

***Berkeley-ISICLES (BISICLES):
High Performance
Adaptive Algorithms
For Ice Sheet Modeling***

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January 12, 2011

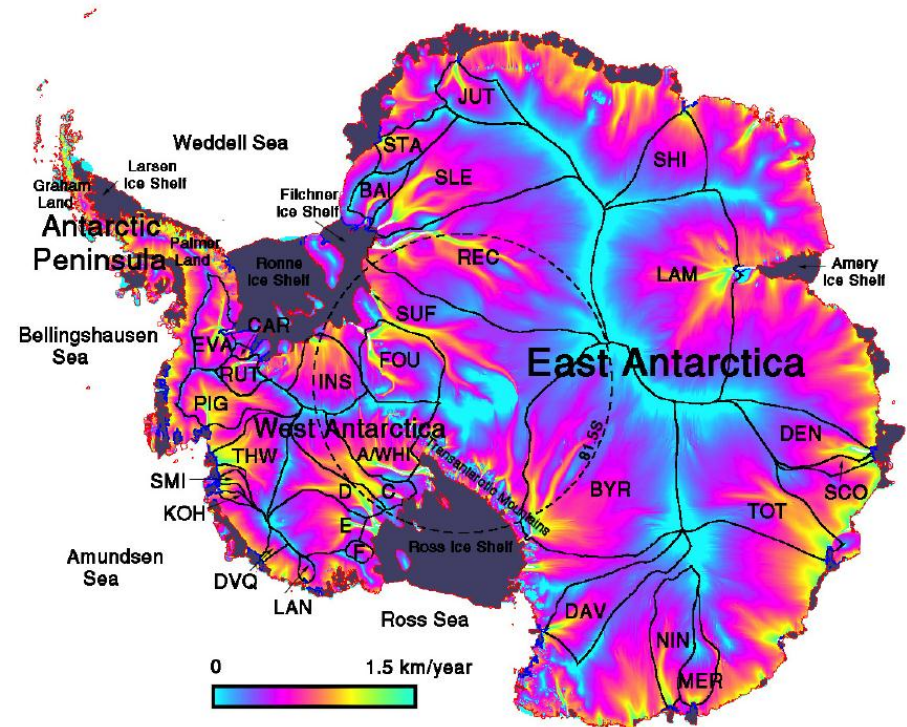
BISICLES - Goal

Goal: Build a parallel, adaptive ice-sheet model

- Localized regions where high resolution needed to accurately resolve ice-sheet dynamics (500 m or better at grounding lines)
- Large regions where such high resolution is unnecessary (e.g. East Antarctica)
- Problem is well-suited for adaptive mesh refinement (AMR)
- Want good parallel efficiency
- Need good solver performance

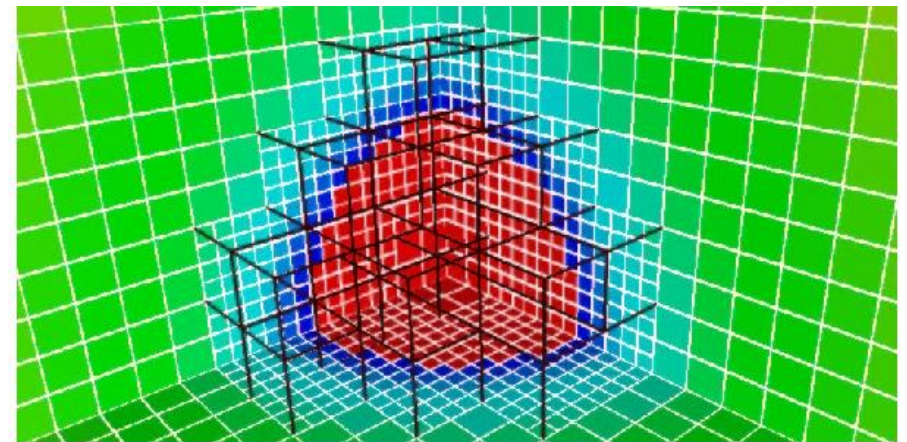
Much higher resolution (1 km versus 5 km) required in regions of high velocity (yellow → green).

[Rignot & Thomas, 2002]



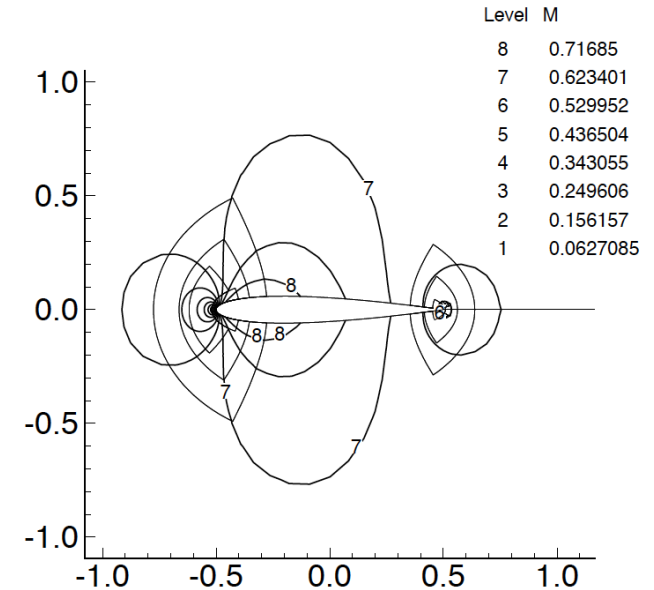
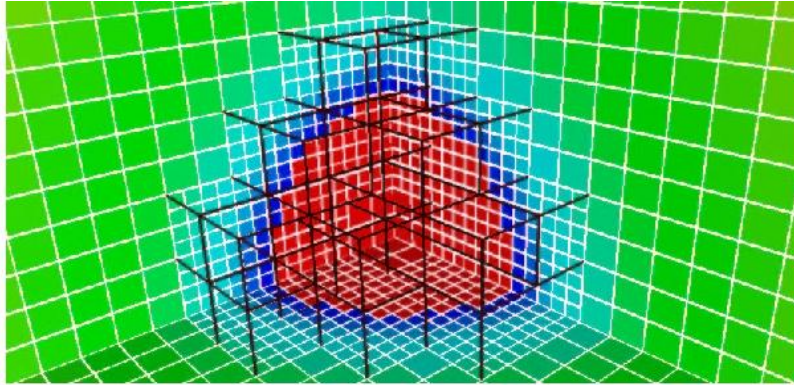
BISICLES - Approaches

- Develop an efficient parallel implementation of Glimmer-CISM by
 - Incorporating structured-grid AMR using the Chombo framework to increase resolution in regions where changes are more rapid,
 - Exploring new discretizations and formulations where appropriate (L1L2)
 - Improving performance and convergence of linear and nonlinear solvers, and
 - Deploying auto-tuning techniques to improve performance of key computational kernels.

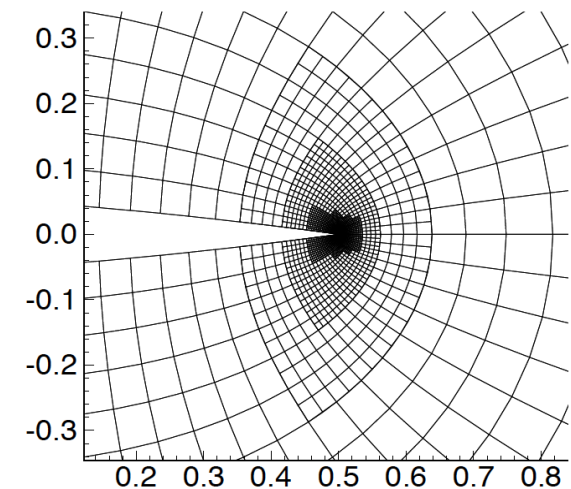


Block-Structured Local Refinement

- Refined regions are organized into rectangular patches.



- Refinement in time as well as in space for time-dependent problems.
- *Algorithmic advantages:*
 - *Build on mature structured-grid discretization methods.*
 - *Low overhead due to irregular data structures, relative to single structured-grid algorithm.*



BISICLES Project Outline

- ❑ Joint work involving LBNL and LANL
 - LBNL: Esmond Ng (PI), Dan Martin (AMR), Woo-Sun Yang (Performance Optimization), Sam Williams (Autotuning)
 - LANL: Bill Lipscomb (co-PI), Doug Ranken (software support)
- ❑ Collaboration with Tony Payne (one of the original authors of Glimmer) and Stephen Cornford (Univ of Bristol, UK)

- ❑ Build AMR implementation of Glimmer-CISM
- ❑ Extensions to existing Chombo infrastructure added as needed
- ❑ Autotuning techniques deployed as components are developed
- ❑ Linear/nonlinear solver improvements

- ❑ Coupling with CESM using existing Glimmer-CISM interface and by developing new interfaces as needed



Models and Approximations

□ Full-Stokes

- Best fidelity to ice sheet dynamics
- Computationally expensive (full 3D coupled nonlinear elliptic equations)

□ Approximate Stokes

- Use scaling arguments to produce simpler set of equations
- Common expansion is in ratio of vertical to horizontal length scales ($\varepsilon = \frac{[h]}{[l]}$)
- E.g. Blatter-Pattyn (most common “higher-order” model), accurate to $O(\varepsilon^2)$
- Still 3D, but solve simplified elliptic system (e.g. 2 coupled equations)

□ Depth-integrated

- Special case of approximate Stokes with 2D equation set (“Shelfy-stream”)
- Easiest to work with computationally
- Generally less accurate



“L1L2” Model (Schoof and Hindmarsh, 2010)

- Asymptotic expansion in 2 flow parameters:
 - ε -- ratio of length scales $\frac{[h]}{[x]}$
 - λ - ratio of shear to normal stresses $\frac{[\tau_{shear}]}{[\tau_{normal}]}$
 - Large λ : shear-dominated flow
 - Small λ : sliding-dominated flow
- Blatter-Pattyn approximates full-Stokes to $O(\varepsilon^2)$ for all λ regimes
- Asymptotic expansion: (e.g. $u(x, z) = u_0 + \varepsilon u_1 + O(\varepsilon^2)$)
 - Leading order velocity term: $u_0 = u_0(x)$ (no vertical dependence)
 - Don't need shear stresses to $O(\varepsilon^2)$ to compute velocity to $O(\varepsilon^2)$
 - Provides basis for depth-integrated approach



“L1L2” Model (Schoof and Hindmarsh, 2010), cont.

- Use this result to construct a computationally efficient scheme:
 1. Approximate constitutive relation relating $grad(u)$ and stress field τ with one relating $grad(u|_{z=b})$, vertical shear stresses τ_{xz} and τ_{zx} given by the SIA / lubrication approximation and other components $\tau_{xx}(x, y, z)$, $\tau_{xy}(x, y, z)$, etc
 2. leads to an effective viscosity $\mu(x, y, z)$ which depends only on $grad(u|_{z=b})$ and $grad(z_s)$, ice thickness, etc
 3. Momentum equation can then be integrated vertically, giving a nonlinear, 2D, elliptic equation for $u|_{z=b}(x, y)$
 4. $u(x, y, z)$ can be reconstructed from $u|_{z=b}(x, y)$



“L1L2” Model (Schoof and Hindmarsh, 2010), cont.

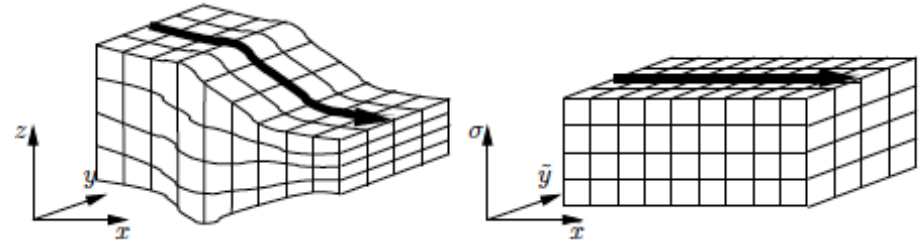
- ❑ Similar formal accuracy to Blatter-Pattyn $O(\varepsilon^2)$
 - Recovers proper fast- and slow-sliding limits:
 - SIA ($1 \ll \lambda \leq \varepsilon^{-1/n}$) -- accurate to $O(\varepsilon^2 \lambda^{n-2})$
 - SSA ($\varepsilon \leq \lambda \leq 1$) - accurate to $O(\varepsilon^2)$

- ❑ Computationally **much** less expensive -- enables fully 2D vertically integrated discretizations.



Discretizations

- ❑ Baseline model is the one used in Glimmer-CISM:
 - Logically-rectangular grid, obtained from a time-dependent uniform mapping.
 - 2D equation for ice thickness, coupled with 2D steady elliptic equation for the horizontal velocity components. The vertical velocity is obtained from the assumption of incompressibility.
 - Advection-diffusion equation for temperature.



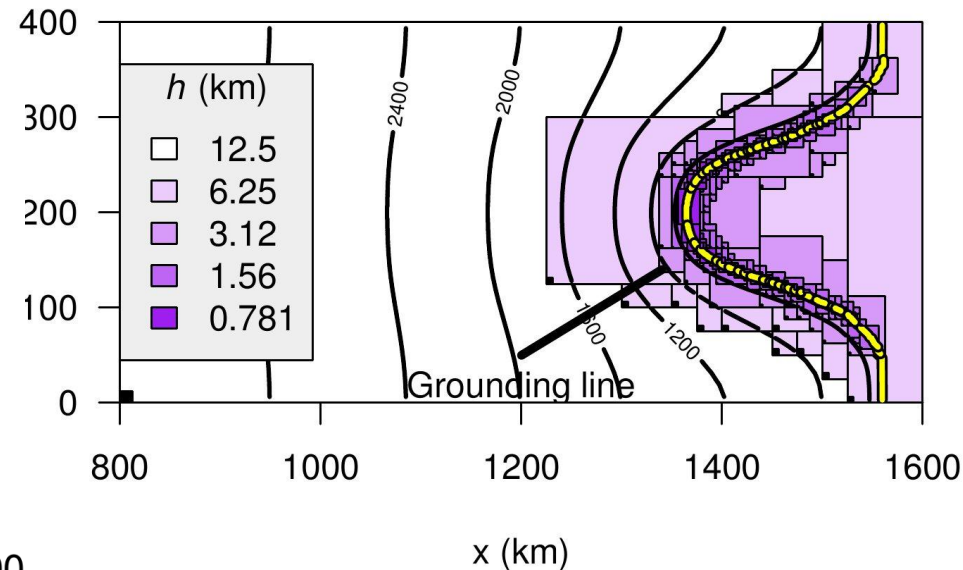
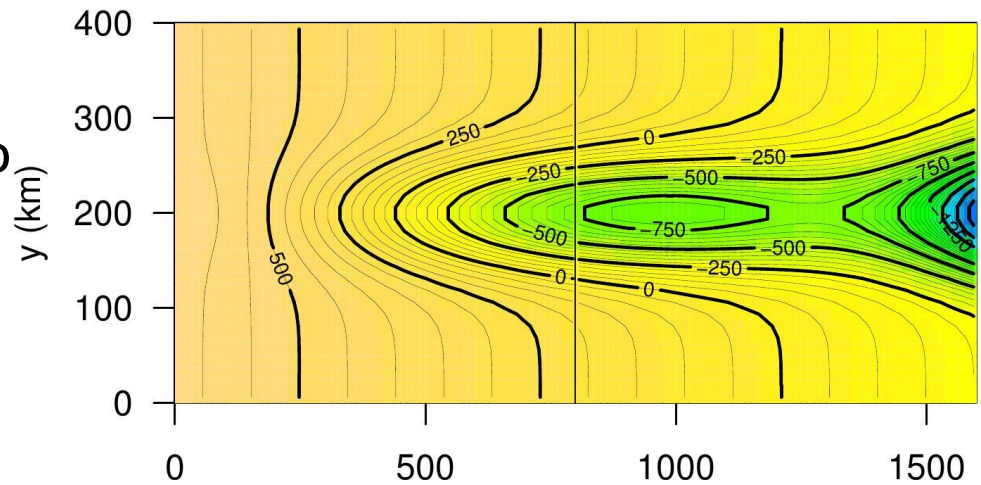
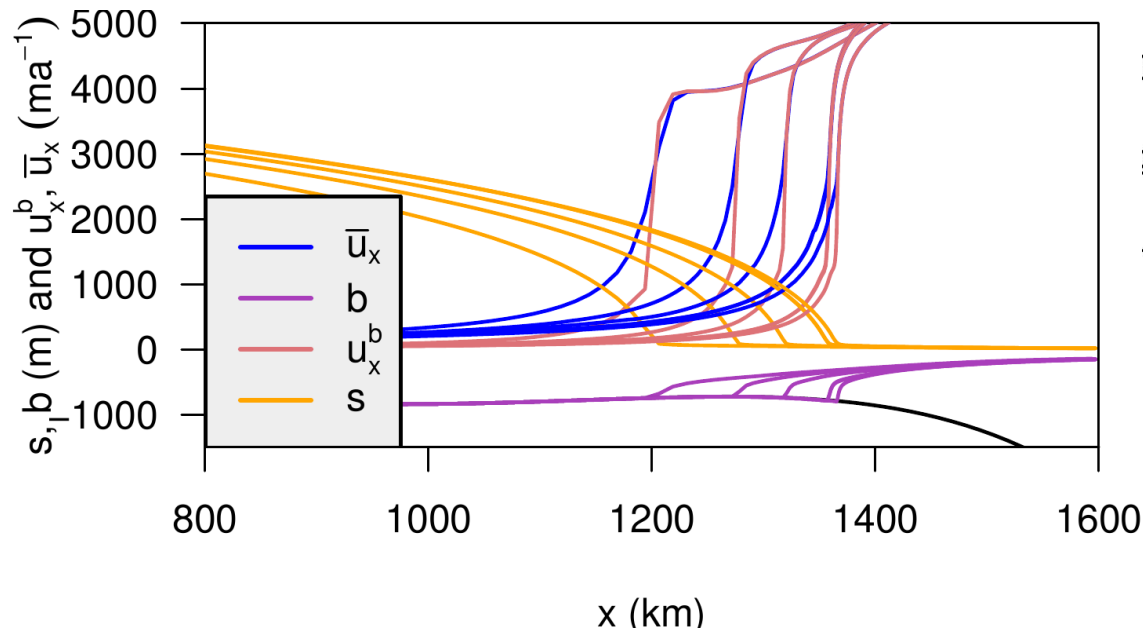
$$\frac{\partial H}{\partial t} = b - \nabla \cdot H\bar{\mathbf{u}}$$

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c} \nabla^2 T - \mathbf{u} \cdot \nabla T + \frac{\Phi}{\rho c} - w \frac{\partial T}{\partial z}$$

- ❑ Use of Finite-volume discretizations (vs. Finite-difference discretizations) simplifies implementation of local refinement.
- ❑ Software implementation based on constructing and extending existing solvers using the Chombo libraries.

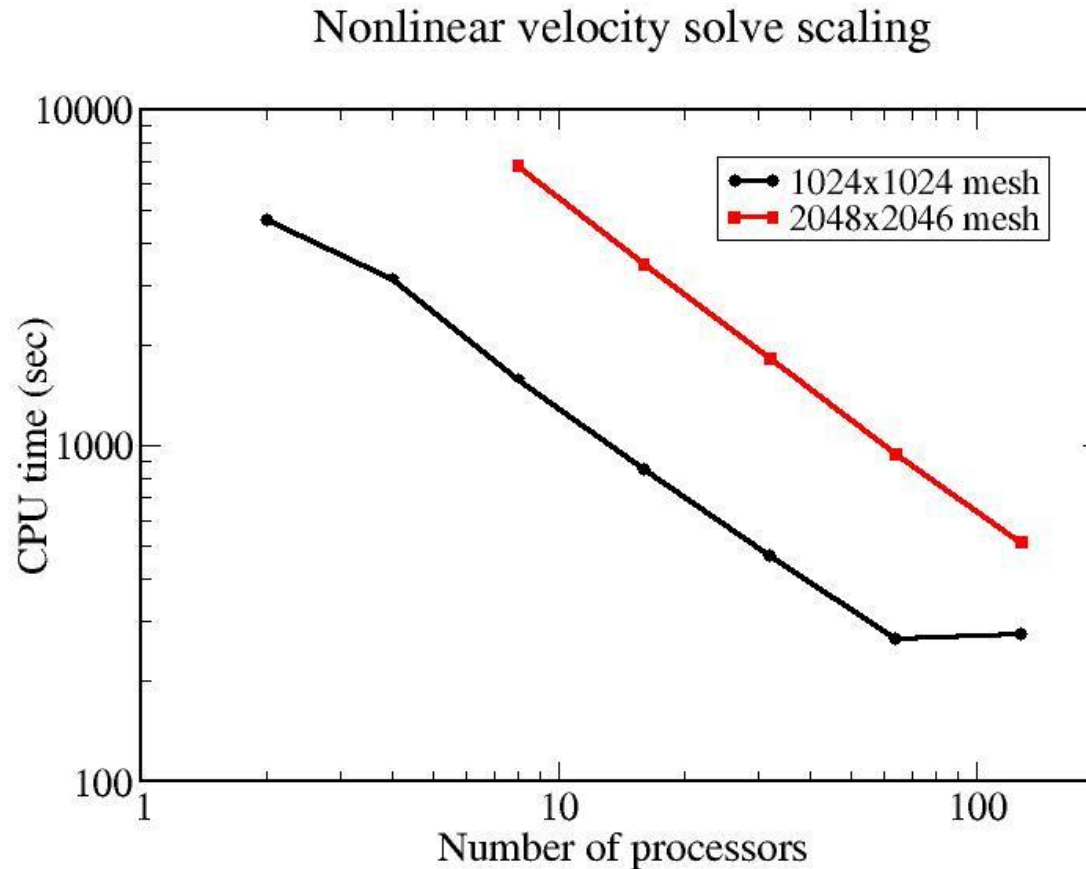
BISICLES results - Grounding line study

- ❑ Bedrock topography based on Katz and Worster (2010)
- ❑ Evolve initially uniform-thickness ice to steady state
- ❑ Repeatedly add refinement and evolve to steady state
- ❑ G.L. advances with finer resolution
- ❑ Appear to need better than 1 km



BISICLES -- Scaling

Initial tests show good strong scaling to at least 128 processors for nonlinear velocity solve (L1L2 approximation):



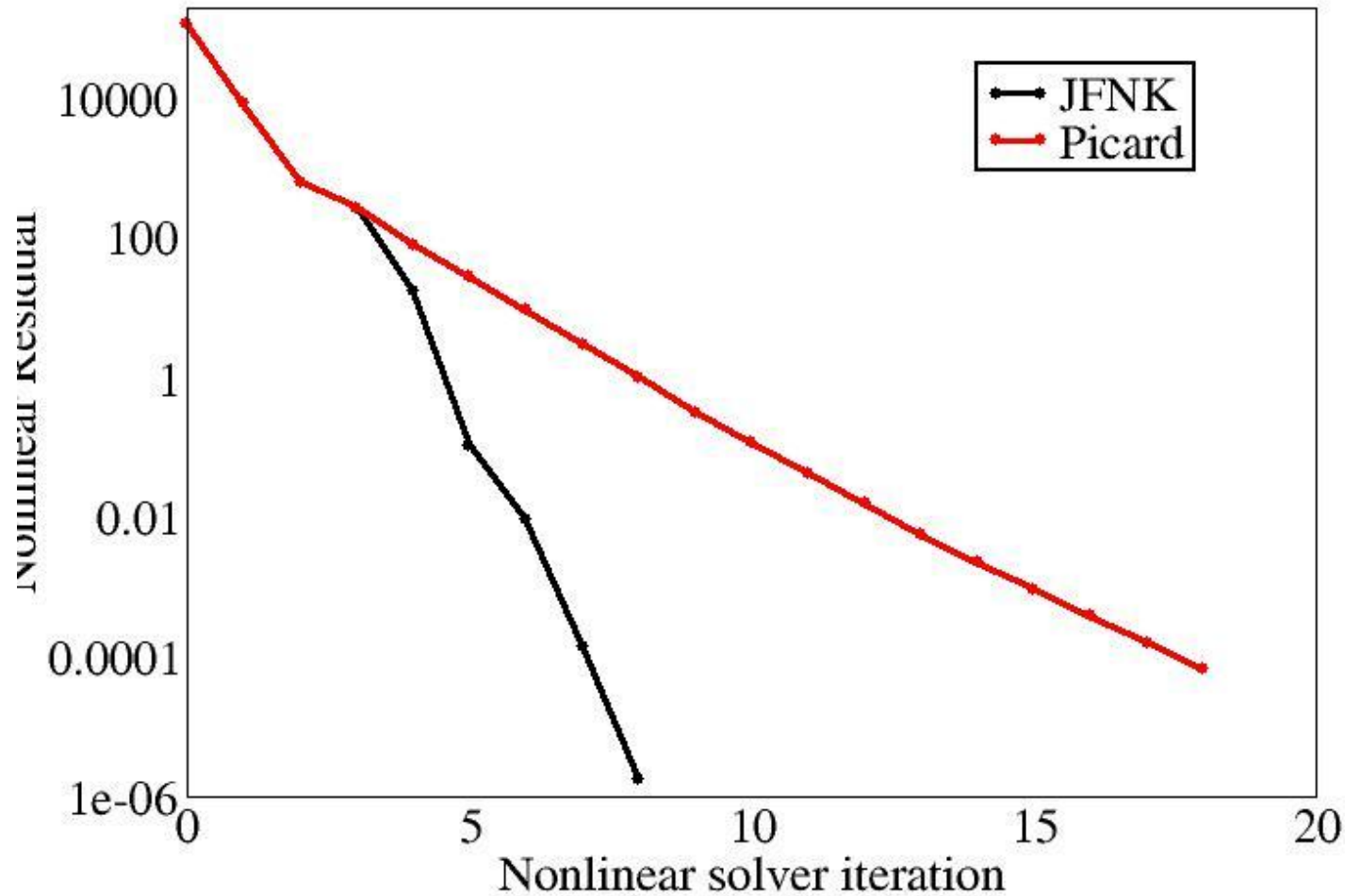
Nonlinear Solver Improvements

- ❑ Most computational effort spent in nonlinear ice velocity solve.
- ❑ Picard iteration:
 - Robust
 - Simple to implement
 - Slow (but steady) convergence
- ❑ Jacobian-free Newton-Krylov (JFNK):
 - More complex to implement
 - Works best with decent initial guess
 - Rapid convergence
 - Well-suited for Chombo AMR elliptic solvers
- ❑ Approach - use Picard iteration initially, then switch to JFNK when convergence slows



Nonlinear Solver Improvements (cont)

Nonlinear Solver Convergence



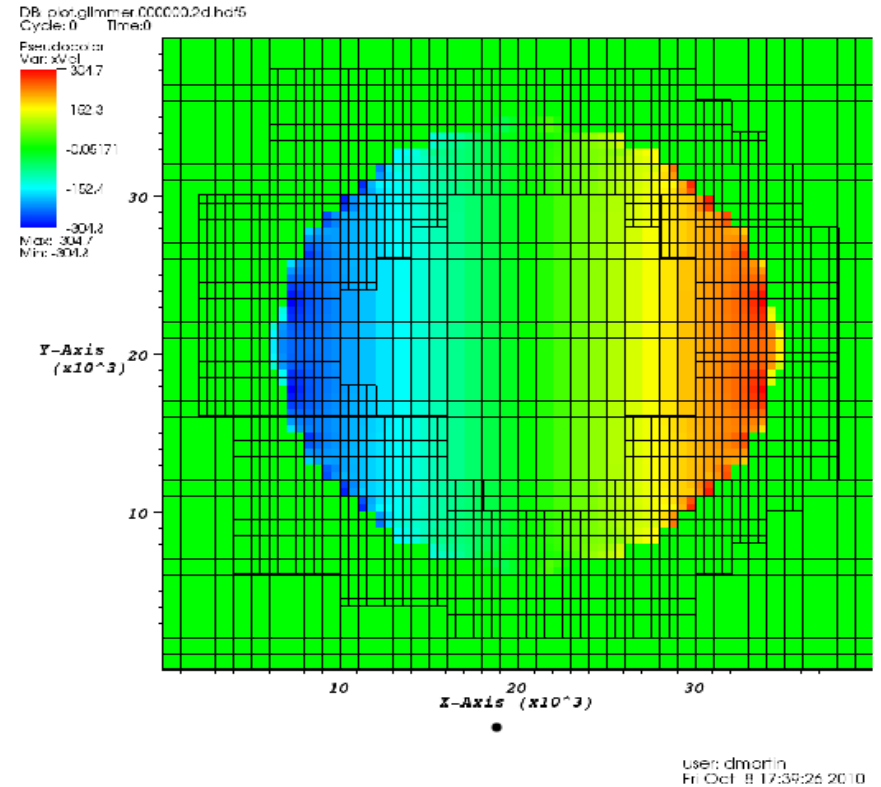
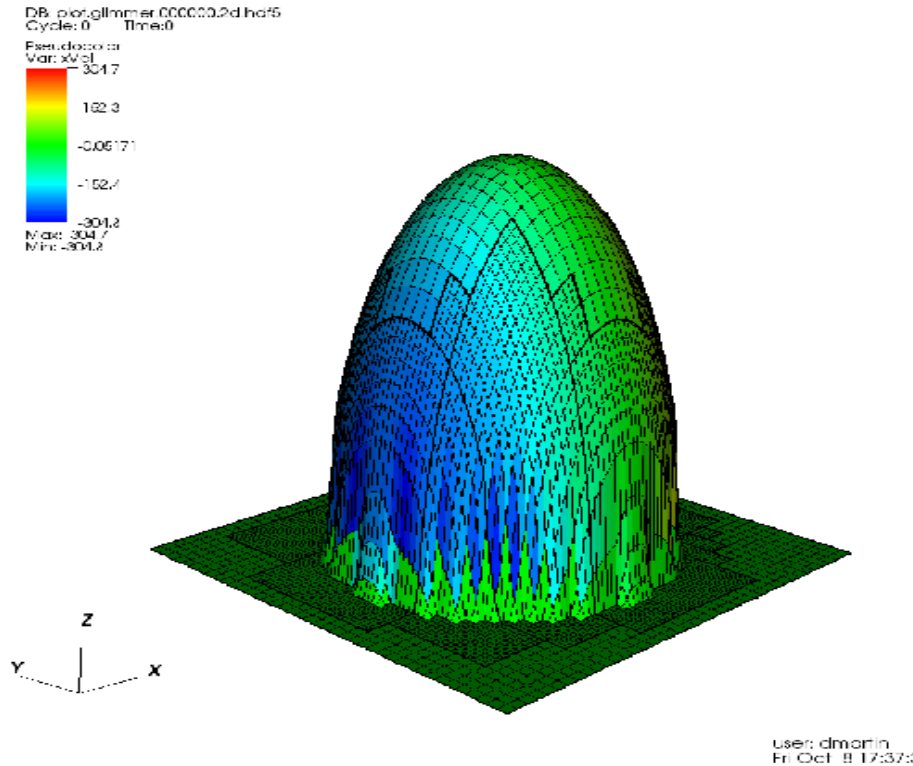
Interface with Glimmer-CISM

- ❑ Glimmer-CISM has coupler to CESM, additional physics
 - Well-documented and widely accepted
- ❑ Our approach - couple to Glimmer-CISM code as an alternate “dynamical core”
 - Allows leveraging existing capabilities
 - Use the same coupler to CESM
 - BISICLES code sets up within Glimmer-CISM and maintains its own storage, etc.
 - Communicates through defined interface layer
 - Instant access to a wide variety of test problems
 - Interface development almost complete
 - Part of larger alternative “dycore” discussion for Glimmer-CISM



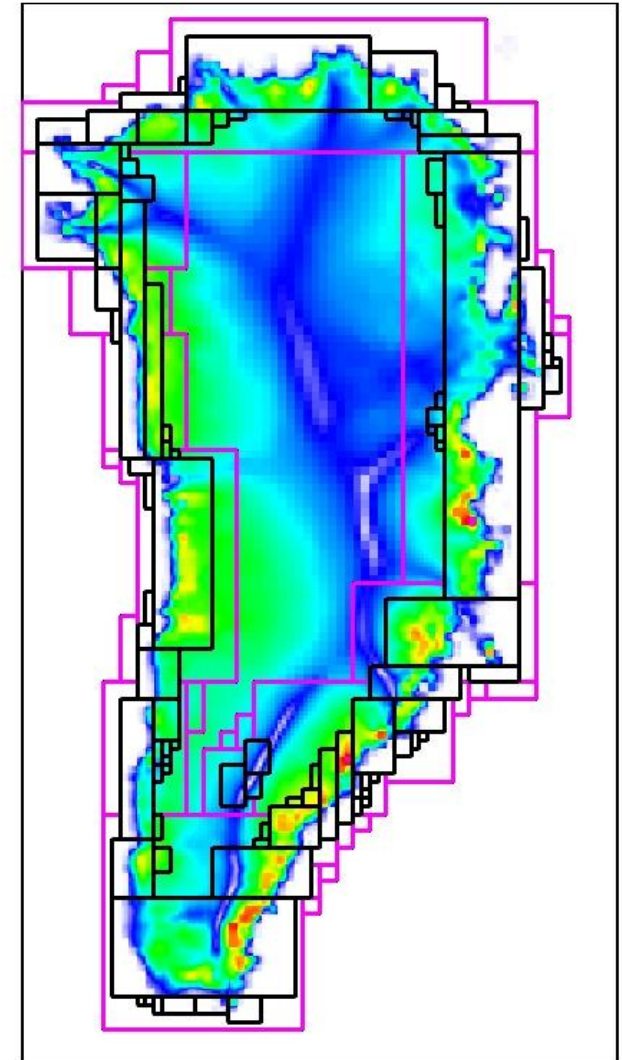
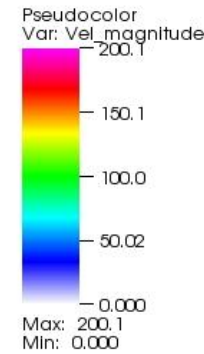
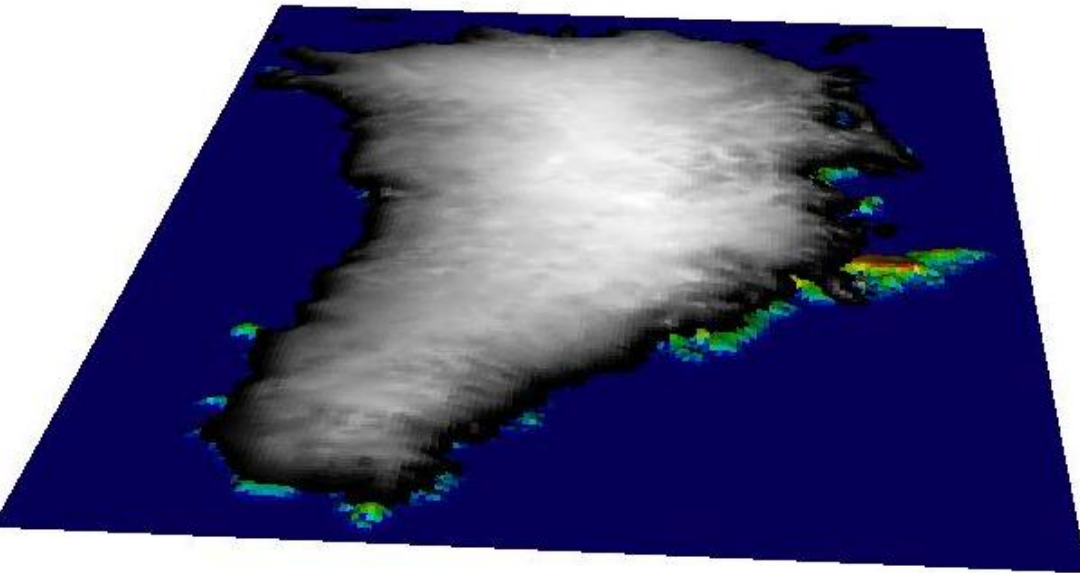
“Hump” test problem

- Standard test problem -- isolated “blob” of ice on level ground



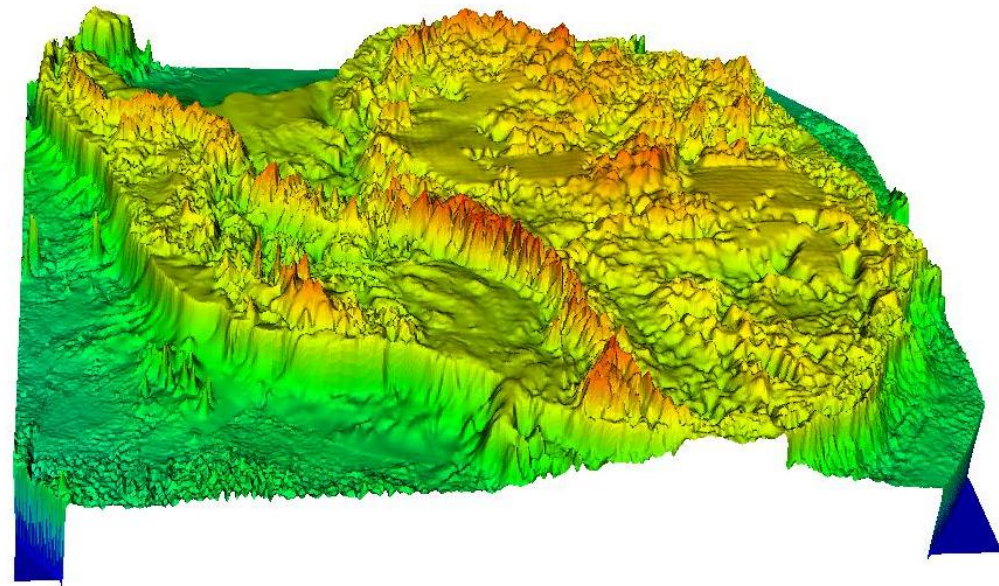
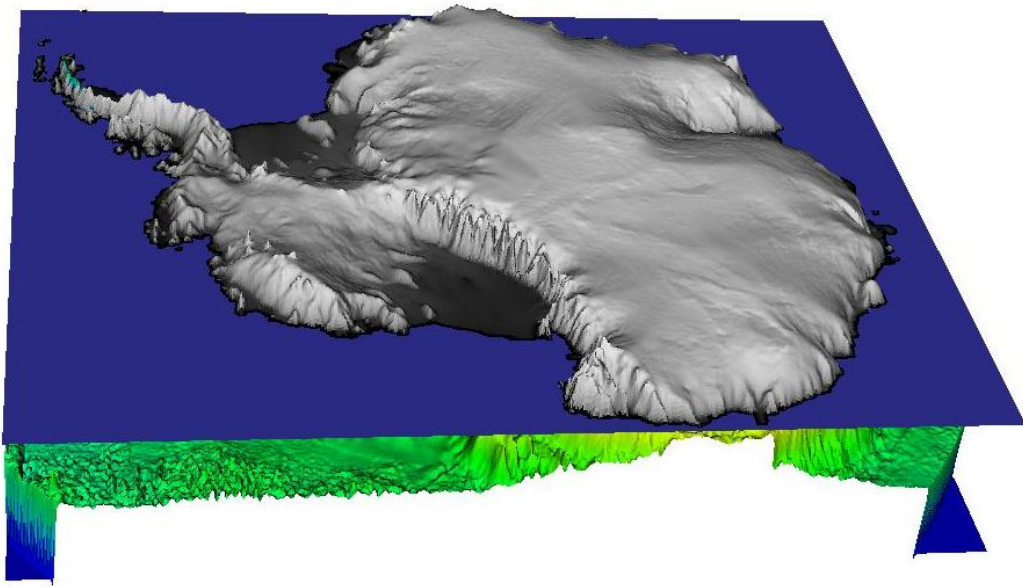
Greenland test problem

- ❑ Problem setup from Steve Price (LANL)
- ❑ Need to process initial condition somewhat in order for solver to converge (still work in progress)



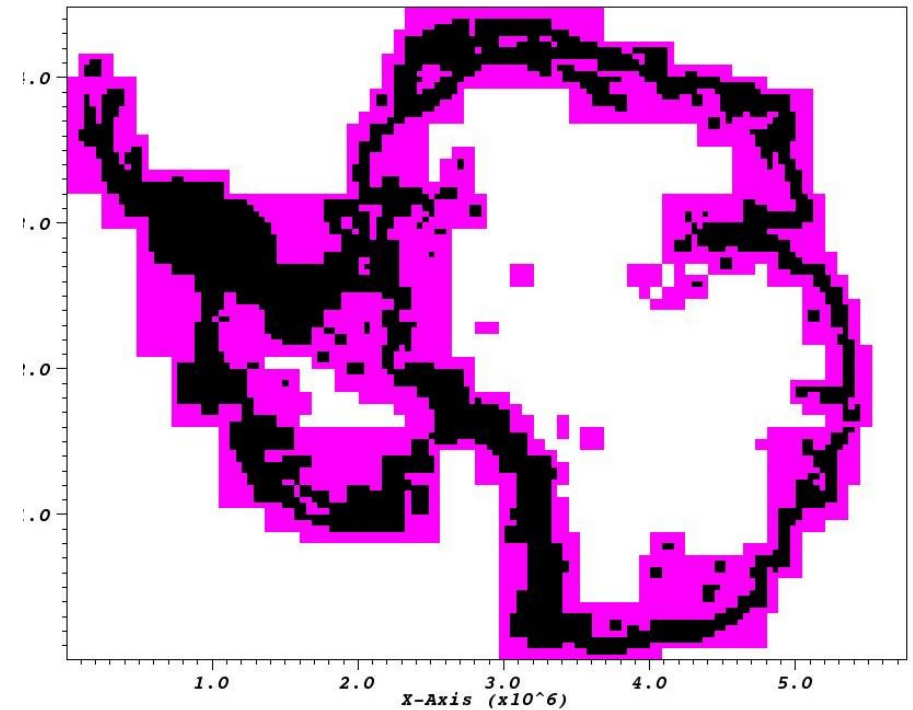
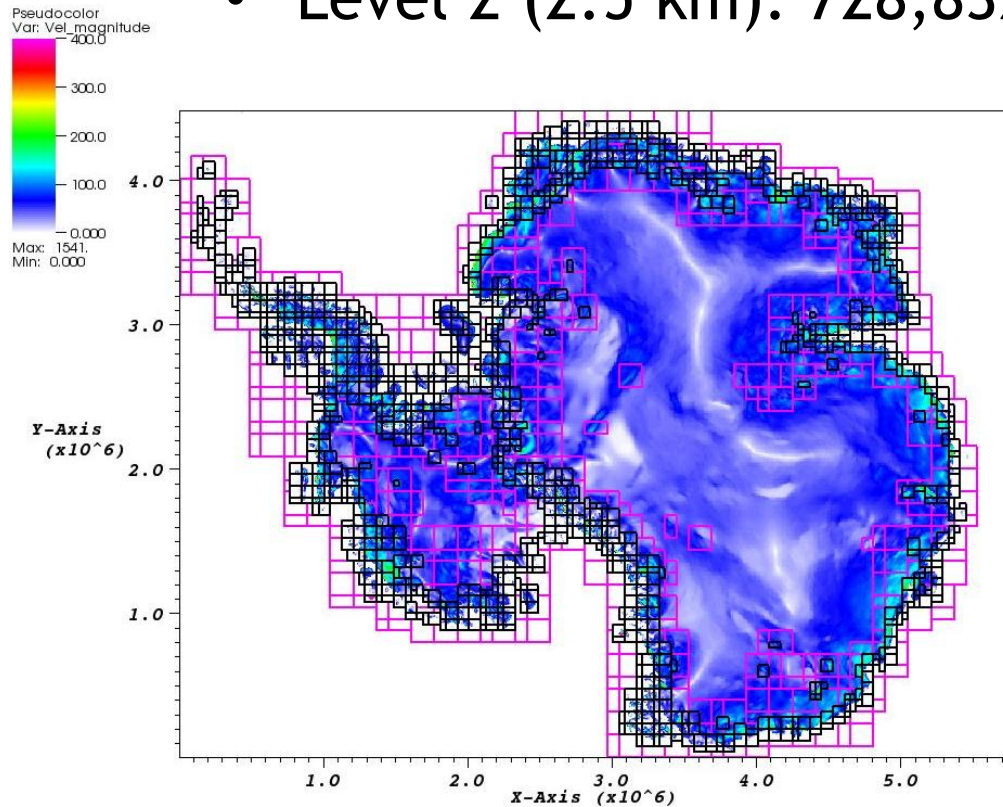
Antarctica

Uses new “model-friendly” problem setup
(Le Brocq, Payne, Vieli (2010))

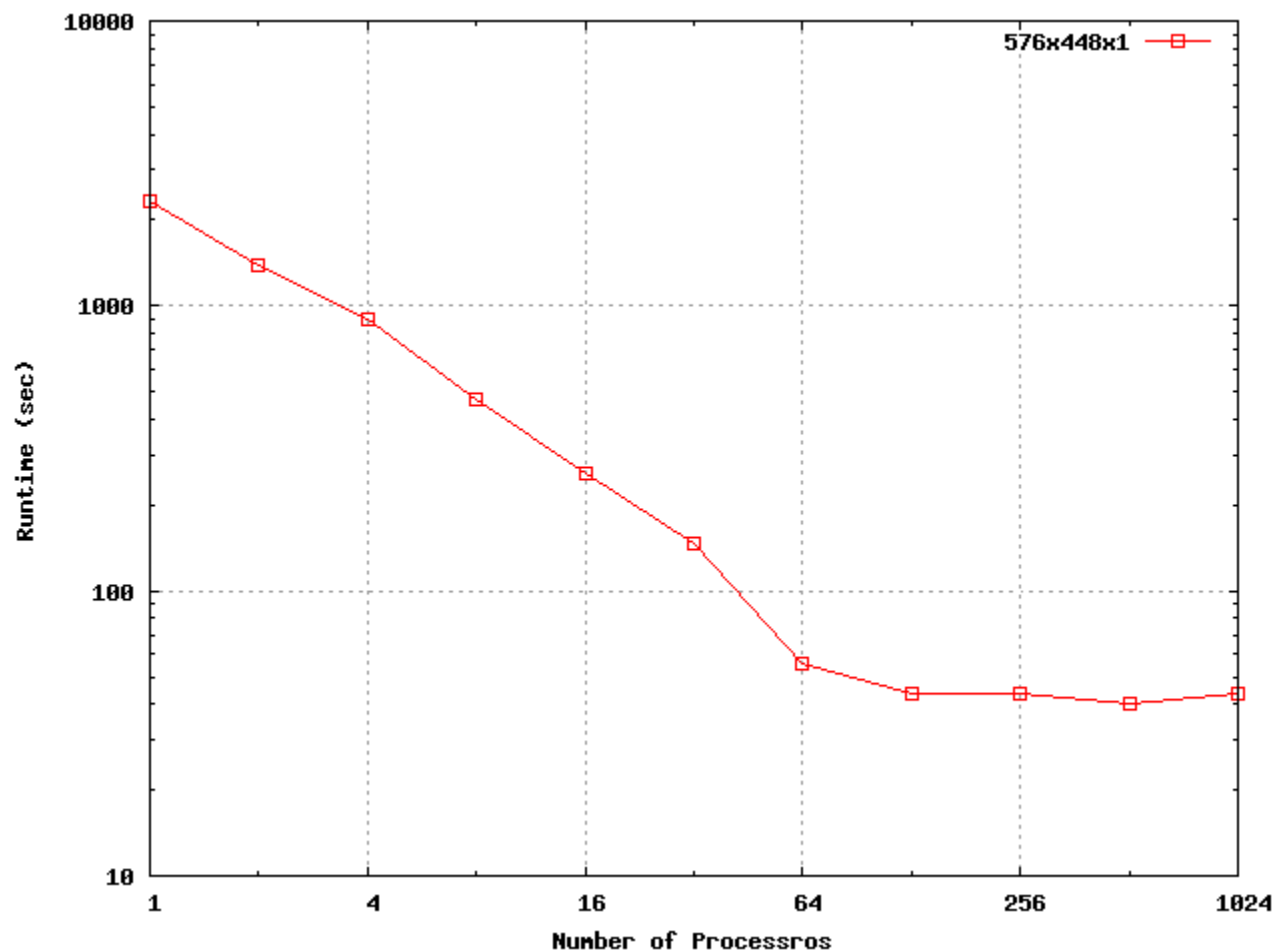


Antarctica, cont

- 10 km base mesh with 2 levels of refinement (5 km, 2.5 km)
 - base level (10 km): 258,048 cells (100% of domain)
 - level 1 (5 km): 431,360 zones (41.8% of domain)
 - Level 2 (2.5 km): 728,832 cells (17.7% of domain)



Parallel scaling, Antarctica benchmark



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BISICLES - Next steps

- ❑ More work with nonlinear velocity solve.
- ❑ Semi-implicit time-discretization for stability, accuracy.
- ❑ Non-isothermal capability
- ❑ Finish coupling with existing Glimmer-CISM code
- ❑ Performance optimization and autotuning.
- ❑ Begin work on full 3D velocity solve.
- ❑ Refinement in time?

