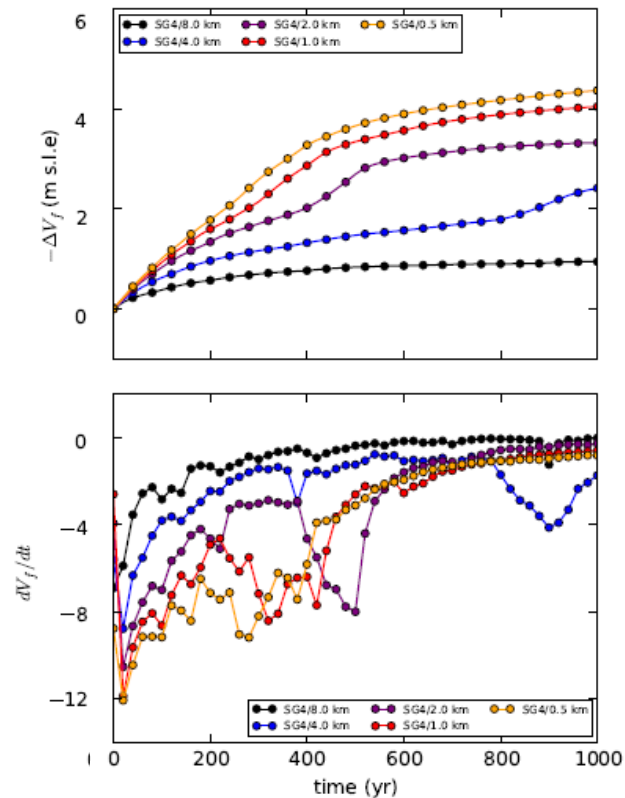


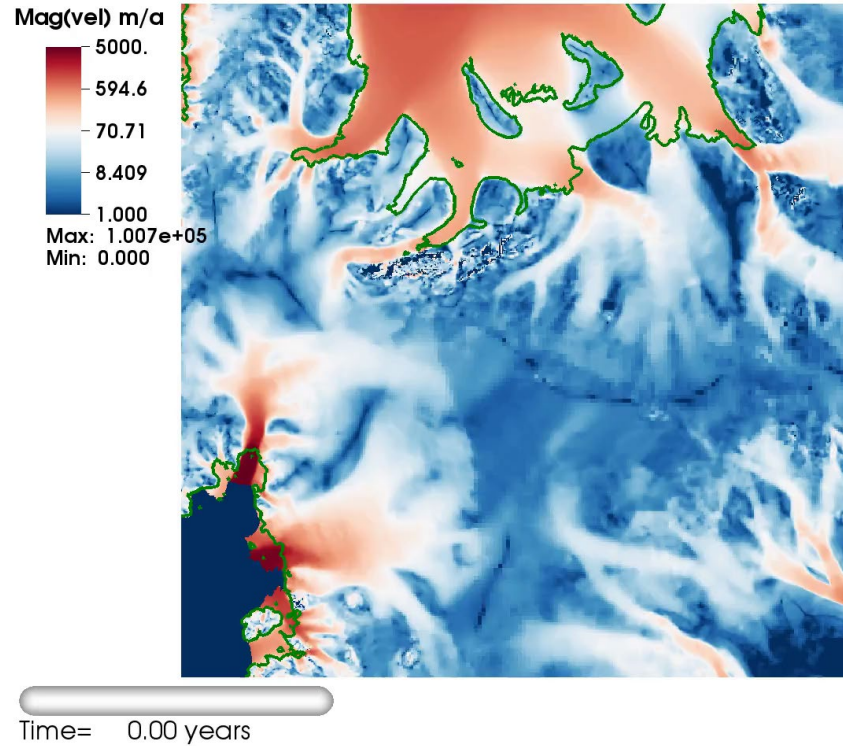


Resolution requirements...

- **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



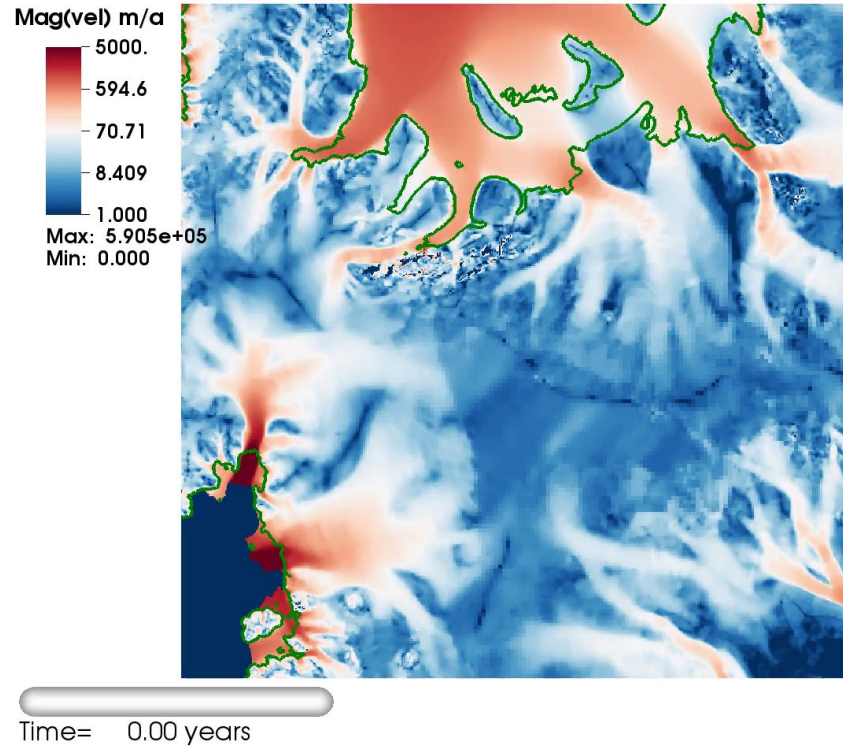
Thwaites-Rutford – 500m Resolution



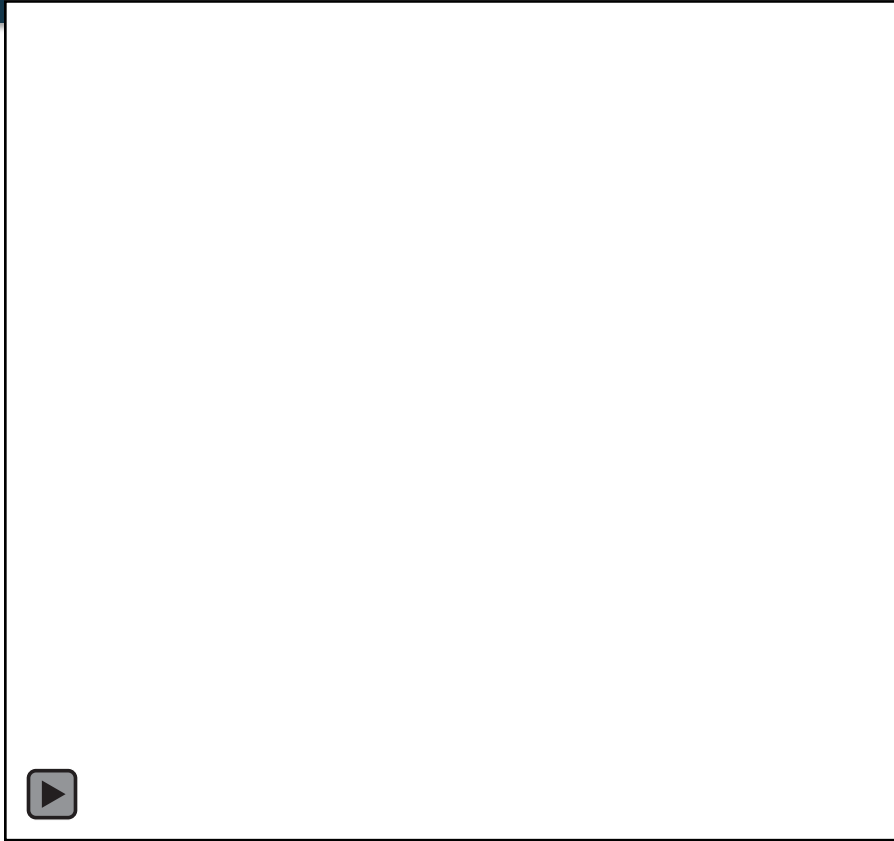
Thwaites-Rutford – 1km Resolution with GLI



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

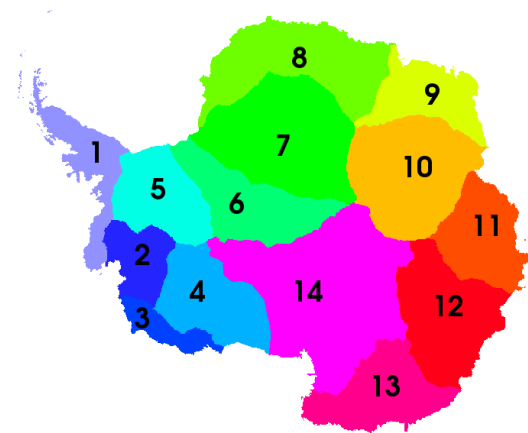
- Divide AIS into sectors

- For each sector in turn (and for some combinations), apply extreme depth-dependent melt forcing

- No melt for $h < 100\text{m}$
- Range up to 400m/a where $h > 800\text{m}$.
- No melt applied in partially-grounded cells

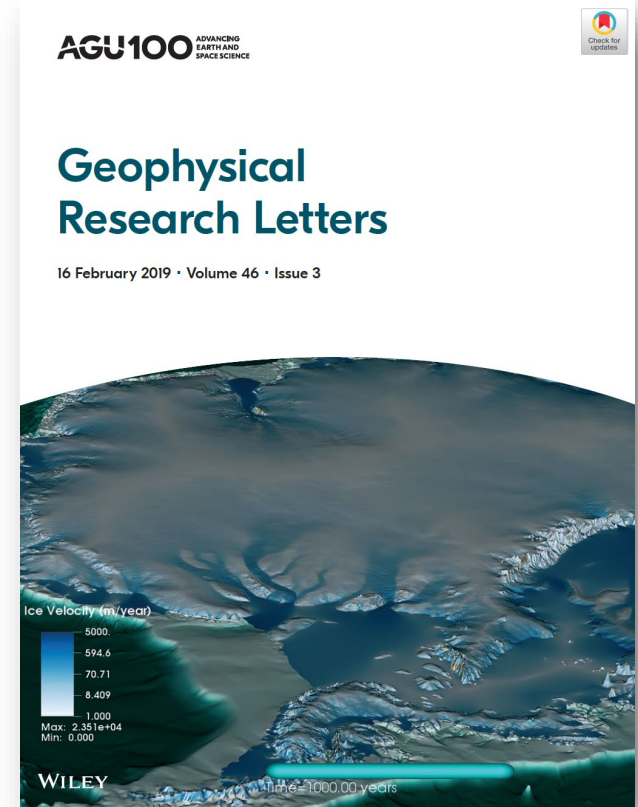
- Run for 1000 years, compare with control (no melt).

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.

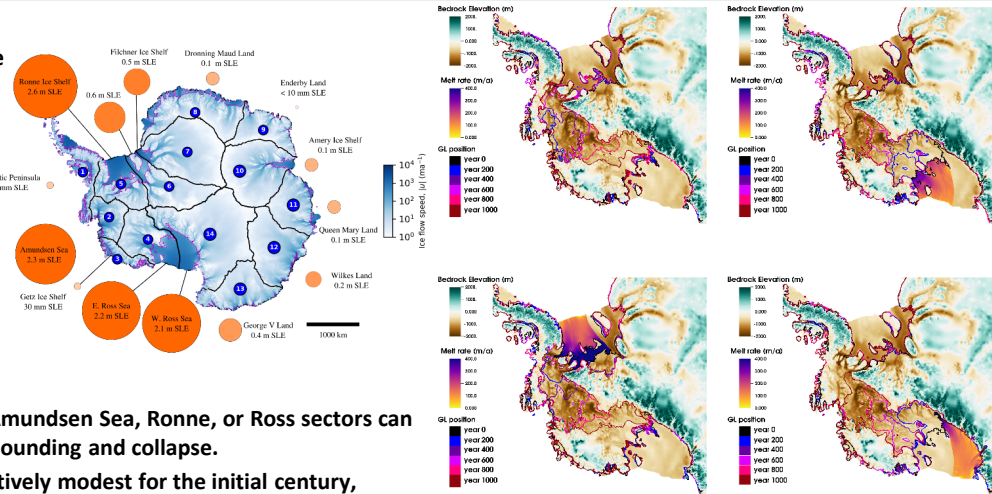
<https://doi.org/10.1029/2018GL081229>



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

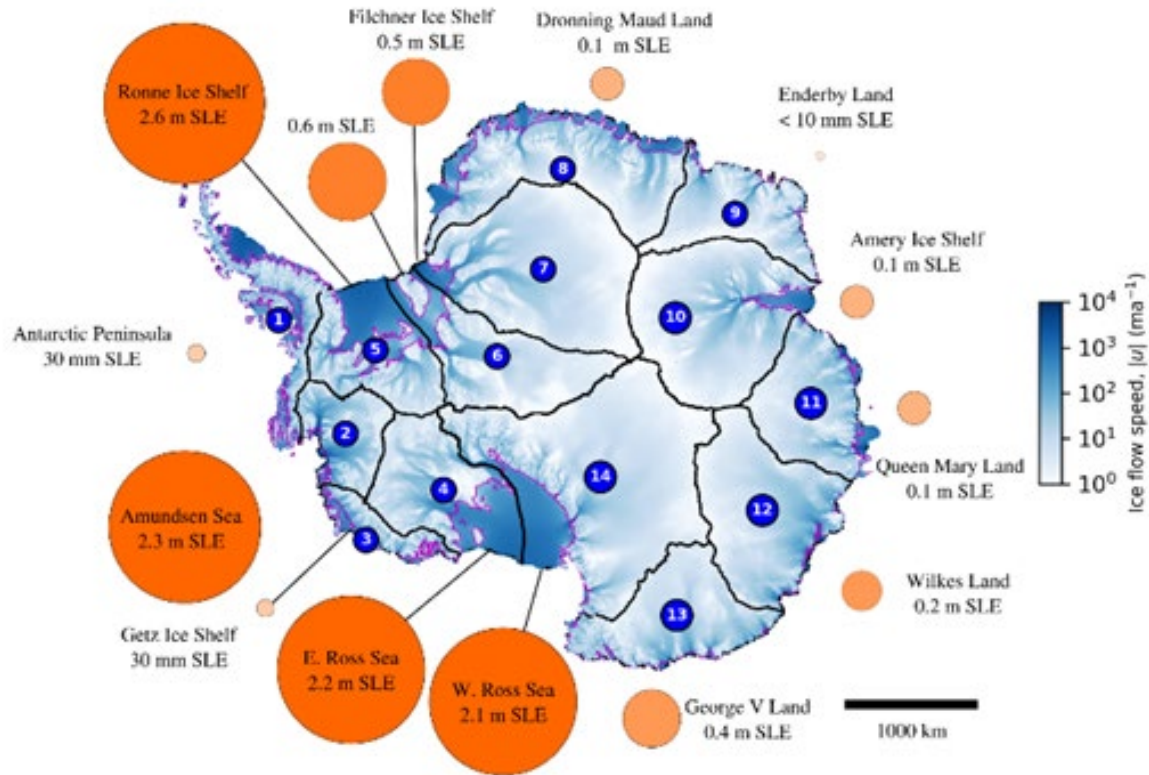
- First fully-resolved, systematic study of millennial-scale ice sheet response to regional ice shelf collapse based on 14 drainage basins.
- Sustained ice-shelf loss in any of the Amundsen Sea, Ronne, or Ross sectors can lead to wholesale West Antarctic ungrounding and collapse.
- Even with extreme 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).

Research Details

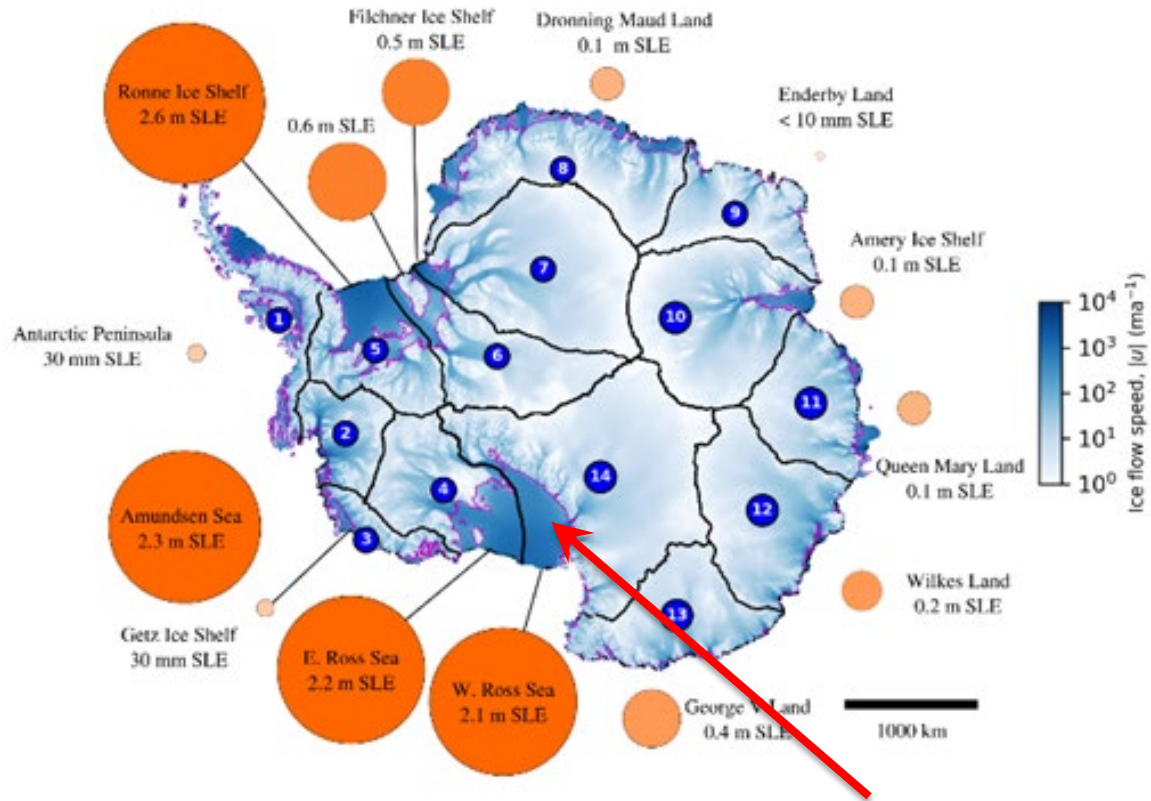
- Systematically apply extreme thinning (up to 400m/year) to ice shelves in a single sector and then evolve ice sheet for 1000 years.
- Uses DOE SciDAC-supported BISICLES adaptive mesh refinement (AMR) ice sheet model which resolves flow down to 1km resolution, essential for accurately capturing realistic 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:



Example: sector 14 (Western Ross)





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

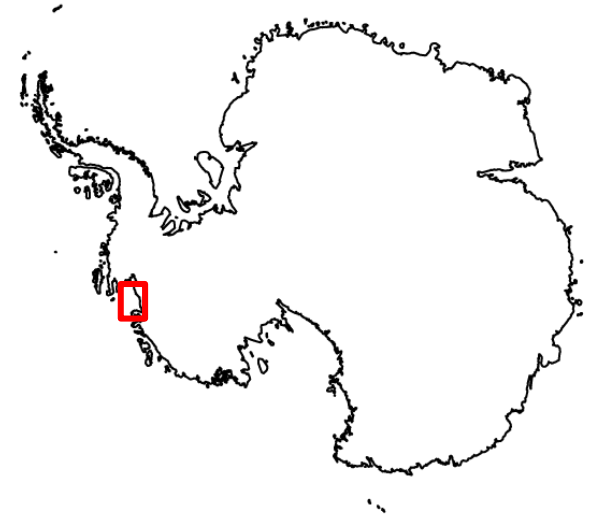
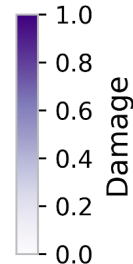
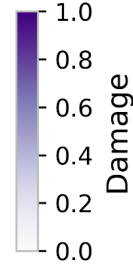
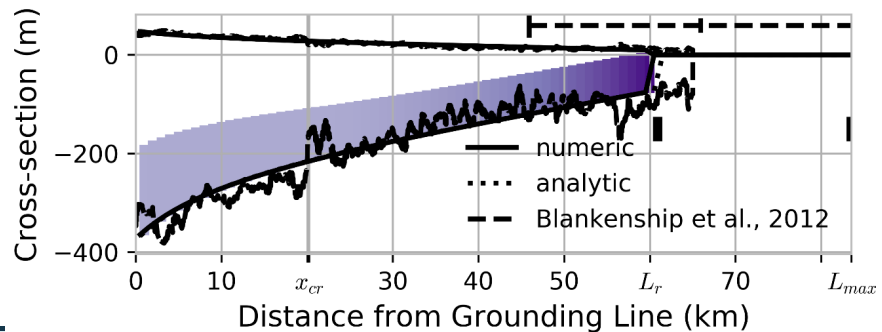
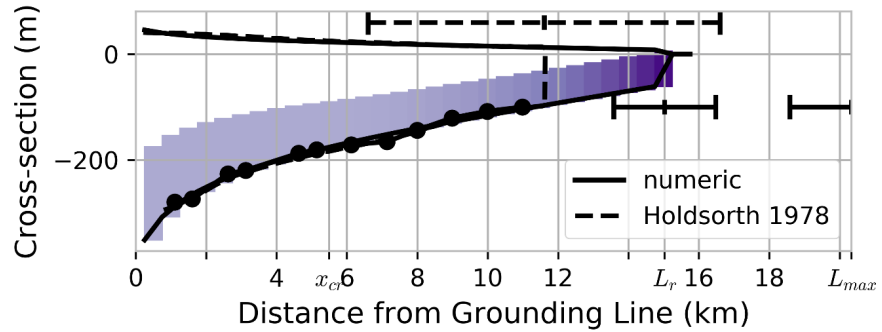
- Model is based on “ideal” ice
- Real ice is damaged – fractures, crevasses, etc...
- How does this affect the ice sheet?

Damage and Fracture...

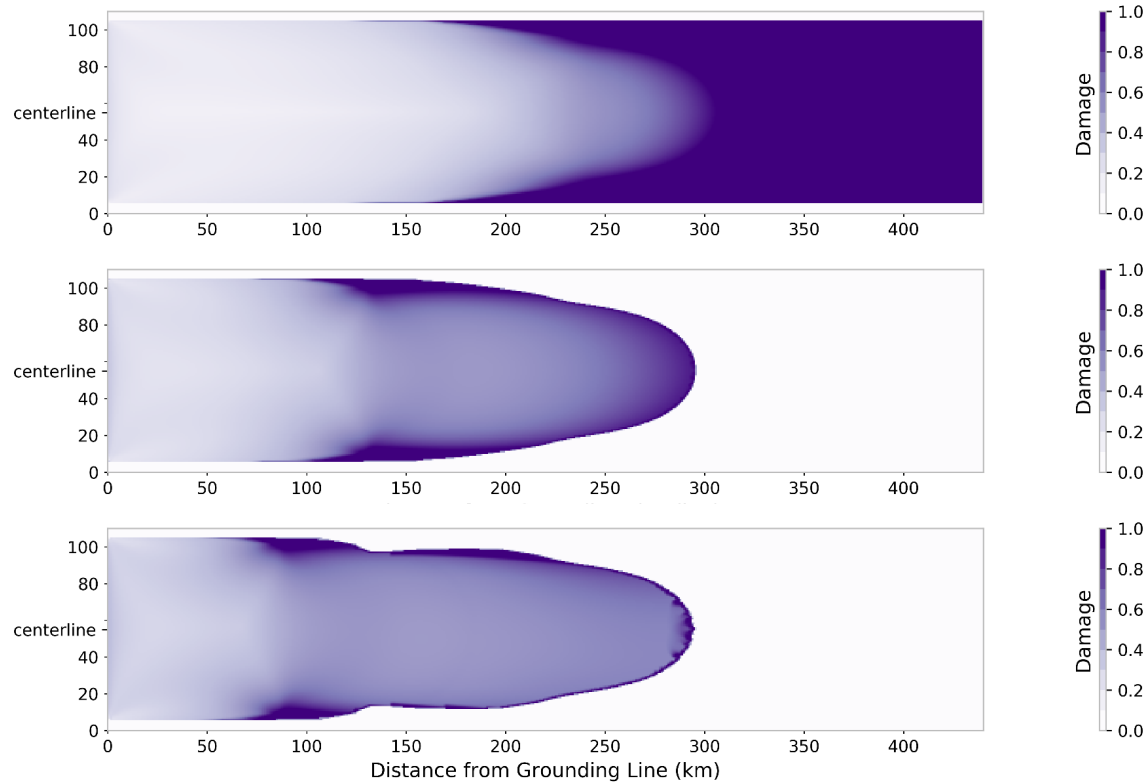
Incorporating “damage” into BISICLES...

- **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)**

Fully-Damaged Termini at Ice Tongues



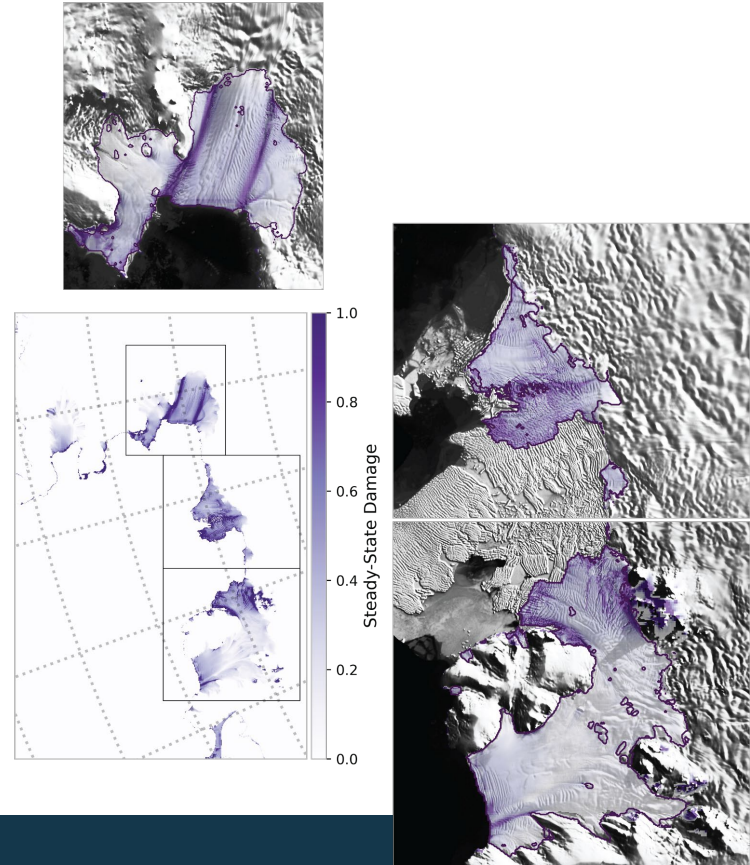
Coupling to Dynamics – Calving and Removal



Damage in the Amundsen Sea region

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

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

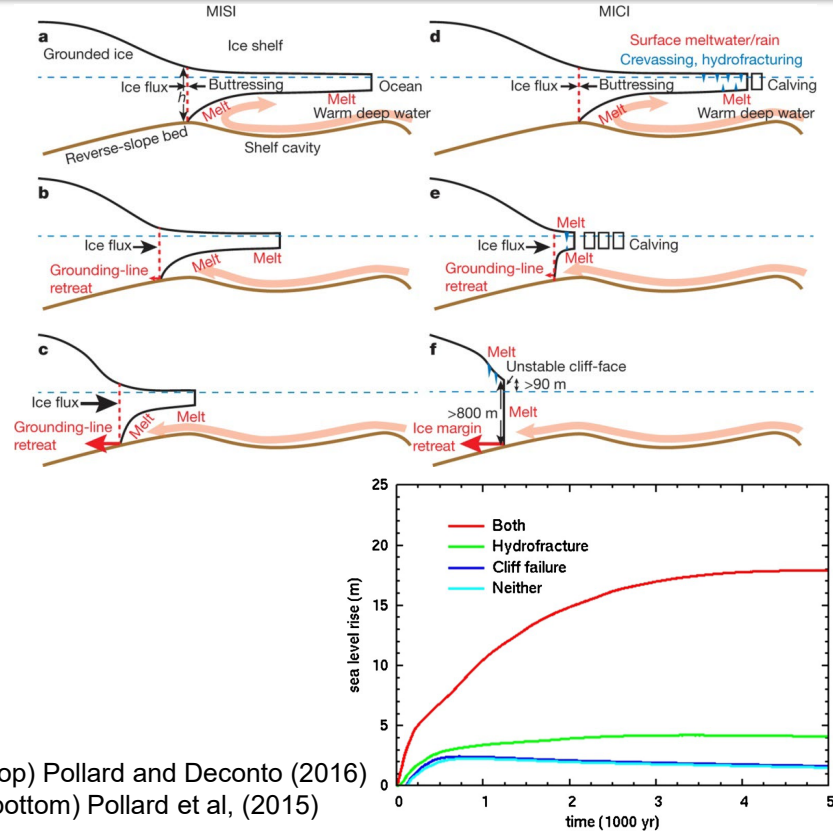


So what can we do with an AMR ice sheet model?

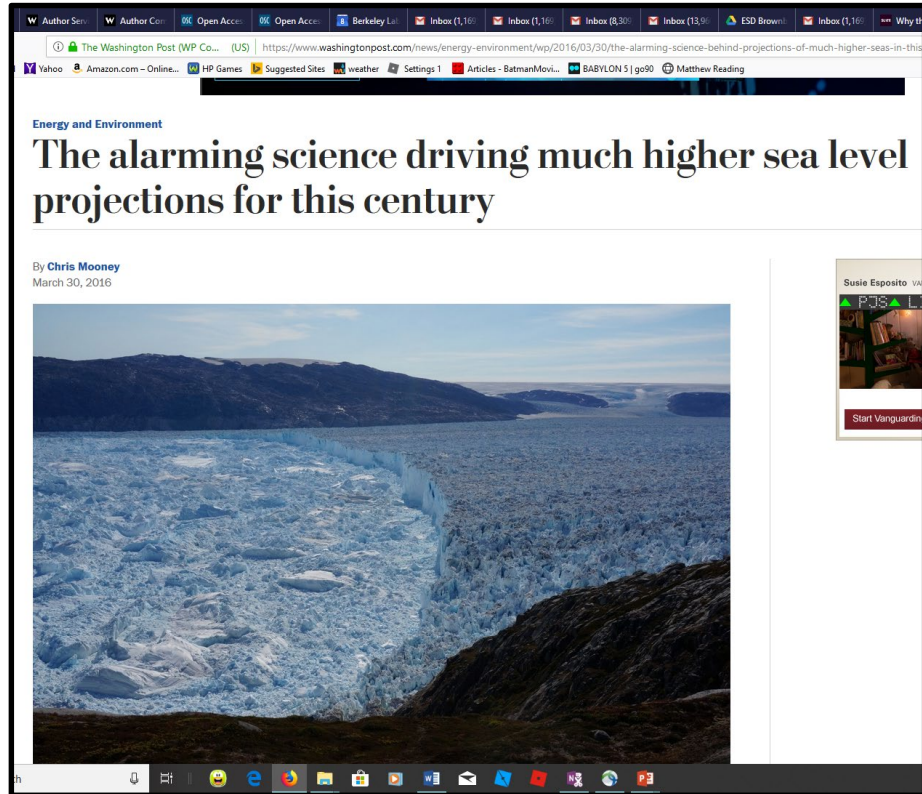
- **Couple with ocean & earth system models...**
- **Examine resolution requirements and convergence of full-scale problems...**
- **Evaluate Antarctic vulnerability...**
- **Add new physics...**
- **Help inform the discussion....**

Marine Ice Cliff Instability

- **Deconto and Pollard (2015)**
 - wanted to be able to match paleorecord of large SLR
- **Surmised mechanism:**
 - hydrofracture (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...**



Washington Post...



The screenshot shows a web browser window displaying a Washington Post article. The browser's address bar shows the URL: <https://www.washingtonpost.com/news/energy-environment/wp/2016/03/30/the-alarming-science-behind-projections-of-much-higher-seas-in-this-century/>. The article is titled "The alarming science driving much higher sea level projections for this century" and is categorized under "Energy and Environment". The author is Chris Mooney, and the article was published on March 30, 2016. The main image is a wide, blue glacier flowing through a valley. On the right side of the article, there is a small advertisement for Susie Esposito's book "Start Vanguardin". The browser's taskbar at the bottom shows various application icons.


W Author Ser... W Author Cor... Open Acc... Berkeley La... Inbox (1,16)... Inbox (1,16)... Inbox (8,30)... Inbox (13,9)... ESD Brown... Inbox (1,16)... Why it

The Washington Post (WP Co... (US) | <https://www.washingtonpost.com/news/energy-environment/wp/2016/03/30/the-alarming-science-behind-projections-of-much-higher-seas-in-this-century/>

Energy and Environment

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

By **Chris Mooney**
March 30, 2016



Susie Esposito vs...
Start Vanguardin

New York Times...

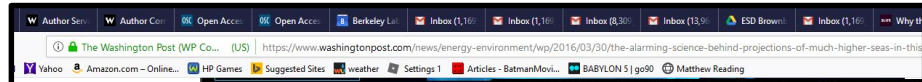
The screenshot shows a web browser window with multiple tabs. The active tab is titled "The Washington Post (WP Co... (US)" and the address bar shows the URL: "https://www.washingtonpost.com/news/energy-environment/wp/2016/03/30/the-alarming-science-behind-projections-of-much-higher-seas-in-the-future/". The browser's address bar also includes "Yahoo", "Amazon.com - Online...", "HP Games", "Suggested Sites", "weather", "Settings 1", "Articles - BatmanMov...", "BABYLON 5 | go90", and "Matthew Reading".

The main content area displays the "Energy and Environment" section header. The article title is "The alarming science behind the projections for this century" (partially visible). The author is "By Chris Mooney" and the date is "March 30, 2016".

The article's main image is a photograph of a vast, cracked ice sheet, likely Antarctica, with a large iceberg in the foreground. The image is taken from an elevated perspective, possibly from an airplane, as a portion of the aircraft's wing and engine nacelle is visible in the bottom right corner.

The article title is "Climate Model Predicts West Antarctic Ice Sheet Could Melt Rapidly".

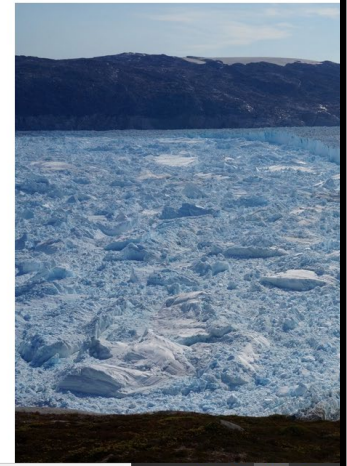
A view from a NASA airplane of large icebergs that have broken from the calving side of Thwaites Glacier in Antarctica in November 2014. A disaster scenario of West Antarctic ice sheet disintegration could occur much sooner than previously thought, new research suggests. Jim Yungel/NASA



Energy and Environment

The alarming science behind sea level rise projections for this century

By **Chris Mooney**
March 30, 2016

A large, detailed aerial photograph of a glacier's edge, showing a dark, rocky coastline meeting a vast, white expanse of ice. The ice has a textured, cracked appearance.

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Ice Apocalypse

Rapid collapse of Antarctic glaciers could flood coastal cities by the end of this century.

By **Eric Holthaus** on Nov 21, 2017

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A view from a NASA satellite of the Antarctic Peninsula in 2014. A disaster scenario suggests, Jim Yungel, 2015

Jeremy Harbeck

Rolling Stone?

W Author Ser... W Author Cor... 0x Open Acc... 0x Open Acc... Berkeley Lab... Inbox (1,16)... Inbox (1,16)... Inbox (8,30)... Inbox (13,9)... ESD Brown... Inbox (1,16)


The Washington Post (WP Co... (US) | https://www.washingtonpost.com/news/energy-environment/wp/2016/03/30/the-alarming-science-behind-projections-of-much-higher

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Energy and Environment


The alarming science projections for this

By Chris Mooney
March 30, 2016



A view from a NASA satellite in 2014. A disaster scenario suggests, Jim Yungel, 15

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The Doomsday Glacier

In the farthest reaches of Antarctica, a nightmare scenario of crumbling ice – and rapidly rising seas – could spell disaster for a warming planet.

By JEFF GOODELL



Thwaites Glacier

Rapid collapse of Antarctic glaciers could flood coastal cities by the end of this century.

By Eric Holthaus on Nov 21, 2017

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Jeremy Harbeck

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

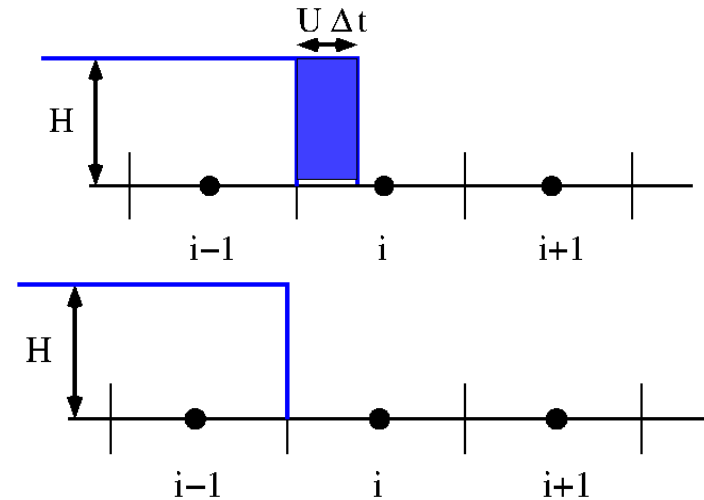
- Extend existing partial-cell scheme (designed for shelf regrowth in MISOMIP)
- BISICLES is a finite-volume code; compute cell-averaged quantities which are updated by ice thickness fluxes across the cell faces.
- Maintain an area fraction ϕ , the fraction of the cell area (2d) containing ice
- Wind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

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

- If there is a cliff,

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

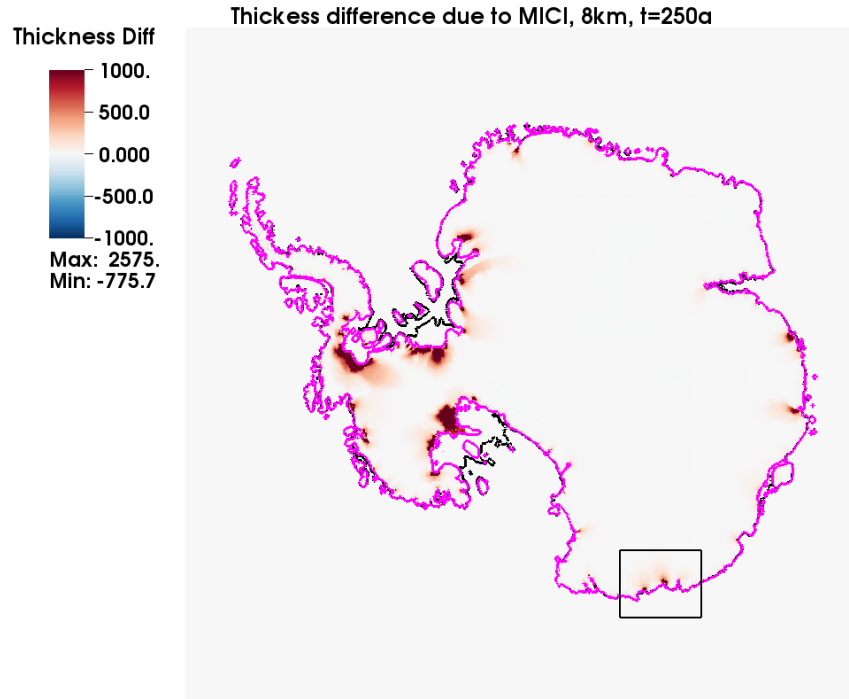
$$h^{new} = h \frac{\phi^{new}}{\phi}$$



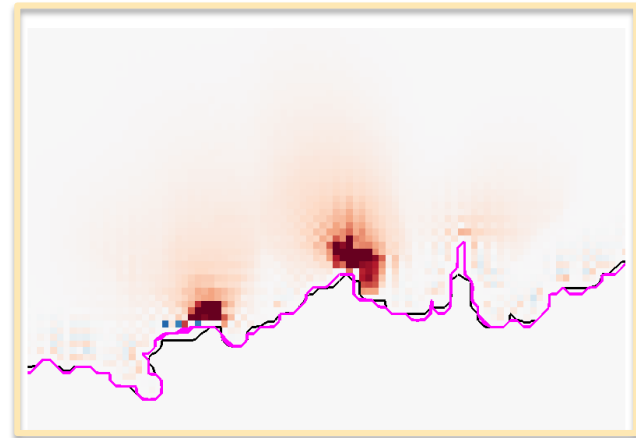
Experiment – 250-year Antarctic simulations

- **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 $O(400\text{m})$ 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**

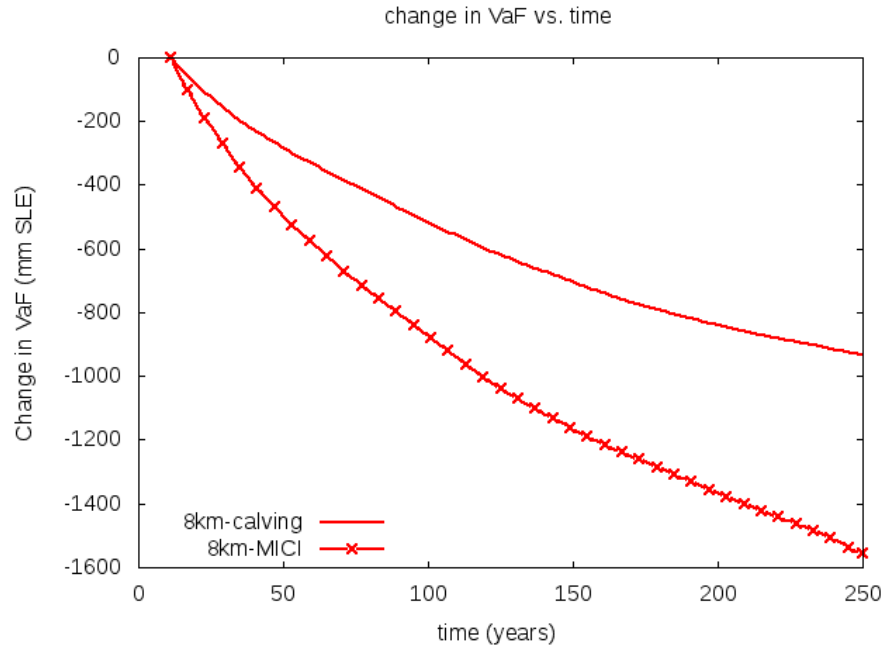
Results – 8km resolution



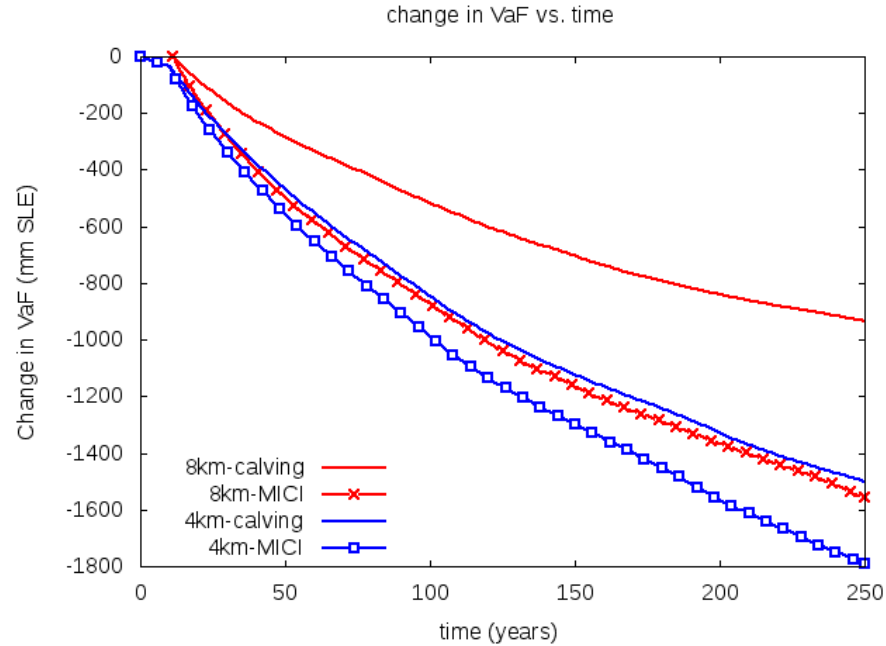
- Ice thickness differences between 8m MICI and no-MICI runs
- Shown at final time (t=250)
- Inset shows Wilkes Basin



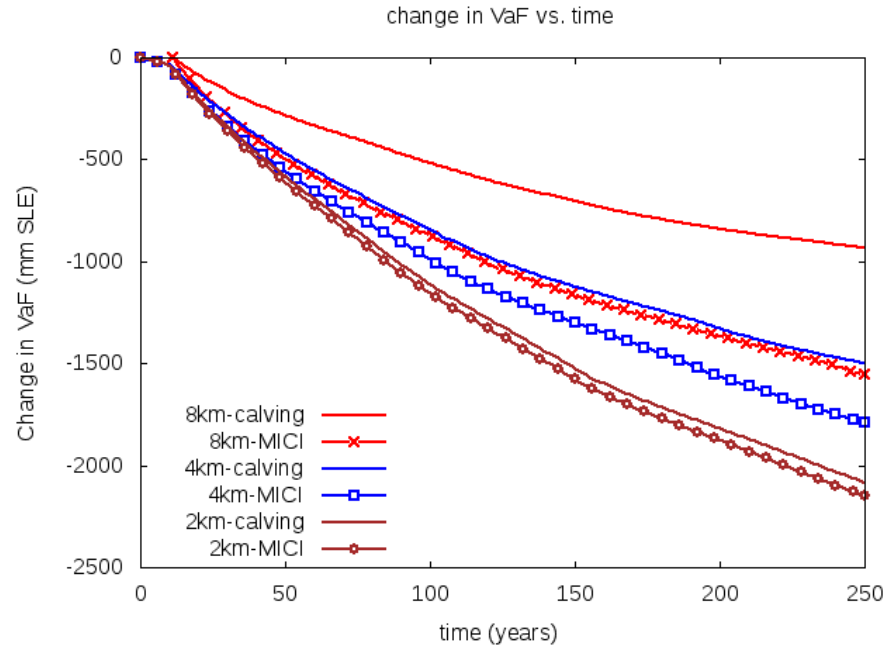
Volume above Flotation...



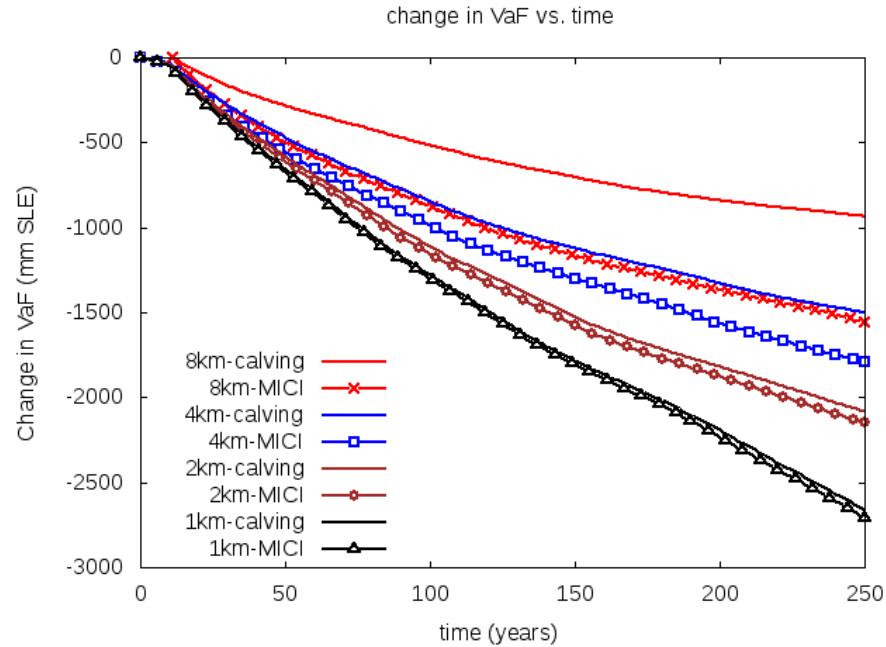
Volume above Flotation...



Volume above Flotation...



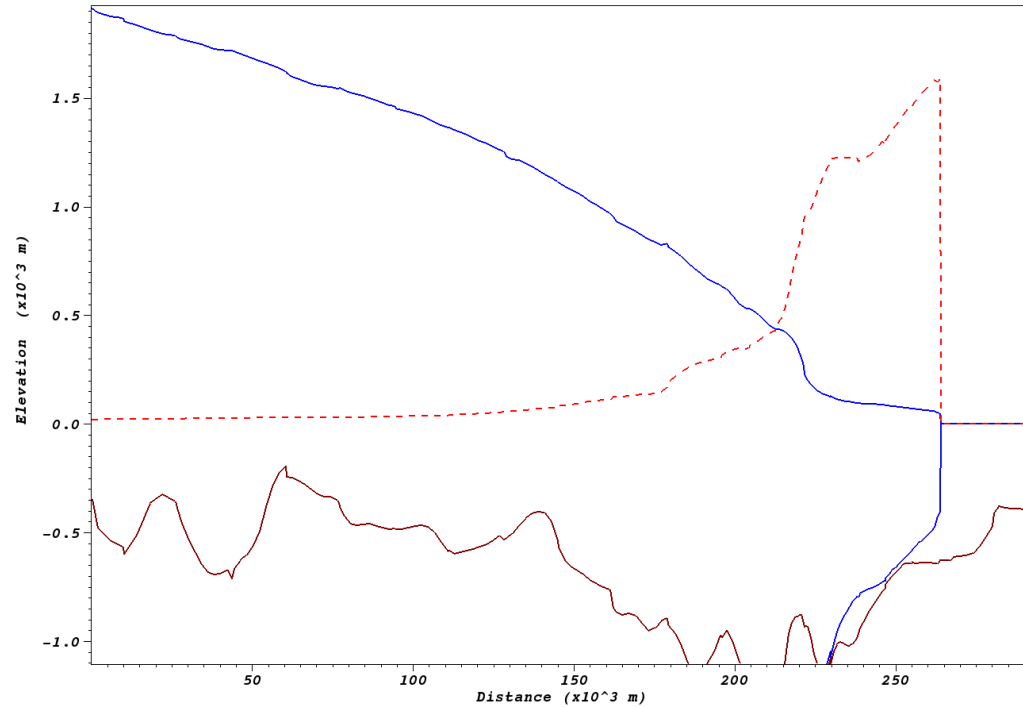
Volume above Flotation...



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 $O(\text{a few GL ice thicknesses})$
- **Suggests that we need to resolve these scales to get retreat dynamics correct.**

One example – Wilkes Basin: 1km resolution

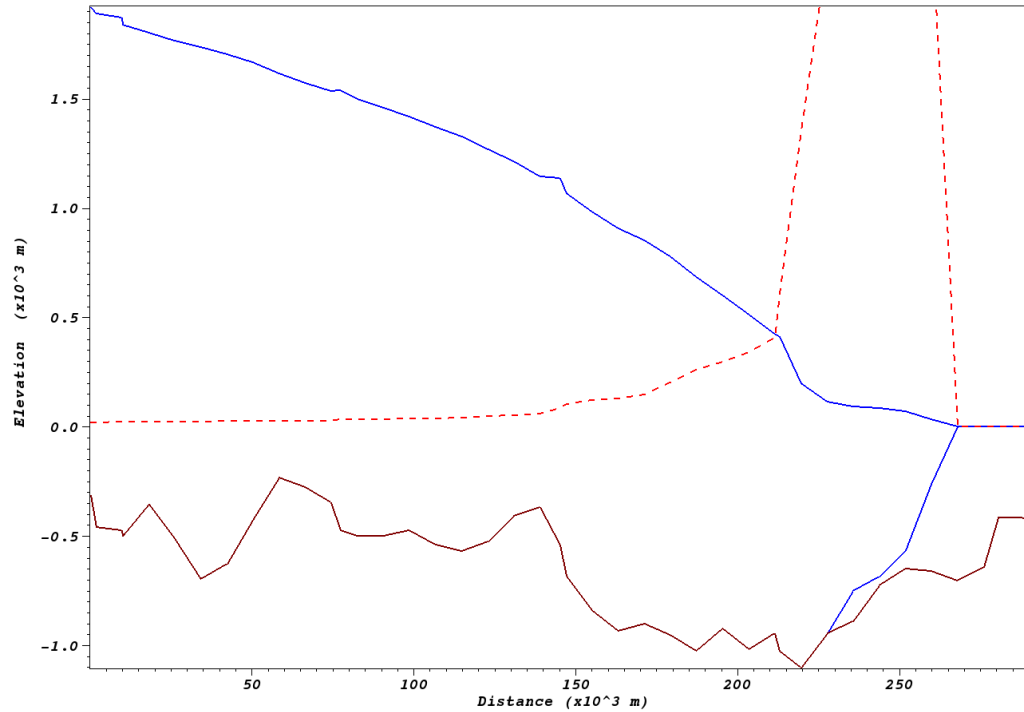


Time= 0.00 years

One example – Wilkes Basin

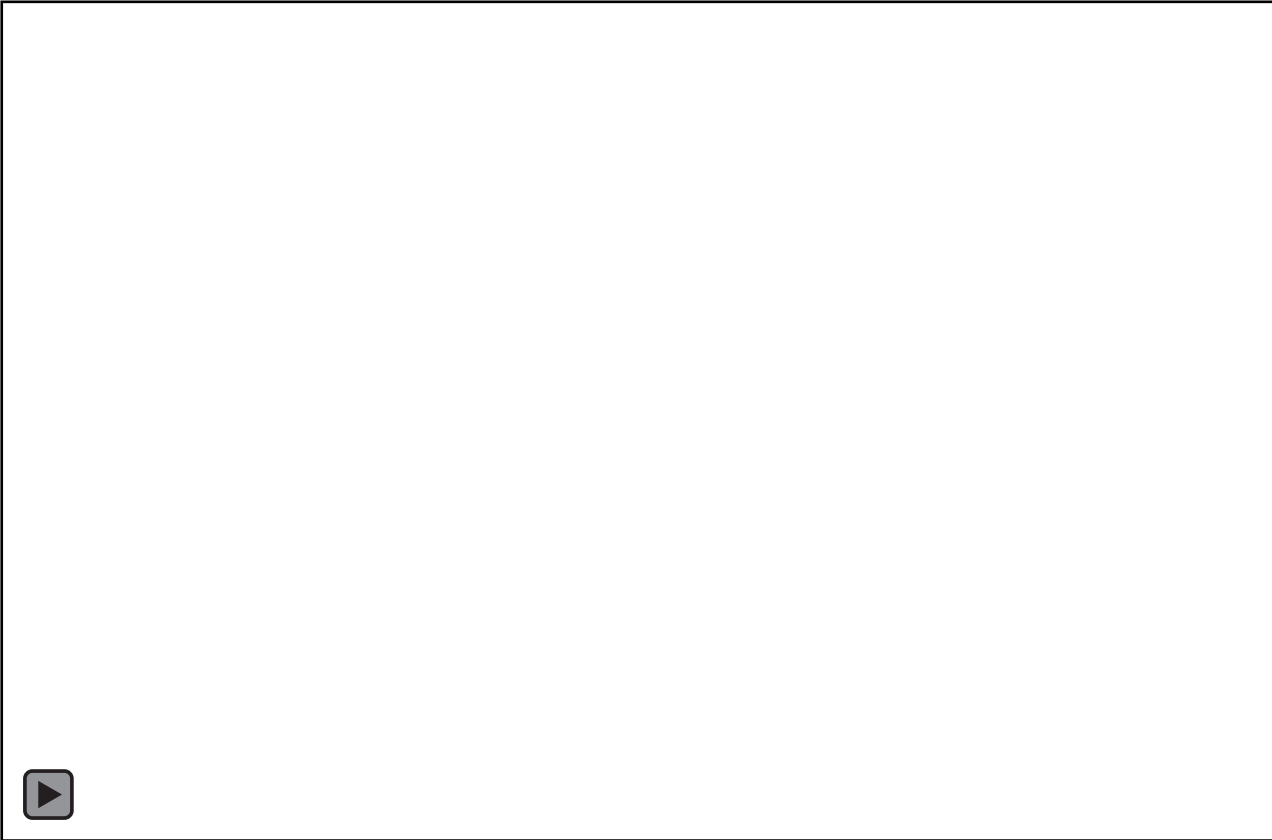


Wilkes Basin: 8km resolution



Time= 0.00 years

Wilkes Basin: 8km resolution



The Atlantic (January 4...)


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SCIENCE

A Terrifying Sea-Level Prediction Now Looks Far Less Likely

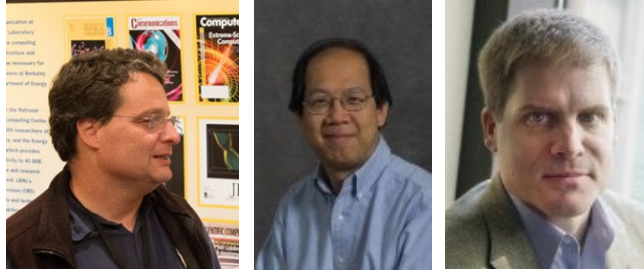
But experts warn that our overall picture of sea-level rise looks far scarier today than it did even five years ago.

ROBINSON MEYER JAN 4, 2019



A boat floats in Neko Harbour, Antarctica, in February 2018. (ALEXANDRE MENEGHINI / REUTERS)

Collaborators and funding



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DOE

- Steph Cornford (Swansea)
- Tony Payne (Bristol)
- Vicky Lee (Bristol)

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- Jeremy Bassis
- Sam Kachuck
- Morgan Whitcomb

University
Of Michigan



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Scientific Discovery
through
Advanced Computing

- ISICLES
- ProSPect & PISCEES partnerships



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