Whole-continent Antarctica simulations using the BISICLES AMR ice-sheet model coupled with the POP2x ocean model

D.F. Martin (DFMartin@lbl.gov)[1], X. Asay-Davis[3,4], S.F. Price[5], S.L. Cornford[2], E.G. Ng[1], W.D. Collins[1]

1. Lawrence Berkeley National Laboratory, Berkeley, CA, USA **2**. University of Bristol, Bristol, UK **3**. PIK, Potsdam, Germany
4. Courant Institute, New York University, New York, NY, USA **5**. Los Alamos National Laboratory, Los Alamos, NM, USA

Motivation

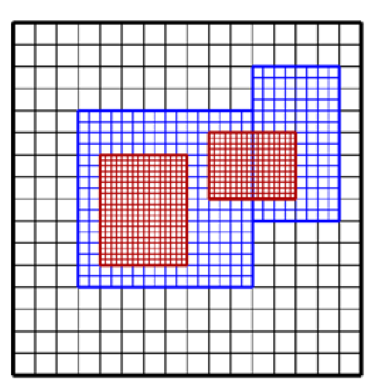
In its AR5 report, the IPCC points to potentially large Antarctic contributions to sea level rise (SLR) which may result from the marine ice sheet instability, particularly from the West Antarctic Ice Sheet (WAIS). Indeed, the paleorecord implies that WAIS has deglaciated in the past.

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.

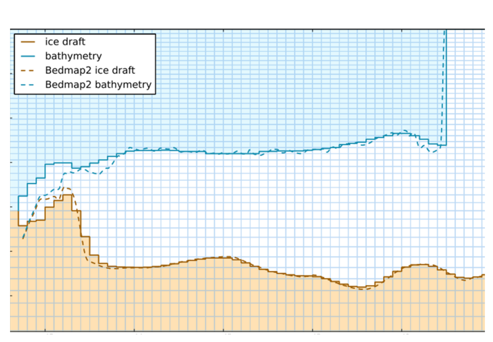


Sample AMR meshes – black mesh is base level (0), blue mesh (level 1) is a factor of 2 finer, while red (level 2) is 4 times finer still

- 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 for 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

Ice-Ocean Coupling

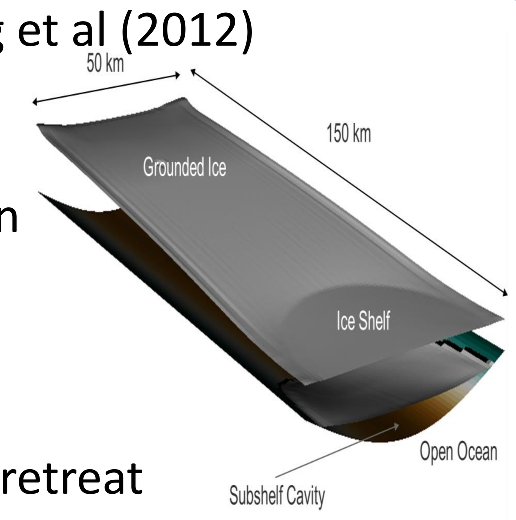
Coupling to POP2x through CISM

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

Idealized Test Case

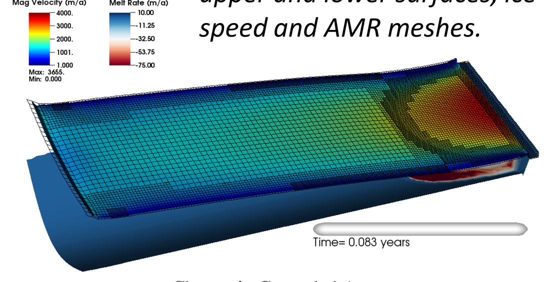
- Idealized domain of Goldberg et al (2012)
- Cavity and forcing similar to Pine Island Glacier
- Ice sheet at sub-km resolution
- Far-field ocean temp=1.8°C

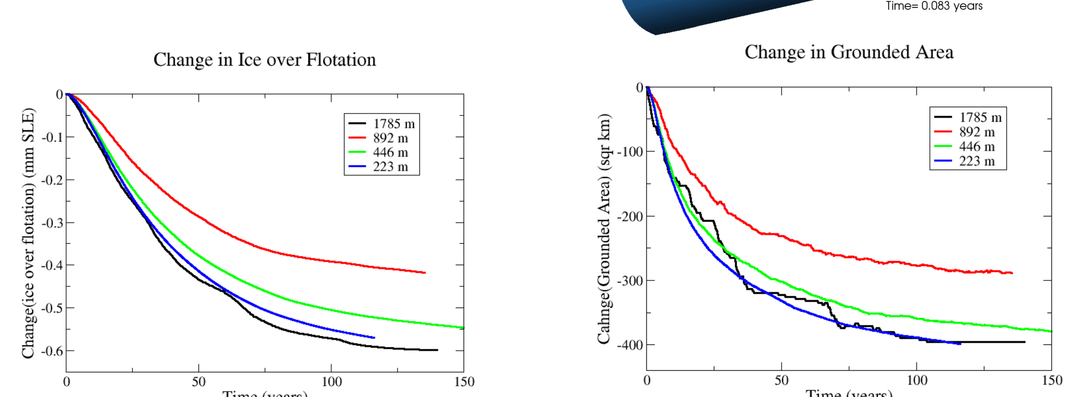


Results:

- Melt-induced grounding-line retreat from steady-state initial condition.
- Using AMR, computed with finest resolution Δx= 223m, 446m, 892m, 1785m

Above, test problem layout. Below, BISICLES-computed upper and lower surfaces, ice speed and AMR meshes.

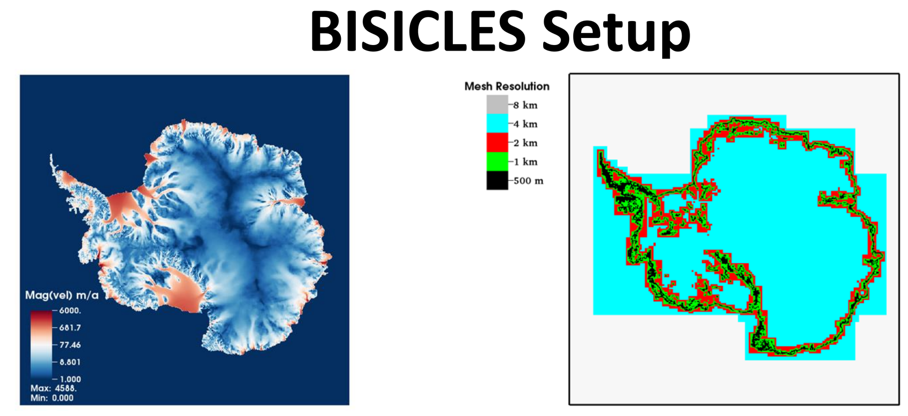




- 892m, 446m, 223m solutions converging at O(Δx)
- 1785m not in the convergent ("asymptotic") regime, so not reliable (despite "agreement" with 223m)
- Reasonable agreement with Goldberg results.

Coupled Antarctica-Southern Ocean

BISICLES Setup

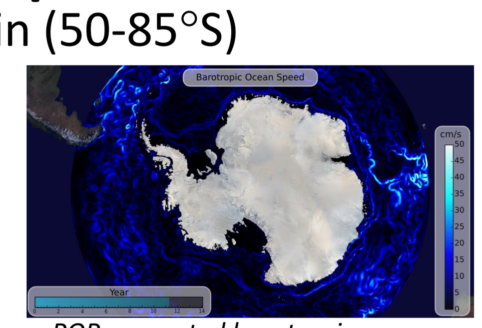


Ice sheet initial condition: Initial basal velocity field (left), and initial AMR meshes (right)

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

POP 2x Setup

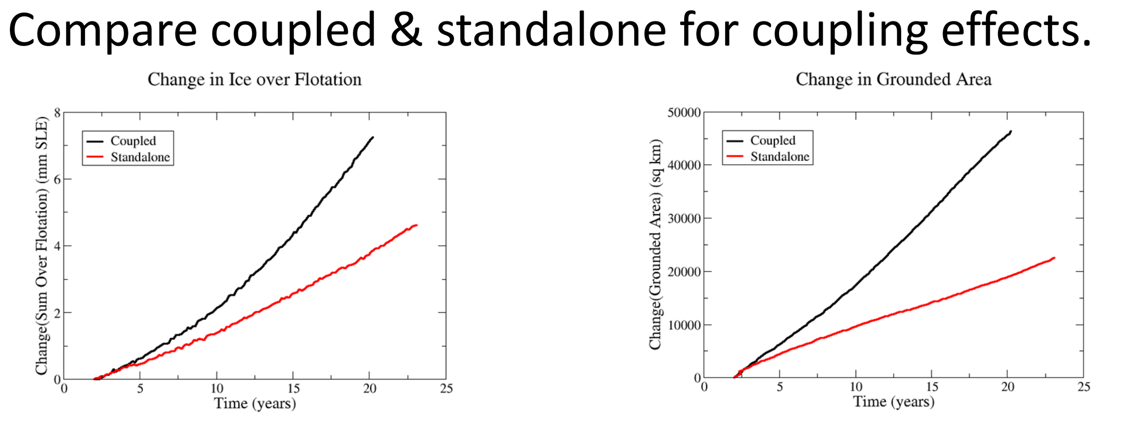
- Regional southern ocean domain (50-85°S)
- 0.1° (~5 km) horiz. res.; 80 vert. levels (10m-250m)
- Monthly mean climatological ("normal year") forcing with monthly restoring to World Atlas (WOA) data at northern boundaries
- 3-year standalone run to initialize
- Bedmap2 geometry for ice shelves and bathymetry



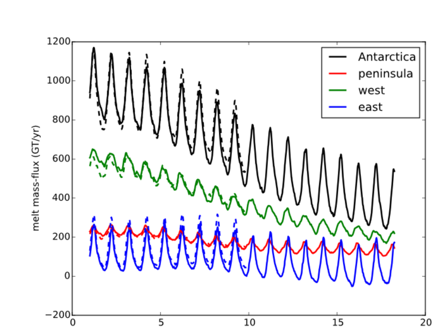
POP-computed barotropic ocean speed on Southern Ocean domain

20-year Coupled Results

- Ran coupled as well as standalone ice and ocean runs.
- 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)



POP-computed subshelf-melt mass fluxes for Antarctic coupled run.

- Artificial Bedmap2 subshelf cavity geometry (Getz,Totten) encourages grounding-line advance.
- **Coupling effect seen – coupled run gains mass faster than standalone, as expected for cooling ocean)**

Computational Cost (edison.nersc.gov):
- POP: 1080 proc for 50 min for each monthly step
- BISICLES 384 proc for 30 min for each monthly step
- **Total: ~1.5M cpu-hrs for a 100 year computation**

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