# Recent progress with the BISICLES dynamical core in CISM

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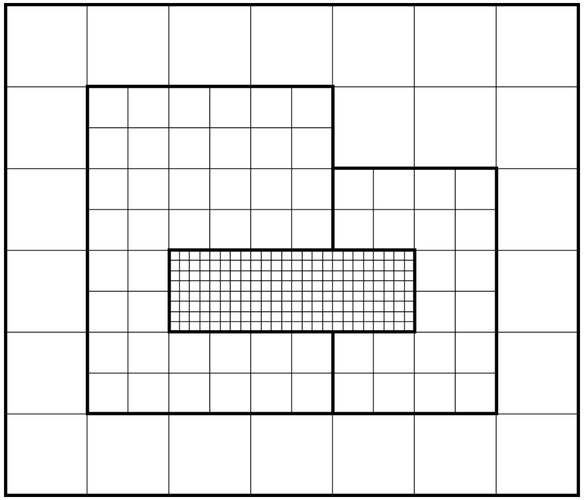
# Berkeley-ISICLES (BISICLES)

- 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)
- Alternate dycore interface to CISM
- Collaboration with LANL and Bristol (U.K.)
- Continuation in SciDAC-funded PISCEES.



# "L1L2" Model (Schoof and Hindmarsh, 2010).

- Uses asymptotic structure of full Stokes system to construct a higher-order approximation
  - Expansion in $\varepsilon = \frac{[H]}{[L]}$ and $\lambda = \frac{[\tau_{shear}]}{[\tau_{normal}]}$ (ratio of shear & normal stresses)
    - Large $\lambda$: shear-dominated flow
    - Small $\lambda$: sliding-dominated flow
  - 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 $O(\varepsilon^2)$

# "L1L2" Model (Schoof and Hindmarsh, 2010), cont.

- Can construct a computationally efficient scheme:

1. Approximate constitutive relation relating $grad(u)$ and stress field $\tau$ with one relating $grad(u|_{z=b})$, vertical shear stresses $\tau_{xz}$ and $\tau_{xz}$ 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 $u|_{z=b}(x,y)$

# *Modified "L1L2" Model (SSA*)*

- Can construct a computationally efficient scheme:
  1. Approximate constitutive relation relating $grad(u)$ and stress field $\tau$ with one relating $grad(u|_{z=b})$, vertical shear stresses $\tau_{xz}$ and $\tau_{xz}$ 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 $u|_{z=b}(x,y)$

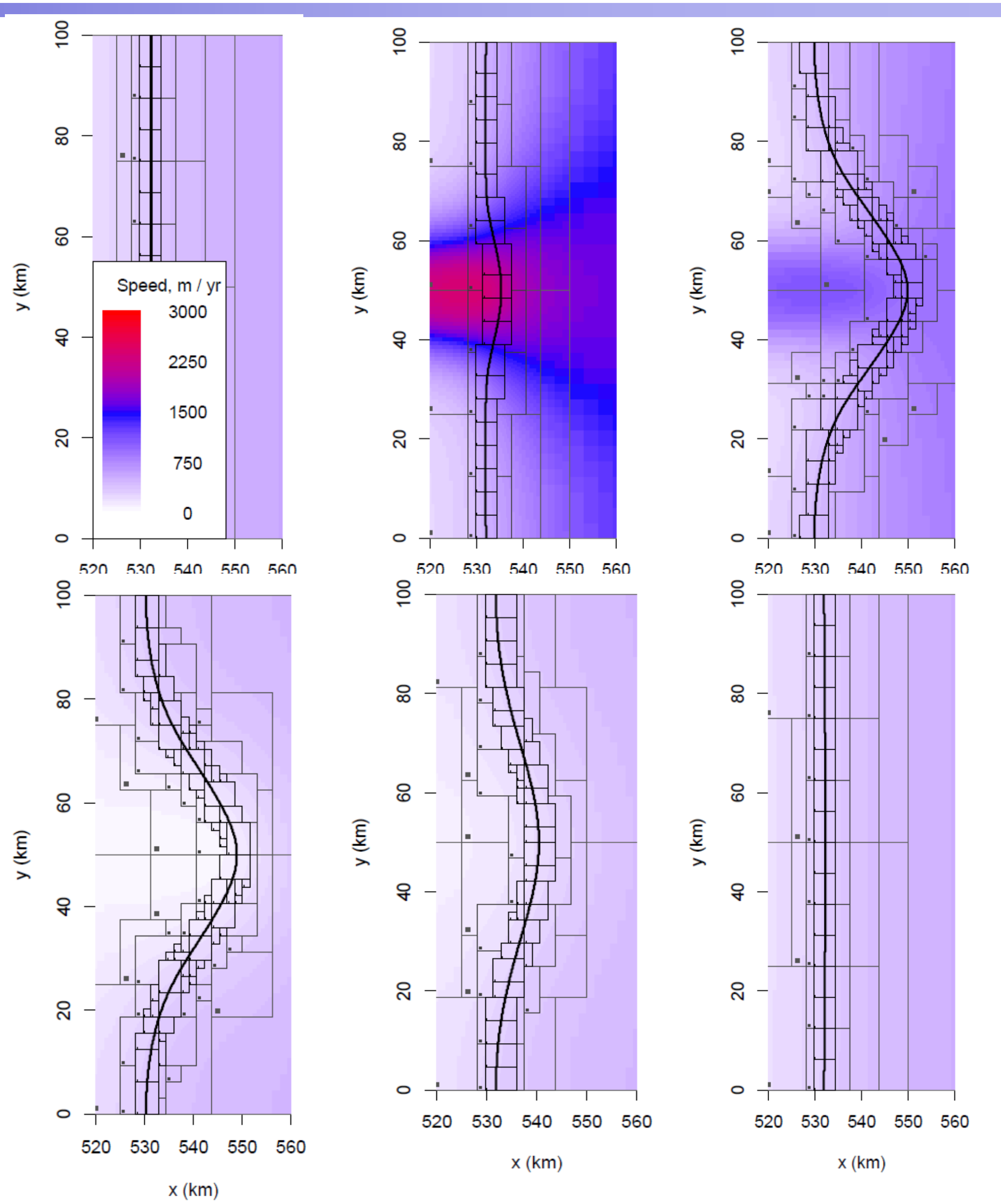
  4. $u(x,y,z)$ can be [illegible] $(x,y)$

  4. Use $u(x,y,z) = u|_{z=b}(x,y)$ (neglect vertical shear in flux velocity)

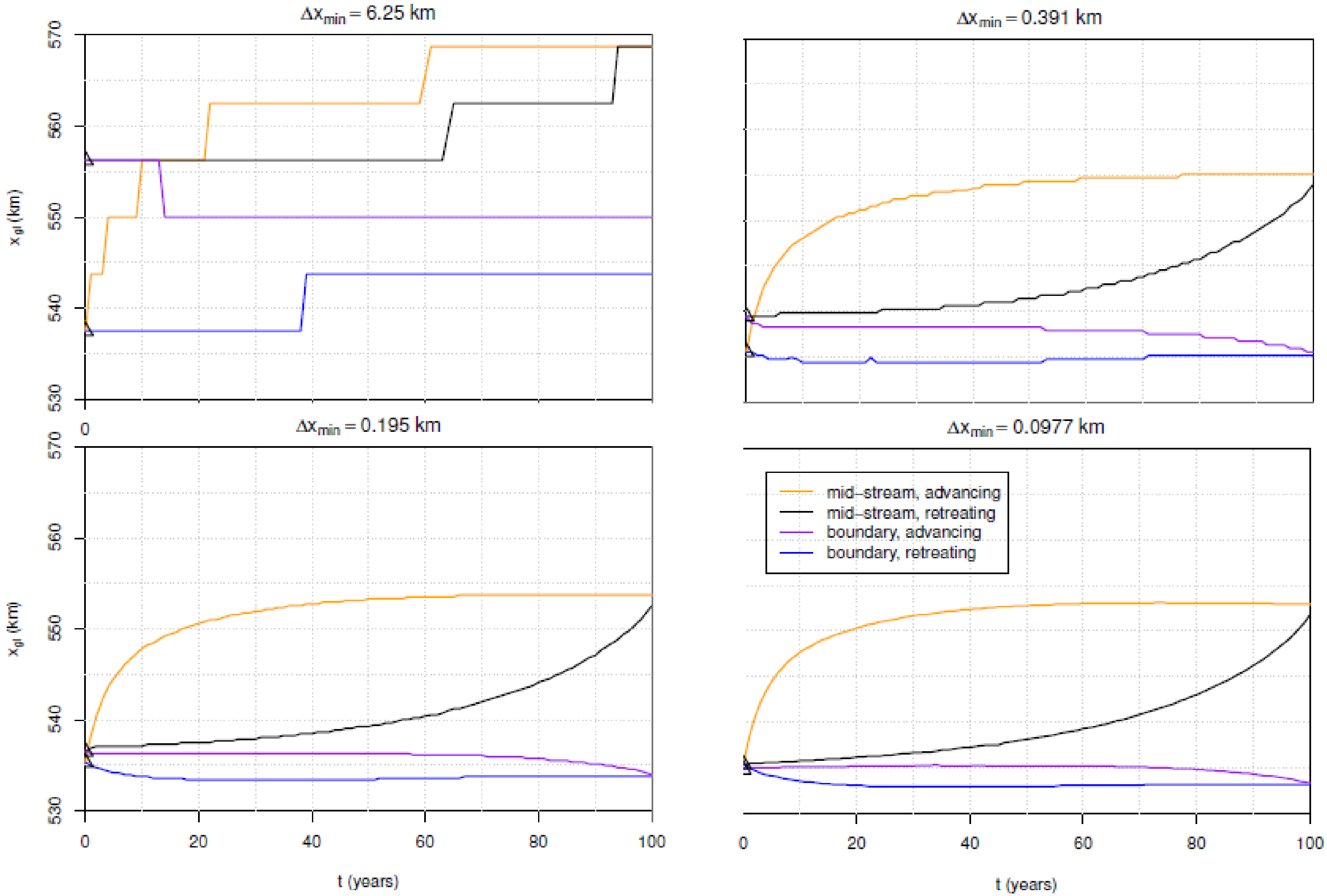
# BISICLES Results - MISMIP3D

## 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)

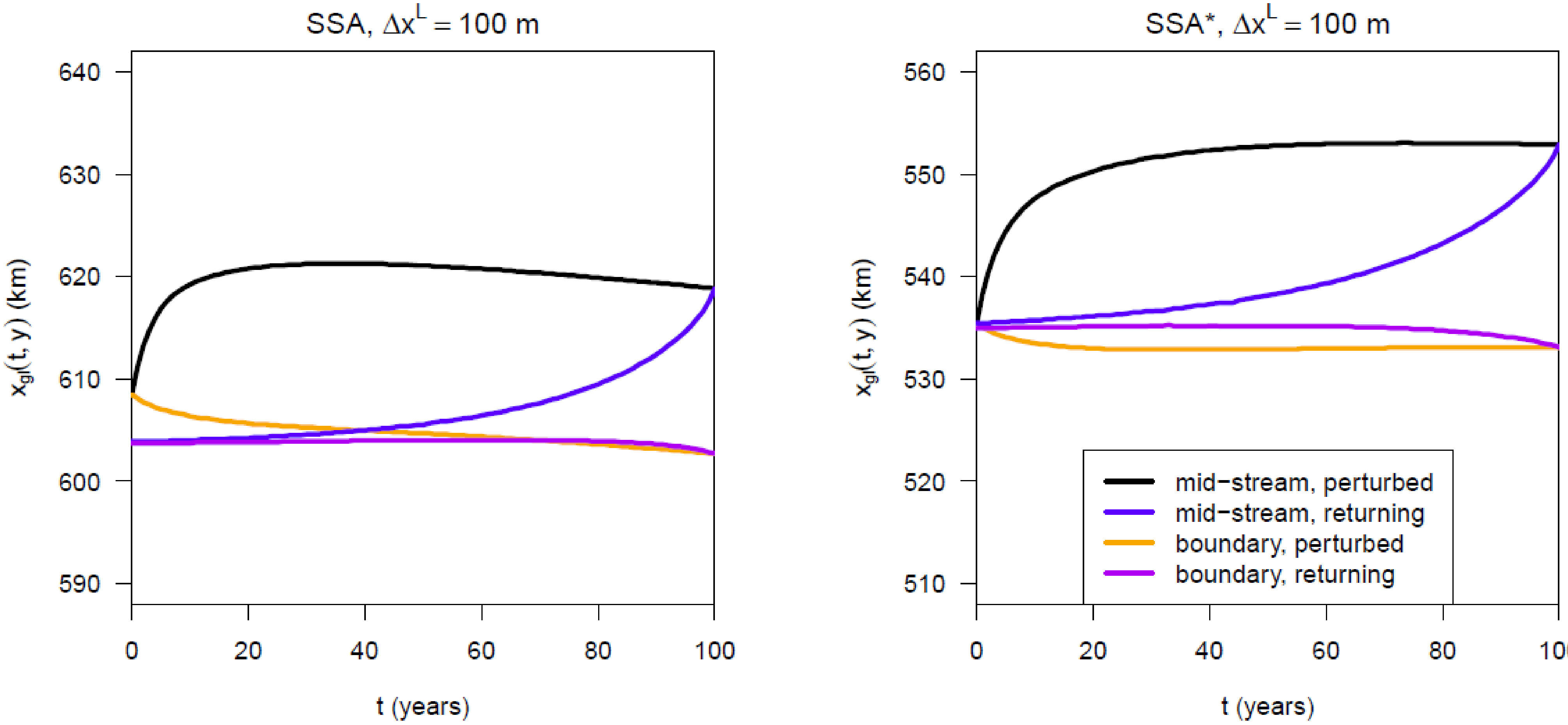


# MISMIP3D (cont): L1L2 (SSA*) Spatial Resolution




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

# MISMIP3D: SSA vs. "L1L2" or "SSA*"




- Direct comparison of SSA vs. SSA*
  - (fully resolved spatially, same numerics, etc)
  - Note difference in steady-state GL positions

# 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 21$^{st}$ Century,
  - ~25 m/a in 22$^{nd}$ Century.

# *Ice2Sea Amundsen (cont)*

**Amundsen Sea Ice Sheet Simulation**

One possible climate scenario (Payne et al.)
simulated using SciDAC-funded BISICLES code

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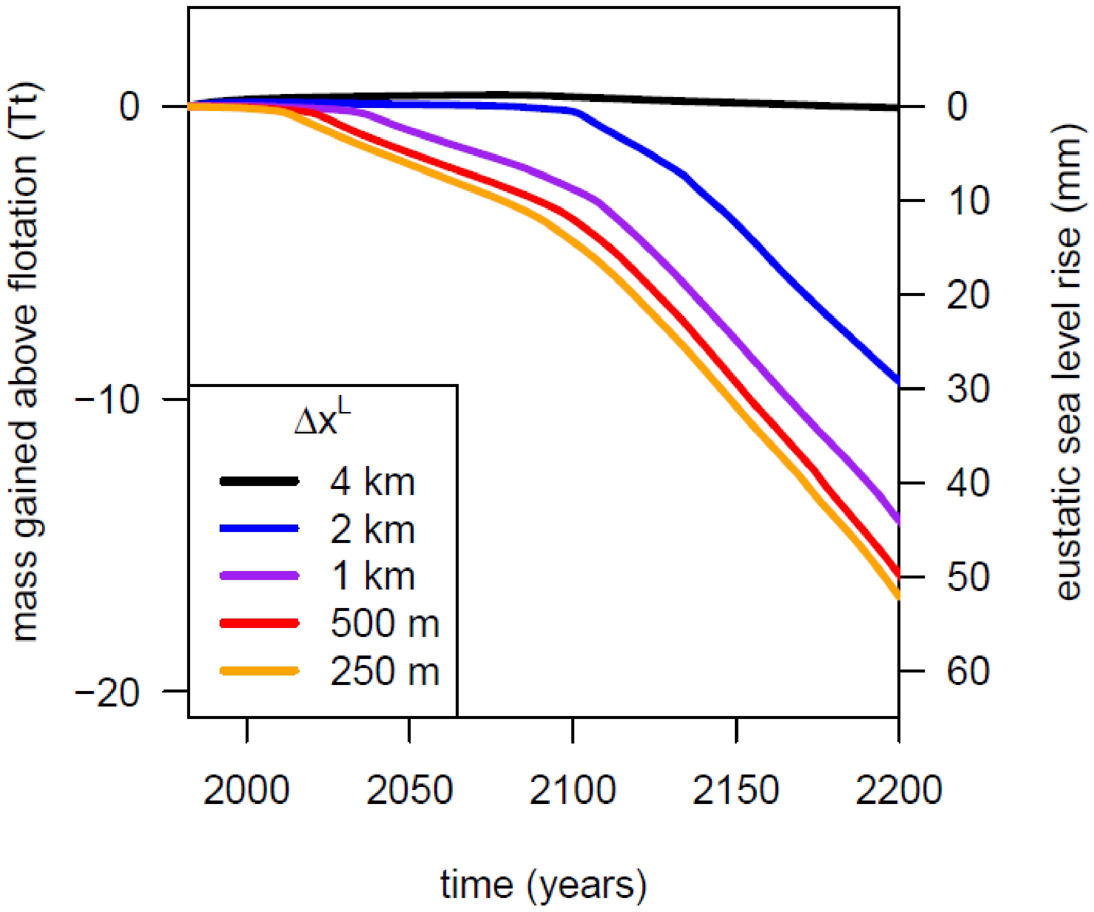
# Ice2Sea Amundsen (cont)

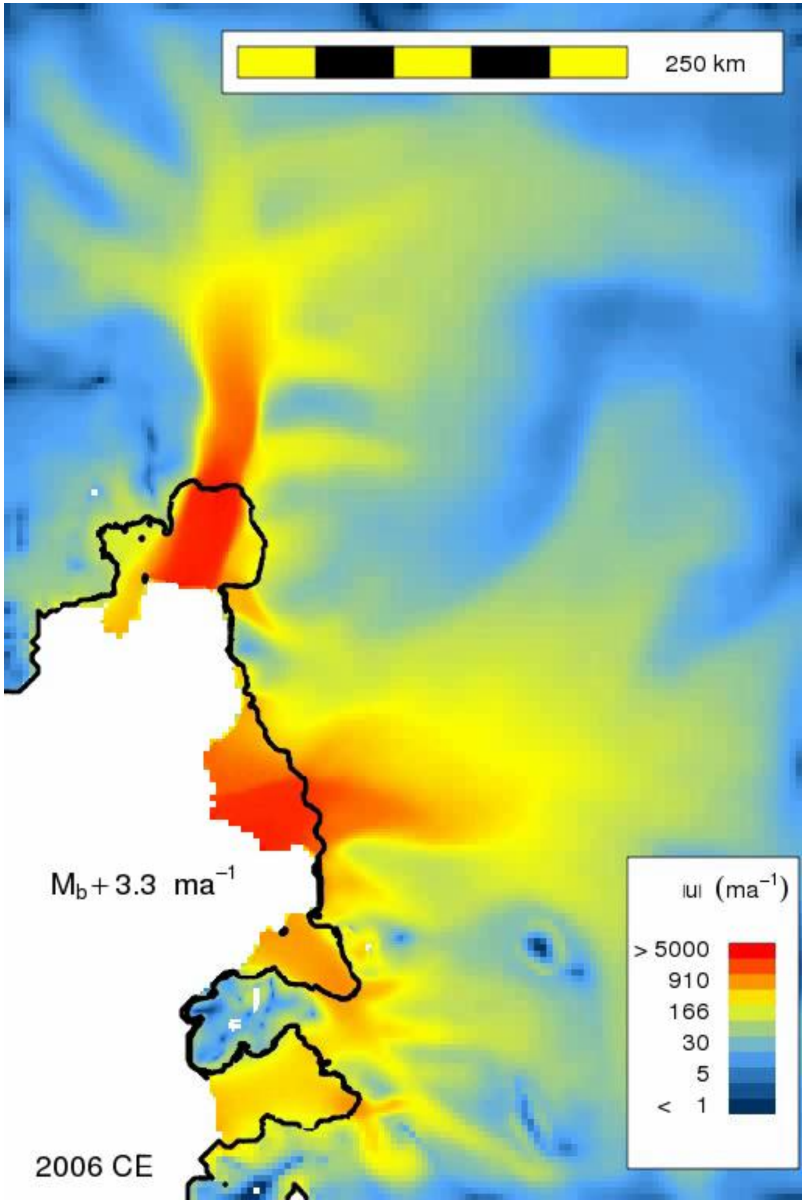
- Need at least 2 km resolution to get any measurable contribution to SLR.
- Appears to converge at first-order in Δx

SLR vs. year, Amundsen Sea Sector



# Ice2Sea Amundsen (cont) – Thwaites?

- In 400 year run, Thwaites destabilizes as well.
- Same forcing as previous run, subshelf melting held constant past 2200.
- Thwaites is very stable, until it tips.



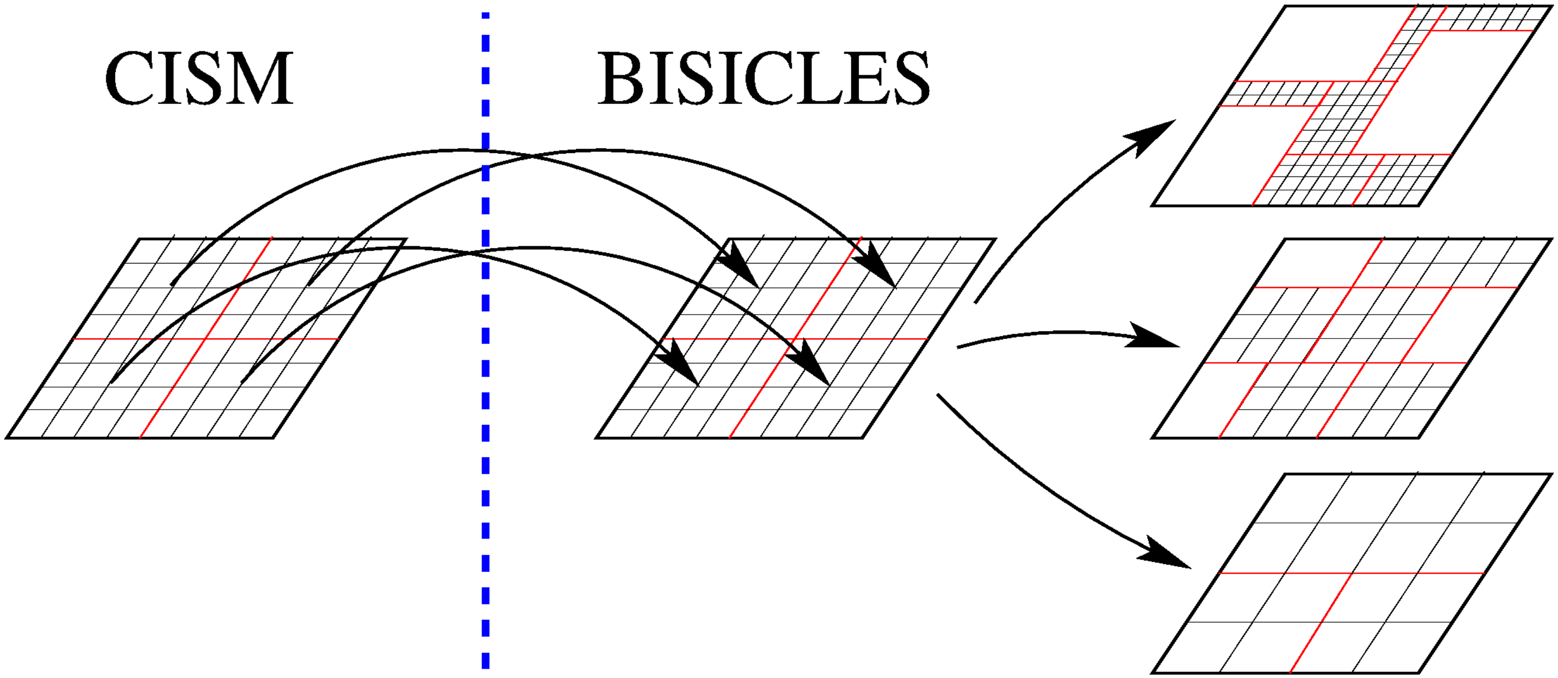
# Recent Code developments

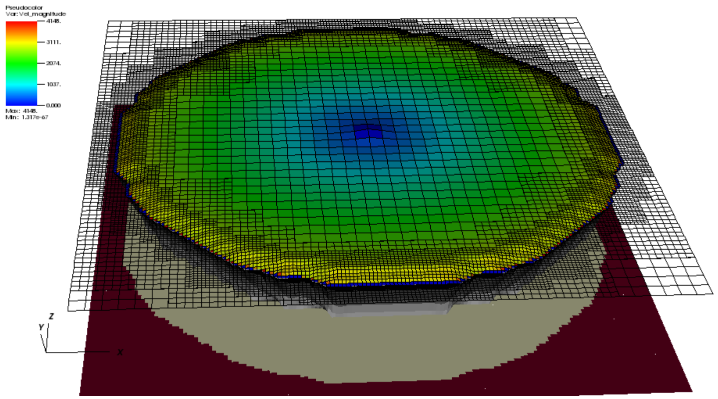
- BISICLES/CISM coupling
- FAS multigrid solver
- Embedded boundary for Grounding lines

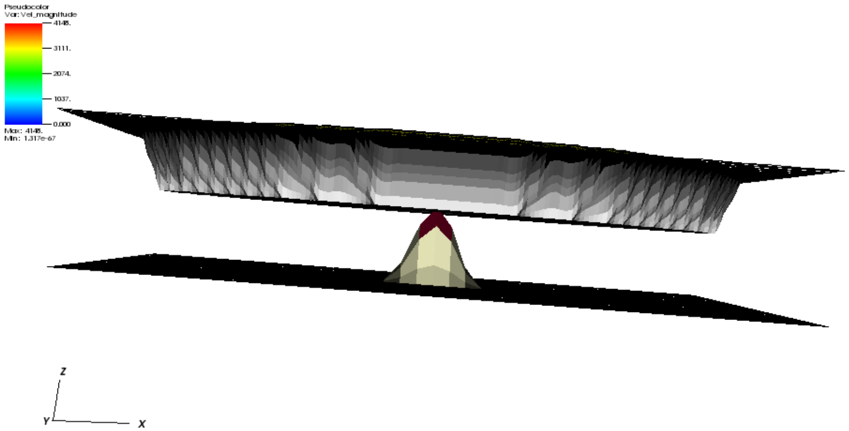
# *CISM/BISICLES coupling update*

- Extension of existing serial coupled code to work in the fully distributed case (no serial bottlenecks)
- CISM (F90) to BISICLES (C++)
- General API design for coupling alternate dynamical cores into CISM
- Moderately complex build process (working to streamline)
- CISM owns "main", problem setup, coupler to CESM, other physics (like isostasy, hydrology, etc)
- CISM hands control to BISICLES, which evolves the ice sheet
- BISICLES passes fields like thickness, velocity back to CISM

# *CISM/BISICLES coupling update (cont)*

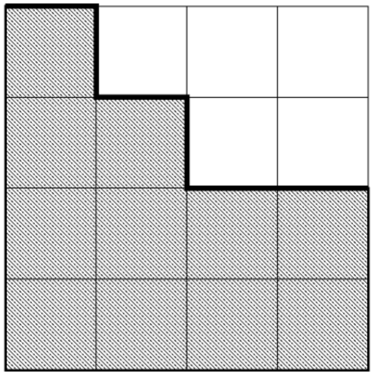


# Embedded Boundary (EB) for Grounding Lines

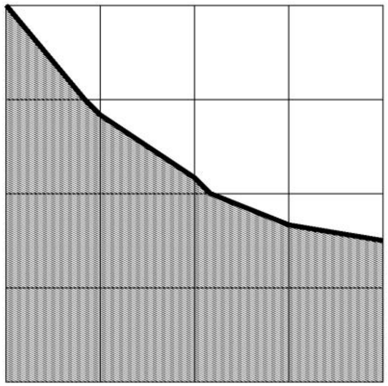
- **Embedded Boundary (EBChombo)**
  - Currently force GL and ice margins to cell faces



  - "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)

# New FAS Multigrid nonlinear solver

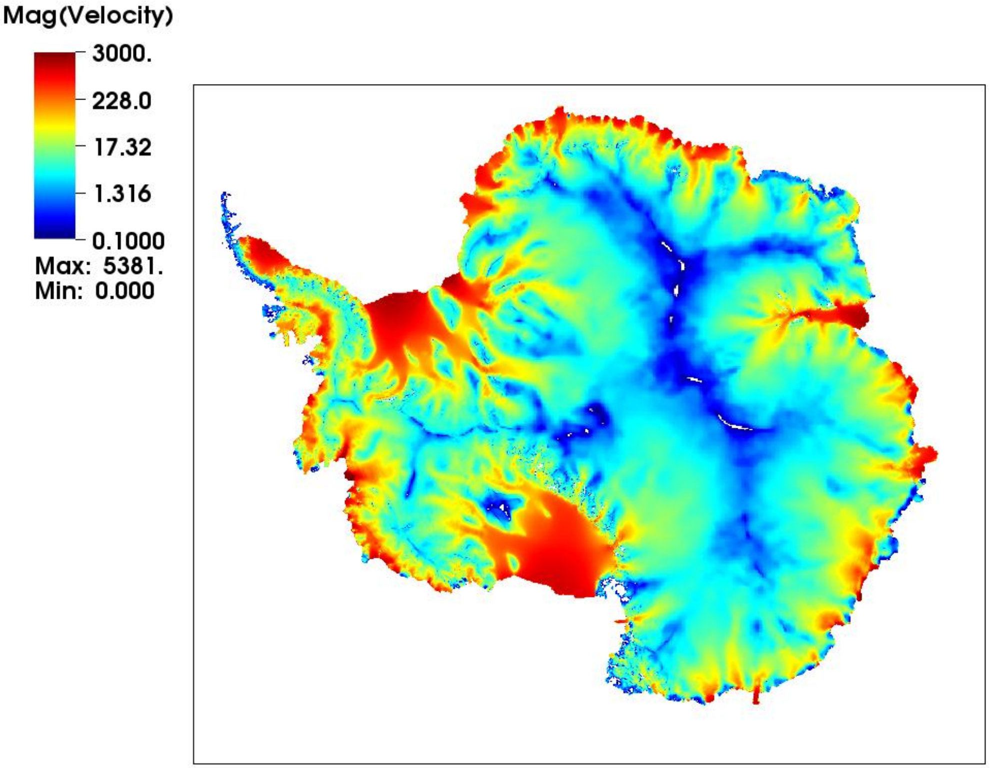
- Full Approximation Storage (FAS) – nonlinear multigrid

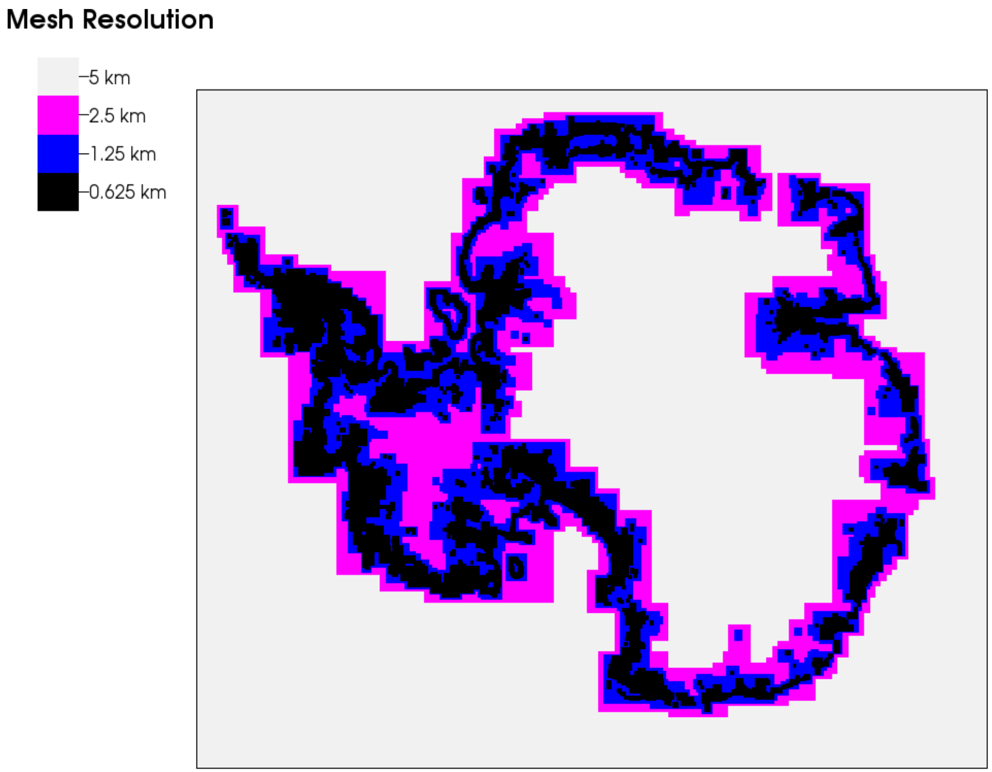
- Picard, JFNK:
  - linear solver nested inside of nonlinear one
  - Linear Multigrid solvers (residual-correction form) work well.

- FAS Multigrid – fully nonlinear solver (no outer solver)
  - Can outperform JFNK/MG
  - More robust (don't need good initial guess)
  - Simpler to implement and maintain
  - Nonlinear convergence similar to MG linear convergence

# Antarctica (Ice2Sea)

- 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)



# Next Steps

- Continue work with CISM/BISICLES hybrid code
  - Fully 2-way coupling
  - Eventual coupling to CESM
- Embedded boundary approach is promising
- More solver improvements
- Full-Stokes dynamical core

# Acknowledgements: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# Extras

# *Linear Solvers – GAMG vs. Geometric MG*