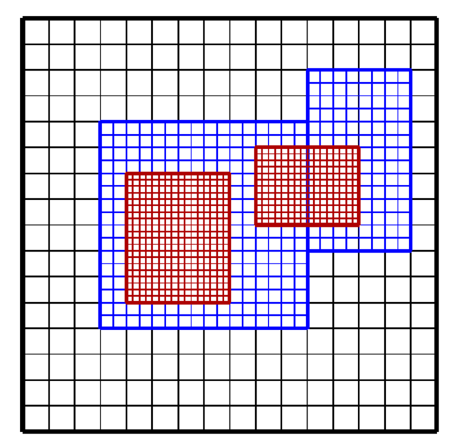
Resolving Grounding Line Dynamics with the BISICLES Adaptive Ice Sheet Model

D.F. Martin (DFMartin@lbl.gov)[1], S.L. Cornford[2], P.O. Schwartz[1], A.M. Le Brocq[3], A.J. Payne[2], W.L. Lipscomb[4], E.G. Ng[1]

1. Lawrence Berkeley National Laboratory, Berkeley, CA, USA **2**. University of Bristol, Bristol, UK **3**. University of Exeter, Exeter, UK **4**. Los Alamos National Laboratory, Los Alamos, NM, USA

Numerical Model

- 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.

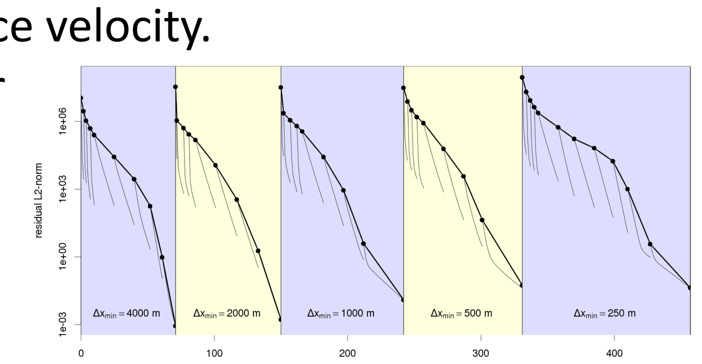


Sample AMR meshes – black mesh is base level (0), blue mesh (level 1) is a factor of 2 finer, while red (level 2) is 4 times finer still

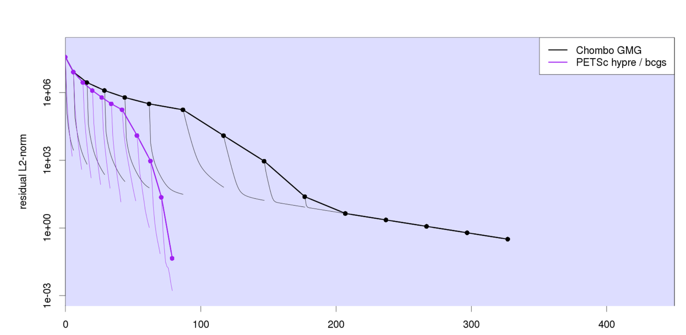
- BISICLES is built upon the LBNL-developed Chombo AMR C++/Fortran framework, which supports scalable block-structured AMR applications.
- BISICLES uses modified version of the Schoof-Hindmarsh (2010) model -- "SSA*"
  - Following Schoof and Hindmarsh, using SIA-like relation to compute stress allows 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*).

Ice Velocity Solvers

- Even with reduction to 2D, momentum balance equation results in a coupled nonlinear elliptic system to be solved for the ice velocity.
- Current approach: JFNK outer nonlinear solver with Chombo native geometric Multigrid (GMG) inner linear solver.
- Upper plot at right: initializing an Amundsen Sea Embayment (ASE) computation
  - Thick line: outer nonlinear solver residual
  - Thin lines: inner linear solver residual
  - First plot: initial uniform 4 km mesh solve.
  - Second plot: add refinement level (2 km) where needed and re-solve for velocity
  - Third plot: add second refinement level (1 km), etc
- Lower plot at right: solver convergence for uniform-mesh 5 km full-continent Antarctica.
  - Chombo GMG can stall for some realistic problems, especially as resolution increases. (black lines at right).
  - PETSc Algebraic Multigrid (AMG) performs much better (purple lines at right).



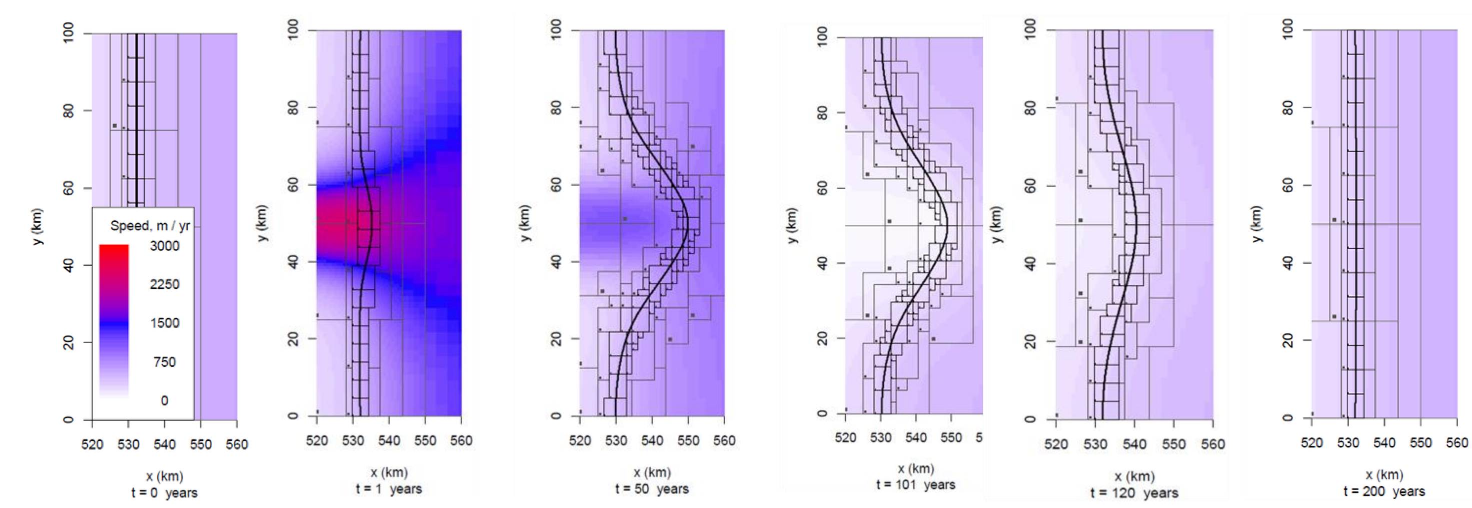
Norm(residual) vs. solver iteration for ASE velocity and AMR mesh initialization.



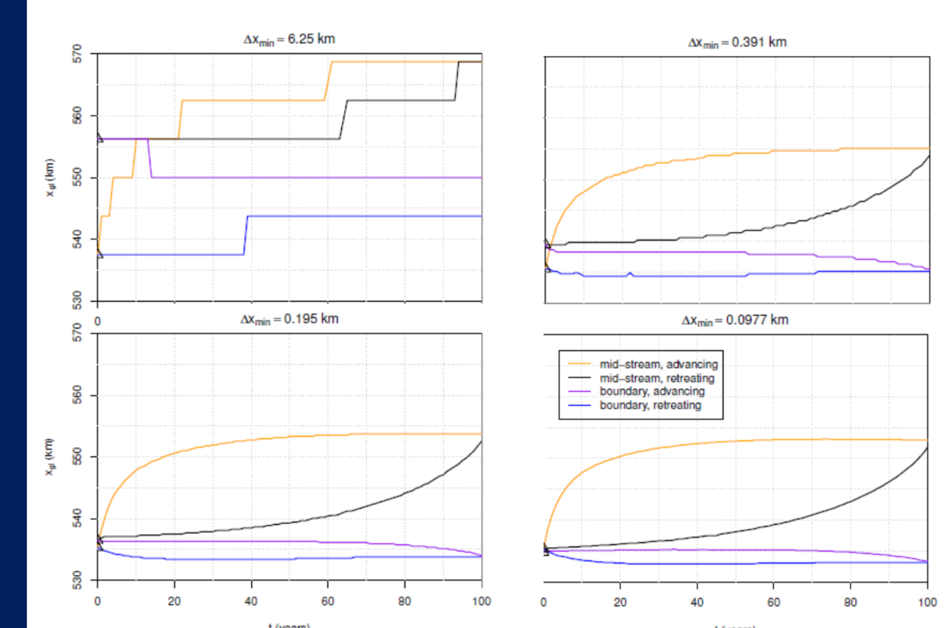
Norm(residual) vs. solver iteration for 5 km Antarctica test case. Black – Chombo GMG, purple – PETSc GAMG.

Model Validation

MISMIP3D – AMR Grounding line Resolution Requirements



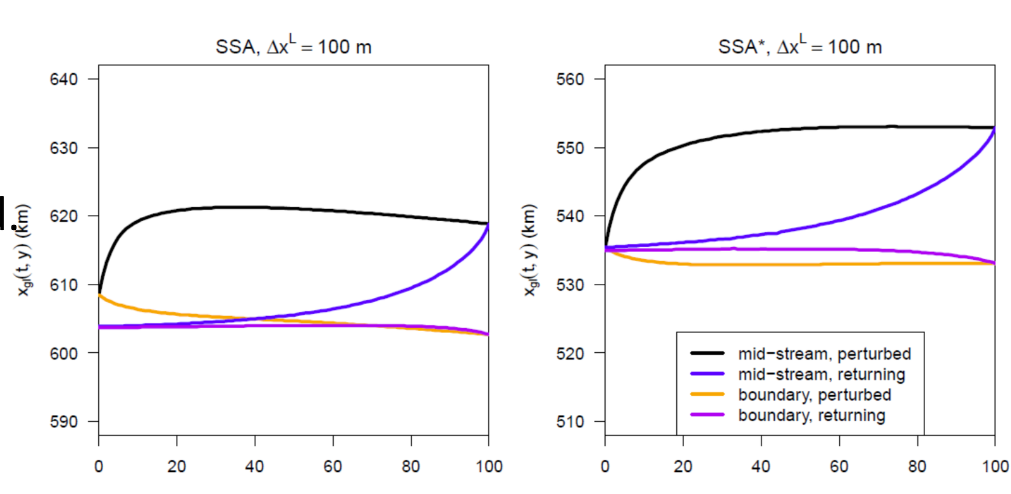
Plots of MISMIP3D solution using AMR – coarsest mesh is 6.5 km, with 5 levels of refinement resulting in 195 m resolution on the finest level. Boxes show refined regions. Coloring depicts velocity solution, solid black line denotes grounding line position. Note reversibility from start->finish..



- Plot at left shows grounding-line position for centerline and edge boundary for increasing finest spatial resolution.
- **Need very fine (200 m) resolution to get full reversibility.**

MISMIP3D – SSA* vs. SSA and Full-Stokes

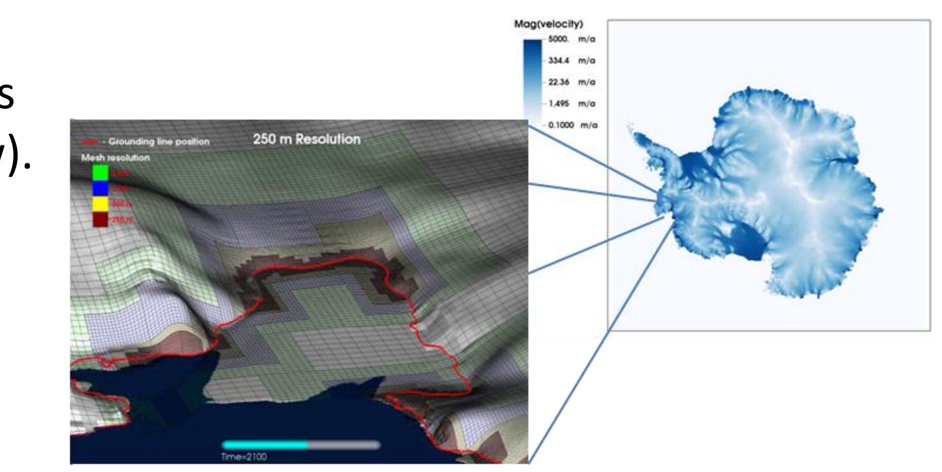
- Plots at right shows MISMIP3D results for SSA and our SSA*.
- 100 m resolution – fully resolved
- Note initial (steady state) GL positions – difference of 75 km!
- Elmer Full-Stokes results agree with SSA*.



Conclusion – need better than SSA for grounding lines, but SSA* seems sufficient (at least in this case).

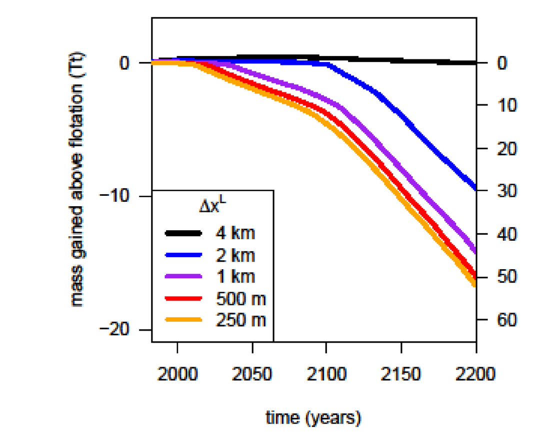
Model Application

- Application to Ice2Sea experiments (Stephen Cornford's talk tomorrow).
- 200-year simulations of RIS/FRIS, Amundsen Sea Embayment (ASE)
- Plot at right shows contribution to SLR for different resolutions



Inset showing typical AMR meshes around Pine Island Glacier

- Need 1 km resolution to get "converged" result.
- Finer than 1 km, appears to be converging at O(mesh spacing) – implies that we're in the asymptotic regime....

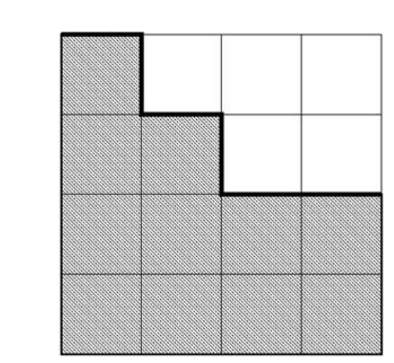


Contribution to SLR vs. time for varying resolutions.

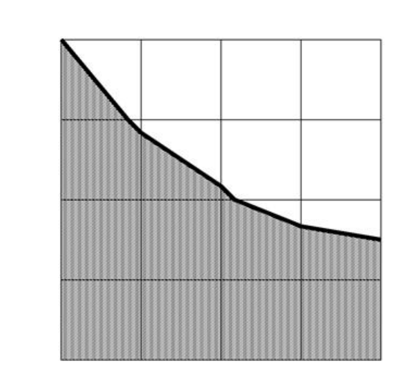
Ongoing Improvements

Embedded Boundary (EBChombo)

- Currently force GL and ice margins to cell faces
  - "Stair-step" discretization
  - **Known to be inadequate from experience with Stefan Problem in other contexts**



- Use Chombo Embedded-boundary support to improve discretization of GL's and ice margins:
  - Use cut-cell approach to discretize around GLs and ice margins.



- Can solve as a Stefan Problem, with appropriate jump conditions enforced at grounding line (as in Schoof, 2007)