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

Dan Martin

Lawrence Berkeley National Laboratory

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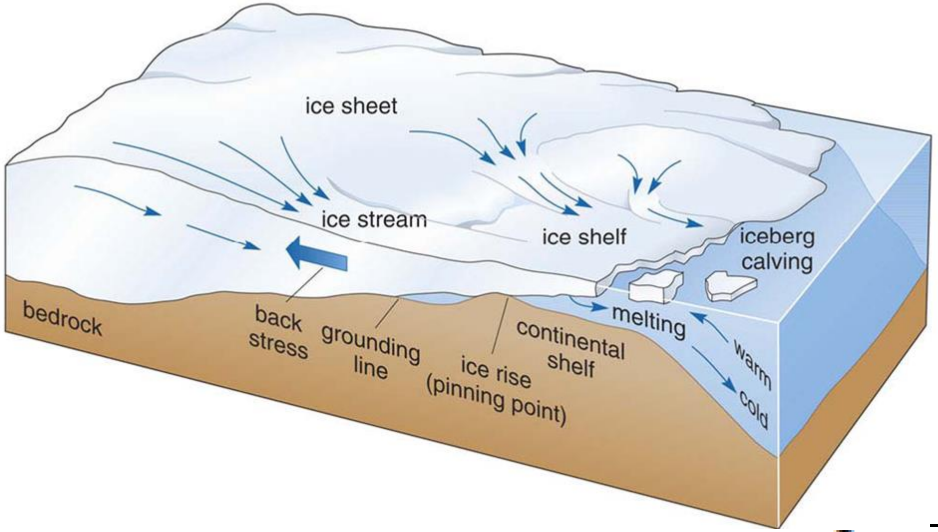
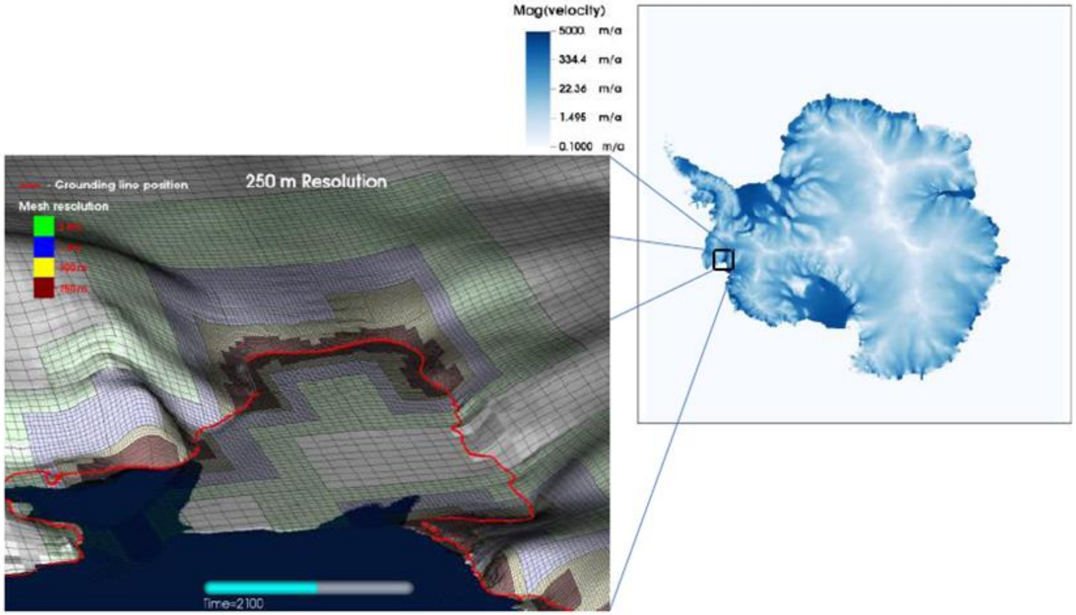
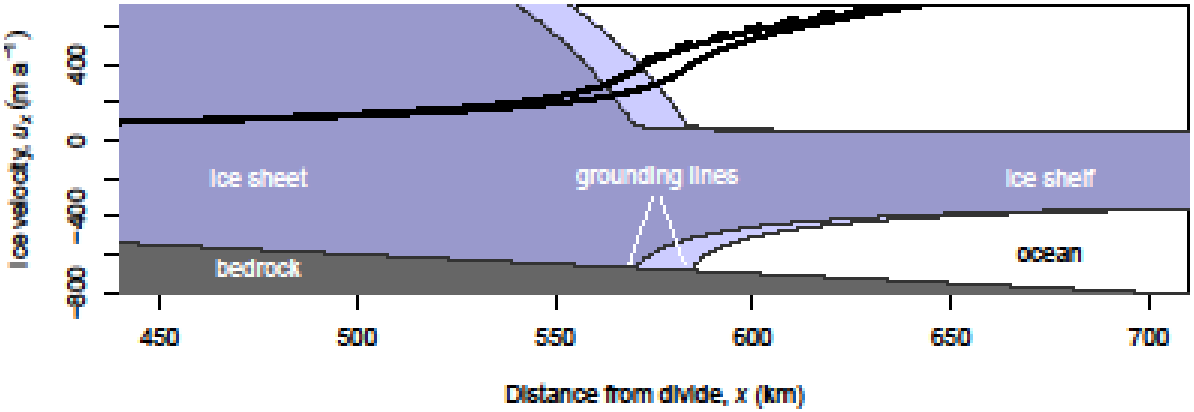
Joint work with:

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

Land Ice Sheets – coupling with Oceans







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.

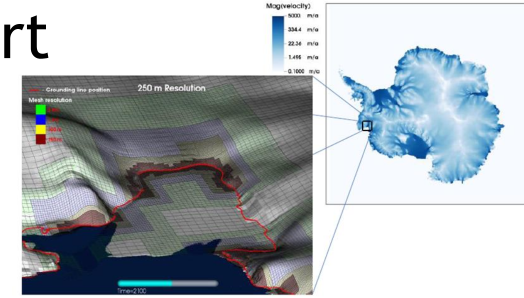
- Melt-driven thinning, loss of shelf buttressing lead to grounding-line retreat.

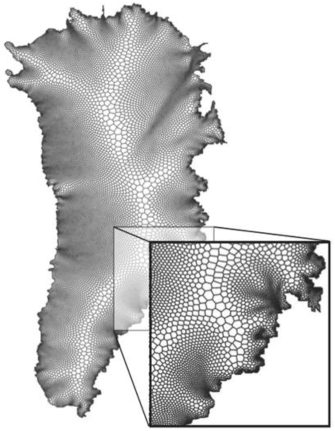
- Paleorecord implies that WAIS has deglaciated in the past.

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

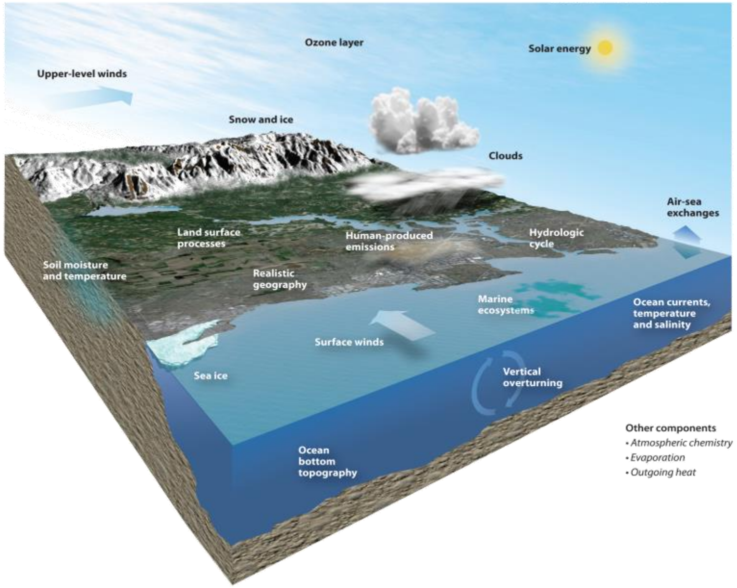




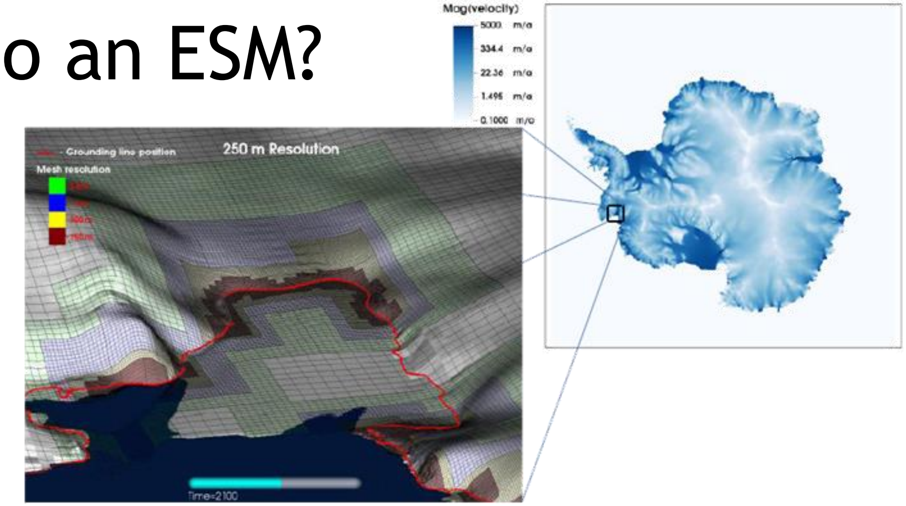
- **ACME** (Accelerated Climate Model for Energy)
  - DOE-sponsored ESM effort
    - 3 science questions (#3 is cryospheric contribution to SLR)
  - Starting point is CESM

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

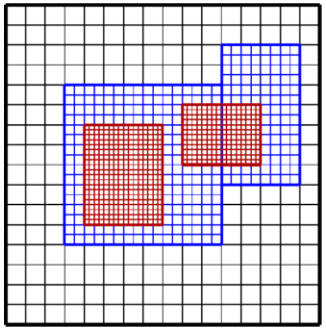
- Series of ice-sheet modeling community model intercomparison projects designed to understand issues in modeling of GLs
  - MISMIP, MISMIP3D, MISMIP+

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

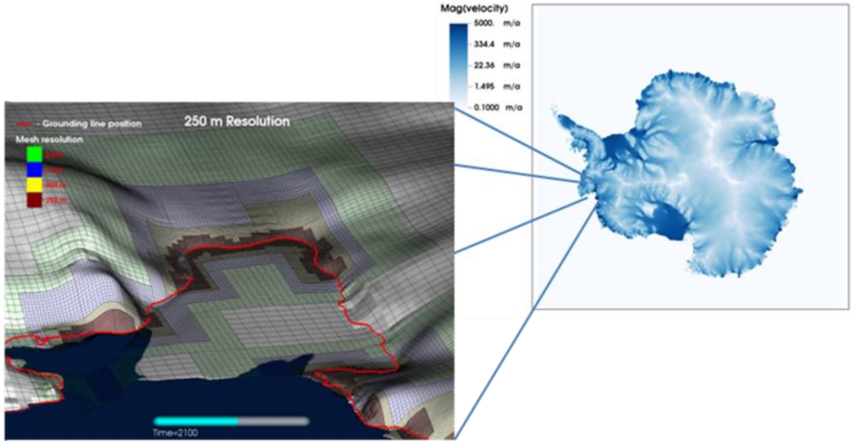
- Prime use case for adaptive mesh refinement (AMR)

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)



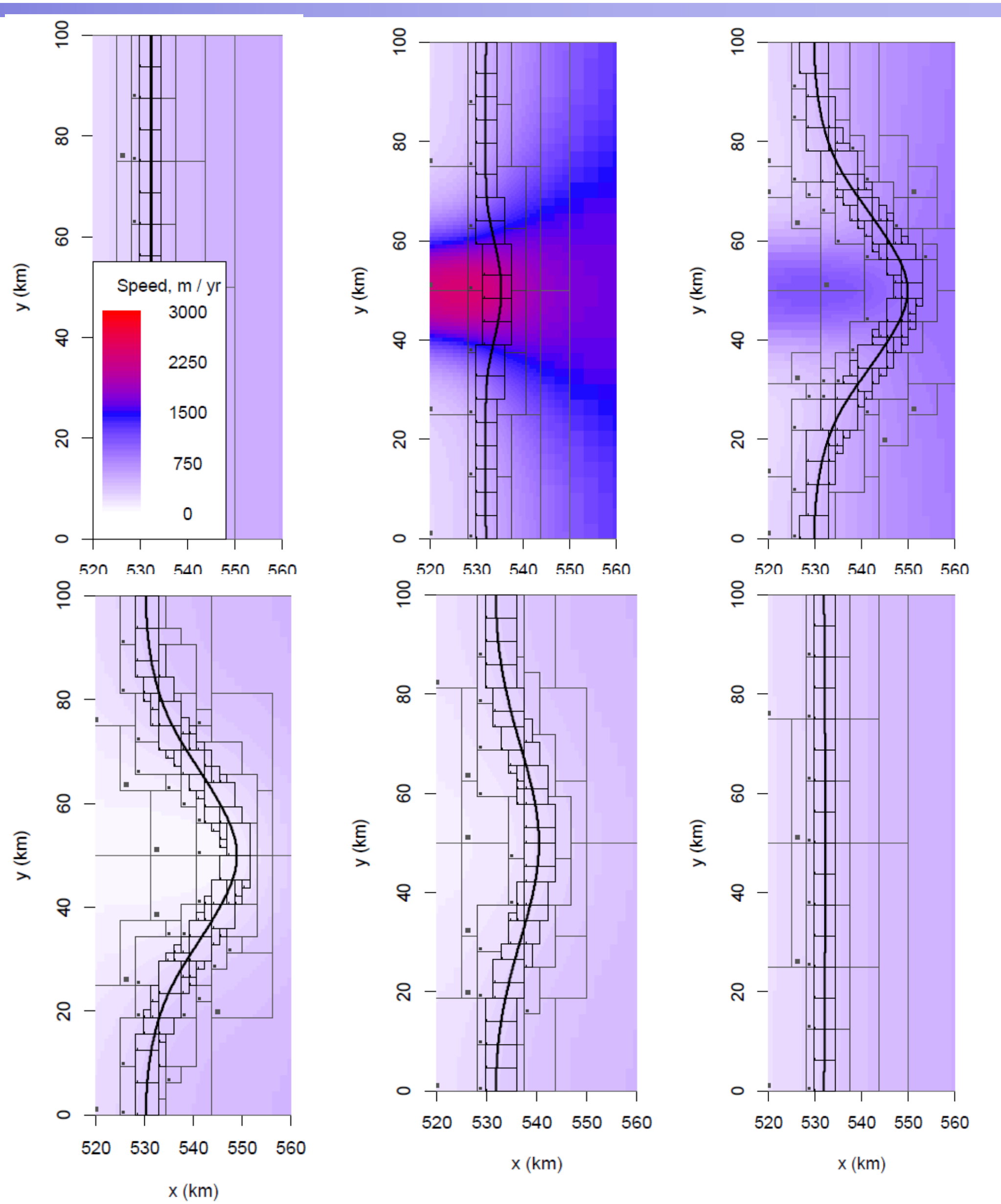
- Collaboration with Bristol (U.K.) and LANL
- Variant of "L1L2" model (Schoof and Hindmarsh, 2009)
- Coupled to Community Ice Sheet Model (CISM).
- Users in Berkeley, Bristol, Beijing, Brussels, and Berlin…



BISICLES Results - MISMIP3D

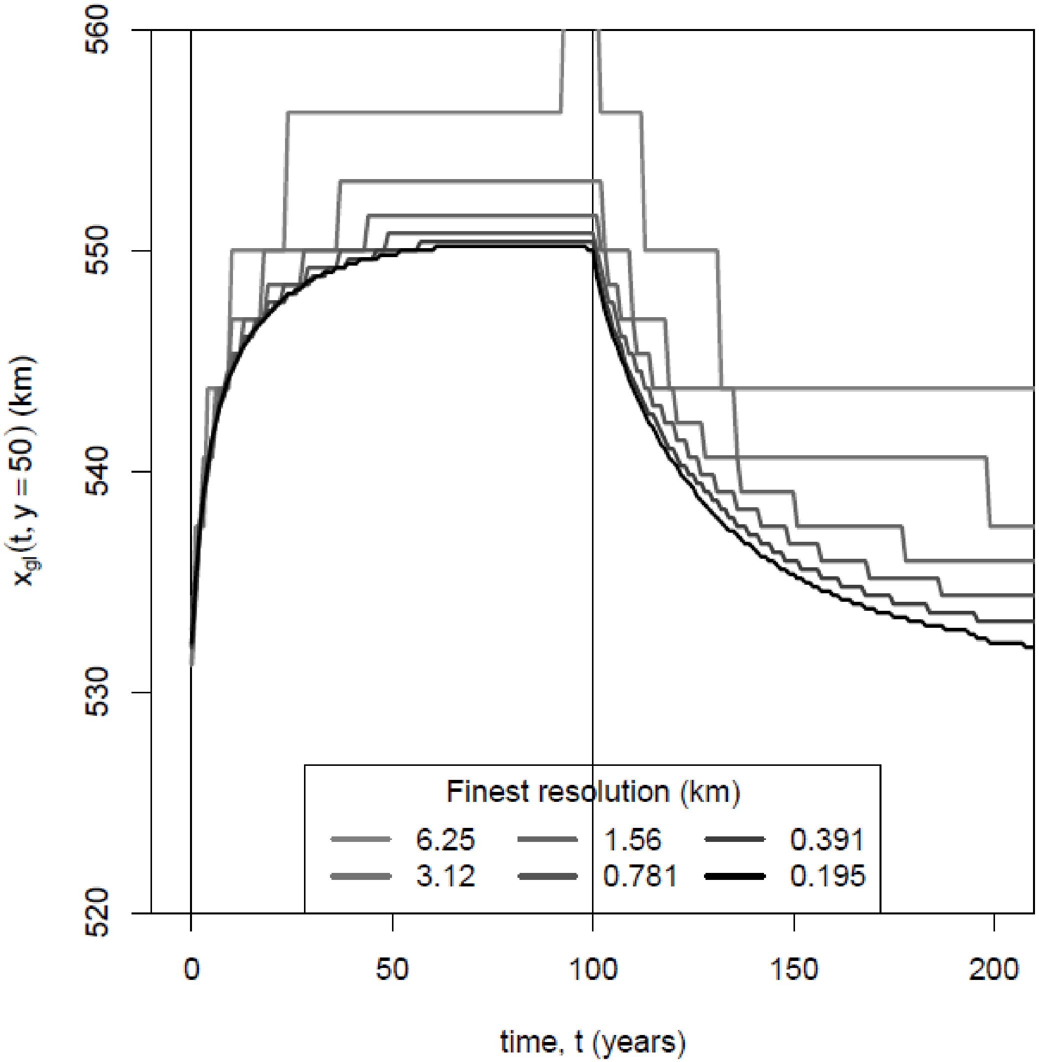
Experiment P75R:
(Pattyn et al (2011)

- 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)

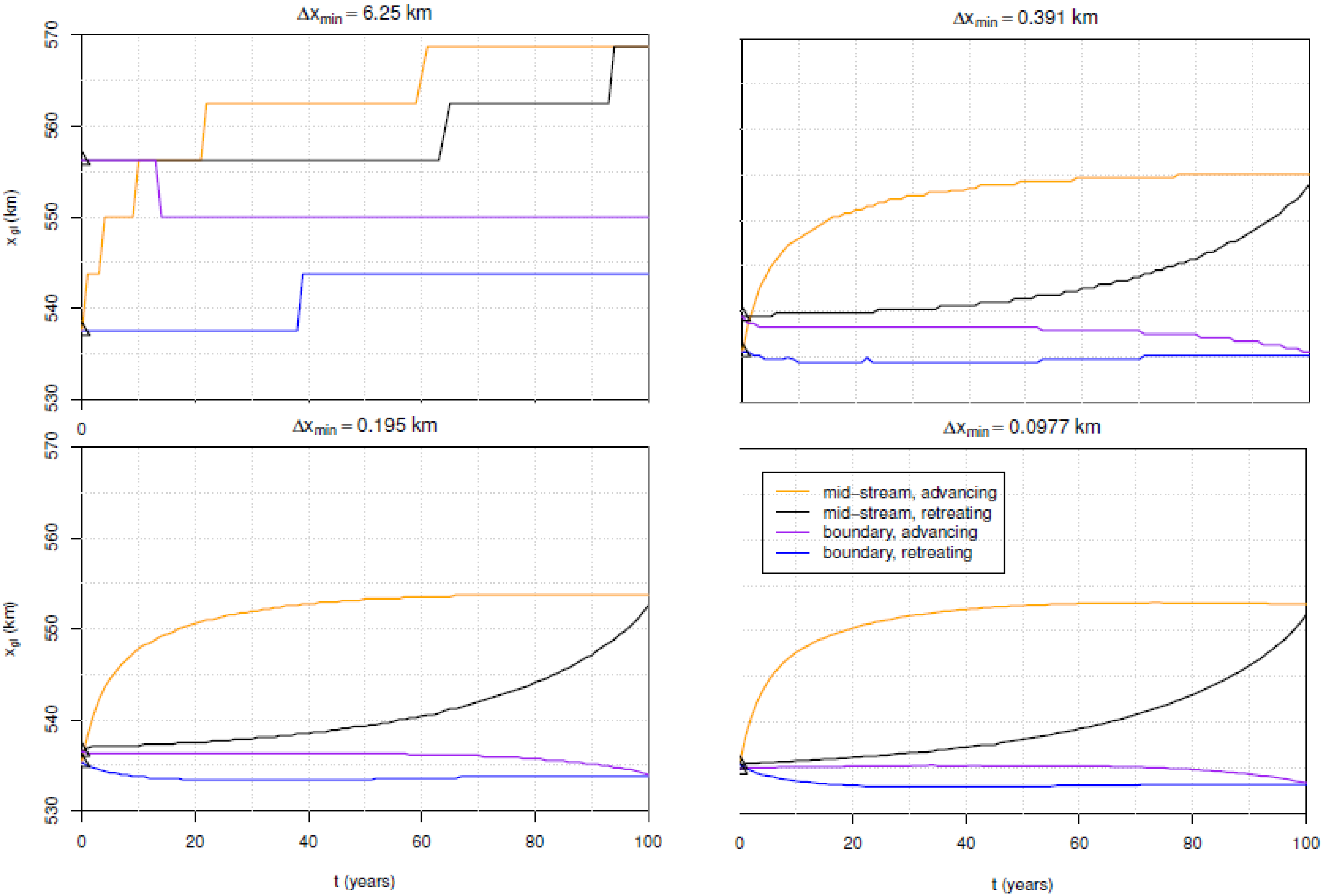


MISMIP3D: Mesh resolution

- 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)

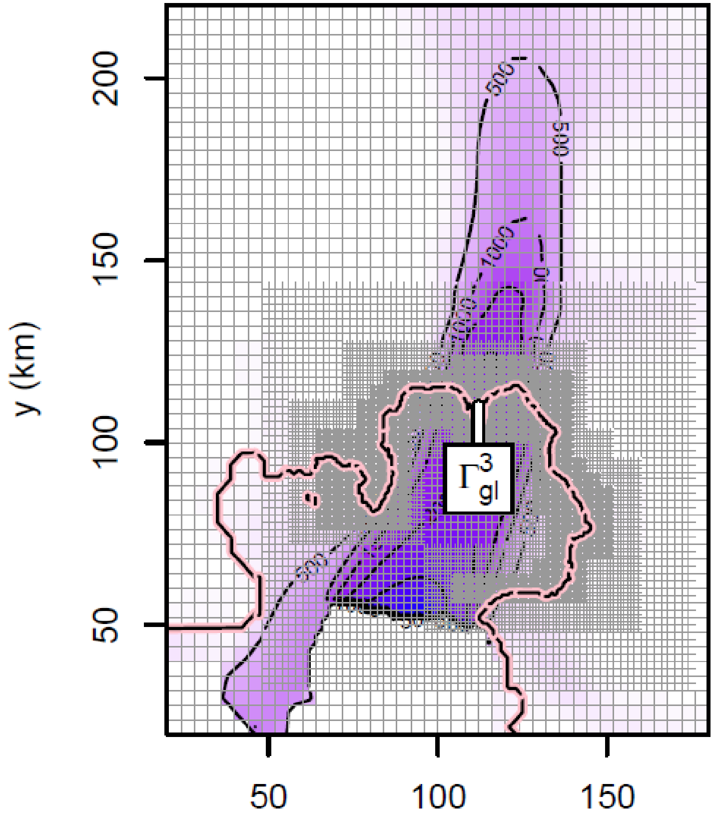


MISMIP3D (cont): Spatial Resolution

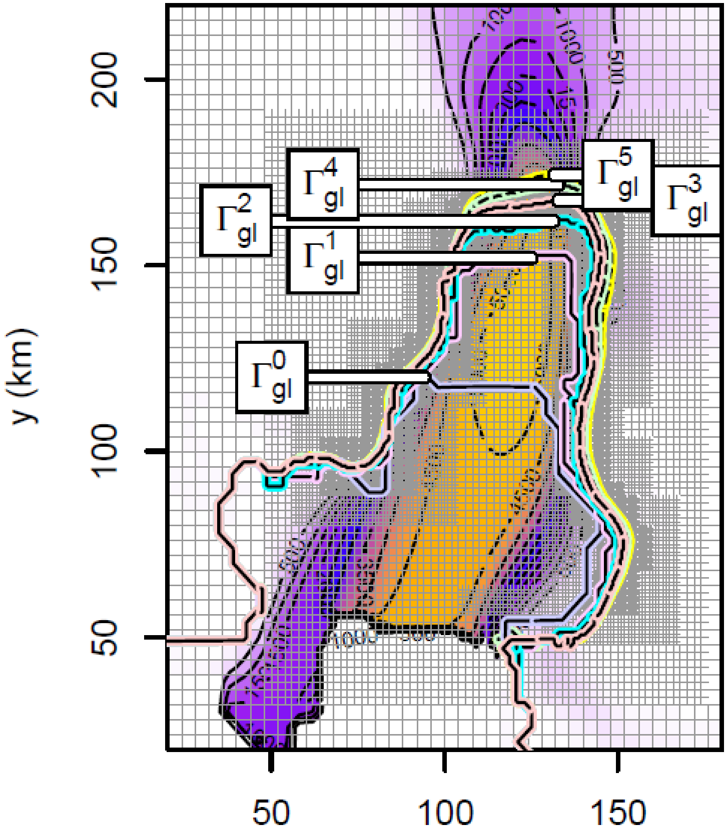


- Very fine (~200 m) resolution needed to achieve full reversibility!

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



Initial Condition



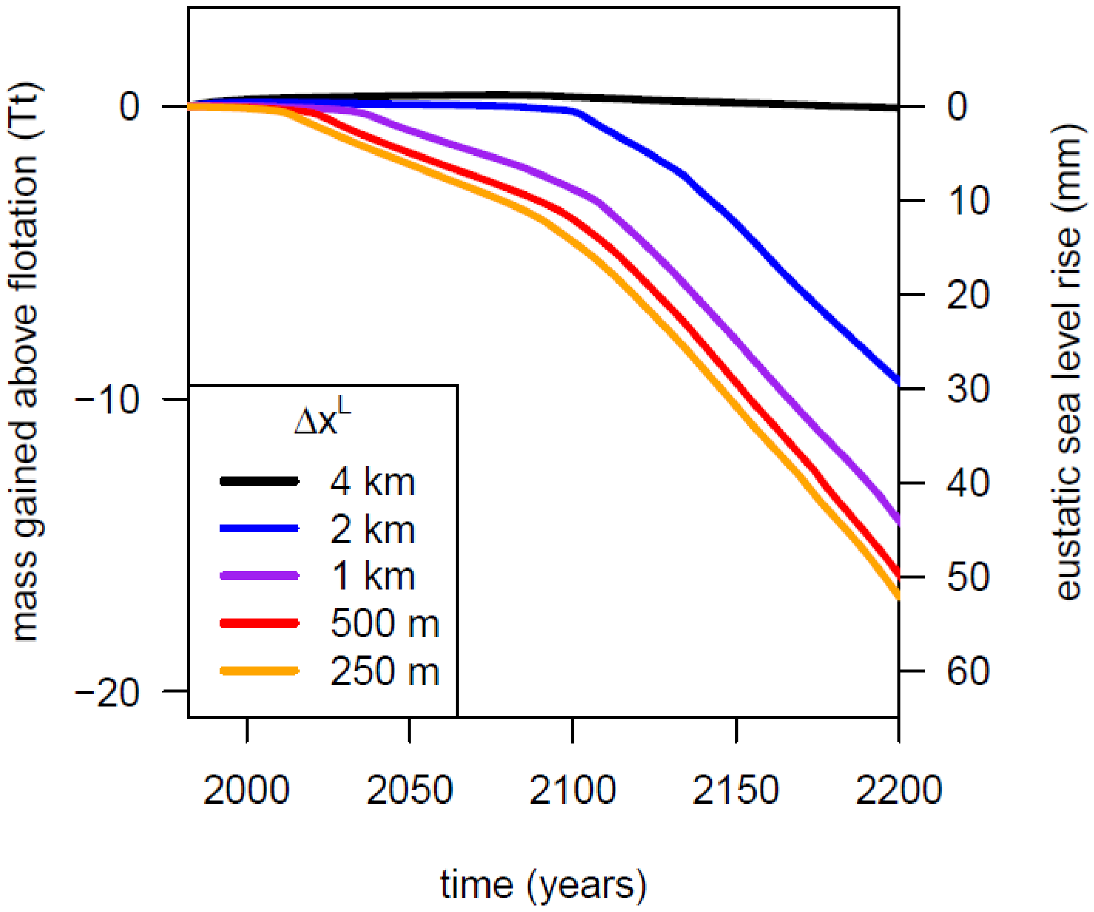
Solution after 30 years

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, The Cryosphere, accepted)

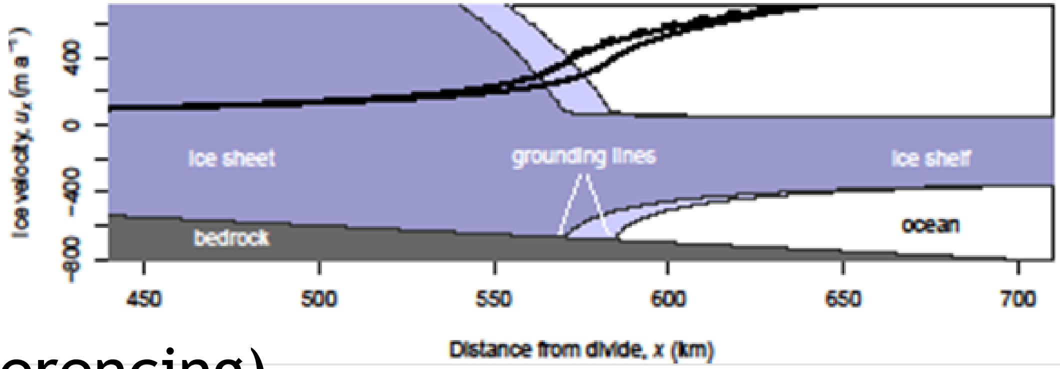
- Need at least 2 km resolution to get any measurable contribution to SLR.
- Sub-km is better.
- Appears to converge at first-order in Δx

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)



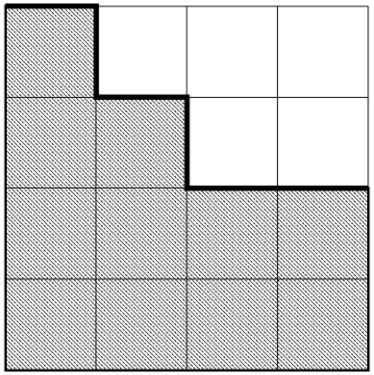
Other approaches

- 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

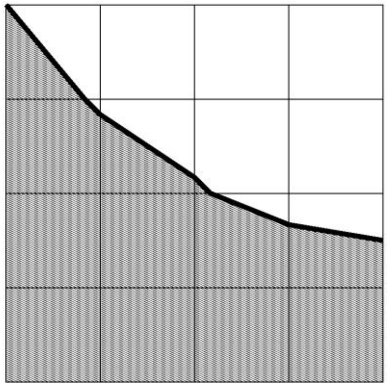
- **Embedded Boundary (EBChombo)**
  - Currently force GL and ice margins to cell faces



  - "Stair-step" discretization

    Known to be inadequate from experience with Stefan Problem in other contexts!

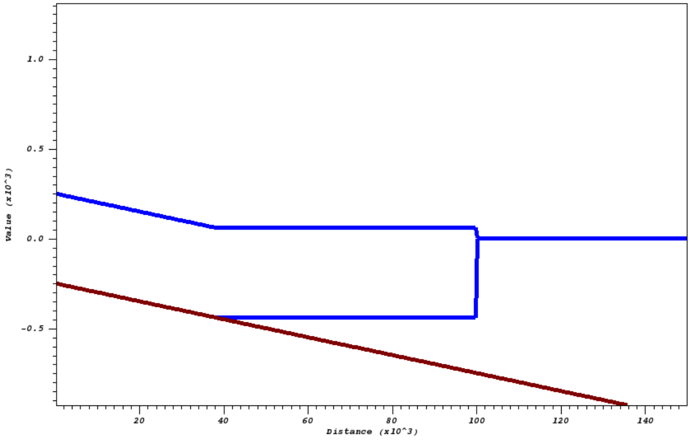
  - Use Chombo Embedded-boundary support to improve discretization of GL's and ice margins.

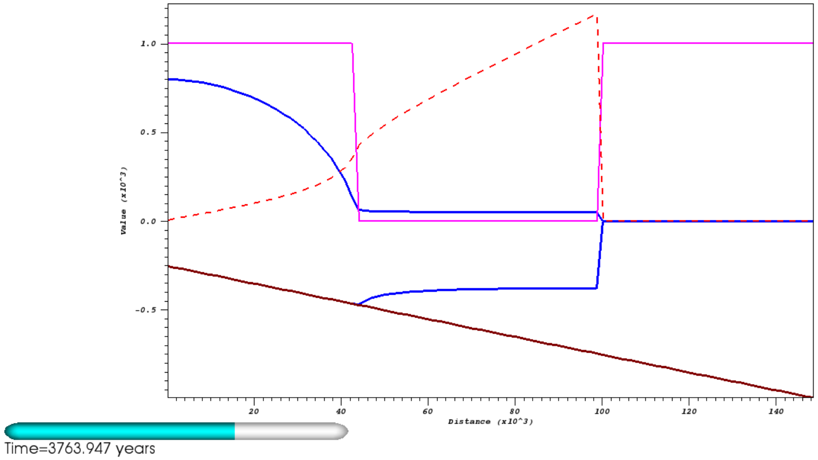


  - Can solve as a Stefan Problem, with appropriate jump conditions enforced at grounding line. (as in Schoof, 2007)

Flowline (1D) model problem

- Based on Vieli and Payne (2005)





- **SSA** Momentum balance reduces to:

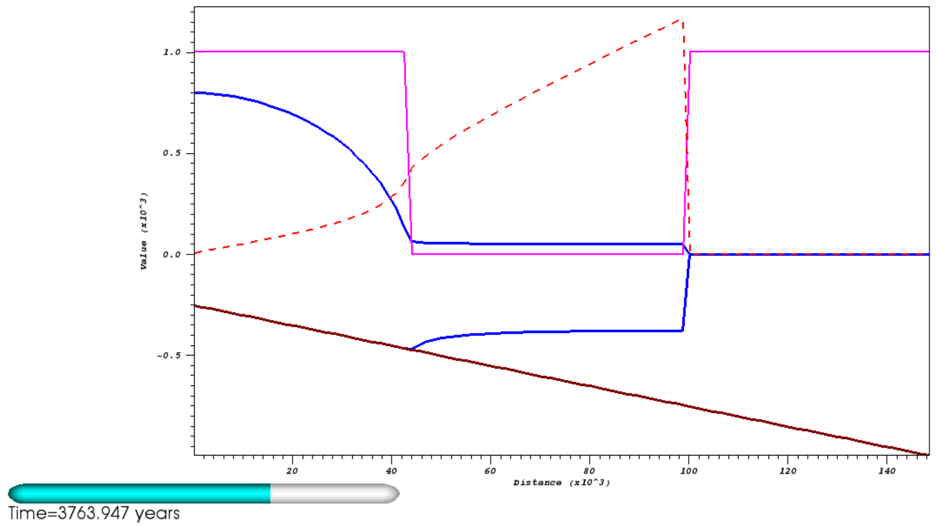
$$\left(\beta - \frac{\partial}{\partial x}\left(4\mu H \frac{\partial}{\partial x}\right)\right) u_b = -\rho g H \frac{\partial s}{\partial x}$$

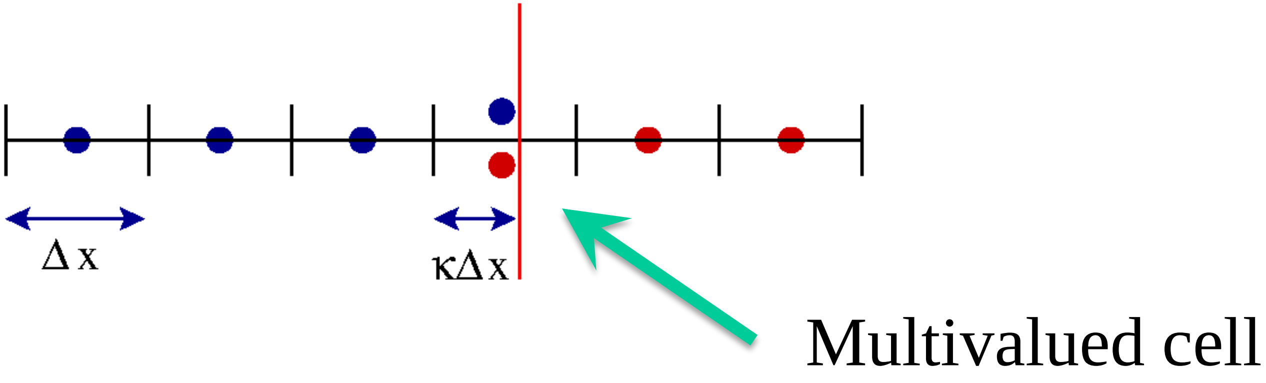
- Mass Conservation reduces to:

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

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):

$$[H] = 0$$

$$[u] = 0$$

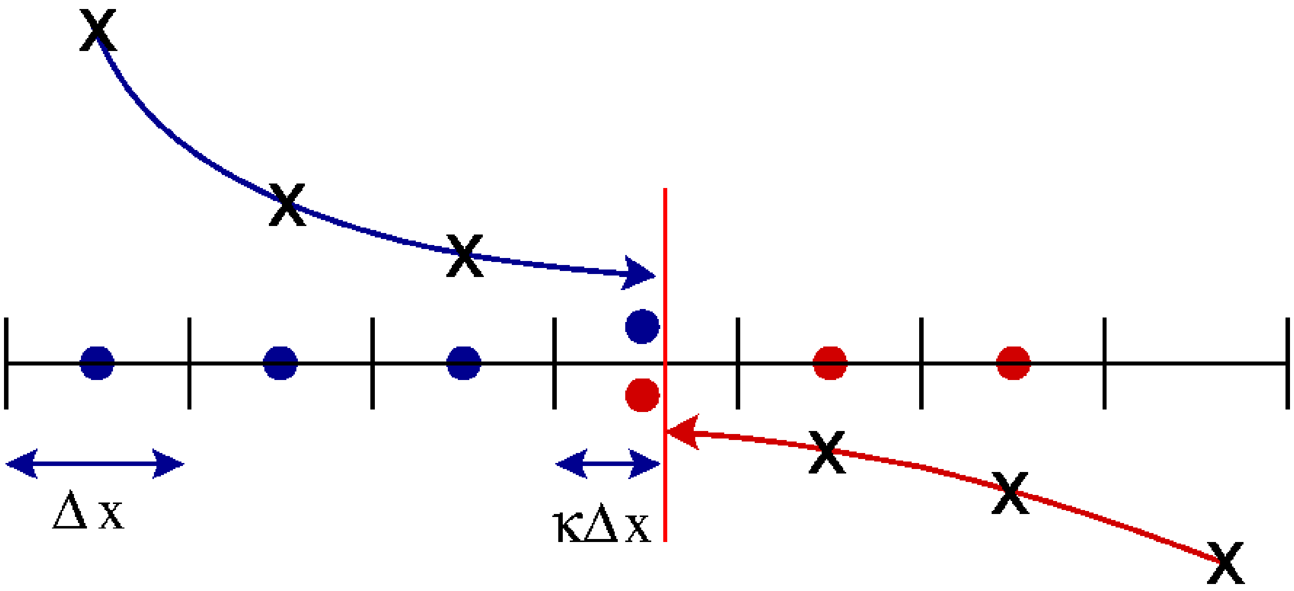
$$[u_b] = 0$$

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

- System currently solved exactly (Gaussian elimination)

Multifluid Velocity Solve (cont)

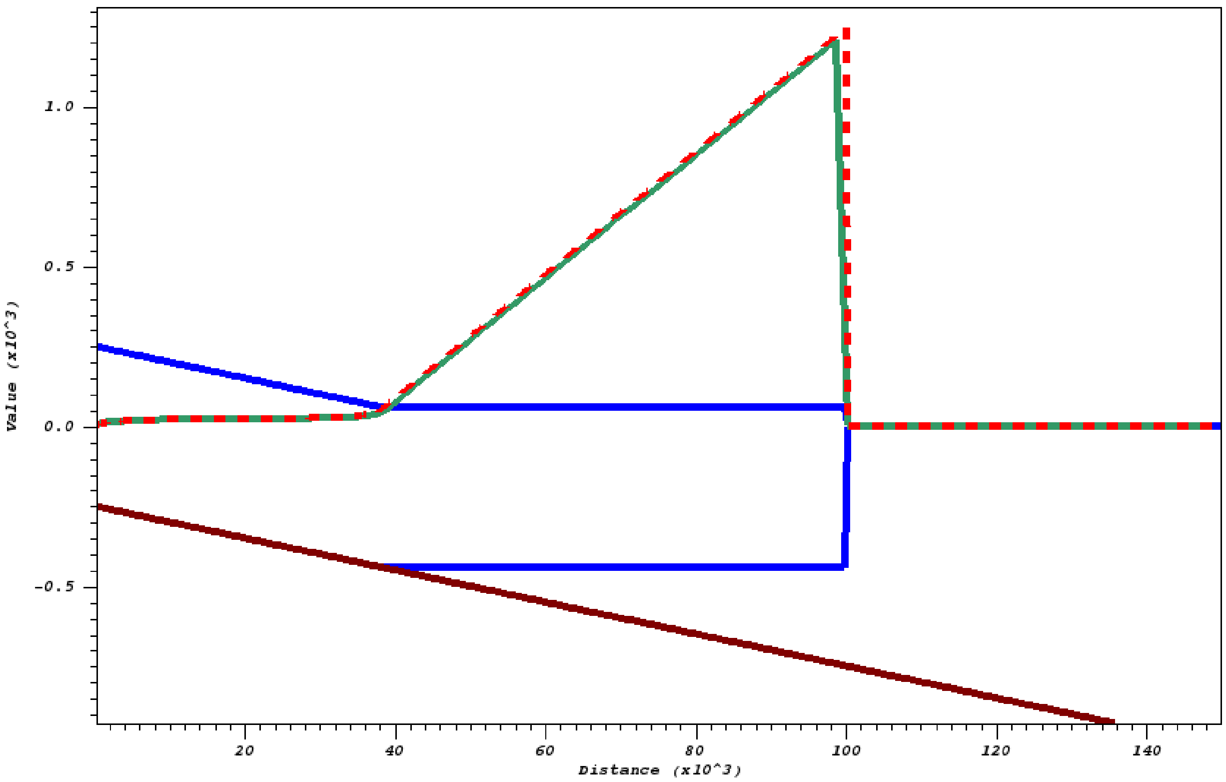
- Multifluid extrapolation to faces:



- 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

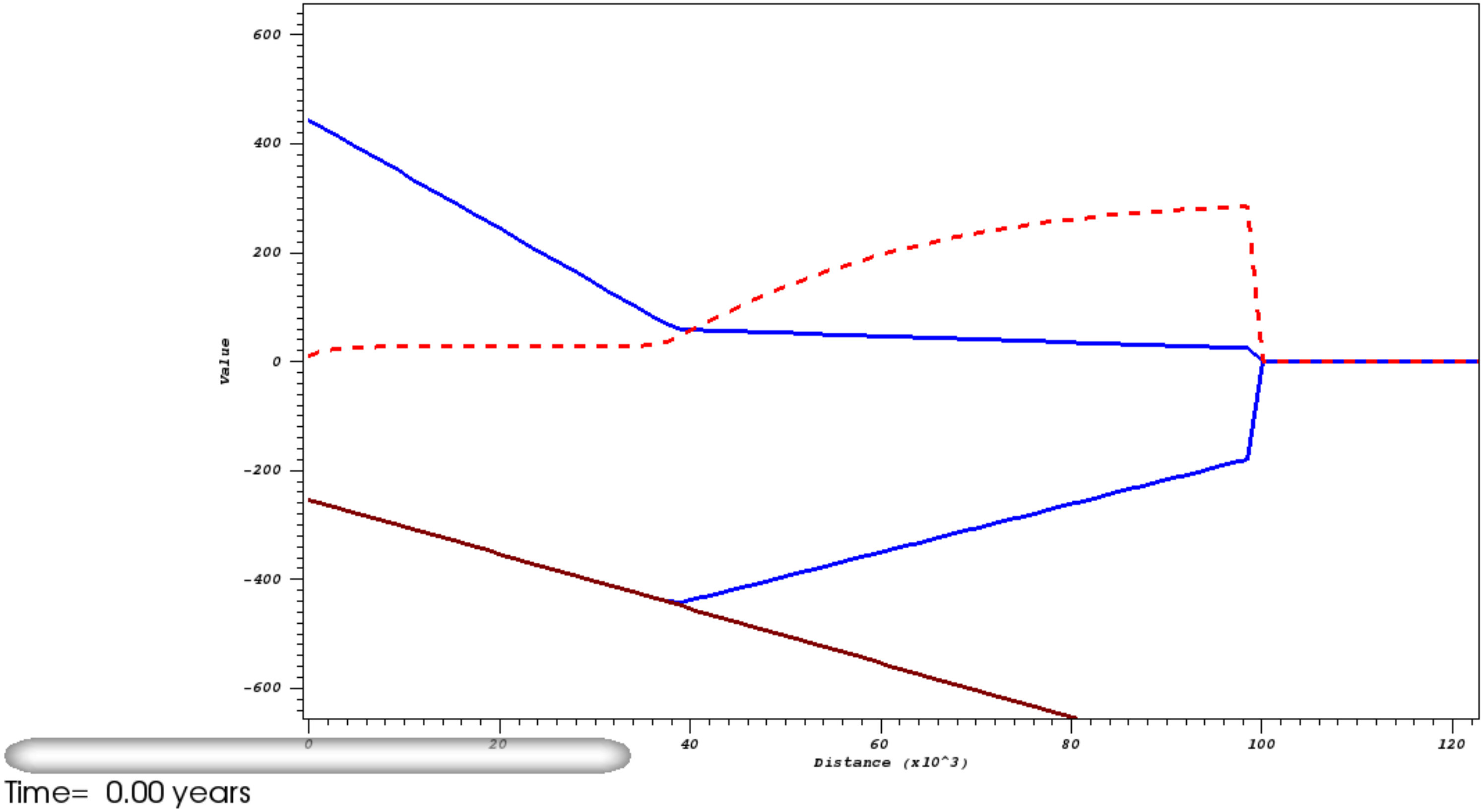
Two possible advection/evolution options:

1. Explicitly move GL based on local thickness change and basal slope. (stability constraint based on gl speed)

1. Recompute GL every time based on finding the levelset where thickness over flotation is zero.
   A. Use finite-volume formulation –
      i. Compute face-centered thickness fluxes (uH)
      ii. Update entire multivalued cell normally.
      iii. Recompute levelset location based on new thickness field.

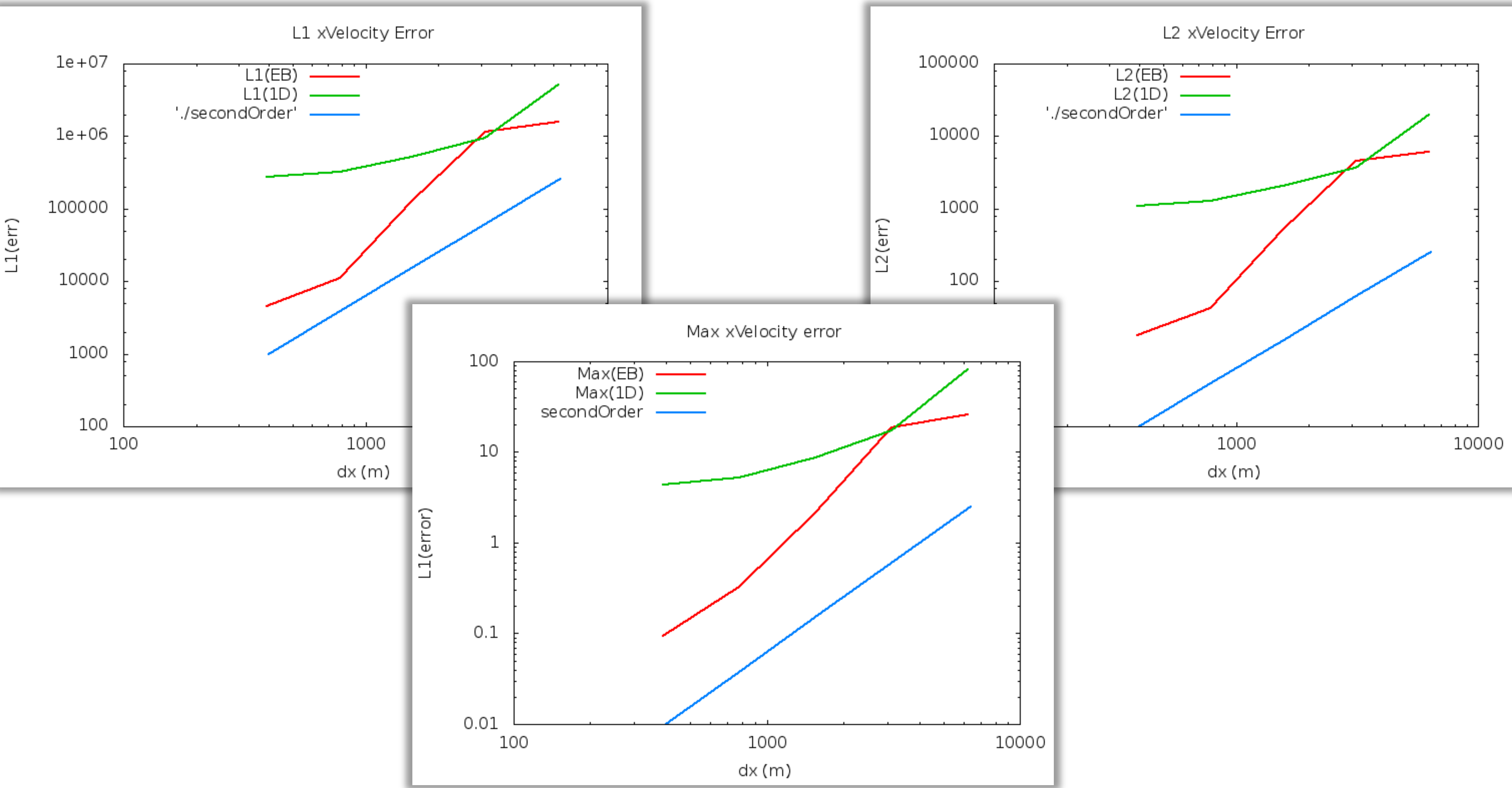
Example – 1D Grounding-line advance

- Planar slope, constant friction $\beta = 1000$, constant snowfall ($\dot{m} = 10m/a$).
- Linear-in-x initial H profile (non-linear shelf velocity)

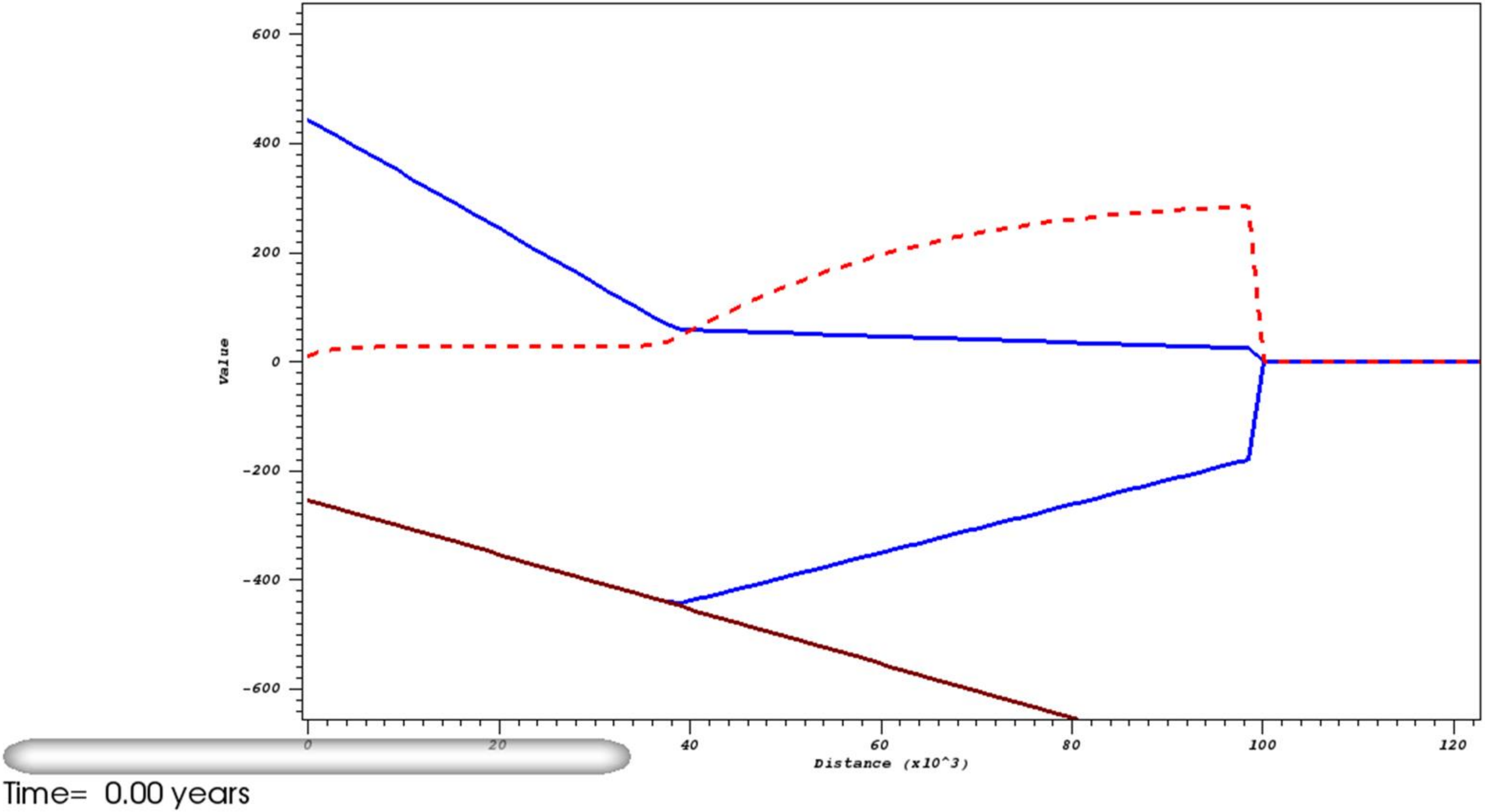


Example – 1D Grounding-line advance (cont)

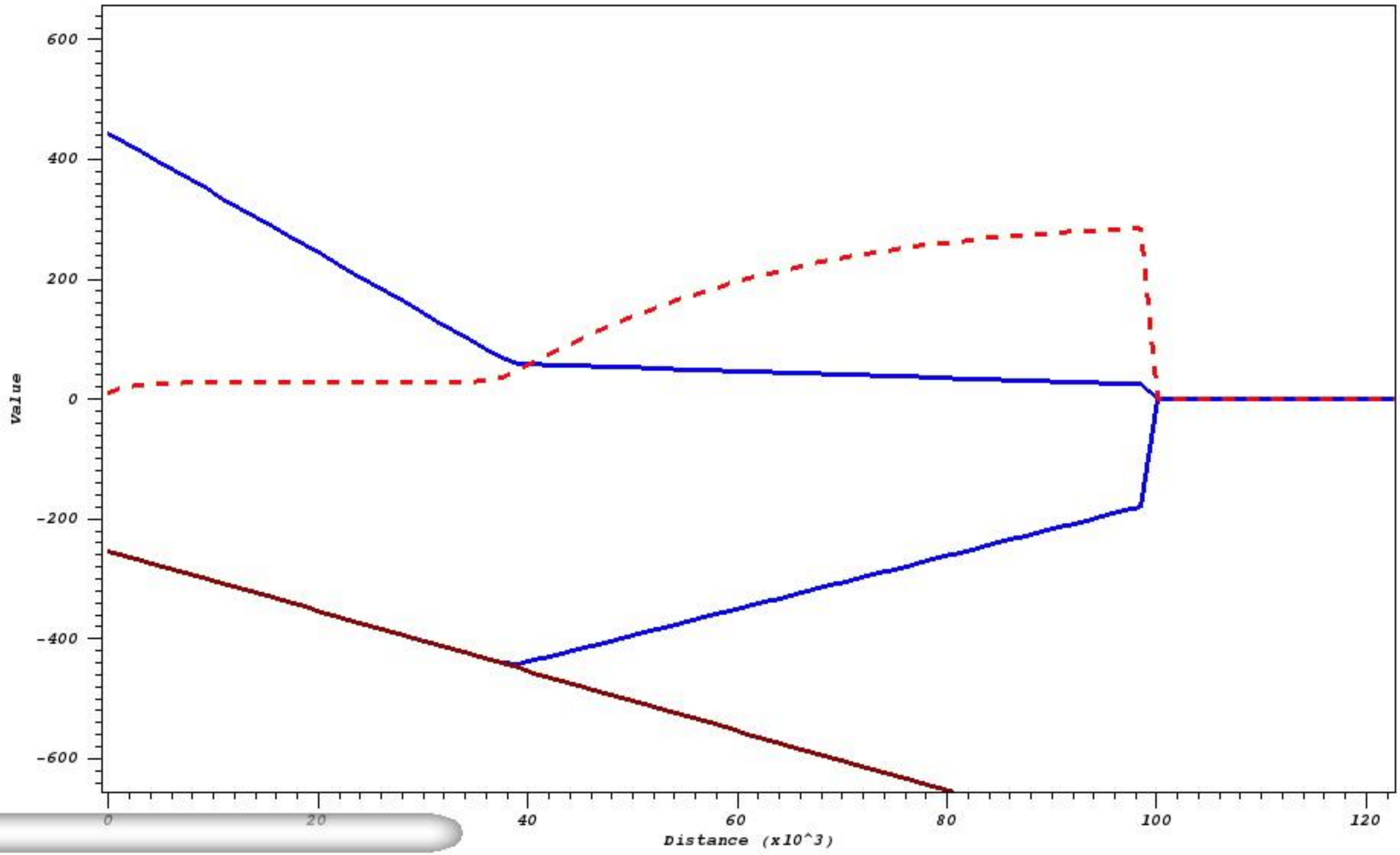
Convergence of initial velocity field



Example – 1D Grounding-line advance (cont)



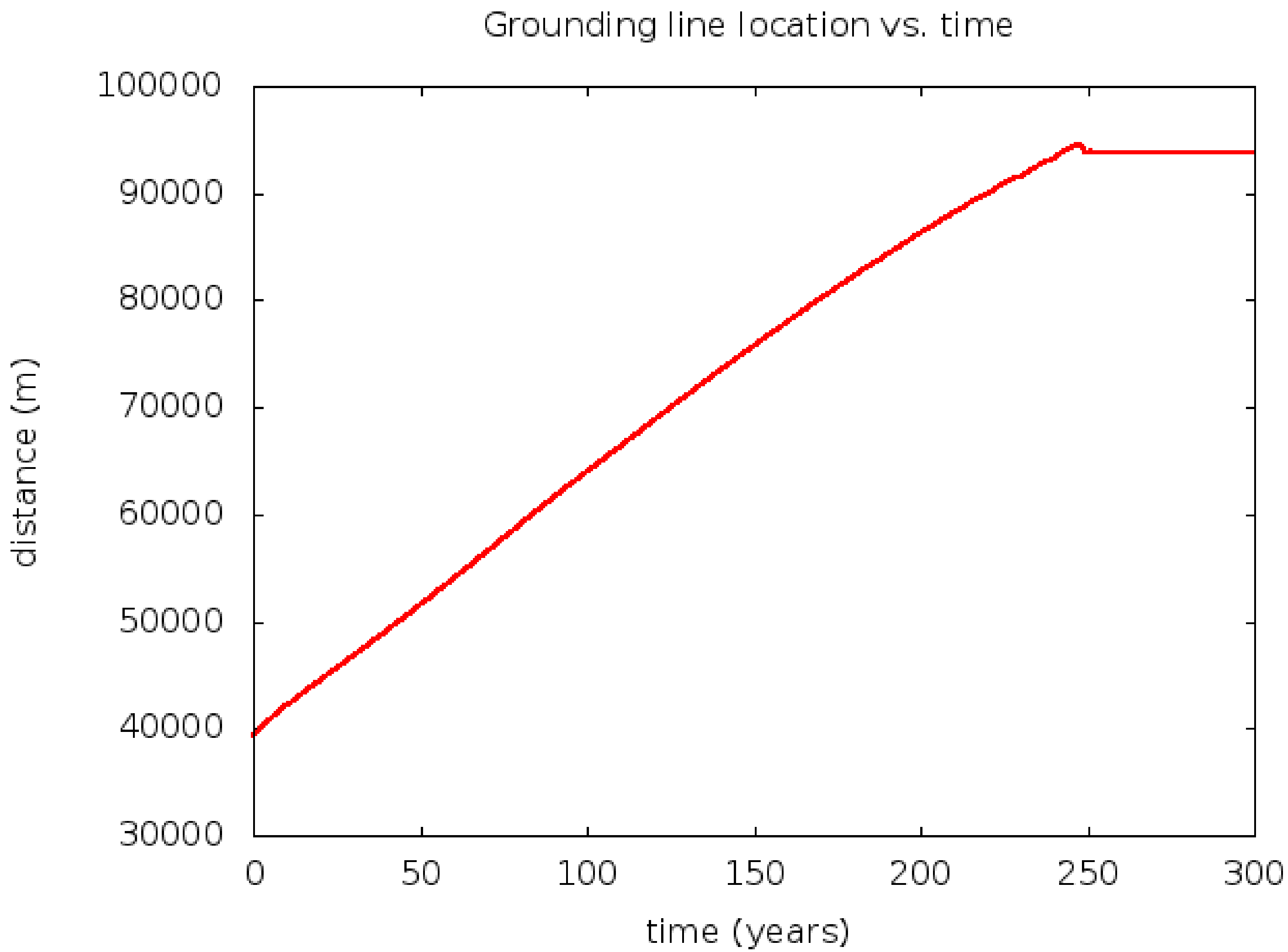
Example – 1D Grounding-line advance (cont)



Time= 0.00 years

Example – 1D Grounding-line advance (cont)

Grounding-point Motion



Conclusions

- Fine (sub 1-km) resolution required to get grounding lines right for “normal” models
- Evidence suggests that better discretizations at grounding lines may help relax resolution requirement
- Can treat GL as multifluid interfaces between 2 phases
- 1D SSA Test code looks promising

Future work

- Further 1D testing:
  - L1L2

- 2D (planview) SSA and L1L2

- (Hopefully) incorporation into “mainline” BISICLES

Acknowledgements:

- US Department of Energy Office of Science (ASCR/BER) SciDAC applications program (PISCEES)
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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.