Improving Grounding Line Discretization using an Embedded-Boundary Approach in BISICLES

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SIAM CSE

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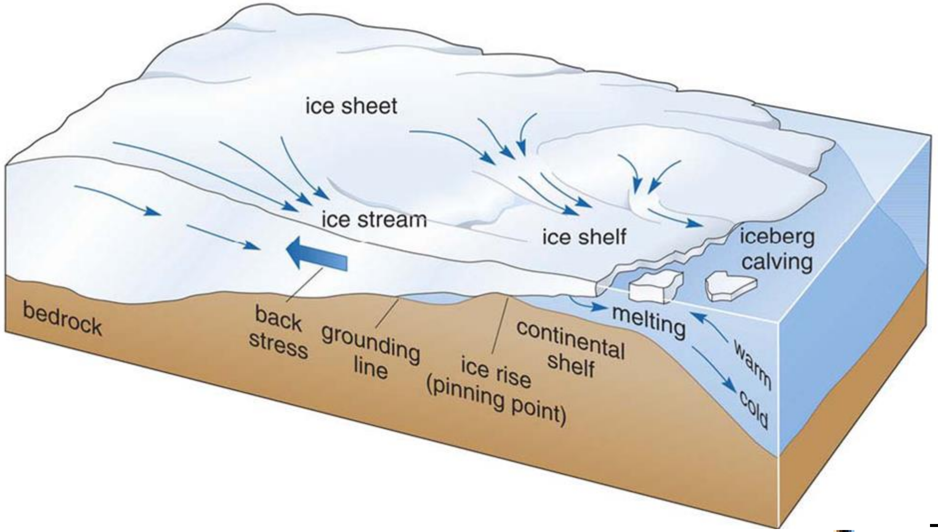
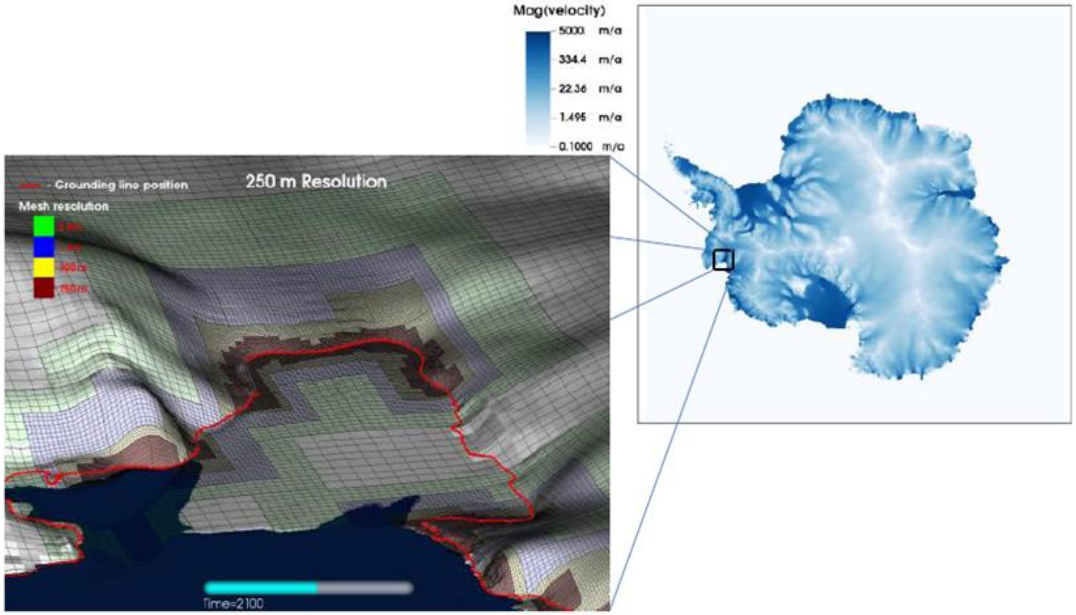
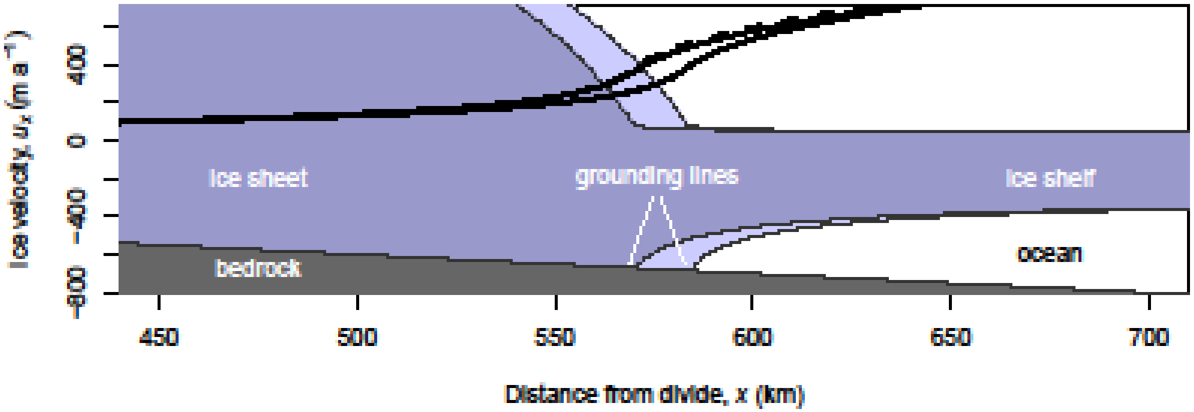
Joint work with:

- **Peter Schwartz** (LBNL)
- Phil Colella (LBNL)
- Stephen Cornford (Bristol)
- Mark Adams (LBNL)
- Esmond Ng (LBNL)

Land Ice Sheets – coupling with Oceans







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Motivation: Projecting future Sea Level Rise

- Potentially large Antarctic contributions to SLR resulting from marine ice sheet instability, particularly from WAIS.

- Climate driver: subshelf melting driven by warm(ing) ocean water intruding into subshelf cavities.

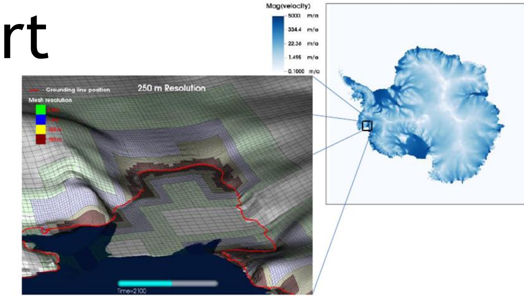
- Melt-driven thinning, loss of shelf buttressing lead to grounding-line retreat.

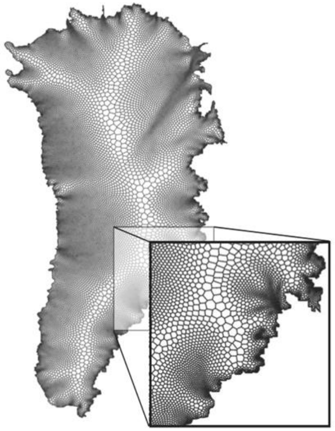
- Paleorecord implies that WAIS has deglaciated in the past.

DOE Context - PISCEES and ACME

Part of the DOE "big picture" in climate

- **PISCEES** (Predicting Ice Sheet and Climate Evolution at Extreme Scales)
  - DOE-sponsored (SciDAC2) ice-sheet modeling effort
  - Leverages DOE modeling, HPC capabilities
  - Dycore development
    - BISICLES – block-structured finite-volume AMR, L1L2
    - FELIX – Finite Element unstructured mesh, Blatter-Pattyn/Stokes
  - Initialization, UQ, V&V

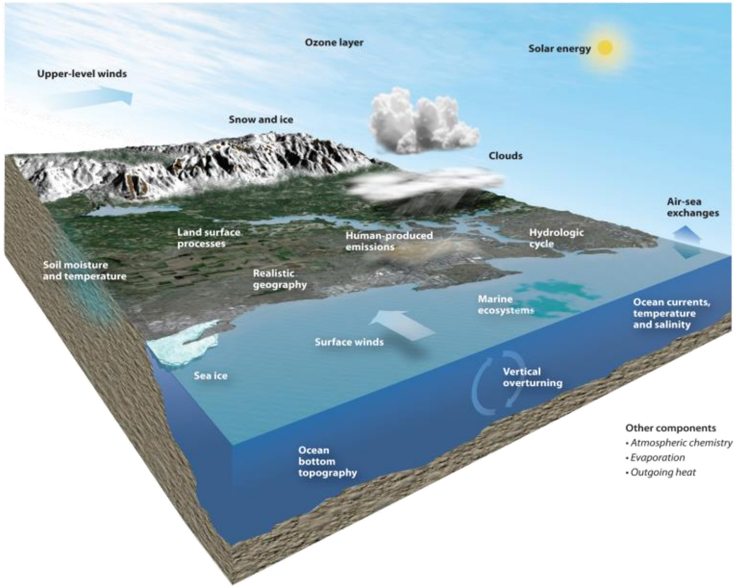




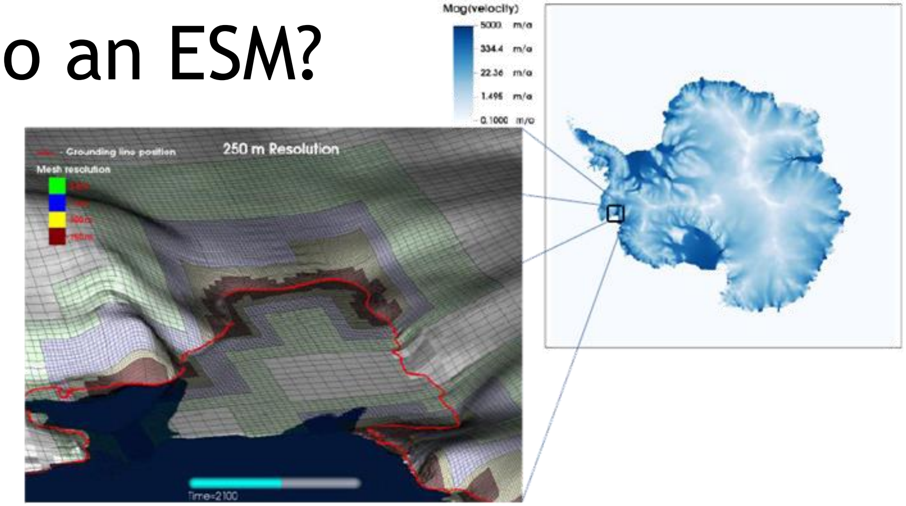
- **ACME** (Accelerated Climate Model for Energy)
  - DOE-sponsored ESM effort
    - 3 science questions (#3 is cryospheric contribution to SLR)
  - Starting point is CESM

Big Picture -- target

- Aiming for coupled ice-sheet-ocean modeling in ESM
- Multi-decadal to century timescales
- Target resolution:
  - Ocean: 0.1 Degree
  - Ice-sheet: 500 m (adaptive)



- Why put an ice-sheet model into an ESM?
  - fuller picture of sea-level change
  - feedbacks may matter on timescales of years, not millenia
- **Credible projections require**
- **correct GL dynamics**



Grounding-line dynamics experiments

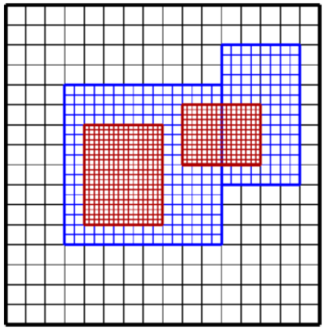
- Series of ice-sheet modeling community model intercomparison projects designed to understand issues in modeling of GLs
  - MISMIP, MISMIP3D, MISMIP+

- All point to a need for very fine spatial resolution to get GL dynamics right (sub-km in most cases)

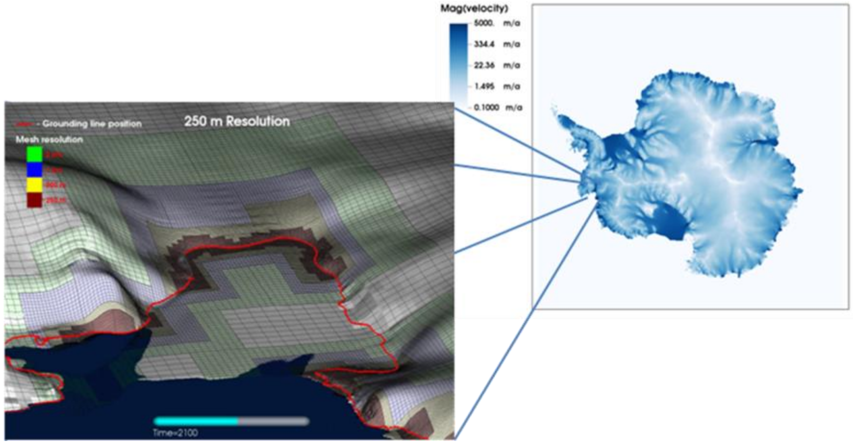
- Prime use case for adaptive mesh refinement (AMR)

BISICLES Ice Sheet Model

- Scalable adaptive mesh refinement (AMR) ice sheet model
  - Dynamic local refinement of mesh to improve accuracy
- Chombo AMR framework for block-structured AMR
  - Support for AMR discretizations
  - Scalable solvers
  - Developed at LBNL
  - DOE ASCR supported (FASTMath)



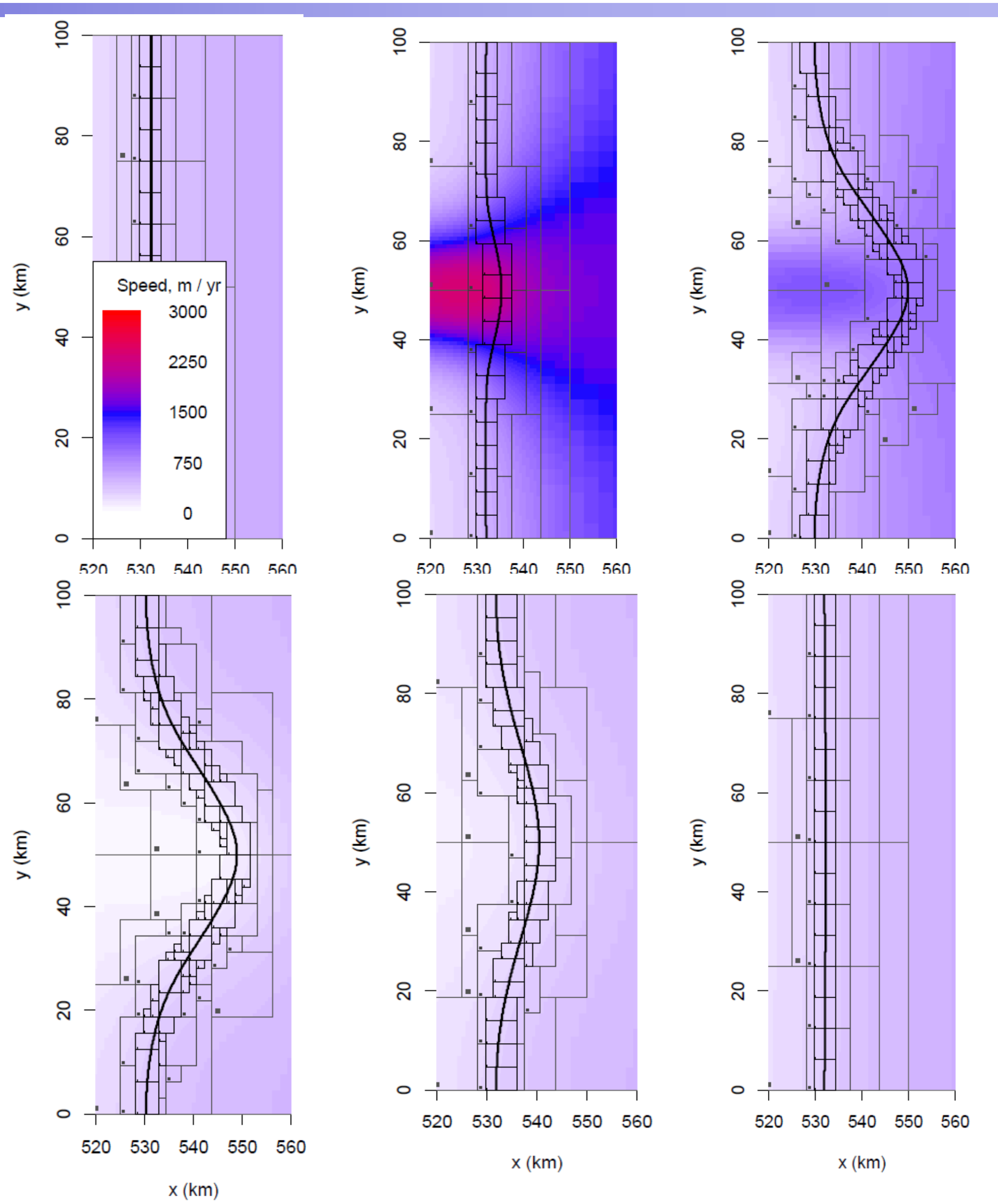
- Collaboration with Bristol (U.K.) and LANL
- Variant of “L1L2” model (Schoof and Hindmarsh, 2009)
- Coupled to Community Ice Sheet Model (CISM).
- Users in Berkeley, Bristol, Beijing, Brussels, and Berlin…



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.
- GL positions match Elmer (full-Stokes)



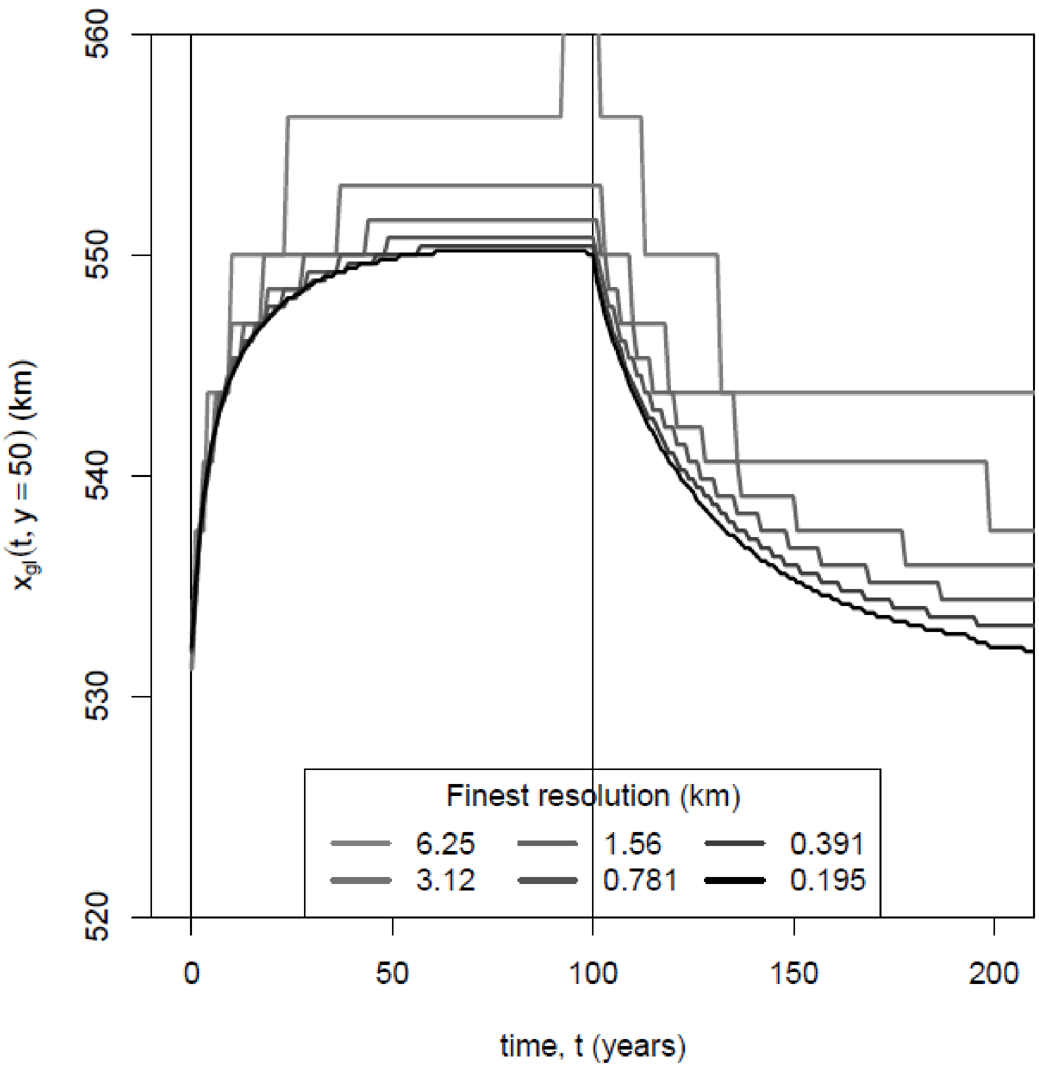
MISMIP3D: Mesh resolution

- Plot shows grounding line position x_{GL} at $y = 50km$ vs. time for different spatial resolutions.

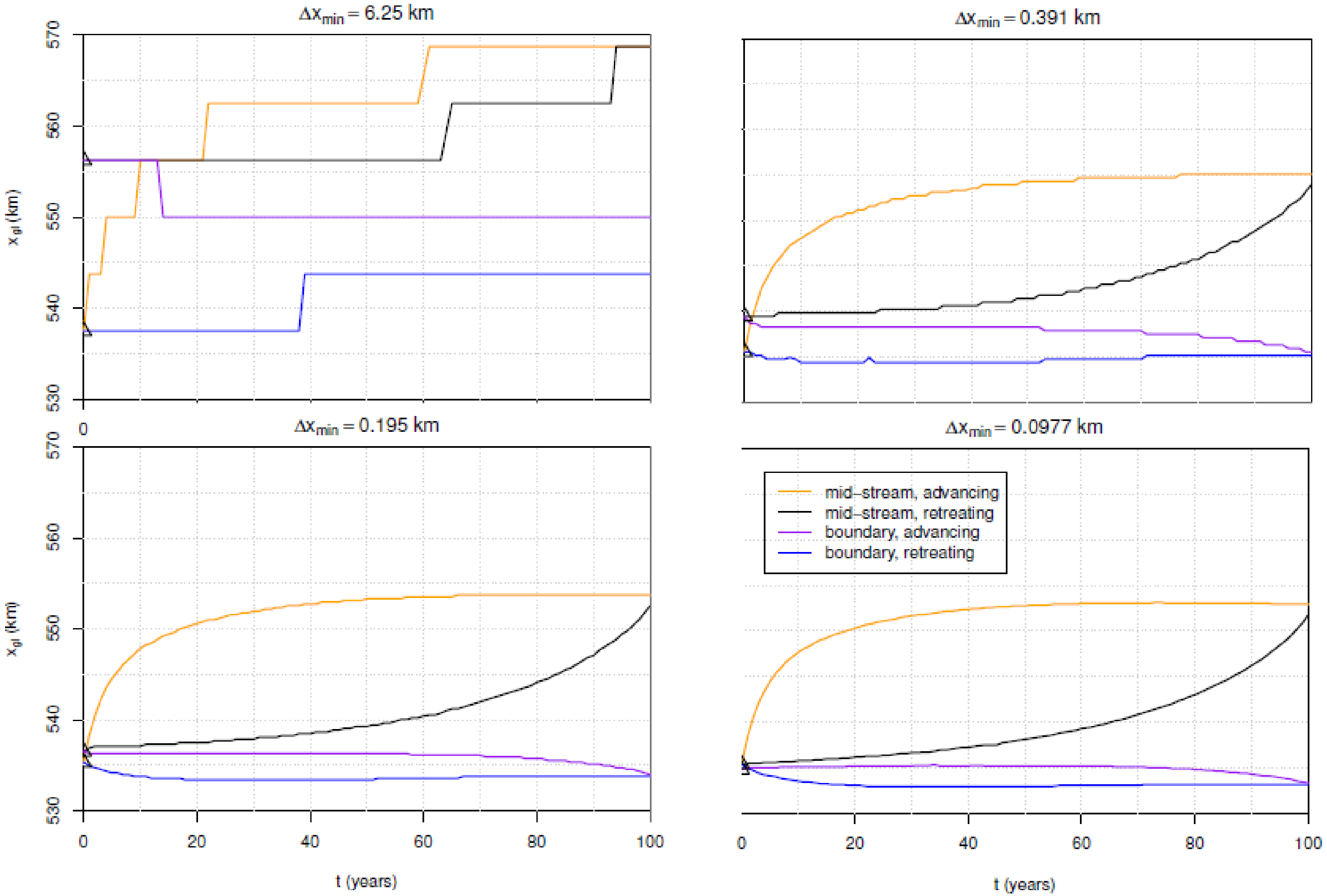
- $\Delta x = 0.195km \rightarrow 6.25\ km$

- Appears to require finer than 1 km mesh to resolve dynamics

- Converges as $O(\Delta x)$ (as expected)

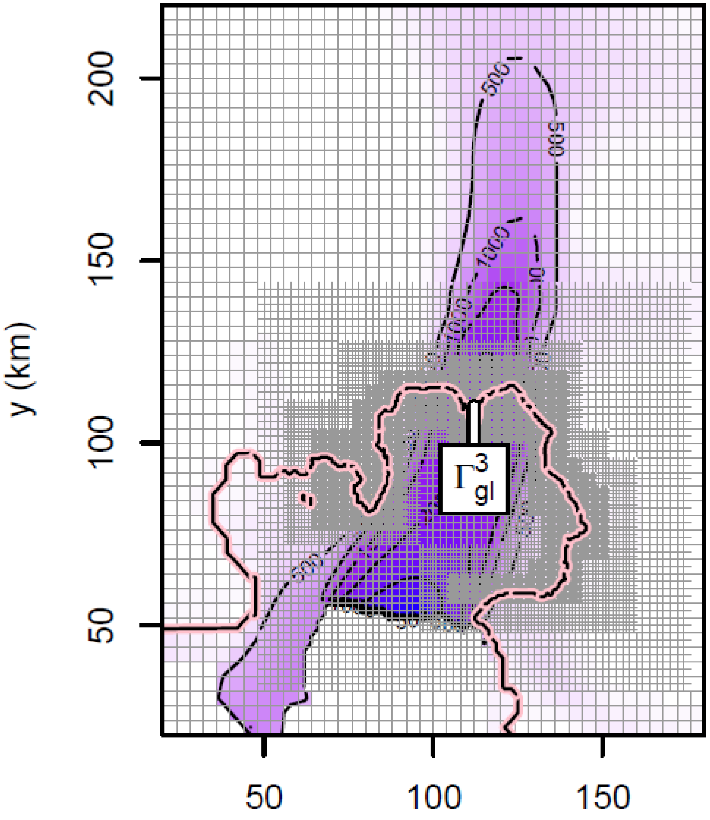


MISMIP3D (cont): Spatial Resolution

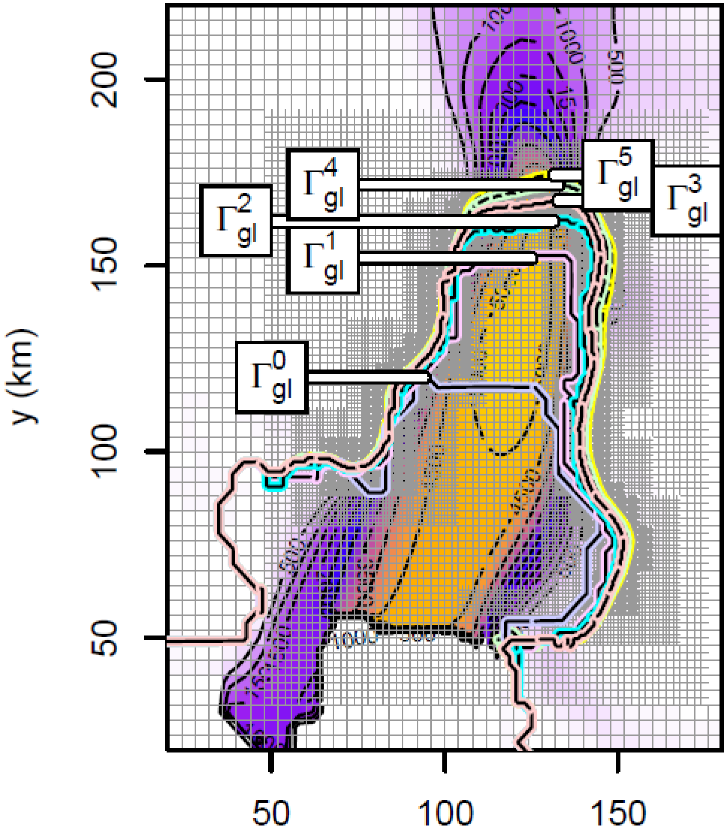


- Very fine (~200 m) resolution needed to achieve full reversibility!

Pine Island Glacier (Cornford, Martin, et al, JCP)



Initial Condition



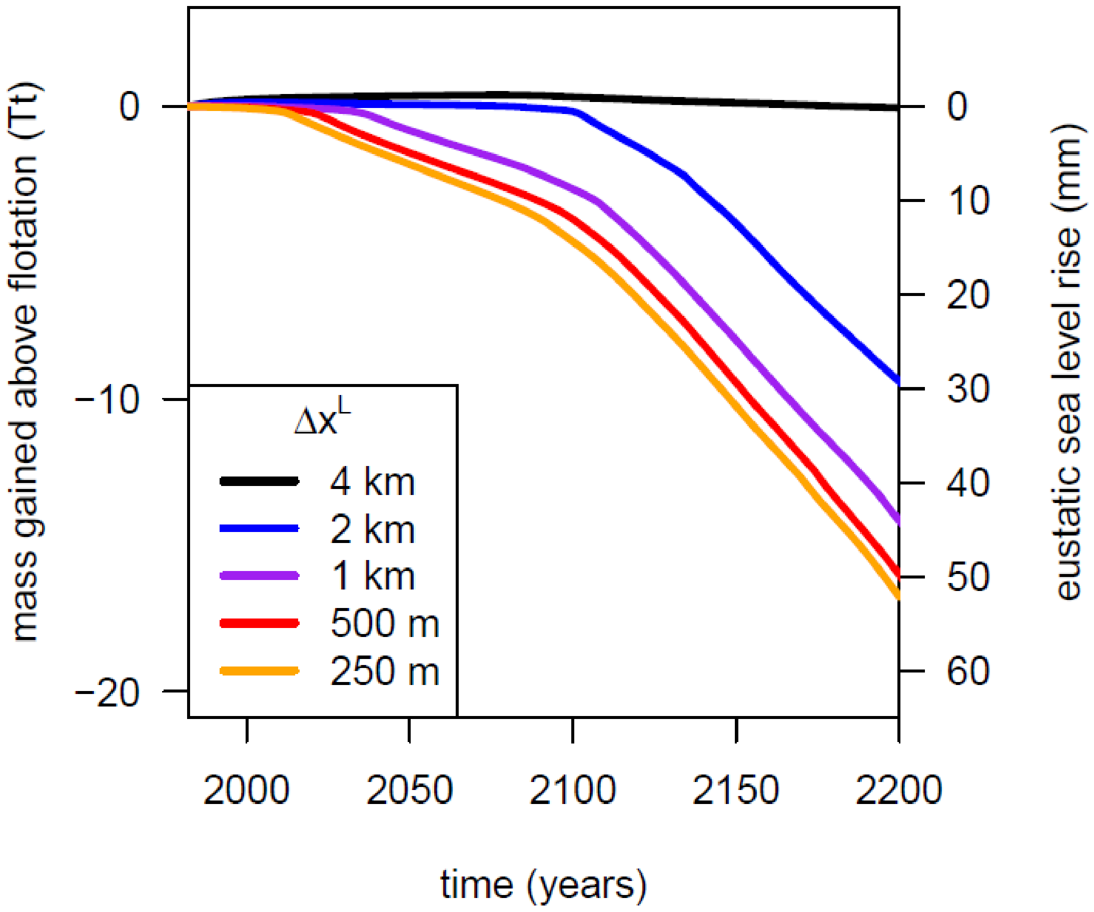
Solution after 30 years

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

Amundsen Sea (Cornford, Martin et al, submitted)

- Need at least 2 km resolution to get any measurable contribution to SLR.
- Sub-km is better.
- Appears to converge at first-order in Δx

SLR vs. year, Amundsen Sea Sector

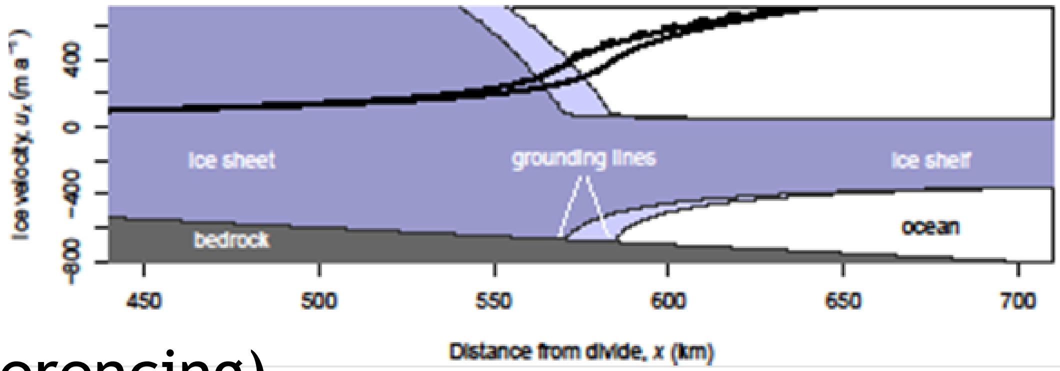


GL Resolution requirements

- Not model-specific; reported by many authors
  - Full-Stokes (Elmer – Durand et al)
  - Hybrid SSA-SIA (PISM-PIK)

- Such resolution requirements are inconvenient, at best.

- Point to the fact that in models with hydrostatic formulations, GL is a singular point (set)
  - Basal friction drops to zero
  - SSA-type equations go from parabolic to elliptic
  - Surface slopes are discontinuous (one-sided differencing)



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Other approaches

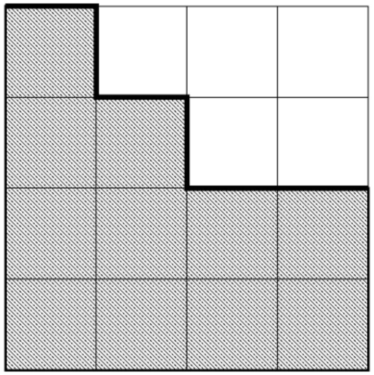
- Sub-km mesh resolution requirements are inconvenient at best for continental-scale models.

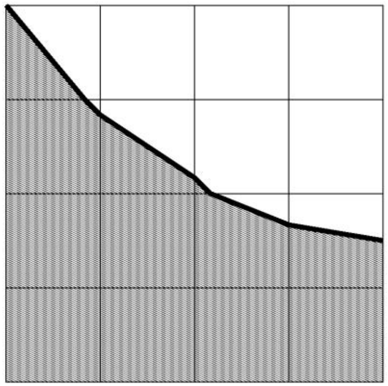
- Many attempts to handle this through subgrid-scale models
  - Transition zones (Pattyn)
  - Partial-cell parameterization (Gladstone et al, Seroussi et al)
  - More complicated asymptotics – (Leguy et al)

Embedded Boundary (EB) for Grounding Lines

- **Embedded Boundary (EBChombo)**
  - Currently force GL and ice margins to cell faces
  - “Stair-step” discretization

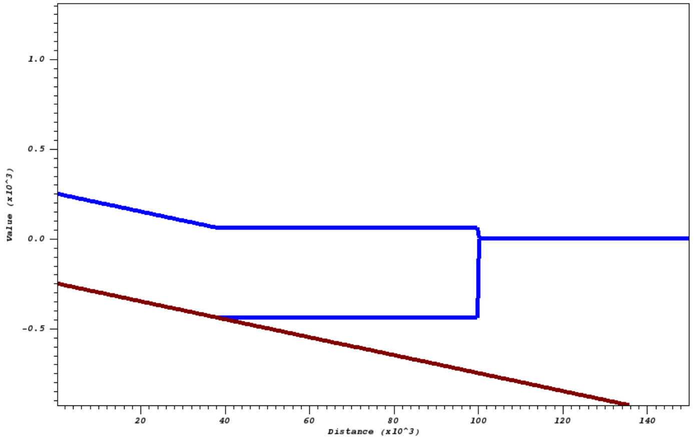
    Known to be inadequate from experience with Stefan Problem in other contexts!
  - Use Chombo Embedded-boundary support to improve discretization of GL’s and ice margins.
  - Can solve as a Stefan Problem, with appropriate jump conditions enforced at grounding line. (as in Schoof, 2007)

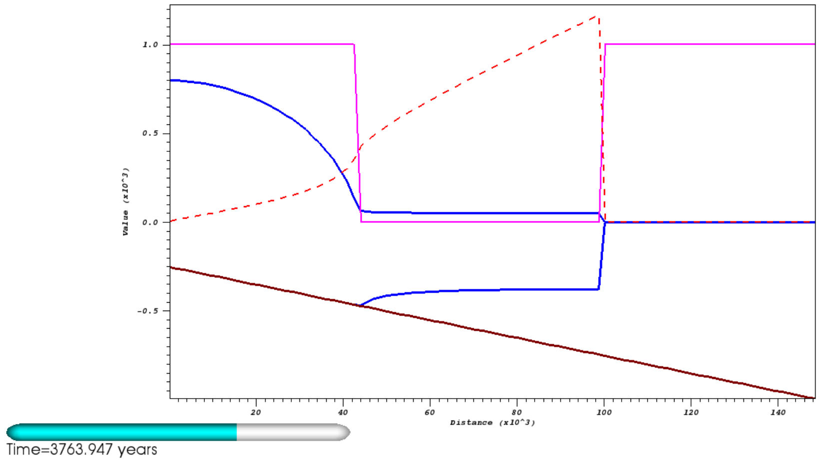




Flowline (1D) model problem

- Based on Vieli and Payne (2005)





- SSA Momentum balance reduces to:

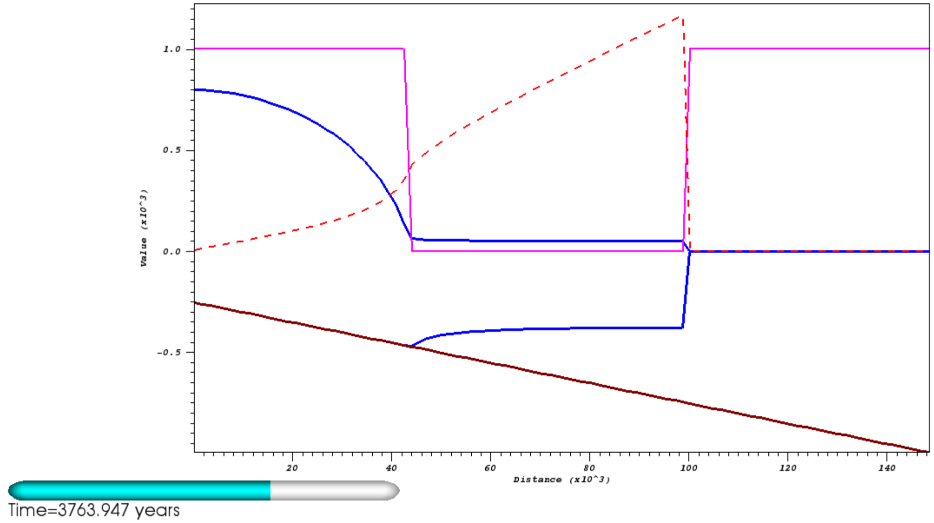
$$\left(\beta - \frac{\partial}{\partial x}\left(4\mu H \frac{\partial}{\partial x}\right)\right) u_b = -\rho g H \frac{\partial s}{\partial x}$$

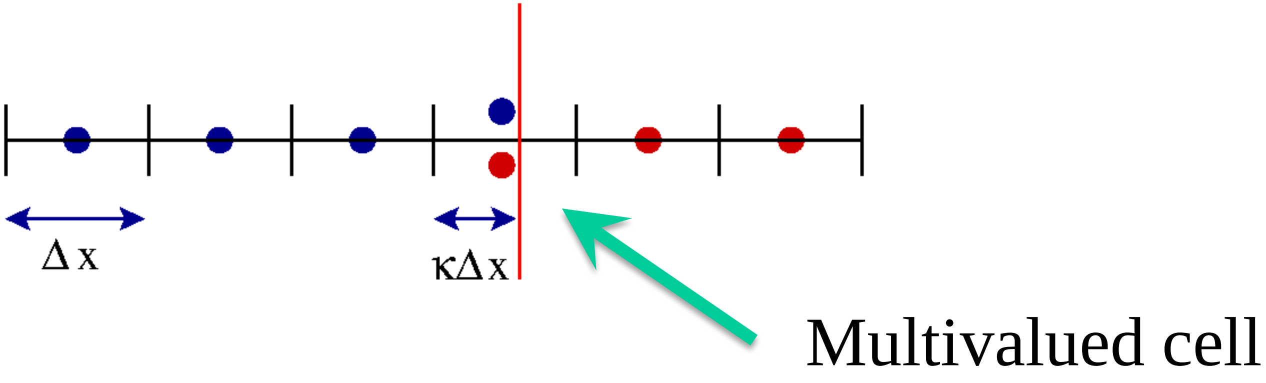
- Mass Conservation reduces to:

$$\frac{\partial H}{\partial t} + \nabla \cdot (uH) = Src$$

Multifluid formulation

- Can conceive of the grounding line problem as a phase-change across a multifluid interface (Stefan problem)
- Discretization follows Crockett, Colella, and Graves (2011)





Multifluid Velocity Solve

- Multifluid discretization (Crockett et al, 2011)
- Grounded, floating "phases" discretized independently
- Phases communicate via interface jump relations
- Quadratic interpolation/extrapolation to interface
- Velocity-solve jump relations (1D):

$$[H] = 0$$

$$[u] = 0$$

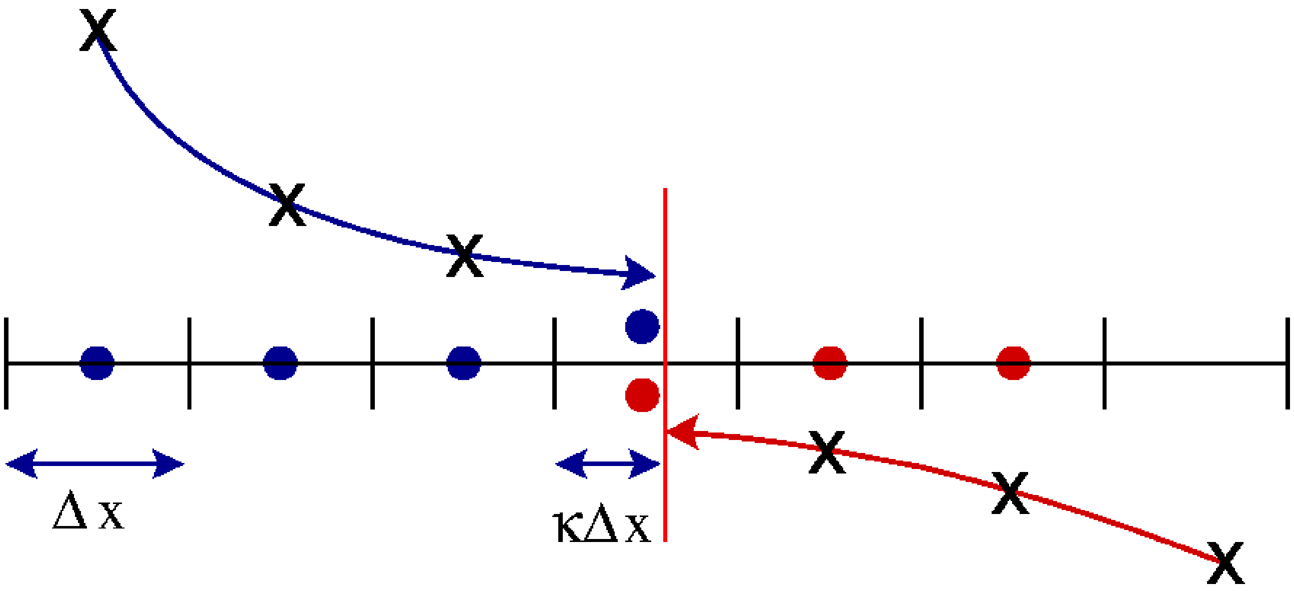
$$[u_b] = 0$$

$$[\tau] = [\mu \frac{\partial u}{\partial x}] = 0$$

- System currently solved exactly (Gaussian elimination)

Multifluid Velocity Solve (cont)

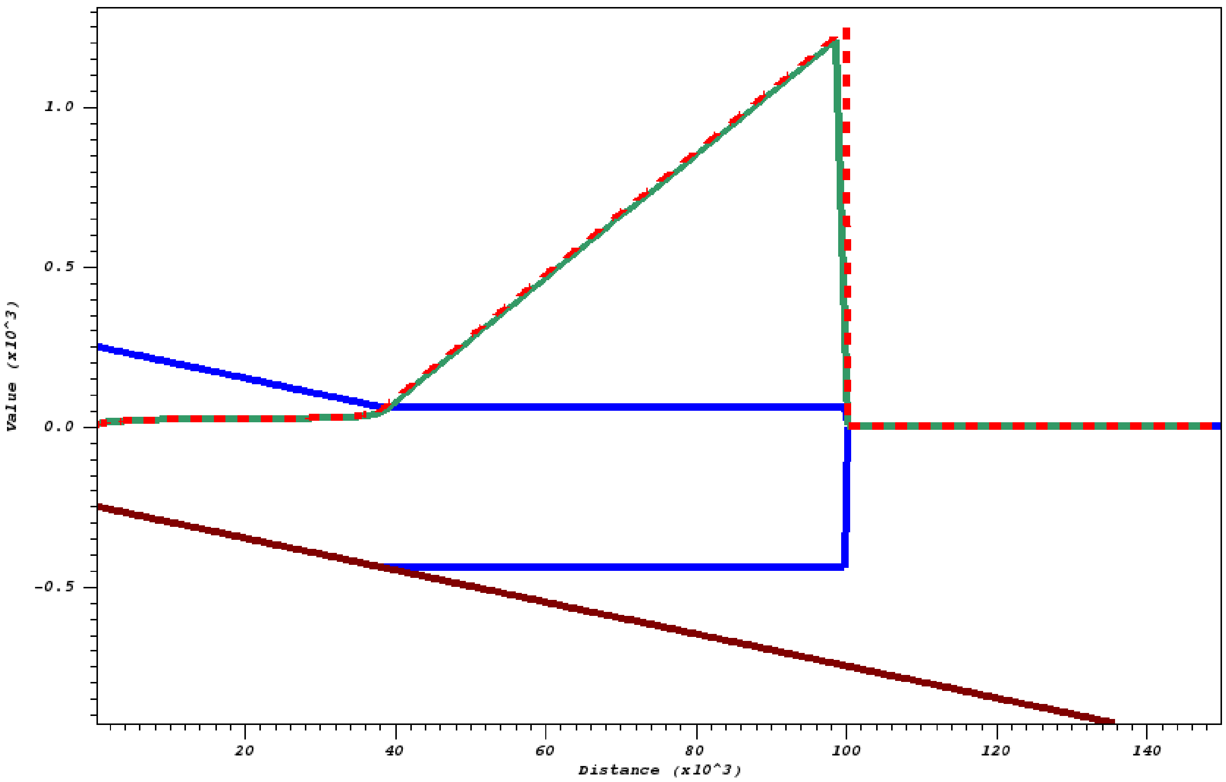
- Multifluid extrapolation to faces:



- Multivalued cell-centered value for each phase in MF cell
- Avoid "small-cell problem" ($\kappa \rightarrow 0$) by not using partial cell values in stencils
- Need quadratic extrapolant to preserve accuracy

Multifluid Velocity Solve (cont)

- Initial velocity solve
- Red dashed line: “regular” discretization Δx =195m
- Green line, multifluid discretization, Δx =1500m



Advection – GL advance/retreat

Two possible advection/evolution options:

1. Recompute GL every time based on finding the levelset where thickness over flotation is zero.

2. Explicitly move GL based on thickness change and basal slope

Conclusions

- Fine (sub 1-km) resolution required to get grounding lines right
- Evidence suggests that better discretizations at grounding lines may help relax resolution requirement
- Can treat GL as multifluid interfaces between 2 phases
- Multifluid velocity solver implemented
- Time-dependent evolution is next!

Acknowledgements:

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- Steph Cornford, Tony Payne at the University of Bristol
- Mark Adams (LBNL)

Extras

BISICLES Results – Ice2Sea Amundsen Sea

- Study of effects of warm-water incursion into Amundsen Sea.
- Results from Payne et al, (2012), submitted.
- Modified 1996 BEDMAP geometry (Le Brocq 2010), basal traction and damage coefficients to match Joughin 2010 velocity.
- Background SMB and basal melt rate chosen for initial equilibrium.
- SMB held fixed.
- Perturbations in the form of additional subshelf melting:
  - derived from FESOM circumpolar deep water
  - ~5 m/a in 21st Century,
  - ~25 m/a in 22nd Century.