Response of the Antarctic ice sheet to ocean forcing using the POPSICLES coupled ice sheet-ocean model

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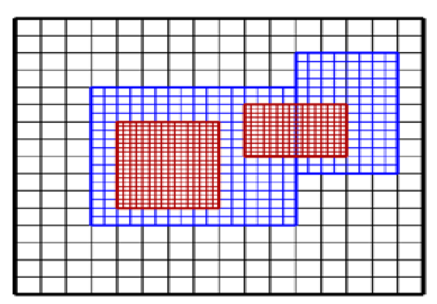
Motivation

One likely climate driver for marine ice-sheet instability is subshelf melting driven by warm(ing) ocean water intruding into subshelf cavities. Modeling this will require coupled ice sheet-ocean modeling in an earth system model (ESM), on multi-decadal to century timescales employing high spatial and temporal resolution. Target resolution for this work: Ocean: **0.1 Degree**, Ice sheet: **500 m** (using adaptive mesh refinement).

Numerical Models

Ice Sheet – BISICLES

- Very fine resolution (better than 1 km) is needed to resolve dynamic features like grounding lines and ice streams – computationally prohibitive for uniform-resolution studies of large ice sheets like Antarctica.
- Large regions where finest resolution is unnecessary – ideal application for adaptive mesh refinement (AMR).
- *Block-structured* AMR:
  - Refine in logically-rectangular patches.
  - Amortize cost of irregular operations over large number of regular structured-mesh operations.
  - *Finite-volume* discretizations simplify coarse-fine coupling.
  - Simplifies dynamic regridding to follow changing features.

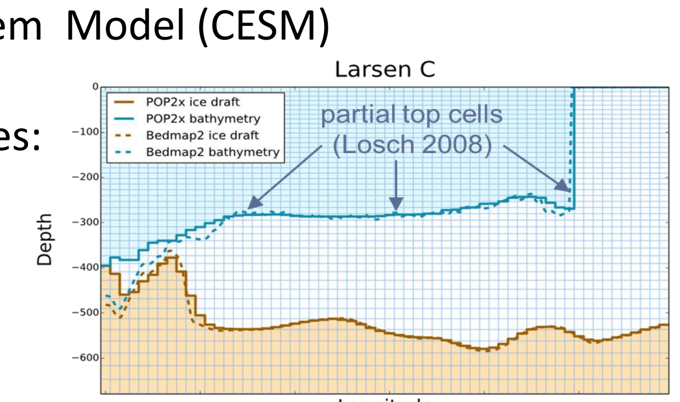


Sample AMR meshes – black mesh is base level (0), blue mesh (level 1) is a factor of 2 finer, while red (level 2) is 4 times finer still

- BISICLES is built upon the LBNL-developed Chombo AMR C++/Fortran framework, which supports scalable block-structured AMR applications.
- Modified version of the Schoof-Hindmarsh (2010) model ("SSA*")
  - Following Schoof and Hindmarsh, using SIA-like relation to compute stress allows vertical integration resulting in a simplified 2D nonlinear elliptic system for ice velocity at the bed.
  - Differ from standard L1L2 method by ignoring vertical shear when reconstructing flux velocities – reasonable approximation in fast-moving regions which improves numerical stability (SSA*).
  - Compares well with full-Stokes results in MISMIP3D experiments

Ocean Model – POP2x

- Ocean model of the Community Earth System Model (CESM)
- z-level, hydrostatic, Boussinesq
- Modified to include cavities under ice shelves:
  - partial top cells
  - boundary-layer method of Losch (2008)
- Subshelf melt rates computed by POP:
  - Methods of Holland and Jenkins (1999), Jenkins et al. (2001), and Losch (2008)
  - sensitive to vertical resolution
  - nearly insensitive to transfer coefficients, tidal velocity, drag coefficient



In POP, partial bottom cells discretize bathymetry. POP2x extends this approach to include partial top cells at upper ice-shelf/ocean boundaries, allowing computation of circulation in ice-shelf cavities.

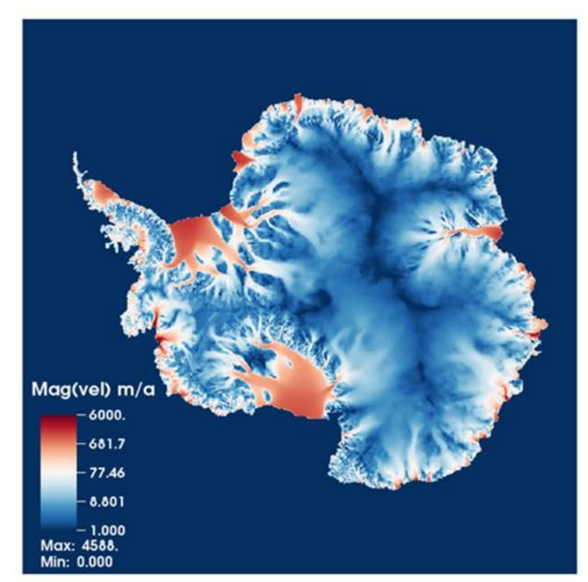
Coupling to POP2x through CISM

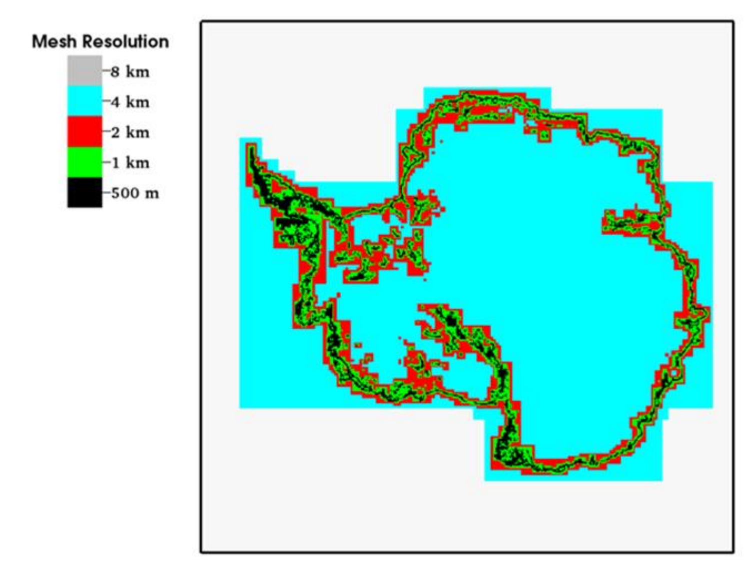
BISICLES is coupled to the Community Ice Sheet Model (CISM) as an external dynamical core, callable from CISM, which is coupled to CESM.

- Synchronous-offline coupling: BISICLES and POP exchange information at fixed coupling intervals.
- Monthly coupling interval arrived at through experimentation
- CISM-BISICLES → POP2x: Instantaneous ice draft, ice shelf basal temperature, grounding line locations.
- POP2x → CISM-BISICLES: Time-integrated subshelf melt rates
- Offline coupling using standard CISM and POP NetCDF file I/O.
- POP bathymetry and ice draft recomputed:
  - smoothing bathymetry and ice draft, thickening ocean column, ensuring connectivity
  - T and S in new cells extrapolated iteratively from neighbors
  - barotropic velocity held fixed; baroclinic velocity modified where ocean column thickens/thins

Coupled Antarctica-Southern Ocean

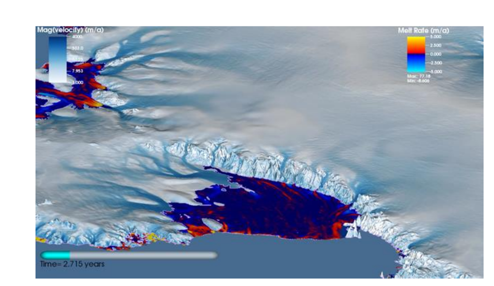
BISICLES Setup





Movie frames showing Ice sheet initial condition: Initial basal velocity field with melt rates painted onto ice shelves (left), initial AMR meshes (right)

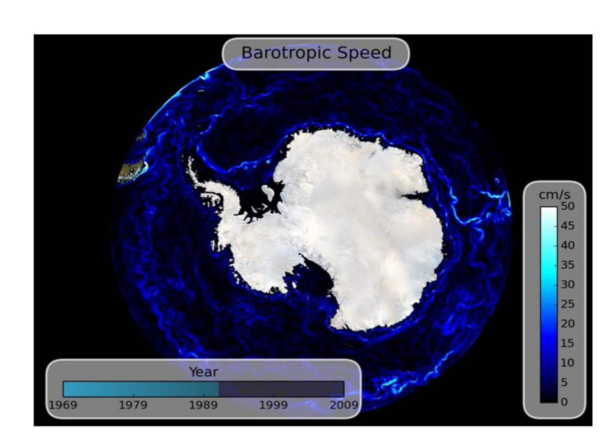
- Bedmap2 (2013) geometry
- Initialize to match Rignot (2011) velocity field.
- Temperature field from Pattyn (2010) spinup
- 500m finest spatial resolution (8 km coarsest mesh)
- Initialize synthetic accumulation field for equilibrium with POP melt rates computed in a standalone spinup run.



Movie frame showing subshelf melt rates painted on floating ice shelves,. Grounded ice coloring indicates the ice velocity.

POP 2x Setup

- Regional southern ocean domain (50-85°S)
- 0.1° (~5 km) horizontal resolution.; 80 vertical levels (10m-250m)
- Monthly restoring to World Ocean Atlas (WOA) data at northern boundaries
- 2 climatologies explored, from Common Ocean-ice Reference Experiments:
  - Monthly mean climatological ("normal year") forcing (NY)
  - CORE Interannual Forcing (CORE-IAF)
- 20-year standalone run to initialize
- Bedmap2 geometry for ice shelves and bathymetry



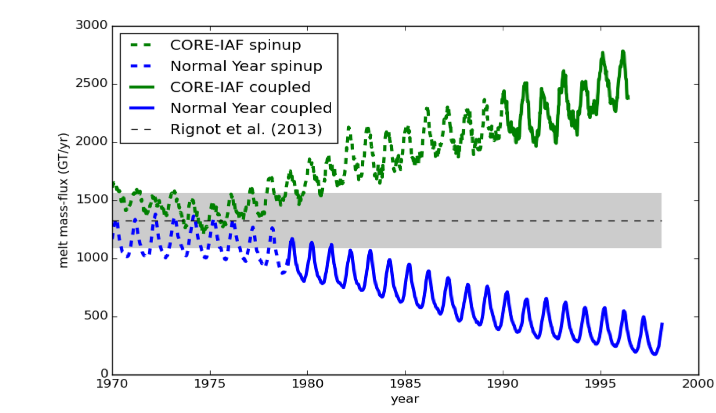
POP-computed barotropic ocean speed on Southern Ocean domain

Companion talk by X.S. Asay-Davis, today at 5:30 PM, Moscone West-3007

Experiment Results

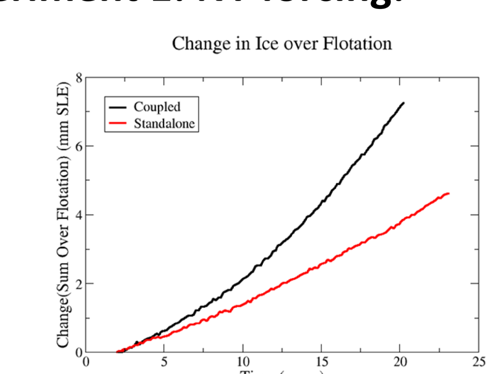
Normal Year vs. Interannual Forcing

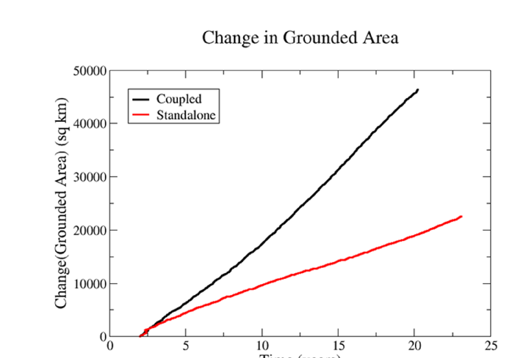
Plot of integrated Antarctic subshelf melt rates at right compared to published values (Rignot et al 2013). NY produces too little melting relative to Rignot values, CORE-IAF produces too much melting.



Total Antarctic melt flux for NY and CORE-IAF forcing, along with published value (Rignot, 2013). Dashed lines are standalone spinup, solid lines are fully-coupled.

Experiment 1: NY forcing:

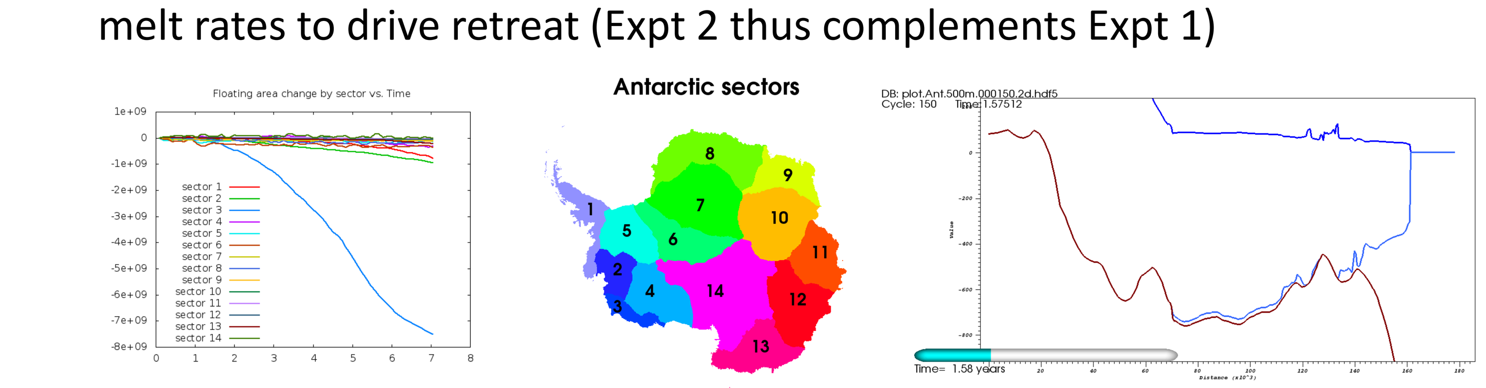




- 20-year coupled experiment. Ran fully-coupled and standalone cases.
- Compare coupled & standalone for coupling effects.
- Standalone ice run shows ice not quite in steady state – standalone run gains ice.
- Melt rates decreasing over time, freezing rates overestimated (right) (POP issues – now fixed.
- **Coupling effect seen – coupled run gains mass faster than standalone, as expected for cooling ocean)**

Experiment 2 – Core-IAF forcing:

- Coupled segment for only 7 years (runs continue)
- Results dominated by Getz regrounding instability: Artificially thin subshelf cavity combined with high melt rates combine to create instability – moderate fluctuations can be O(subshelf cavity thickness), causing a localized regrounding event. Local regrounding removes subshelf melt component of the mass balance, resulting in large unbalanced accumulation, resulting in catastrophic regrounding. (Nonphysical artifact of artificially thin subshelf cavities in Bedmap2 bathymetry)
- Results for other shelf systems look promising – expect future increases in melt rates to drive retreat (Expt 2 thus complements Expt 1)



Experiment 2 results: (left) sector-by-sector change in floating area vs. time. Note that regrounding in sector 3 (Getz) dominates. (center) Map showing Antarctic sectors. (right) Movie frame of cross-section through Getz system showing regrounding around km 130.

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