Modeling Antarctic Ice Sheet Dynamics using Adaptive Mesh Refinement

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Joint work with:

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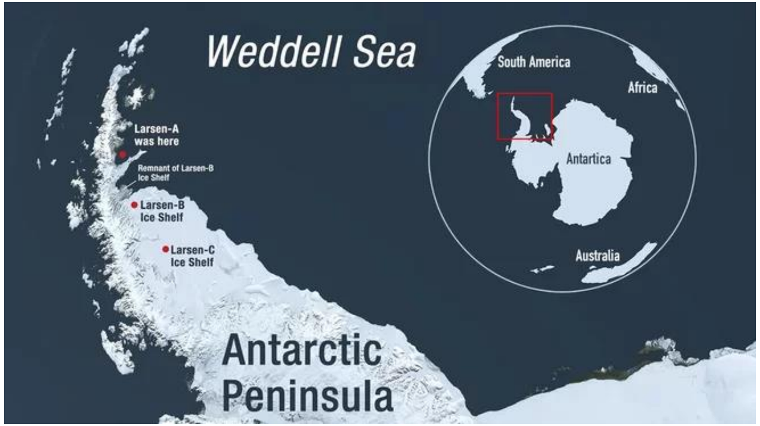
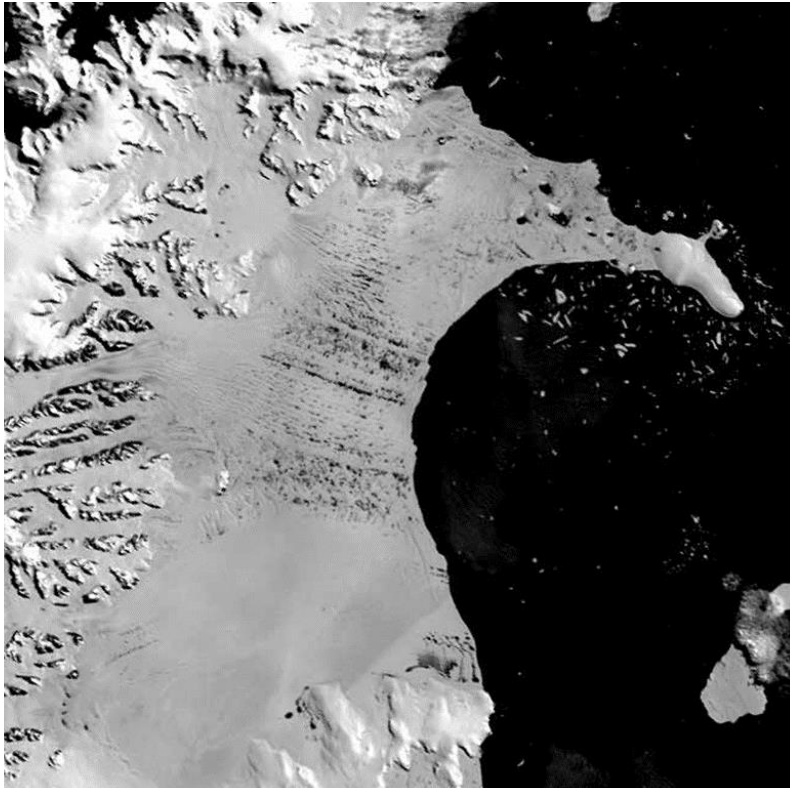
- **Stephen Price (LANL)**
- **Esmond Ng (LBNL)**

Marine Ice Sheets: Larsen B Breakup (2002)

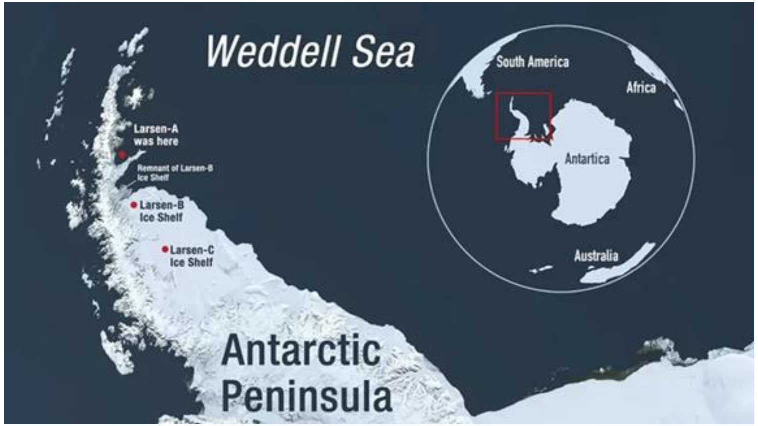
- **January 31, 2002**

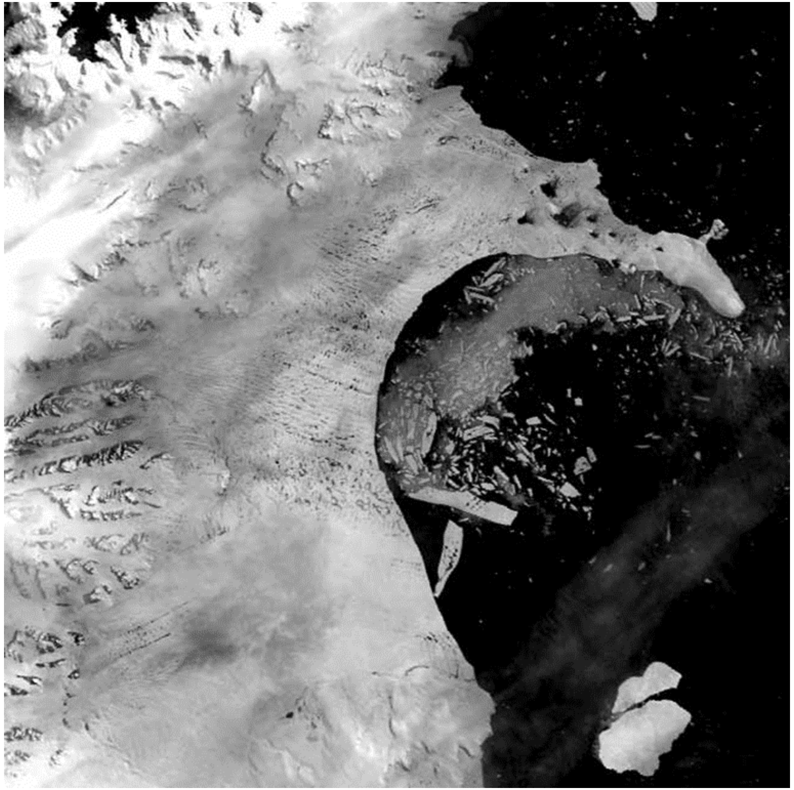




Marine Ice Shelves: Larsen B Breakup (2002)

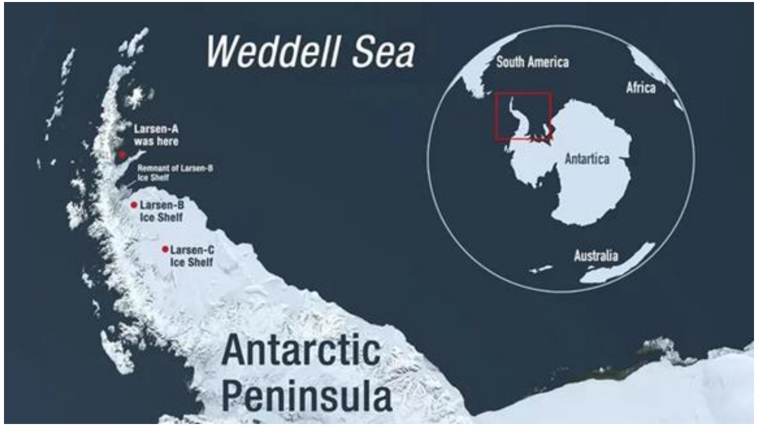
- **February 17, 2002**

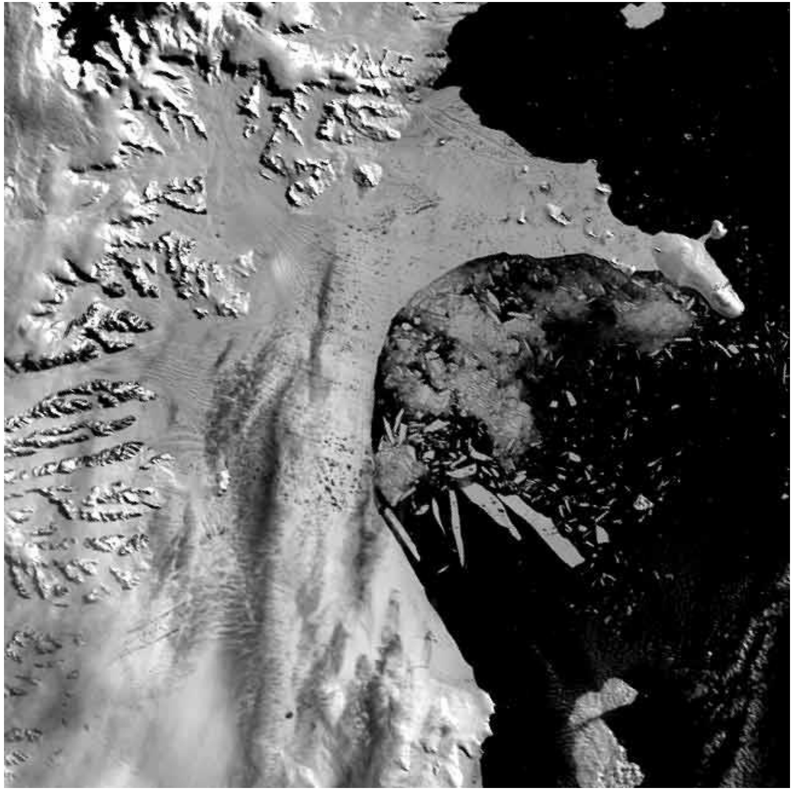




Marine Ice Shelves: Larsen B Breakup (2002)

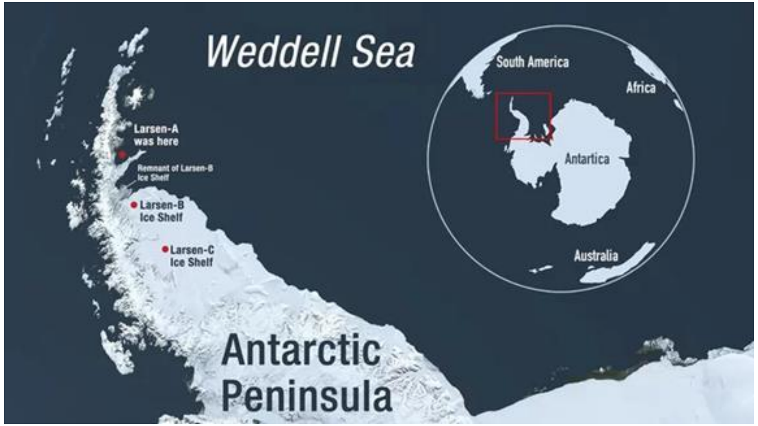
- **February 23, 2002**

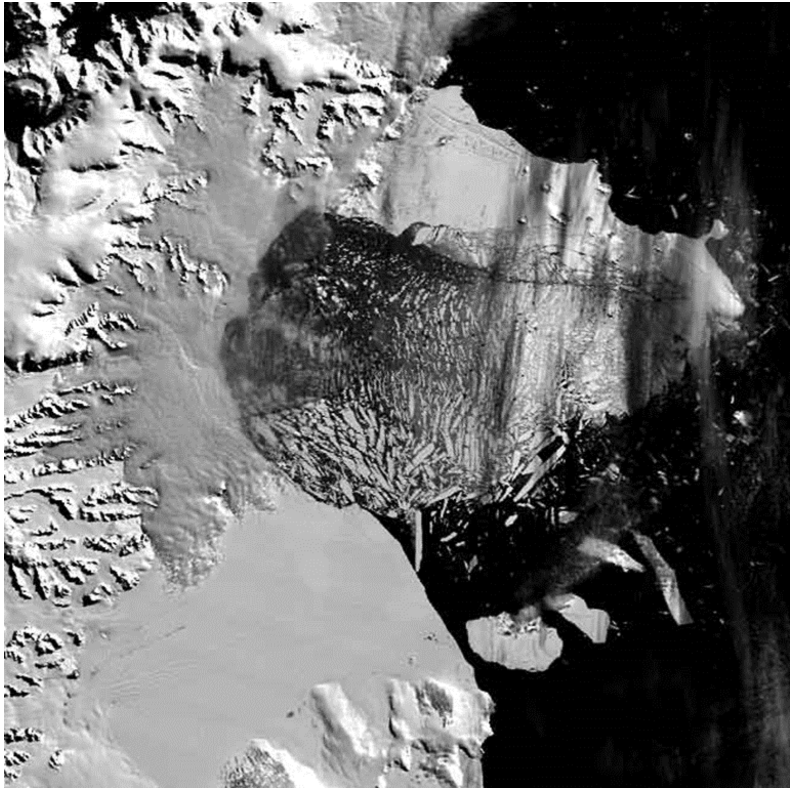




Marine Ice Shelves: Larsen B Breakup (2002)

- **March 5, 2002**





Aftermath…

- **3,250 square kilometers (1,250 square miles)**
- **Breakup took about 1 month**
- **Likely due to exceptionally warm summer**
  - Melt pools on surface –- surface melting -> hydrofracture
  - Warm ocean temperatures in the Weddell Sea

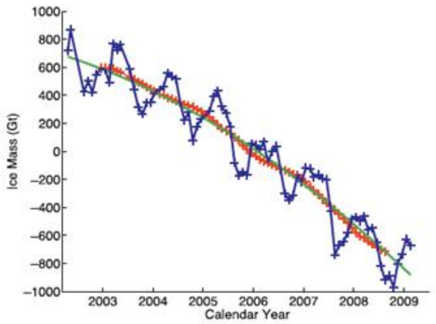
- **Results: Larsen A and B glaciers**
  - **abrupt acceleration, about 300% on average**
  - mass loss went from **2–4 gigatonnes per year** in 1996 and 2000 (gigatonne = one billion metric tonnes), to between **22 - 40 gigatonnes per year** in 2006.
  - Not the last! (Wilkins, 2008-2009)

Why do we care?

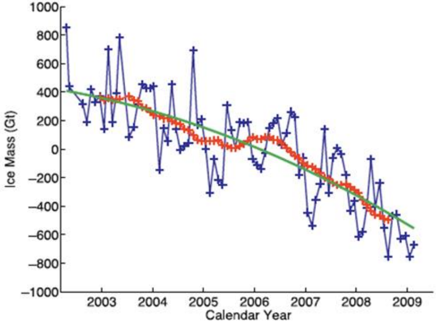
Global Sea Level Budget:

- **Ocean thermal expansion**: ~1 mm/yr
- **Glaciers and ice caps**: ~1 mm/yr
- **Ice sheets**: ~1 mm/yr
    - Greenland 0.6 mm/yr
    - Antarctica 0.4 mm/yr
- **Terrestrial storage**: ~0 mm/yr
    - Dam retention -0.3 mm/yr
    - Groundwater depletion 0.3 mm/yr

The ice sheet contribution has roughly **doubled** since 2000 and will likely continue to increase.



Greenland ice mass loss

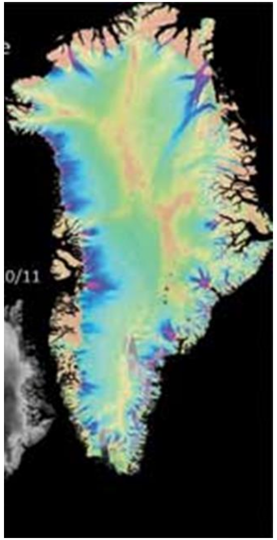


Antarctic ice mass loss
(Velicogna 2009)

Currently two ice sheets…

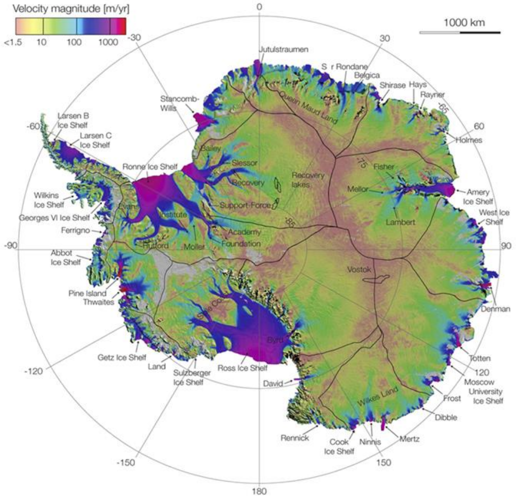
Greenland Ice Sheet

5-7 m Sea Level Equivalent (SLE)



Antarctic Ice Sheet

60 m SLE (4-5m in marine-grounded parts of West Antarctica)



How Ice sheets work…

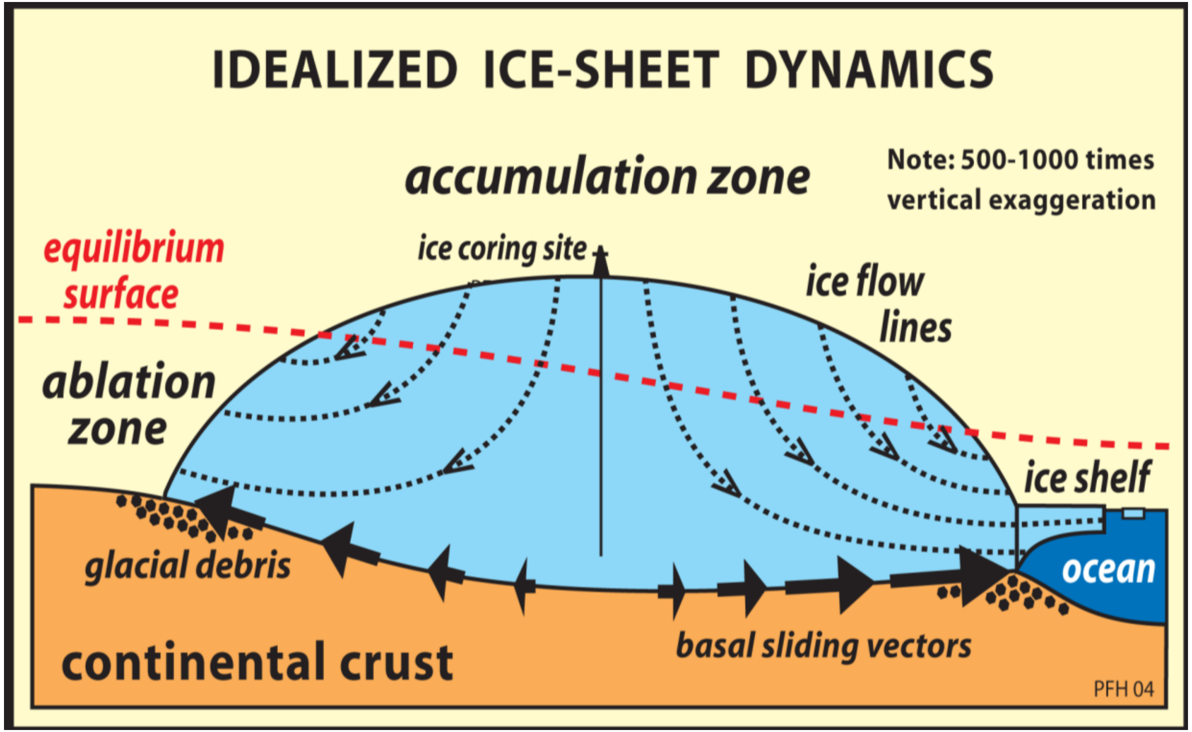
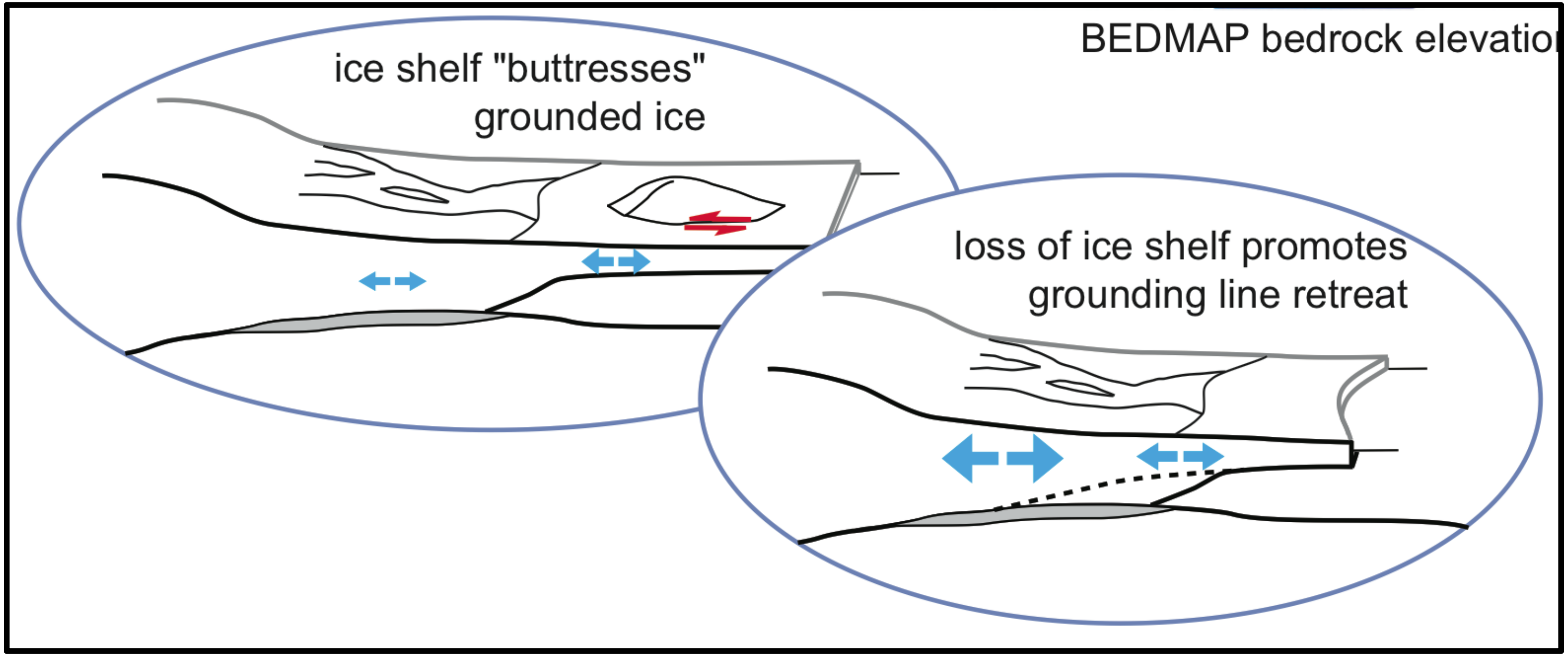
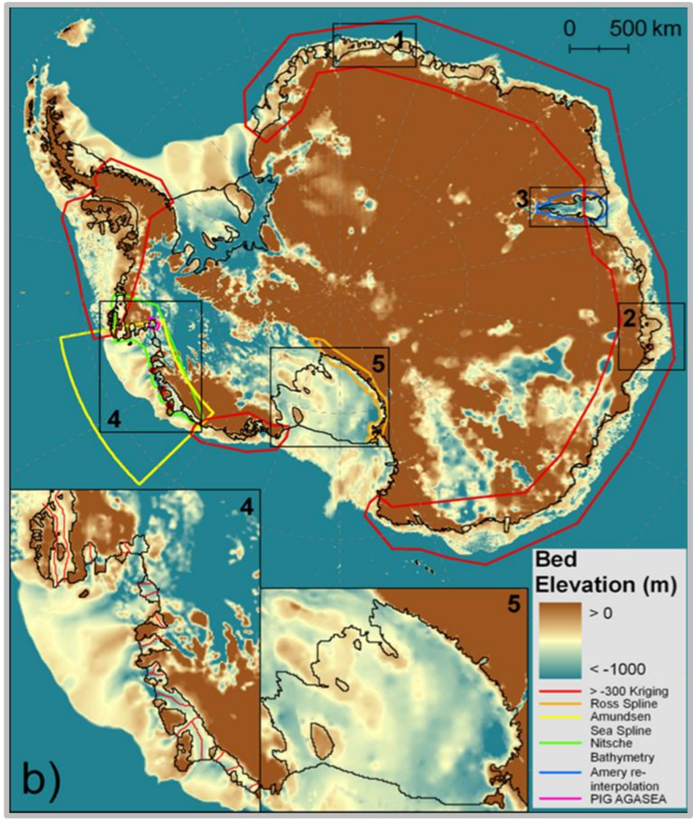


Image: http://www.snowballearth.org

Antarctic Marine Ice Sheet Instability



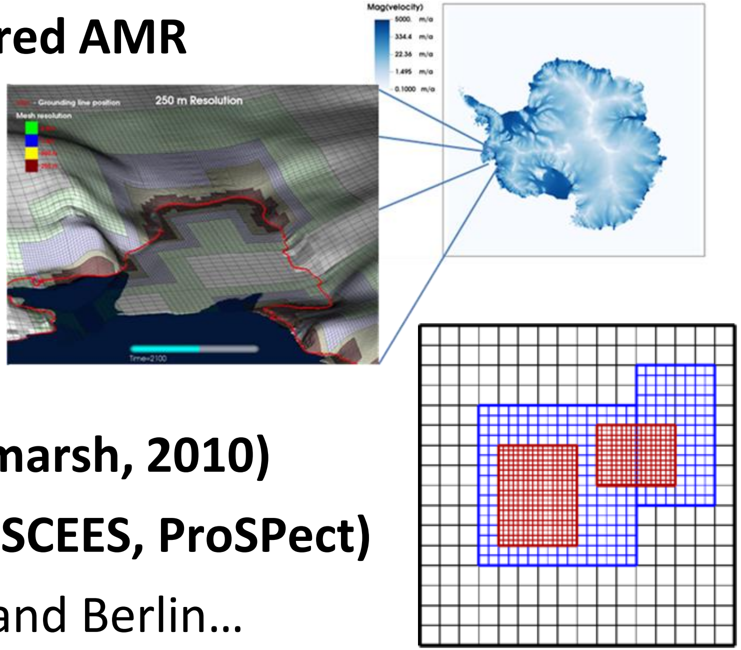
Antarctic Marine Ice Sheet Instability



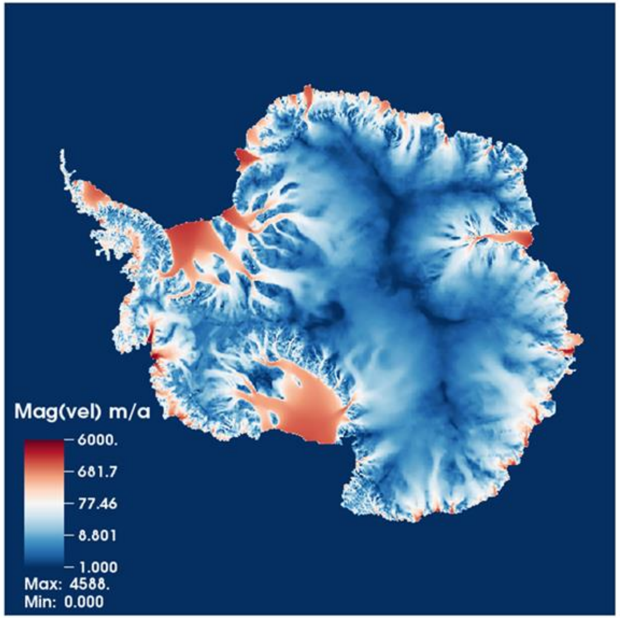
LeBrocq et al., 2010

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, 2010)**
- **Now in second-round of SciDAC funding (PISCEES, ProSPect)**
- Users in Berkeley, Bristol, Beijing, Brussels, and Berlin…



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

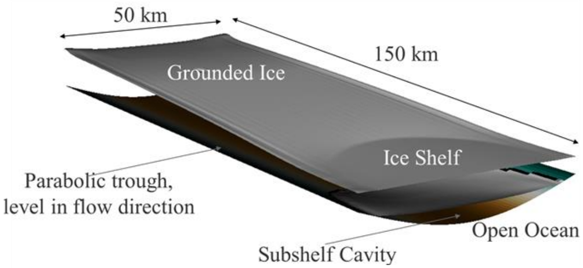


- Ice sheets -- Localized regions where high resolution needed to accurately resolve ice-sheet dynamics (500 m or better at grounding lines)
- Antarctica is really big – too big to resolve at that level of resolution.
- Large regions where such fine resolution is unnecessary (e.g. East Antarctica)

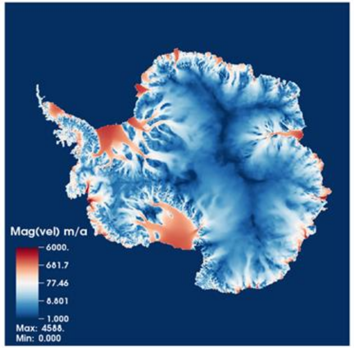
- Well-suited for adaptive mesh refinement (AMR)
- Problems still large: need good parallel efficiency
- Dominated by nonlinear coupled elliptic system for ice velocity solve: good linear and nonlinear solvers

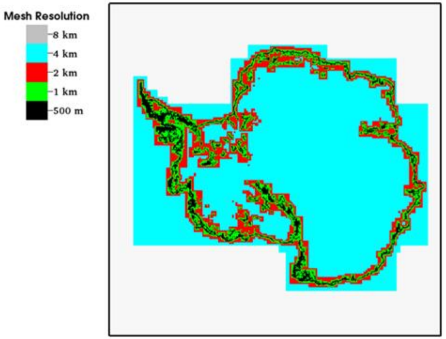
Target Problems

- **Idealized Ice-Ocean interaction test problems**
  - Simple/small geometries designed to understand GL dynamics and ice-ocean interactions
  - MISMIP3D, MISMIP+, MISOMIP



- **Realistic full-scale**
  - Fully-resolved (500m) full-continent
  - Antarctica





BISICLES: Models and Approximations

Physics: Non-Newtonian viscous flow: $\mu(\dot{\epsilon}^2, T) = A(T)(\dot{\epsilon}^2)^{\frac{(1-n)}{2}}$

Where $\dot{\epsilon}^2$ is the strain rate invariant, typically $n = 3$

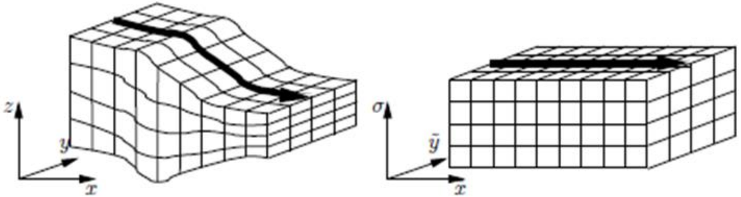
- **"Full-Stokes"**
  - Best fidelity to ice sheet dynamics
  - Computationally expensive (full 3D coupled nonlinear elliptic equations)
- **Approximate Stokes**
  - Use scaling arguments to produce simpler set of equations
  - Common expansion is in ratio of vertical to horizontal length scales ($\varepsilon = \frac{[h]}{[l]}$)
  - E.g. Blatter-Pattyn (most common "higher-order" model), accurate to O(ε^2)
  - Still 3D, but solve simplified elliptic system (e.g. 2 coupled equations)

“L1L2” Model (Schoof and Hindmarsh, 2010)

- **Uses asymptotic structure of full Stokes system to construct a higher-order approximation**
  - Expansion in ε= $\frac{[H]}{[L]}$ and λ= $\frac{[\tau_{shear}]}{[\tau_{normal}]}$ (ratio of shear & normal stresses)
    - Large λ: shear-dominated flow
    - Small λ: 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)**
  - 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:**
  - Logically-rectangular grid, obtained from a time-dependent uniform mapping.
  - 2D equation for ice thickness *H:*



$$\frac{\partial H}{\partial t} = b - \nabla\cdot(H\overrightarrow{u})$$

  - Vertically-integrated momentum balance results in 2D **nonlinear** viscous tensor solve (viscosity a function of velocity) for velocity $\overrightarrow{u_b}$ at the base of the ice:

$$\beta^2\overrightarrow{u_b} + \nabla\cdot\left[\mu(\dot{\varepsilon}^2)\left(\vec{\nabla} + \vec{\nabla}^T\right)\overrightarrow{u_b} - 2\mu\,(\nabla\cdot\overrightarrow{u_b})\right] = -\frac{g}{\rho}H\,\vec{\nabla}s$$

β^2 **= friction coefficient,** $\dot{\varepsilon}$**= strain rate invariant of ice velocity,** g **= gravity,** ρ **= ice density,** H **= ice thickness,** $\vec{\nabla}s$ **= horizontal gradient of upper surface**

  - Enthalpy formulation for energy

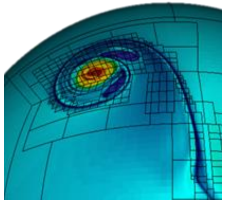
Discretizations, cont

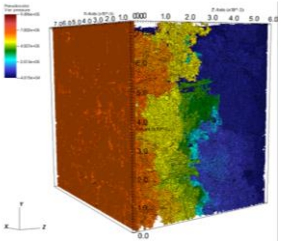
- Use of Finite-volume discretizations (vs. Finite-difference discretizations) simplifies implementation of local refinement.
- Software implementation based on constructing and extending existing solvers using the Chombo libraries.

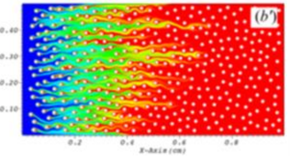
Chombo – Scalable Adaptive Mesh Refinement (AMR)

FASTMATH

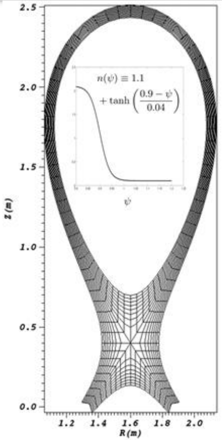
Scalable adaptive mesh refinement (AMR) framework.
Enables implementing scalable AMR applications with support for complex geometries.

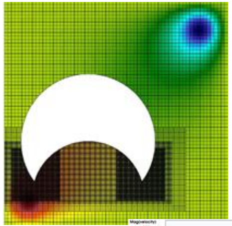




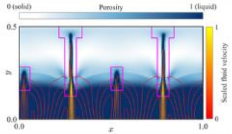


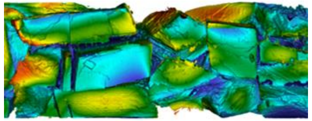
- **Adaptive Mesh Refinement (AMR)**
  - Block structured AMR dynamically focuses computational effort where needed to improve solution accuracy
  - Designed as a developers’ toolbox for implementing scalable AMR applications
  - Implemented in C++/Fortran
  - Solvers for hyperbolic, parabolic, and elliptic systems of PDEs
- **Complex Geometries**
  - Embedded-boundary (EB) methods use a cut-cell approach to embed complex geometries in a regular Cartesian mesh
  - EB mesh generation is extremely efficient
  - Structured EB meshes make high performance easier to attain
- **Higher-order finite-volume**
  - Higher (4th)-order schemes reduce memory footprint and improve arithmetic intensity
  - Good fit for emerging architectures
  - Both EB and mapped-multiblock approaches to complex geometry

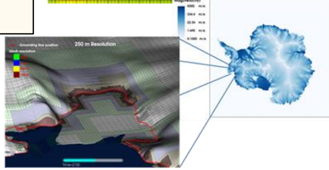




http://Chombo.lbl.gov

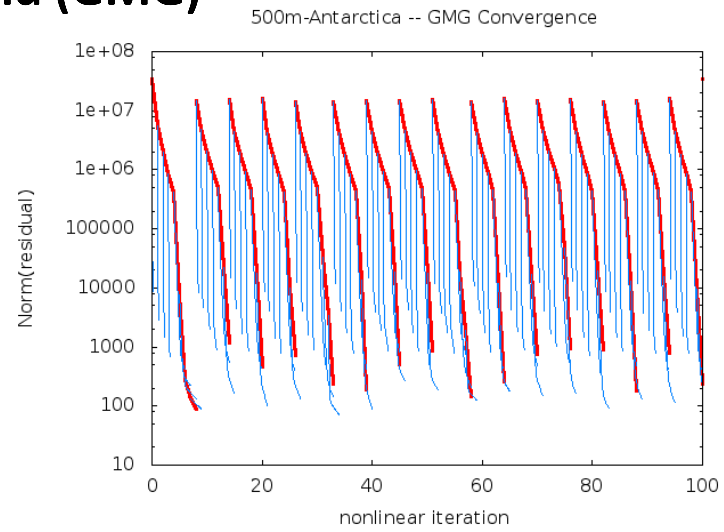






Nonlinear and Linear Solvers

- **90% of computational time spent in nonlinear viscous tensor solve**
- **Jacobian-Free Newton Krylov (JFNK) + Picard iterative nonlinear solvers**
- **Need good linear solver performance!**
- **Chombo native solvers – Geometric MultiGrid (GMG)**
  - Follows Naturally from AMR hierarchy
  - When it works, it works really well (after some tuning)
  - Matrix-free!
  - Relatively efficient
- **Other problems require AMG solvers**
  - Link to PETSc (HYPRE, GAMG)



Mesh resolution requirements for marine AIS

Experiment – 1000-year Antarctic simulations

- **Range of finest resolution from 8 km (no refinement) to 500m (4 levels of factor-2 refinement)**

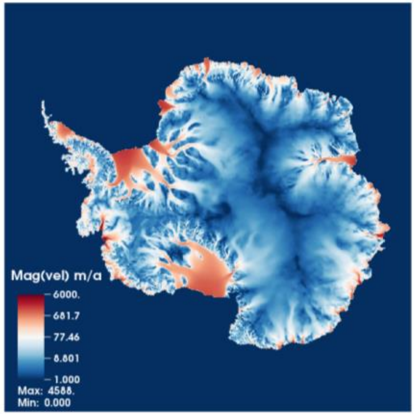
- **Subgrid basal friction parameterization (e.g. Seroussi et al)**
  - Experience shows that it buys us about a factor of 2x

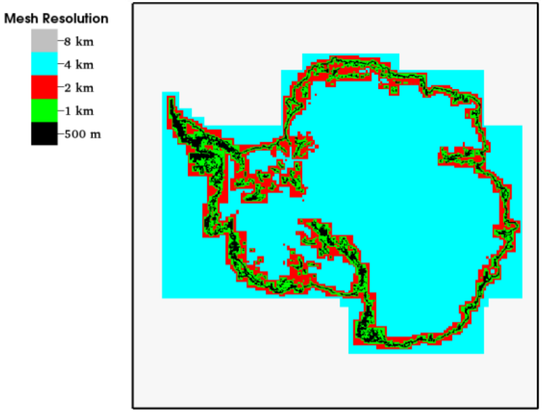
- **At initial time, subject ice shelves to extreme (outlandish) depth-dependent melting:**
  - No melt for h < 100m
  - Range up to 400m/a where h > 800m.
  - **No melt applied in partially-grounded cells**

- **For each resolution, evolve for 1000 years**

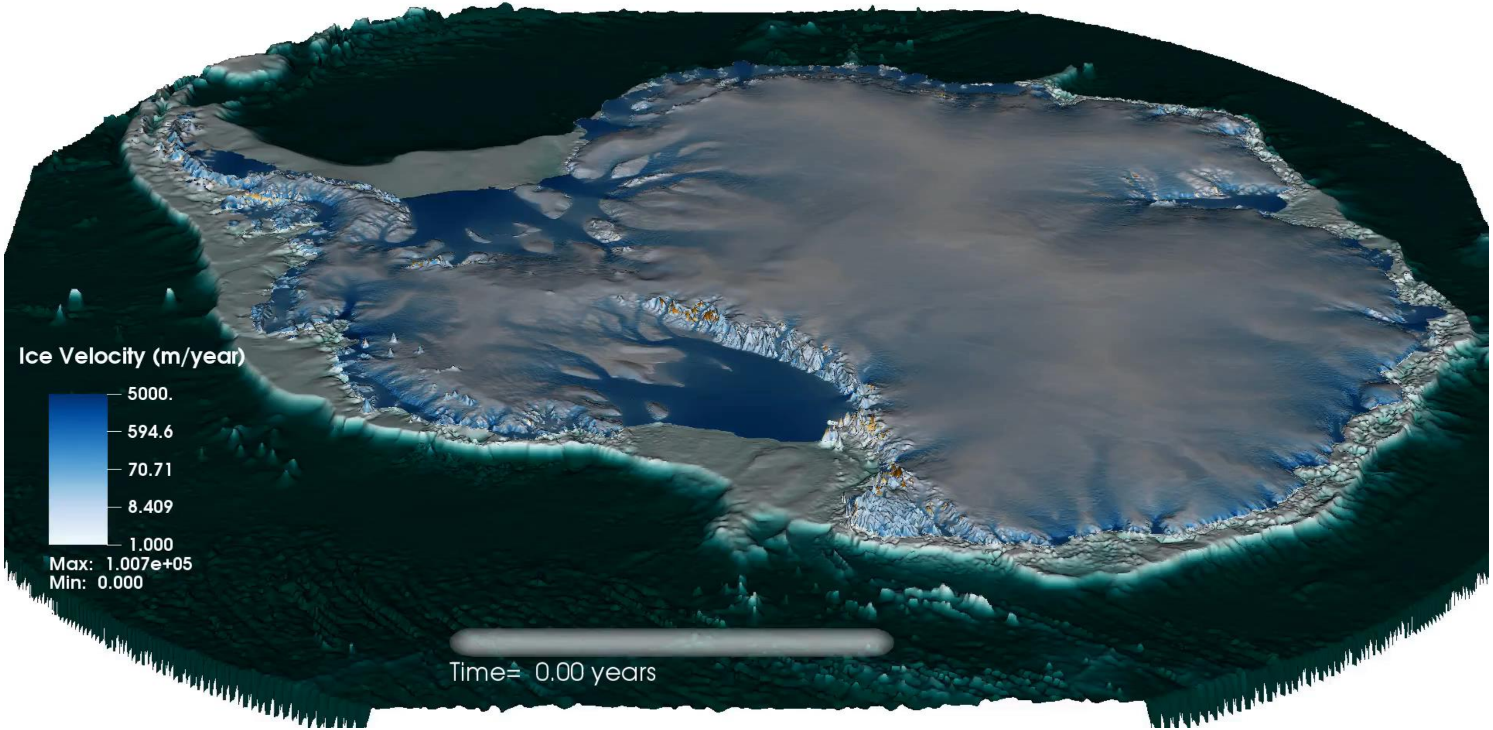
Initial Condition for Antarctic Simulations

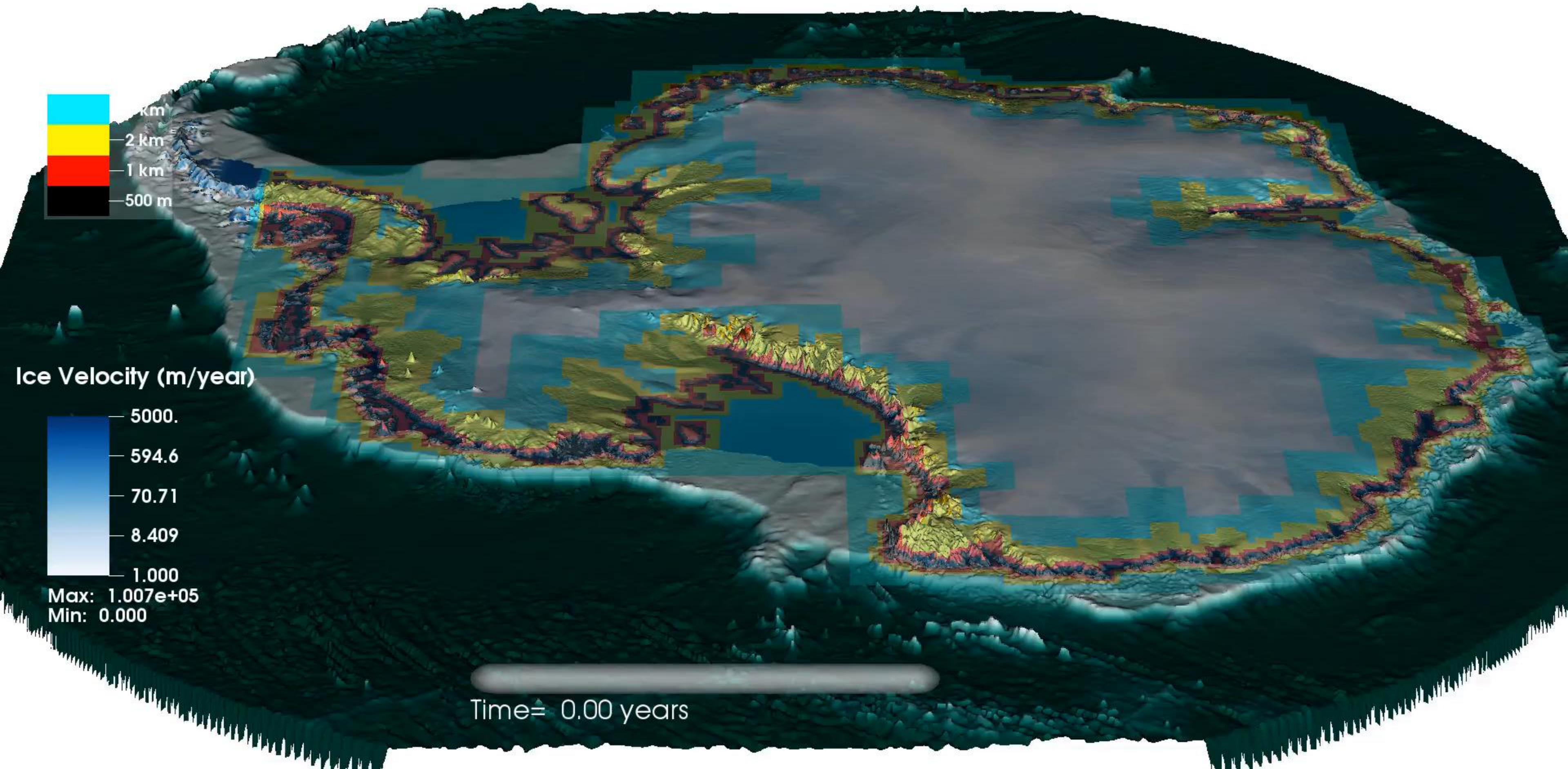
- Full-continent Bedmap2 (2013) geometry
- Temperature field from Pattyn (2010)
- Initialize basal friction to match Rignot (2011) velocities
- SMB: Arthern et al (2006)
- AMR meshes: 8 km base mesh, adaptively refine to Δx_f





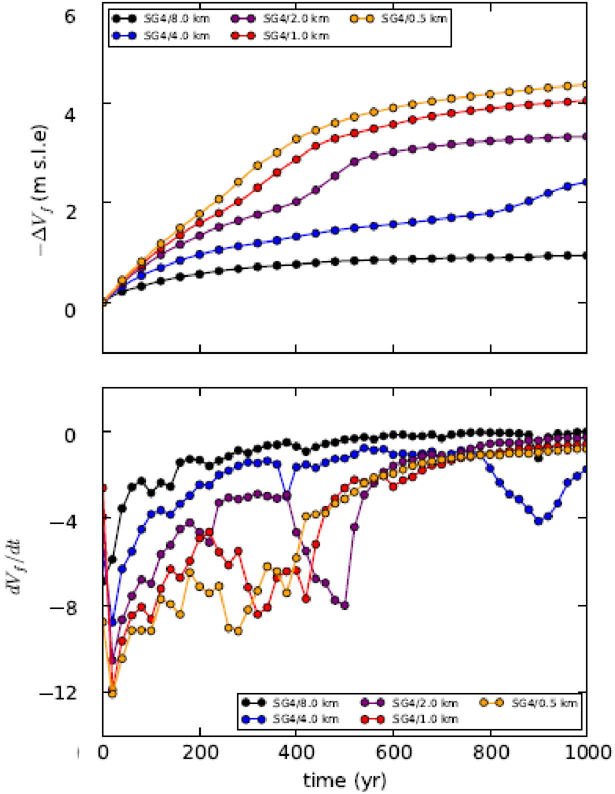
Antarctic ice loss simulation using the SciDAC-supported BISICLES ice sheet model




km
2 km
1 km
500 m
Ice Velocity (m/year)
5000.
594.6
70.71
8.409
1.000
Max: 1.007e+05
Min: 0.000
Time= 0.00 years

Resolution requirements…

- **Upper plot** – Contribution to SLR
    - Convergent at sufficient resolution
- **Lower plot** -- Rate of Change
    - Big spike – WAIS collapse
    - Timing, pathways are a function of resolution



"Adaptive mesh refinement versus subgrid friction interpolation in simulations of Antarctic Ice Dynamics", Cornford, Martin, Lee, Payne, Ng, *Annals of Glaciology*, 57 (73), 2016

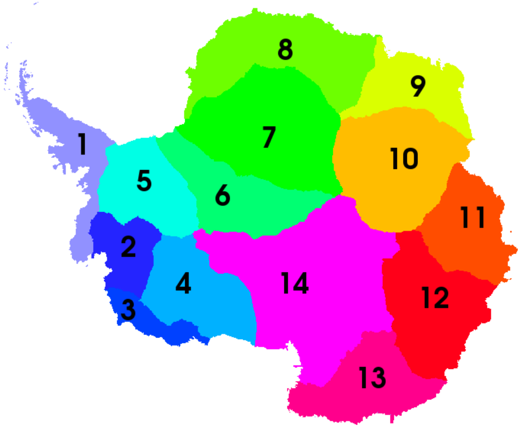
Evaluating Antarctic Vulnerability…

- **Next step – restrict forcing regionally**

Antarctic vulnerability to warm-water forcing

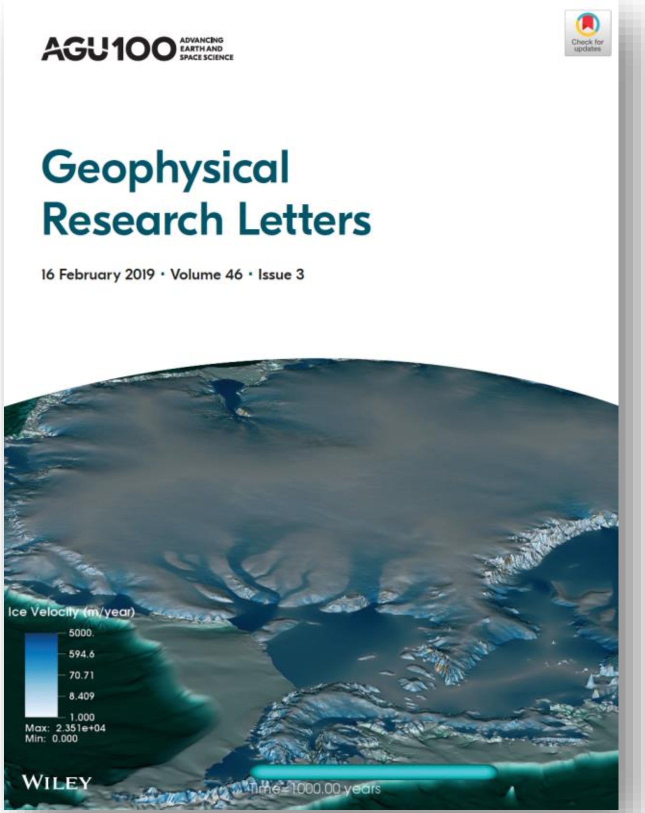
- **Basic idea – try to understand where AIS is vulnerable to forcing from warm-water incursions**
- **Divide AIS into sectors**
- **For each sector in turn (and for some combinations), apply extreme depth-dependent melt forcing**
  - No melt for h < 100m
  - Range up to 400m/a where h > 800m.
  - **No melt applied in partially-grounded cells**
- **Run for 1000 years, compare with control (no melt).**

Antarctic sectors



Martin, D. F., Cornford, S. L., & Payne, A. J. (2019). **Millennial-scale vulnerability of the Antarctic Ice Sheet to regional ice shelf collapse**. *Geophysical Research Letters*, 46, 1467–1475.

https://doi.org/10.1029/2018GL081229



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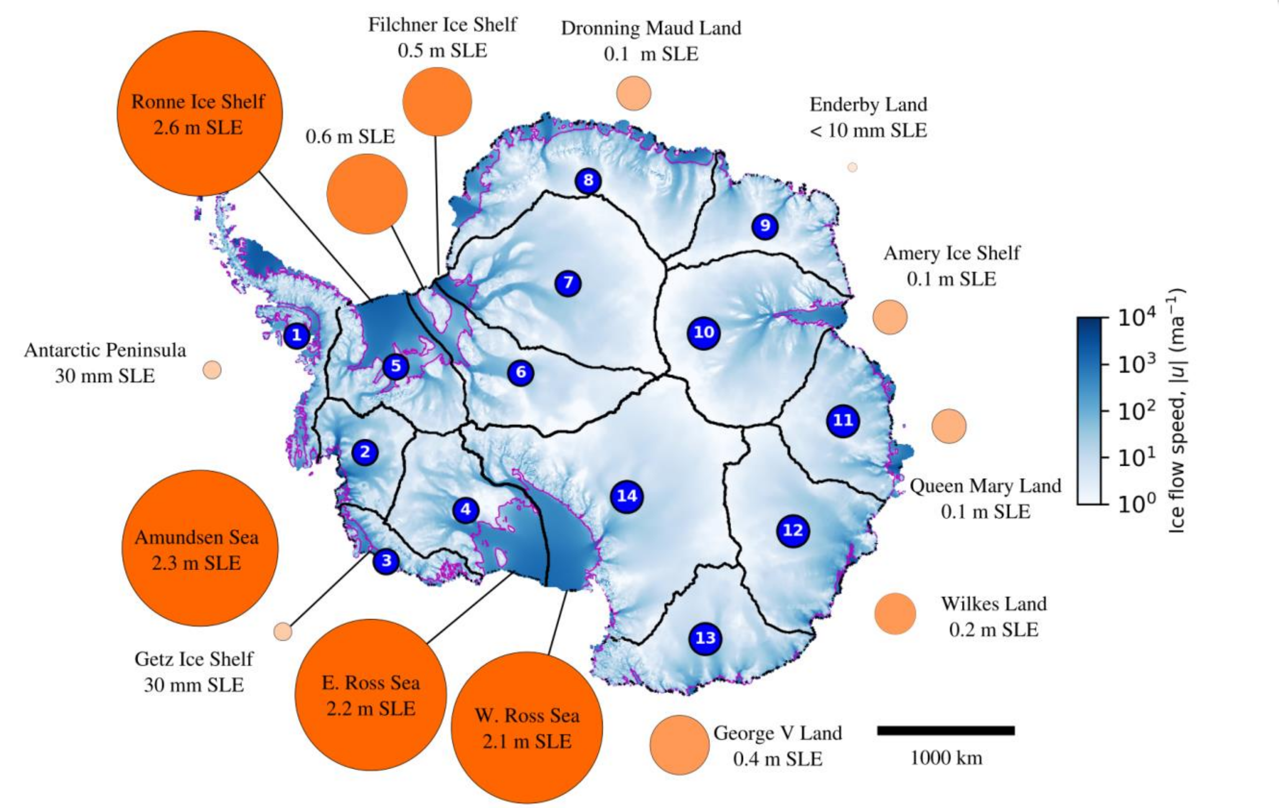
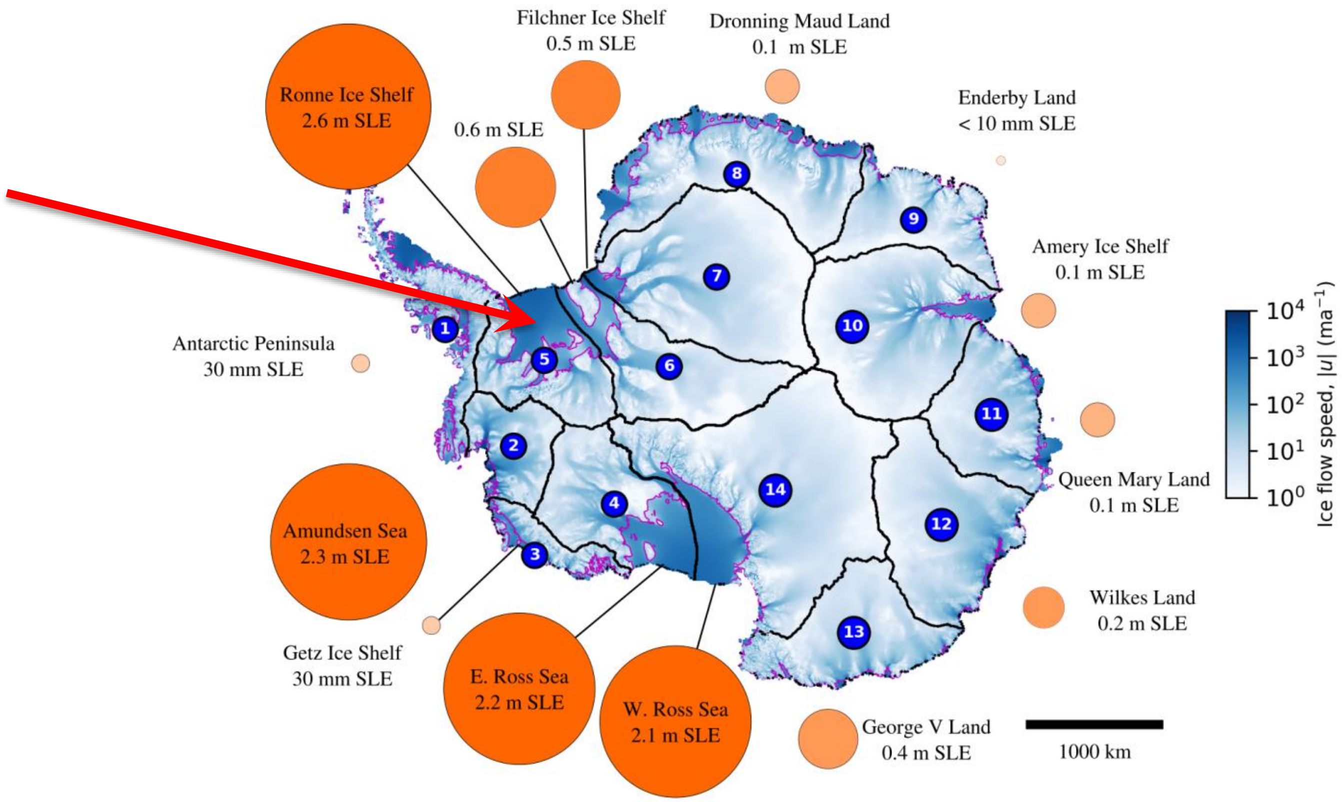
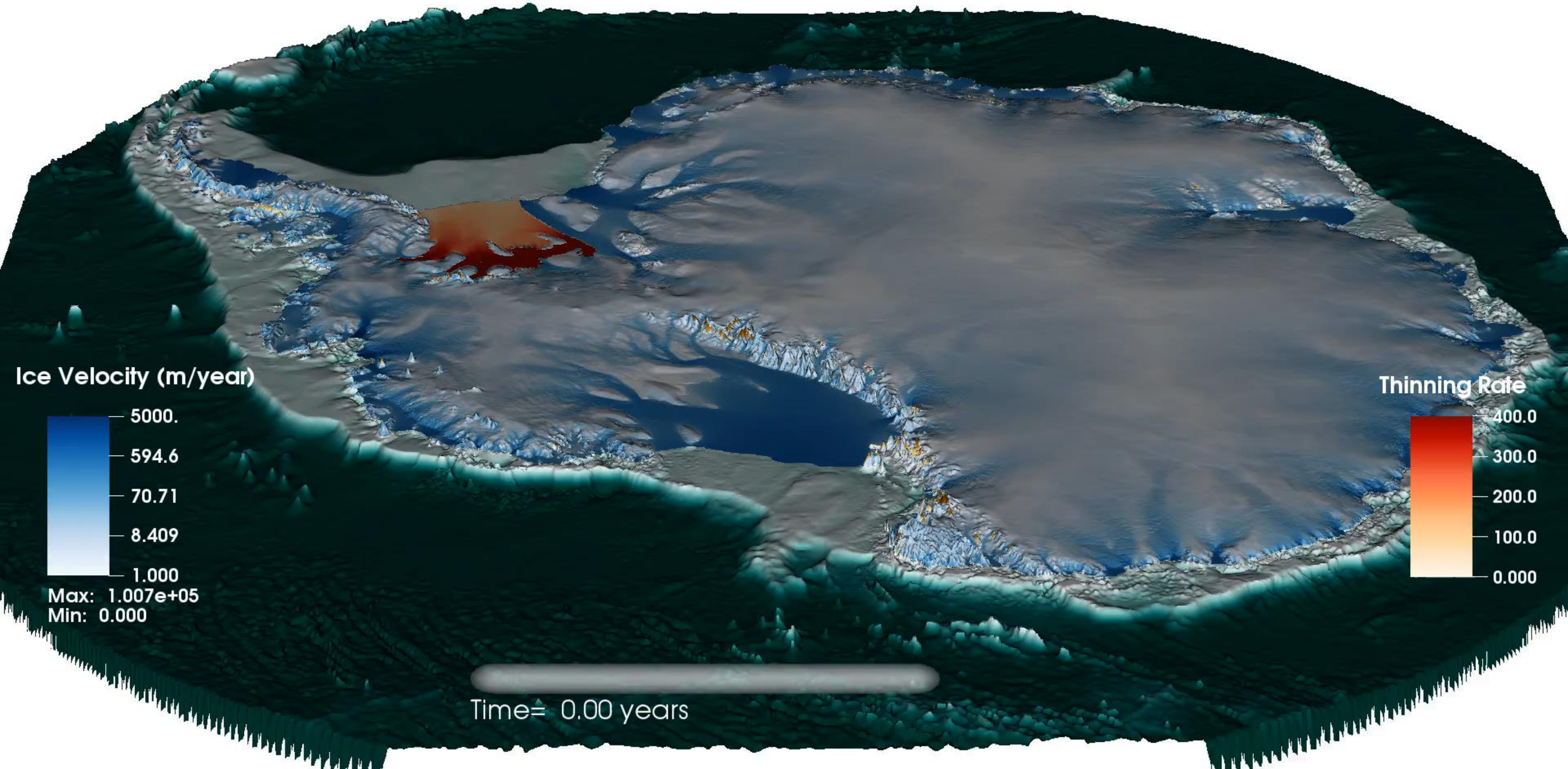
Antarctic Vulnerability results:



Sector 5 (Weddell Sea/Ronne Ice Shelf)

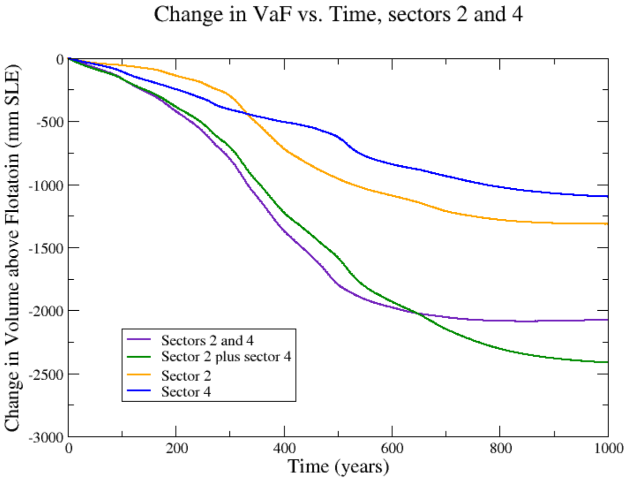


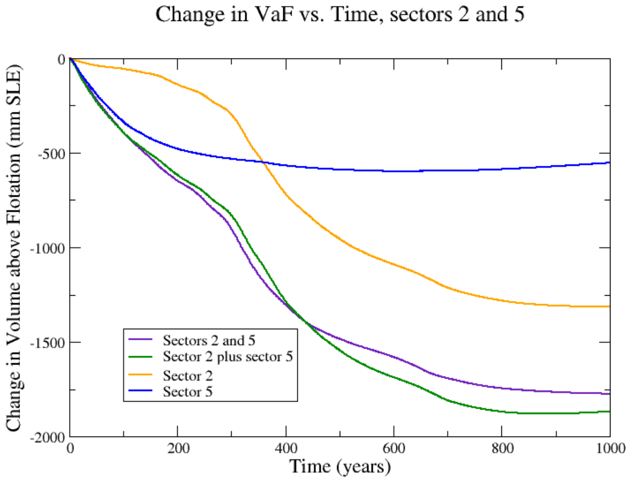

Ice Velocity (m/year)
5000.
594.6
70.71
8.409
1.000
Max: 1.007e+05
Min: 0.000
Thinning Rate
400.0
300.0
200.0
100.0
0.000
Time= 0.00 years

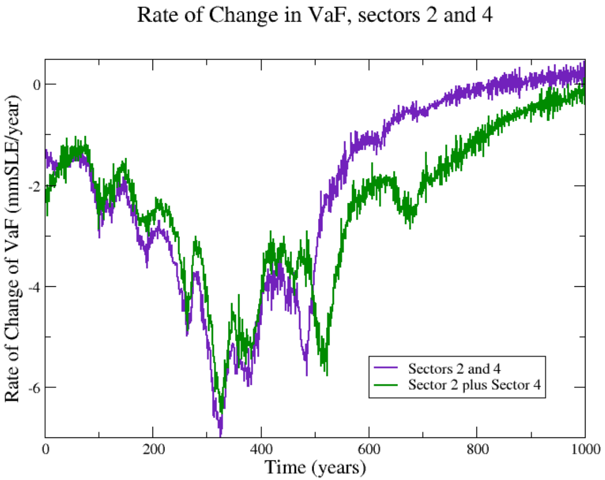
Regional Independence

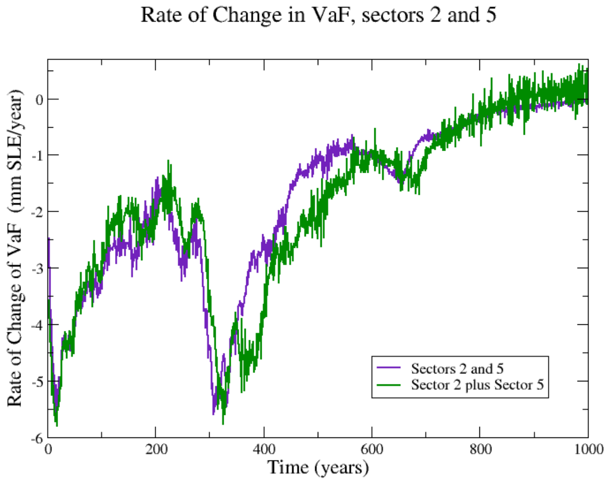
- **Resource limitations often force models to look at individual sectors/drainage basins**
- **Relies on the assumption of regional independence**
- **Can look at combinations of sectors to see if they behave independently…**

- Yellow, Blue – single sectors
- Purple – combination
- Green – sum of the two single-sector runs
- For WAIS sectors, roughly independent at start, after O(200a), start to interact


Change in VaF vs. Time, sectors 2 and 4


Change in VaF vs. Time, sectors 2 and 5


Rate of Change in VaF, sectors 2 and 4


Rate of Change in VaF, sectors 2 and 5

Summary

- First fully-resolved, systematic study of millennial-scale ice sheet response to regional ice shelf collapse based on 14 drainage basins.
- Sustained ice-shelf loss in **any** of the Amundsen Sea, Ronne, or Ross sectors can lead to wholesale West Antarctic collapse.
- Even with extreme forcing, loss is relatively modest for the initial century, increasing markedly afterward in West Antarctic collapse scenarios.
- Results indicate that Antarctic drainage basins are dynamically independent for 1-2 centuries, after which dynamic interactions between basins become increasingly important (and regional modeling results will be increasingly inaccurate).
- Combination of AMR and NERSC resources made this possible – 35,000 years of fully-resolved full-continent Antarctic simulation.

Acknowledgements:

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- **NERSC**

Thank you!