Millennial-scale Vulnerability of the Antarctic Ice Sheet to localized subshelf warm-water forcing

Dan Martin

Lawrence Berkeley National Laboratory

August 18, 2017

Joint work with:

- **Stephen Cornford** (Swansea)
- Tony Payne (Bristol)
- Vicky Lee (Bristol)
- Esmond Ng (LBNL)
- Stephen Price (LANL)

- Work supported by the Department of Energy
- Computations performed at NERSC

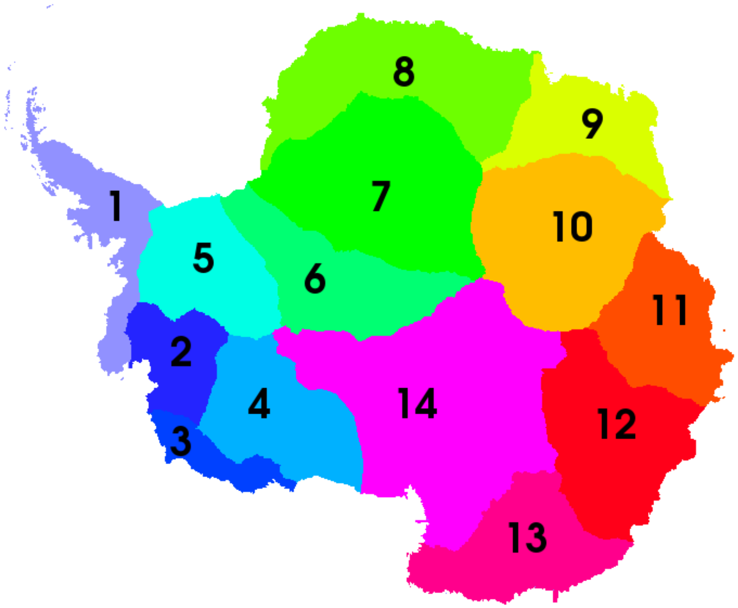
Motivation: Potential future Sea Level Rise

- Potentially large Antarctic contributions to SLR resulting from marine ice sheet instability, particularly from WAIS.
- Climate driver: subshelf melting driven by warm(ing) ocean water intruding into subshelf cavities.
- Evidence that this is already underway in ASE sector. (elsewhere, too?)
- Paleorecord implies that WAIS has deglaciated in the past.

Antarctic vulnerability to warm-water forcing

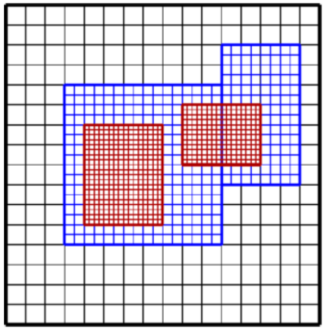
- **Basic idea - try to understand where AIS is vulnerable to forcing from warm-water incursions**
- Divide AIS into sectors
- For each sector in turn (and for some combinations), apply extreme depth-dependent melt forcing
  - No melt for h < 100m
  - Range up to 400m/a where h > 800m.
  - **No melt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

Antarctic sectors

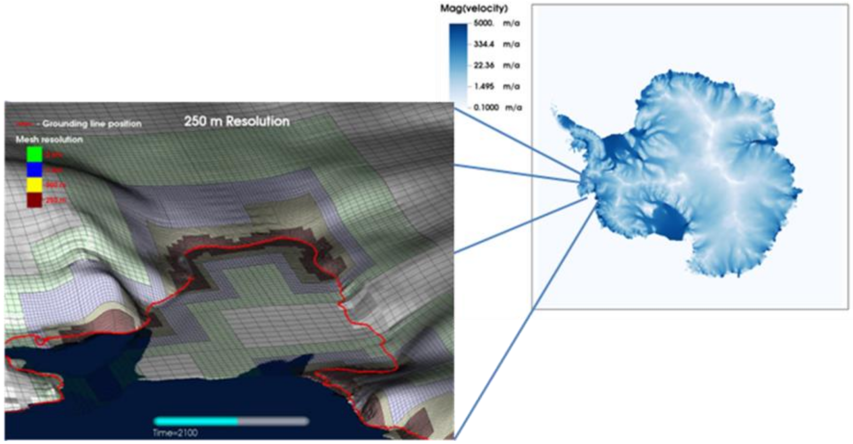


BISICLES Ice Sheet Model

- 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)

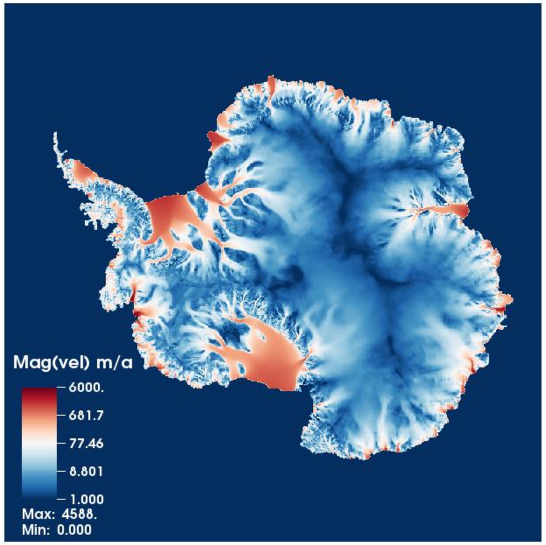


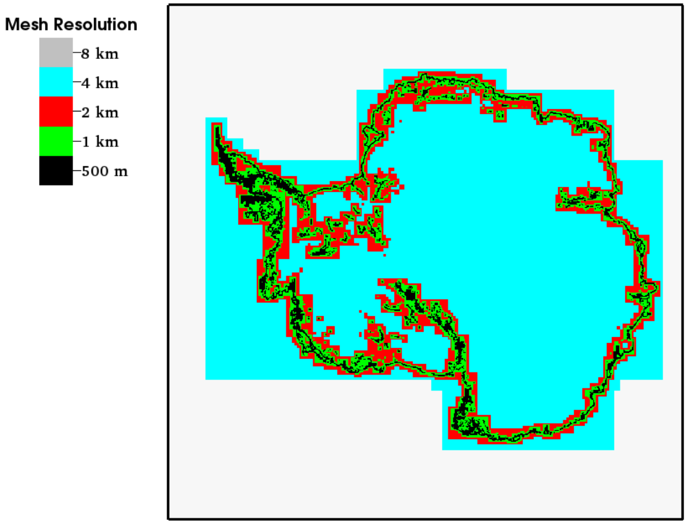
- Collaboration with Bristol (U.K.) and LANL
- Variant of “L1L2” model (Schoof and Hindmarsh, 2009)
- Users in Berkeley, Bristol, Beijing, Brussels, and Berlin…
- **Release v 1.0!**



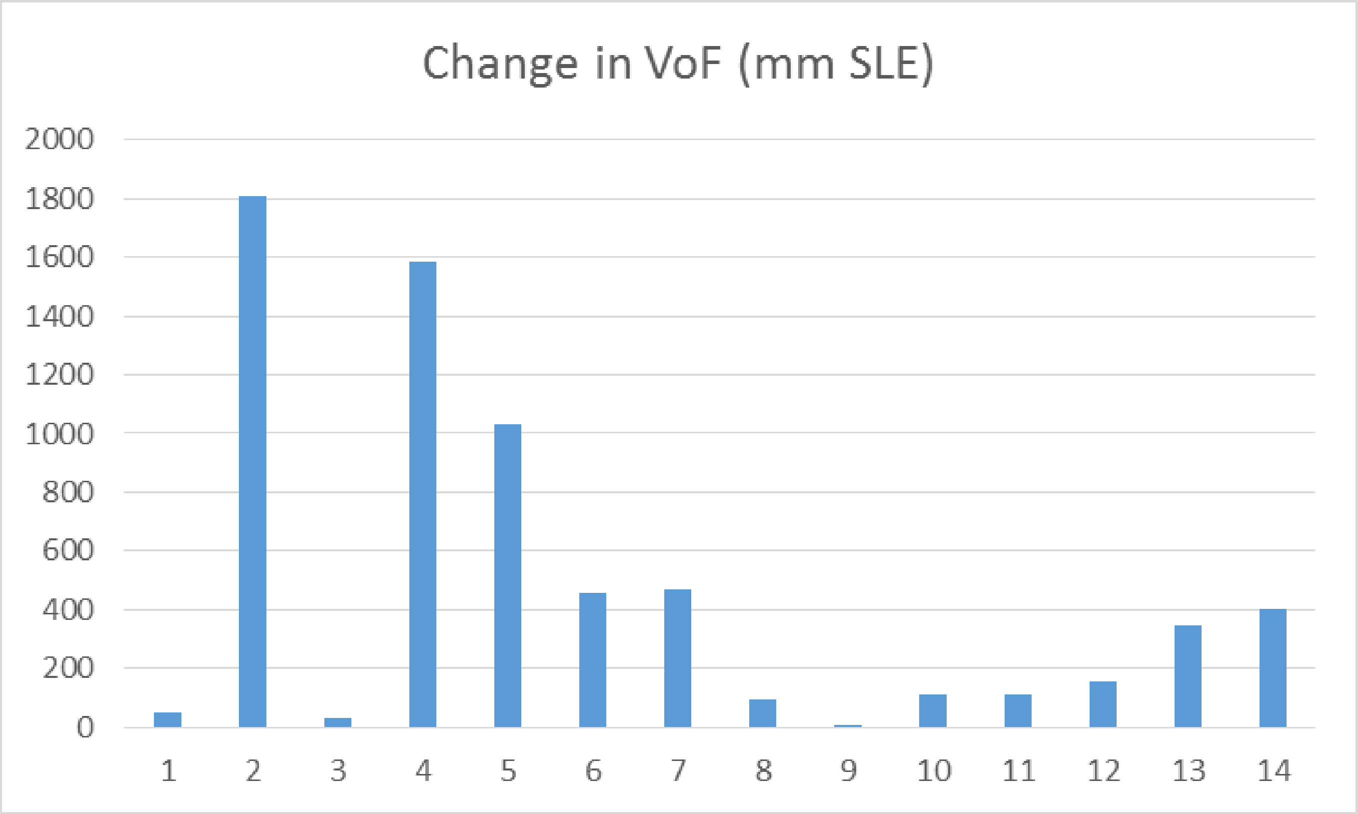
Initial Condition for Antarctic Simulations

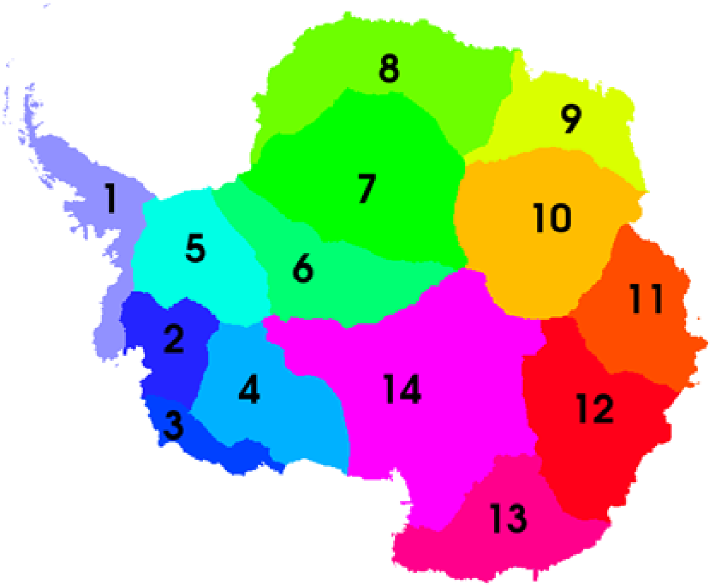
- Full-continent modified Bedmap2 (2013) geometry
- Temperature field from Pattyn (2010)
- Initialize basal friction to match Rignot (2011) velocities
- SMB: Arthern et al (2006)
- AMR meshes: 8 km base mesh, adaptively refine to Δx_f = 1 km
- Subgrid-scale basal friction scheme at grounding lines
  - **(Cornford et al, 2016 - adequate for Antarctic GL dynamics)**





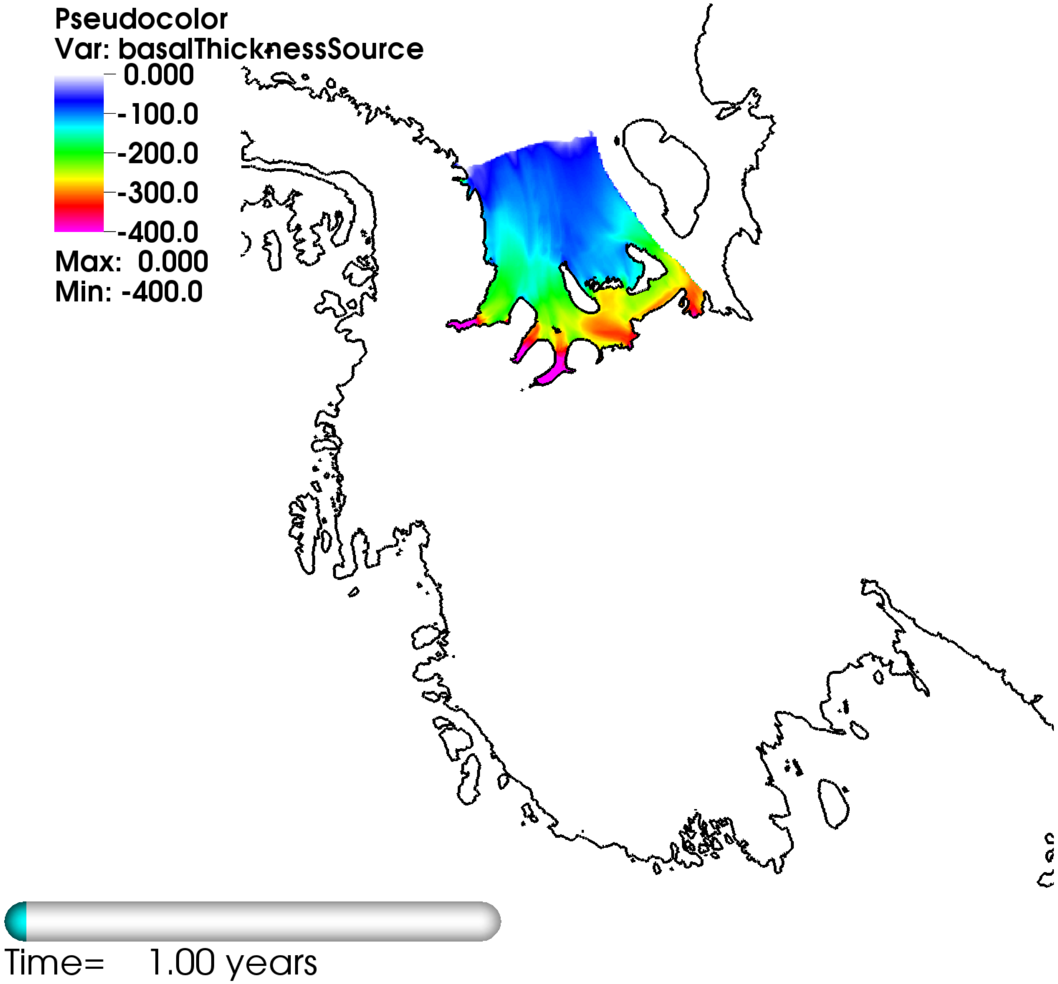
Results -



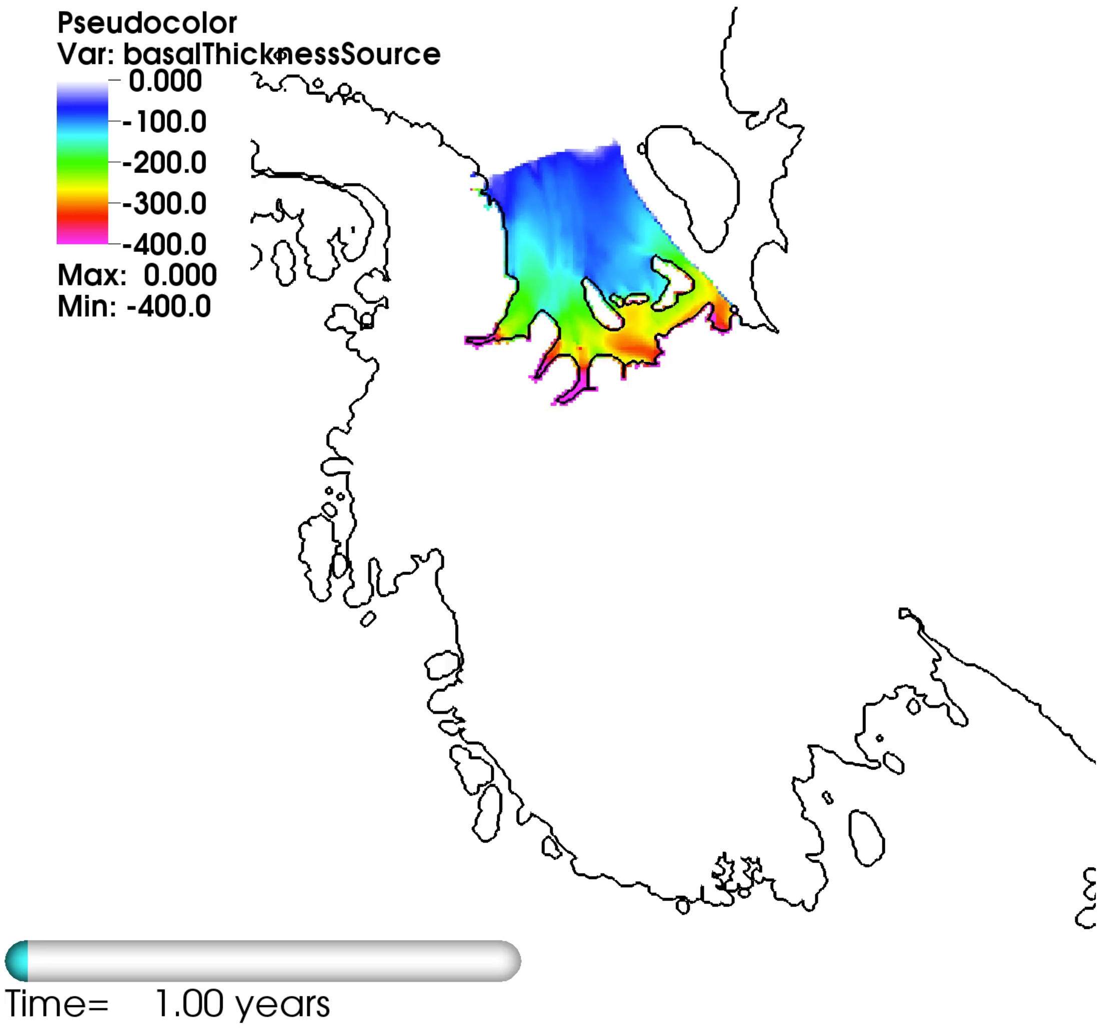


Change in Volume over flotation relative to control

Sector 5, cont

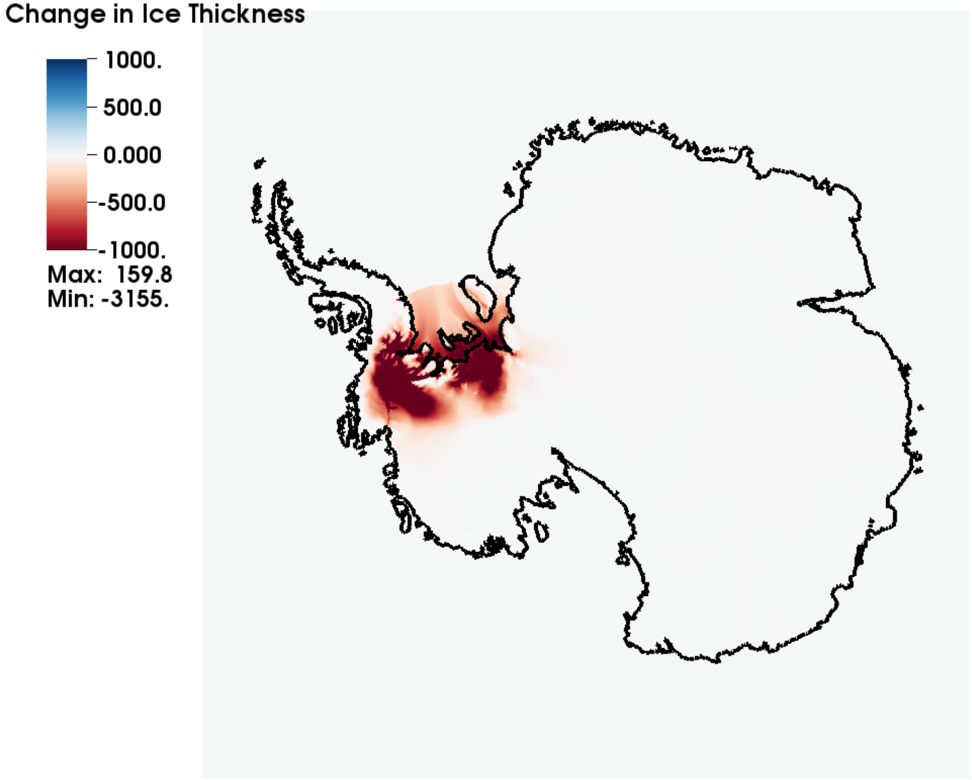


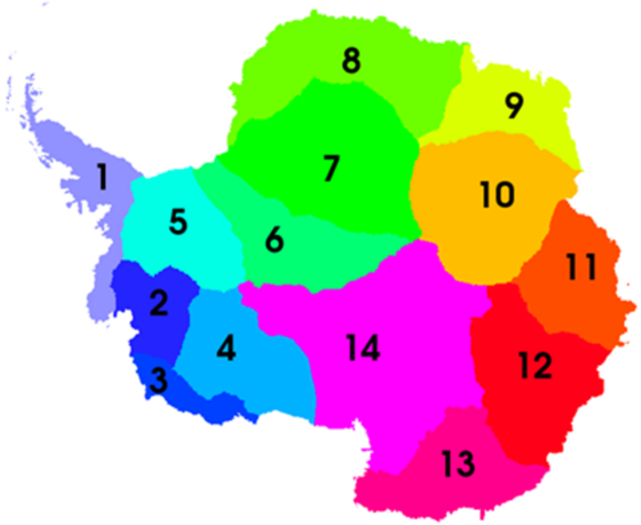
Sector 5, cont



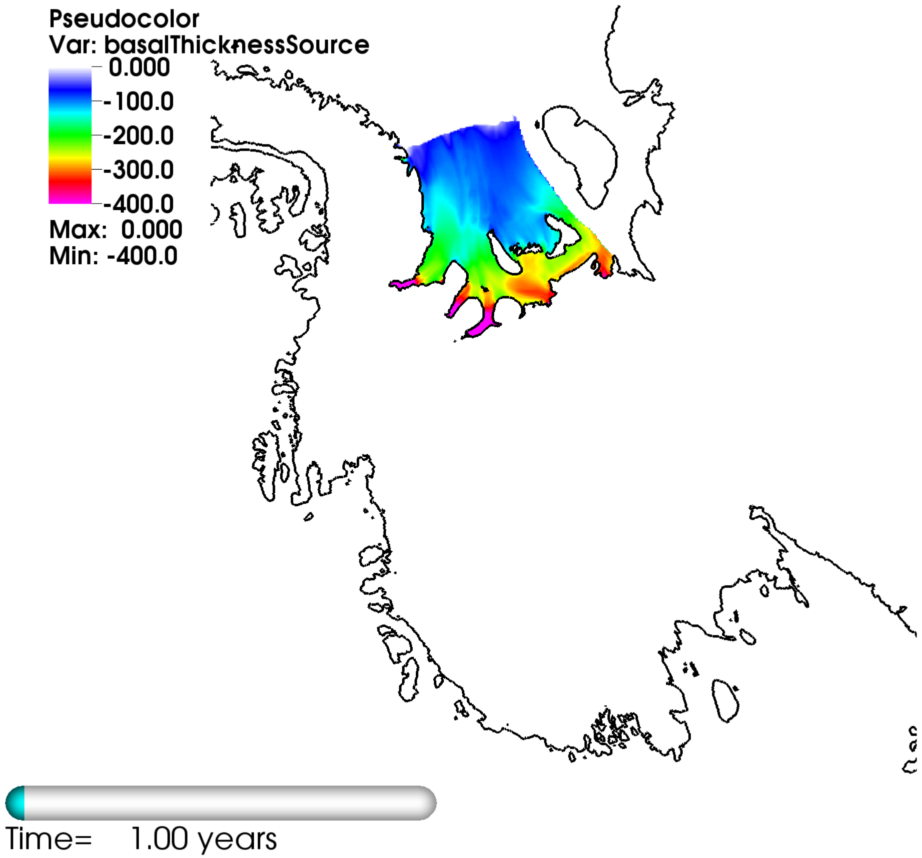
Sector 5 (Western Ronne)

- GL retreat moves out of sector…
- Substantial retreat into WAIS even after direct forcing ends
- 1.03 m SLE

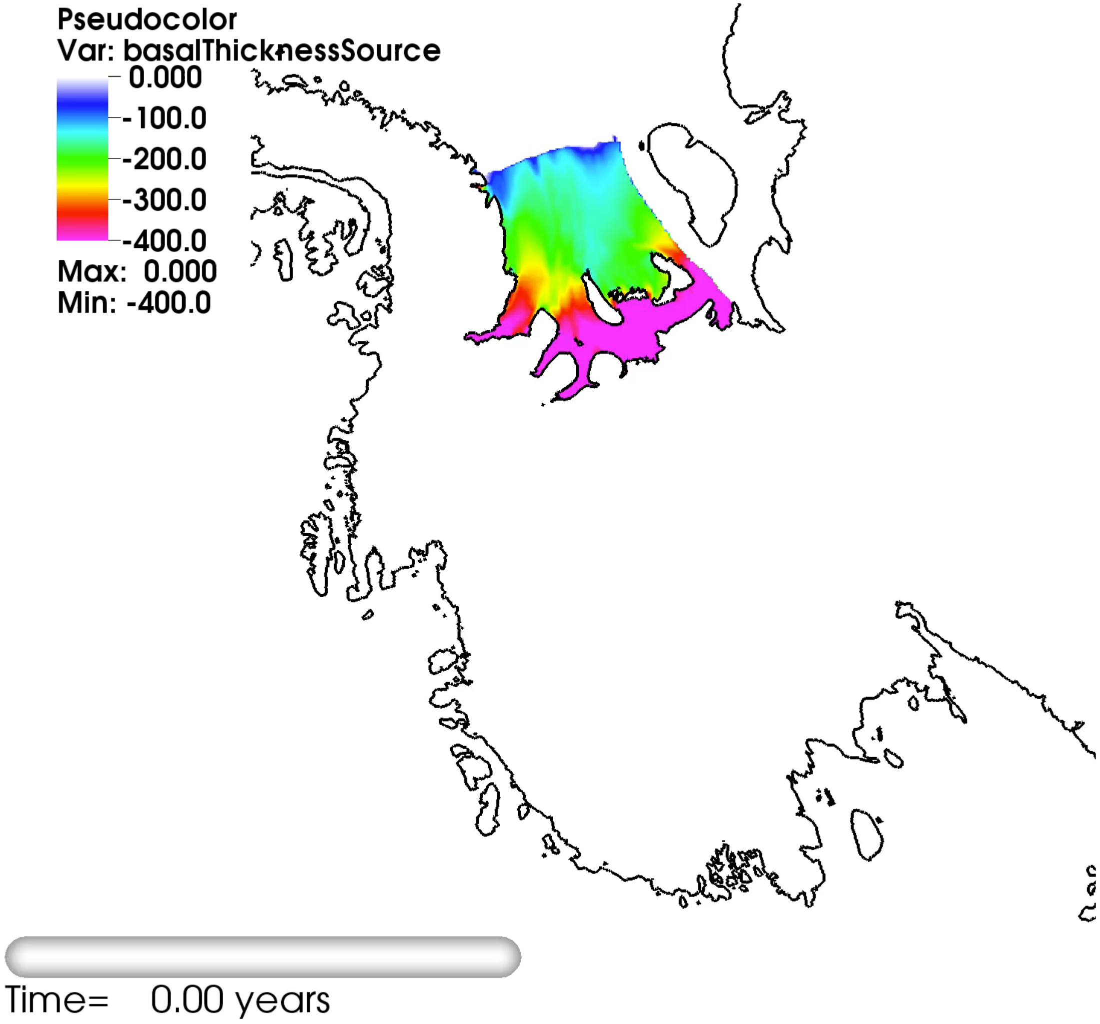




Sector 5 - interior melting

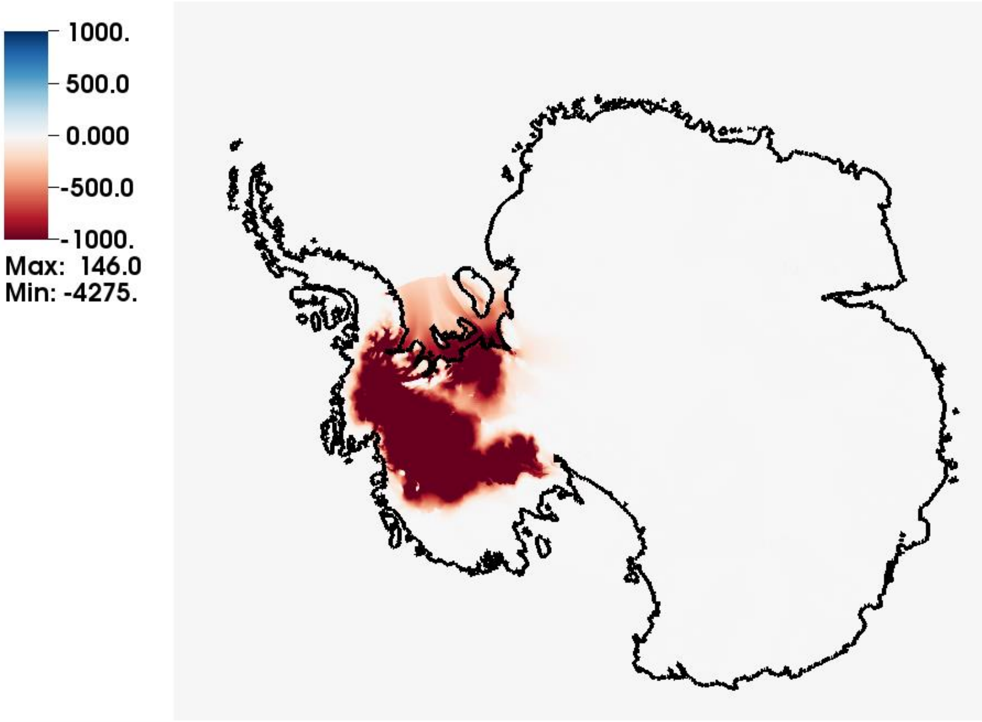


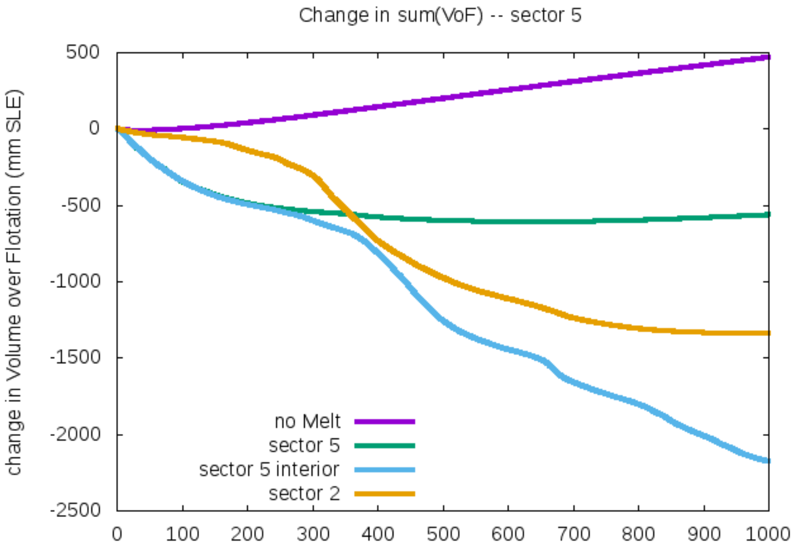
Sector 5, interior melting

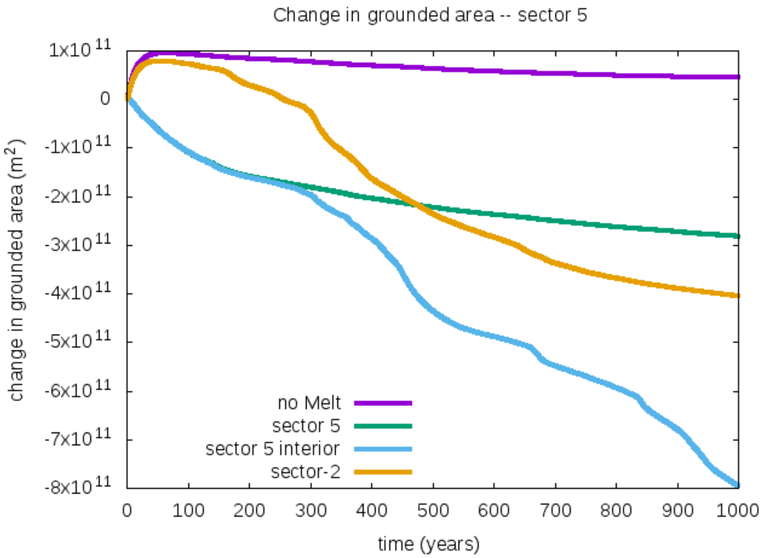


Sector 5 -- Interior melting..

- Allow melt to follow GL into interior

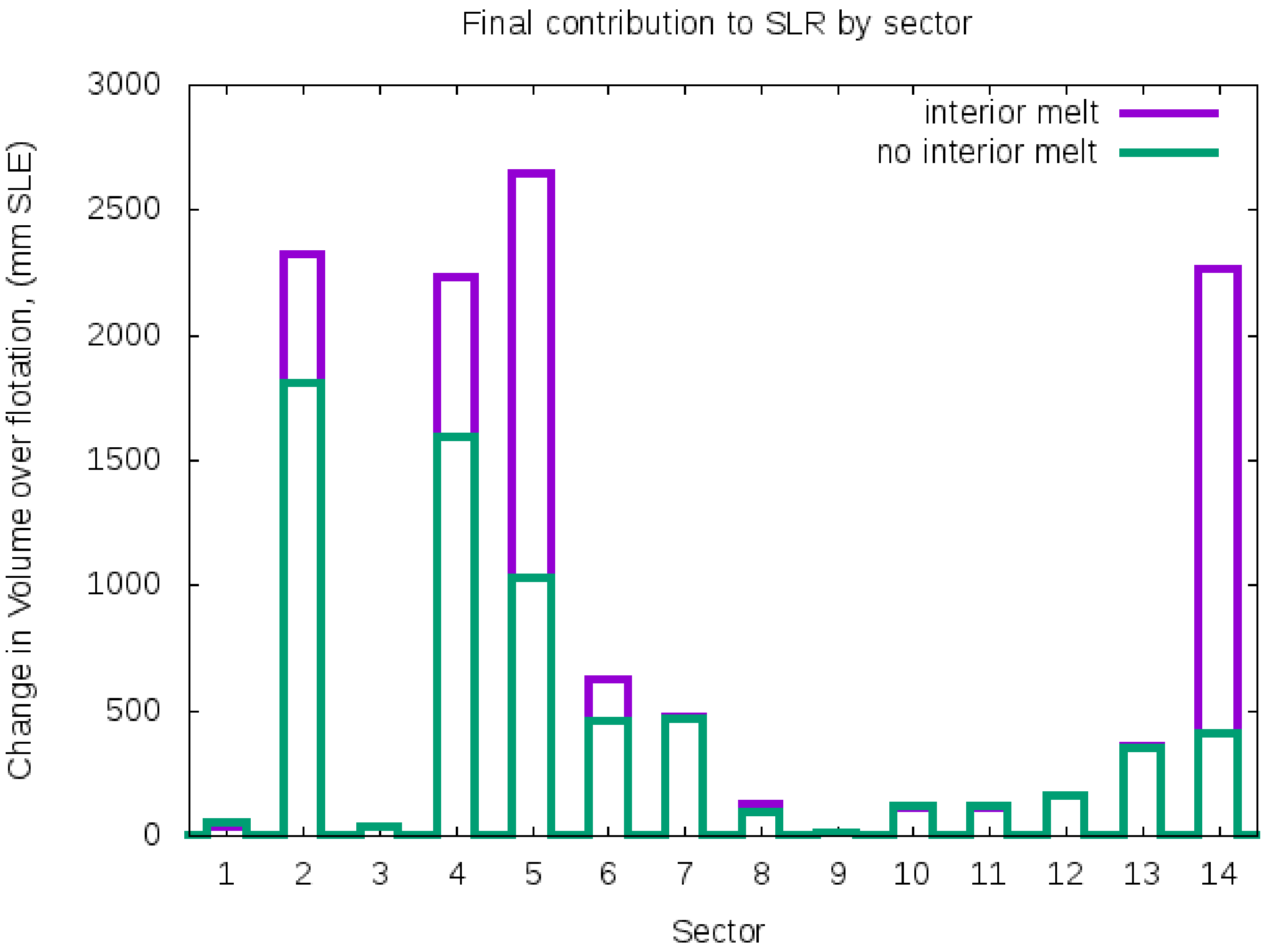


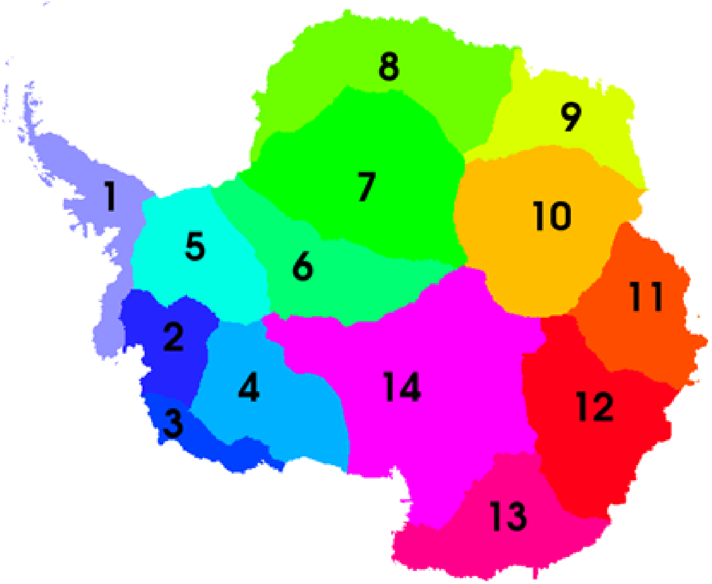




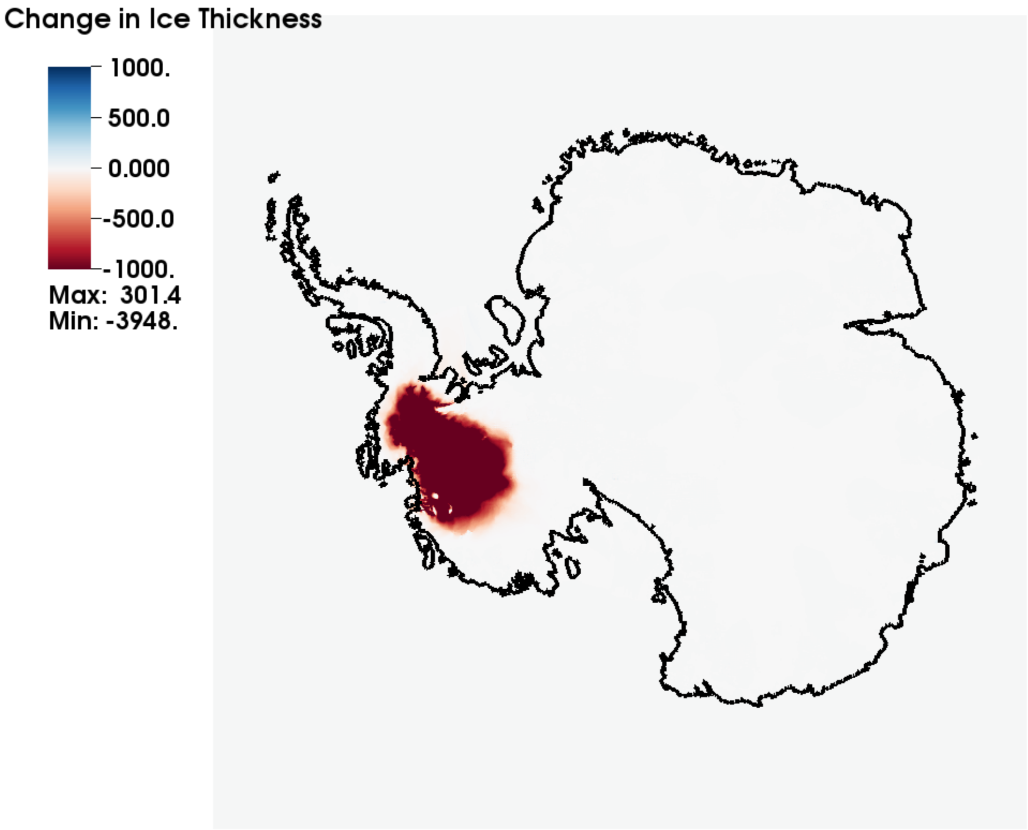
- Increase to 2.64 m SLE (from 1.03 m SLE)

Results - contribution to SLR

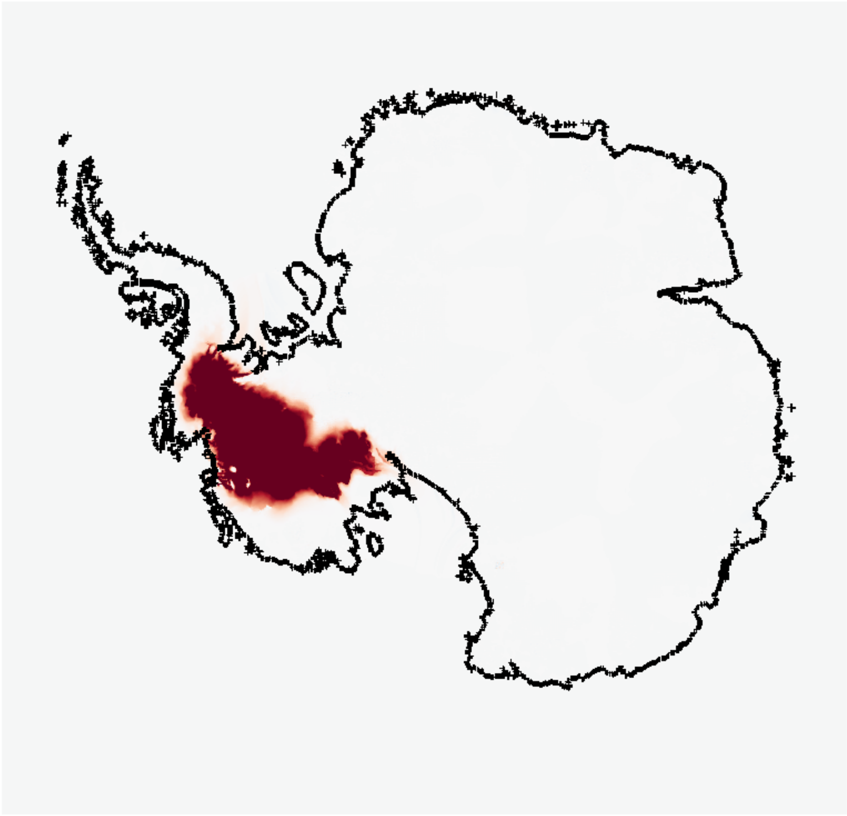




Sector 2 (ASE)

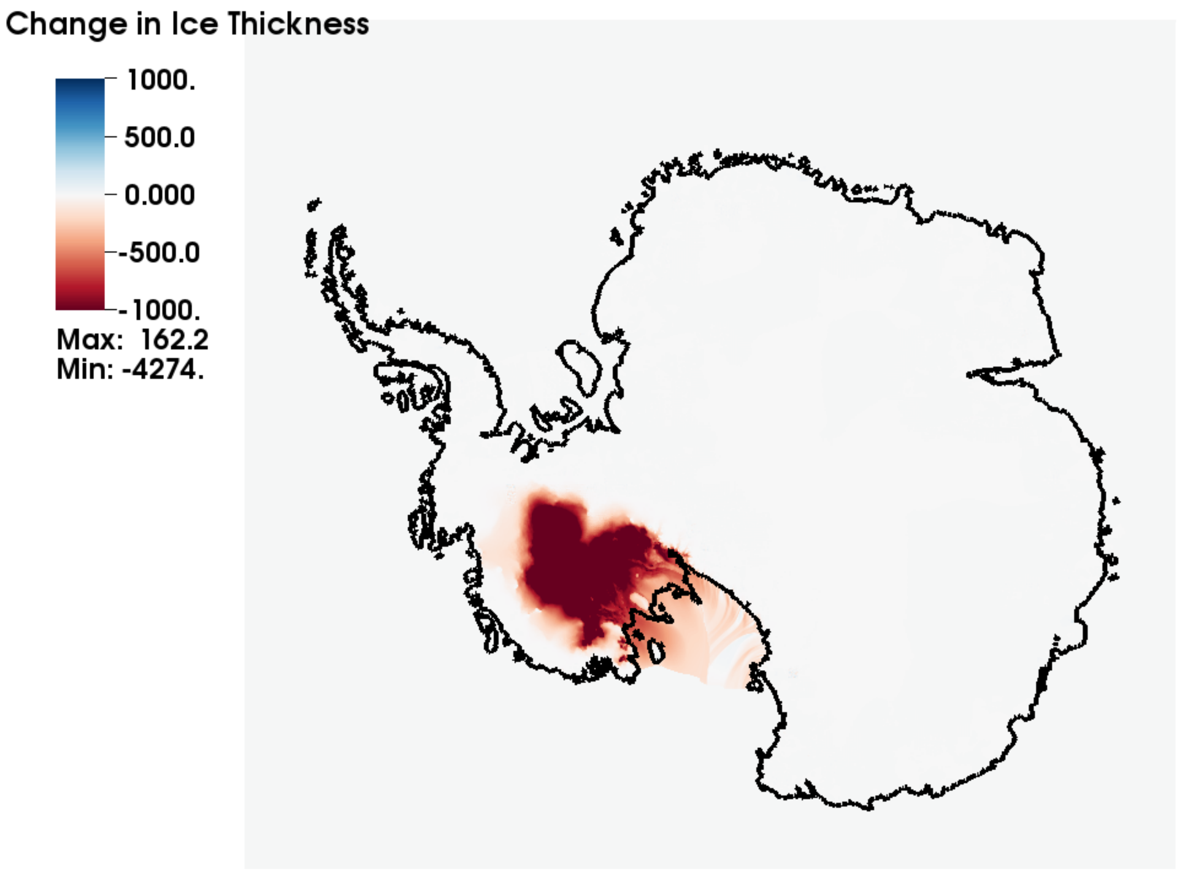


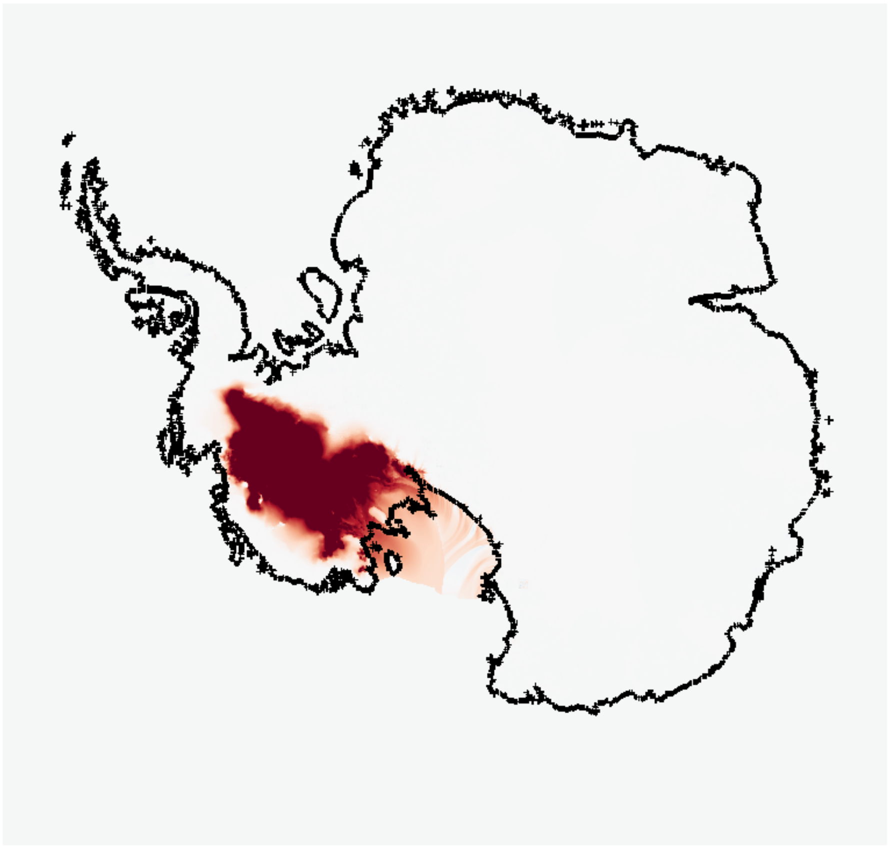
Sector 2 (ASE): 1.8m SLE



Sector 2-interior: 2.3m SLE

Sector 4

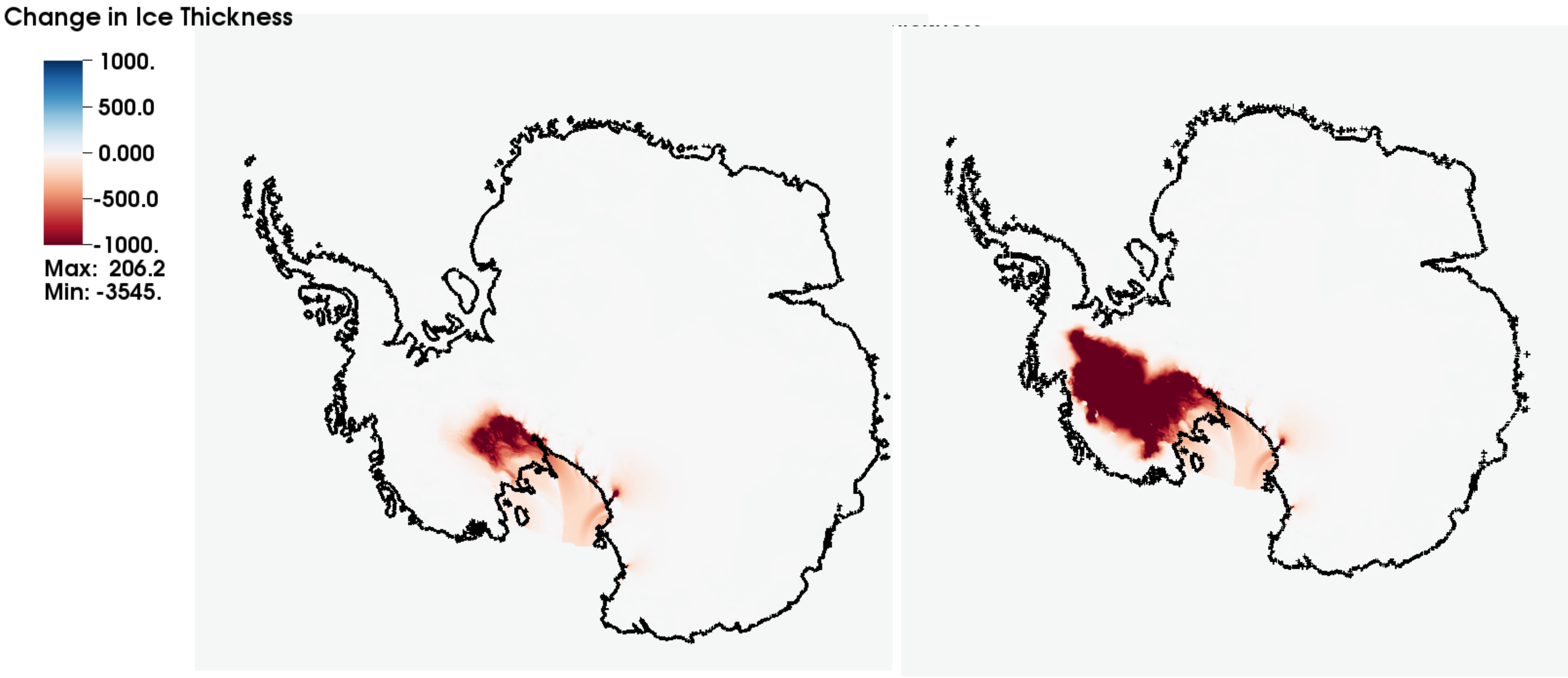




Sector 4 (Ross): 1.59m SLE

Sector 4-interior: 2.2m SLE

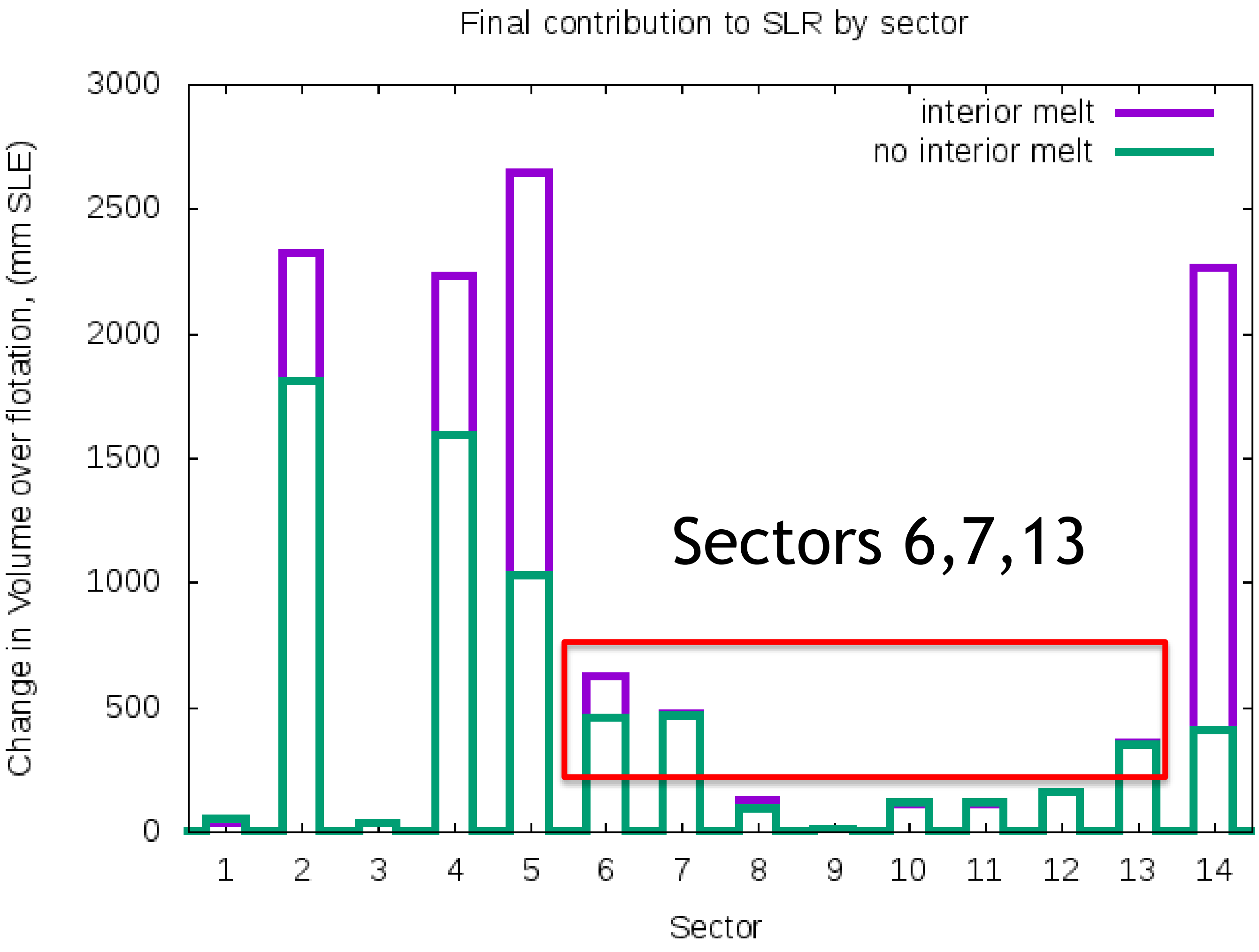
Sector 14

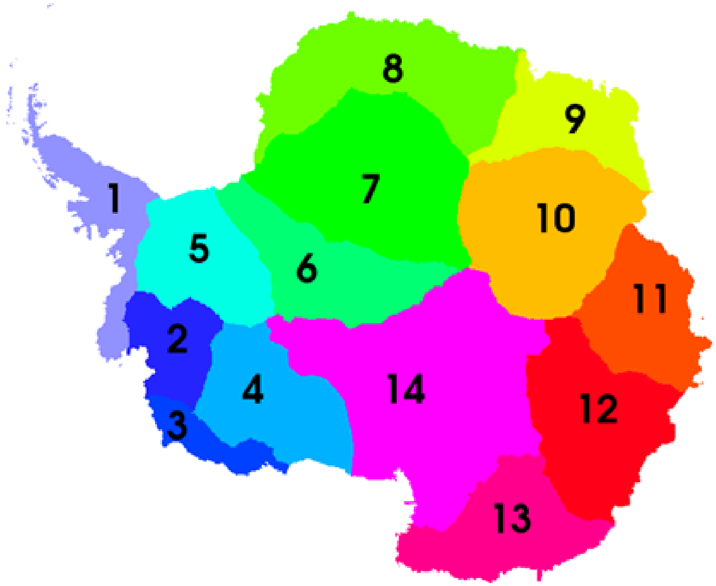


Sector 14: 0.404 m SLE

Sector 14-interior: 2.2 m SLE

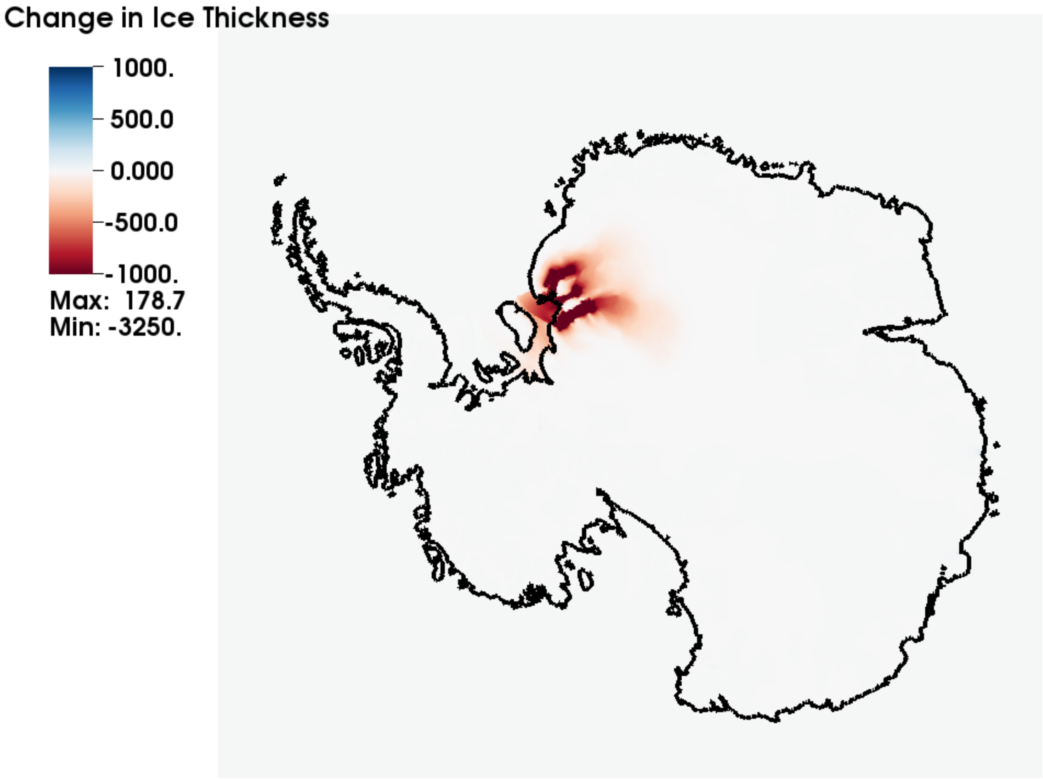
Intermediate Loss Sectors

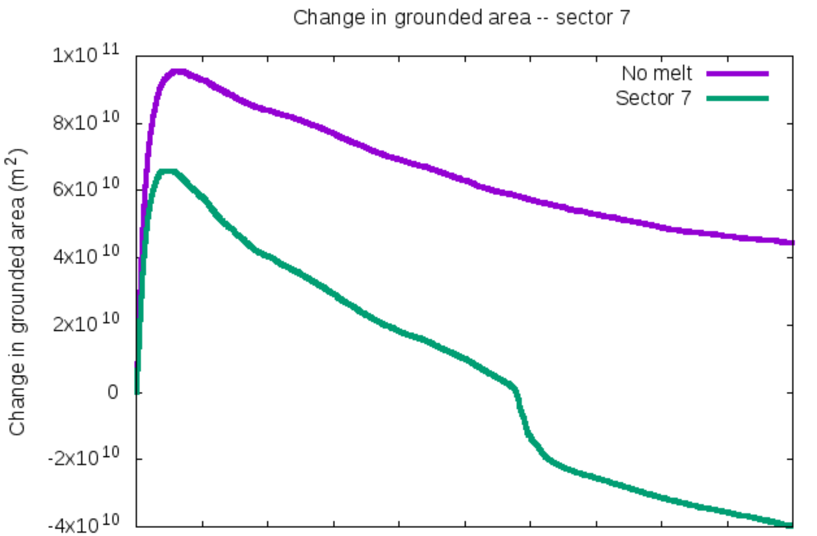


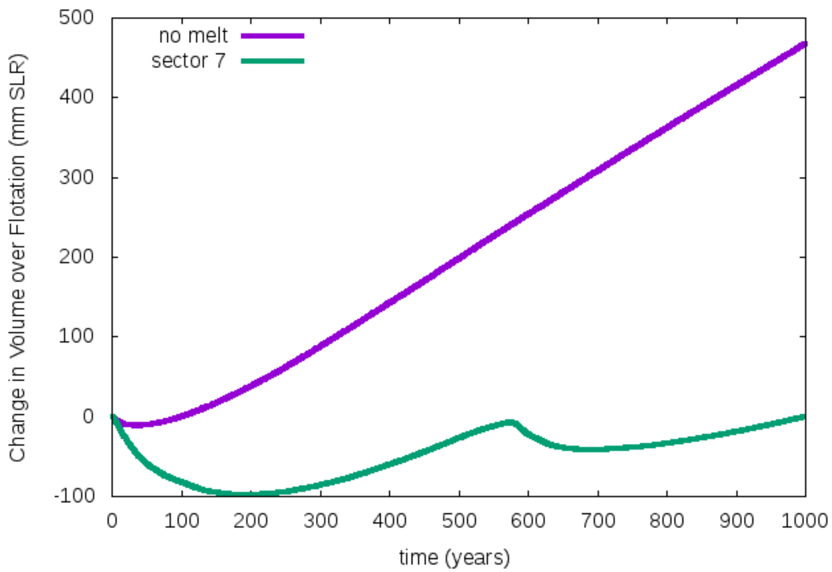


Intermediate loss sectors - Sector 7

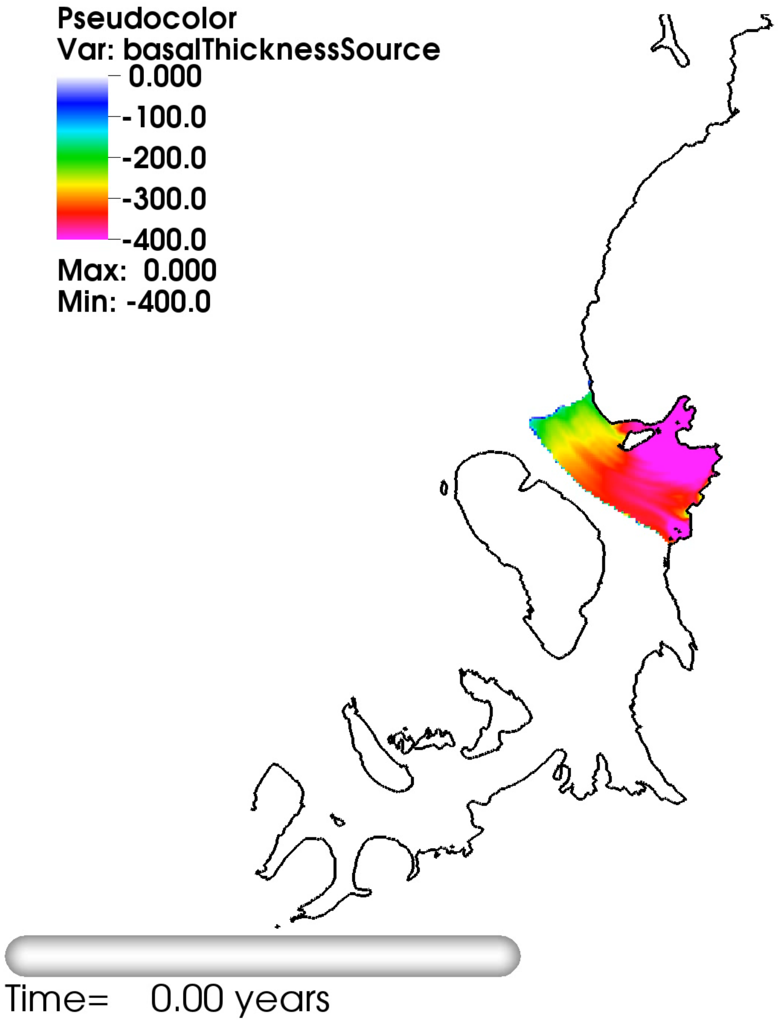
- Sector 7 (Recovery Ice Stream)
  - 0.467 m SLE
  - (no effect from extended melt)



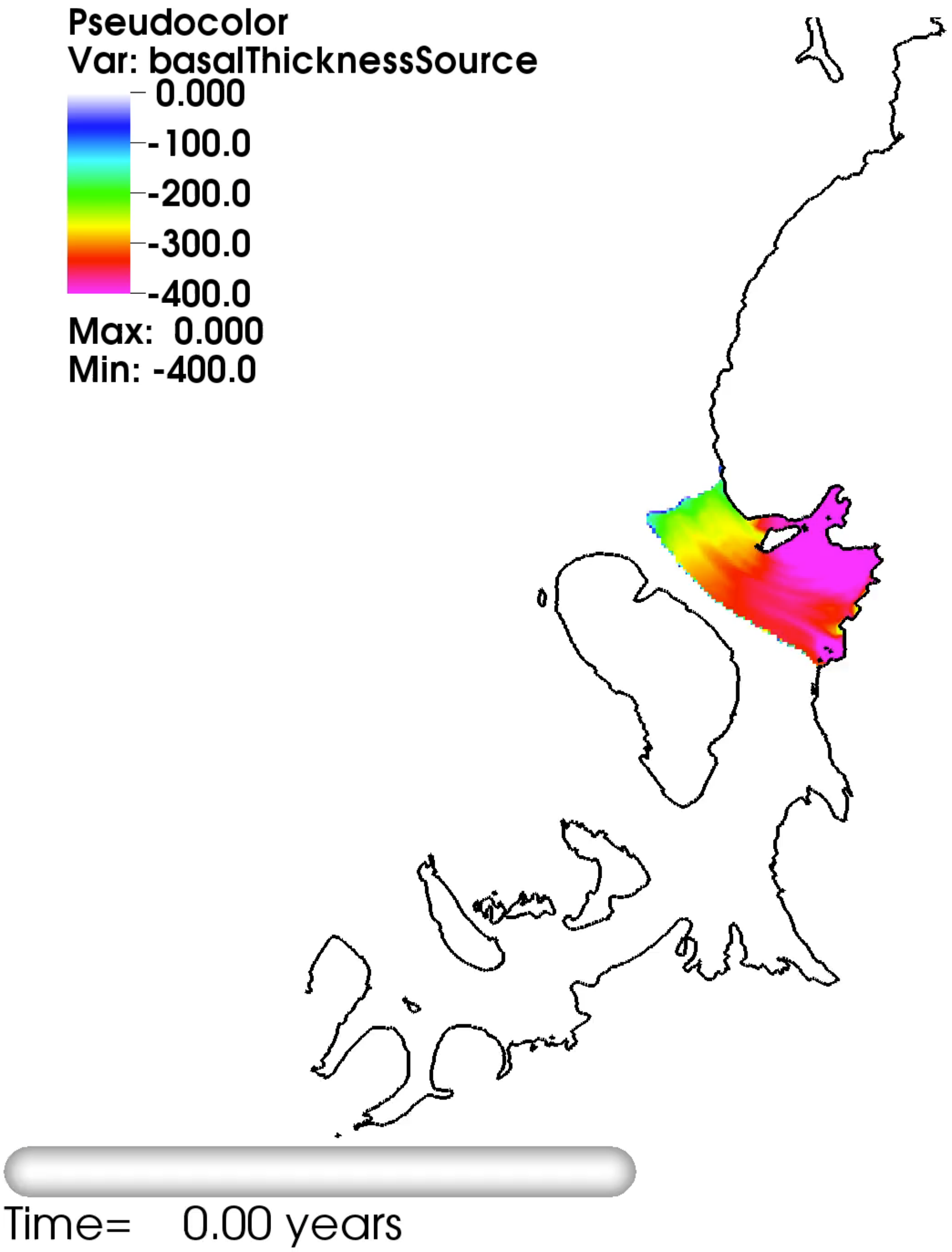




Sector 7, cont

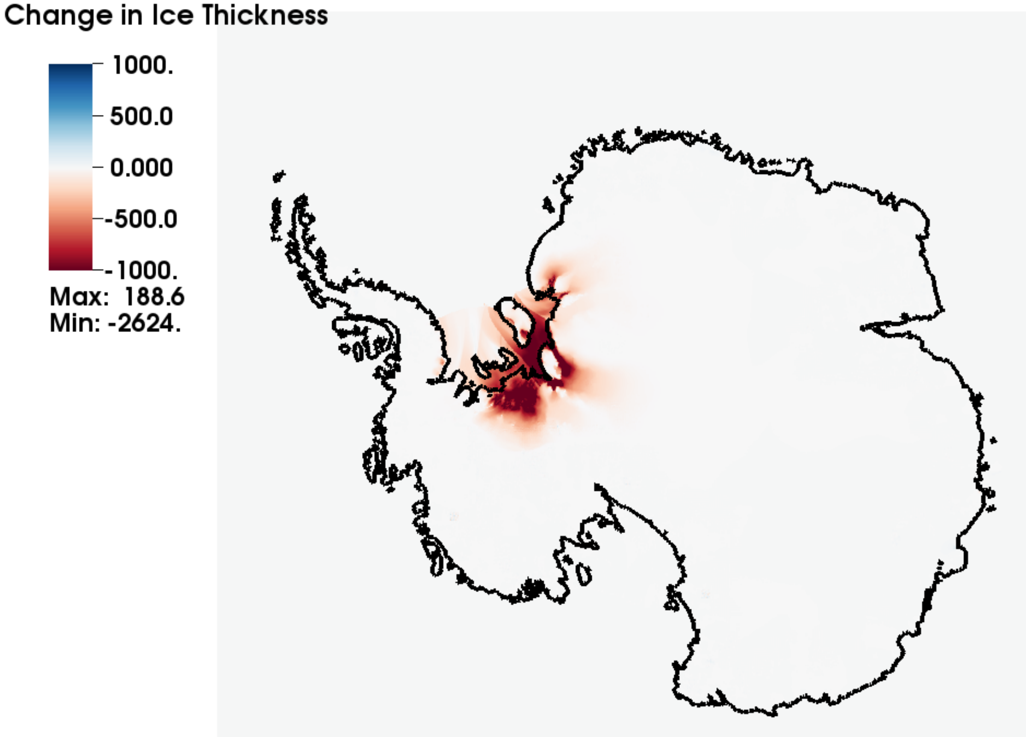


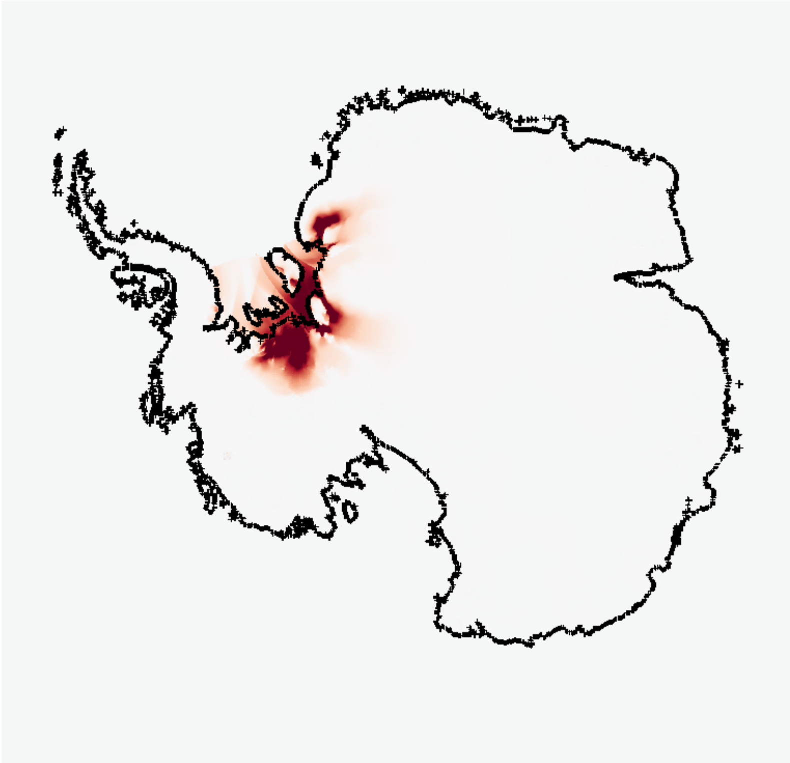
Sect



Pseudocolor
Var: basalThicknessSource
0.000
-100.0
-200.0
-300.0
-400.0
Max: 0.000
Min: -400.0
Time= 0.00 years

Sector 6

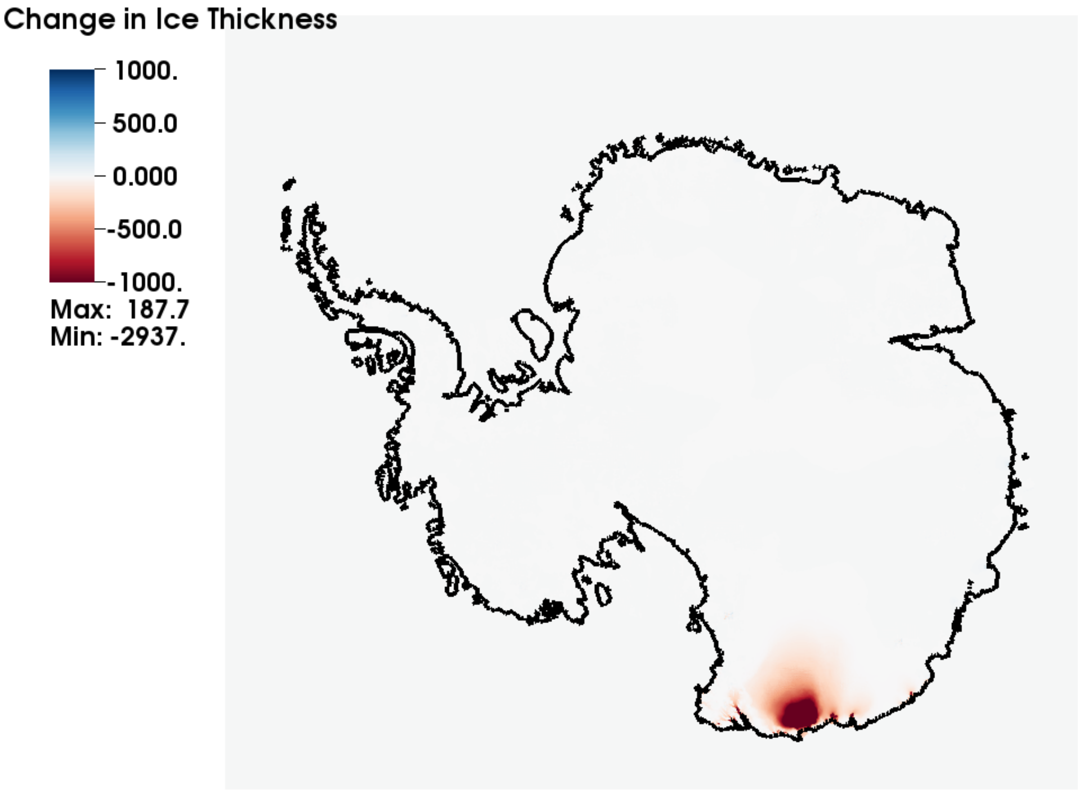




Sector 6: 0.457 m SLE

Sector 6-interior 0.617 m SLE

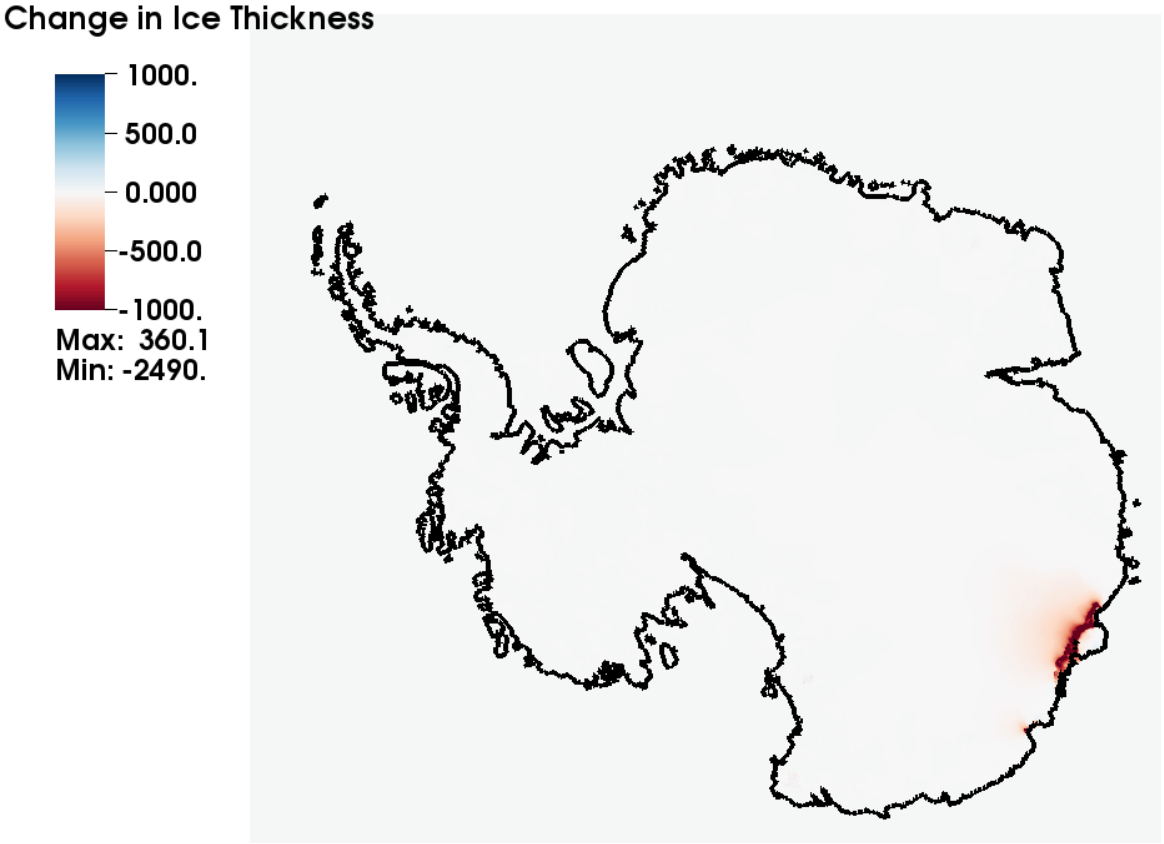
Sector 13



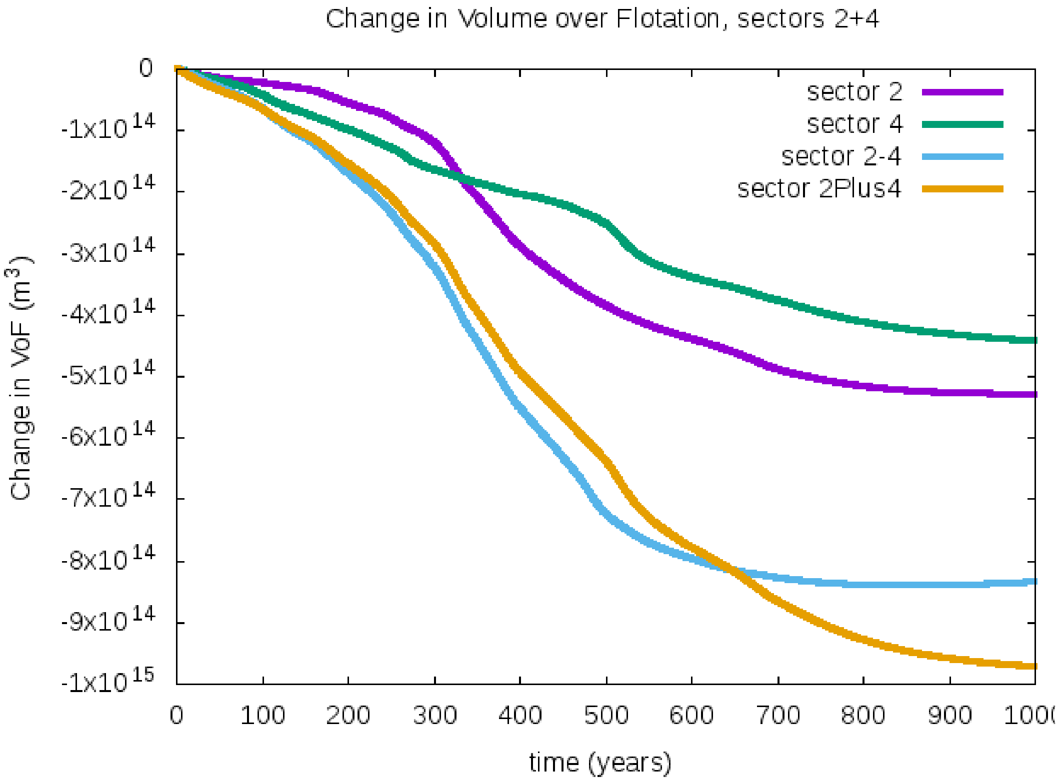
Sector 13: 0.345 m SLE

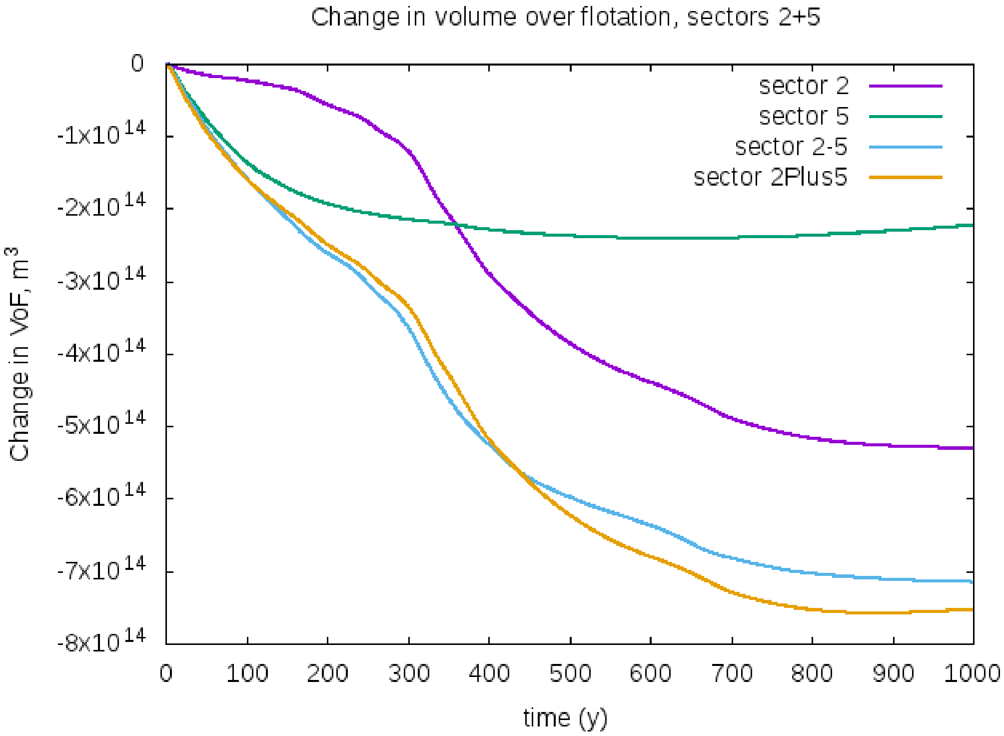
What about Totten?

- With Bedmap2 topography, limited vulnerability..
- Sector 12 – 0.156m SLE

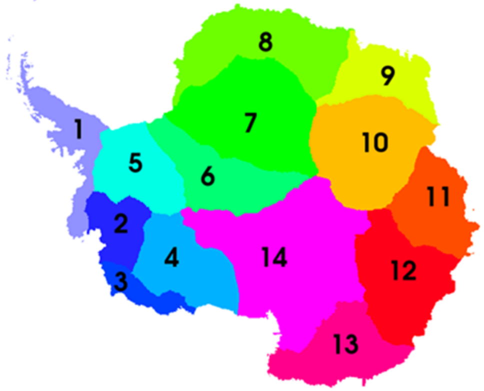


Combinations: 2 (ASE) &4 (Ross), 2&5 (Ronne))





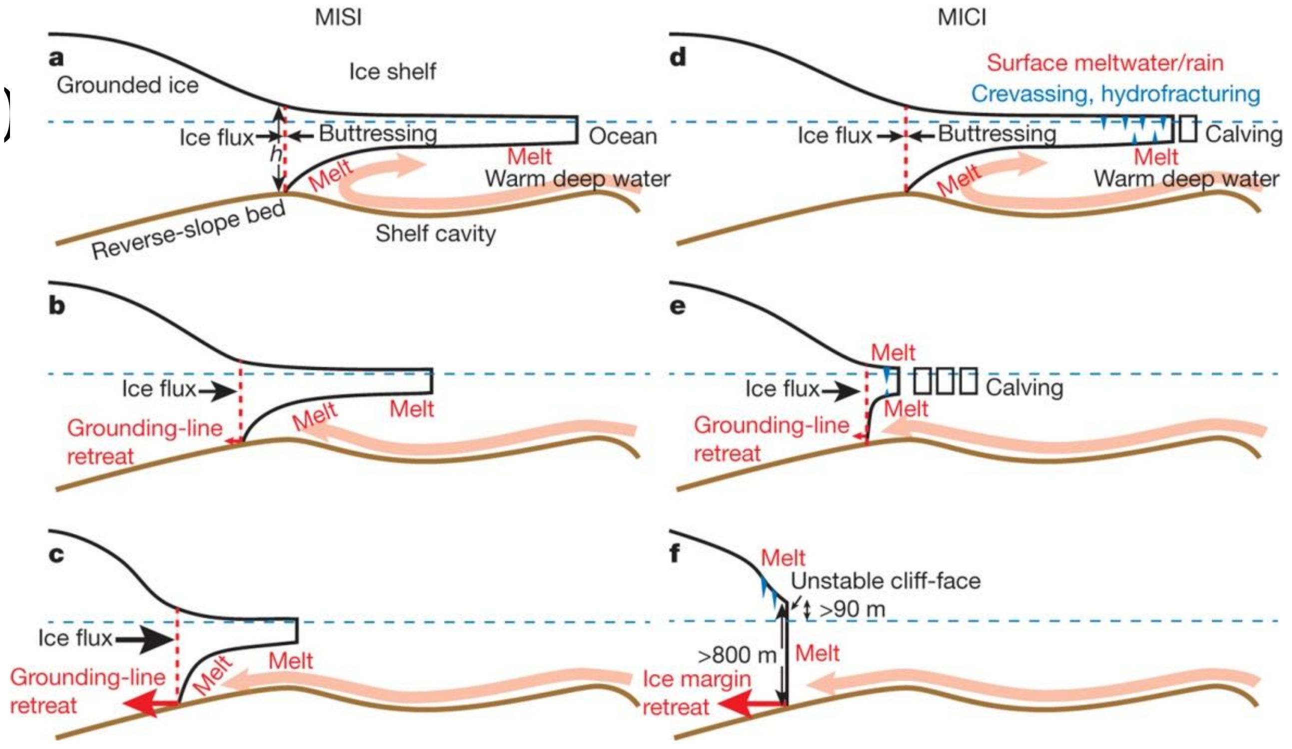
- Green, purple – single sectors
- Blue – combination of the two
- Yellow – sum of the two single-sector runs
- For WAIS sectors, roughly independent at start, after O(200a), start to interact



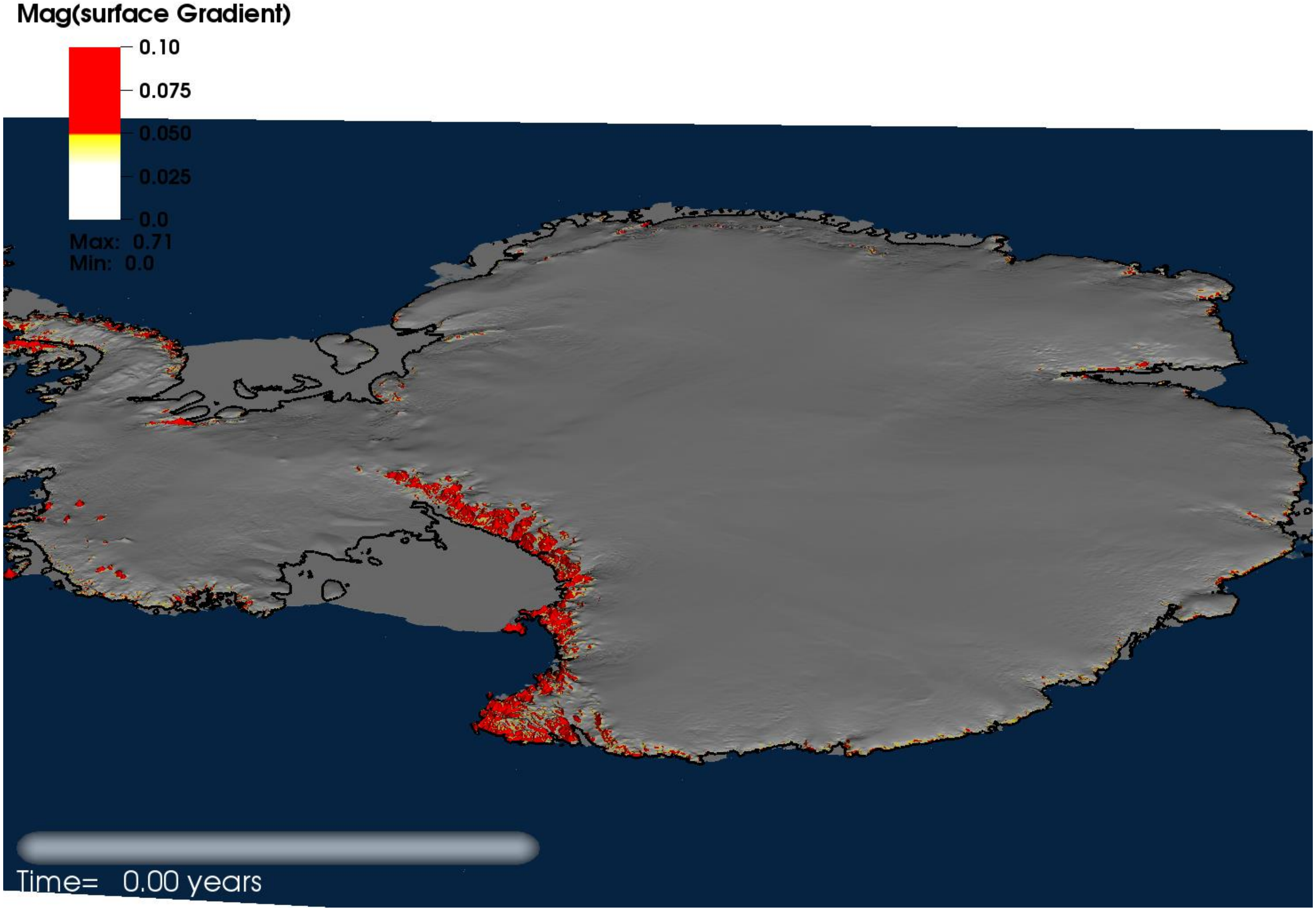
What about Cliff Collapse?

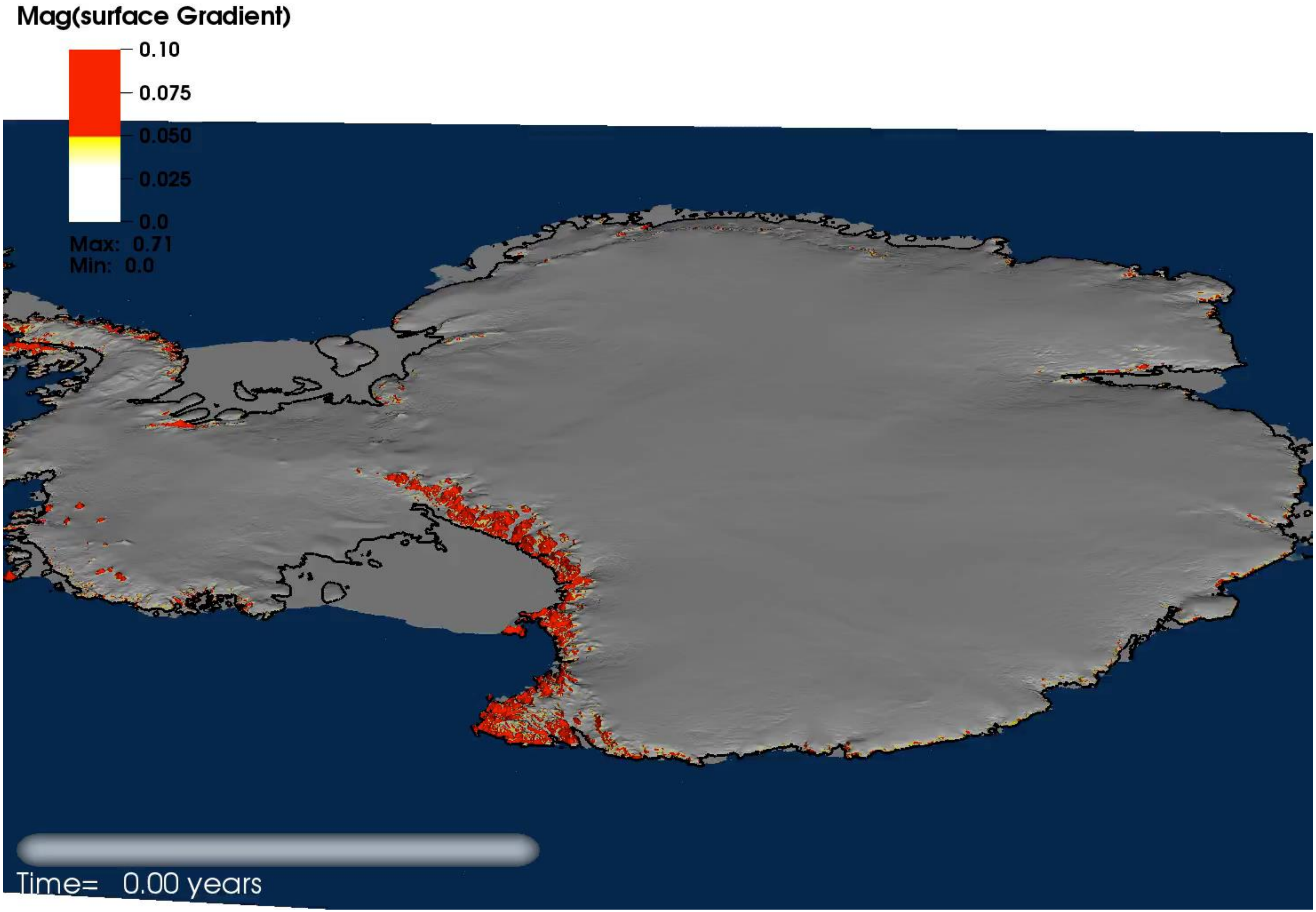
Background:

- Deconto and Pollard (2015) – wanted to be able to match paleorecord of large SLR
- Surmised mechanism:
  - hydrofacture (eliminate ice shelves)
  - Cliff collapse (drive retreat into EAS basins)
  - Allows for much greater SLR



What about Cliff Collapse? (cont)




Mag(surface Gradient)
0.10
0.075
0.050
0.025
0.0
Max: 0.71
Min: 0.0
Time= 0.00 years

Our results…

- Can look at local slopes to see if we get "cliffs"
  - Yes, but sporadic and ephemeral

- Best guess is 2 factors in play
  - BISICLES is able to resolve the ice front/margin
    - Spatially & temporally
  - See large drawdowns of ice thickness in interior

- Provisional conclusion – cliff-collapse not the answer here?

- (next step – implement a cliff-collapse model in BISICLES and test)

Conclusions (and caveats)

- Primary vulnerability still WAIS.
- Limited potential from EAS
- WAIS vulnerable from any of three sectors
  - (2 of which are large cold ice shelves)

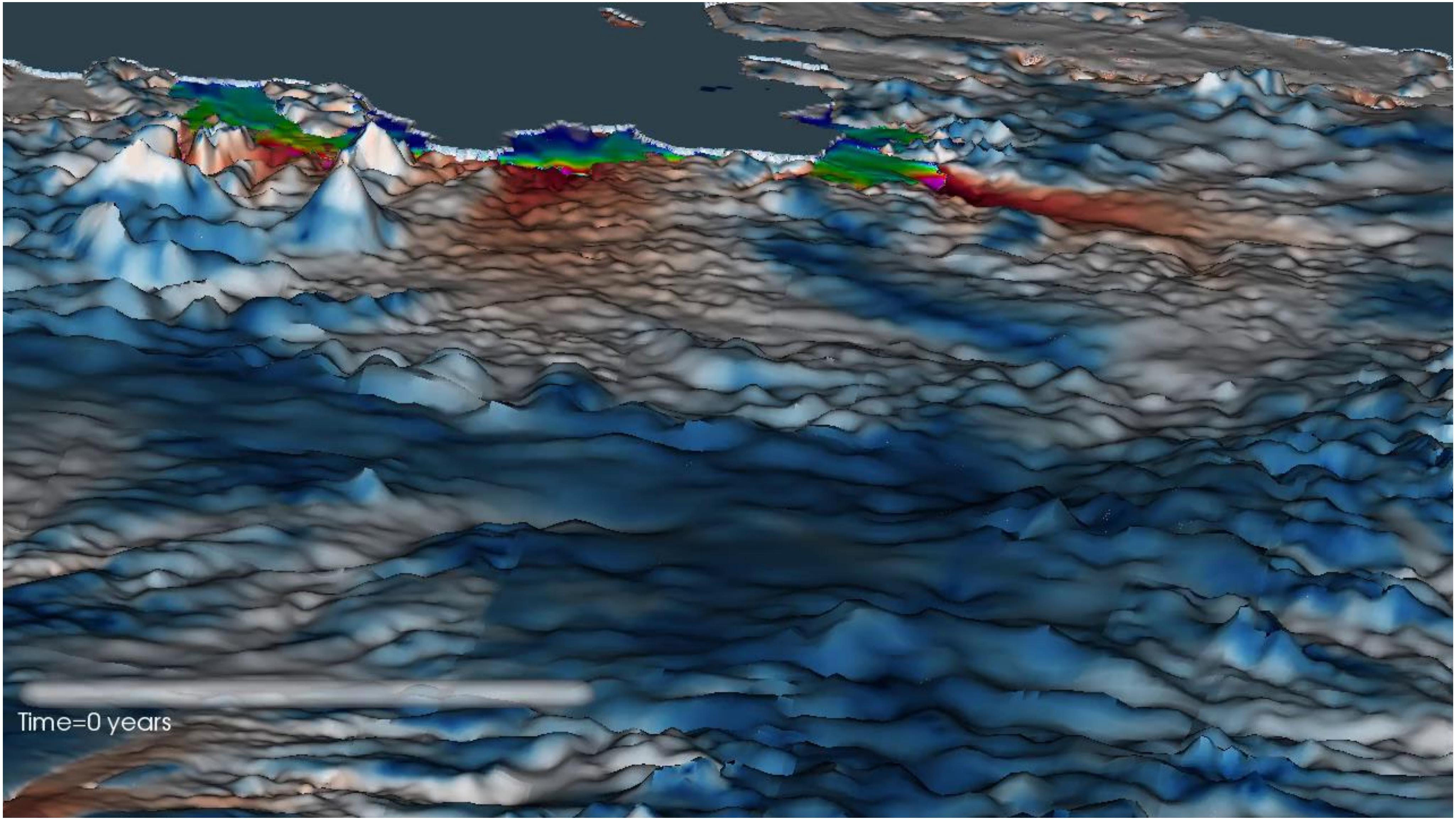
- Intermediate vulnerability in Filchner, Western Ross

- Assumption of basin independence OK for a few hundred years
- Cliff collapse doesn't appear to be a factor – no cliffs!
  - Diffusive thinning upstream
  - High spatial and temporal resolution

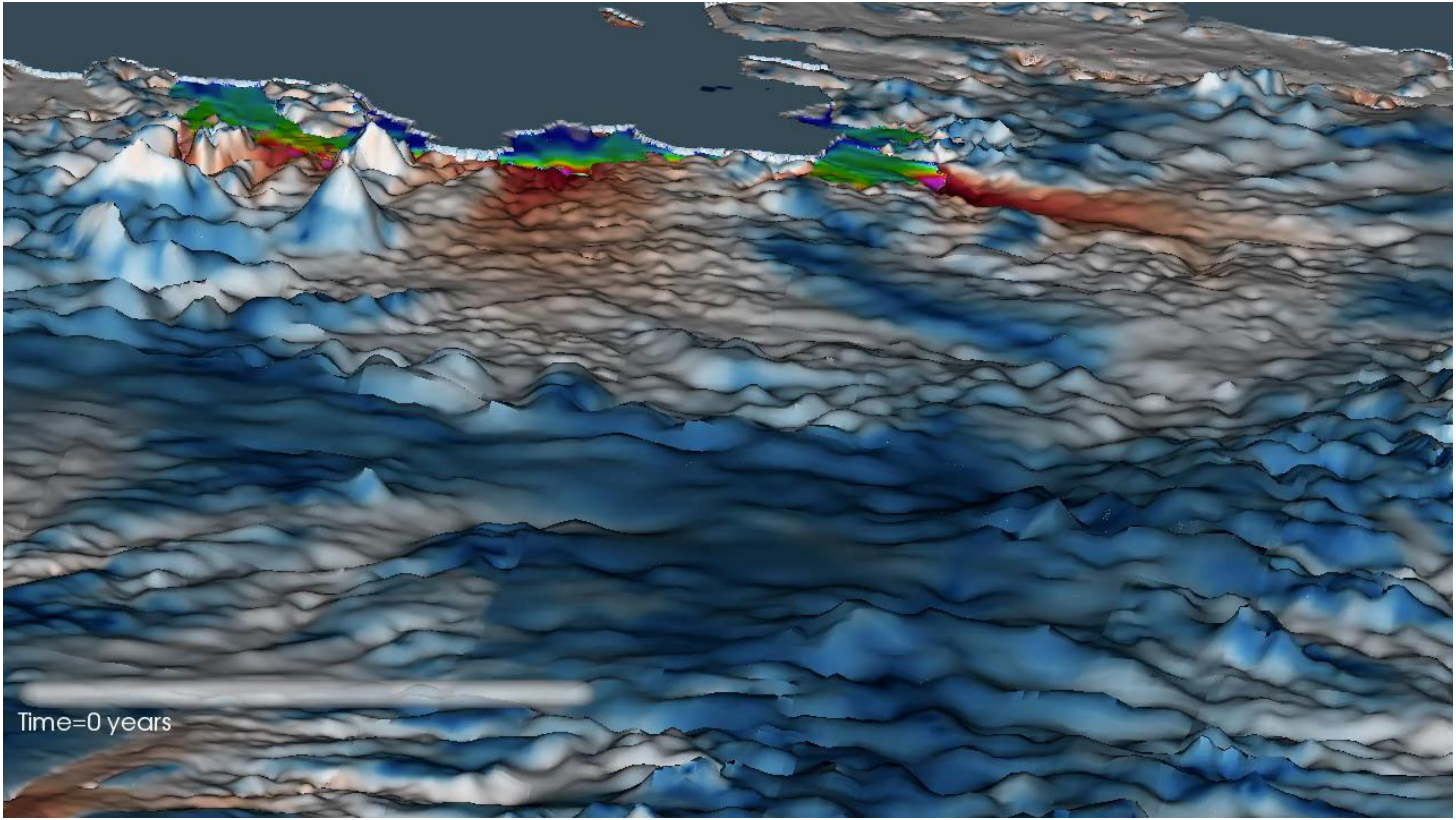
- Everything dependent on Bedmap2 geometries…

Thank you!

Sector 2 (cont)

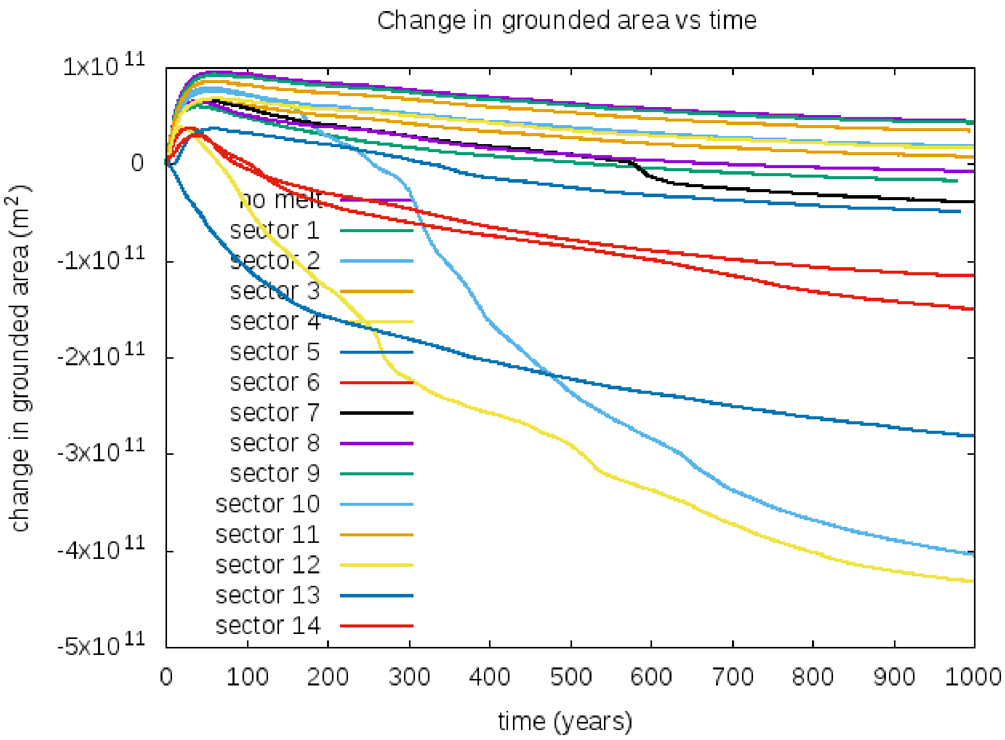


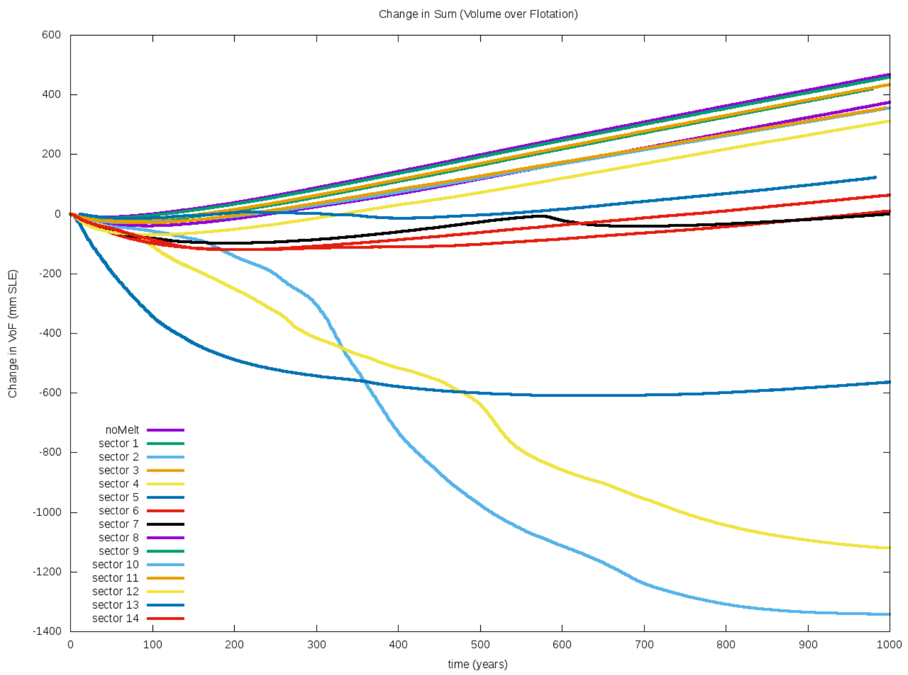
Sector 2 (cont)



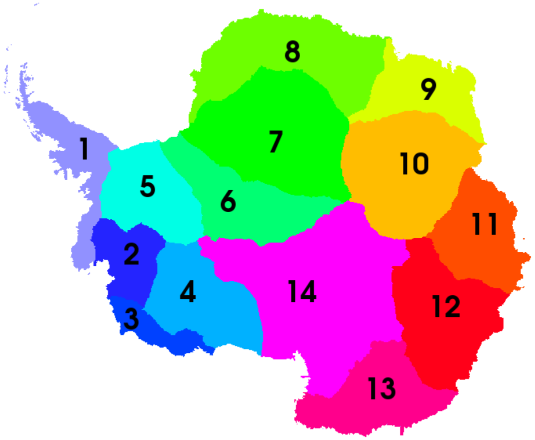
Extras

Results -- summary

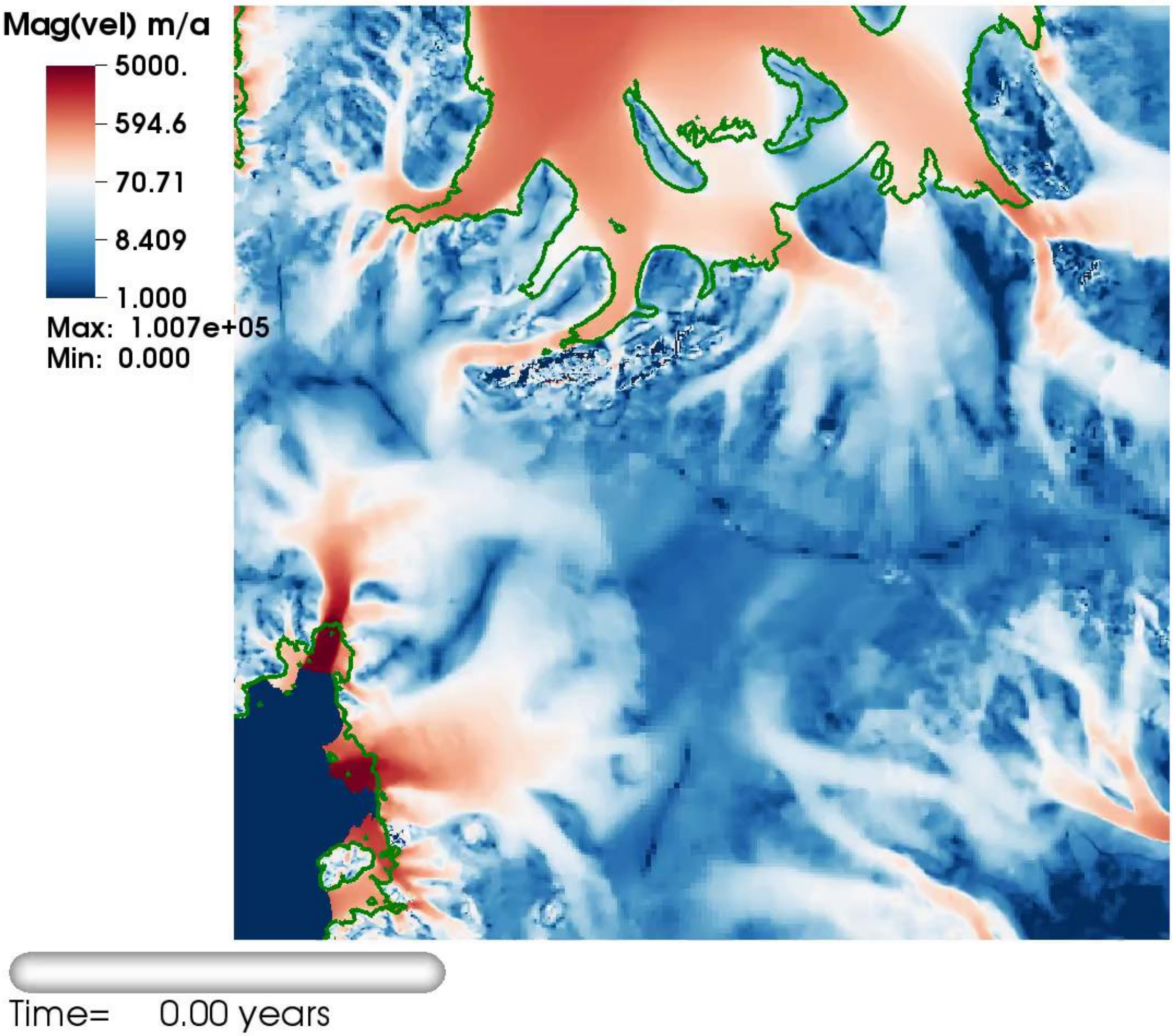




- WAIS-connected sectors (2,4,5) – largest response
- Intermediate response from 6,7,13,14
- Sector 11 – issues with Bedmap2

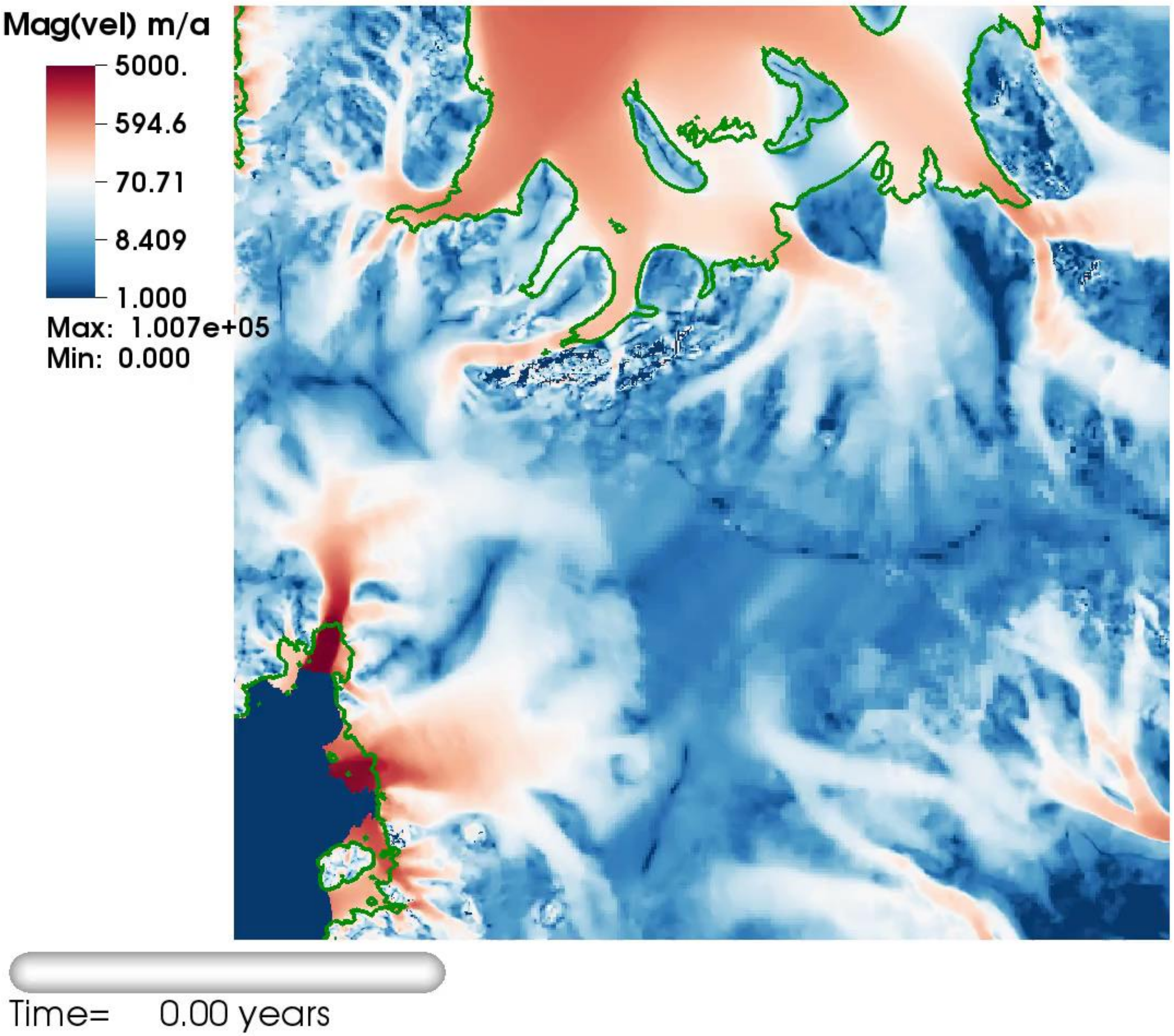


WAIS – 1km Resolution with GLI

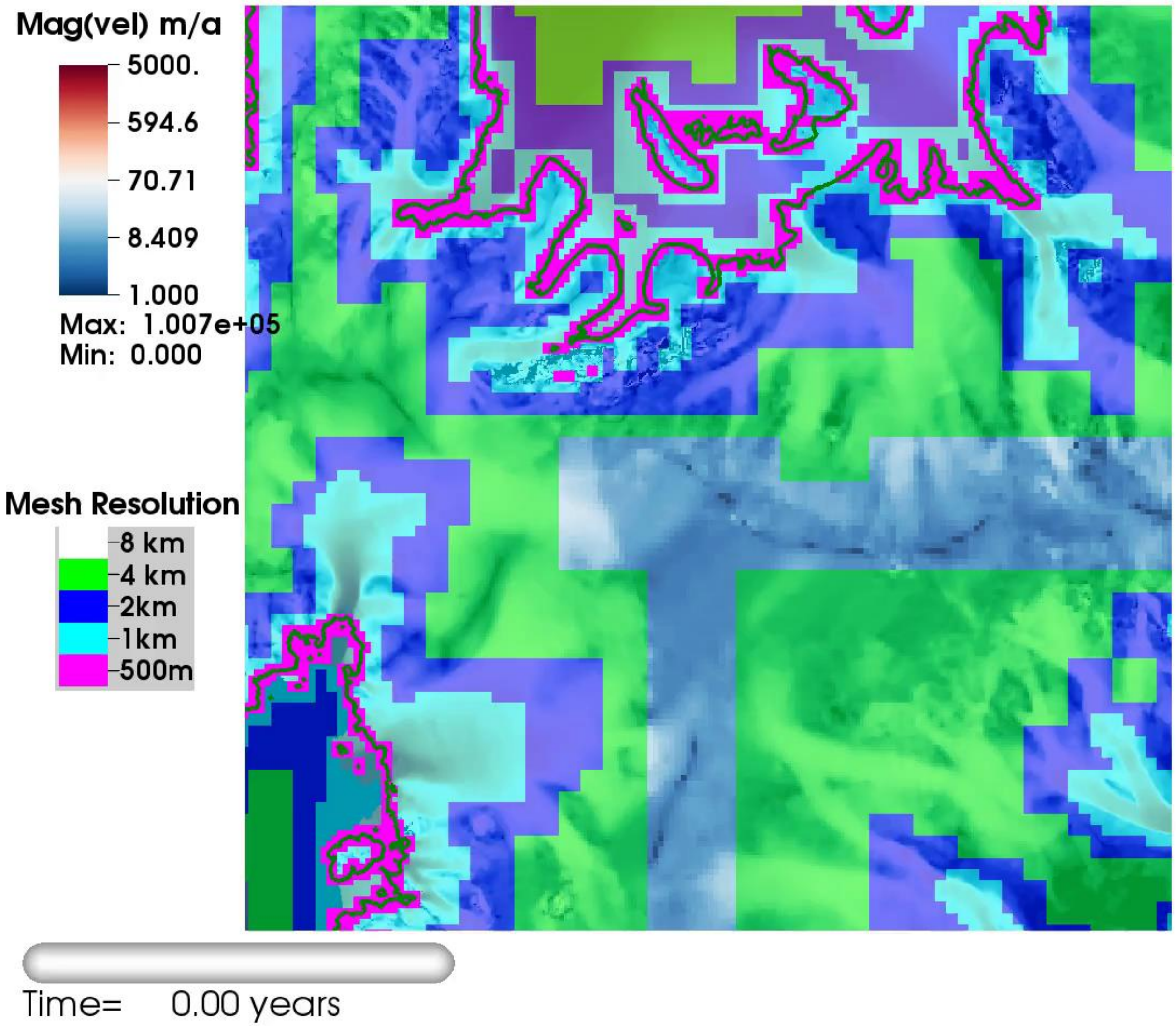


U.S. DEPARTMENT OF ENERGY | Office of Science | BISICLES | Berkeley Lab | PIK | Los Alamos National Laboratory EST. 1943 | University of Bristol

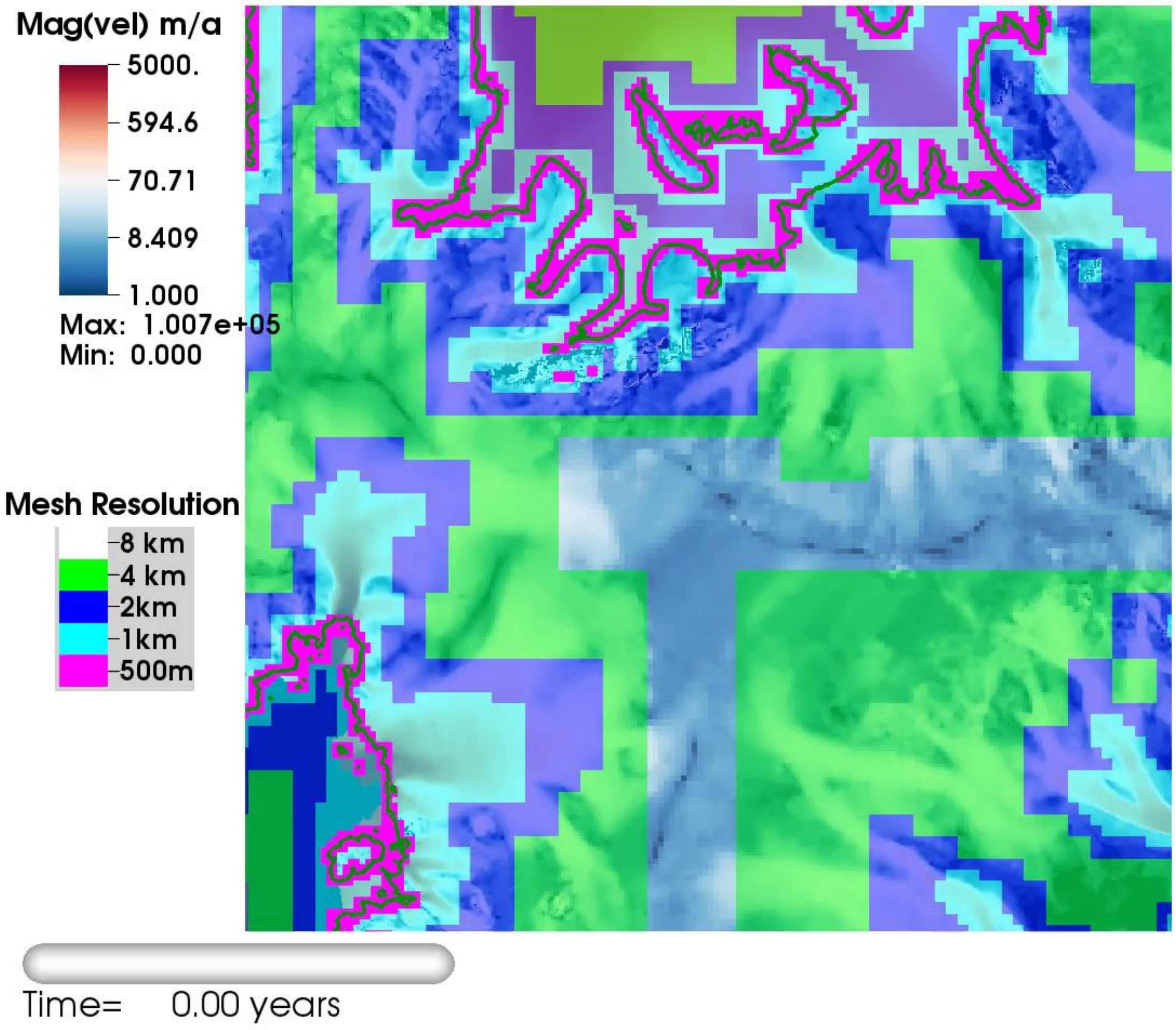
WAIS – 1km Resolution with GLI



Mesh evolution (500m mesh)



Mesh evolution (500m finest mesh)



Experiment – 1000-year Antarctic simulations

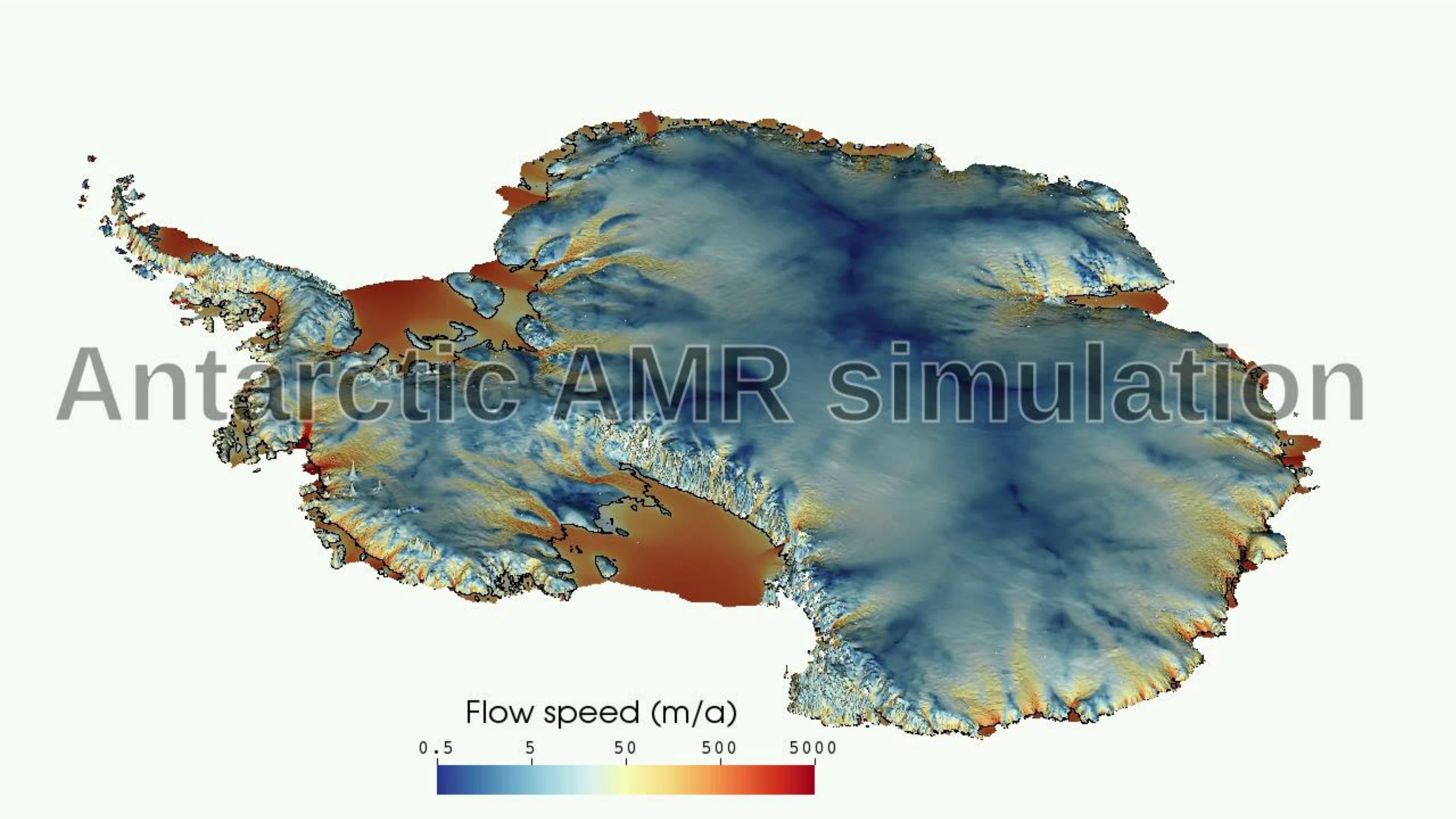
- Range of finest resolution from 8 km (no refinement) to 500m (4 levels of factor-2 refinement)

- 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 $h < 100$m
  - Range up to 800m/a where $h > 400$m.
  - **No melt applied in partially-grounded cells**

- For each resolution, evolve for 1000 years

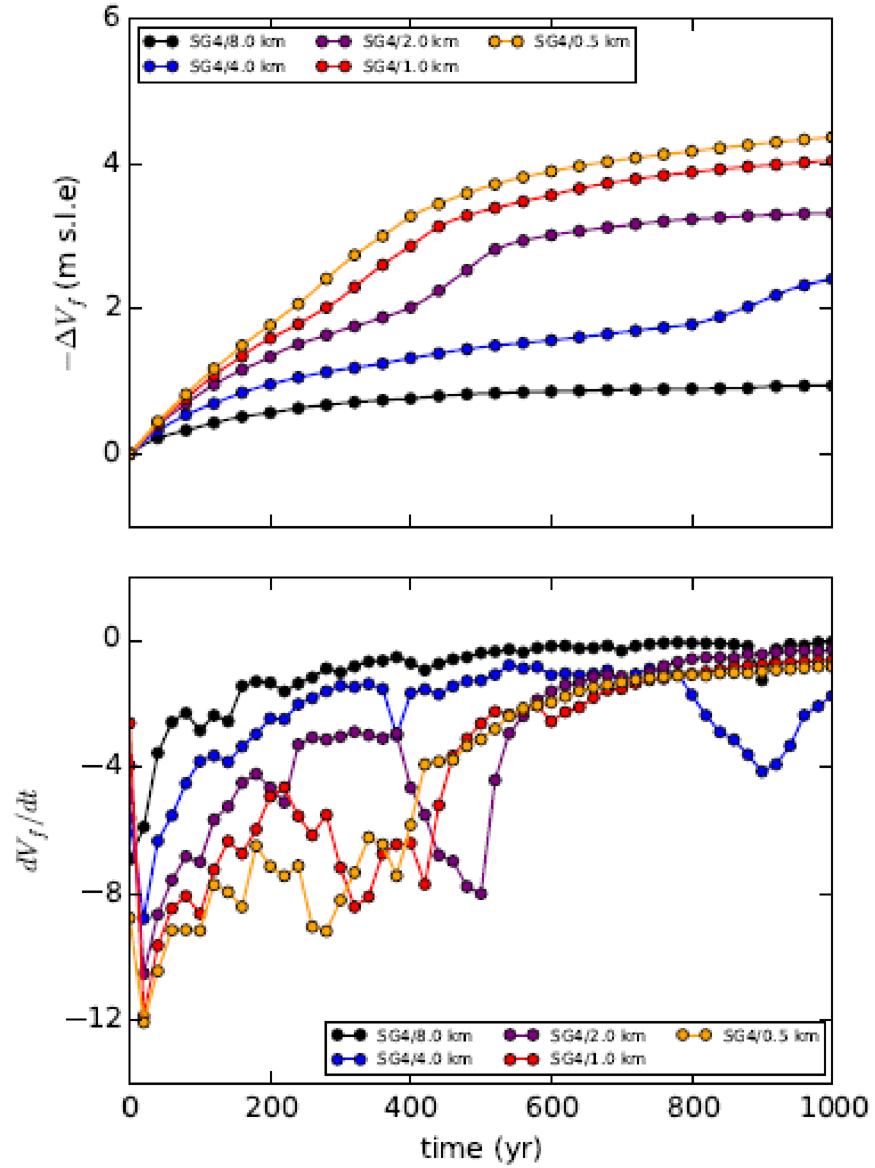
Results:



Results, cont.

- **Upper plot** – Change in VoF
  - Convergent at sufficient resolution

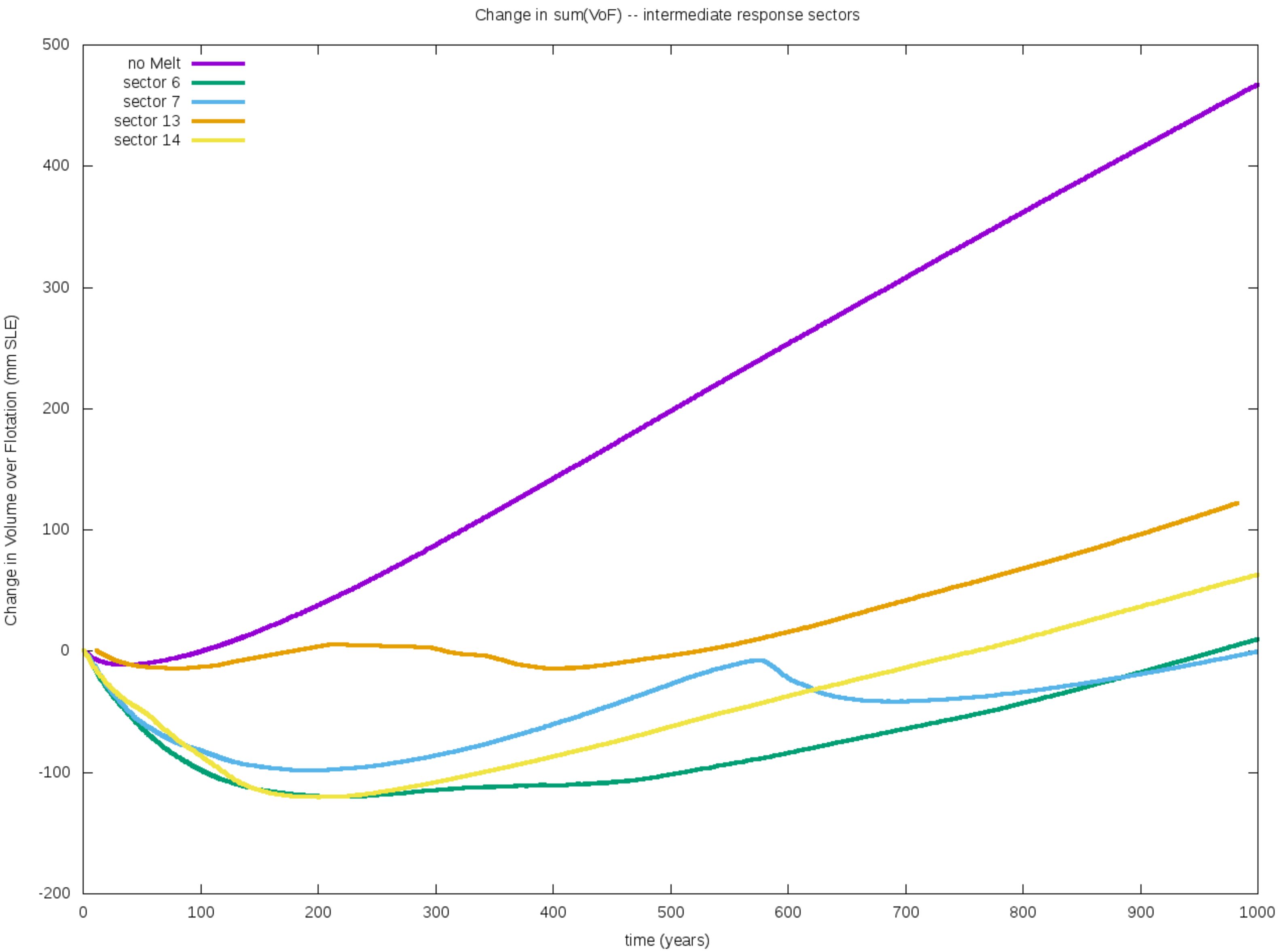
- **Lower plot** -- Rate of Change
  - Big spike – WAIS collapse
  - Timing is a function of resolution



Questions we'd like to answer:

- **Assess vulnerabilities:**
  - Where is the Antarctic Ice Sheet vulnerable to instability driven by warm-water incursion into subshelf cavities?
- **Assumption of basin independence**

Intermediate loss sectors



Thwaites-Rutford - effect of resolution