Modeling Antarctic Ice with Adaptive Mesh Refinement

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Applied Numerical Algorithms Group

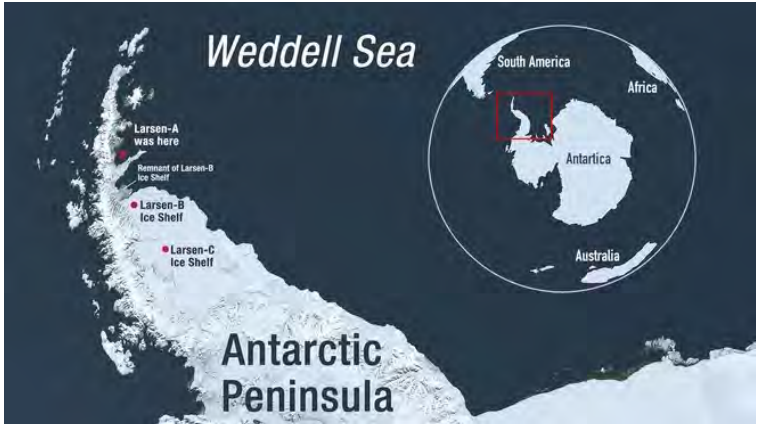
Who I am…

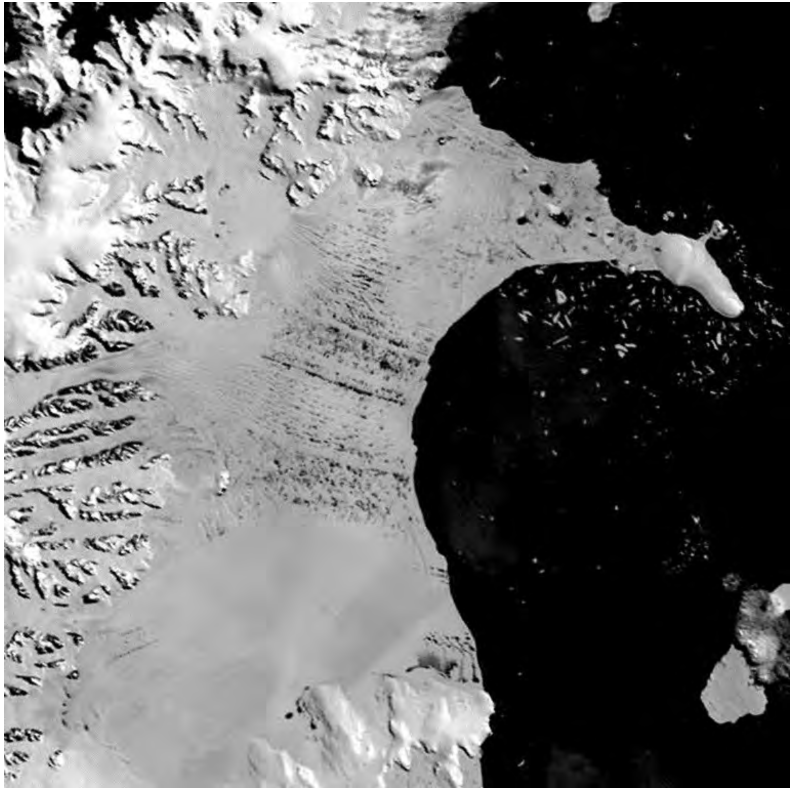
- Grew up outside Philadelphia, HS in Orlando
- Undergrad: Mechanical Engineering at the University of Florida
- Grad school: PhD in Mechanical engineering at UC Berkeley (fluids)
- Came to LBL as a post-doc, never left (23 years ago)
- Currently the group lead for the Applied Numerical Algorithms Group in CRD

- Focus on developing algorithms and software for solving systems of PDEs efficiently and accurately for real applications
- Married, 2 boys (16 and 13)
- Hobbies: cycling, music, travel (broke my sternum last year in a silly mountain-bike crash)

Marine Ice Sheets: Larsen B Breakup (2002)

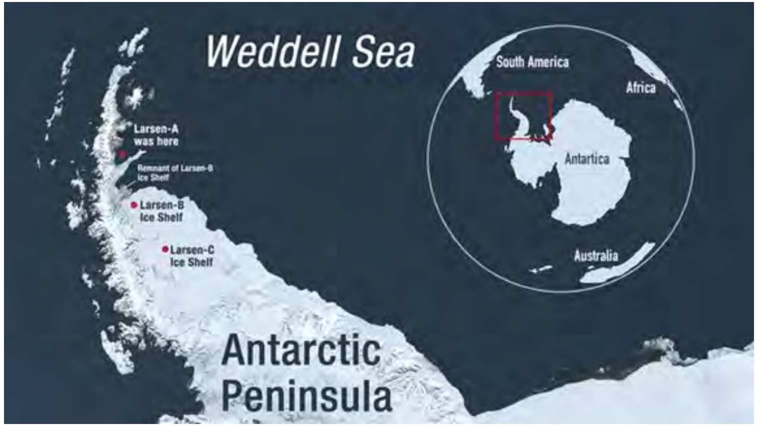
- **January 31, 2002**

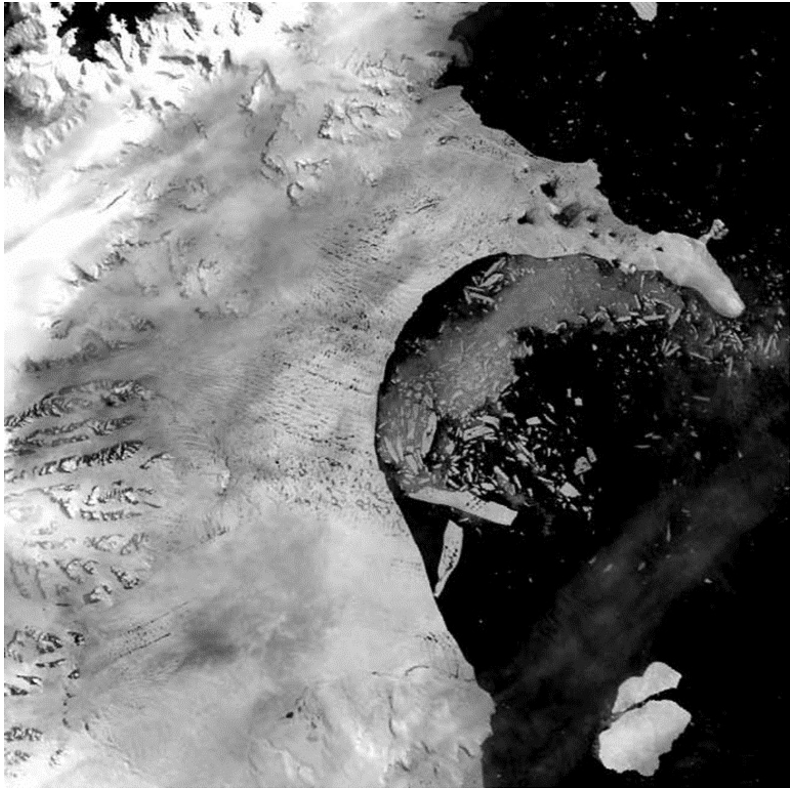




Marine Ice Shelves: Larsen B Breakup (2002)

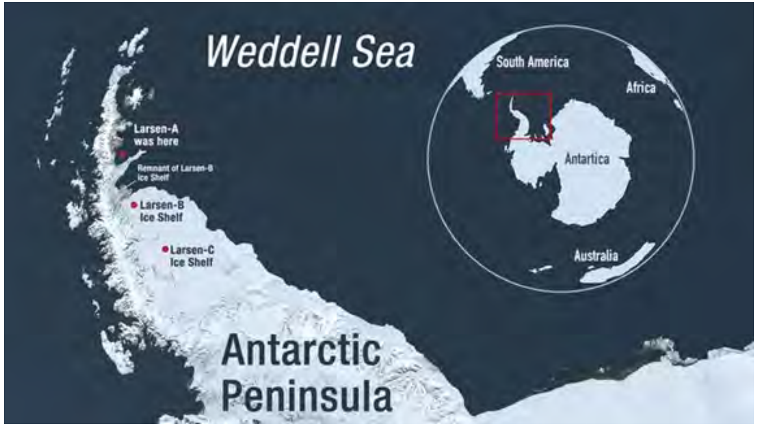
- **February 17, 2002**

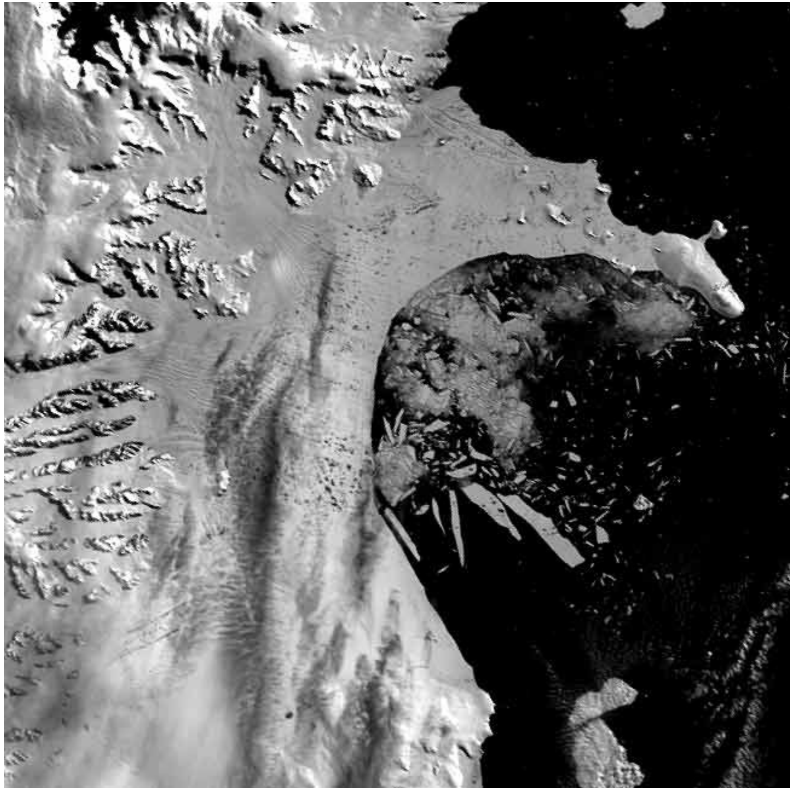




Marine Ice Shelves: Larsen B Breakup (2002)

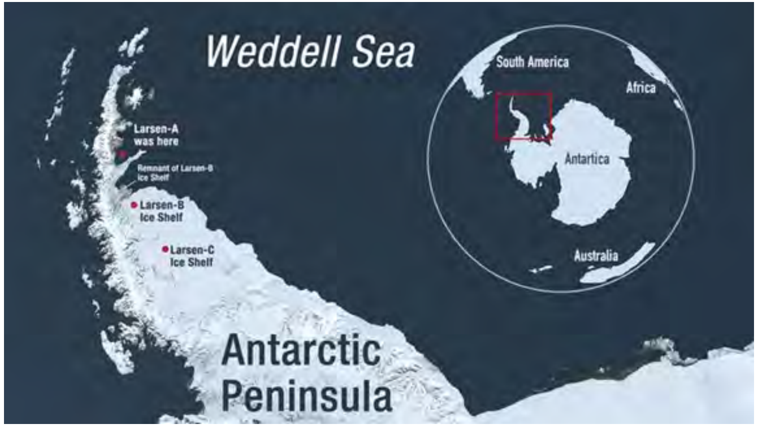
- **February 23, 2002**

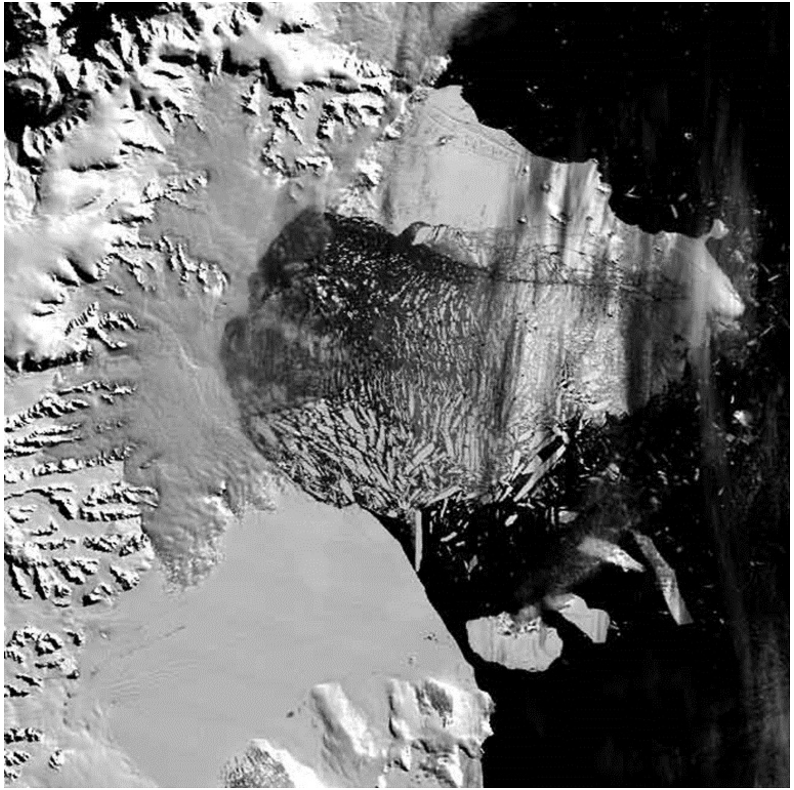




Marine Ice Shelves: Larsen B Breakup (2002)

- **March 5, 2002**





Aftermath…

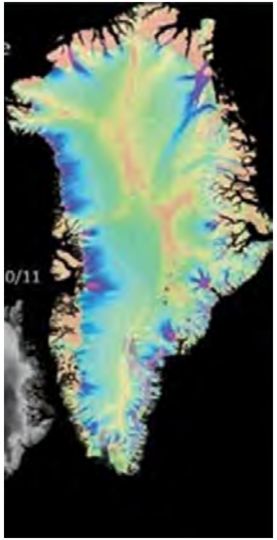
- **3,250 square kilometers (1,250 square miles)**
- **Breakup took about 1 month**
- **Likely due to exceptionally warm summer**
  - Melt pools on surface –- surface melting -> hydrofracture
  - Warm ocean temperatures in the Weddell Sea

- **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? Currently two ice sheets…

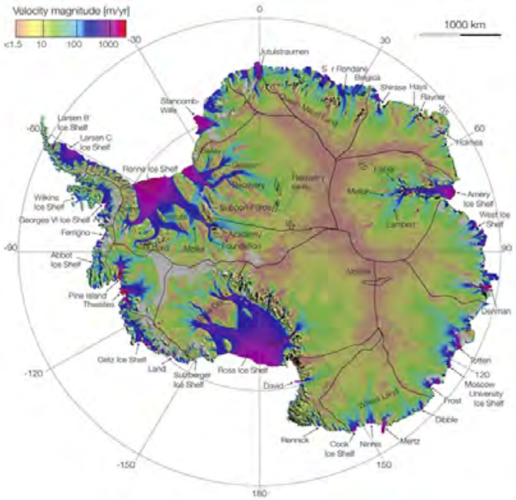
Greenland Ice Sheet

5-7 m Sea Level Equivalent (SLE)



Antarctic Ice Sheet

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



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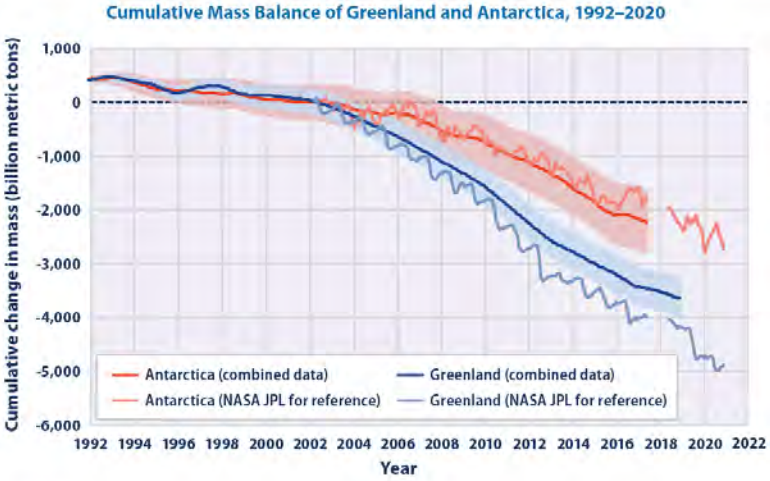
Why do we care?

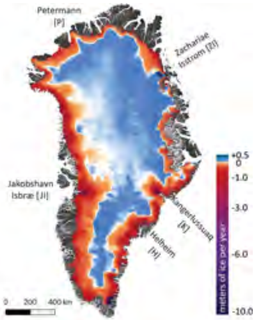
Global Sea Level Budget:

- **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

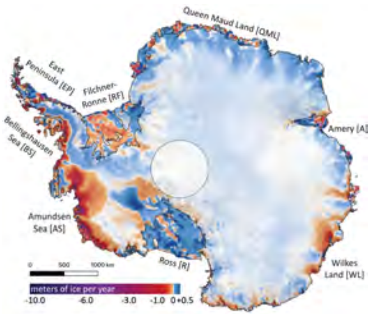


(src: http://epa.gov/climate-indicators)

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



Patterns of ice loss from (left) Greenland and (right) Antarctica (Smith, et al, *Nature,* 2020)



State of the art, 2007

- **IPCC AR4: called out existing ice sheet modeling state of the art as inadequate**

- **DOE ASCR response:**
  - Call for next-generation ice sheet model development
  - **ISICLES:** 6 (small) funded projects (O(1-2 FTE) each)
  - included LBL-led AMR effort: Berkeley-ISICLES (**BISICLES**), engaged with BER-funded climate scientists & glaciologists at LANL…
  - Synergy with similar Bristol (UK)-led effort (1 postdoc)

How Ice sheets work…

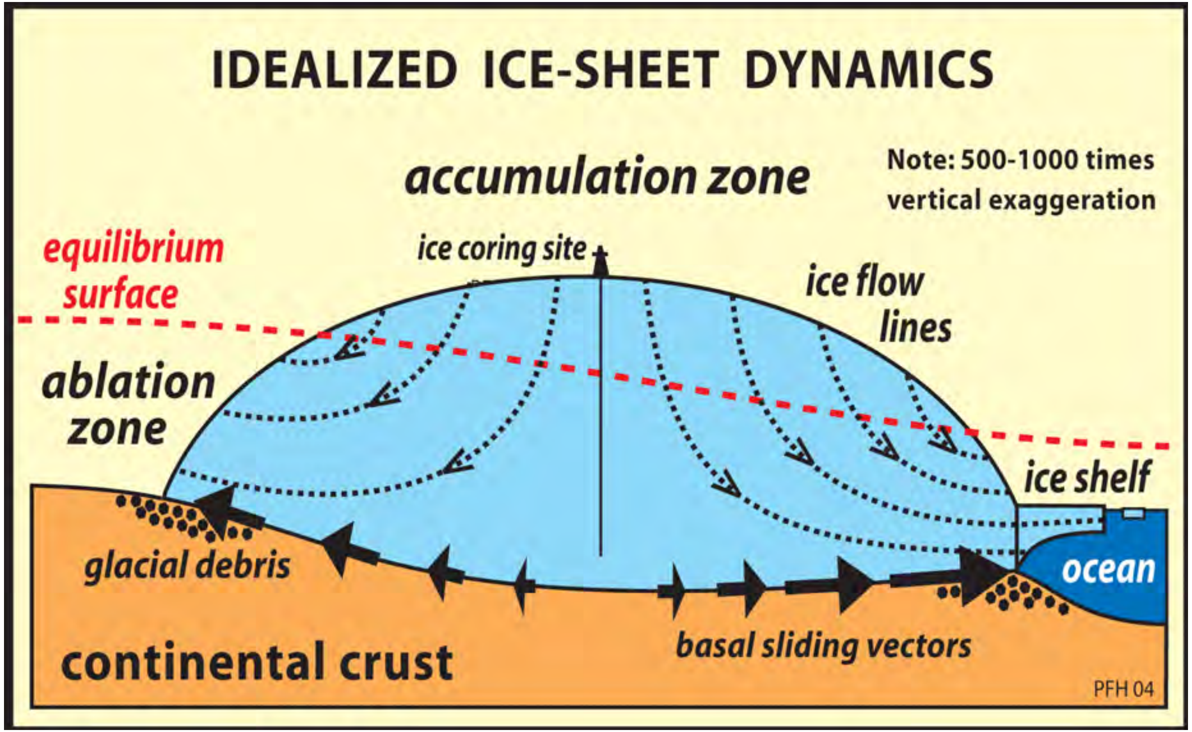
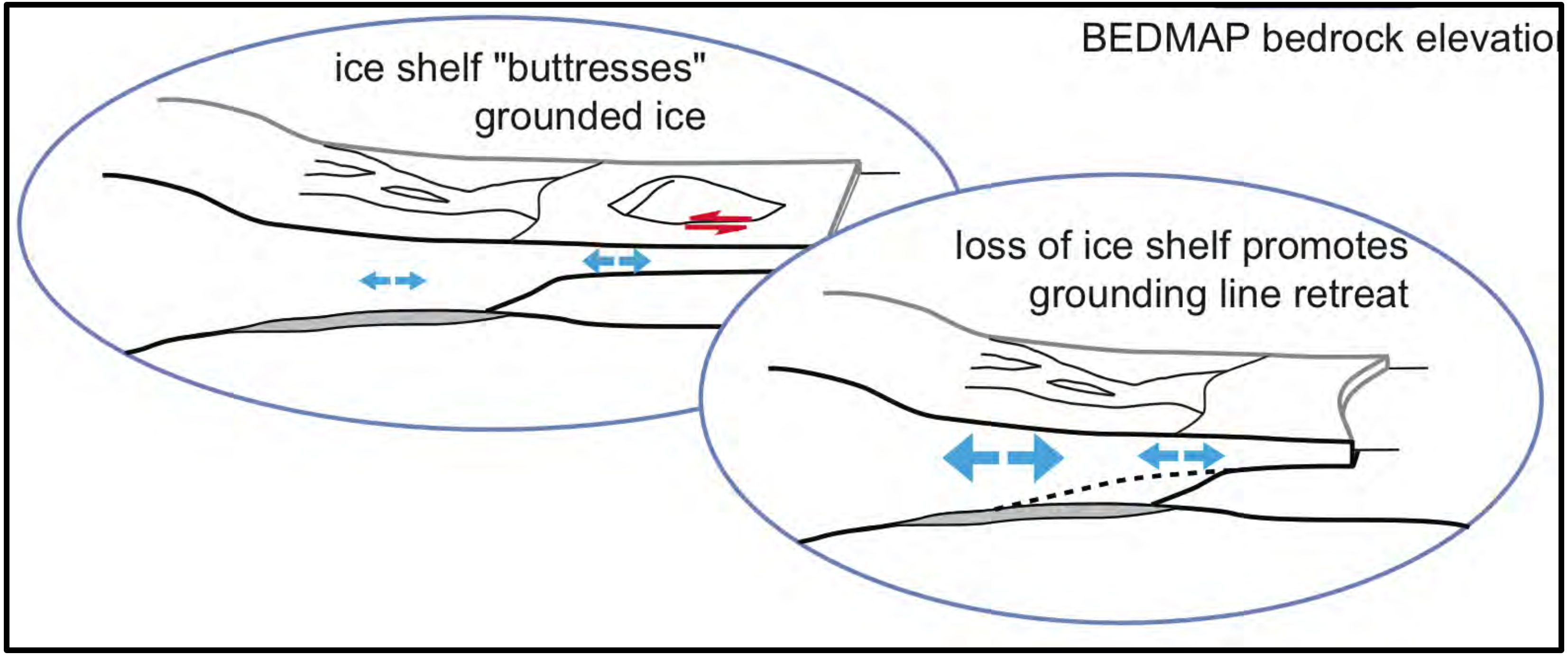
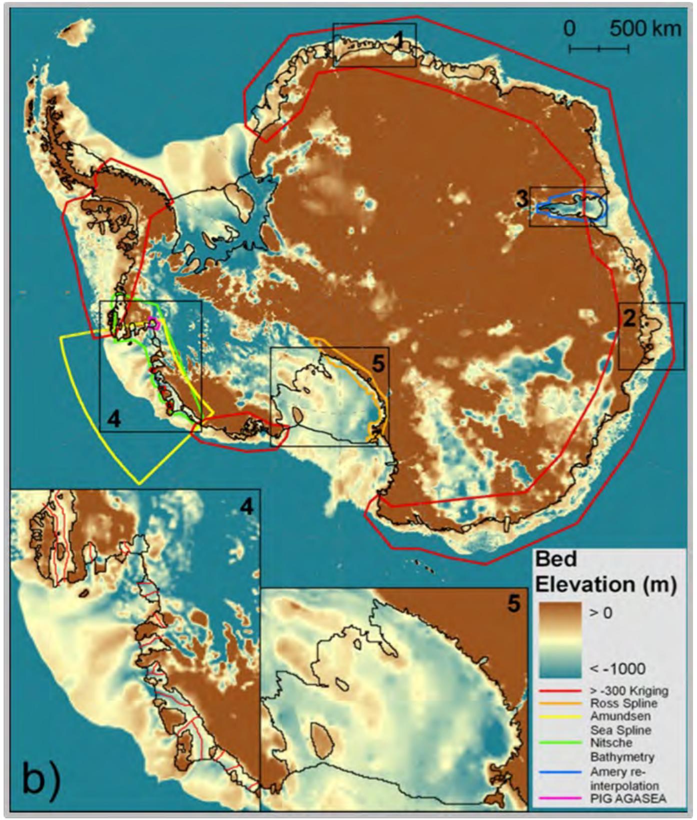


Image: http://www.snowballearth.org

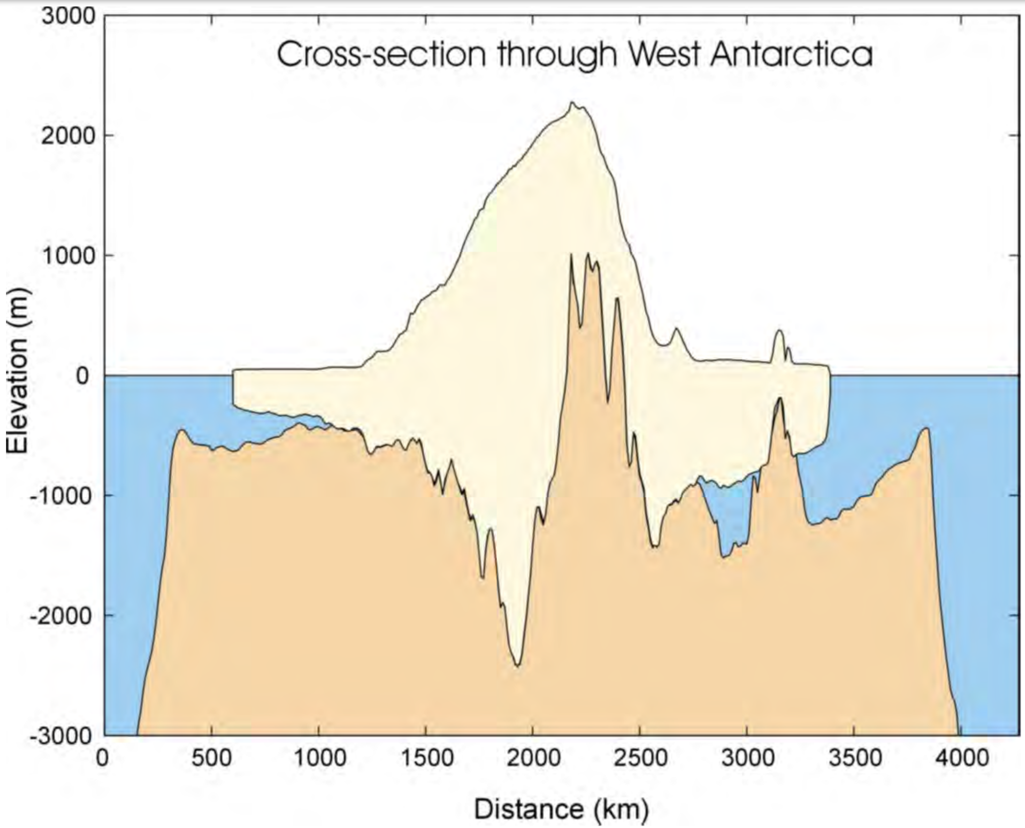
Antarctic Marine Ice Sheet Instability



Antarctic Marine Ice Sheet Instability



LeBrocq et al., 2010


Cross-section through West Antarctica
Elevation (m)
3000
2000
1000
0
-1000
-2000
-3000
0
500
1000
1500
2000
2500
3000
3500
4000
Distance (km)

What does an ice sheet model look like?

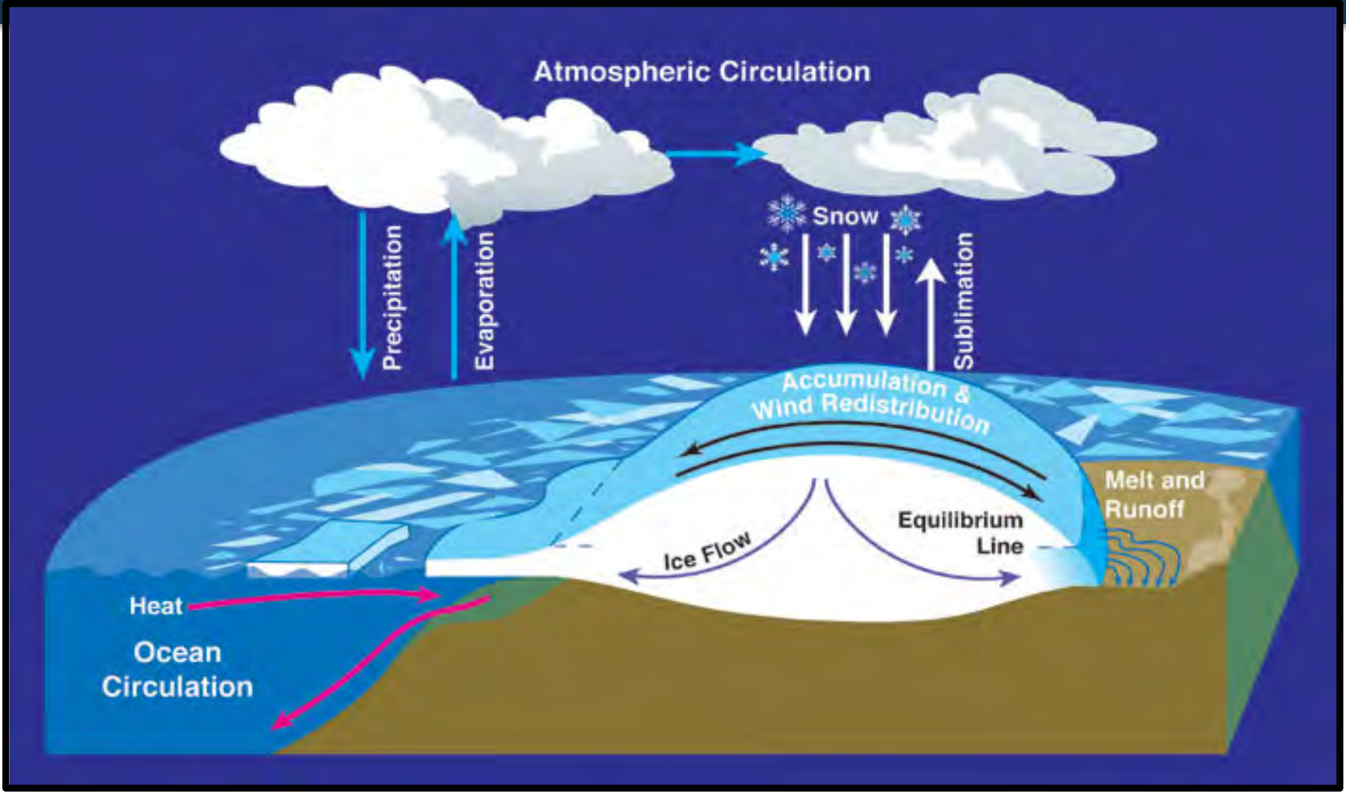


Image source: http://www.nasa.gov/images/content/53743main_atmos_circ.jpg

$$\frac{\partial H}{\partial t} + \nabla \cdot (\vec{u}H) = B - m$$

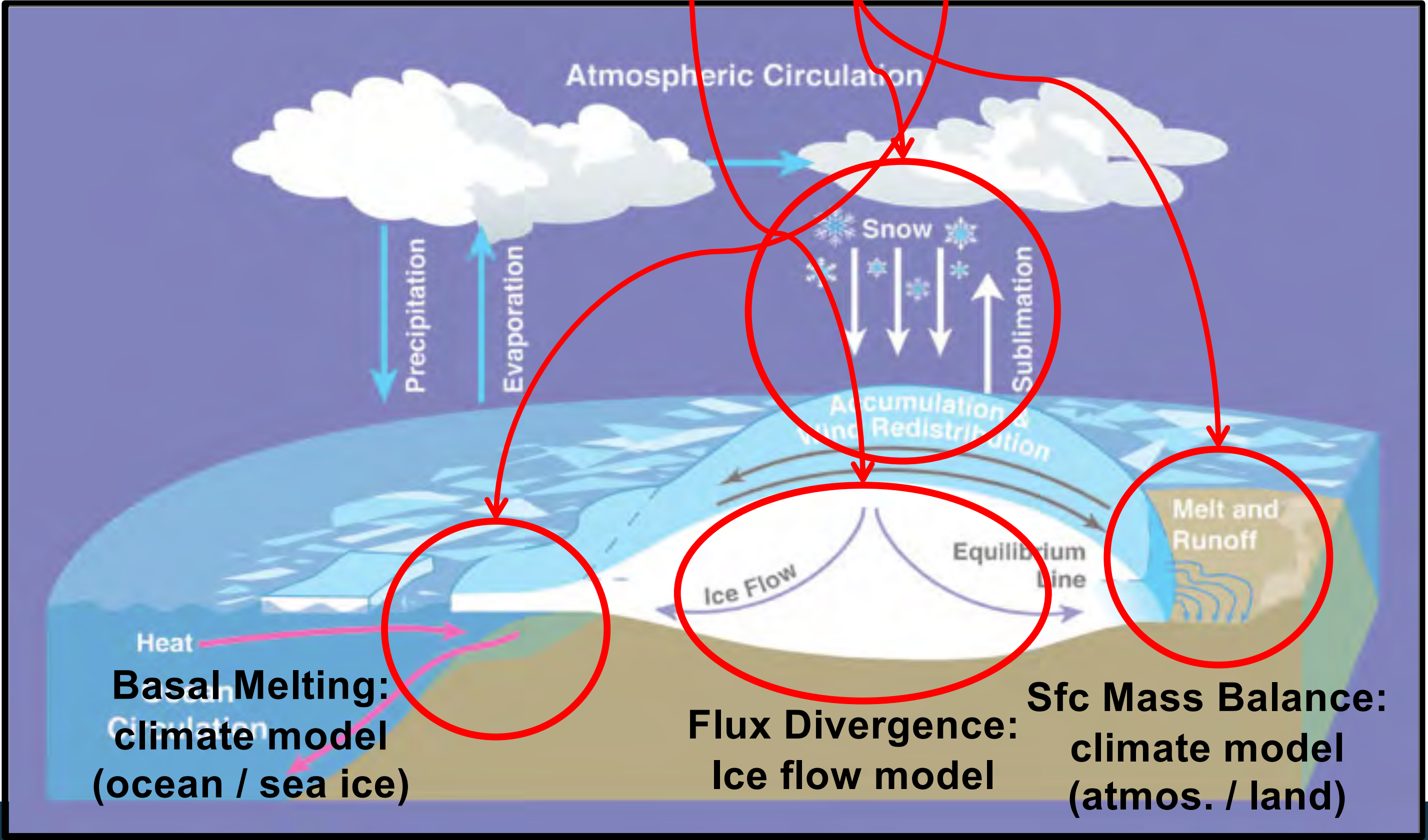


Image source: http://www.nasa.gov/images/content/53743main_atmos_circ.jpg

Models and Approximations

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

- **"Full-Stokes" (pressure forces balance viscous stresses)**
  - 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 $\left(\varepsilon = \frac{[h]}{[l]}\right)$
  - 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)
- **Depth-integrated**
  - "Shallow Ice" and "Shallow-Shelf" approximations (accurate to O(ε))
  - Special case of approximate Stokes with 2D equation set
  - Easiest to work with computationally, generally less accurate

"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 $O(\varepsilon^2)$

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

Can construct a computationally efficient scheme:

- Approximate constitutive relation relating $grad(u)$ and stress field τ with one relating $grad(u|_{z=b})$, vertical shear stresses τ_{xz} and τ_{xz} given by the SIA / lubrication approximation and other components $\tau_{xx}(x,y,z)$, $\tau_{xy}(x,y,z)$, etc

- Leads to an effective viscosity $\mu(x,y,z)$ which depends only on $grad(u|_{z=b})$ and $grad(z_s)$, ice thickness, etc

- Momentum equation can then be integrated vertically, giving a nonlinear, 2D, elliptic equation for $u|_{z=b}(x,y)$

- $u(x,y,z)$ can be reconstructed from $u|_{z=b}(x,y)$

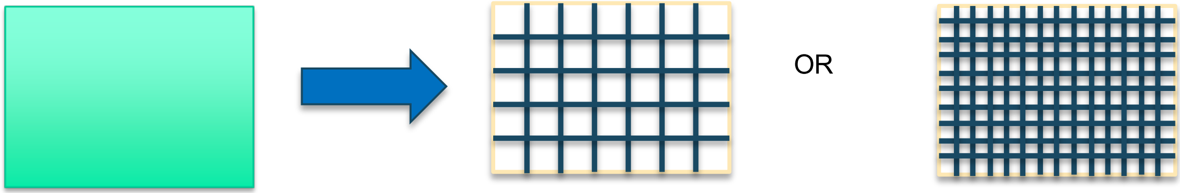
Discrete math for simulations

- Computers are really good at simple arithmetic (+,-, ×, ÷)
- The equations in physics are usually continuous and complicated. (heat conduction:

$$\frac{\partial T}{\partial t} = k\,\nabla^2 T = \; k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2}$$

where *T* = temperature, *t* = time, *k* is the "conductivity" (a physical property)

- So, we break up the world into small pieces (*cells*) by laying down a *computational mesh* in the *domain* and then approximating our continuous calculus equations by a bunch of simpler arithmetic ("discrete") ones for each cell. (cell spacing = "Δx")

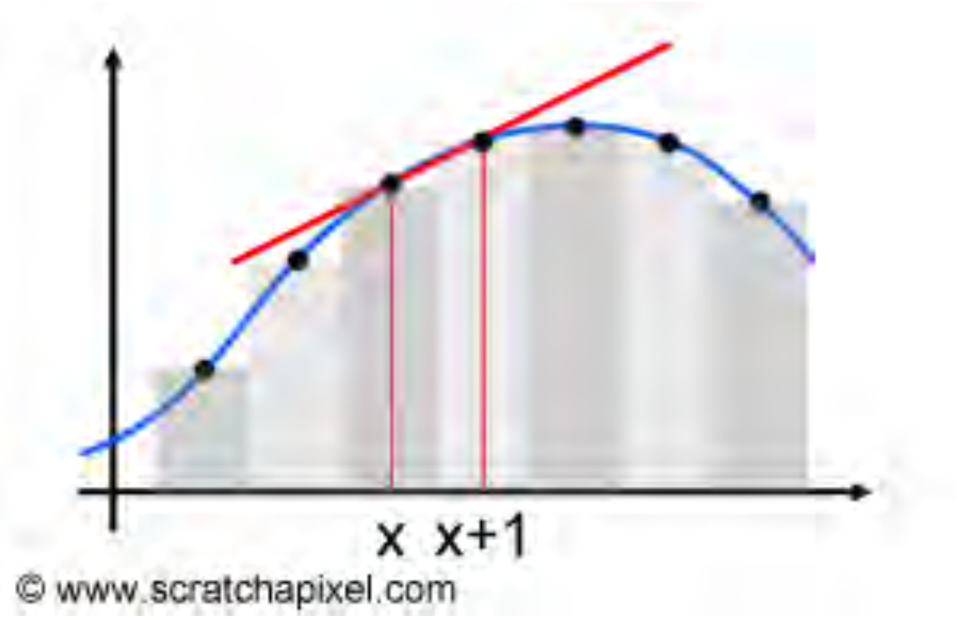


Discrete Math for Simulations (cont)

Example -- approximating derivatives:

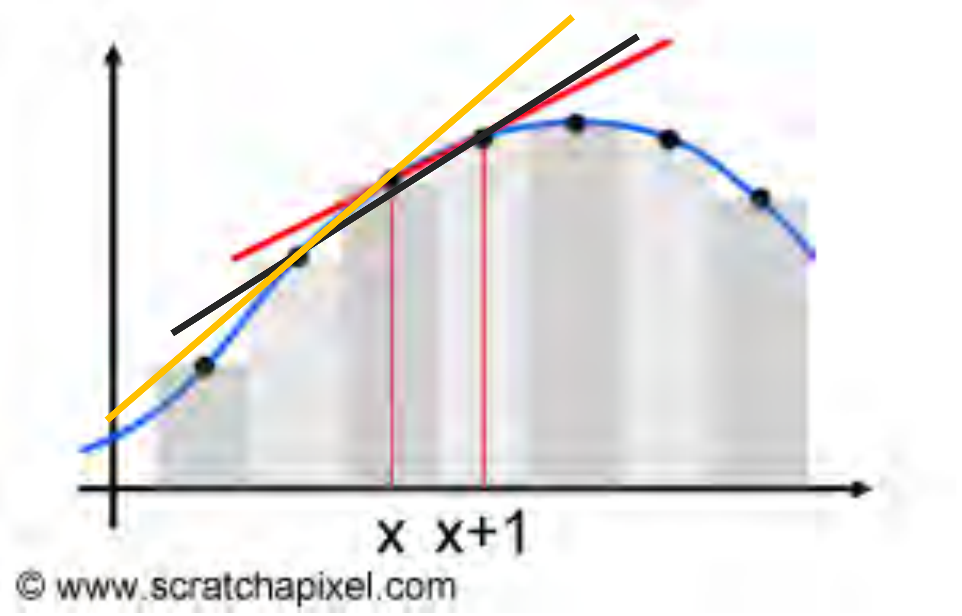
$$\frac{df}{dx} \approx \frac{\Delta f}{\Delta x}$$

$$= \frac{(f_{i+1} - f_i)}{(x_{i+1} - x_i)}$$



Discrete Math for Simulations (cont)

Example -- approximating derivatives:

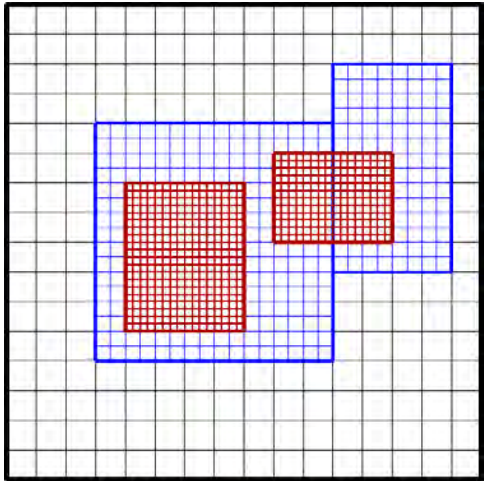


$$\frac{df}{dx} \approx \frac{\Delta f}{\Delta x}$$

$$= \frac{(f_{i+1} - f_i)}{(x_{i+1} - x_i)} \quad \textbf{or} \quad \frac{(f_{i+1} - f_{i-1})}{2\Delta x} \quad \textbf{or} \quad \frac{(f_i - f_{i-1})}{\Delta x}$$

Adaptive Mesh Refinement

- The finer the mesh, the more accurate your simulation is (like more pixels in a digital camera).
- Finer mesh = more "unknowns" to solve for.
- More unknowns = more expensive to solve.
  (in 3d, $\Delta x \rightarrow \frac{\Delta x}{2}$ *means 16x cost!)*
- Often, need fine mesh (higher resolution) in some places, but not in others.
- *Adaptive Mesh Refinement* (AMR): Local refinement of computational mesh to improve accuracy only where important.

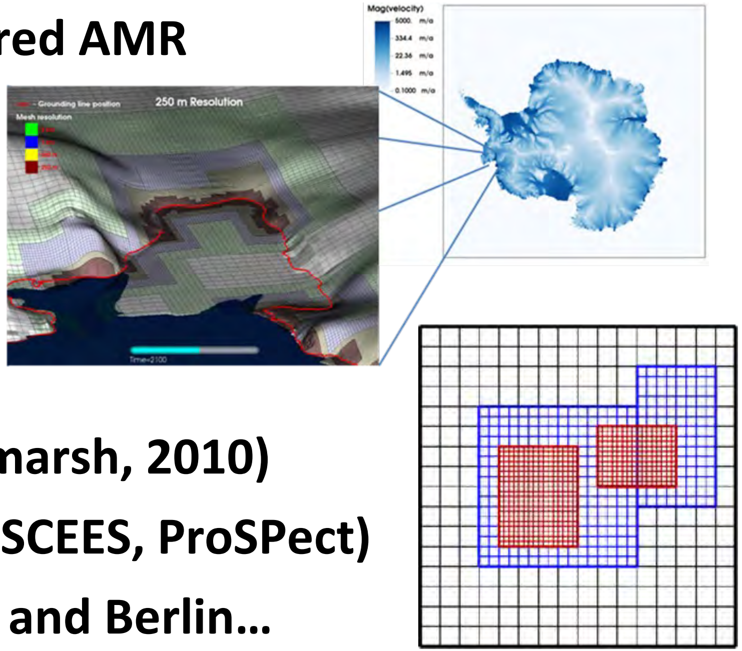


(Figure courtesy of Ann Almgren)

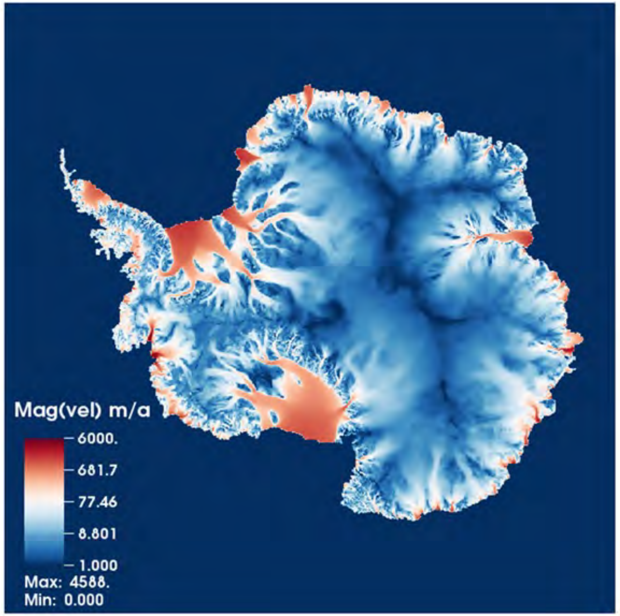
- AMR lets you *dynamically* focus computational effort where you need it

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?)



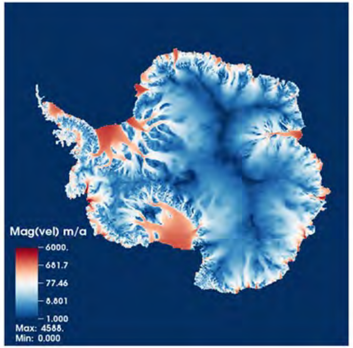
- Ice sheets -- Localized regions where high resolution needed to accurately resolve ice-sheet dynamics (500 m or better at grounding lines)
- Antarctica is really big – too big to resolve at that level of resolution.
- Large regions where such fine resolution is unnecessary (e.g. East Antarctica)

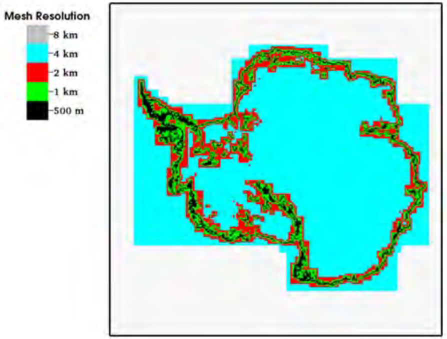
- Well-suited for adaptive mesh refinement (AMR)
- Problems still large: need good parallel efficiency
- Dominated by nonlinear coupled elliptic system for ice velocity solve: good linear and nonlinear solvers

Target Problems

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

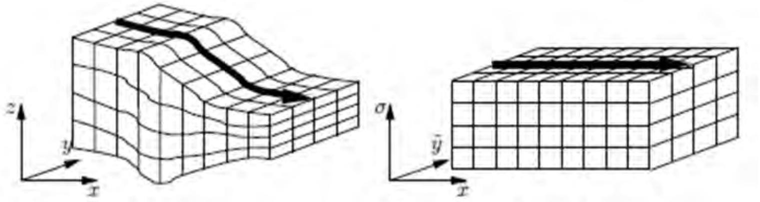
- **Realistic full-scale**
  - Fully-resolved (500m) full-continent
  - Antarctica





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:

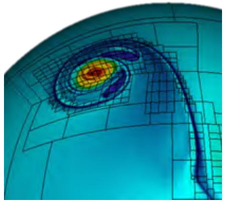
$$\beta^2\overrightarrow{u_b} + \nabla \cdot \left[\mu(\dot{\varepsilon}^2)\left(\vec{\nabla} + \vec{\nabla}^T\right)\overrightarrow{u_b} - 2\mu\,(\nabla \cdot \overrightarrow{u_b})\right] = -\frac{g}{\rho}H\,\vec{\nabla}s$$

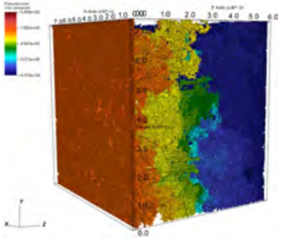
β^2 = friction coefficient, $\dot{\varepsilon}$= strain rate invariant of ice velocity, g = gravity, ρ = ice density, H = ice thickness, $\vec{\nabla}s$ = horizontal gradient of upper surface

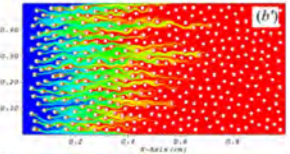
  - Enthalpy formulation for energy

Chombo – Scalable Adaptive Mesh Refinement (AMR)

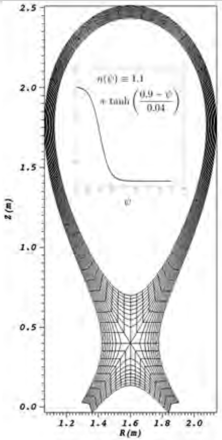
Scalable adaptive mesh refinement (AMR) framework.
Enables implementing scalable AMR applications with support for complex geometries.

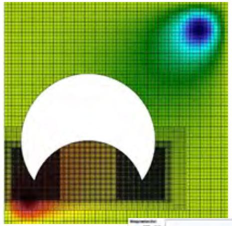




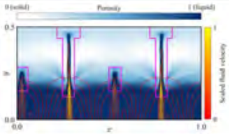


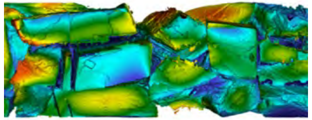
- **Adaptive Mesh Refinement (AMR)**
  - Block structured AMR dynamically focuses computational effort where needed to improve solution accuracy
  - Designed as a developers' toolbox for implementing scalable AMR applications
  - Implemented in C++/Fortran
  - Solvers for hyperbolic, parabolic, and elliptic 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

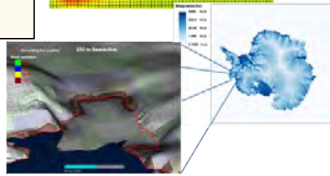




http://Chombo.lbl.gov







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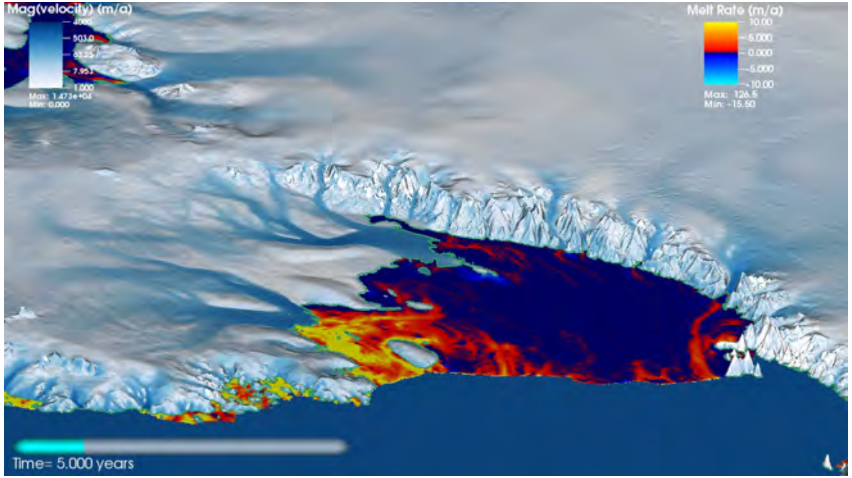
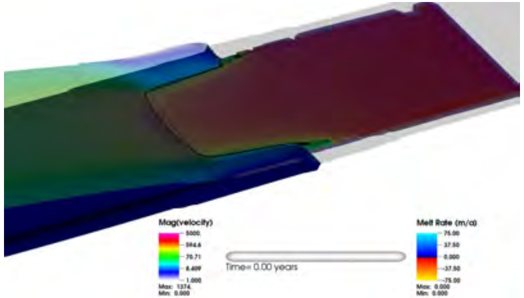
So what can we do with an AMR ice sheet model?

- **Couple with ocean & earth system models…**





Ice-ocean coupled models:

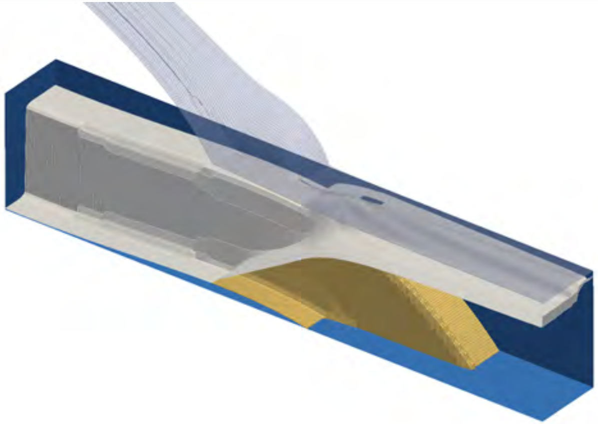
- **Ocean Circulation Model: POP2x**
- **Ice Sheet: BISICLES**
- **POP + BISICLES = *POPSICLES***

Coupling: Synchronous-offline

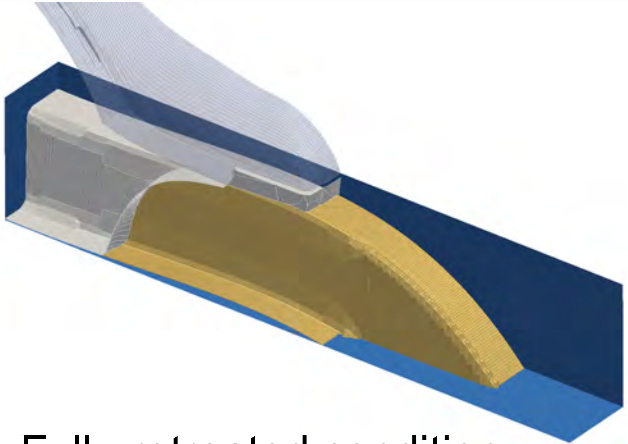
- Monthly coupling time step ~ based on experimentation
- BISICLES → POP2x: (instantaneous values)
  - ice draft, basal temperatures, grounding line location
- POP2x → BISICLES: (time-averaged values)
  - (lagged) sub-shelf melt rates
- Coupling offline using standard CISM and POP netCDF I / O
- POP bathymetry and ice draft recomputed:
  - smoothing bathymetry and ice draft, thickening ocean column, ensuring connectivity
  - T and S in new cells extrapolated iteratively from neighbors
  - barotropic velocity held fixed; baroclinic velocity modified where ocean column thickens/thins

[1]Goldberg et al. (2012)

MISOMIP (Asay-Davis et al (2015))



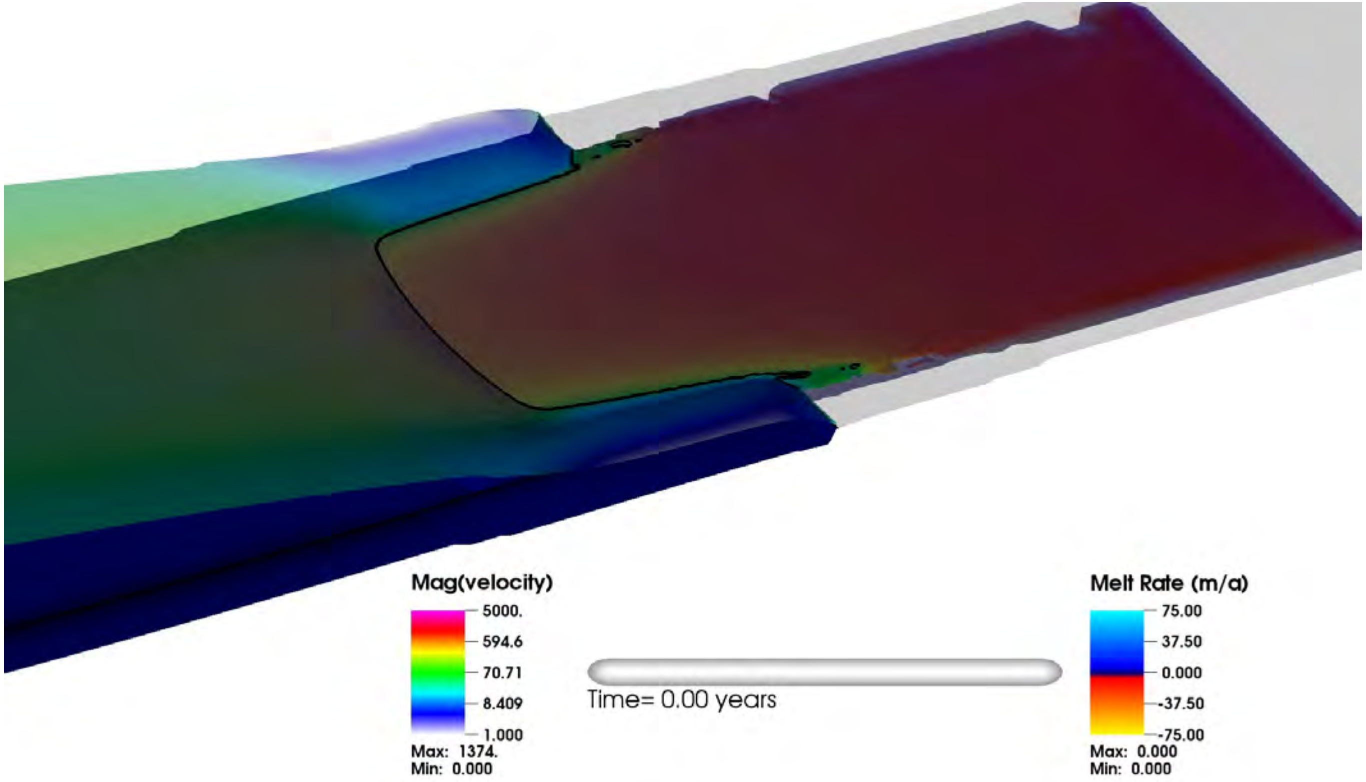
Steady-state initial condition



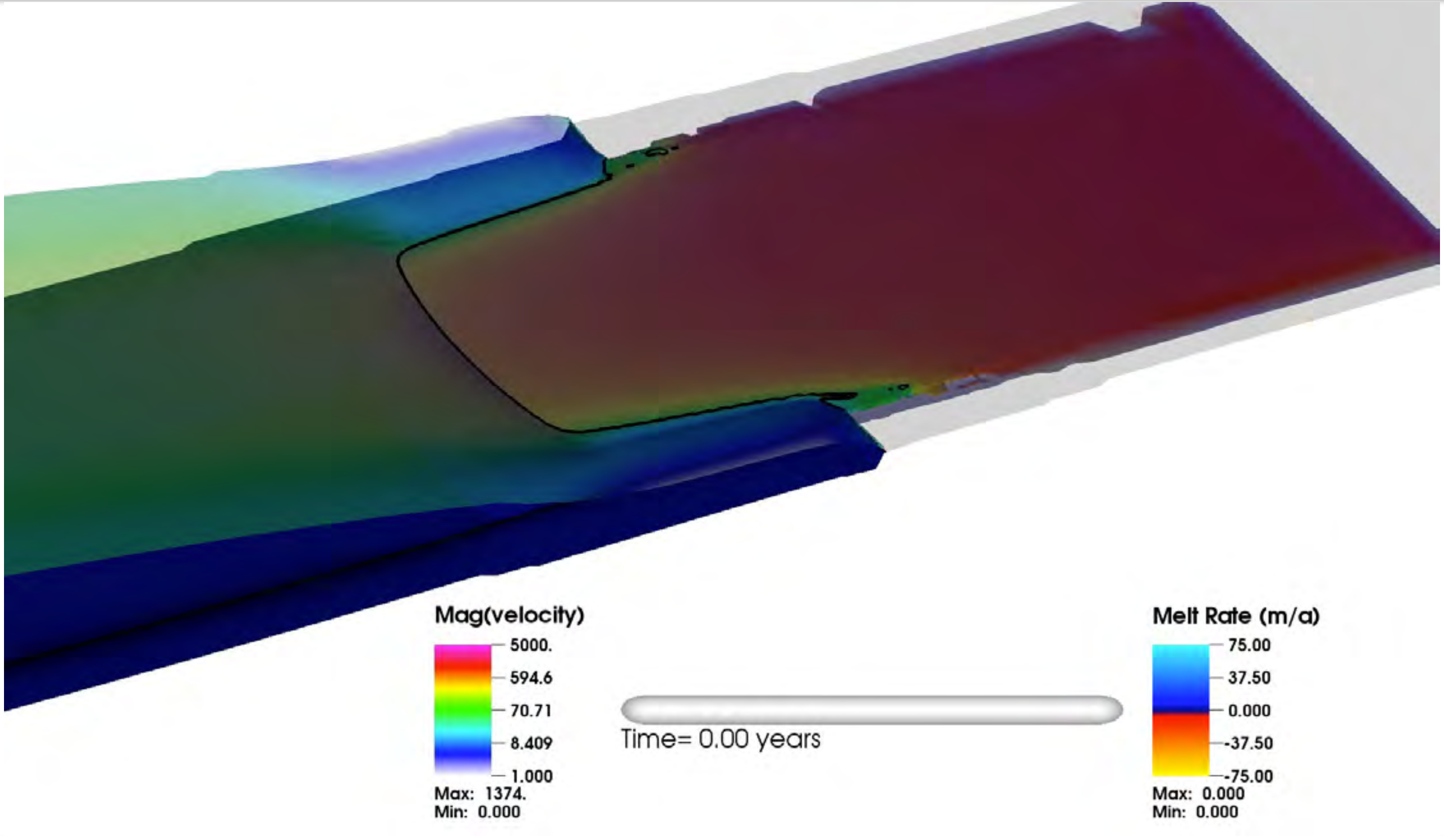
Fully-retreated condition

- Marine Ice Sheet-Ocean Model Intercomparison Project
- Ice Sheet coupled to Ocean Model through melt rates
- Driven by far-field forcing –
  - 0 < t < 100 years: Warm Phase (1 C)
  - 100 < t < 200 years: Cold Phase (-1.9 C)

“MISOMIP” test problem



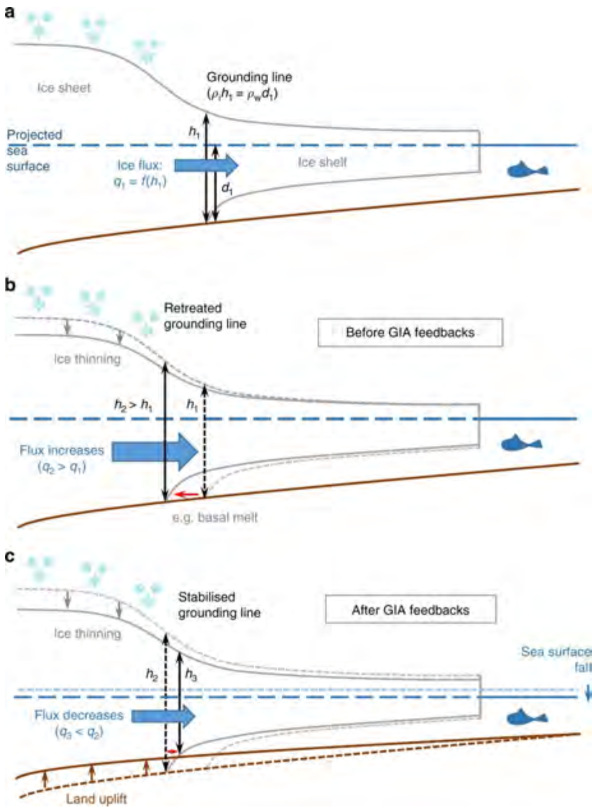
“MISOMIP” test problem



Solid-earth response coupling

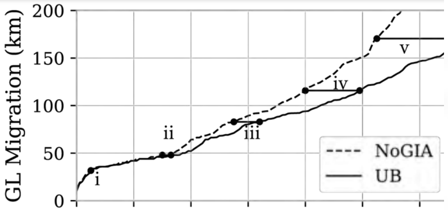
- Loading and unloading due to changes in ice sheets causes a response in the solid earth under the ice
  - Glacial Isostatic Adjustment (GIA)
  - Unloading -> “rebound”
- Rebound could potentially help stabilize the ice sheet

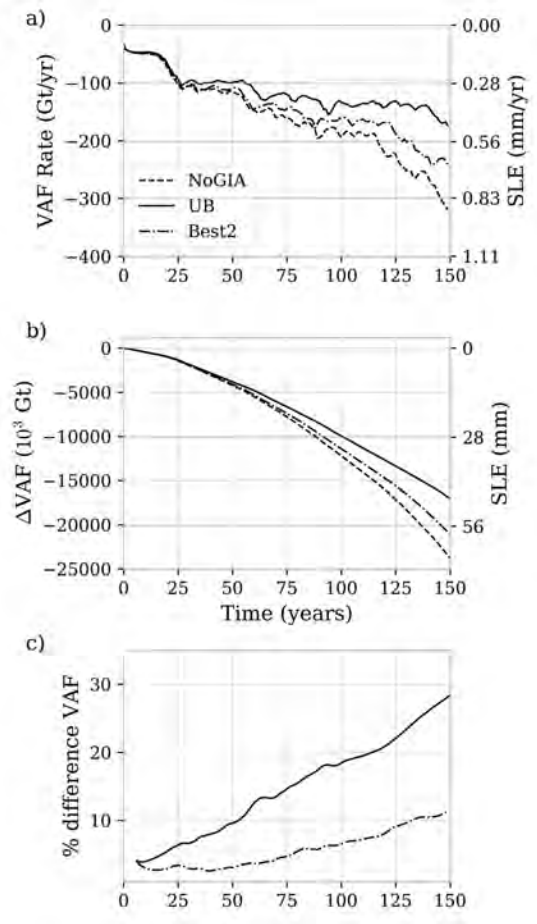
- Depends on:
  - Mantle properties
  - Rate of ice sheet change



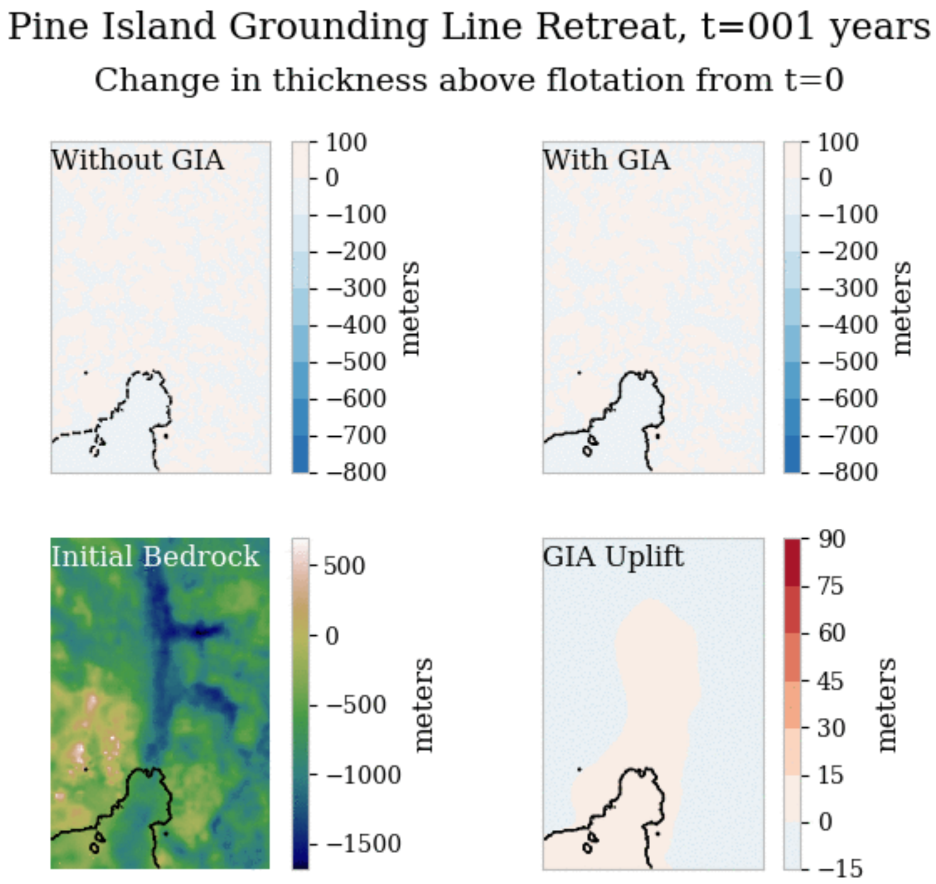
Solid earth response coupling (cont)

- Recent work: coupled BISICLES to a solid earth model to study impacts
- Some evidence that mantle under WAIS is hotter and weaker than elsewhere
- Result: including coupling with GIA can slow retreat and reduce contribution to sea level rise.
- **Timescale is crucial –** requires that retreat occur at similar timescale as GIA response
  - If retreat is too fast, GIA response is too slow to have an impact
  - Essential that we get the timescales of ice sheet response correct!

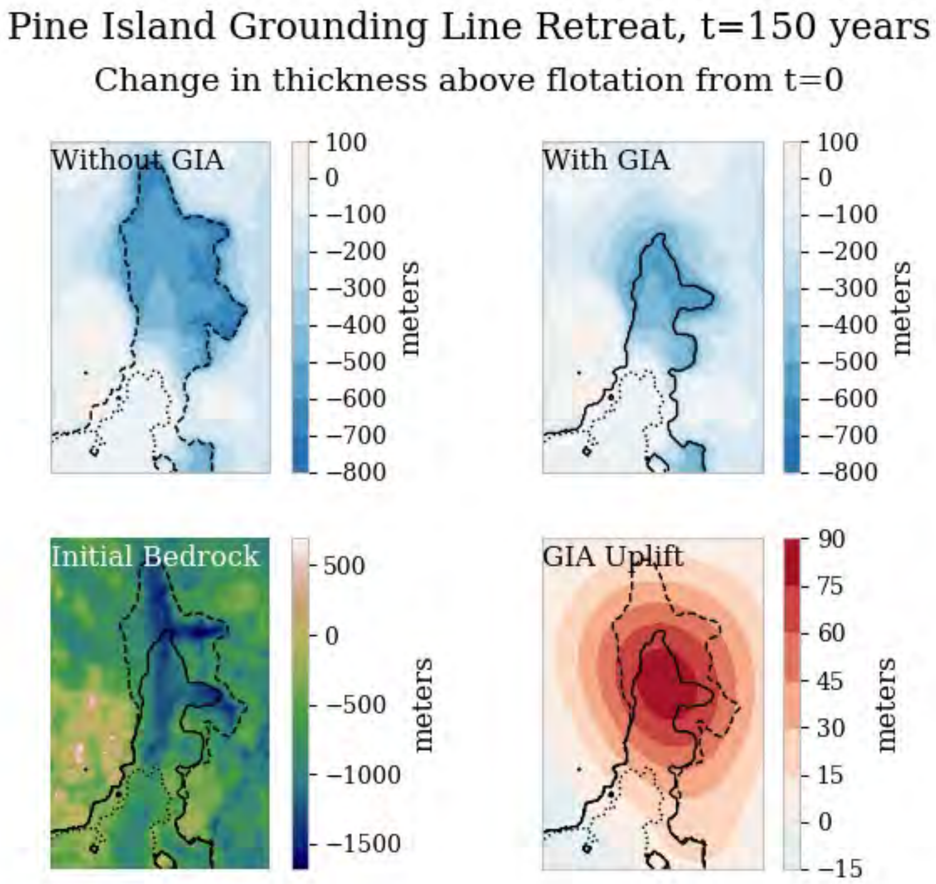




(Kachuck, Martin, Bassis, and Price, GRL, 2020)

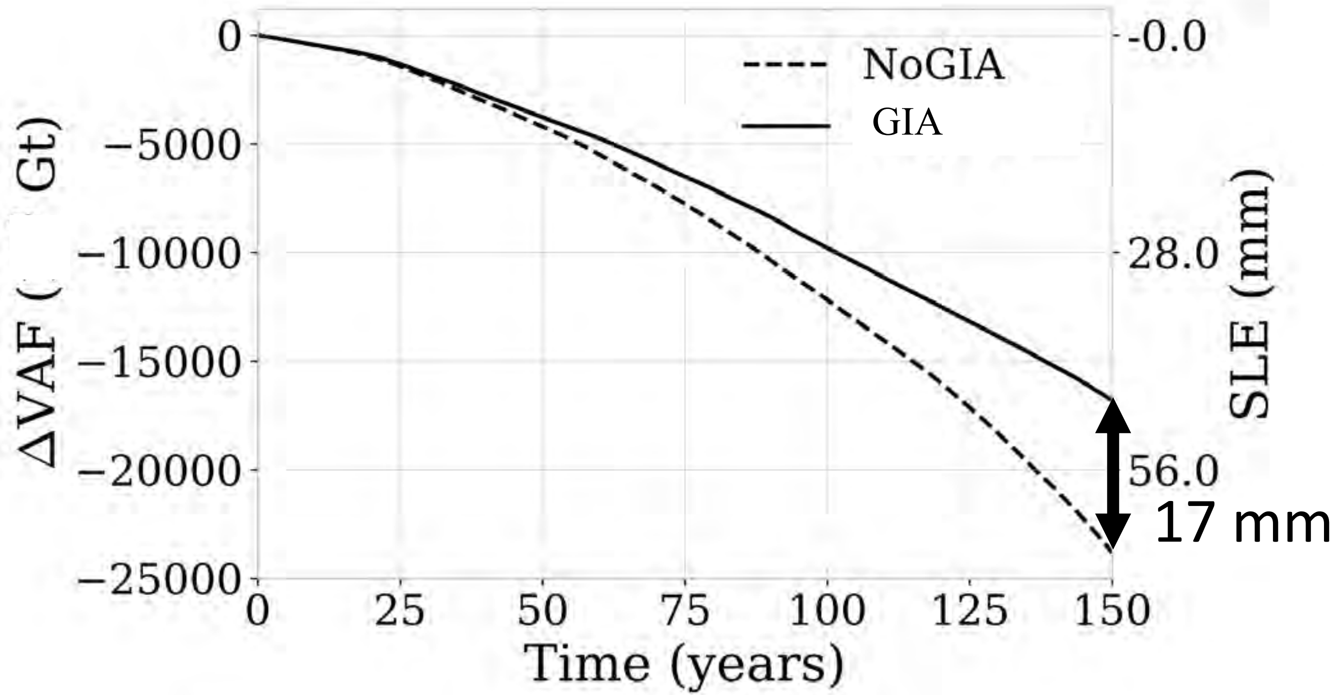


Kachuck, et al. (GRL, 2020)



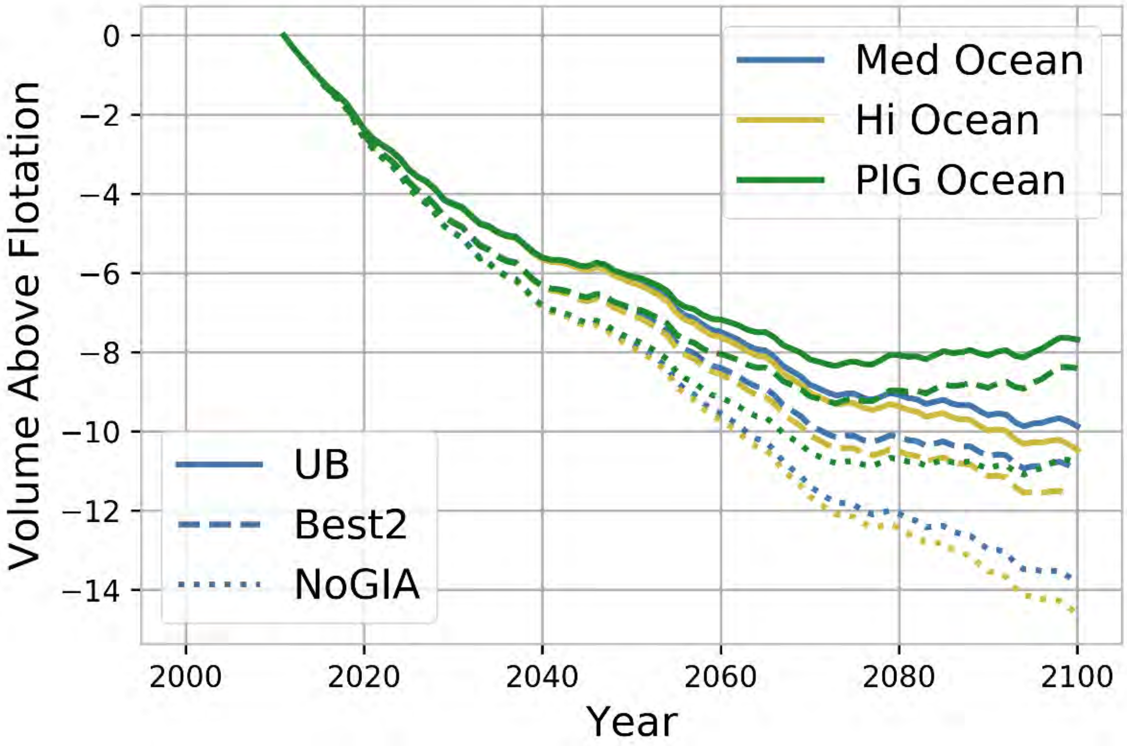
Kachuck, et al. (GRL, 2020)

GIA Slows retreat of Pine Island



Kachuck, et al. (GRL, 2020)

GIA Slows retreat of Pine Island & Thwaites



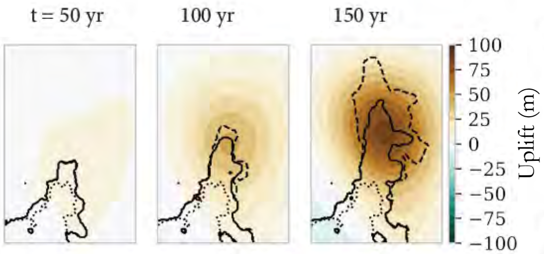
Rapid Viscoelastic Deformation Slows Marine Ice Sheet Instability at Pine Island Glacier, West Antarctica

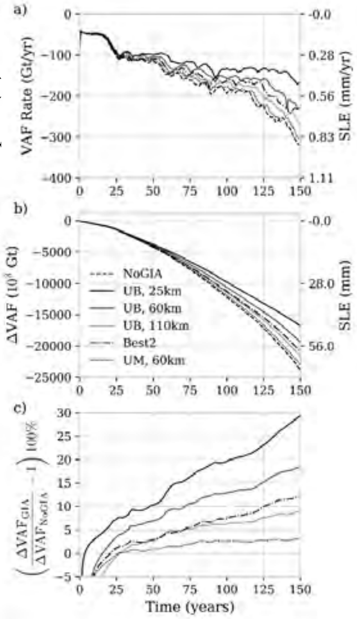
Scientific Achievement

We examine the feedback between ice sheet dynamics and solid-earth viscoelastic response and its impact on grounding-line (GL) stability and sea level rise (SLR).

Significance and Impact

- Solid-earth feedbacks, from viscoelastic glacial isostatic adjustment (GIA) in response to unloading from ice sheet thinning, have the potential to mitigate GL retreat and mass loss due to marine ice sheet instability.
- Full dynamic coupling of a viscoelastic solid-earth deformation model to the DOE-supported BISICLES ice sheet model in a new GIANT-BISICLES model.
- Bedrock uplift due to the viscoelastic response of a low-viscosity mantle can rapidly reduce ocean depth near the grounding line and stabilize the marine ice sheet instability over decades to centuries.
- Viscoelastic uplift on timescales similar to grounding line migration can be a leading term in determining rates of SLR due to the marine ice sheet instability.





Top: *Viscoelastic uplift of the grounding line (GL) slows retreat. The regional uplift at three times: t=50, 100, and 150 years for model with solid-earth response, also showing the initial GL (dotted) and predicted GL with uplift (GIA -solid) and without uplift (NoGIA - dashed) contours shown. The maximum uplift is predicted just in front of the grounding line.*
Right: *Results from coupling Pine Island Glacier flow to*
GIA-related deformation over 150 years for different rheologies. a) Volume above flotation (VAF) loss rate in Gigatons of ice and millimeters of equivalent sea level rise (SLE). b) Change in total VAF (ΔVAF) relative to t=0. c) Percentage difference ΔVAF (from b) between models with GIA-related deformation relative to without.

Research Details

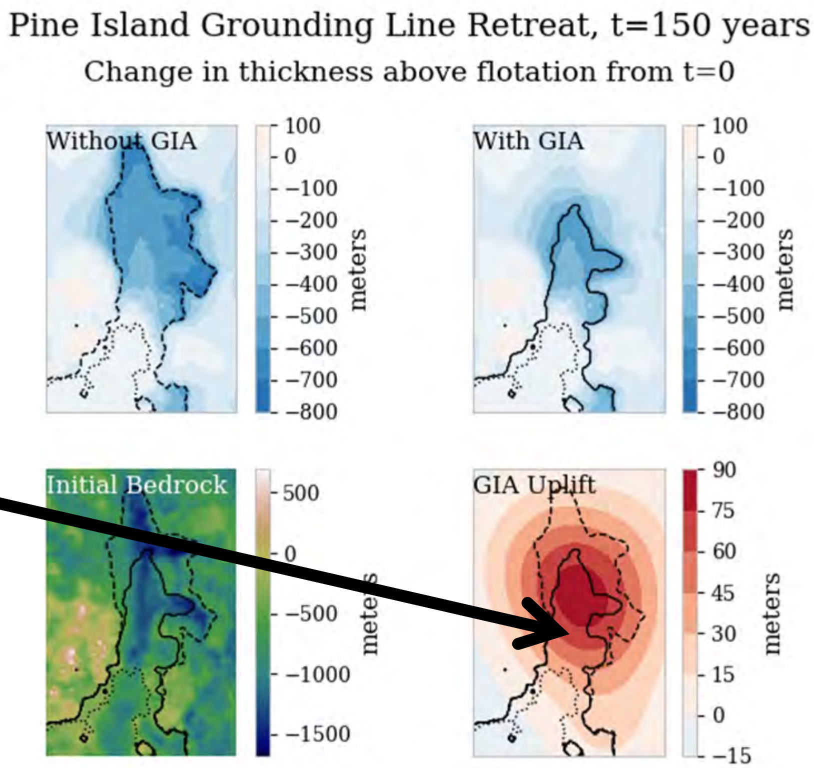
- Coupled solid-earth/ice sheet model used to simulate West Antarctica's Pine Island Glacier for a range of potential mantle viscosities.
- Uses DOE SciDAC-supported BISICLES adaptive mesh refinement (AMR) ice sheet model which resolves flow down to 500m resolution, essential for accurately capturing realistic grounding line dynamics.

Kachuck, Martin, Bassis, and Price (2020). Geophysical Research Letters, **DOI 10.1029/2019GL086446**. Contact: Samuel Kachuck (skachuck@umich.edu)

But… (there's always a "but"…)

- **Go back and account for *all* of the water in the domain…**

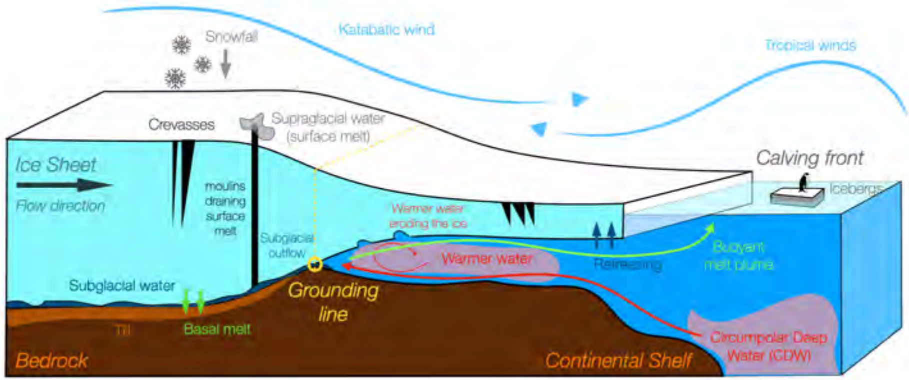
- **Impact of rising seafloor…**
  - Squeezes out open-ocean water, raises sea levels elsewhere
  - This effect of GIA outweighs the reduced ice loss…
  - (still evaluating what this means)



Subglacial Hydrology

- Water under the ice can lubricate the bed of the ice, changing the basal friction
- Greenland summer melt
- Antarctic Subglacial lakes
- **Very dynamic** – transitions between inefficient “distributed” system and efficient “channelized” system

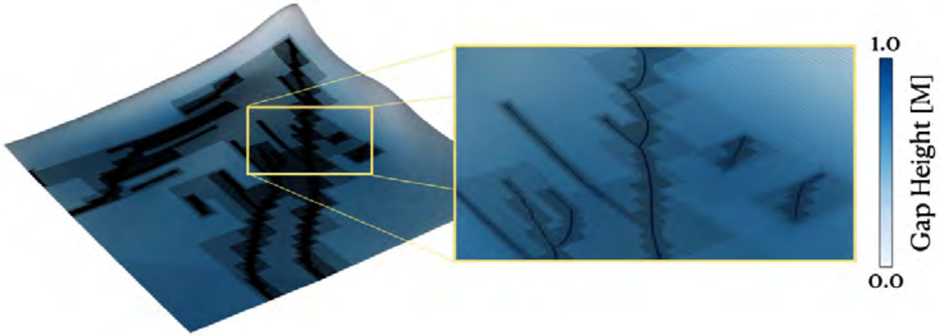
- Want to be able to model this!



SUHMO

- **Su**bglacial **H**ydrology **Mo**del
- AMR model
  - Adapts mesh as channels evolve

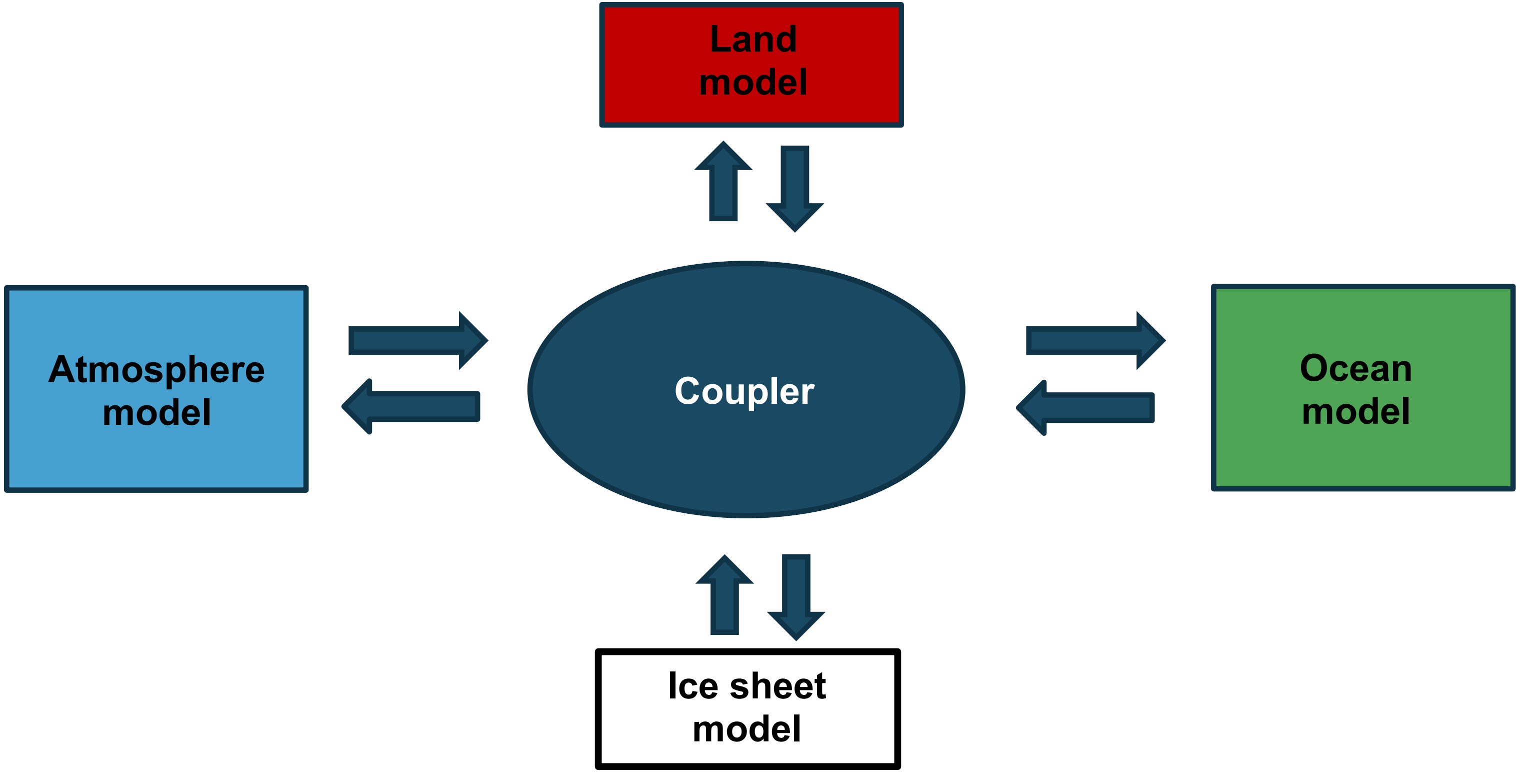
- **Status:**
  - Published 2022
  - **Couple to BISICLES!**



Global Earth System Models

- **The Energy Exascale Earth System Model (E3SM)**
  - DOE's high-resolution global earth system model
  - Currently in development
  - Effort underway at LBL to couple BISICLES as an ice sheet model component
- **UK Earth System Model (UKESM)**
  - First fully-coupled Antarctic response
  - Coupling is hard!

Coupling structure



So what can we do with an AMR ice sheet model?

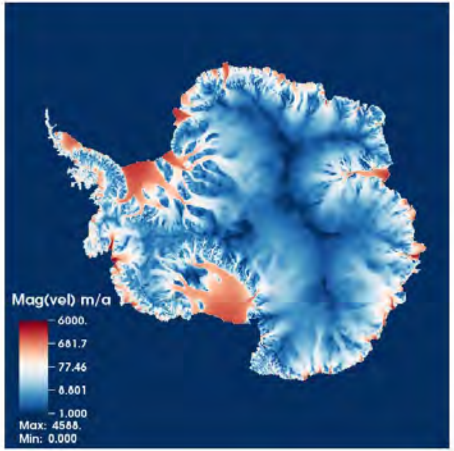
- **Couple with ocean & earth system models…**

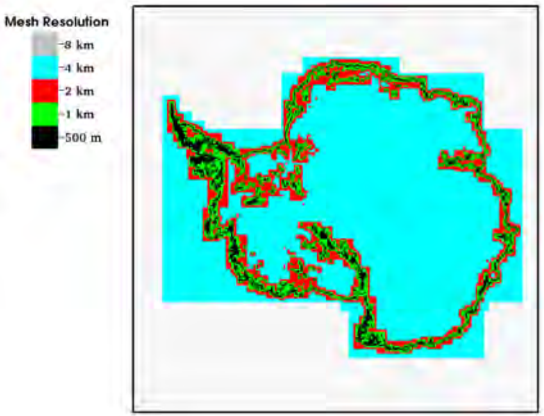
- **Examine resolution requirements and convergence of full-scale problems…**

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

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**





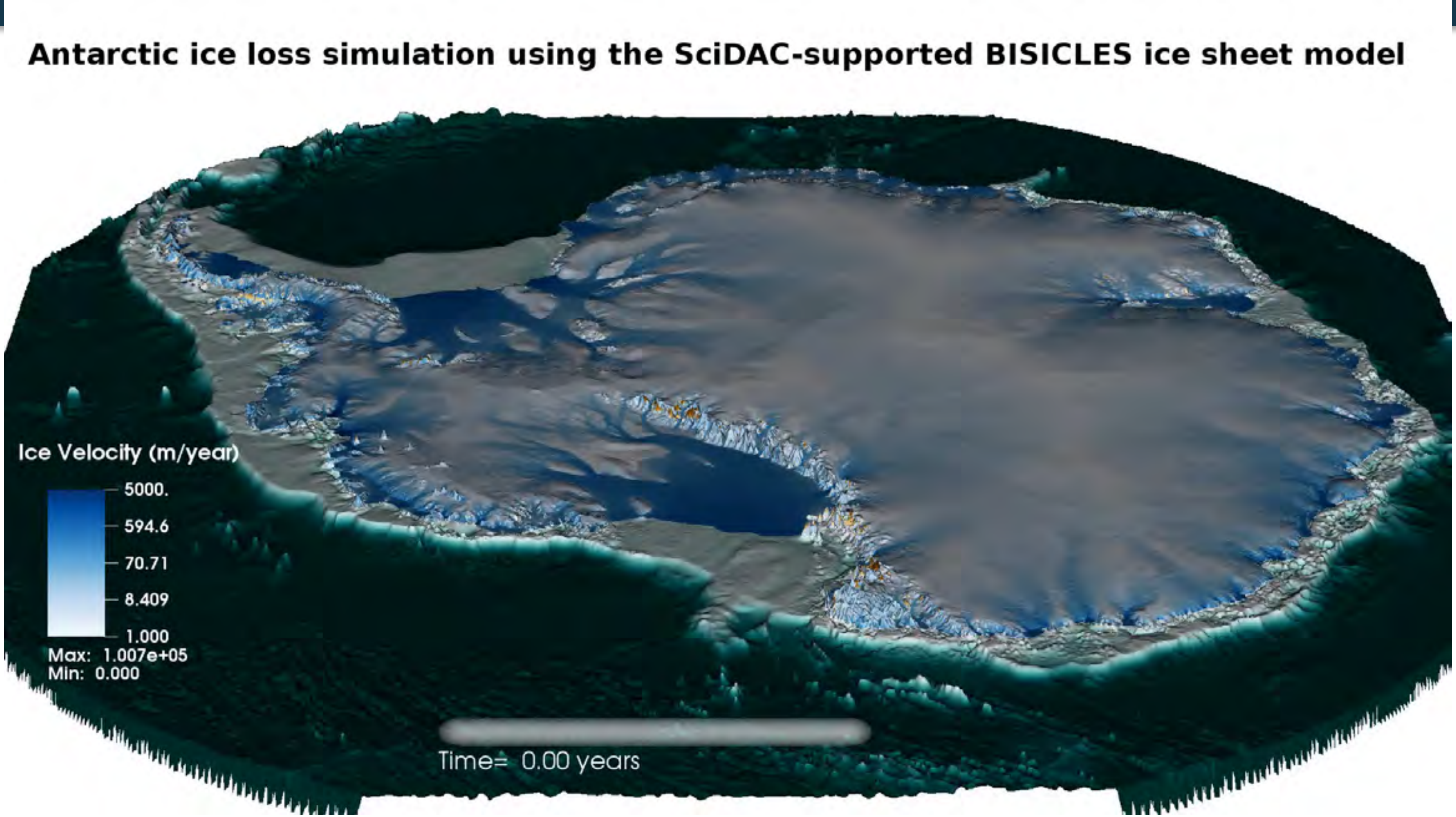
Experiment – 1000-year Antarctic simulations

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

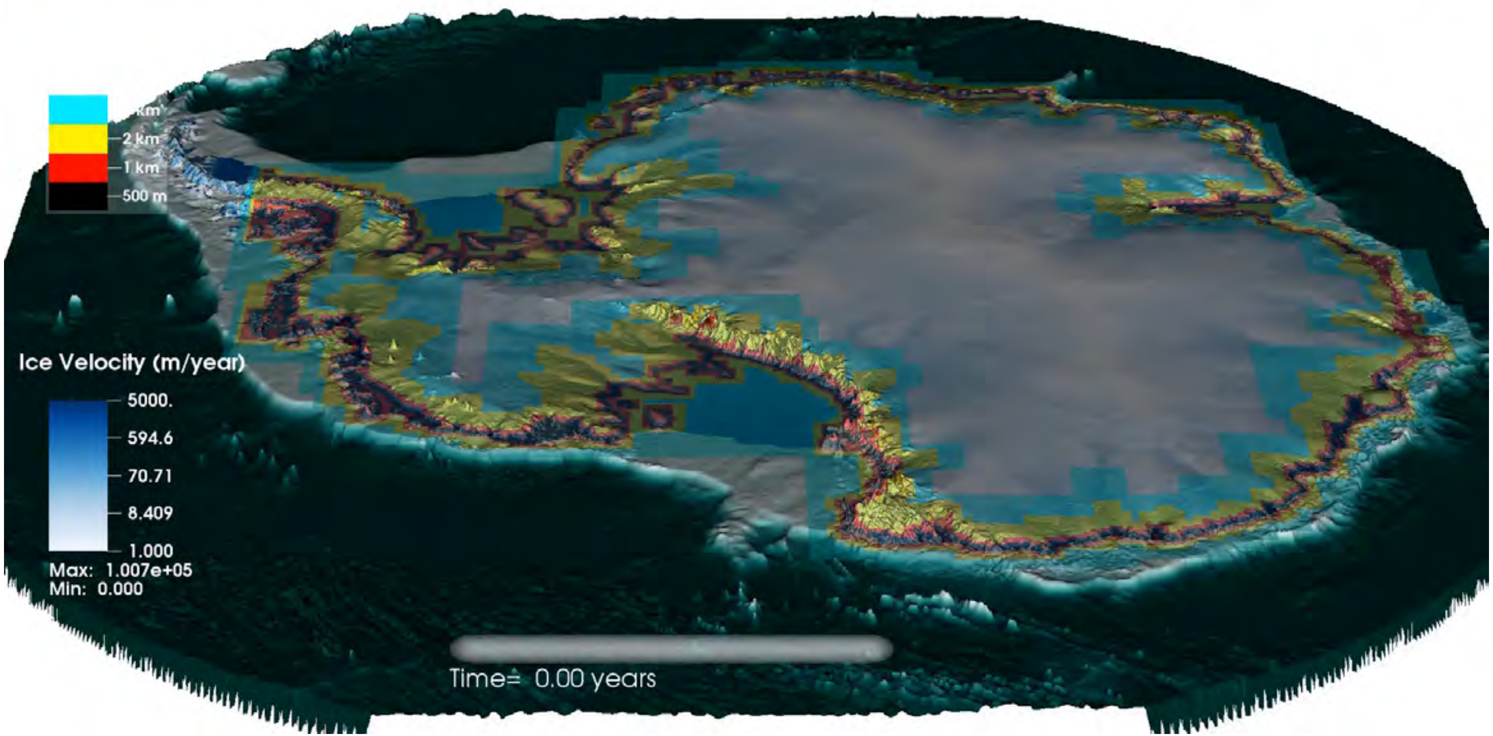
- **Subgrid basal friction parameterization (e.g. Seroussi et al)**
  - Experience shows that it buys us about a factor of 2x

- **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**


Antarctic ice loss simulation using the SciDAC-supported BISICLES ice sheet model
Ice Velocity (m/year)
5000.
594.6
70.71
8.409
1.000
Max: 1.007e+05
Min: 0.000
Time= 0.00 years

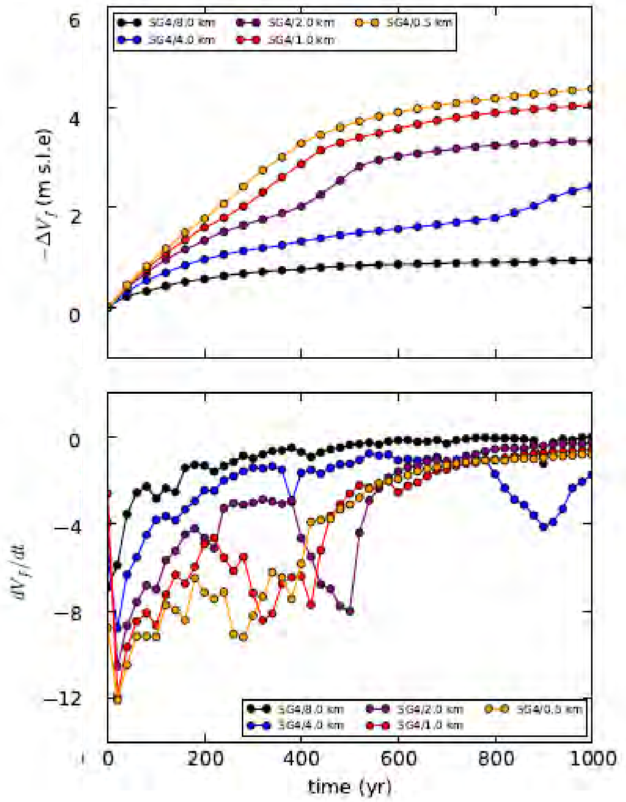
Antarctic ice loss simulation using the SciDAC-supported BISICLES ice sheet model



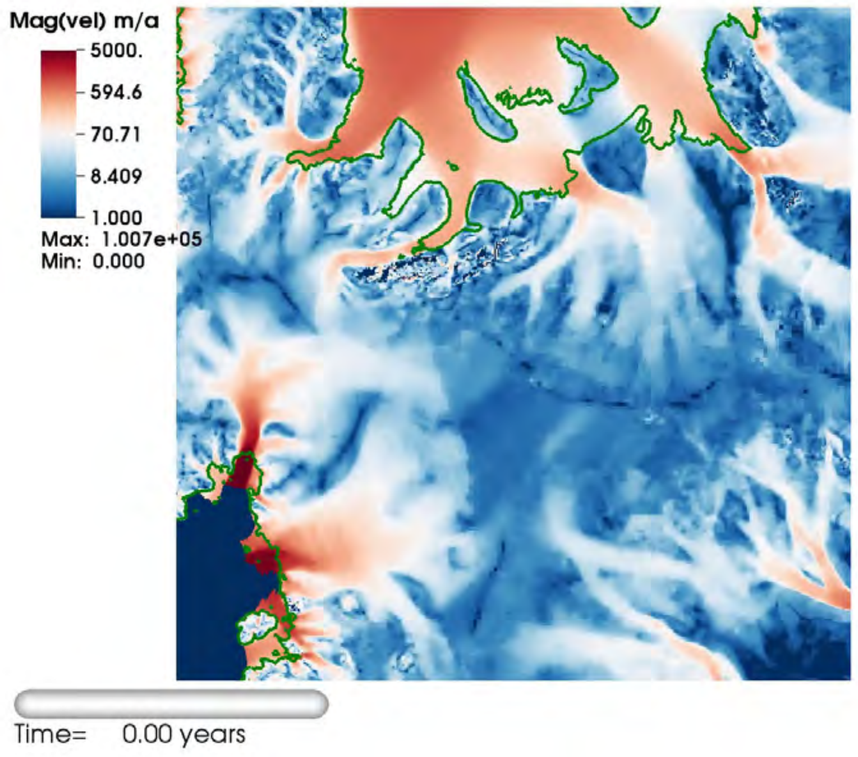
Resolution requirements…

- **Upper plot** – Contribution to SLR
  - Convergent at sufficient resolution

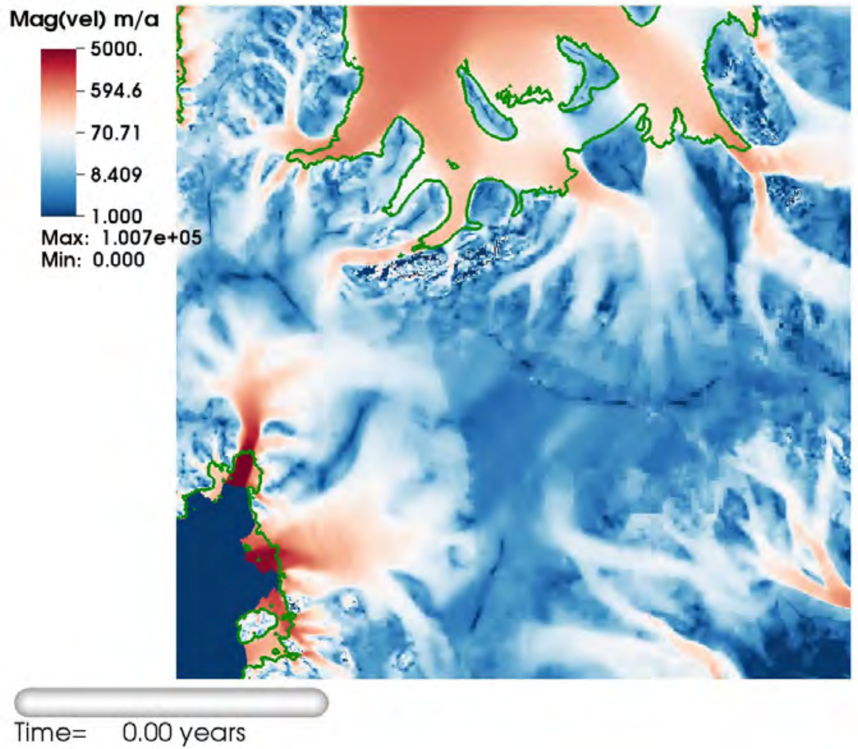
- **Lower plot --** Rate of Change
  - Big spike – WAIS collapse
  - Timing, pathways are a function of resolution



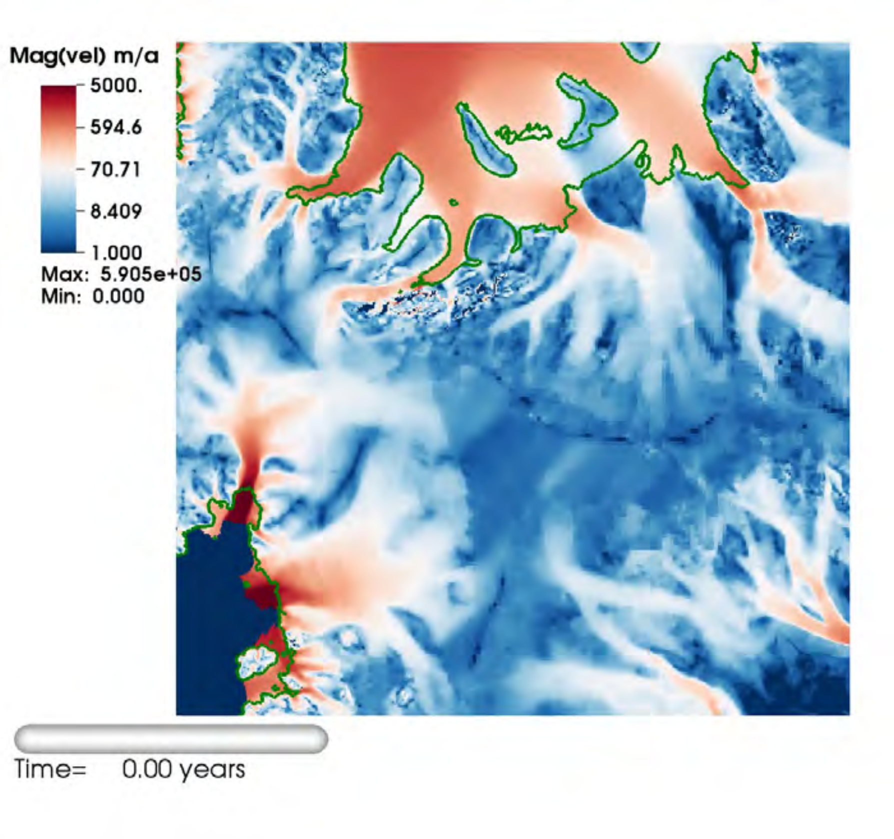
Thwaites-Rutford – 500m Resolution



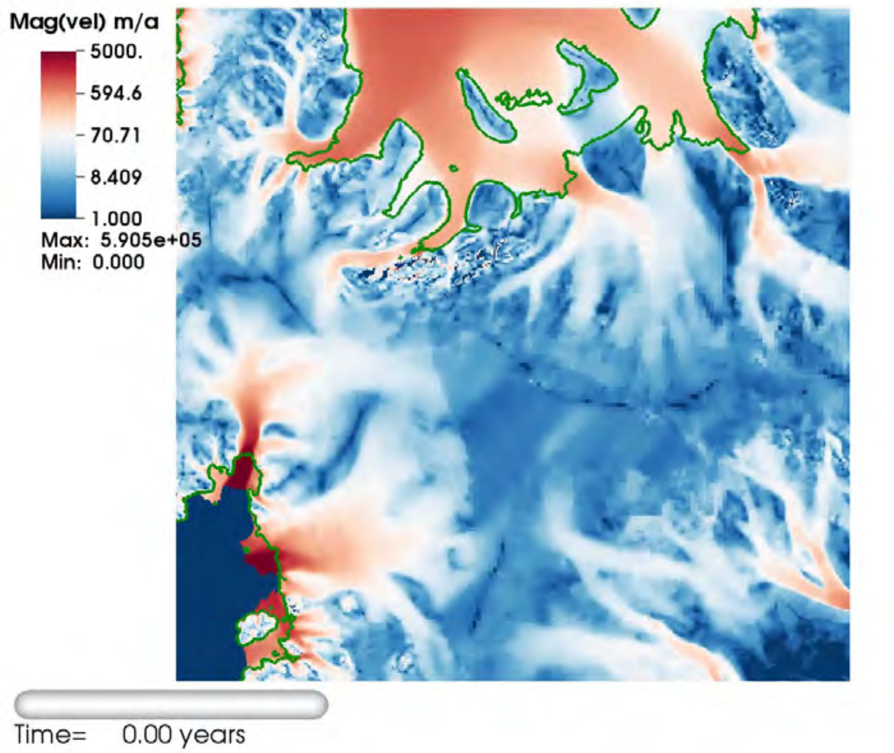
Thwaites-Rutford – 1km Resolution with GLI



Thwaites-Rutford, 2km, with GLI



Thwaites/Rutford, 2 km, with GLI



Results, cont

- **Complete WAIS collapse in sufficiently-resolved runs.**
- **Lower-resolutions produce lower GL mobility, lower SLR contributions.**
  - Thwaites: no or delayed retreat for coarser resolutions (4 km)
- **Qualitative difference between under-resolved and sufficiently resolved (in the asymptotic regime)**
- **Subgrid scheme is worth about a factor of 2 in mesh spacing.**
- **Max change in Volume over Flotation is approx. 4 m S.L.E.**

Conclusions: resolution requirements

- **For this exercise, subgrid GL interpolation scheme is worth roughly a factor of 2 in resolution (one level of AMR refinement for us)**
- **1 km or better resolution needed to get dynamics right**
- **Under-resolution can produce *qualitatively* wrong response**
- **Fine resolution needed at the GL at all times.**

So what can we do with an AMR ice sheet model?

- **Couple with ocean & earth system models…**
- **Examine resolution requirements and convergence of full-scale problems…**
- **Evaluate Antarctic vulnerability**

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 ice-shelf collapse**

- **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).**

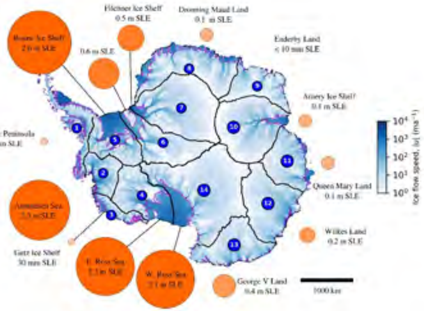
Martin, D. F., Cornford, S. L., & Payne, A. J. (2019). **Millennial-scale vulnerability of the Antarctic Ice Sheet to regional ice shelf collapse**. *Geophysical Research Letters*, 46, 1467–1475.

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

Millennial-scale Vulnerability of the Antarctic Ice Sheet to Regional Ice Shelf Collapse

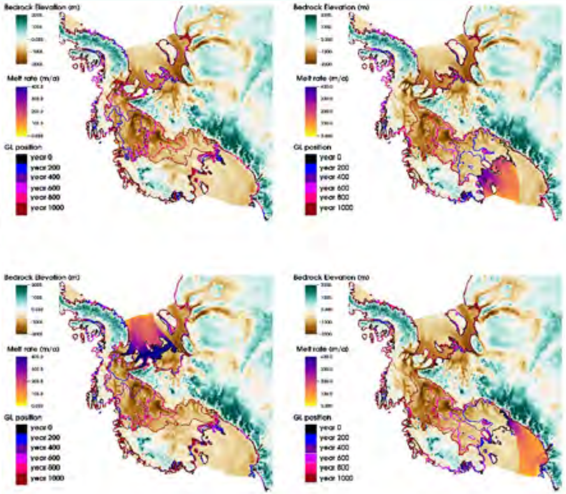
Scientific Achievement

We use a highly-resolved model of the Antarctic Ice Sheet to systematically examine vulnerability to regional collapse of its floating ice shelves and the potential for large resulting contributions to sea level rise (SLR).



Significance and Impact

- 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 ungrounding and 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).



Left: *Antarctic vulnerability to localized ice shelf collapse. Initial modeled flow speed is shown in shaded blue. Magenta lines indicate initial grounding-line locations. Mass loss above flotation (contribution to sea level rise, in eustatic sea level equivalent, SLE) after 1000 years of extreme, sustained ice shelf thinning originating in the numbered sectors is illustrated by the adjacent circle area.*

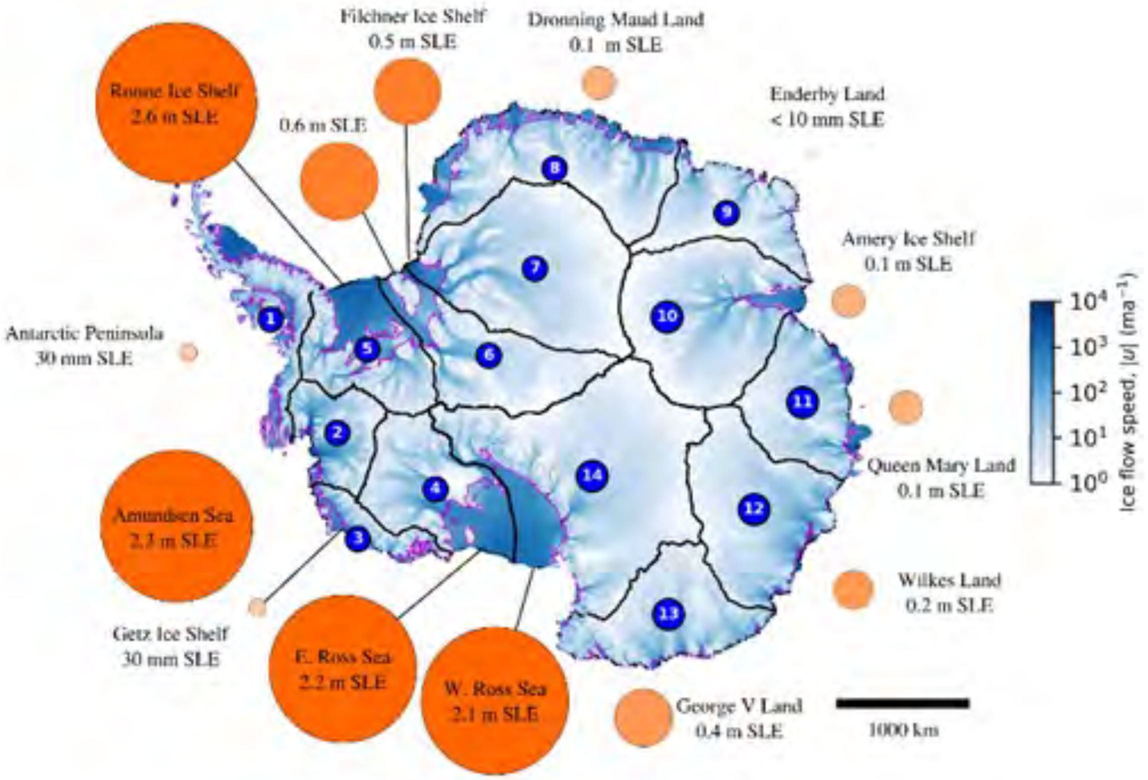
Right: *Grounding-line evolution illustrated with contours every 200 years for the Amundsen Sea (upper left), the Eastern Ross (upper right), the Ronne (lower left), and the Western Ross (lower right) sectors. Colormap shows initial melt-forcing distribution for each case.*

Research Details

- Systematically apply extreme thinning (up to 400m/year) to ice shelves in a single sector and then evolve ice sheet for 1000 years.
- Uses DOE SciDAC-supported BISICLES adaptive mesh refinement (AMR) ice sheet model which resolves flow down to 1km resolution, essential for accurately capturing realistic grounding line dynamics.
- The combination of scalable AMR and NERSC computing resources enabled this work, entailing 35,000 years of Antarctic simulation.

Martin, Cornford, and Payne (2019). Geophysical Research Letters, **DOI 10.1029/2018GL081229**. Contact: Dan Martin (DFMartin@lbl.gov)

Antarctic Vulnerability Results:



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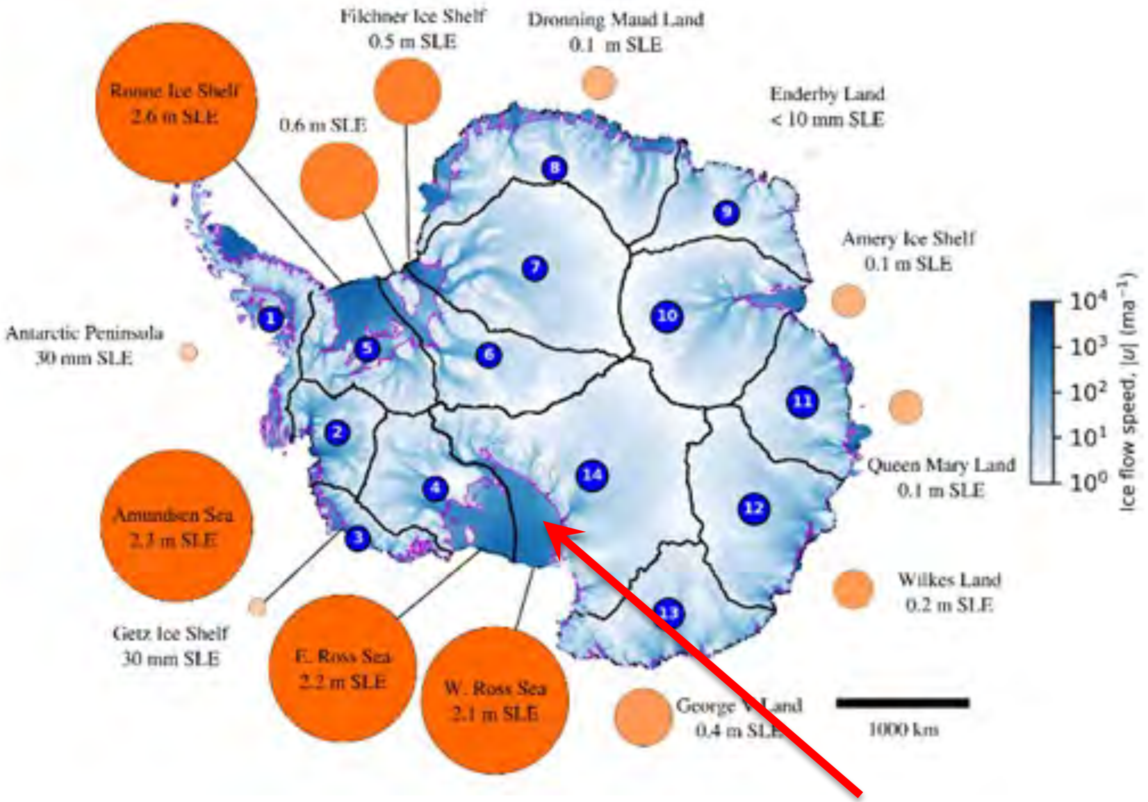
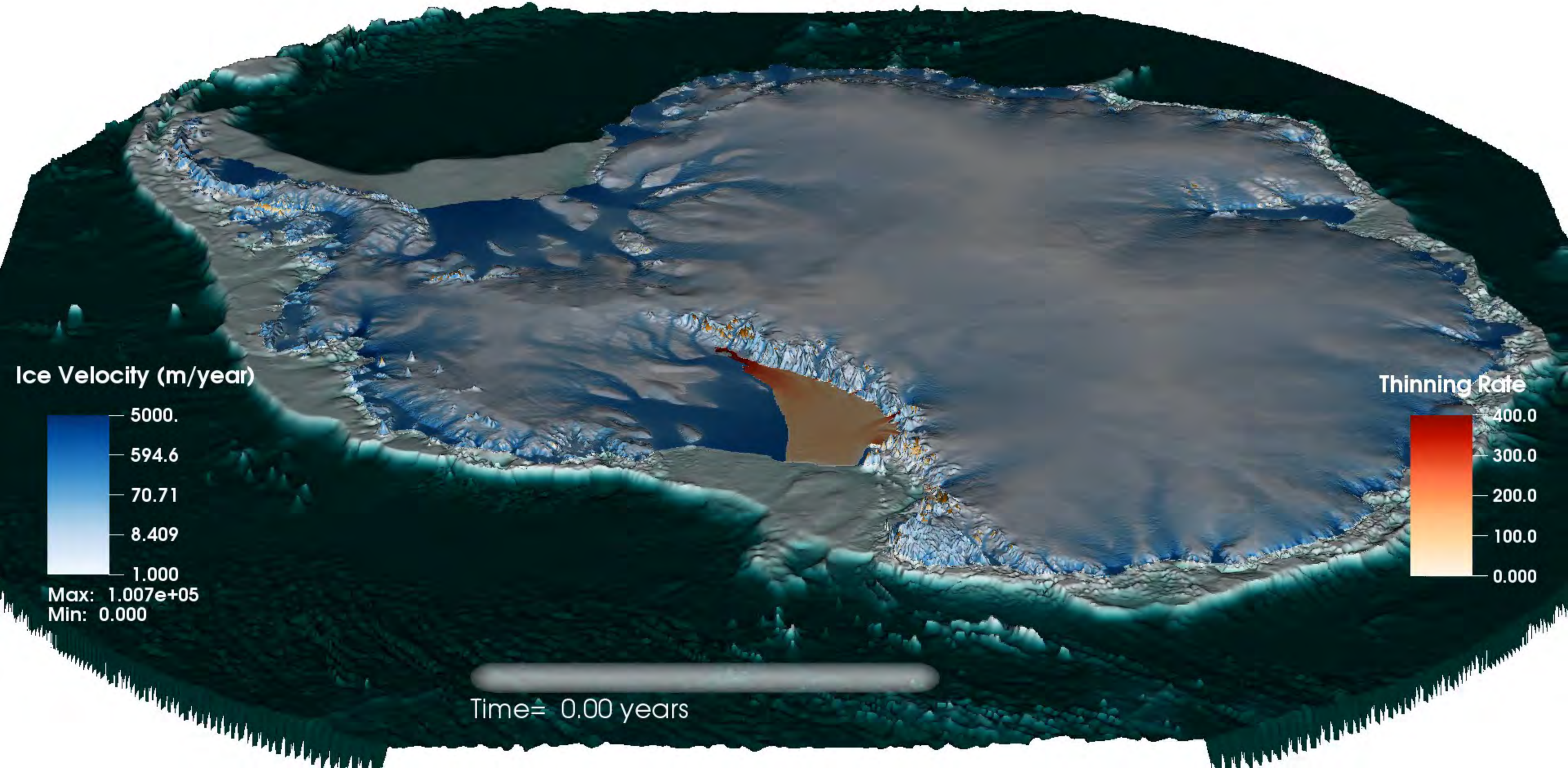
Example: sector 14 (Western Ross)





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

So what can we do with an AMR ice sheet model?

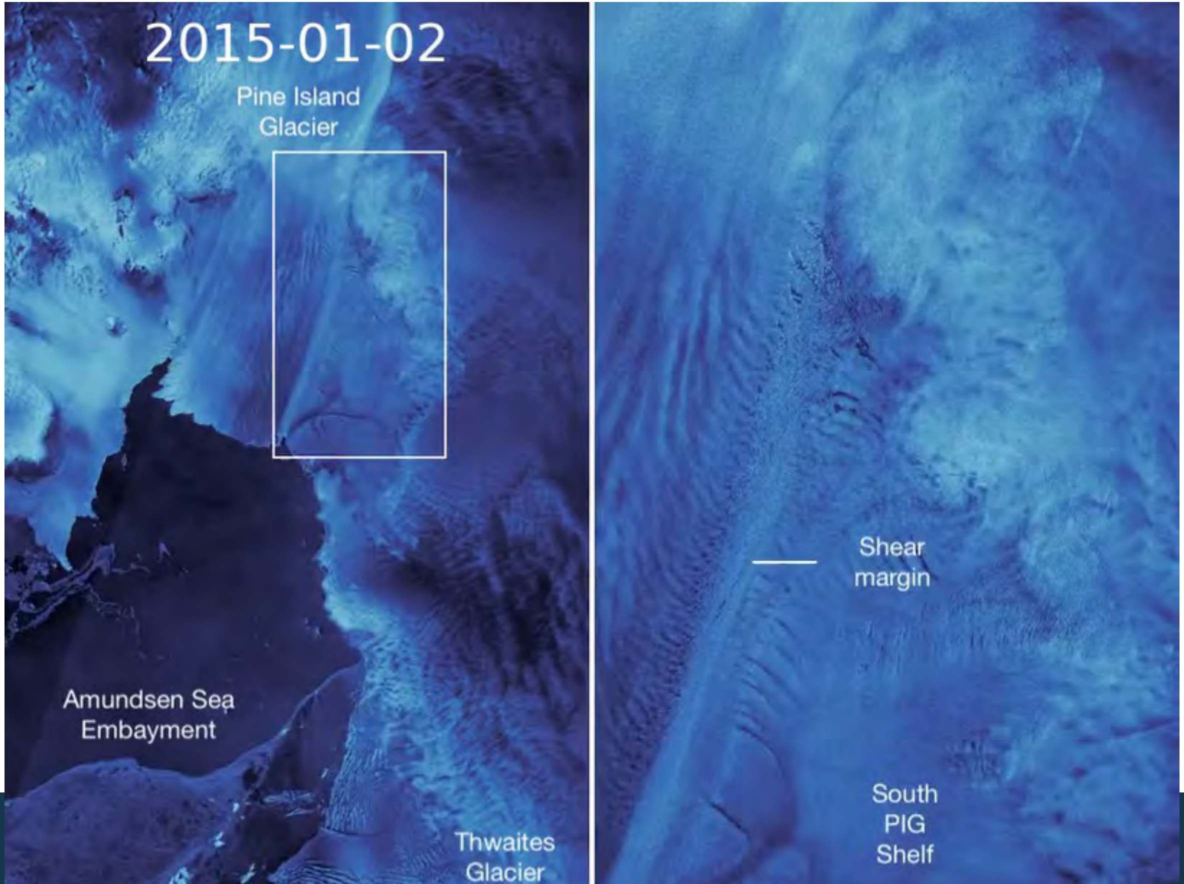
- **Couple with ocean & earth system models…**
- **Examine resolution requirements and convergence of full-scale problems…**
- **Evaluate Antarctic vulnerability…**
- **Add new physics…**

Damage and fracture

- Model is based on “ideal” ice
- Real ice is damaged – fractures, crevasses, etc…

- How does this affect the ice sheet?

Damage and Fracture…



Incorporating "damage" into BISICLES…

- **Additional "damage" parameter represents extent to which crevasses fully penetrate the ice**
  - 0 = undamaged ice
  - 1 = "fully-damaged" ice
- **Can evolve the "damage"….**
  - Transport (crevasses flow with the ice)
  - Evolution (crevasses grow and heal depending on local stress/strain state)
- **Work with Kachuck and Bassis (U. Michigan)**

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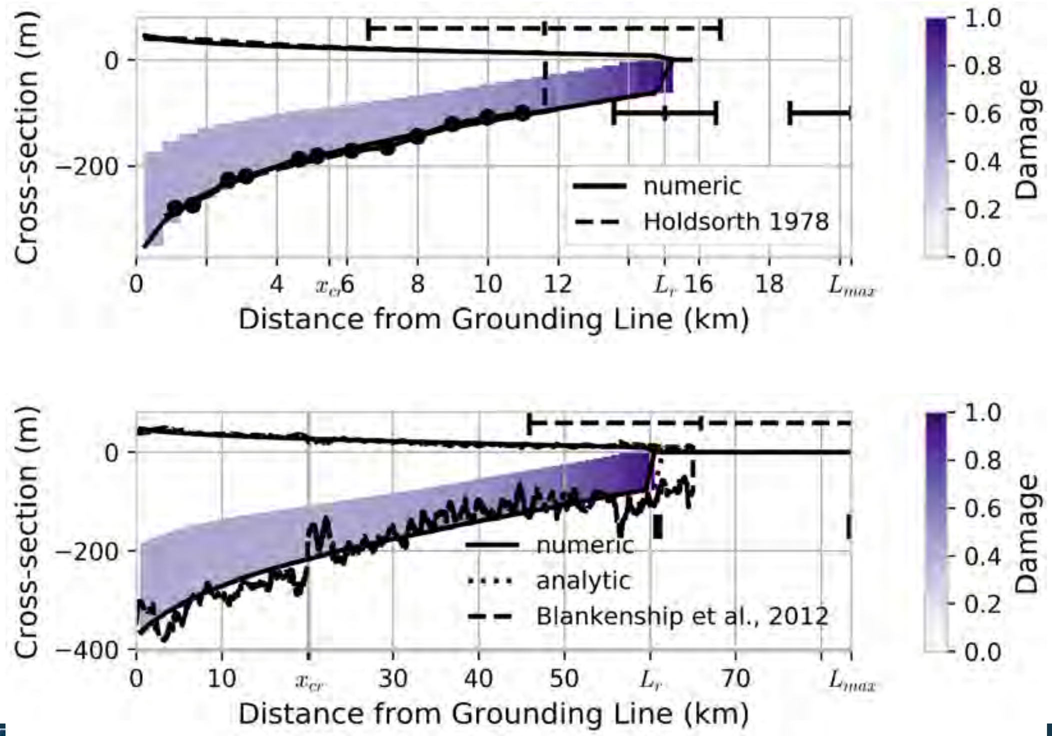
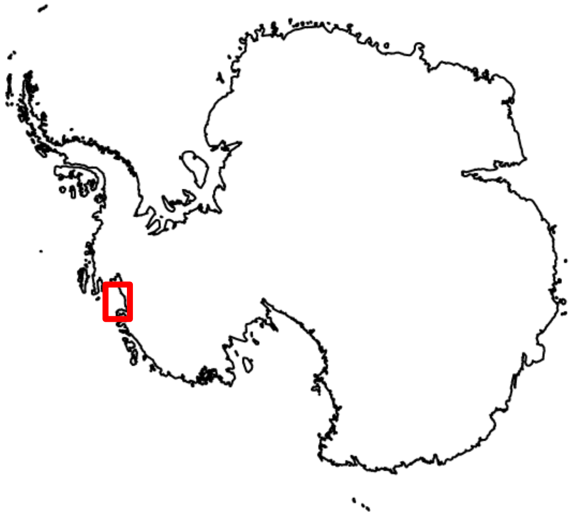
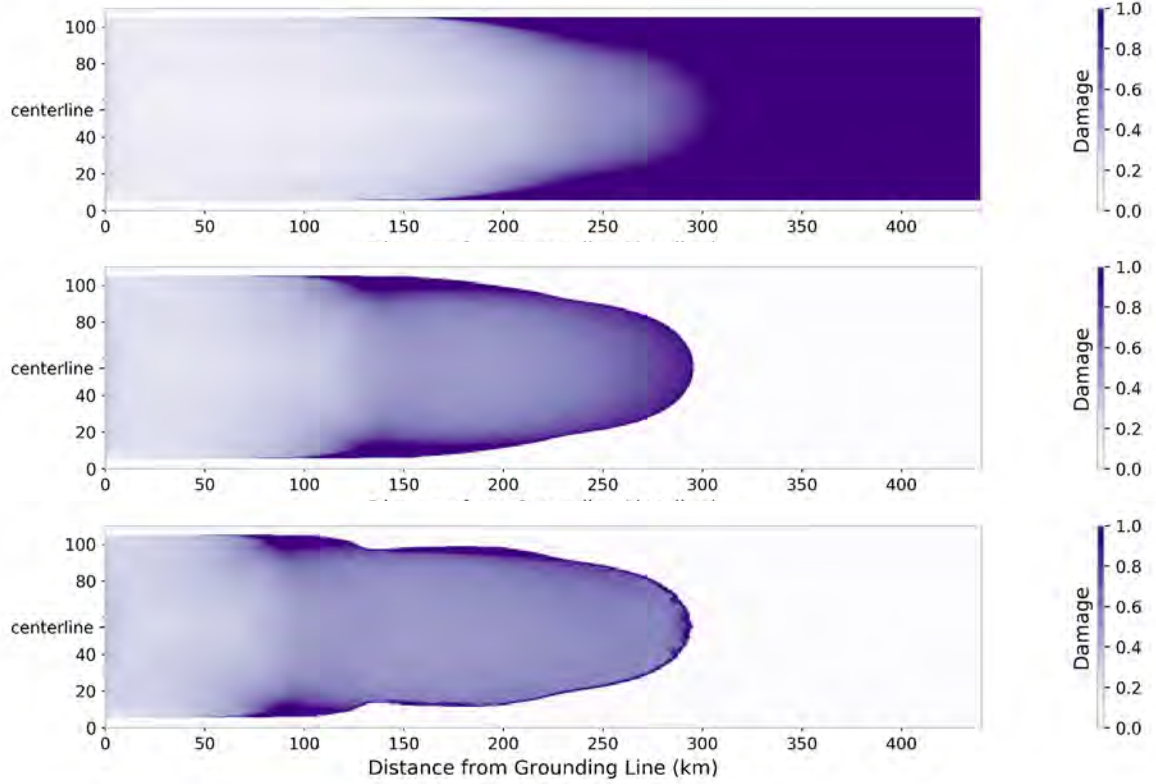
Fully-Damaged Termini at Ice Tongues





Kachuck, et al. (Journal of Glaciology, in review)

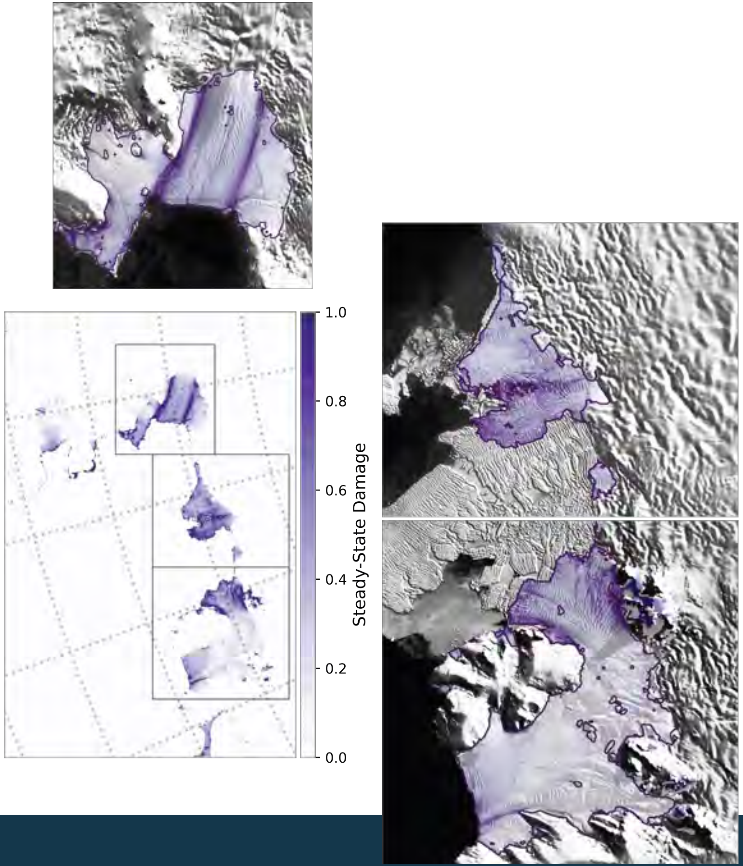
Coupling to Dynamics – Calving and Removal



Damage in the Amundsen Sea region

- **Evolve to steady-state**
- **Damage patterns match observations!**

- **Can start to predict calving, damage evolution, etc.**

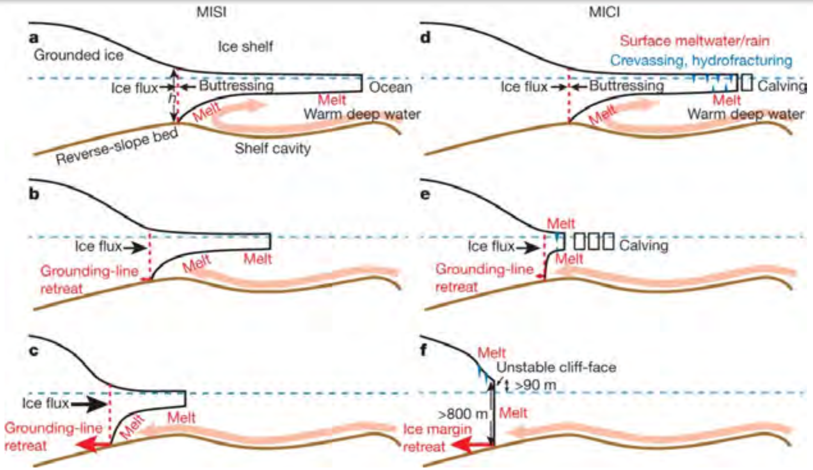


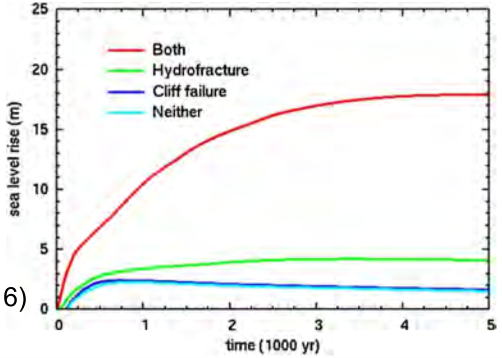
So what can we do with an AMR ice sheet model?

- Couple with ocean & earth system models…
- Examine resolution requirements and convergence of full-scale problems…
- Evaluate Antarctic vulnerability…
- Add new physics…
- Help inform the discussion….

Marine Ice Cliff Instability

- **Deconto and Pollard (2015)**
  - wanted to be able to match paleorecord of large SLR
- **Surmised mechanism:**
  - hydrofacture (eliminate ice shelves)
  - Resulting ice cliffs exceed yield strength of ice.
  - Cliff collapse (drive retreat into EAS basins)
  - Allows for much greater SLR
- **Matches current observations of hydrofracture and max cliff size…**





(top) Pollard and Deconto (2016)
(bottom) Pollard et al, (2015)

Washington Post…

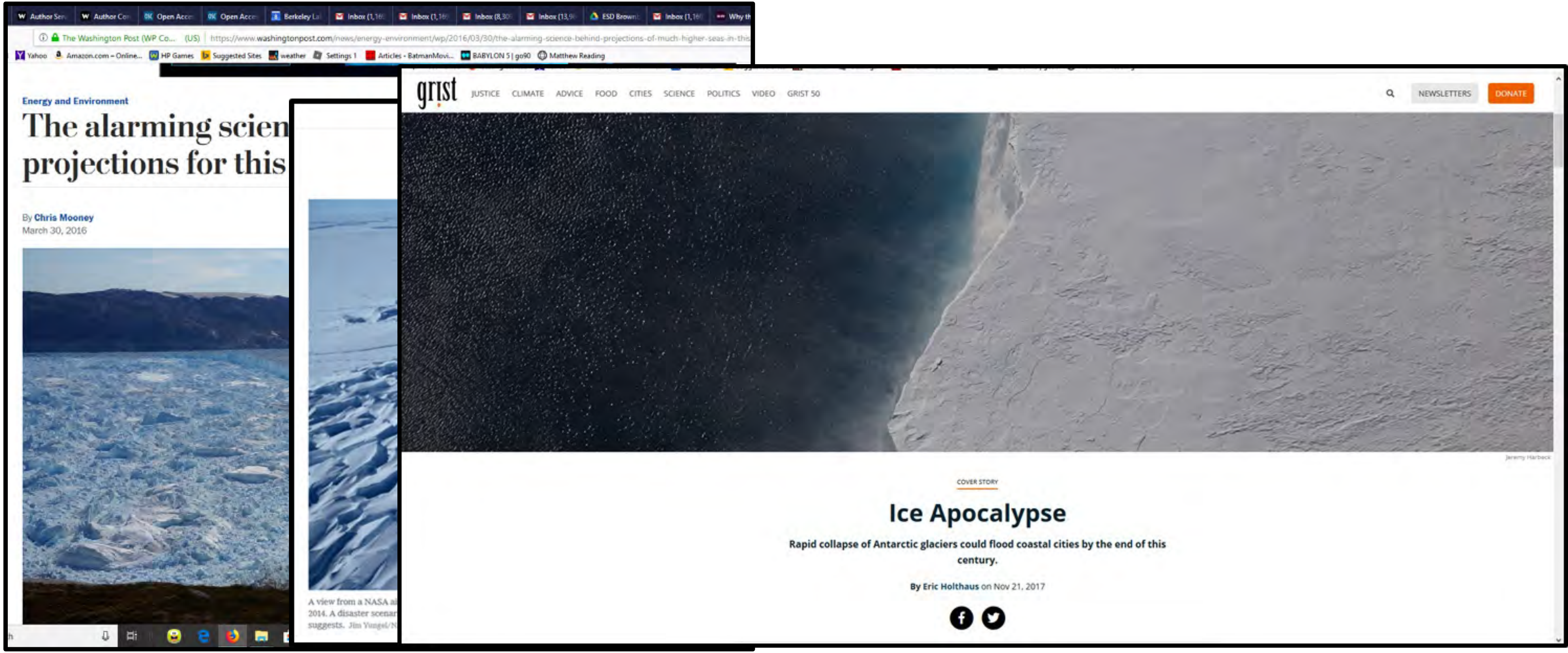
Energy and Environment

The alarming science driving much higher sea level projections for this century

By Chris Mooney
March 30, 2016

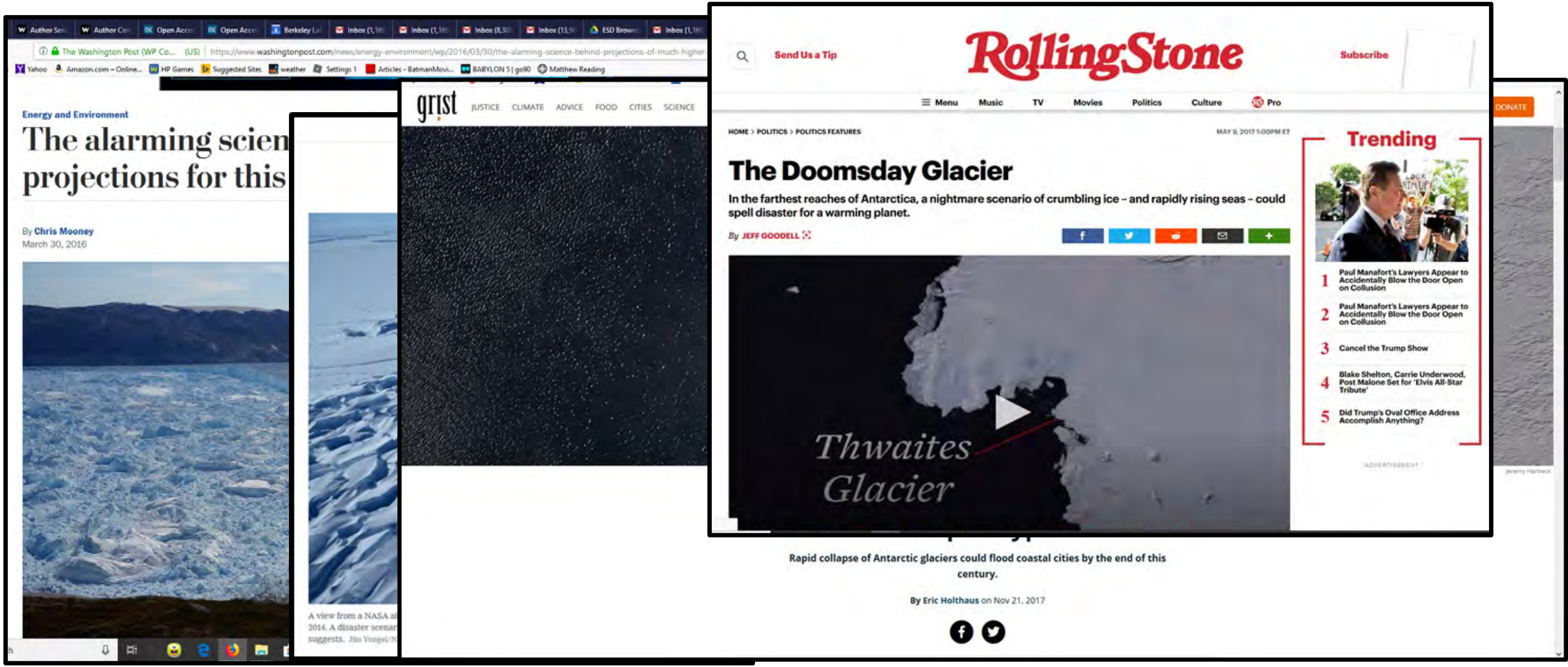
New York Times…

Grist...



Energy and Environment
The alarming scien
projections for this
By Chris Mooney
March 30, 2016
A view from a NASA ai
2014. A disaster scenar
suggests.
grist
JUSTICE CLIMATE ADVICE FOOD CITIES SCIENCE POLITICS VIDEO GRIST 50
NEWSLETTERS
DONATE
COVER STORY
Ice Apocalypse
Rapid collapse of Antarctic glaciers could flood coastal cities by the end of this century.
By Eric Holthaus on Nov 21, 2017

Rolling Stone?



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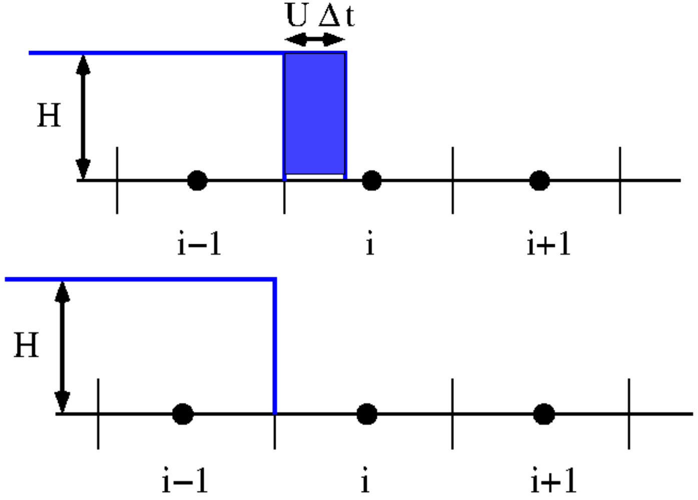
Is MICI a symptom of under-resolution?

- Original work was on a 10 km mesh!
- We hadn’t noticed persistent cliffs…

BISICLES cliff-collapse scheme

- **Extend existing partial-cell scheme (designed for shelf regrowth in MISOMIP)**
- **BISICLES is a finite-volume code; compute cell-averaged quantities which are updated by ice thickness fluxes across the cell faces.**
- **Maintain an area fraction ϕ, the fraction of the cell area (2d) containing ice**
- **Wind up with an effective thickness:**

$$\tilde{h} = \frac{h}{\varphi}$$



- **If there is a cliff,**

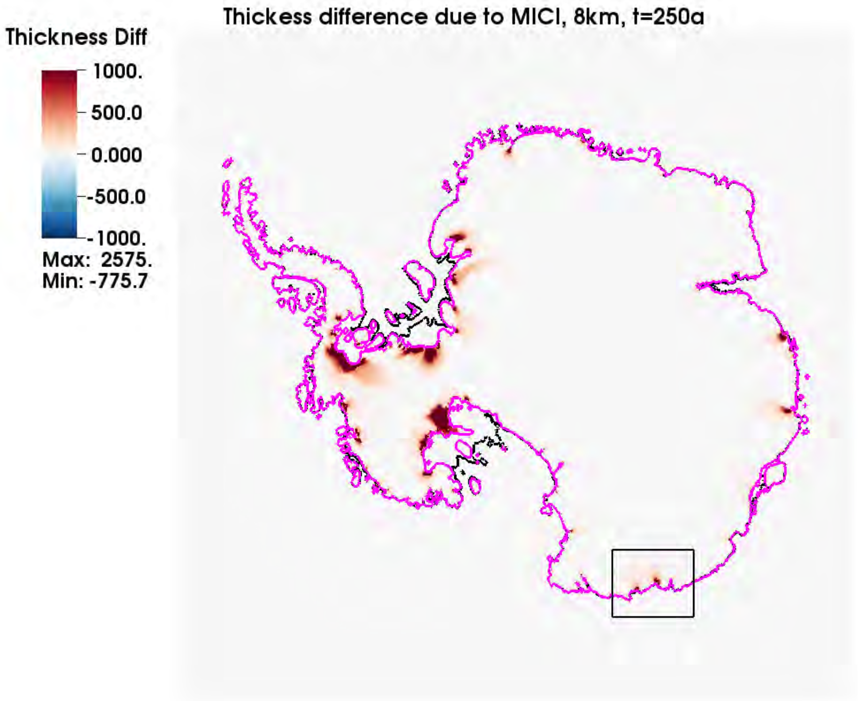
$$\varphi^{new} = \varphi - r\frac{\Delta t}{\Delta x}$$

$$h^{new} = h\frac{\varphi^{new}}{\varphi}$$

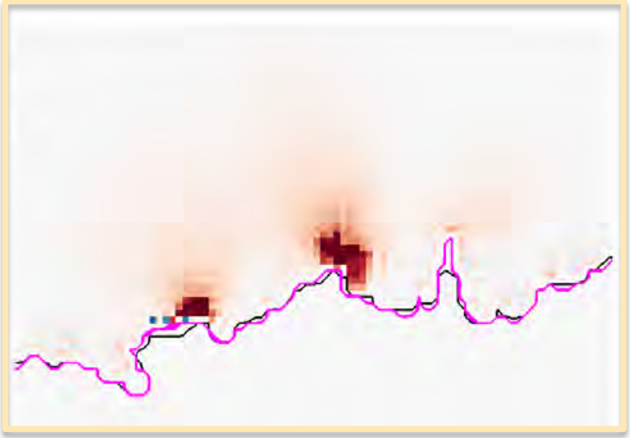
Experiment – 250-year Antarctic simulations

- **Designed to trigger MICI wherever possible**
- **Range of finest resolution from 8 km (no refinement) to 1km (3 levels of factor-2 refinement)**
- **Shelf-thinning: 10 years of an aggressive shelf-thinning regime – thins most shelves down to O(400m) to weaken enough to be susceptible to hydrofracture.**
- **Hydrofracture: calve off any floating ice thinner than 500m.**
- **Run with and without MICI**
  - Use Pollard and Deconto MICI parameters: 100m threshold, 3km/year recession rate
- **Evolve for 250 years**

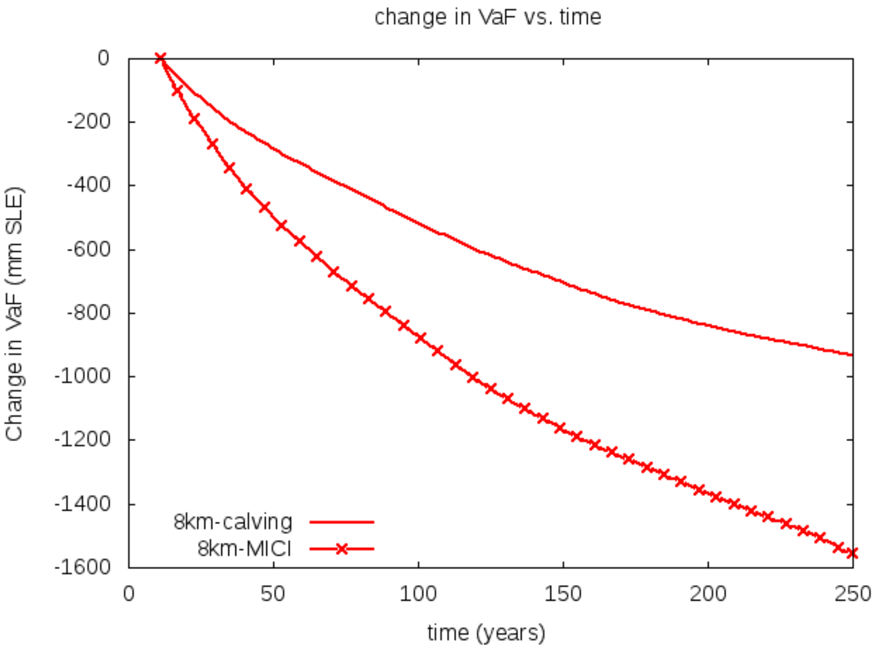
Results – 8km resolution



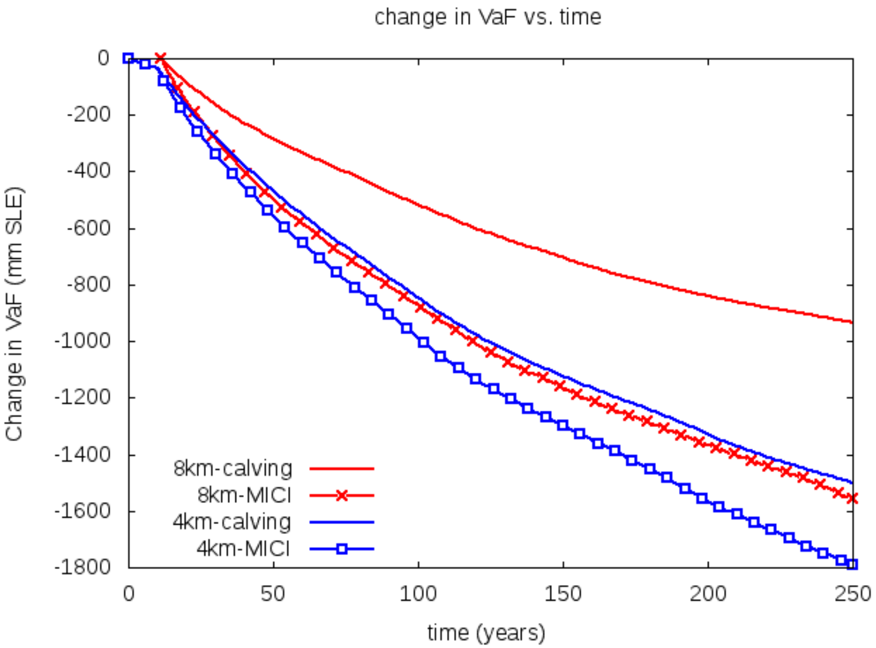
- Ice thickness differences between 8m MICI and no-MICI runs
- Shown at final time (t=250)
- Inset shows Wilkes Basin



Volume above Flotation…



Volume above Flotation…



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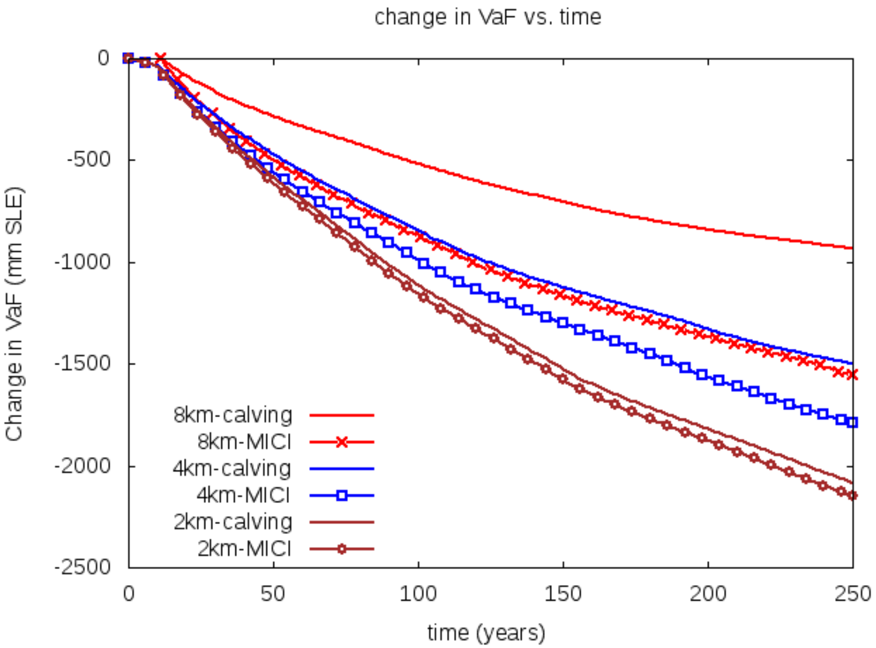

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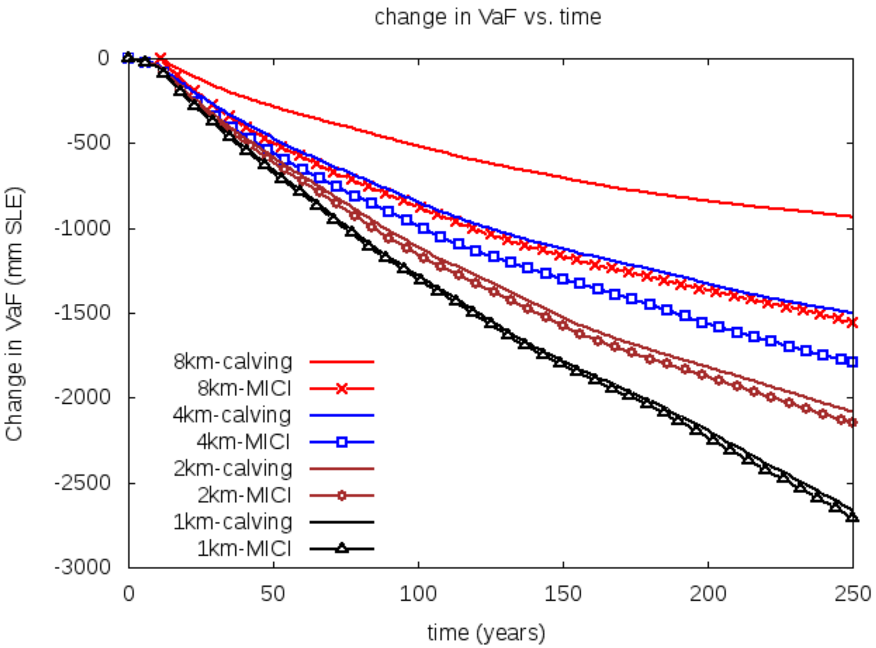
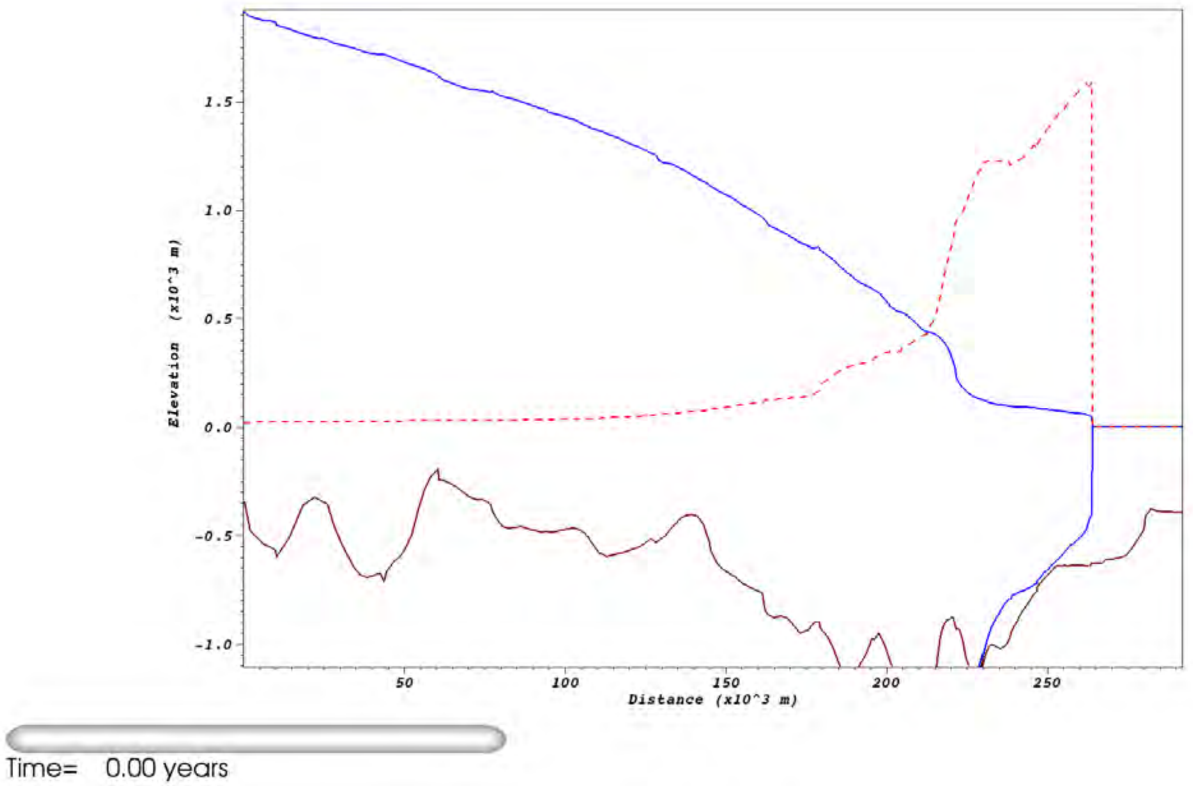


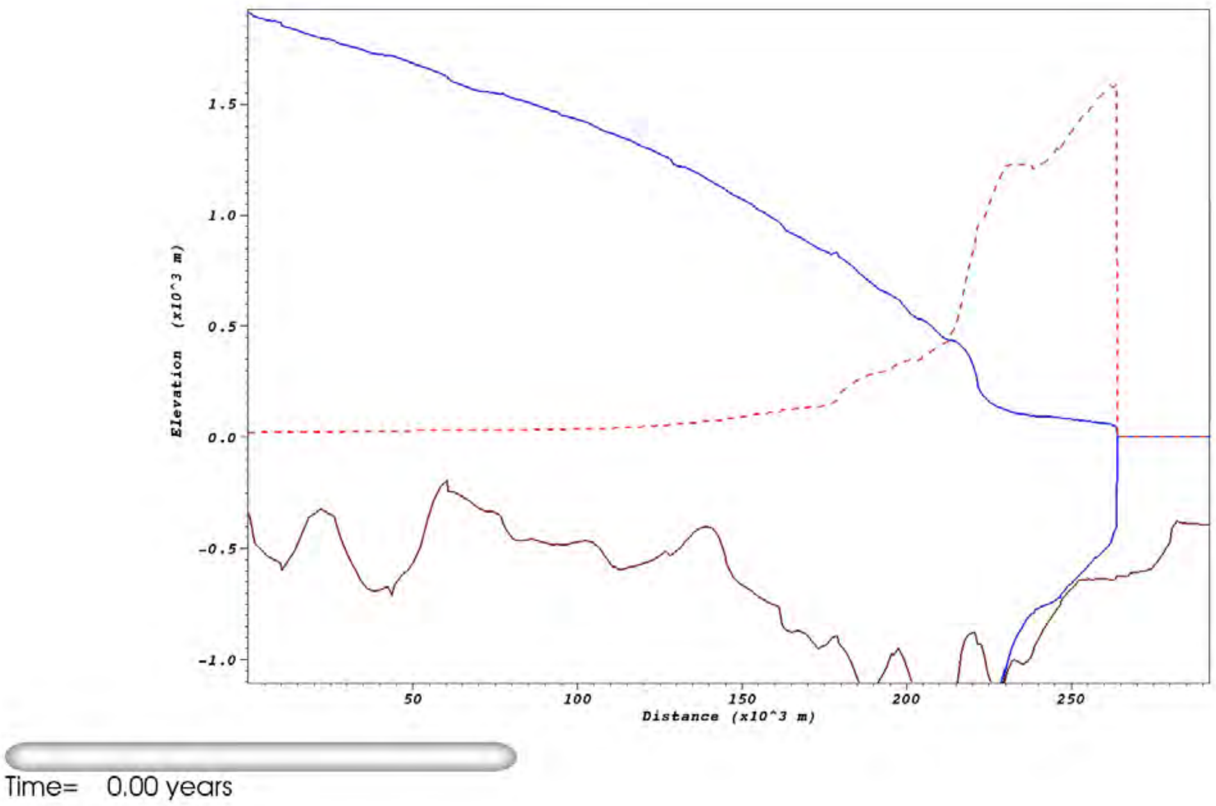
Alternative hypothesis

- **Ice dynamics works to prevent/remove ice cliffs on macro scales**
  - Local acceleration
  - Upstream thinning
- **These ice dynamics operate on “fine” scales in the context of continental-scale ice sheet models**
  - Likely O(a few GL ice thicknesses)
- **Suggests that we need to resolve these scales to get retreat dynamics correct.**

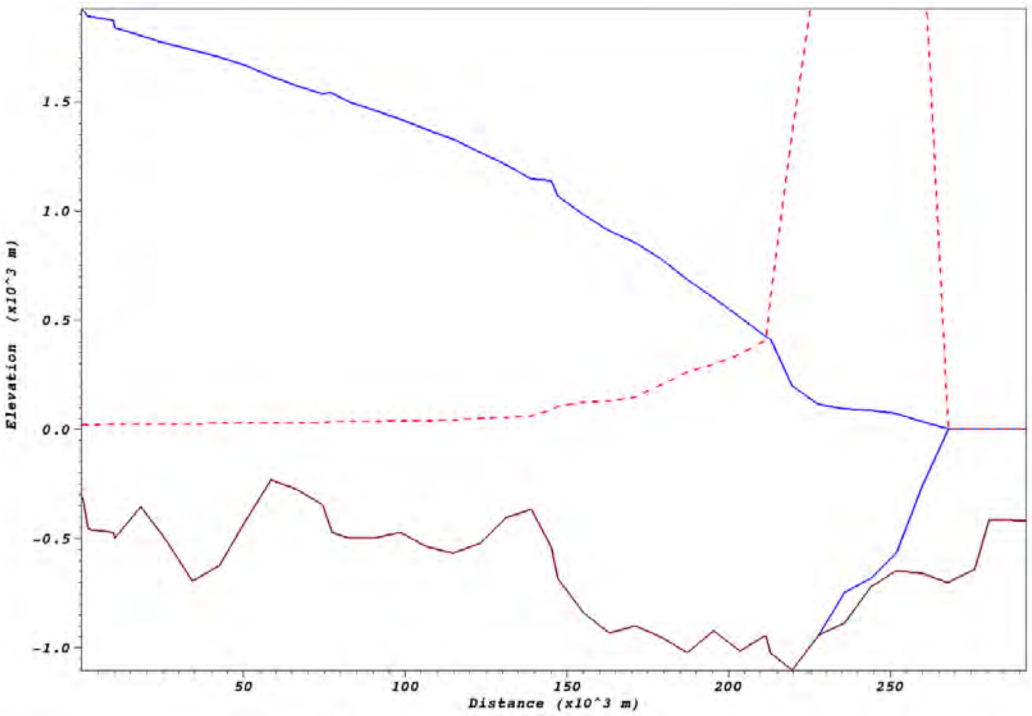
One example – Wilkes Basin: 1km resolution



One example – Wilkes Basin

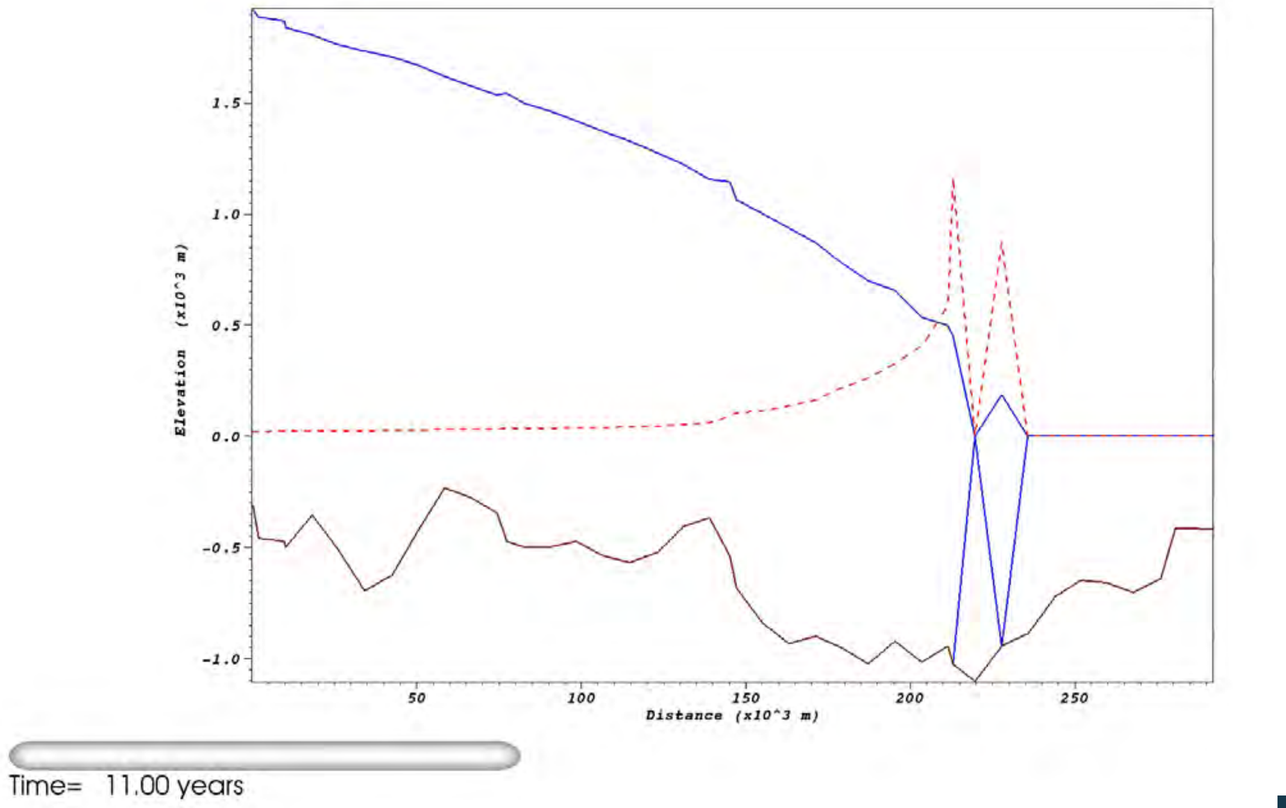


Wilkes Basin: 8km resolution



Time= 0.00 years

Wilkes Basin: 8km resolution



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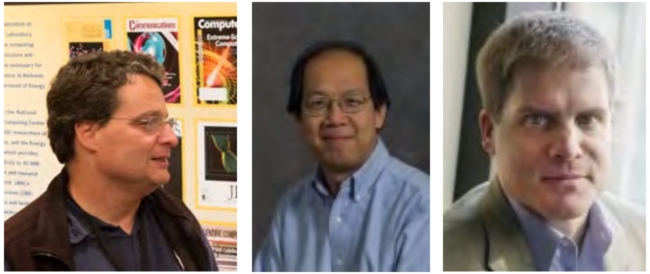
Collaborators and funding



LBNL/CRD

- Steve Price (LANL)
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- Tony Payne (Bristol)
- Vicky Lee (Bristol)

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- ISICLES
- ProSPect & PISCEES partnerships

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2 posters in the CSA poster session

- **Duncan Carpenter: “Does Damaged Ice affect Ice Sheet Evolution??**

- **Harry Zou: Evaluation of Graphics Processing Units (GPUs) Performance of BISICLES Ice-Sheet Flow Solver**

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Thank you!