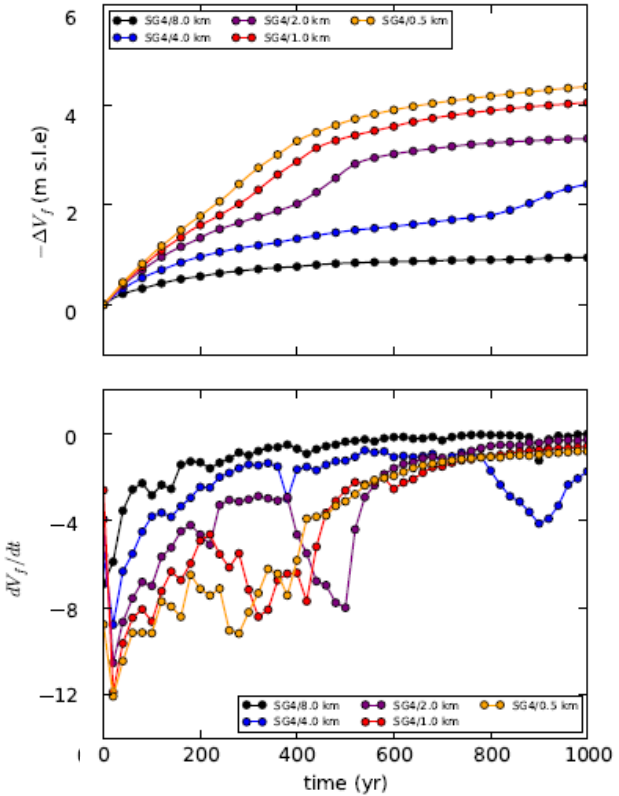
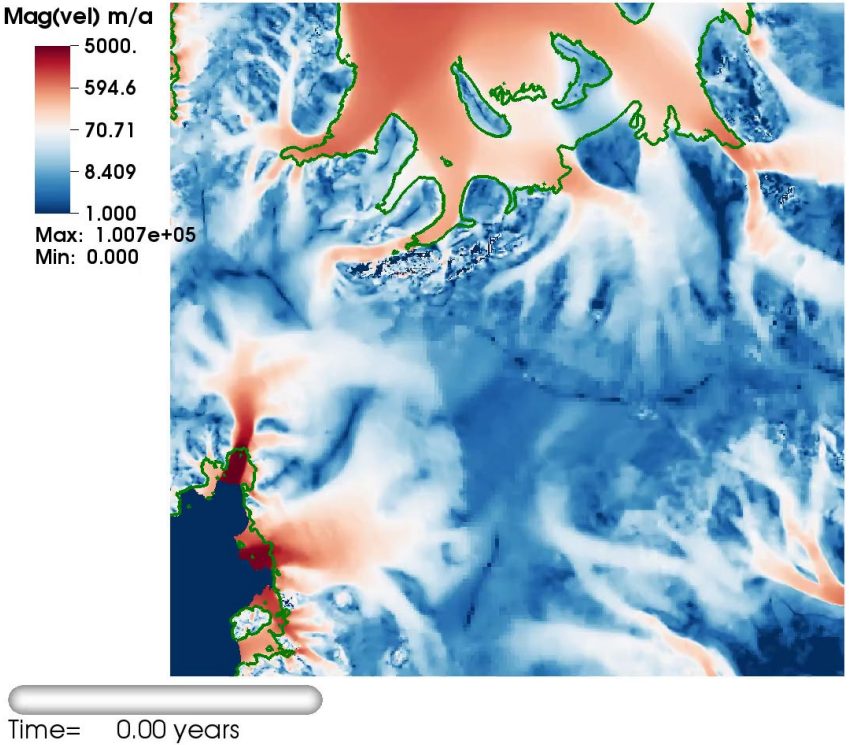
Resolution requirements…

- **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

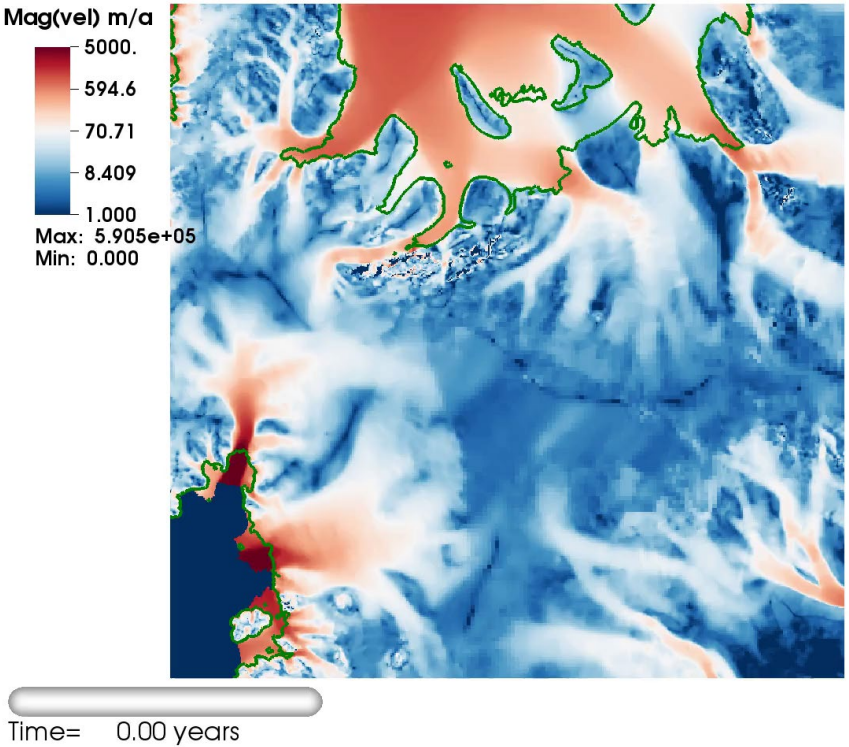


Thwaites-Rutford – 500m Resolution



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

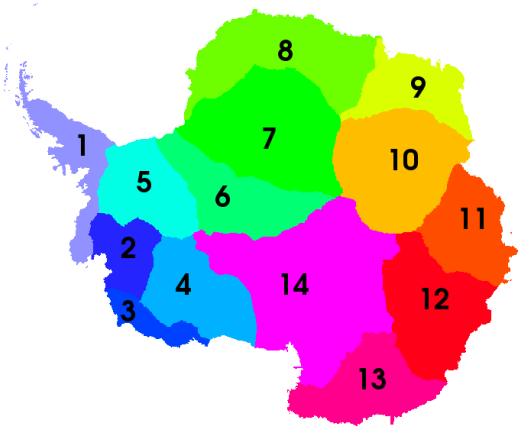
- **Basic idea – try to understand where AIS is vulnerable to forcing from ice-shelf collapse**

- **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**

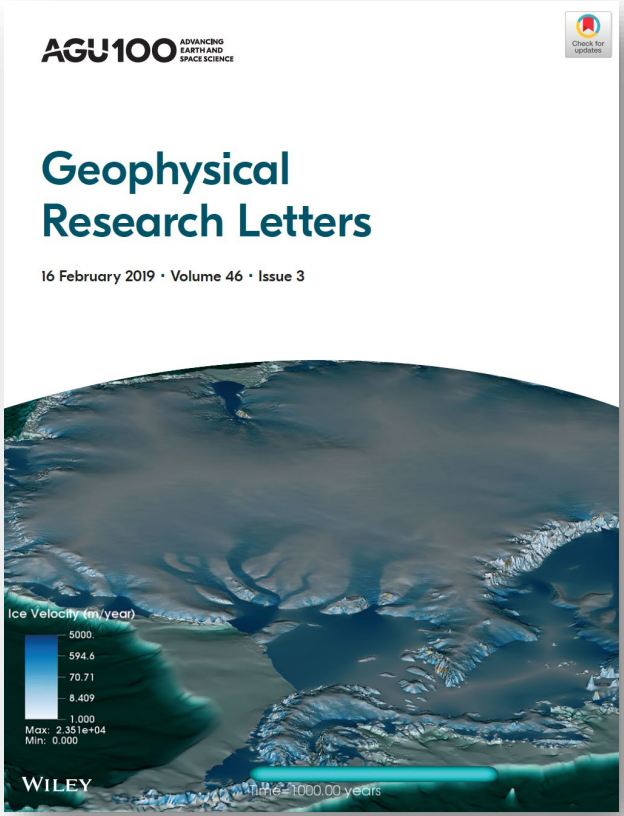
- **Run for 1000 years, compare with control (no melt).**

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.

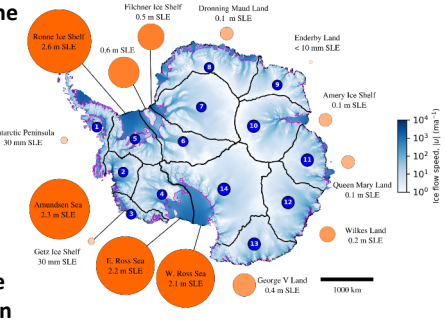
https://doi.org/10.1029/2018GL081229

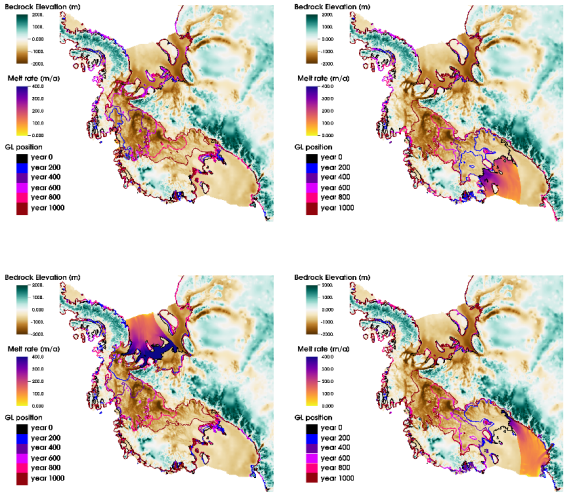


Millennial-scale Vulnerability of the Antarctic Ice Sheet to Regional Ice Shelf Collapse

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).

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)

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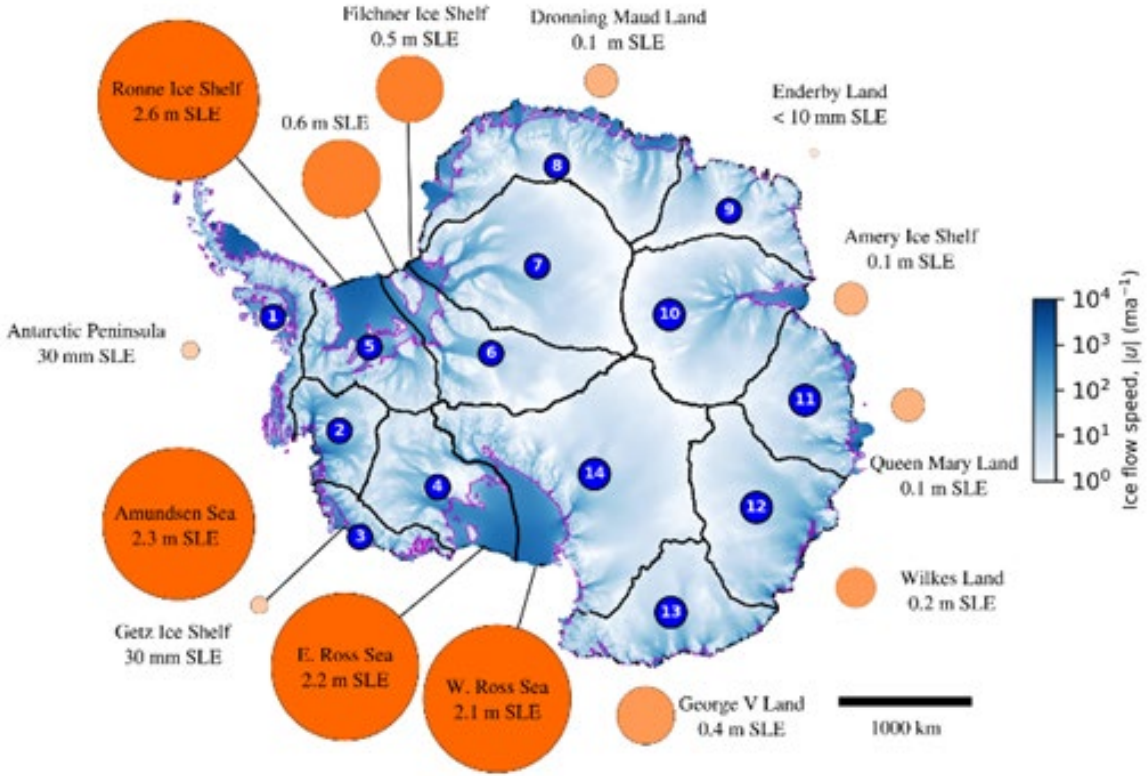
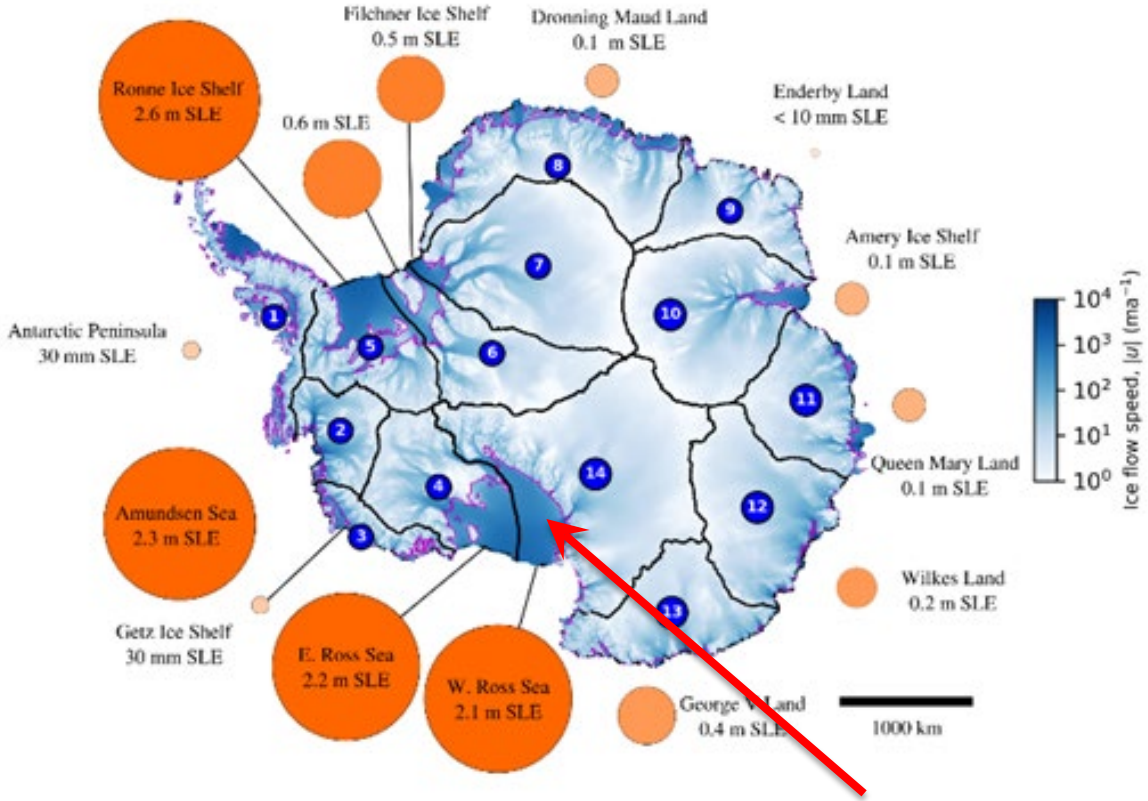
Antarctic Vulnerability Results:



Example: sector 14 (Western Ross)



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

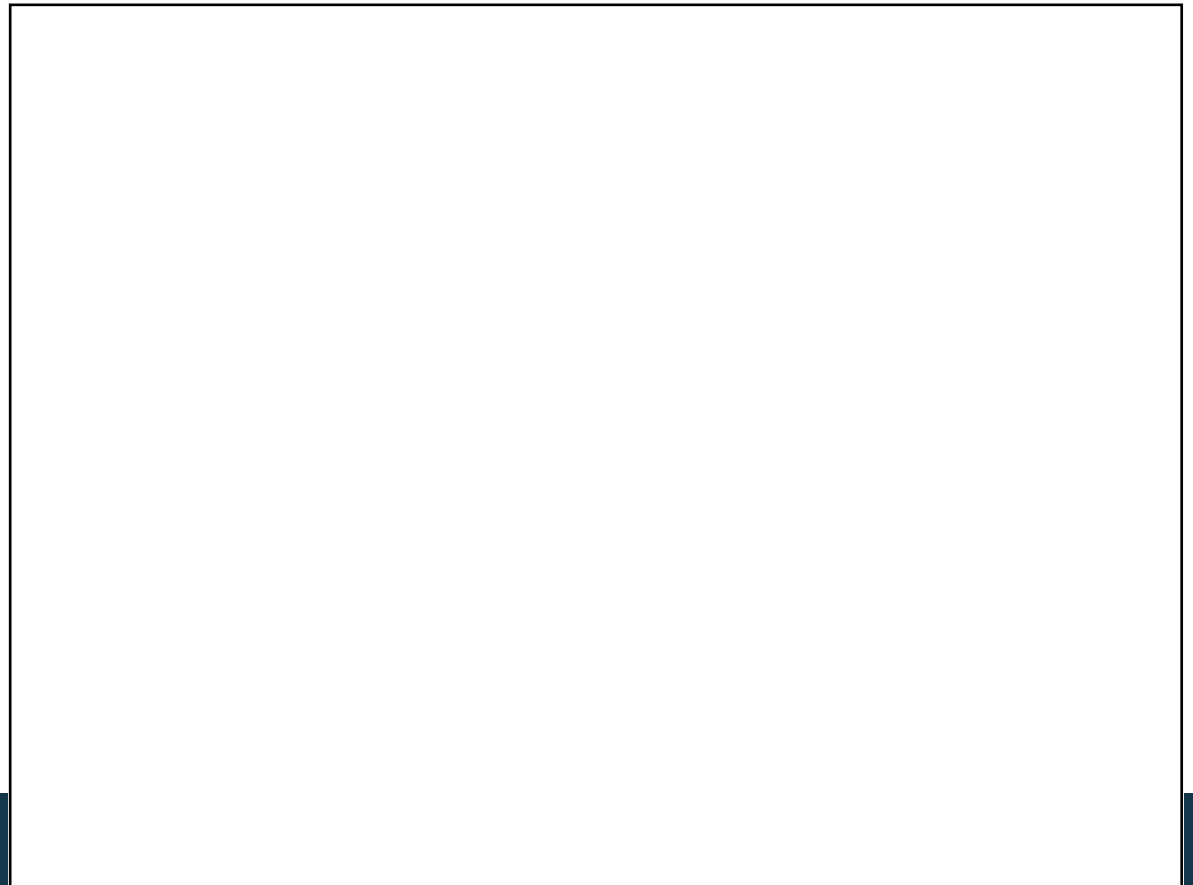
- **Couple with ocean & earth system models…**
- **Examine resolution requirements and convergence of full-scale problems…**
- **Evaluate Antarctic vulnerability…**
- **Add new physics…**

Damage and fracture

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

- How does this affect the ice sheet?

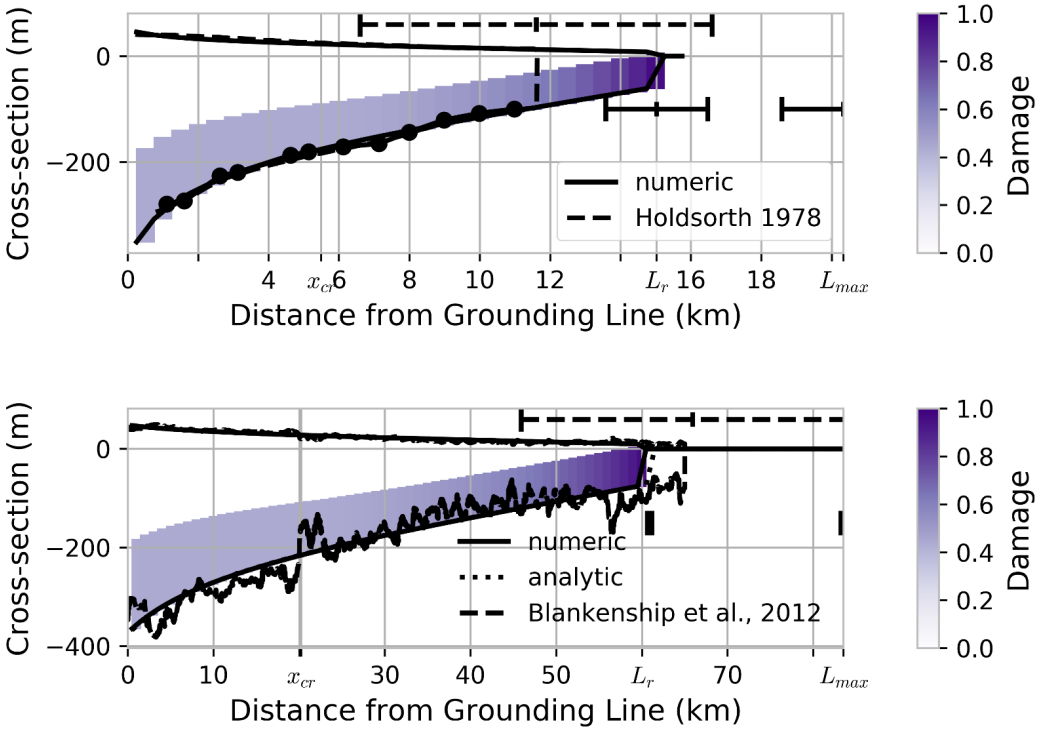
Damage and Fracture…

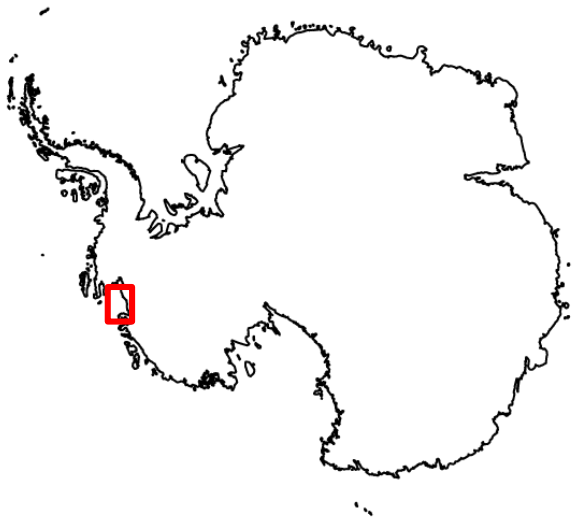


Incorporating “damage” into BISICLES…

- **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)**

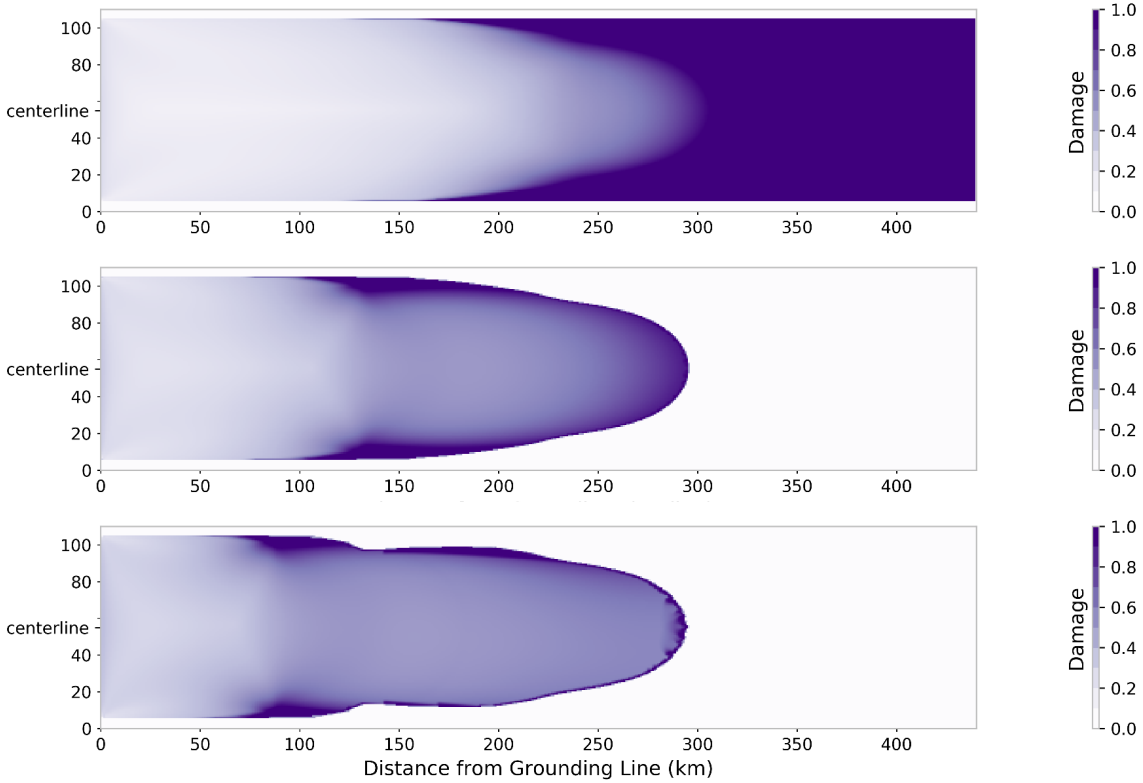
Fully-Damaged Termini at Ice Tongues





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

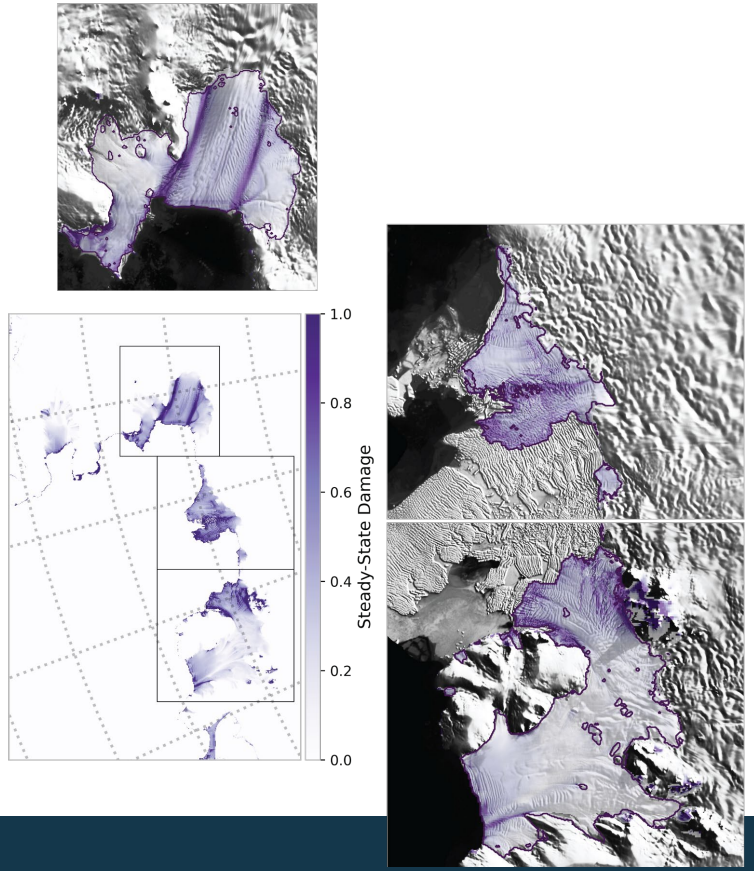
Coupling to Dynamics – Calving and Removal



Damage in the Amundsen Sea region

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

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

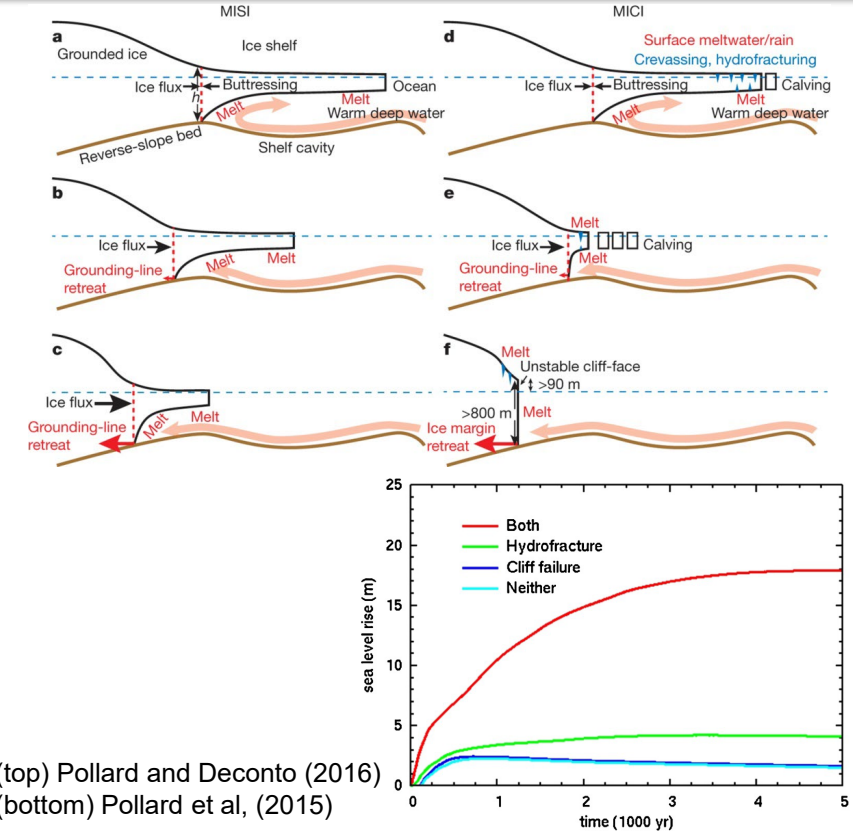


So what can we do with an AMR ice sheet model?

- **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)

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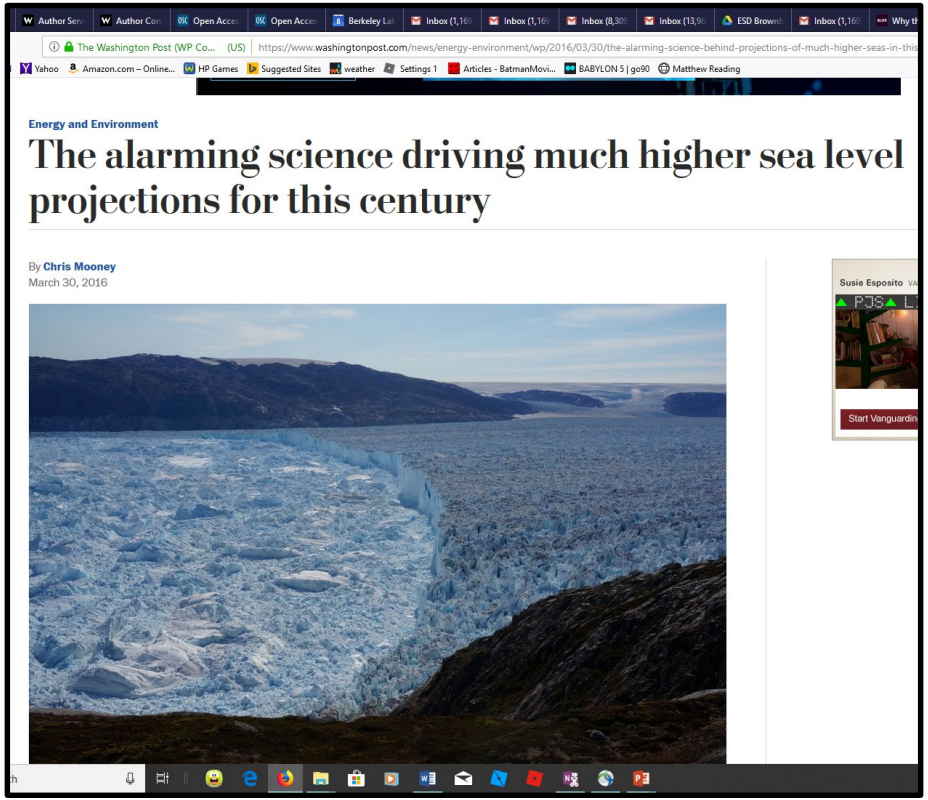
Washington Post…



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New York Times…

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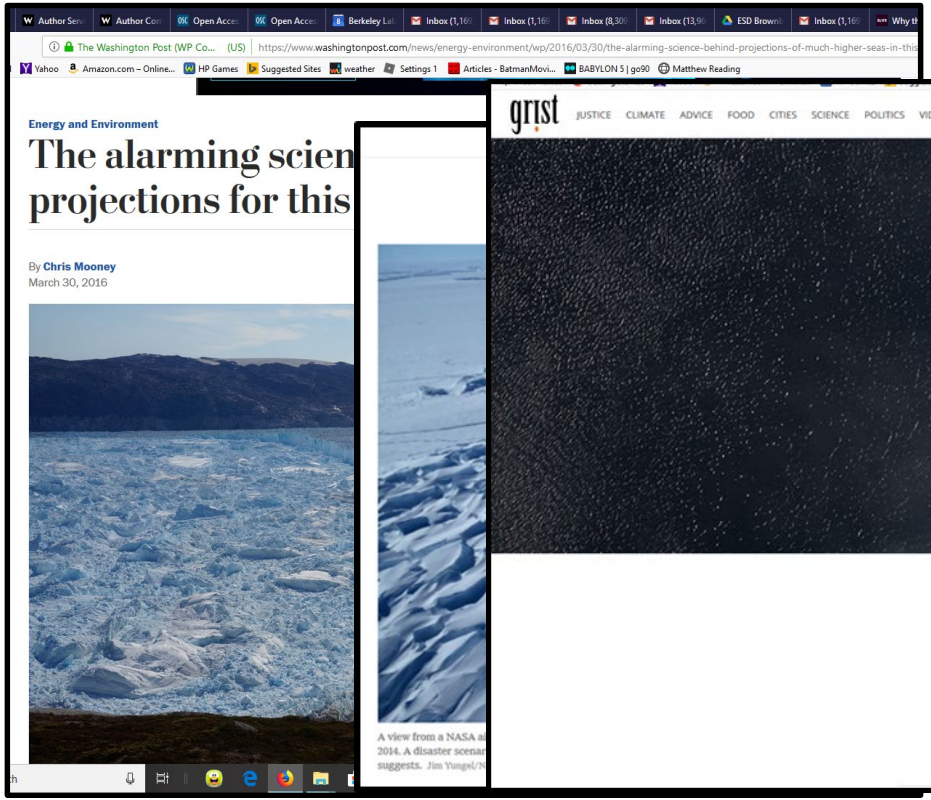
Grist...



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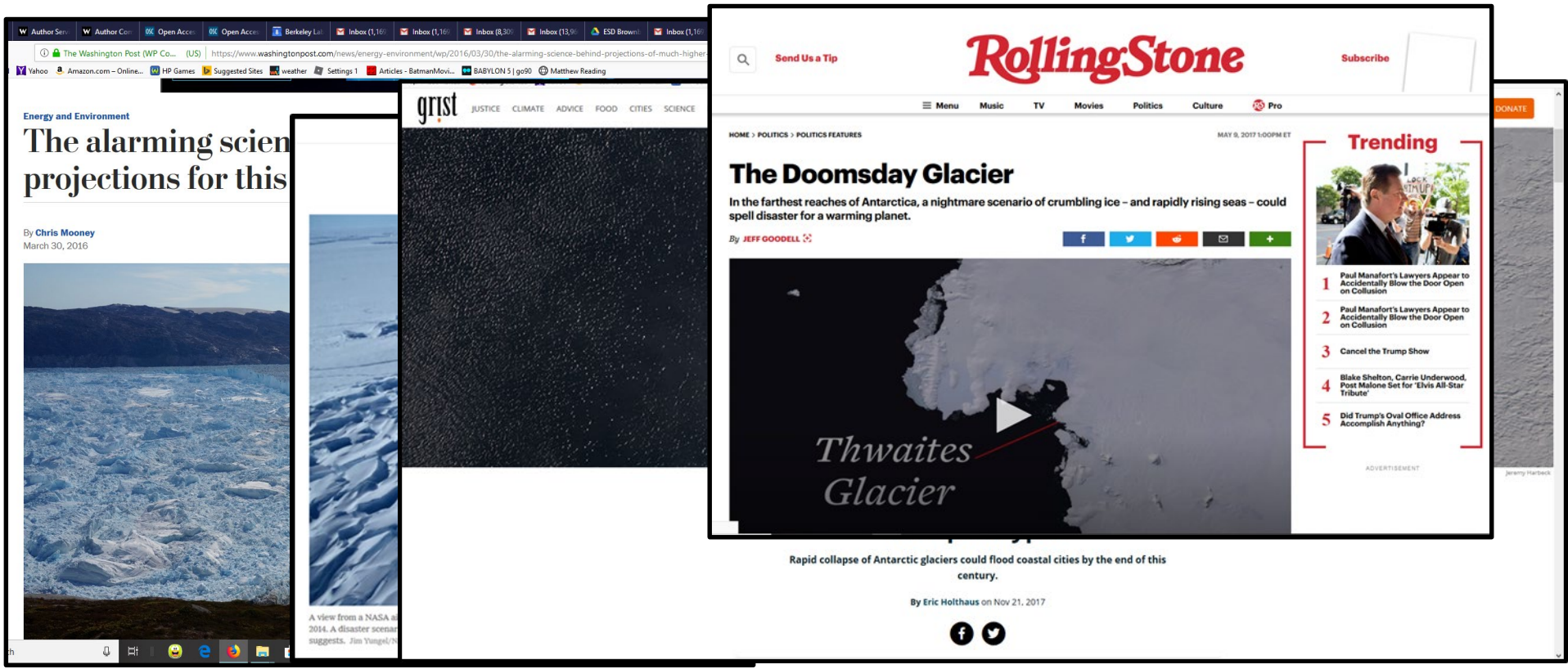
Rolling Stone?



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

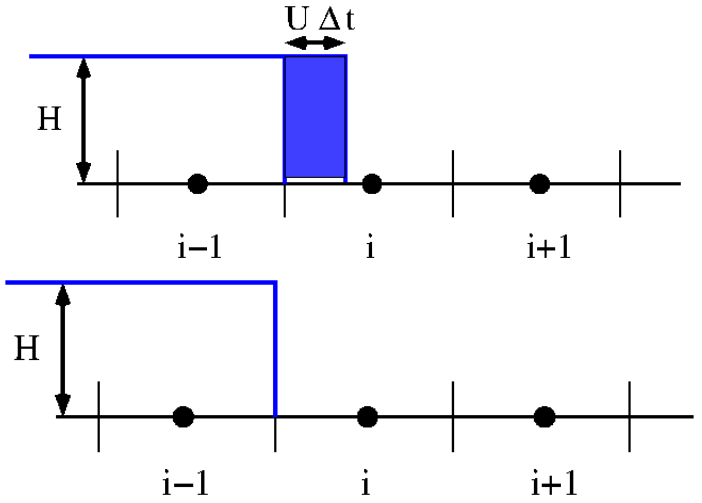
- Extend existing partial-cell scheme (designed for shelf regrowth in MISOMIP)
- BISICLES is a finite-volume code; compute cell-averaged quantities which are updated by ice thickness fluxes across the cell faces.
- Maintain an area fraction ϕ, the fraction of the cell area (2d) containing ice
- Wind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

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

- If there is a cliff,

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

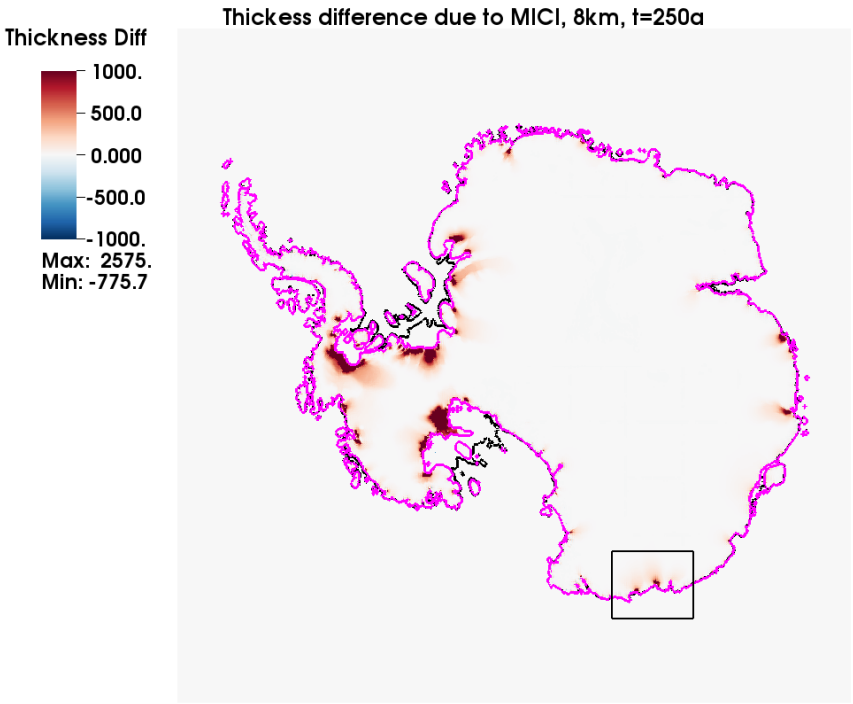
$$h^{new} = h\frac{\varphi^{new}}{\varphi}$$



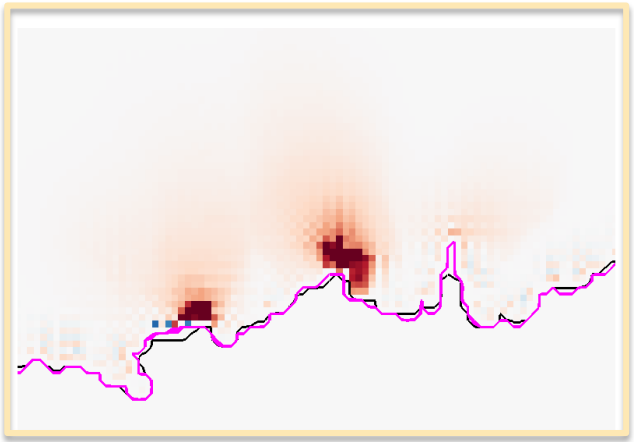
Experiment – 250-year Antarctic simulations

- **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**

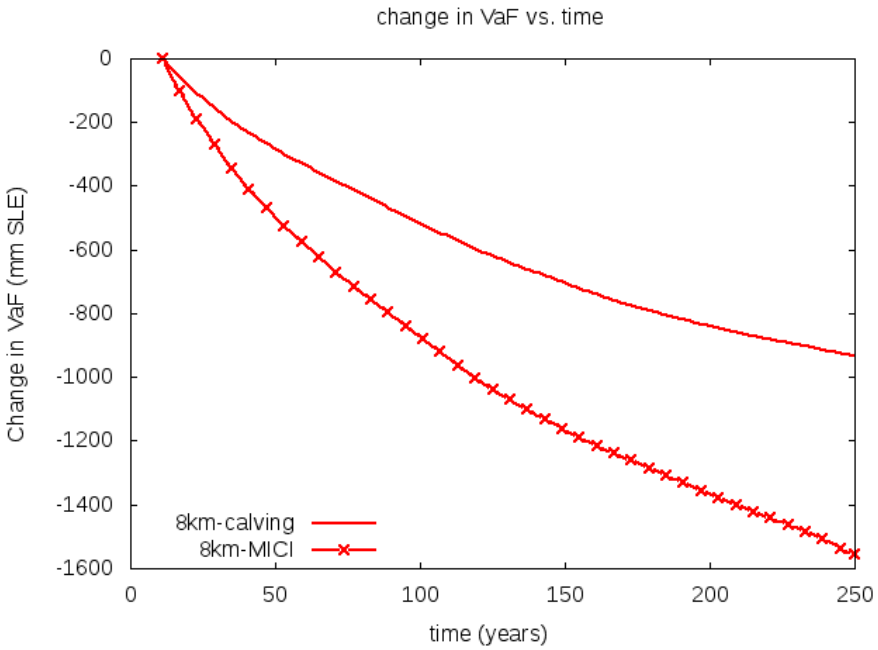
Results – 8km resolution



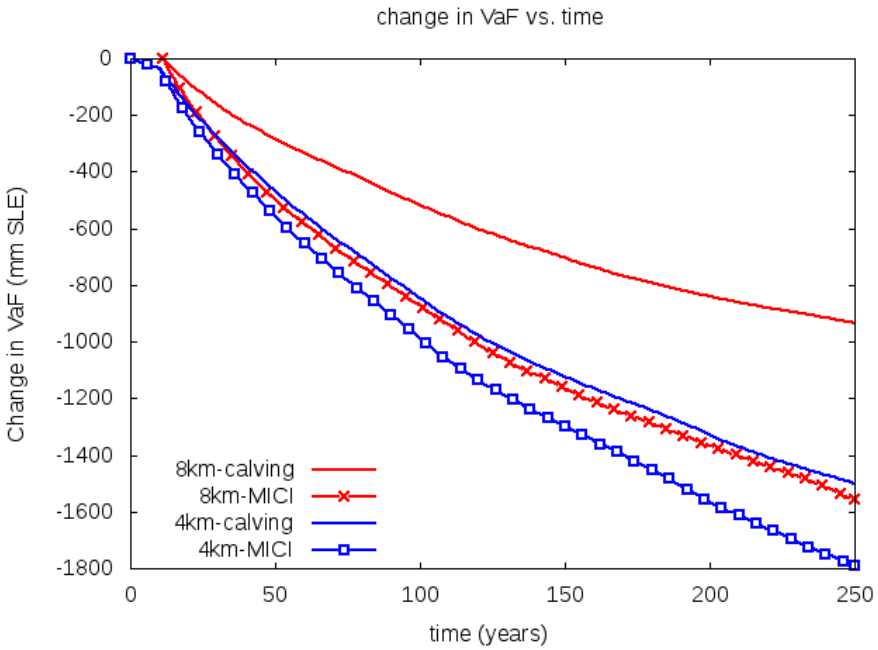
- Ice thickness differences between 8m MICI and no-MICI runs
- Shown at final time (t=250)
- Inset shows Wilkes Basin



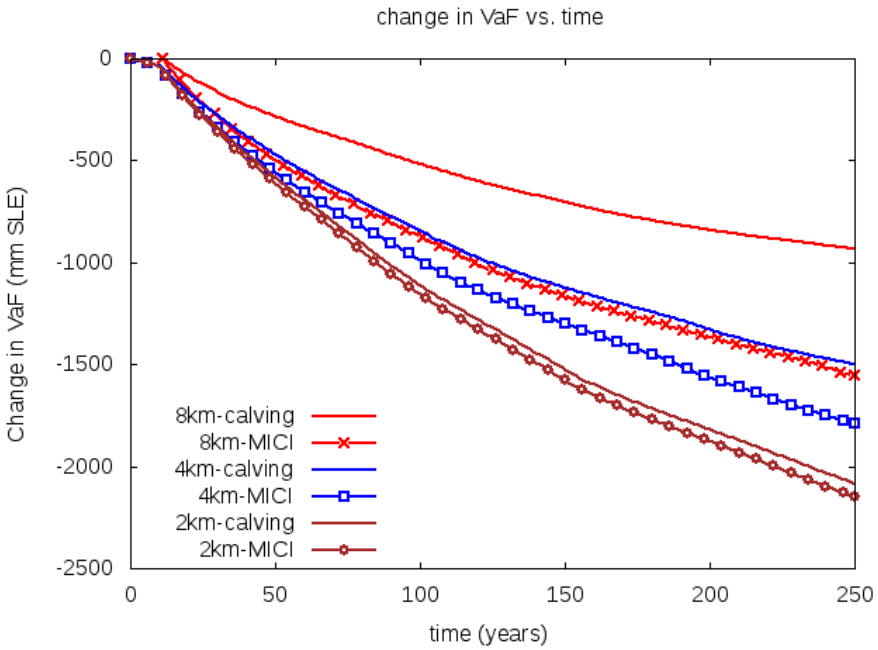
Volume above Flotation…



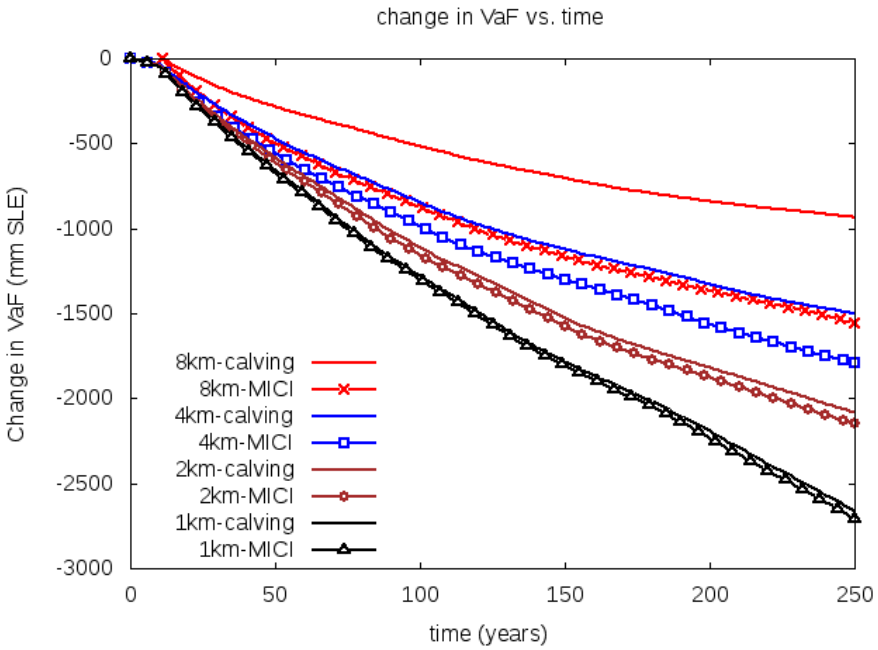
Volume above Flotation…



Volume above Flotation…



Volume above Flotation…



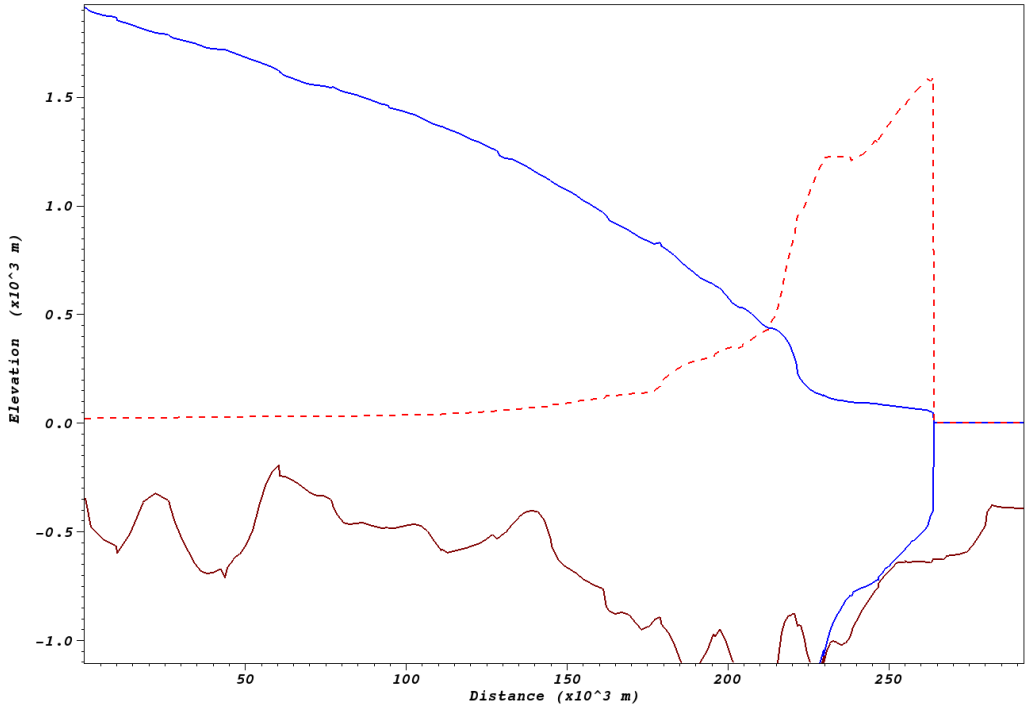
Alternative hypothesis

- **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(a few GL ice thicknesses)

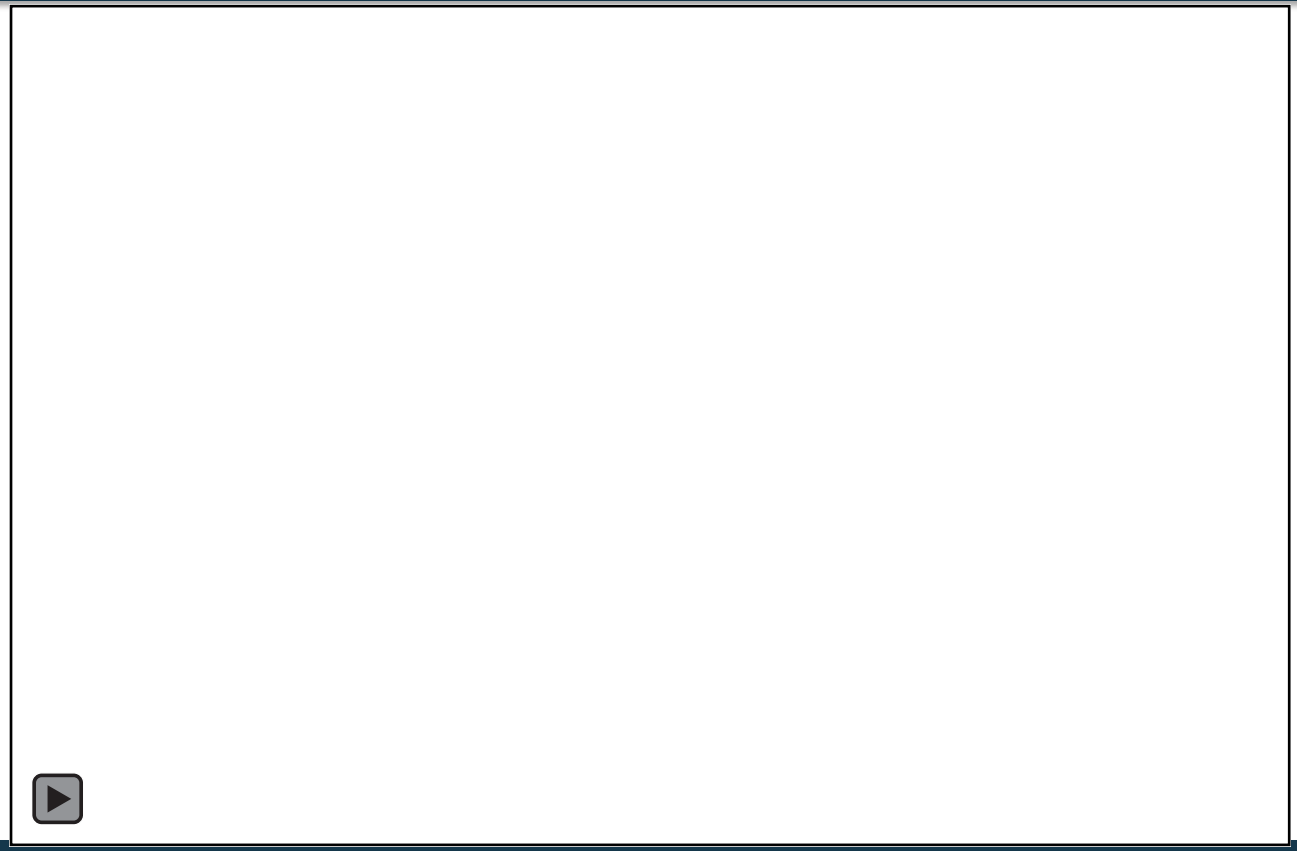
- **Suggests that we need to resolve these scales to get retreat dynamics correct.**

One example – Wilkes Basin: 1km resolution

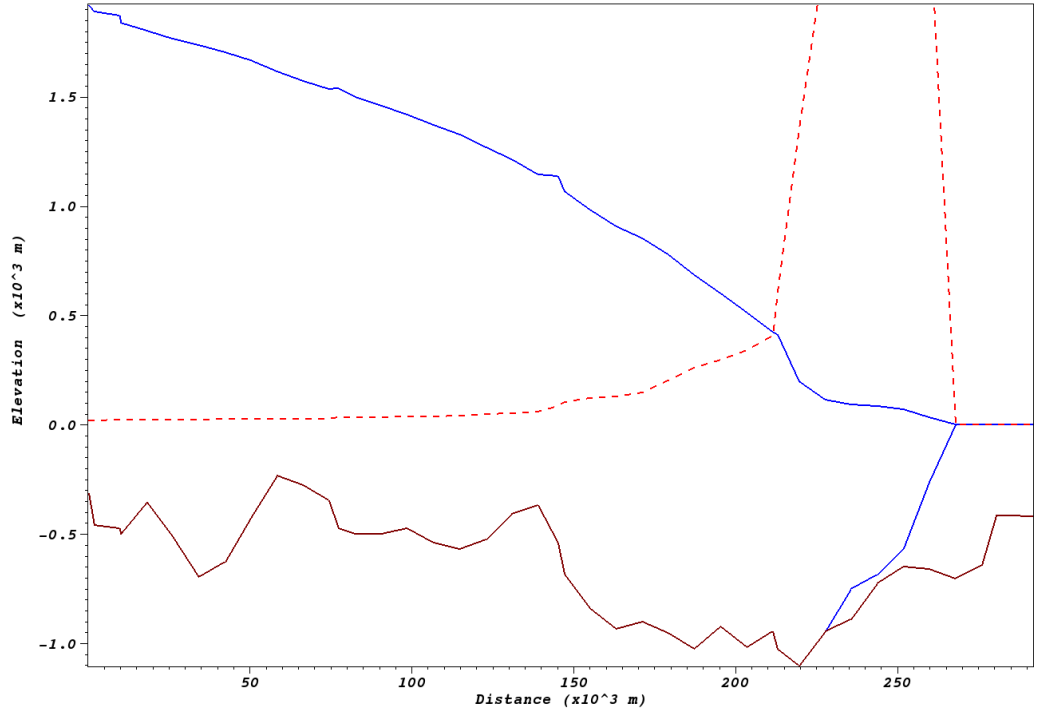


Time= 0.00 years

One example – Wilkes Basin

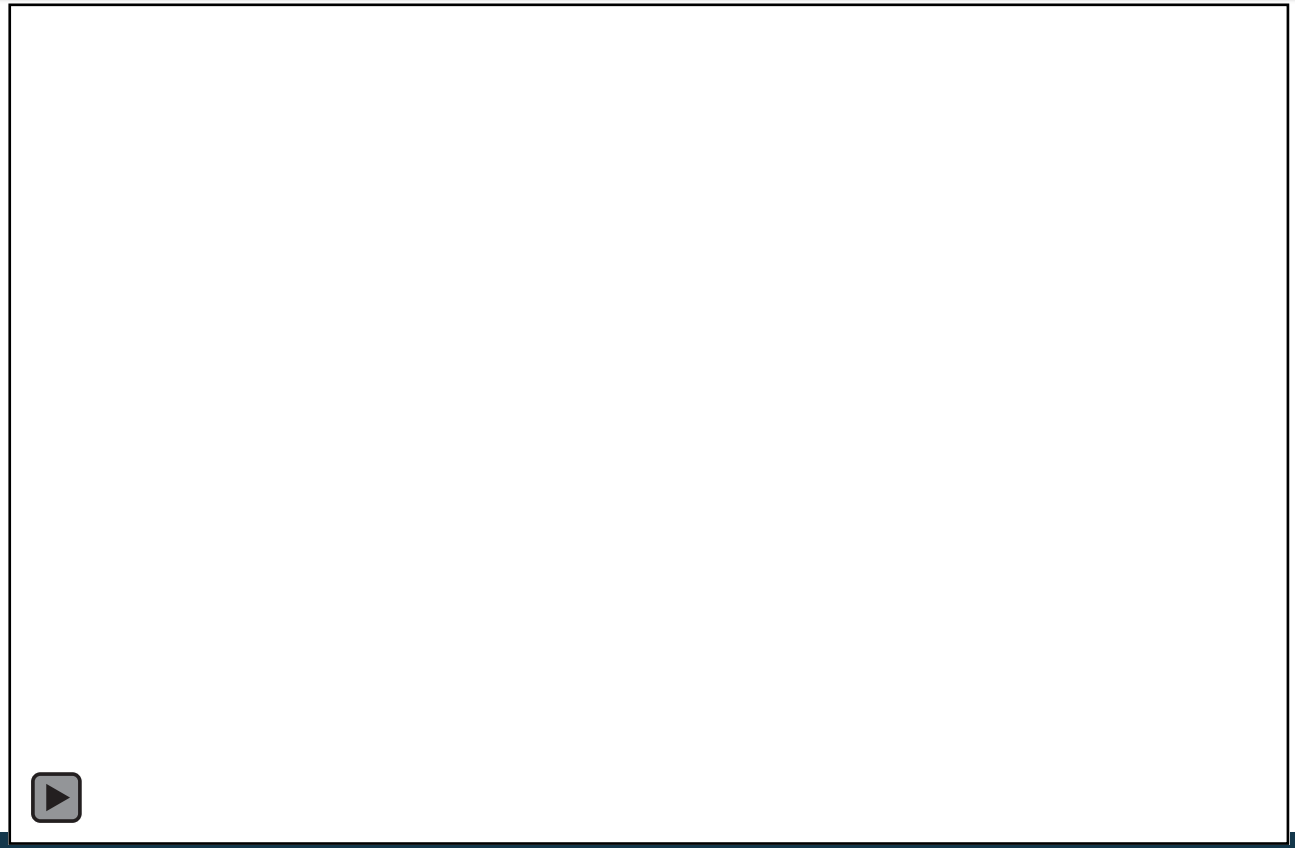


Wilkes Basin: 8km resolution

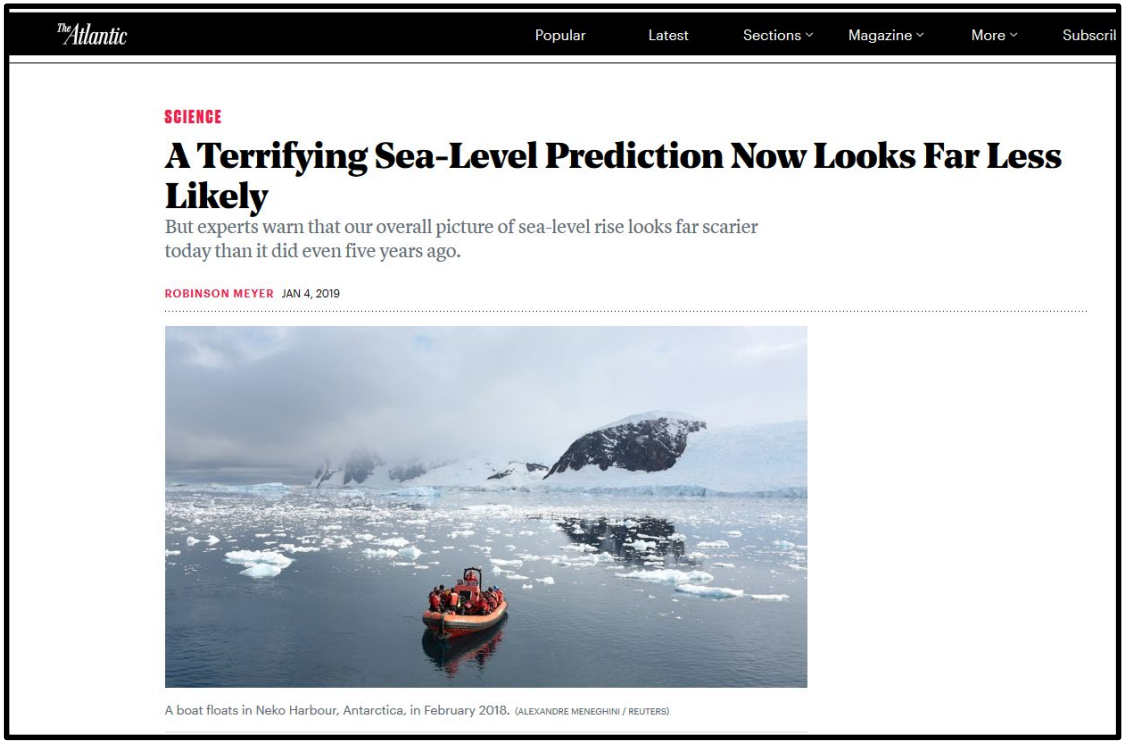


Time= 0.00 years

Wilkes Basin: 8km resolution



The Atlantic (January 4…)



The Atlantic Popular Latest Sections Magazine More Subscril

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)

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- Bill Lipscomb (NCAR)

DOE

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- Tony Payne (Bristol)
- Vicky Lee (Bristol)

UK

- Jeremy Bassis
- Sam Kachuck
- Morgan Whitcomb

University Of Michigan

SciDAC
Scientific Discovery through Advanced Computing

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- ProSPect & PISCEES partnerships

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E3SM
Energy Exascale Earth System Model

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