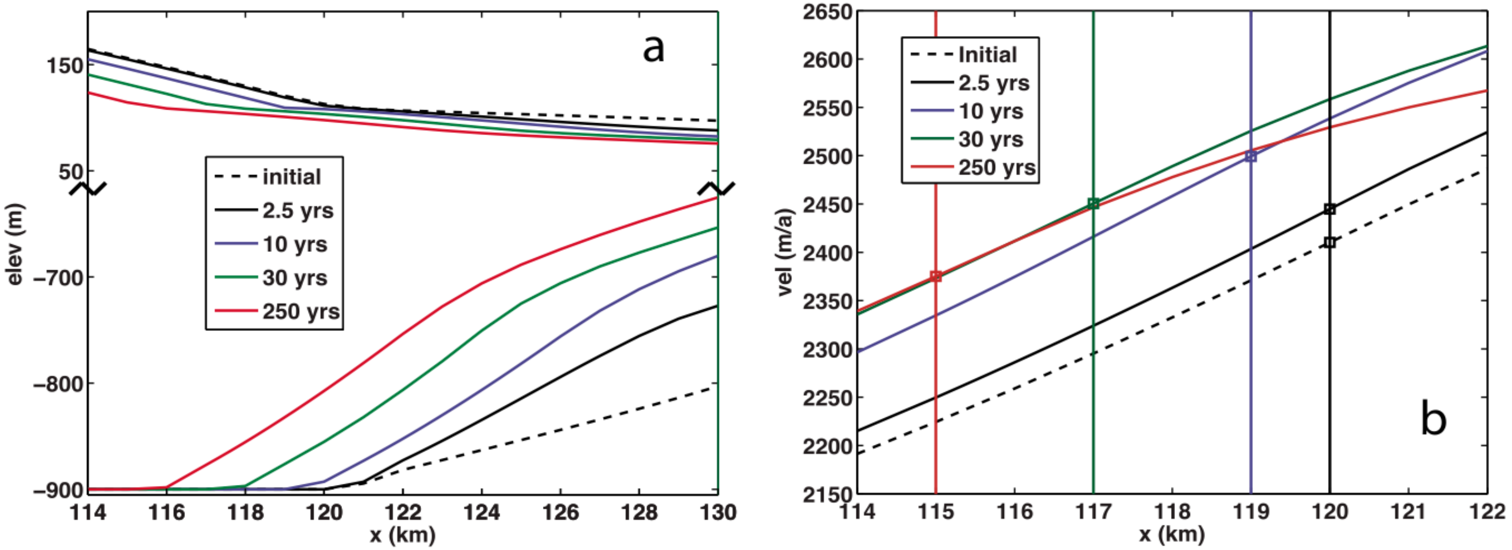
- time averaged sub-shelf melt rates

Coupling offline using standard CISM and POP netCDF I / O

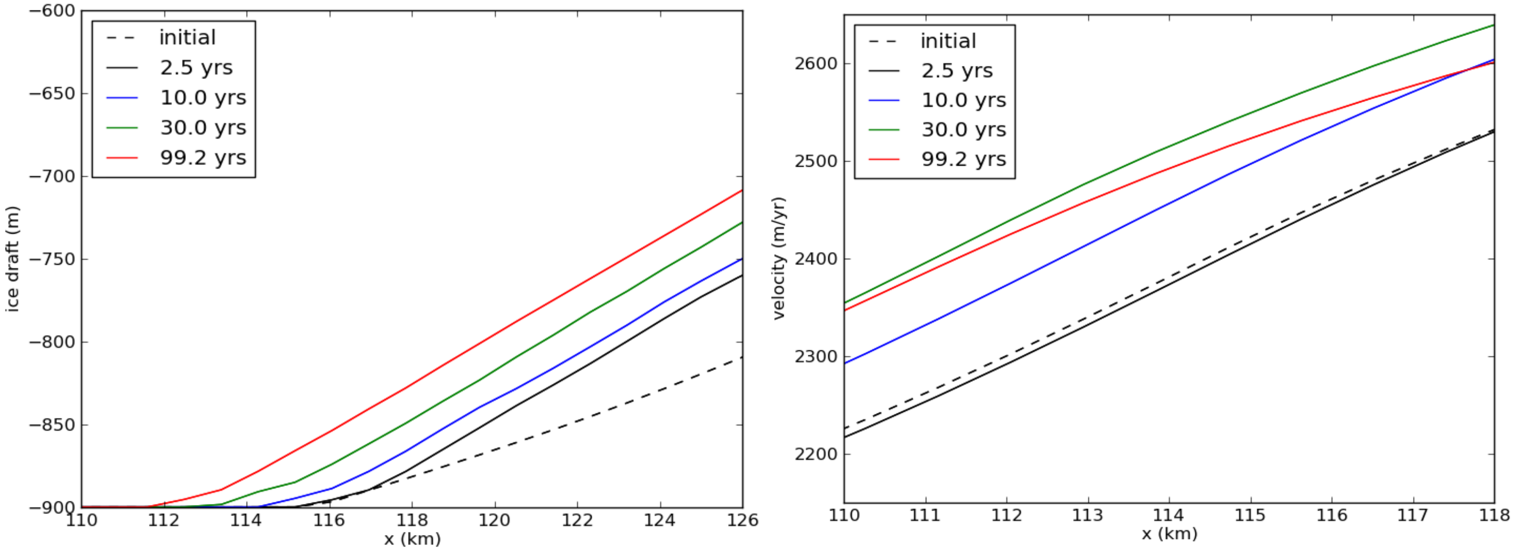
Coupled Models: Goldberg Test Problem



BISICLES + POP2x: coupled, idealized experiments



Ice shelf base profiles, $z_b(t)$ Centerline velocity profiles (m/yr)



BISICLES + POP2x: coupled, Antarctic experiments

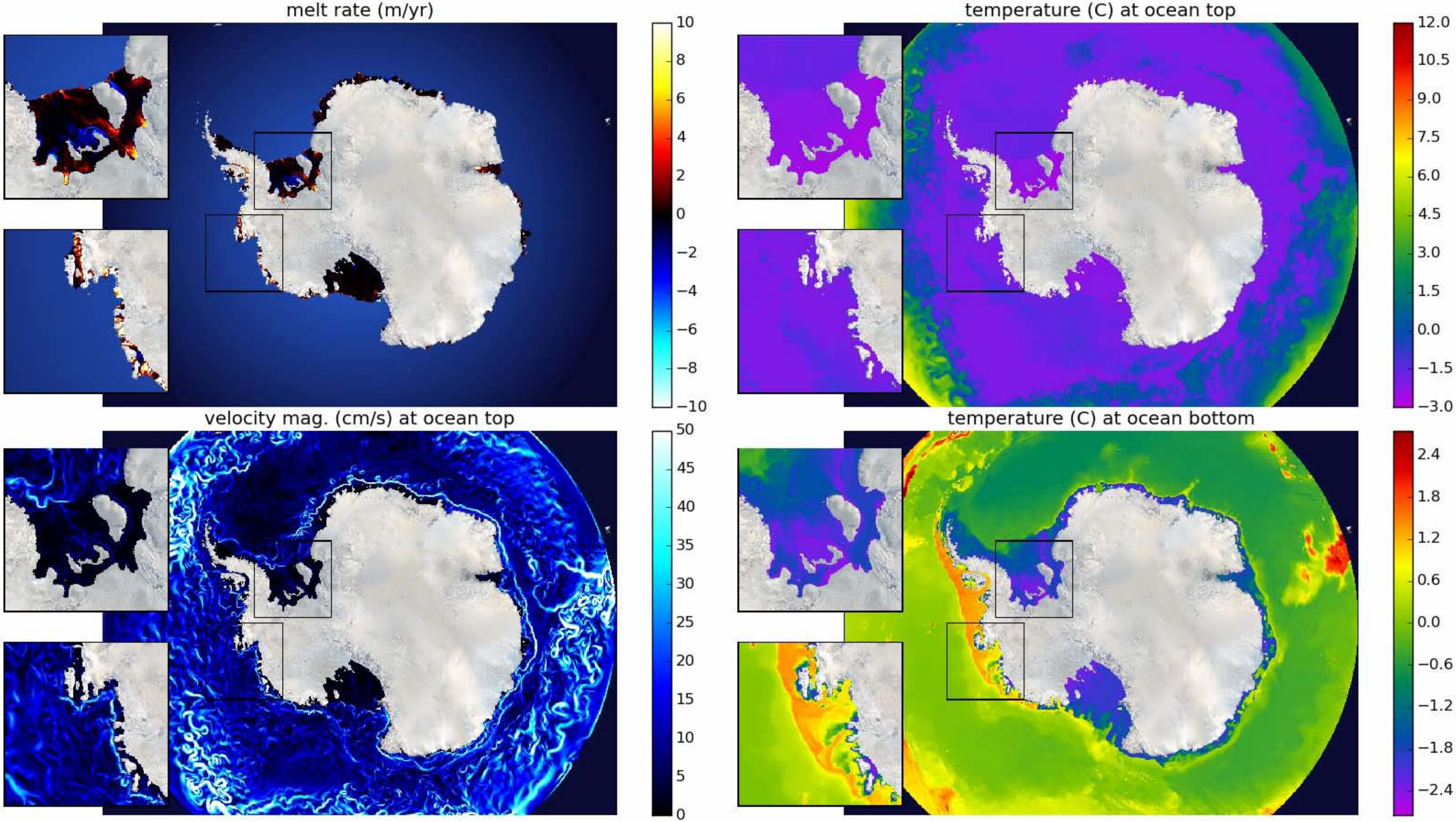
Offline ice-ocean coupling time step once per year:

- Re-grid / filter ocean geom. after shelf geom. change
- Run 2 months of ocean model spin-up ++
- Run additional 1 yr of ocean model **
- Average 1 yr of melt rates (minus 2 month spin-up) and pass to ice sheet model
- Evolve ice sheet model (with sub-shelf melt)

Notes:

++ barotropic mode initialization difficult with anything other than model at rest and sea-surface height = 0

** 1 yr coupling freq. is somewhat arbitrary initial choice, but supported by results (in general, no large, unrealistic changes in ice geometry)



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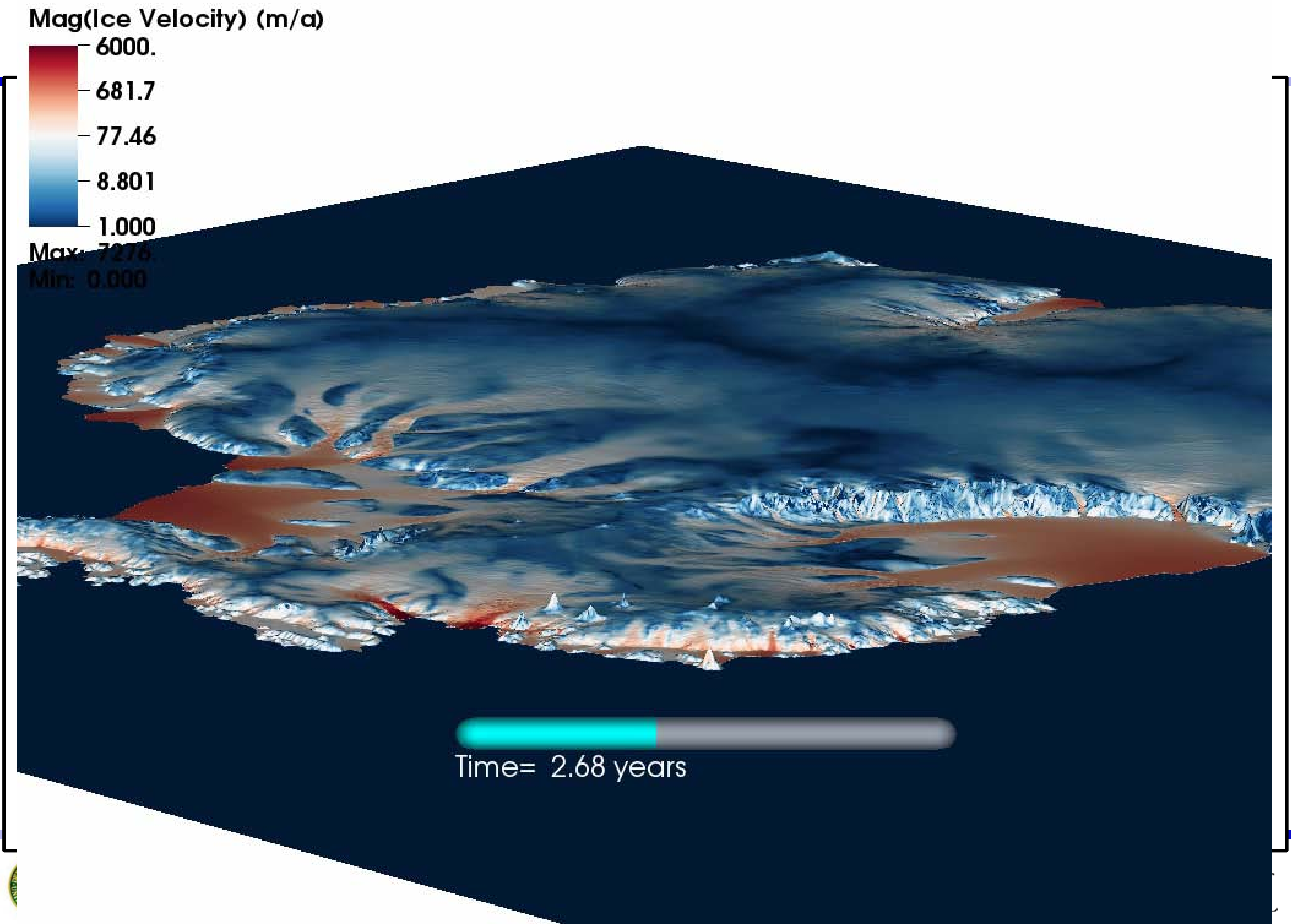

Mag(Ice Velocity) (m/a)
6000.
681.7
77.46
8.801
1.000
Max: 7276
Min: 0.000
Time= 2.68 years

Issues emerging from coupled runs

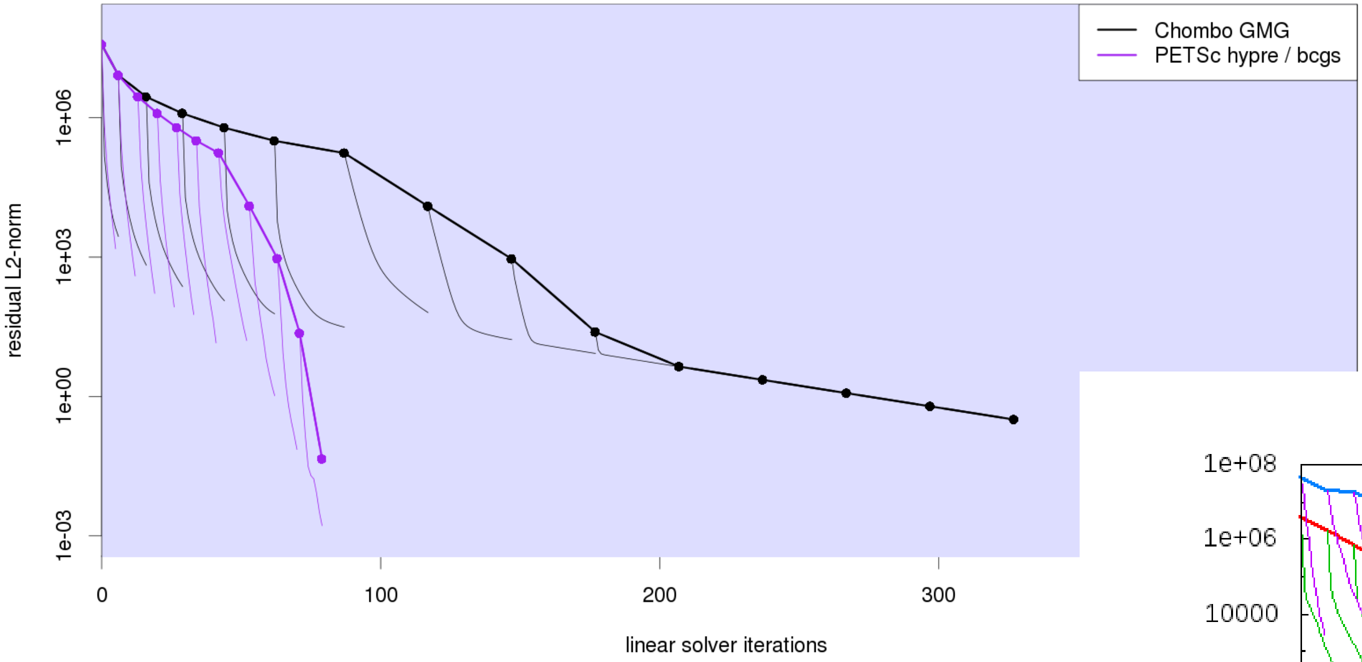
- POP2X Cold bias
  - cold water advected around Antarctic peninsula, decreasing melting.
  - Seems to be a result of either incorrect forcing (wind), or incorrect fresh-water fluxes (sea ice)
  - Currently experimenting with ways to fix the issue

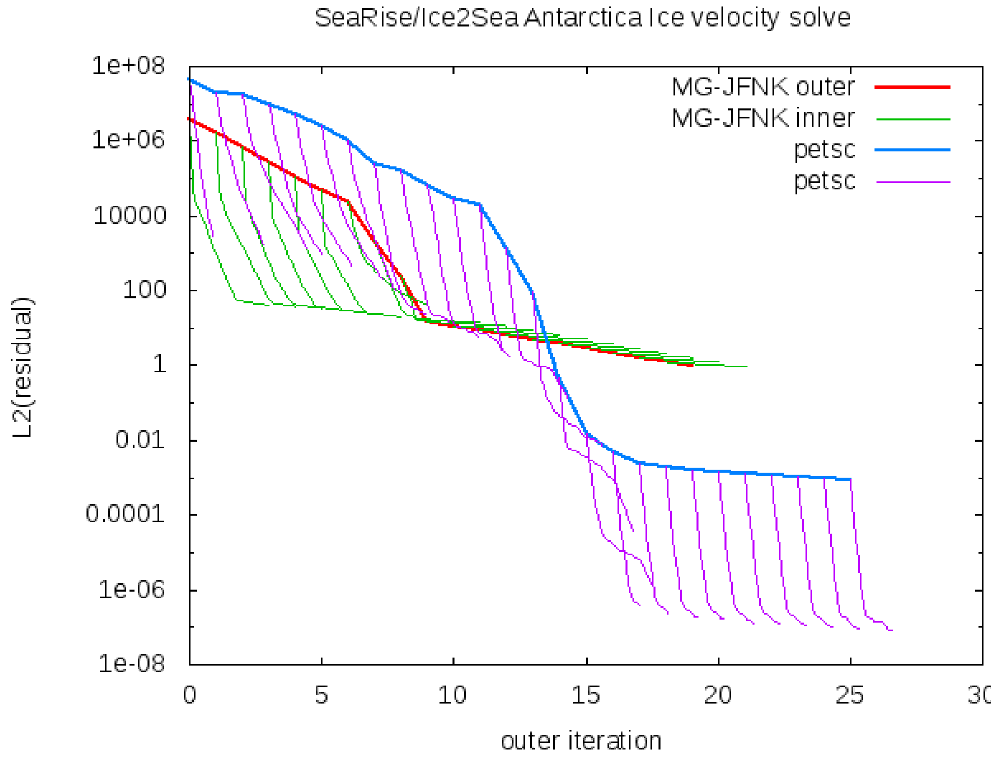
- POP2x restarts
  - Need to spin up from rest after every coupling interval
  - (let to fluctuations between different spun-up states)
  - Xylar thinks he's managed to fix this – testing…
- 2 codes means 2x sensitivity to LCF changes!

Thank you!

Extras

Linear Solvers - PETSc GAMG vs. Geometric MG



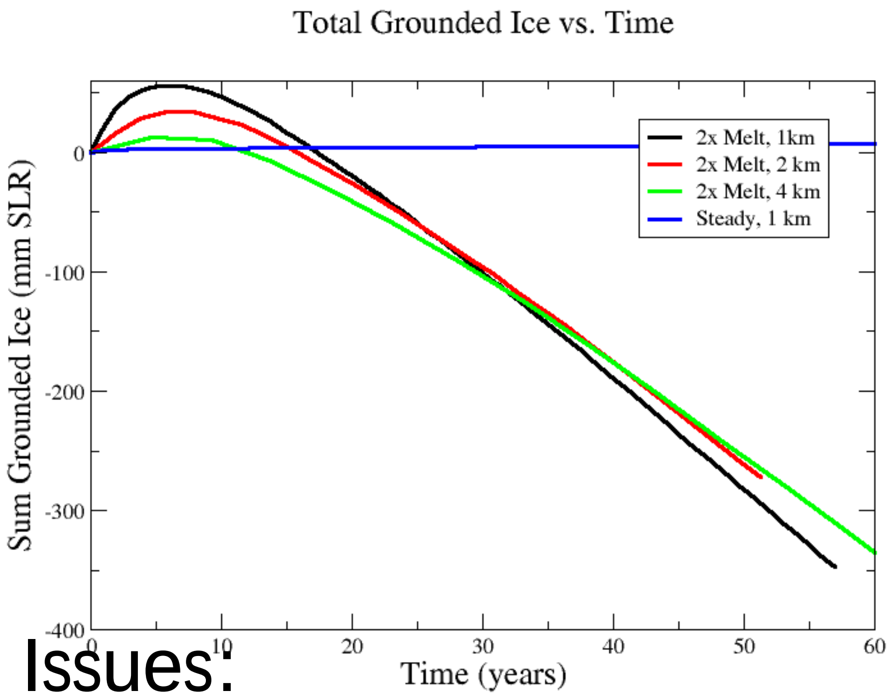


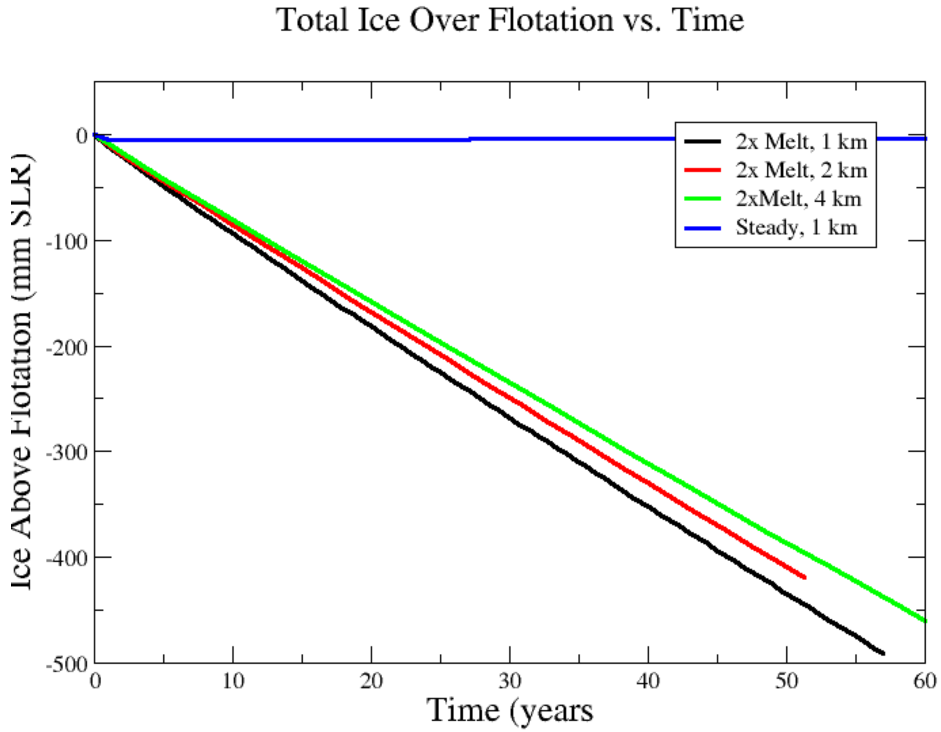
- Chombo native geometric multigrid (GMG) stalls/fails in many high-resolution cases.

- PETSc GAMG algebraic MG works well when GMG fails.

BISICLES Standalone: Enhanced Melting

- Double POP2X Melting

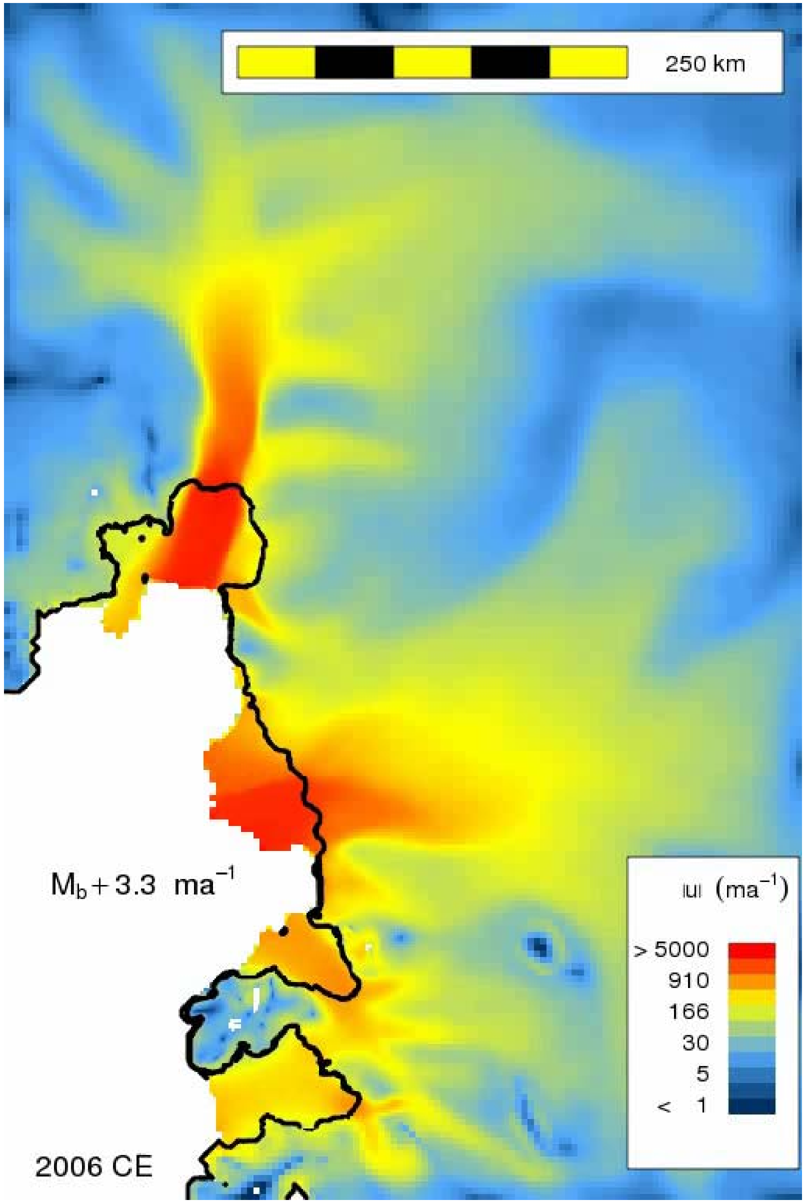




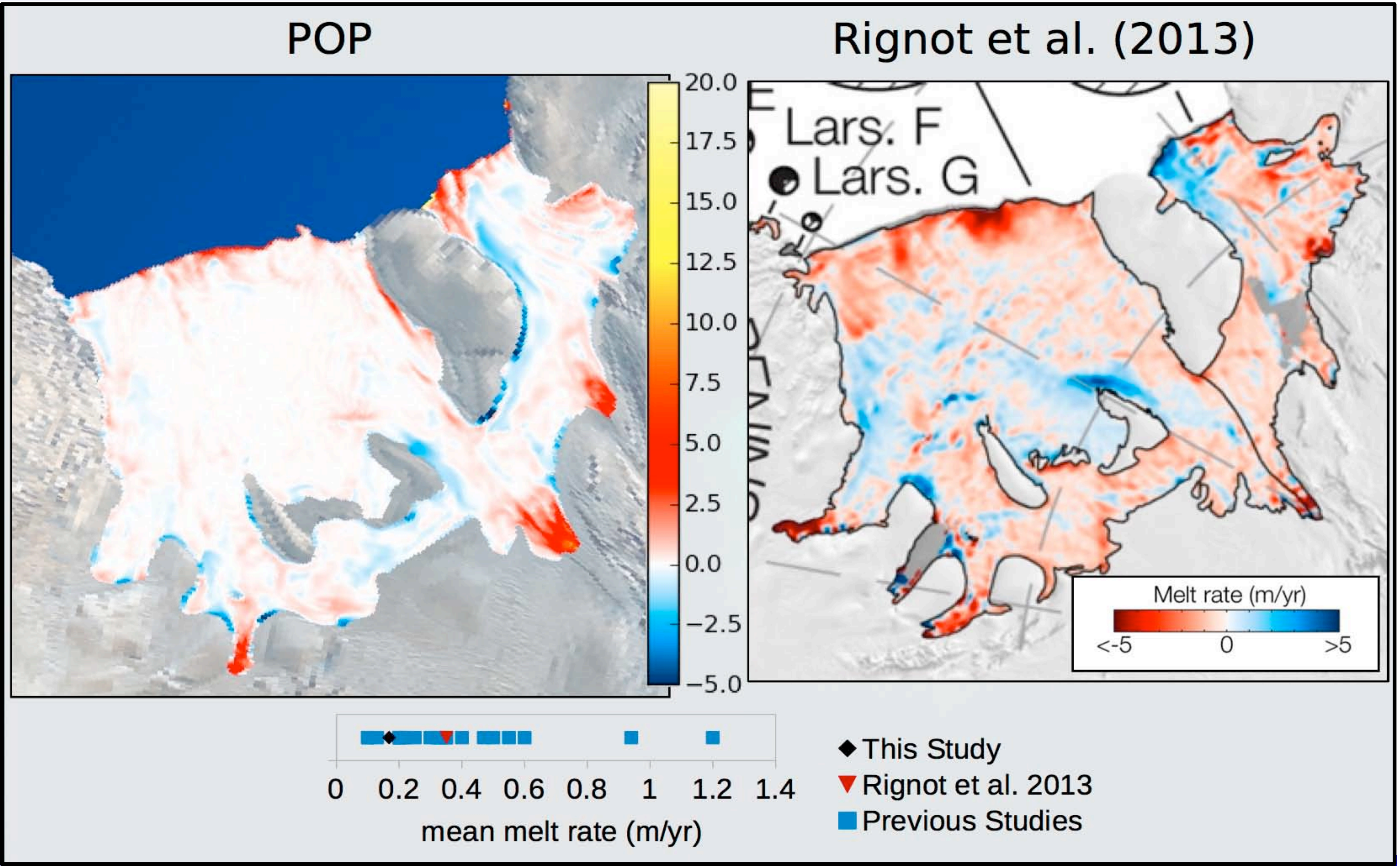
- Issues:
  - Refreezing zones – rapid freezing, then held at flotation
  - Melt doesn't follow retreating GL.

Ice2Sea Amundsen - Thwaites?

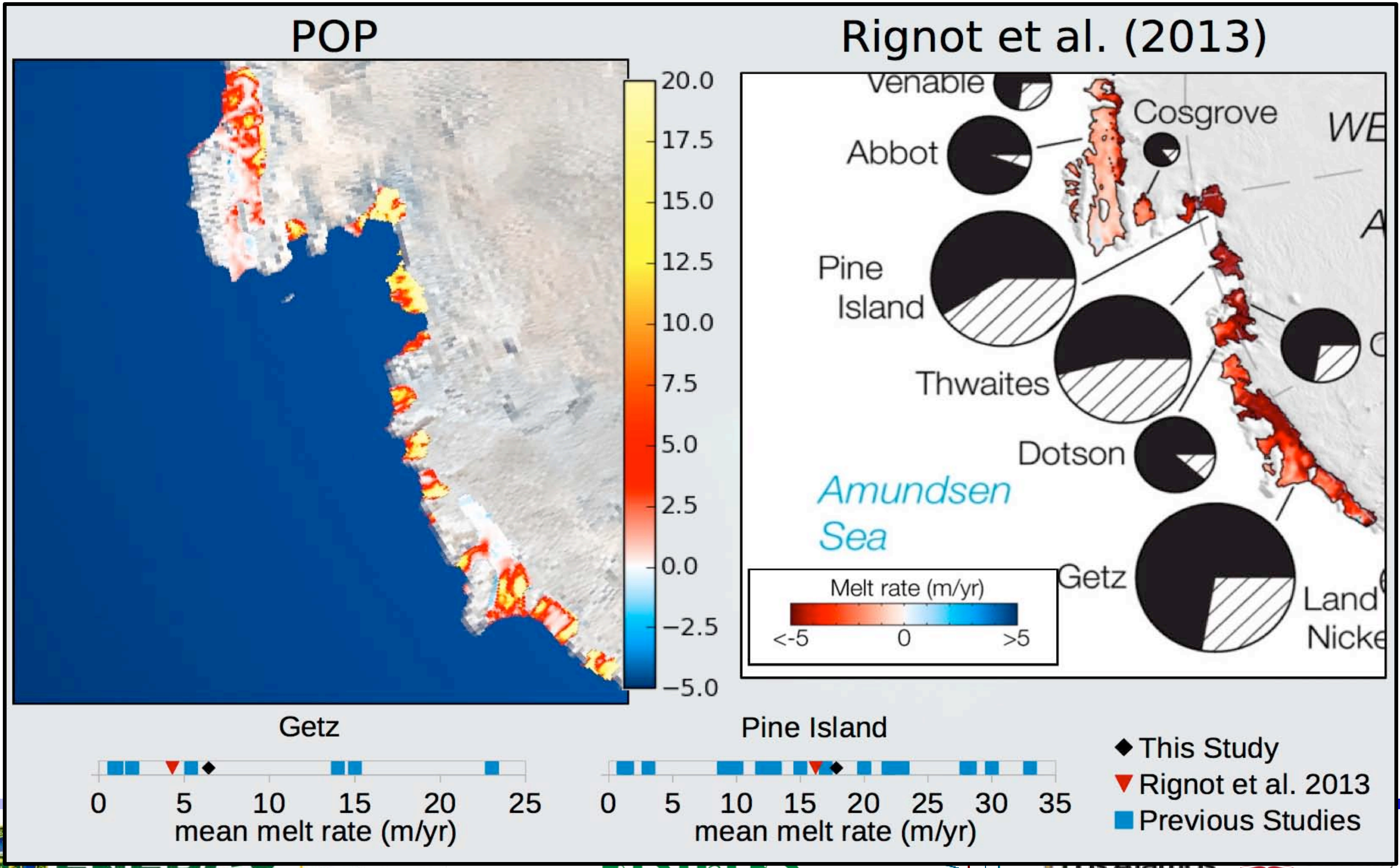
- In 400 year run, Thwaites destabilizes as well.
- Same forcing as previous run, subshelf melting held constant past 2200.
- Thwaites is very stable, until it tips.



POP2x realistic experiments (uncoupled)



POP2x: realistic experiments (uncoupled



Motivation: Future Sea Level Rise (SLR)

Projections: For RCP8.5, [projected] global mean SLR for 2081–2100 (relative to 1986–2005) [is] 0.45–0.81 m … range at 2100 is 0.53–0.97 m

Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause [21st century *SLR*] substantially above the likely range

Paleorecord:

Pliocene warm intervals: CO_2 levels 250-400 ppm; temperatures 2° C to 3.5° C warmer than pre-industrial; records suggest deglaciation of West Antarctica and parts of East Antarctica *with global mean sea level not >20 m above present*

Last Interglacial: global temperatures were not more than 2° C above pre-industrial; global mean sea level at least 5 m higher than present; Greenland likely contributed 1.4 - 4.3 m, *implying a contribution from Antarctica*