# High-resolution coupled ice sheet-ocean modeling using the POPSICLES model

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## Motivation

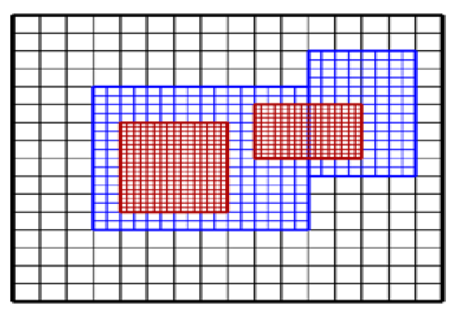
In its AR5 report, the IPCC points to potentially large Antarctic contributions to sea level rise (SLR) which may result from the marine ice sheet instability, particularly from the West Antarctic Ice Sheet (WAIS). Indeed, the paleorecord implies that WAIS has deglaciated in the past.

One likely climate driver for this 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. The target resolution for this work is: 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.

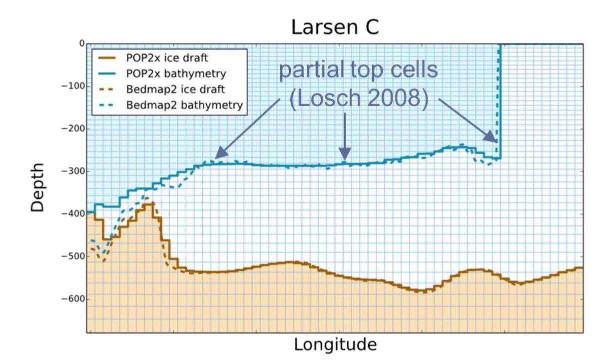


*Sample AMR meshes – black mesh is base level (0), blue mesh (level 1) is a factor of 2 finer, while red (level 2) is 4 times finer still*

- BISICLES is built upon the LBNL-developed Chombo AMR C++/Fortran framework, which supports scalable block-structured AMR applications.
- BISICLES uses a 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)




*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.*

- 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

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

## Ice-Ocean Coupling

### 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

## POPSICLES on Edison

**Software pieces:**

- **BISICLES** – C++, built on the FASTMath-supported Chombo AMR framework
- **CISM** – Fortran, used as driver for BISICLES and as coupling interface with POP via NetCDF file I/O
- **POP2x** – Fortran ocean model
- **POPSICLES** -- core set of python scripts to manage runs and component interactions
- Distributed using MPI for parallelism

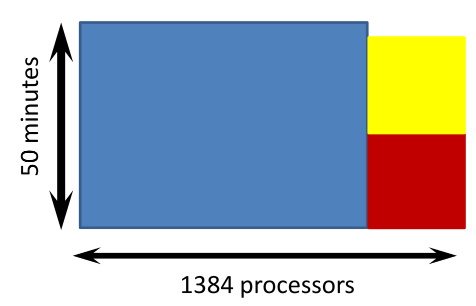



*Illustration of POPSICLES work distribution during a single coupling interval. Blue: POP2x, Red: BISICLES, Yellow: POPSICLES setup for next interval*

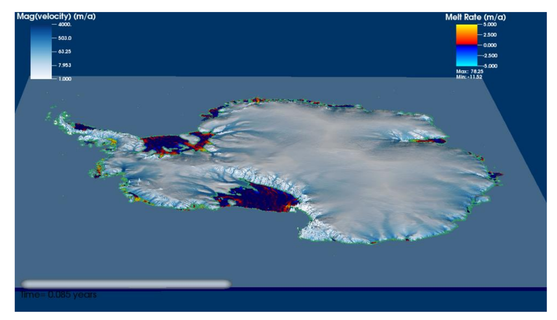
- For each 1-month coupling interval:
  - POP: 1080 processors, 50 min
  - BISICLES: 384 processors, ~30 min
  - Extra "BISICLES" time used to set up POP grids for next step

- Total: 1464 proc x 50 min = ~15,000 CPU-hours/simulation year (~1.5M CPU-hours/100 years)

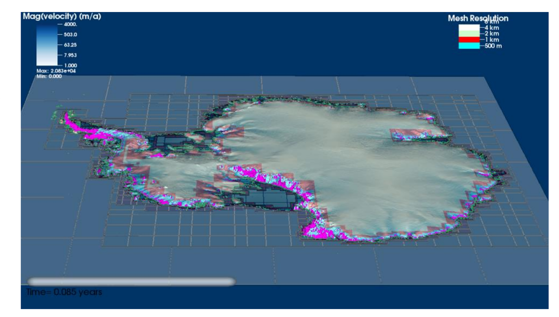
- NERSC queues normally allow O(1 simulation year/day) throughput for full-continent/Southern Ocean problem.

## Coupled Antarctica-Southern Ocean

### BISICLES Setup



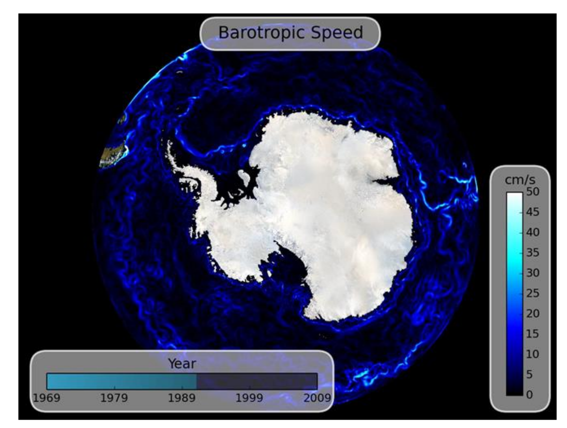
*Movie frames showing Ice sheet initial condition: Initial basal velocity field with melt rates painted onto ice shelves (left), initial AMR meshes (right)*



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

### POP 2x Setup

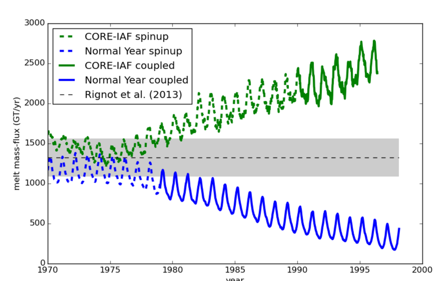
- Regional southern ocean domain (50-85°S)
- 0.1° (~5 km ) horizontal resolution.; 80 vertical levels (10m-250m)
- Monthly restoring to World Ocean Atlas (WOA) data at northern boundaries
- 2 climatologies explored, from Common Ocean-ice Reference Experiments:
  - Monthly mean climatological ("normal 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*

### Modeling Issues

- Difficulty putting AIS into steady-state (tendency for grounding lines to advance without strong localized melting.)
- Artificial Bedmap2 subshelf cavity geometry (Getz Ice Shelf) encourages unstable grounding-line advance/regrounding.
- Difficulty finding correct ocean forcing (NY produces too little melting, 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.*

- Regional-configuration POP precludes sea ice model.
- Coupled ice-ocean system – harder to control complex system behavior.
- Despite these, coupled results differ from both standalone ice- and ocean model results, indicating importance and effectiveness of coupling.

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