Resolving Grounding Line Dynamics using the BISICLES Adaptive Ice Sheet Model

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February 16, 2012

U.S. DEPARTMENT OF ENERGY | Office of Science

BISICLES

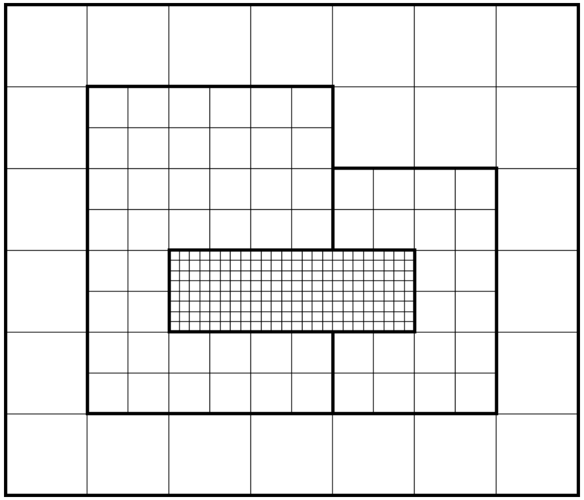
Berkeley Lab

Los Alamos NATIONAL LABORATORY EST. 1943

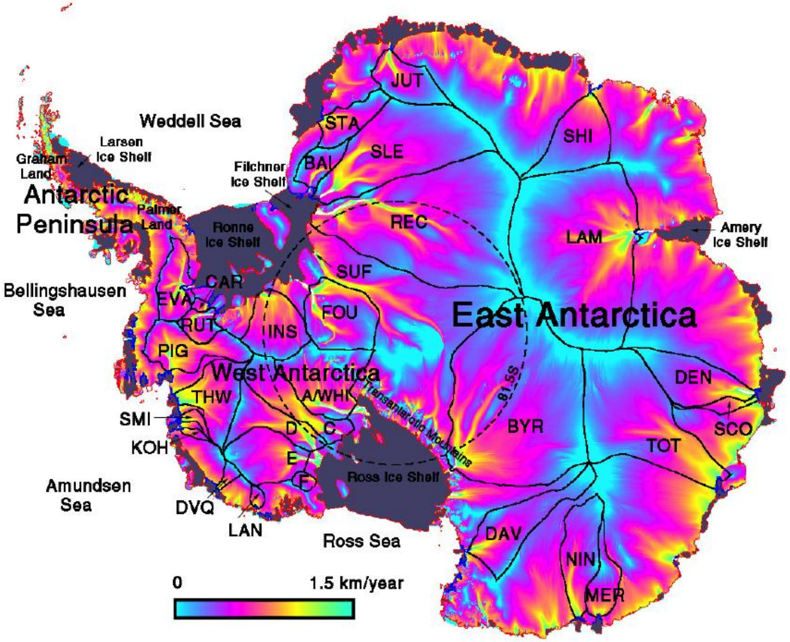
University of BRISTOL

Berkeley-ISICLES (BISICLES)

- DOE ISICLES-funded project to develop a scalable adaptive mesh refinement (AMR) ice sheet model/dycore
  - Local refinement of computational mesh to improve accuracy
- Use Chombo AMR framework to support block-structured AMR
  - Support for AMR discretizations
  - Scalable solvers
  - Developed at LBNL
  - DOE ASCR supported (FASTMath)
- Interface to CISM (and CESM) as an alternate dycore
- Collaboration with LANL and Bristol (U.K.)



Why is this useful? *(another BISICLE for another fish?)*



[Rignot & Thomas, 2002]

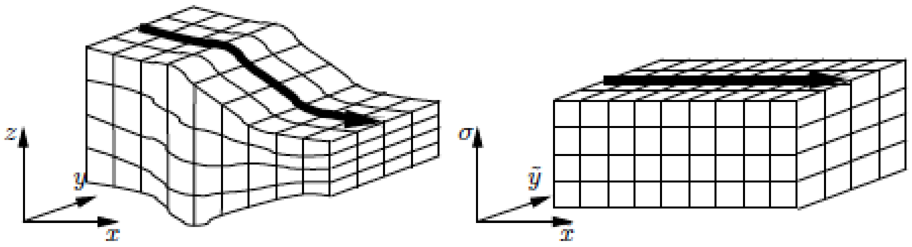
- Ice sheets -- Localized regions where high resolution needed to accurately resolve ice-sheet dynamics (500 m or better at grounding lines)
- Antarctica is really big – too big to resolve at that level of resolution.
- Large regions where such fine resolution is unnecessary (e.g. East Antarctica)
- Well-suited for adaptive mesh refinement (AMR)
- Problems still large: need good parallel efficiency
- Dominated by nonlinear coupled elliptic system for ice velocity solve: good linear and nonlinear solvers

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

- Uses asymptotic structure of full Stokes system to construct a higher-order approximation
  - Expansion in ε -- ratio of length scales $\frac{[h]}{[x]}$
  - Computing velocity to $O(\varepsilon^2)$ only requires τ to $O(\varepsilon)$
- Computationally **much** less expensive -- enables fully 2D vertically integrated discretizations. (can reconstruct 3d)
- 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 $O(\varepsilon^2)$

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.



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

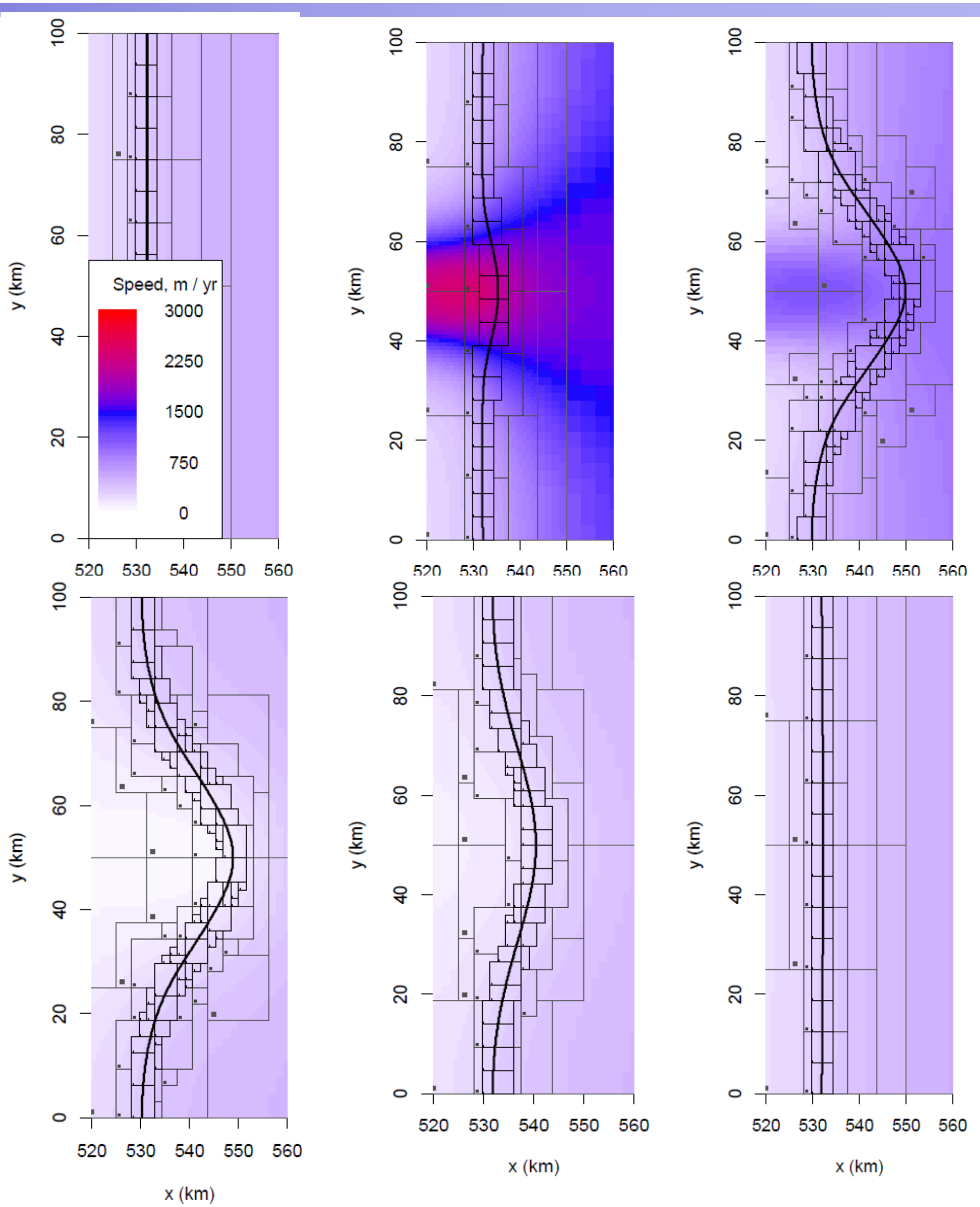
$$\frac{\partial T}{\partial t} = \frac{k}{\rho c}\nabla^2 T - \mathbf{u}\cdot\nabla T + \frac{\Phi}{\rho c} - w\frac{\partial T}{\partial z}$$

- 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 - MISMIP3D

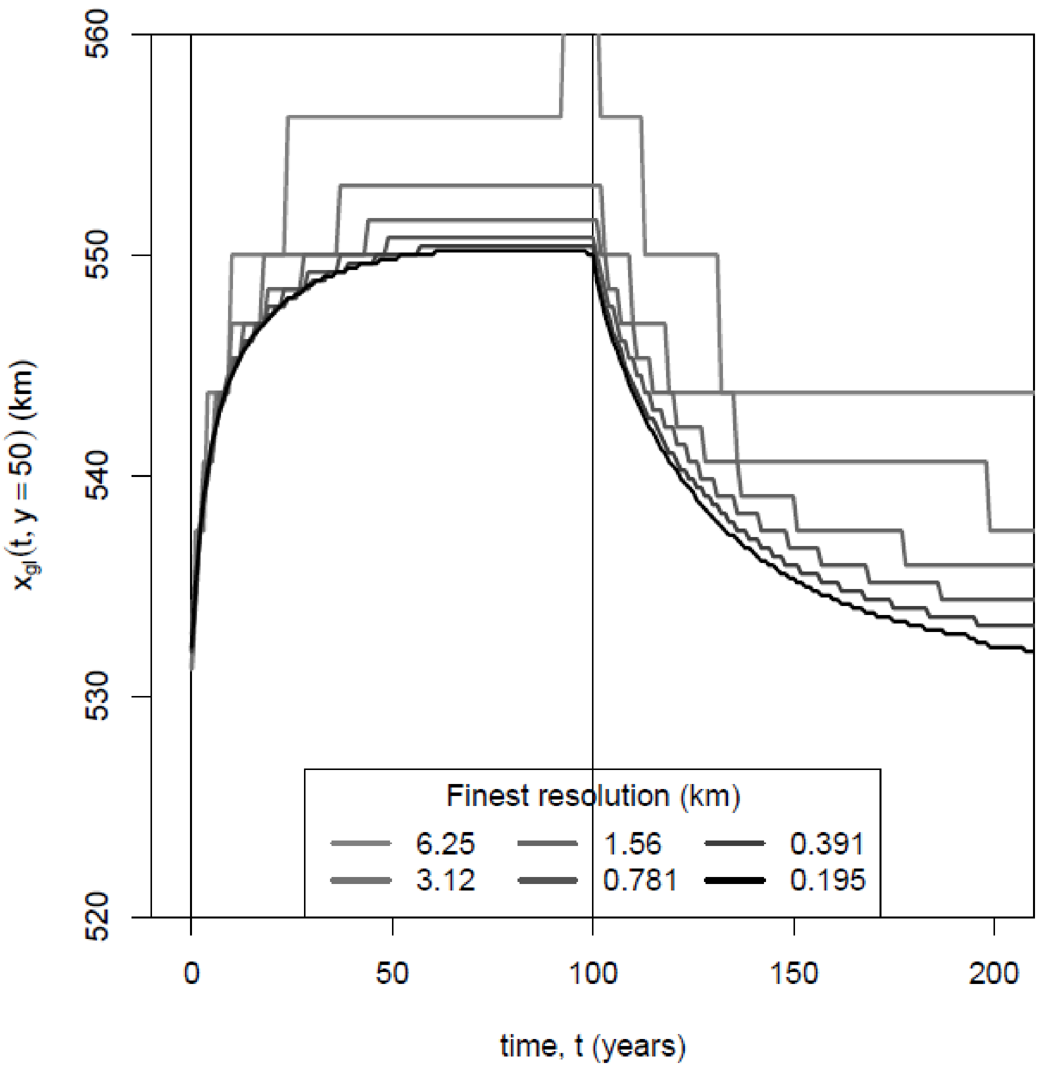
Experiment P75R:
(Pattyn et al (2011))

- Begin with steady-state (equilibrium) grounding line.
- Add Gaussian slippery spot perturbation at center of grounding line
- Ice velocity increases, GL advances.
- After 100 years, remove perturbation.
- Grounding line should return to original steady state.
- Figures show AMR calculation:
  - $\Delta x_0 = 6.5km$ base mesh,
  - 5 levels of refinement
  - Finest mesh $\Delta x_4 = 0.195km$.
  - t = 0, 1, 50, 101, 120, 200 *yr*
- Boxes show patches of refined mesh.



MISMIP3D (cont)

- Plot shows grounding line position x_{GL} at $y = 50km$ vs. time for different spatial resolutions.
- $\Delta x = \mathbf{0.195}\boldsymbol{km} \rightarrow \mathbf{6.25}\ \boldsymbol{km}$
- Appears to require finer than 1 km mesh to resolve dynamics
- Converges as O(Δx) (as expected)

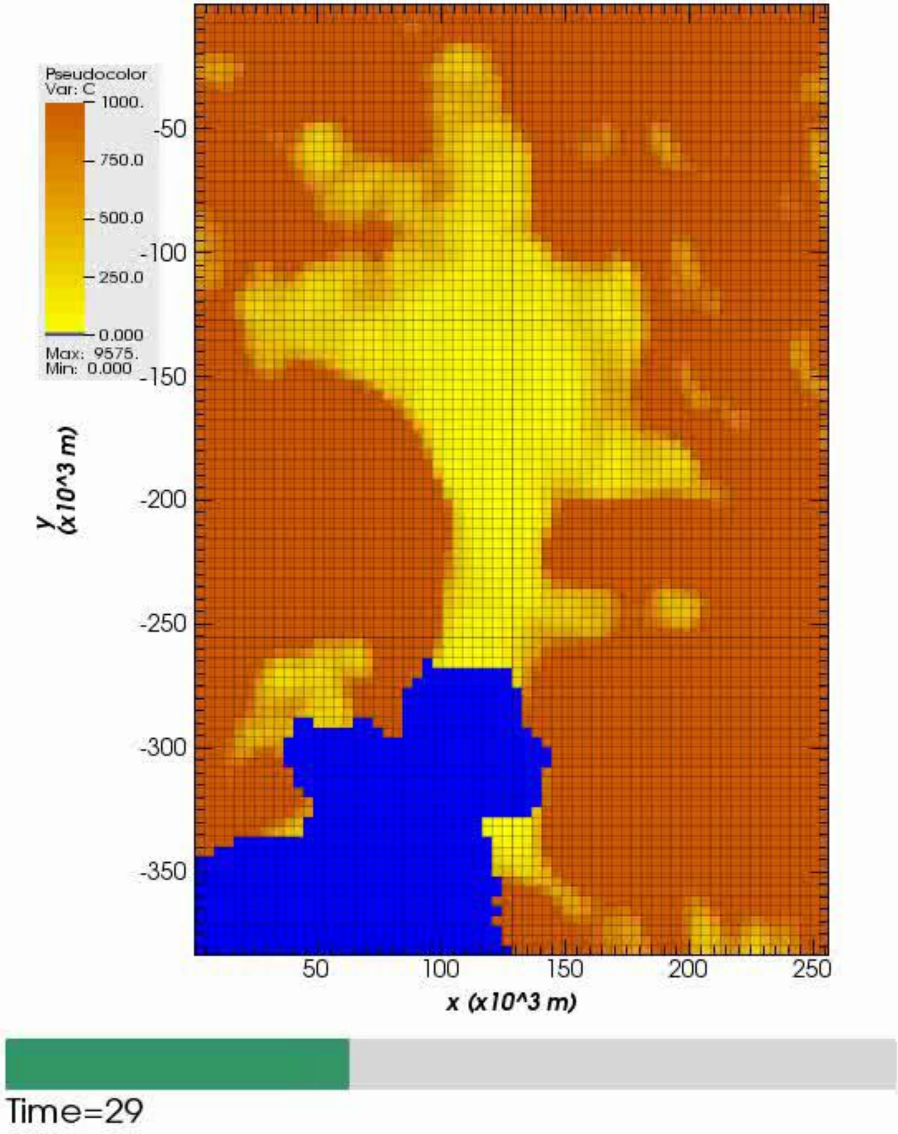


BISICLES Results – Pine Island Glacier

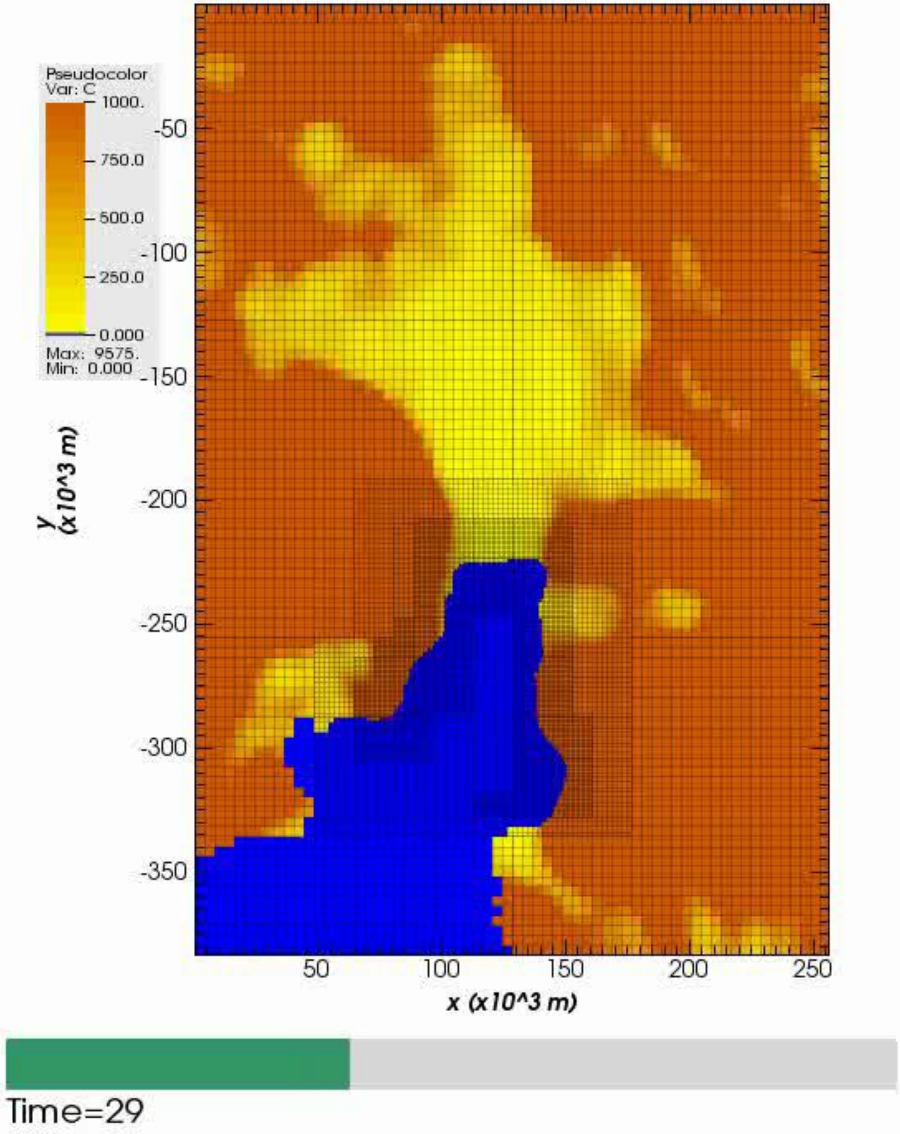
- Cornford, et al, JCP (2011, submitted)
- PIG configuration from LeBrocq:
  - Bathymetry: combined Timmerman (2010), Jenkins (2010), Nitsche (2007)
  - AGASEA thickness
  - Isothermal ice, A=4.0$\times 10^{-17}\ Pa^{-\frac{1}{3}} m^{-1/3} a$
  - Basal friction chosen to roughly agree with Joughin (2010) velocities
- Specify melt rate under shelf:
  - $M_s = \begin{cases} 0 & H < 50m \\ \frac{1}{9}(H-50) & 50 \le H \le 500m \\ 50 & H > 500\,m \end{cases}$ m/a
- Constant surface flux = 0.3 m/a
- Evolve problem – refined meshes follow the grounding line.
- Calving model and marine boundary condition at calving front

PIG (cont)

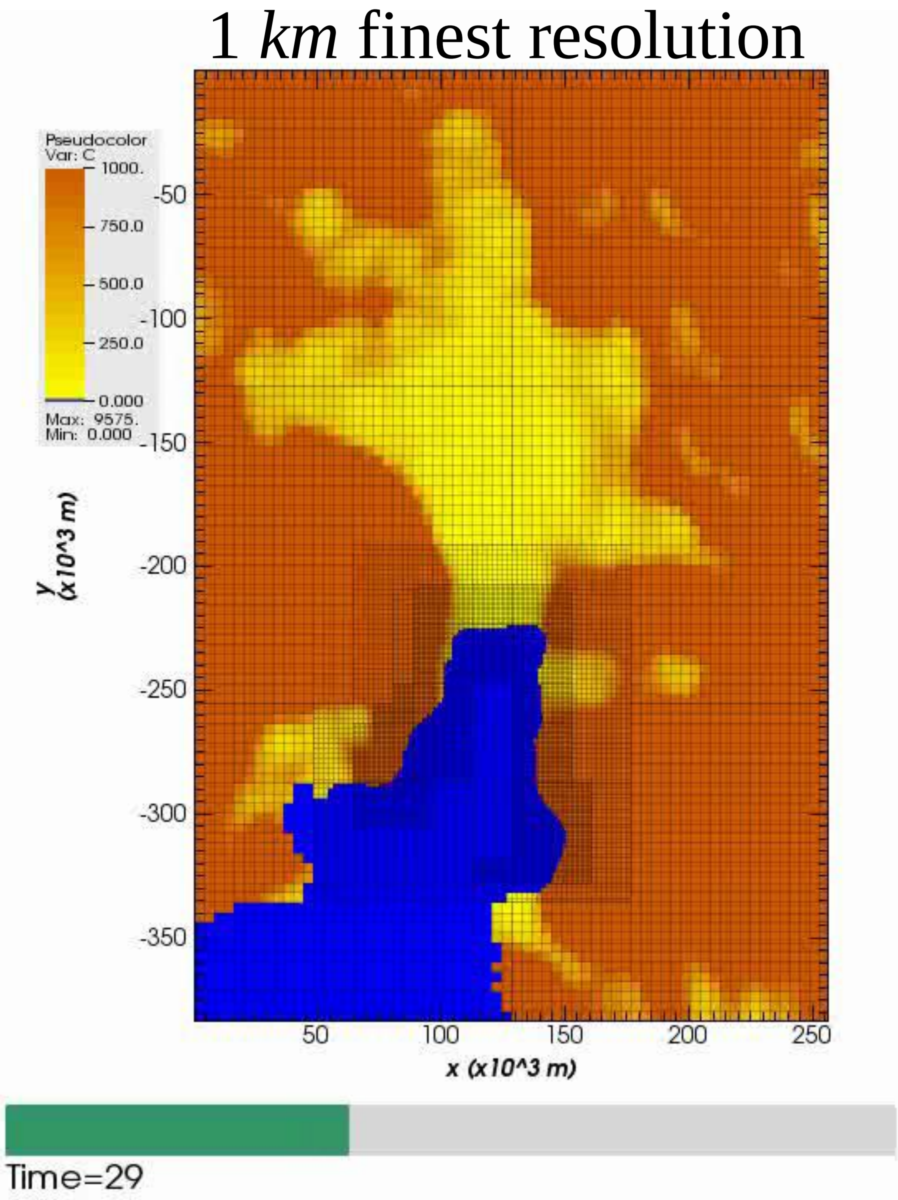
4 *km* uniform mesh

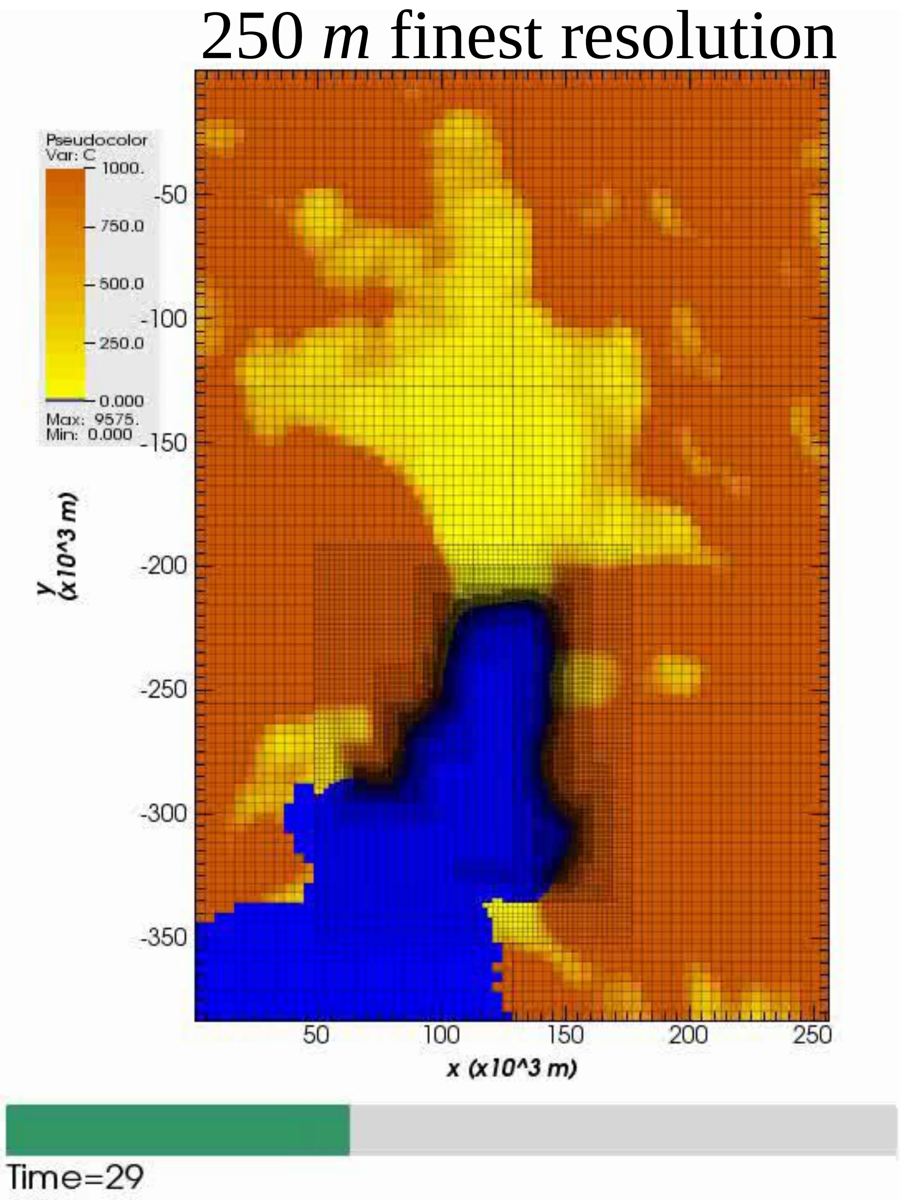


1 *km* finest resolution

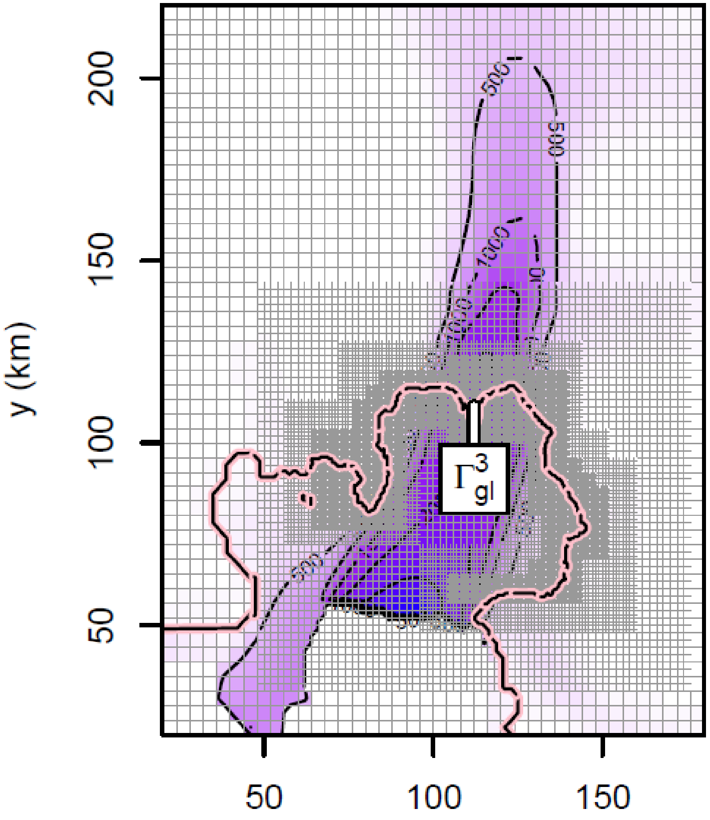


PIG, cont

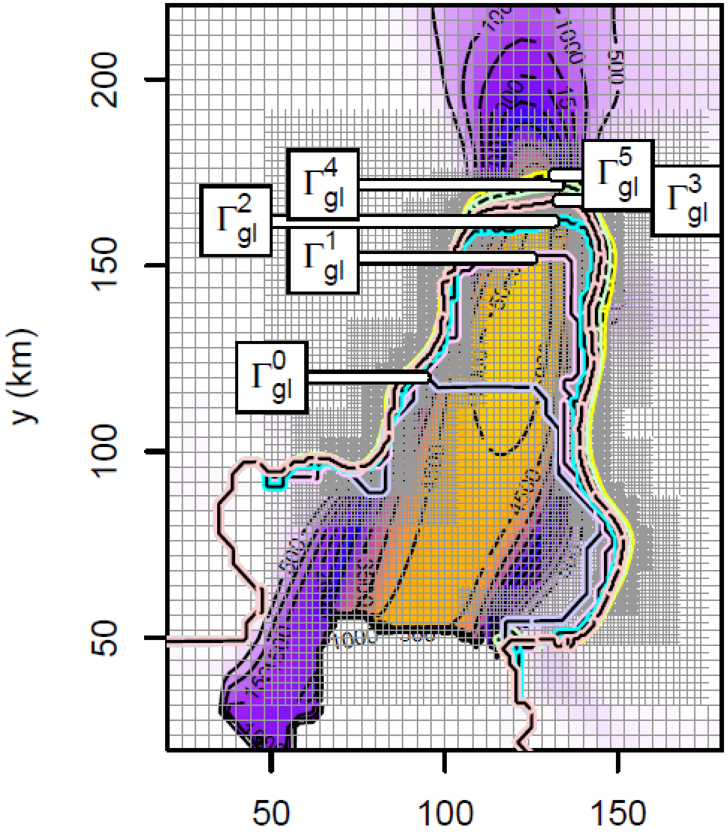

1 km finest resolution
Pseudocolor
Var: C
1000.
750.0
500.0
250.0
0.000
Max: 9575.
Min: 0.000
y (x10^3 m)
x (x10^3 m)
Time=29


250 m finest resolution
Pseudocolor
Var: C
1000.
750.0
500.0
250.0
0.000
Max: 9575.
Min: 0.000
y (x10^3 m)
x (x10^3 m)
Time=29

PIG, cont



Initial Condition

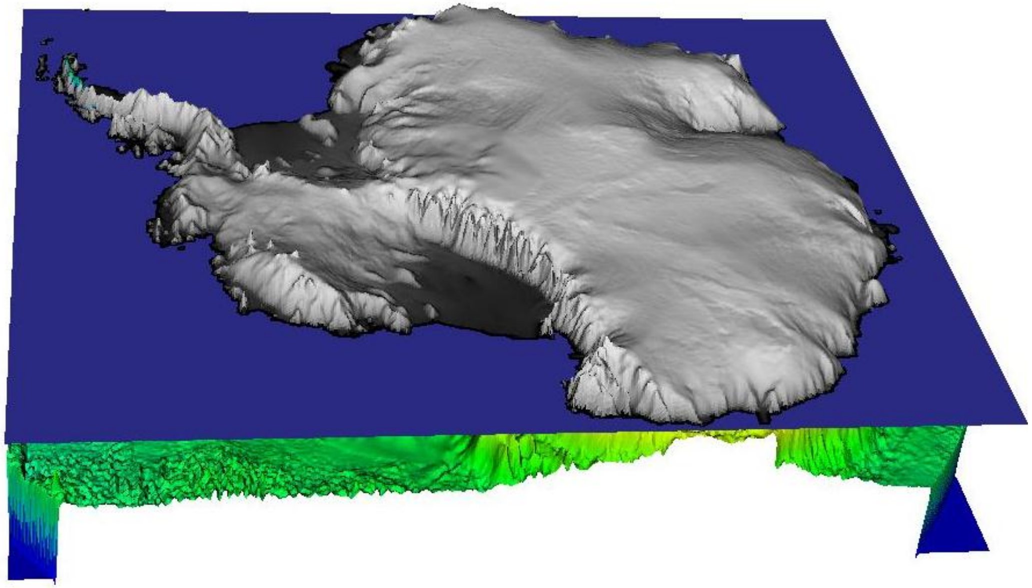


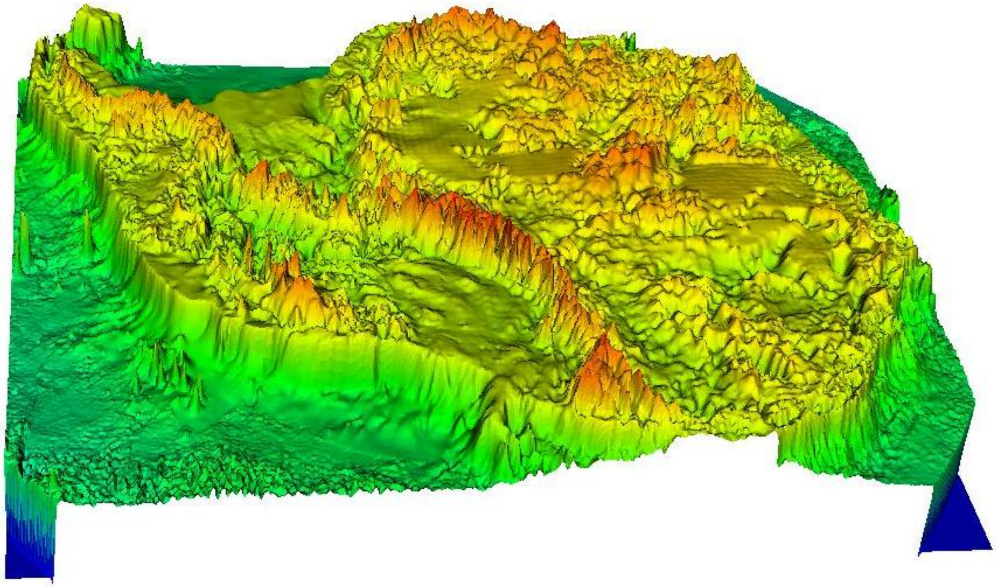
Solution after 30 years

Coloring is ice velocity, Γ_{gl} is the grounding line. Superscripts denote number of refinements. Note resolution-dependence of Γ_{gl}

Continental-scale: Antarctica

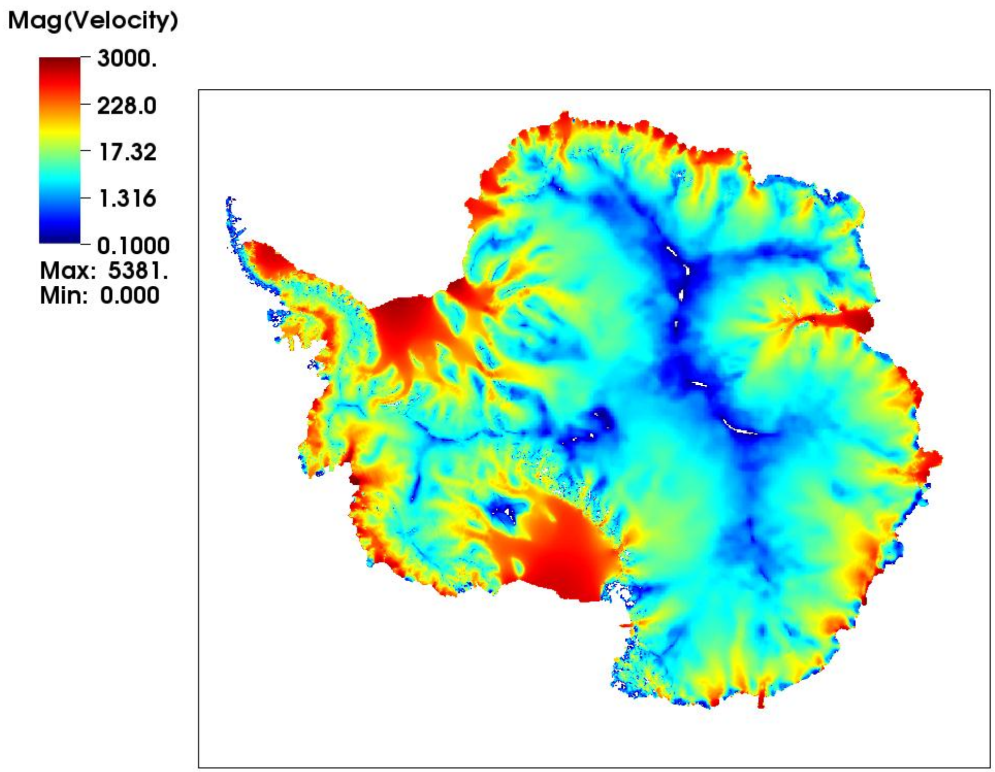
- Ice2sea geometry: LeBrocq, Timmerman, Jenkins, Nitsche
- Temperature field from Pattyn and Gladstone

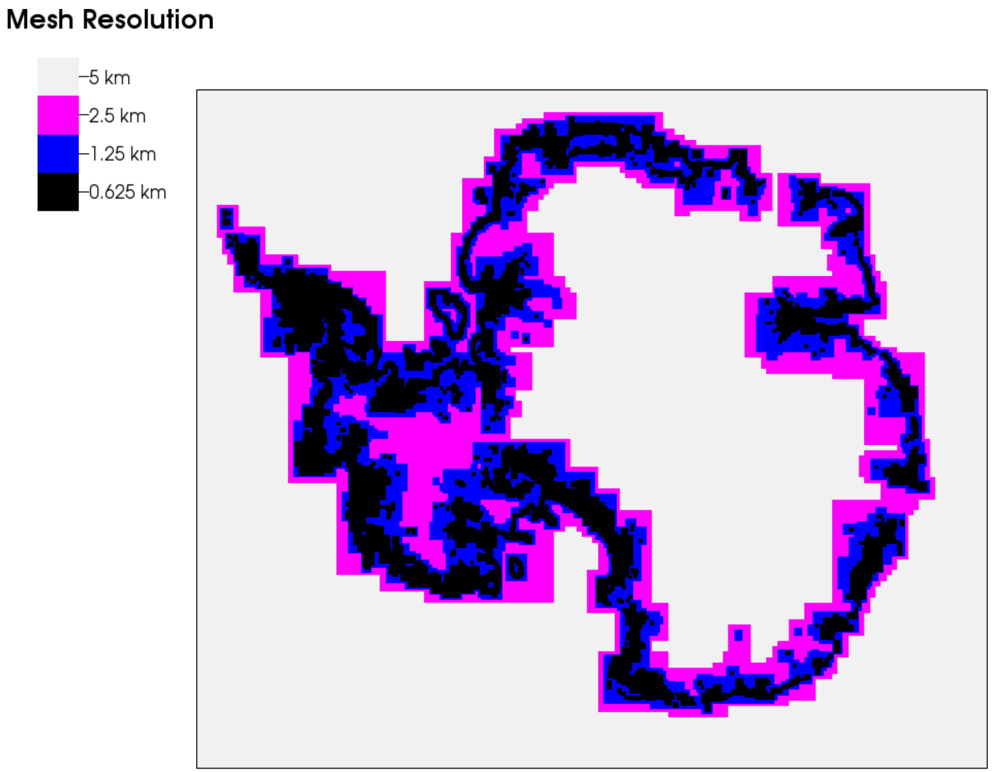




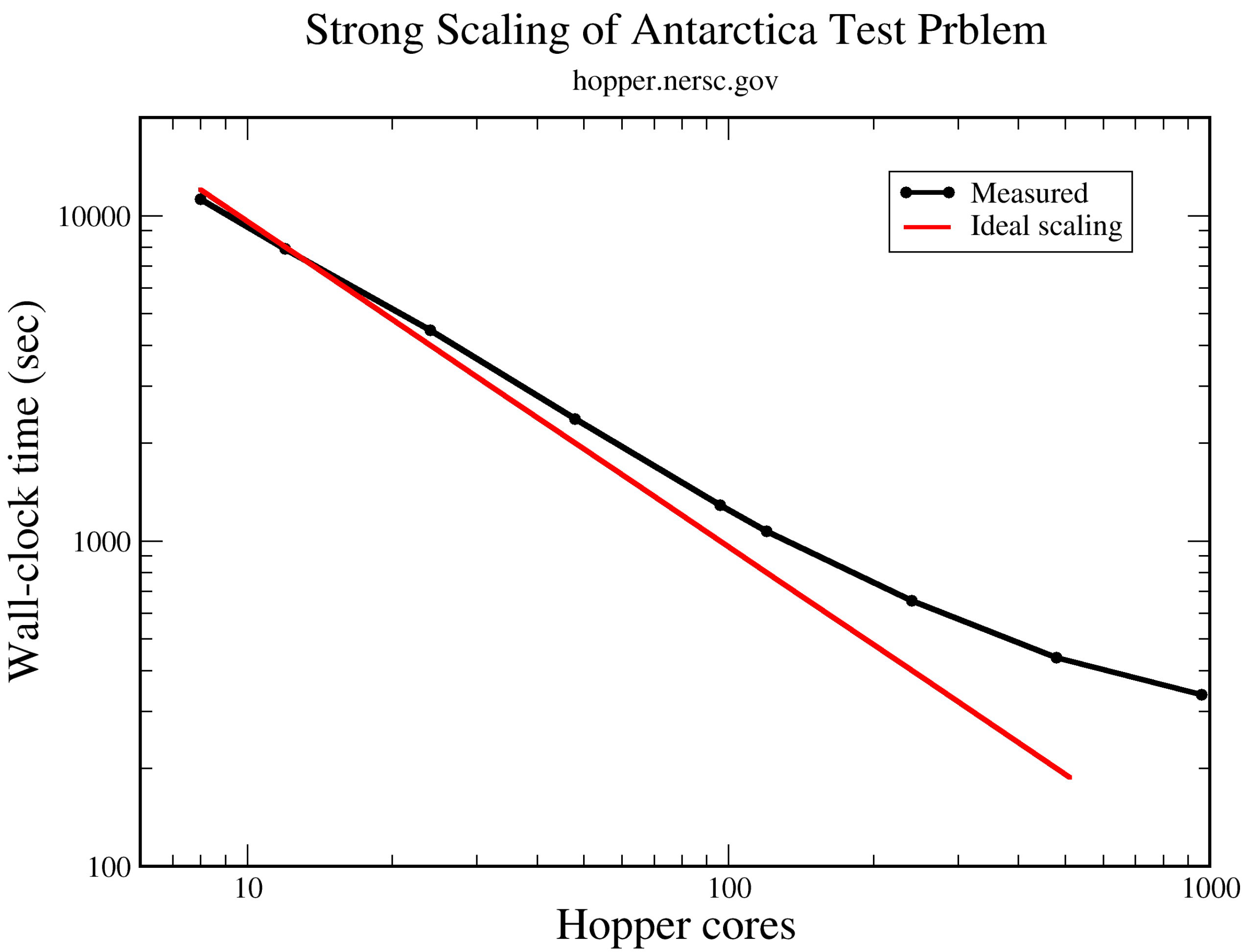
Antarctica, cont

- Refinement based on Laplacian(velocity), grounding lines
- 5 km base mesh with 3 levels of refinement
  - base level (5 km): 409,600 cells (100% of domain)
  - level 1 (2.5 km): 370,112 cells (22.5% of domain)
  - Level 2 (1.25 km): 955,072 cells (14.6% of domain)
  - Level 3 (625 m): 2,065,536 cells (7.88% of domain)





Parallel scaling, Antarctica benchmark



(Preliminary scaling result – includes I/O and serialized initialization)

BISICLES – Next steps

- More work with linear and nonlinear velocity solves.
  - PETSc/AMG linear solvers look promising (in progress)
- Semi-implicit time-discretization for stability, accuracy.
- Finish coupling with existing Glimmer-CISM code and CESM
- Full-Stokes for grounding lines?
- Embedded-boundary discretizations for GL’s and margins.
- Performance/scaling optimization and autotuning.
- Refinement in time?