Applying the BISICLES Ice Sheet Dynamical Core to Full-scale Antarctic Problems

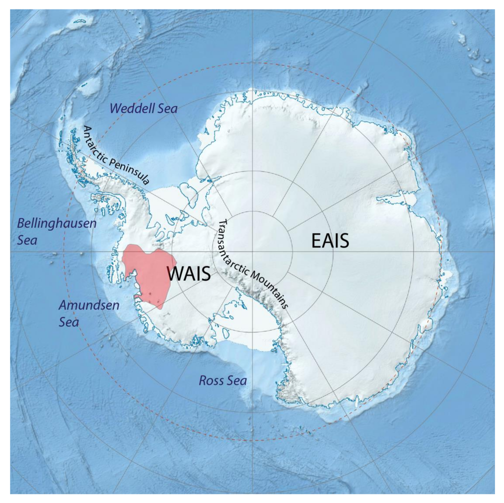
D.F. Martin[1], E.G. Ng[1], X. S. Asay-Davis[2], C. Jackson[3], M.S. Waibel[4], S.F. Price[5], S.L. Cornford[6]

1. Lawrence Berkeley National Laboratory, **2**. PIK, Potsdam, Germany, **3**. University of Texas, **4**. Portland State University, **5**. Los Alamos National Laboratory, **6**. University of Bristol, Bristol, UK

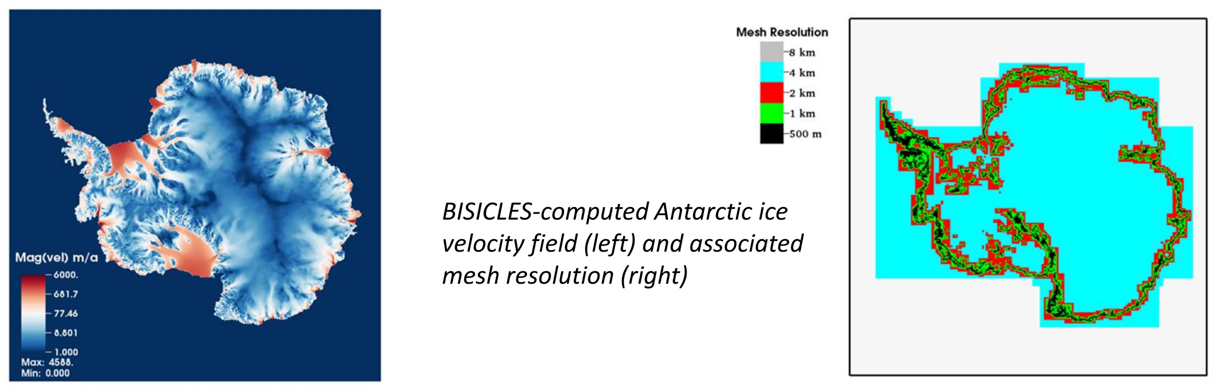
Motivation

In its AR5 report, the IPCC points to potentially large Antarctic contributions to sea level rise (SLR) resulting from the marine ice sheet instability, in which marine ice sheets like those found in the West Antarctic Ice Sheet (WAIS) experience large-scale retreat and mass loss. Indeed, the paleorecord implies that WAIS has deglaciated in the past.

One likely climate driver for this instability is submarine melting of floating ice shelves 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. Using the BISICLES dynamical core, PISCEES has begun to perform a set of realistic studies designed to understand this interaction.

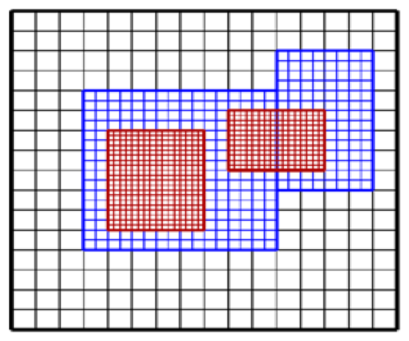


BISICLES



BISICLES-computed Antarctic ice velocity field (left) and associated mesh resolution (right)

- 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.
  - Dynamic regridding follows 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 and FASTMath-supported Chombo AMR C++/Fortran framework, which supports scalable block-structured AMR applications.
- Dynamic regridding allows high-resolution mesh to follow rapidly-moving grounding lines and evolving flow features.
- BISICLES uses a modified version of the Schoof-Hindmarsh (2010) momentum-balance approximation ("SSA*").

Ice-Ocean Coupling

Coupling to POP2x through CISM

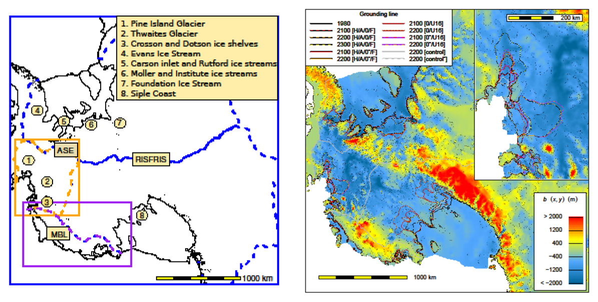
Understanding the interaction between marine ice sheets and the ocean, requires fully-coupled ice-ocean models. To that end, the POPSICLES model couples the BISICLES ice sheet model with the POP2X ocean model. POP2X is a version of the CESM ocean model (POP2) modified to resolve circulation in subshelf cavities.

BISICLES is coupled to the Community Ice Sheet Model (CISM) as an external dynamical core, callable from CISM, which is coupled to CESM and to POP2X.

- Synchronous-offline coupling: BISICLES and POP exchange information at fixed (monthly) 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.

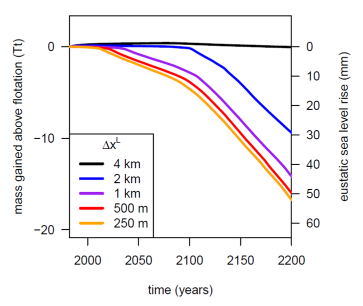
Century-Scale WAIS Simulations

- Cornford, Martin, et al., to appear in *The Cryosphere.*
- Systematic high-resolution study of 1, 2, and 3-century WAIS response to a range of climate forcings using the BISICLES model -- most comprehensive study to date, and the first to fully-resolve grounding-line dynamics.



(Left) WAIS model domains and systems of interest. (right) WAIS bed topography and model-computed grounding line positions.

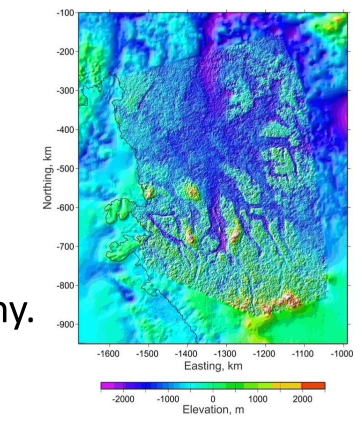
- Global climate model (GCM) output fed to regional atmospheric and ocean models, which in turn generated submarine melting and precipitation forcing patterns used to force the ice sheet.
- **Key findings**:
  - Running with a range of spatial resolutions demonstrated the need for high-resolution models (500m resolution in the Amundsen Sea region, sub-km resolution elsewhere).
  - WAIS mass loss continues to be dominated by the effects of subshelf melting & resulting grounding-line retreat, which will outpace effects of changes in accumulation (snowfall).
  - Mass loss from the Amundsen Sea region will continue to be the dominant effect until the 22nd century, when warm-water incursion will drive mass loss in the Ronne-Filchner region.
  - Most extreme example -- WAIS retreat resulting in 20cm SLR by 2100, 50cm by 2200.



Amundsen Sea sector mass loss vs. finest spatial resolution. Under-resolution substantially underestimates mass loss. 500m spatial resolution needed to resolve dynamics.

Bed Topography UQ

Subglacial topography can have a controlling effect on ice sheet dynamics, but is difficult to observe. While some regions have been mapped to very high resolutions, many dynamically important regions will remain under-constrained for the foreseeable future, with large uncertainties remaining in the bed topography.



Thwaites bed – high-resolution (250 m) inner bed grafted onto 1km-resolution Bedmap2 bed.

- UT collaborators produced variants of the widely-used Bedmap2 Antarctic topography dataset which are statistically consistent with high-resolution measurements of Thwaites Glacier and which can be used to explore effects of bed uncertainty on ice-sheet dynamics.
- Currently exploring minimum forcing which causes ice sheet instability.

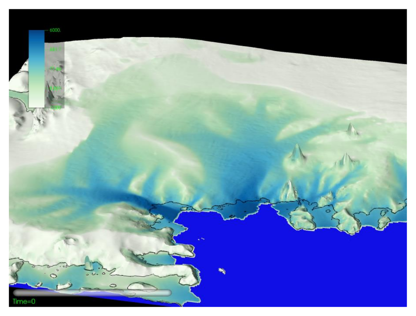
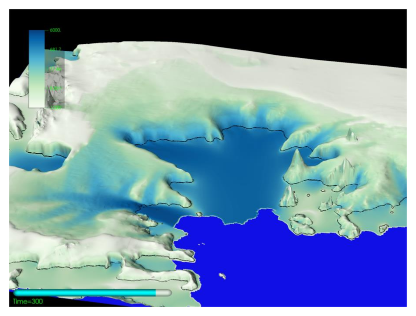
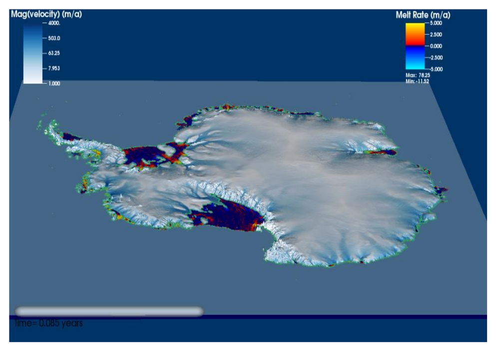


Illustration of BISICLES simulation of Thwaites Glacier retreat, (left) present-day, and (right) after 300 years.

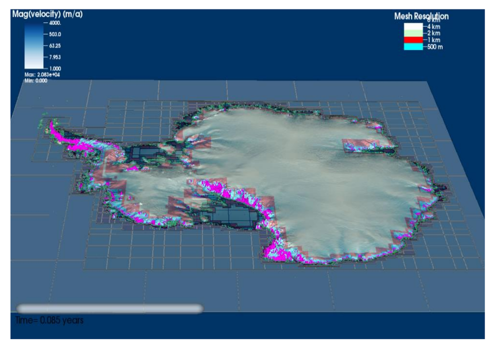


POPSICLES Coupled Antarctica-Southern Ocean Simulations

BISICLES Ice sheet Setup



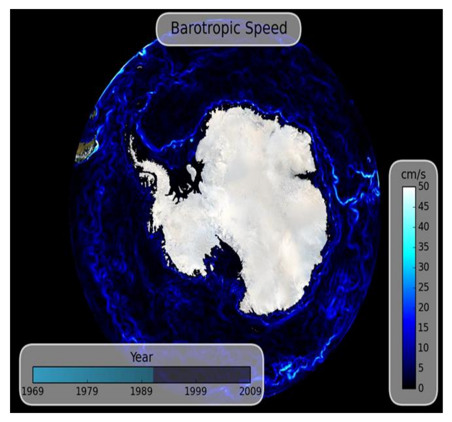
Movie frames showing Ice sheet initial condition: Initial basal velocity field with melt rates painted onto ice shelves (left), initial AMR meshes (right).



- Full-continent Bedmap2 (2013) geometry.
- Initialize to match Rignot (2011) velocity field.
- 500m finest spatial resolution ensures fully-resolved GL dynamics.
- To isolate effects of ocean interaction, initialize synthetic accumulation field for equilibrium with melt rates computed in a standalone spinup run.

POP 2x Ocean Model Setup

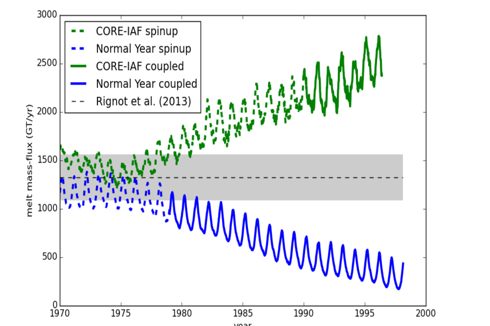
- Regional southern ocean domain (50-85°S)
- 0.1° (~5 km) horizontal resolution.; 80 vertical levels (10m-250m).
- Monthly restoring to World Ocean Atlas (WOA) data at northern boundaries.
- 2 climatologies explored, from Common Ocean-ice Reference Experiments:
  - Monthly mean climatological ("normal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



POP-computed barotropic ocean speed on Southern Ocean domain

What we've learned (so far)

- Difficult to put AIS into steady-state (tendency for grounding lines to advance without strong localized melting).
- Artificial Bedmap2 subshelf bathymetry (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).
- Complex coupled ice-ocean system harder to control.
- **Despite these, coupled results indicate importance and effectiveness of coupling.**
- Computational cost on Edison – 15,000 CPU-hrs/simulation year.



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.