Towards Decadal-scale response of the Antarctic ice sheet to a warming ocean using the POPSICLES coupled ice sheet-ocean model

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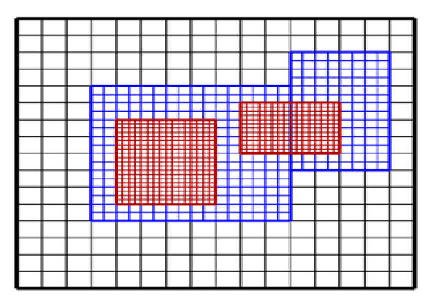
Motivation

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.

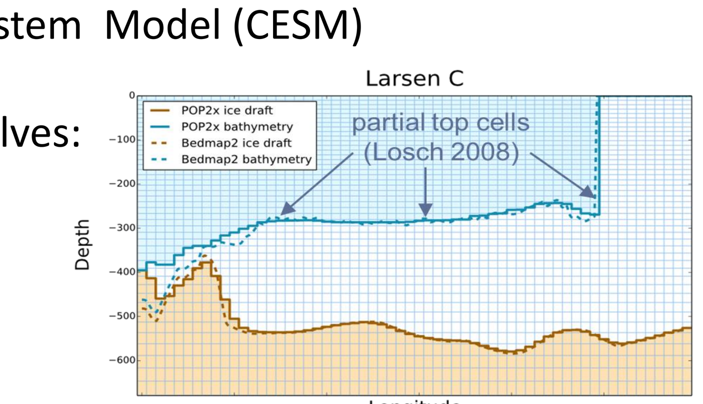


Sample AMR meshes – black mesh is base level (0), blue mesh (level 1) is a factor of 2 finer, while red (level 2) is 4 times finer still

- 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.

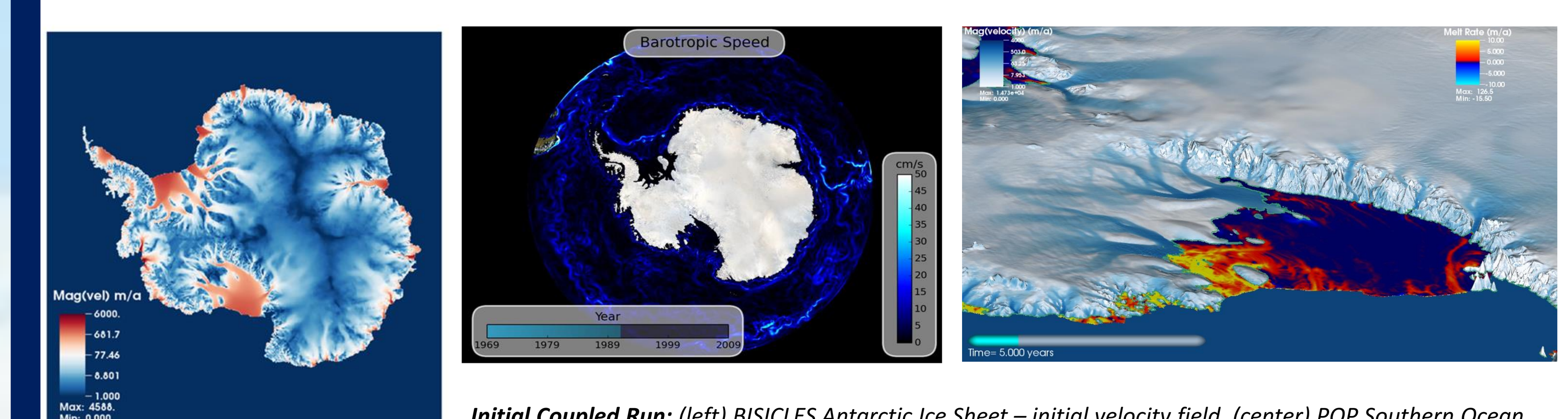
Coupling to POP2x through CISM

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

- 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

The Story so Far: Coupled Antarctica-Southern Ocean

Previous (EGU 2015) Attempts at Coupled Runs (failed)

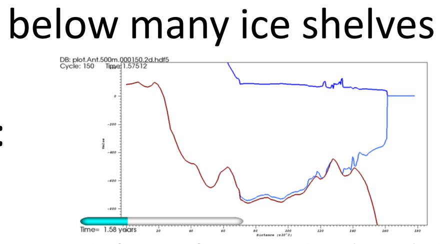


Initial Coupled Run: *(left) BISICLES Antarctic Ice Sheet – initial velocity field, (center) POP Southern Ocean domain – barotropic velocity, (right) Coupled simulation – movie frame showing POP-computed melt rates painted onto the Ross Ice Shelf. Blue colormap depicts grounded ice speed.*

- Used Bedmap2 (2013) geometry for ice **and** ocean (Ice thickness, topography)
- Initialize Antarctic Ice Sheet (AIS) velocities to match Rignot (2011).
- BISICLES Ice Sheet 500m finest spatial resolution (8 km coarsest mesh)
- AIS initially in steady-state -- compute synthetic accumulation field for equilibrium with POP melt rates computed in a standalone spinup run.
- POP2x Ocean Model: 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
- Climatology -- Common Ocean-ice Reference Experiments: (CORE) Interannual Forcing (CORE-IAF)
- 20-year standalone run to initialize, followed by 20-year coupled run.
- Ran on NERSC's Edison (Cray xc30) – 15,000 CPU hours/simulation year.

Lessons Learned (2015)

- **Warm bias:**
  - CORE-IAF produces too much melting (warm bias due to mixing of CDW into upper ocean, too much stratification from freshwater forcing – ocean model issue.)
- **Coupled problem dominated by "regrounding instability"**:
  - Ocean cavity thickness artificially set to one meter below many ice shelves (e.g. Getz) where bathymetry data is lacking.
  - combines with high melt rates to create instability:
    - thickness fluctuations of O(cavity thickness)
    - causes localized regrounding event.
    - local regrounding removes subshelf melt partt of the mass balance, resulting in large unbalanced accumulation
    - Result: catastrophic ice-shelf grounding. (Nonphysical artifact of artificially thin subshelf cavities, amplified by synthetic SMB fields)

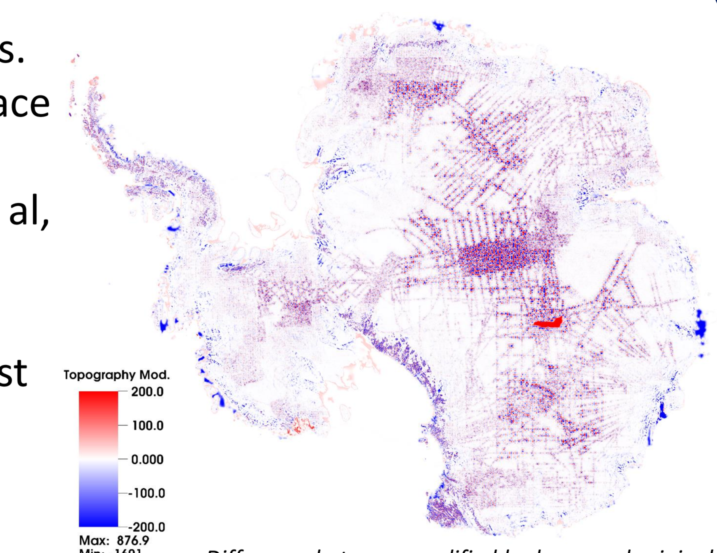


Movie frame of cross-section through Getz system showing regrounding around km 130; note artificially thin subshelf cavity.

Primary lesson: Need new bedmap

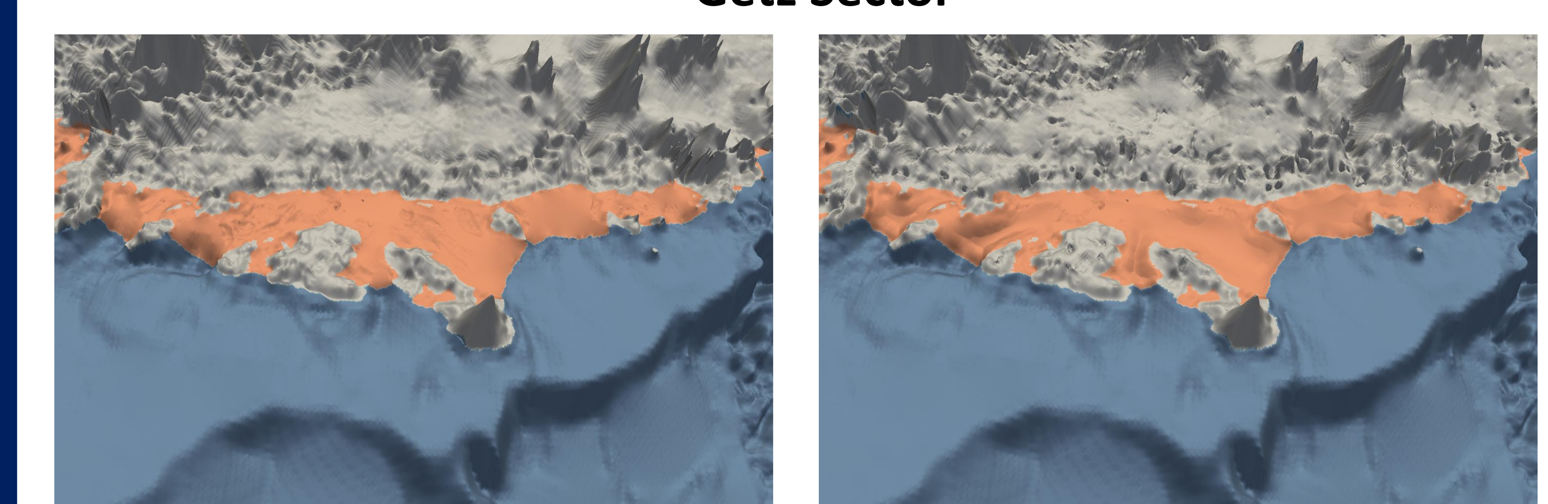
Modified Bedmap

- Need improved bedmap for coupled runs.
- Where possible, preserve upper ice surface
- Approach for modifying bathymetry:
  - Use new observations (Greenbaum et al, 2015) for Totten.
  - Use RTOPO1 to deepen (rather than simply replace) bathymetry under most ice shelves in the Amundsen and Bellingshausen regions.
  - Cavities under Dalton, Nivlisen, Shackleton, and Stange ice shelves thickened based on the distance from the grounding line. (ad hoc)
  - Smooth discontinuities between grounded and floating sections.
  - Topography under grounded ice was deepened in regions (Rutford, Pine Island Ice Streams) to better match velocity observations (mass-conserving bed (Nais et al, 2015, Cornford et al, 2016)).



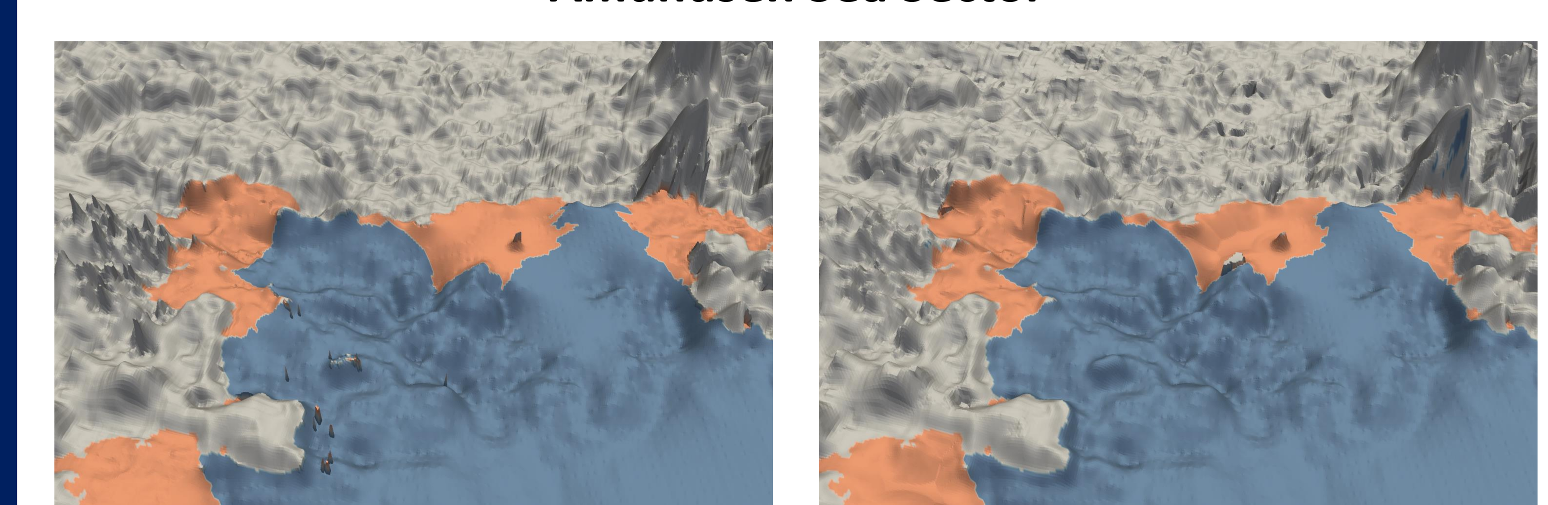
Difference between modified bedmap and original Bedmap2 topography. Blue means deepening.

Getz Sector



Original Bedmap2 (left) and modified (right) bathymetry under Getz Ice shelf – note deepened channels from RTOPO1

Amundsen Sea Sector



Original Bedmap2 (left) and modified (right) bathymetry under Pine Island and Thwaites Systems

Next Steps

- POPSICLES code modifications necessitated by NERSC changes are underway
- Relaxed/spun-up AIS initial condition on modified bed based on "present-day" (Rignot) observations has been generated.
- New 20-year coupled run planned with more realistic forcing.

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