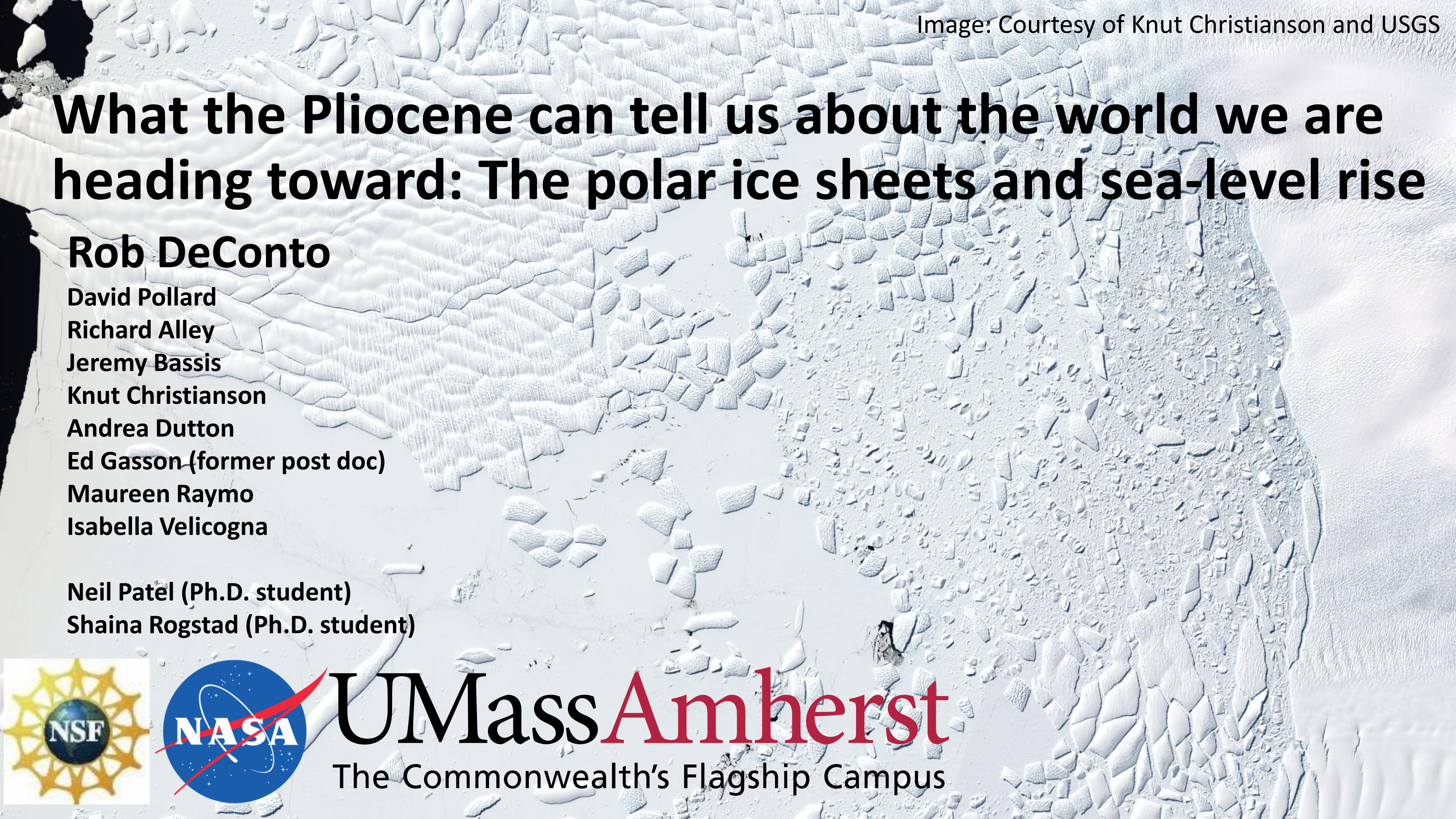


Image: Courtesy of Knut Christianson and USGS

What the Pliocene can tell us about the world we are heading toward: The polar ice sheets and sea-level rise

Rob DeConto

David Pollard
Richard Alley
Jeremy Bassis
Knut Christianson
Andrea Dutton
Ed Gasson (former post doc)
Maureen Raymo
Isabella Velicogna

Neil Patel (Ph.D. student)
Shaina Rogstad (Ph.D. student)

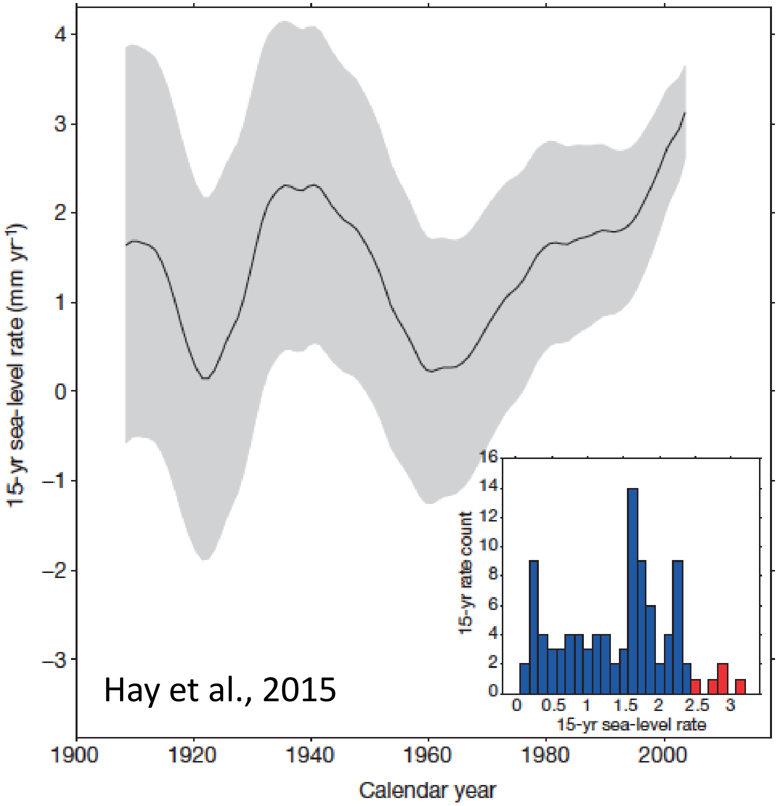
UMass Amherst
The Commonwealth's Flagship Campus

March 2nd, 2018
Scituate Massachusetts

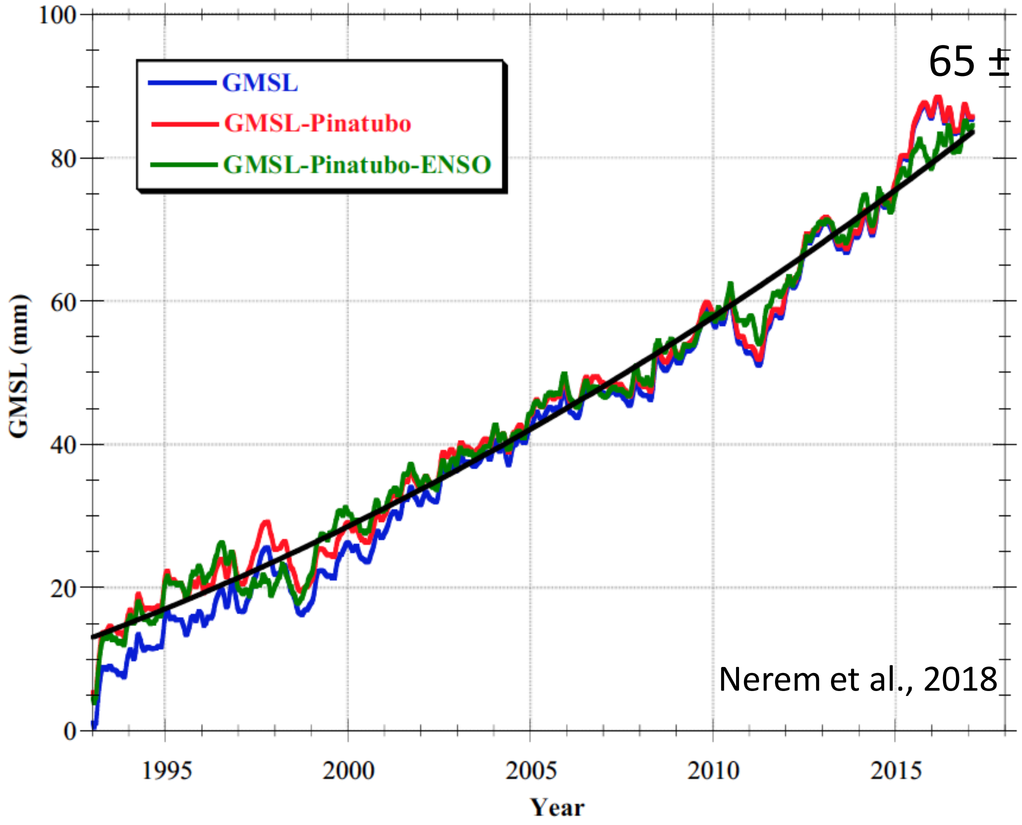
photo: cnn.com

Historical and recent perspectives on global mean sea-level rise

GMSL has risen ~18 cm since 1900

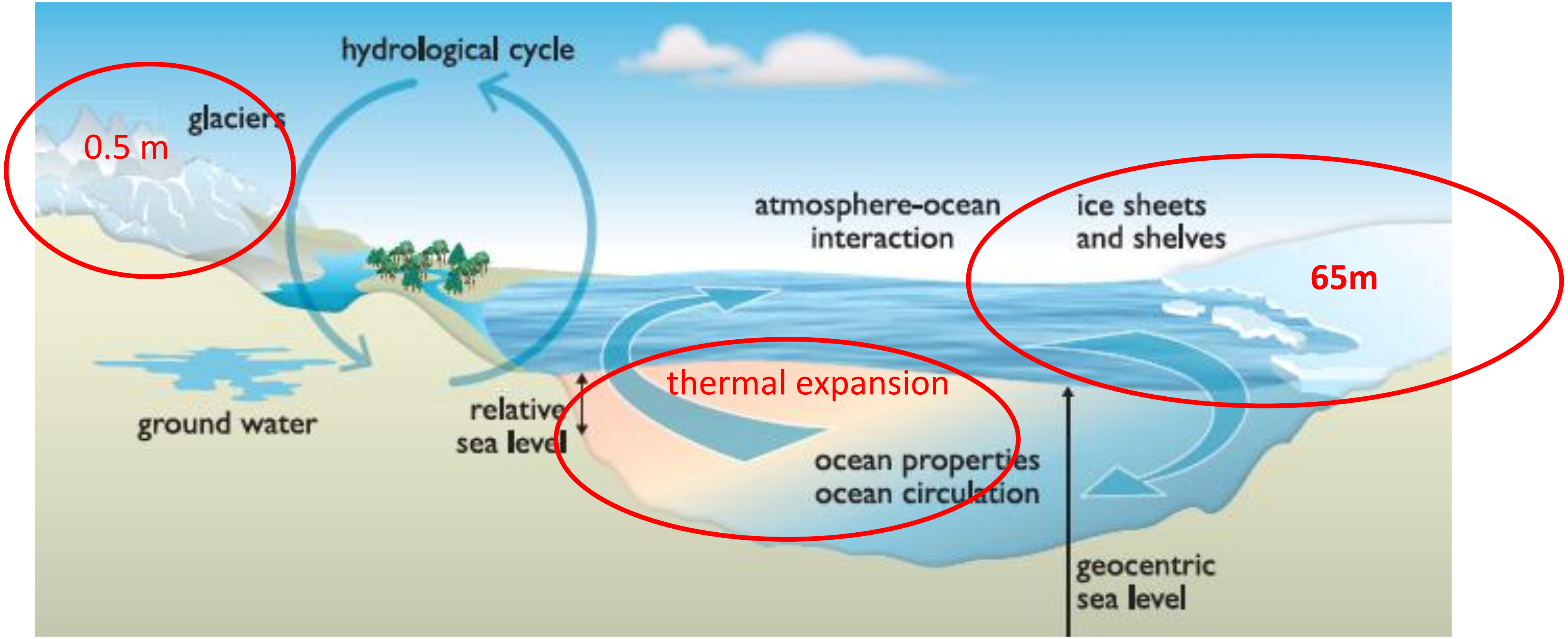


The pace is accelerating, now >3 mm/yr



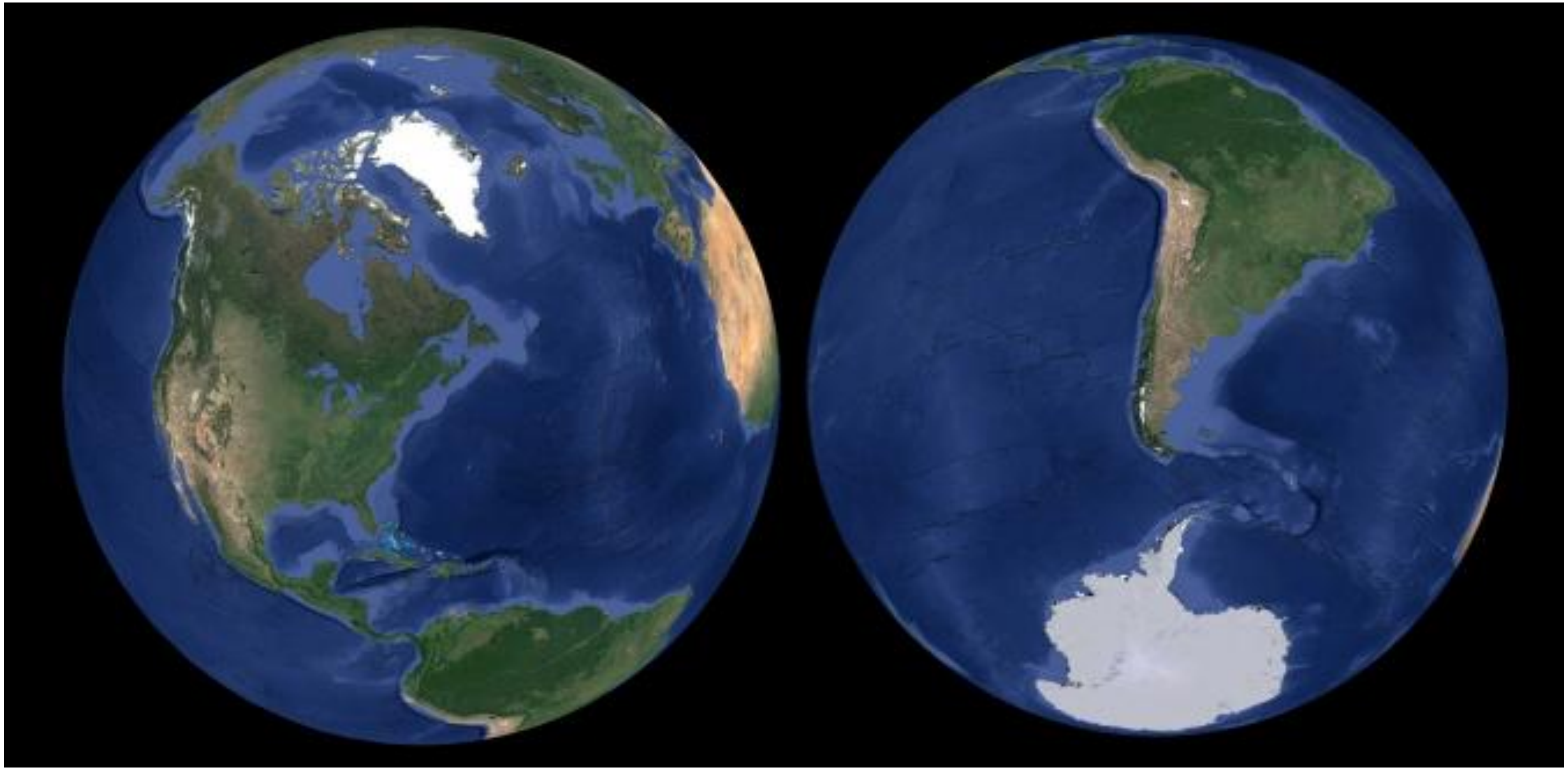
65 ± 12 cm by 2100

Potential contributions to future sea level rise

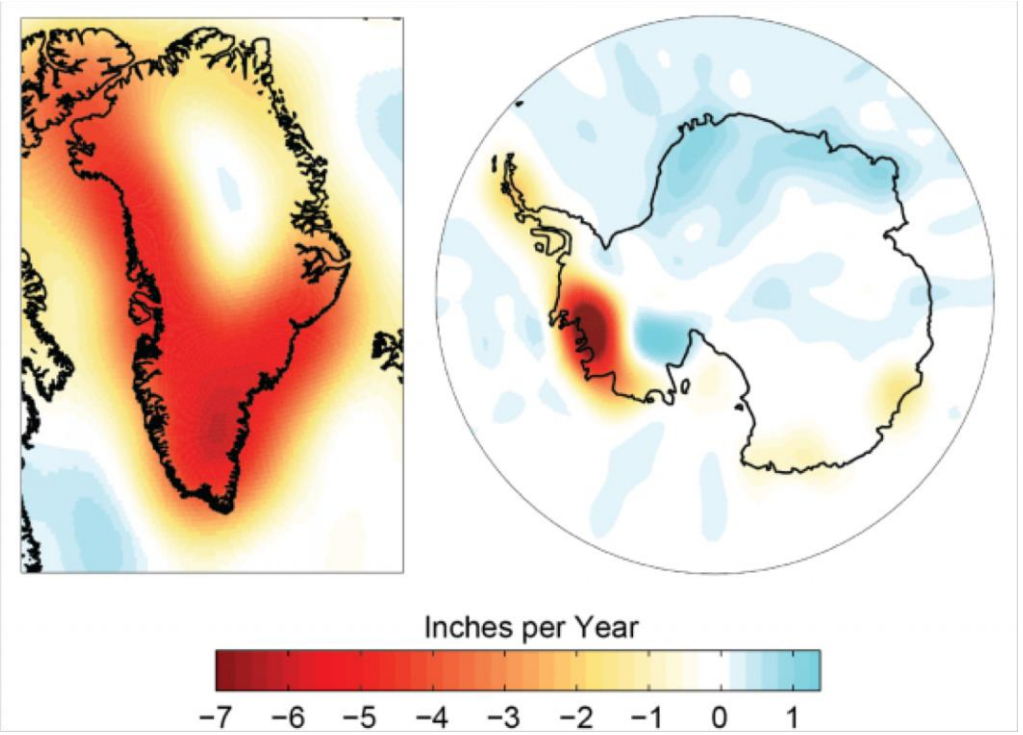


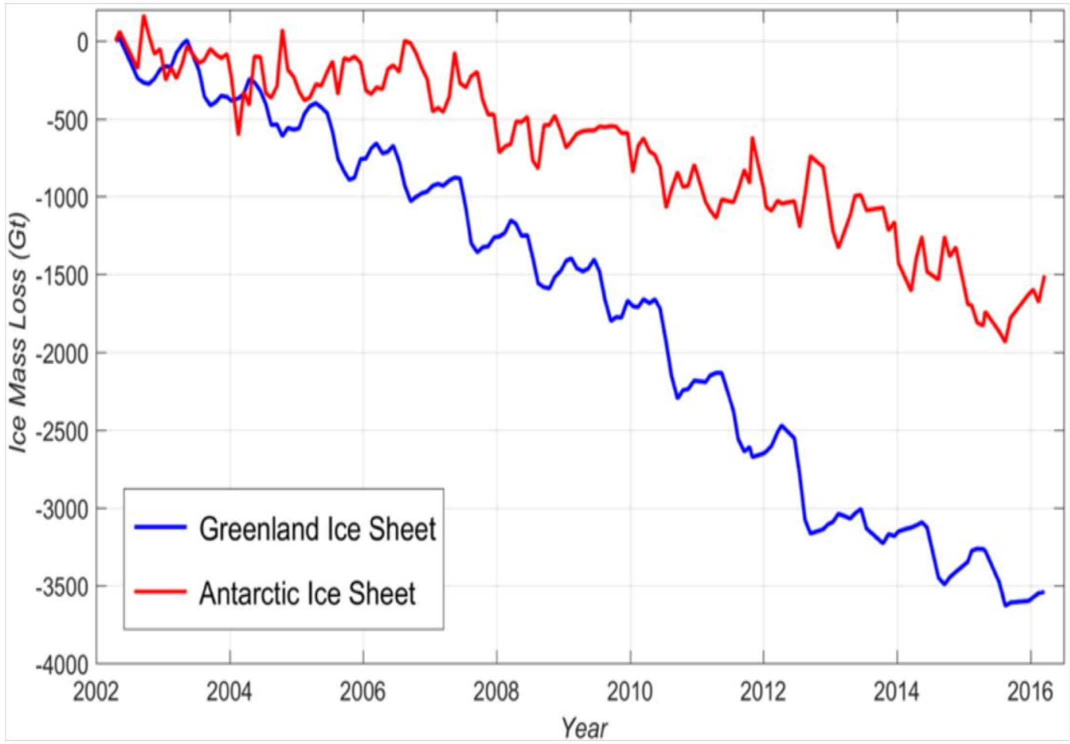
IPCC AR5 2013

Potential sea-level rise from
Greenland: 7m
Antarctica: 57m



Sea level rise is accelerating and the sources are changing





Leulliet and Nerem., 2016

Data source: NASA.

Water equivalent ice loss between 2003 and 2013 measured by the GRACE satellites

Cumulative mass loss from the Greenland and Antarctic Ice sheets. Note the general acceleration of mass loss. Today, Greenland is contributing more to sea level rise than Antarctica, but that situation could change.

Mass balance of the Antarctic Ice Sheet from 1992 to 2017

Nature, 2018

The IMBIE team*

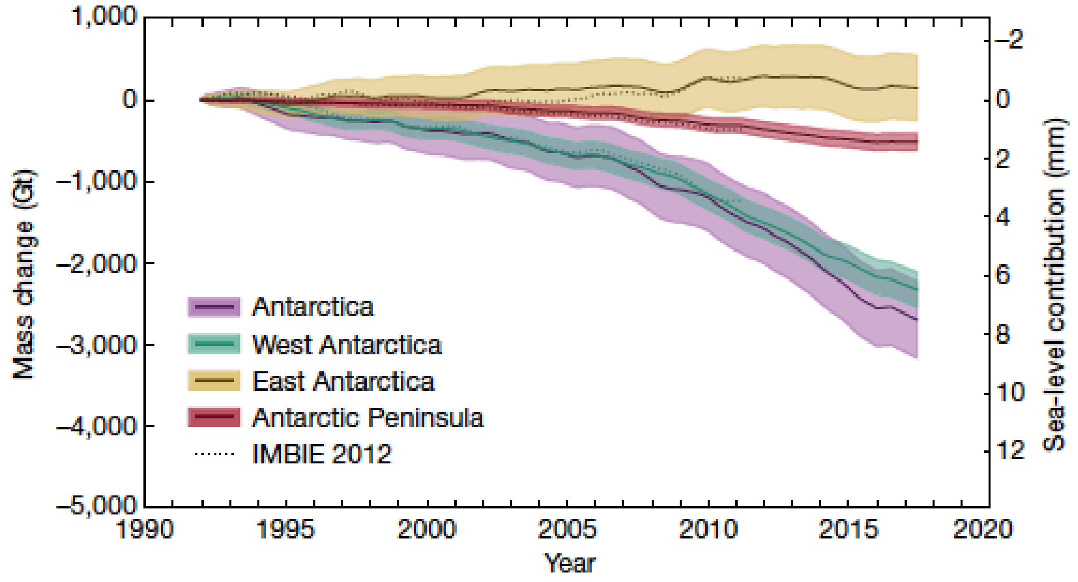


Table 1 | Rates of ice-sheet mass change

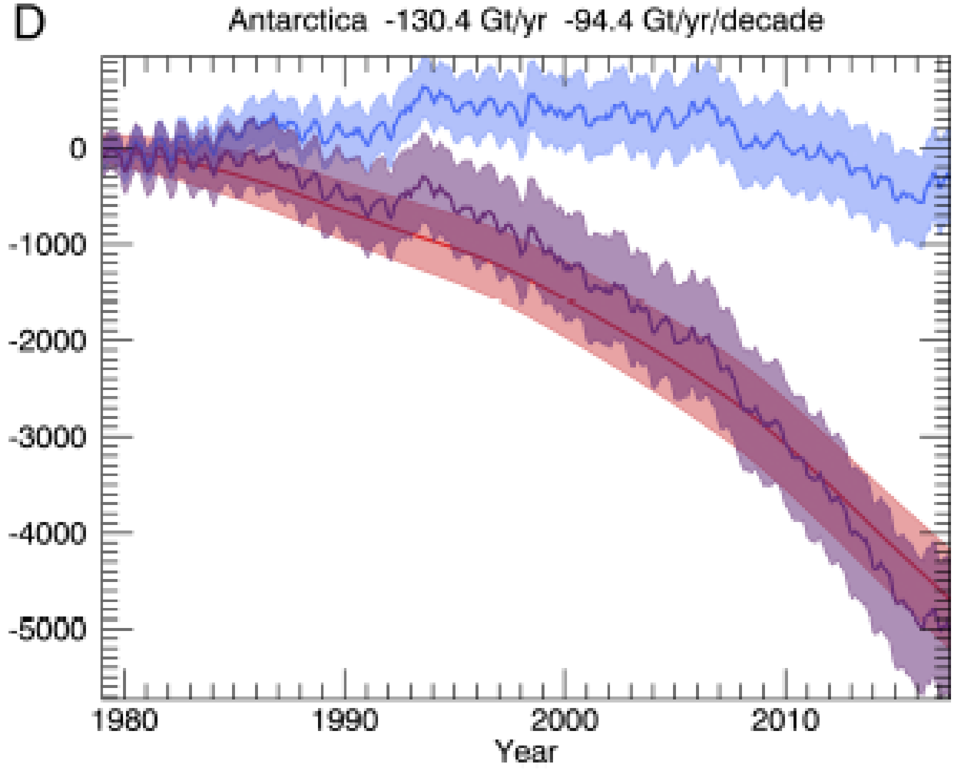
	1992–1997 (Gt yr^{-1})	1997–2002 (Gt yr^{-1})	2002–2007 (Gt yr^{-1})	2007–2012 (Gt yr^{-1})	2012–2017 (Gt yr^{-1})	1992–2011 (Gt yr^{-1})	1992–2017 (Gt yr^{-1})
EAIS	11 ± 58	8 ± 56	12 ± 43	23 ± 38	–28 ± 30	13 ± 50	5 ± 46
WAIS	–53 ± 29	–41 ± 28	–65 ± 27	–148 ± 27	–159 ± 26	–73 ± 28	–94 ± 27
APIS	–7 ± 13	–6 ± 13	–20 ± 15	–35 ± 17	–33 ± 16	–16 ± 14	–20 ± 15
AIS	–49 ± 67	–38 ± 64	–73 ± 53	–160 ± 50	–219 ± 43	–76 ± 59	–109 ± 56

Rates were determined from all satellite measurements over various epochs for the EAIS, WAIS and APIS, which combined constitute the AIS. The period 1992–2011 is included for comparison to a previous assessment[18], which reported mass-balance estimates of 14 ± 43 Gt yr^{-1} for the EAIS, –65 ± 26 Gt yr^{-1} for the WAIS, –20 ± 14 Gt yr^{-1} for the APIS and –71 ± 53 Gt yr^{-1} for the AIS. The small differences in our updated estimates for this period are due to our inclusion of more data. Errors are 1σ.

Four decades of Antarctic Ice Sheet mass balance from 1979–2017

Eric Rignot[a,b,1], Jérémie Mouginot[a,c], Bernd Scheuchl[a], Michiel van den Broeke[d], Melchior J. van Wessem[d], and Mathieu Morlighem[a]

PNAS, 2019

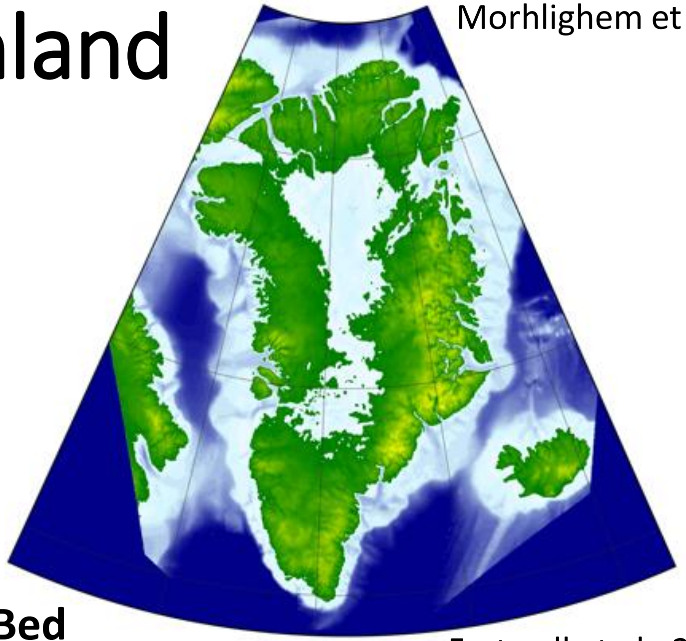


Antarctica and Greenland are different!

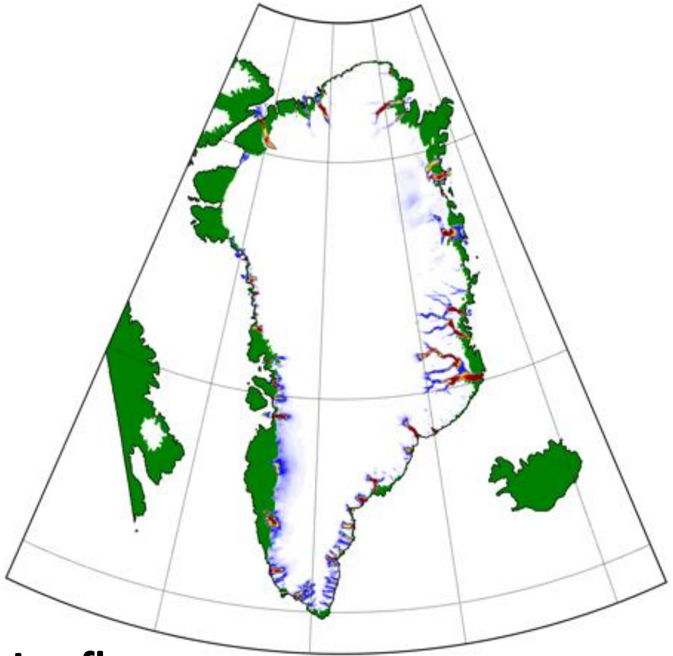
Unlike Greenland, most of the Antarctic ice sheet margin is in direct contract with the ocean.

The deep, wide, sub-glacial basins in Antarctica, are >2 km below sea level in some places, with the bedrock sloping downward, away from the margin, toward the continental interior.

In contrast, much of the Greenland ice margin terminates on land, around the terrestrial margin of the island.

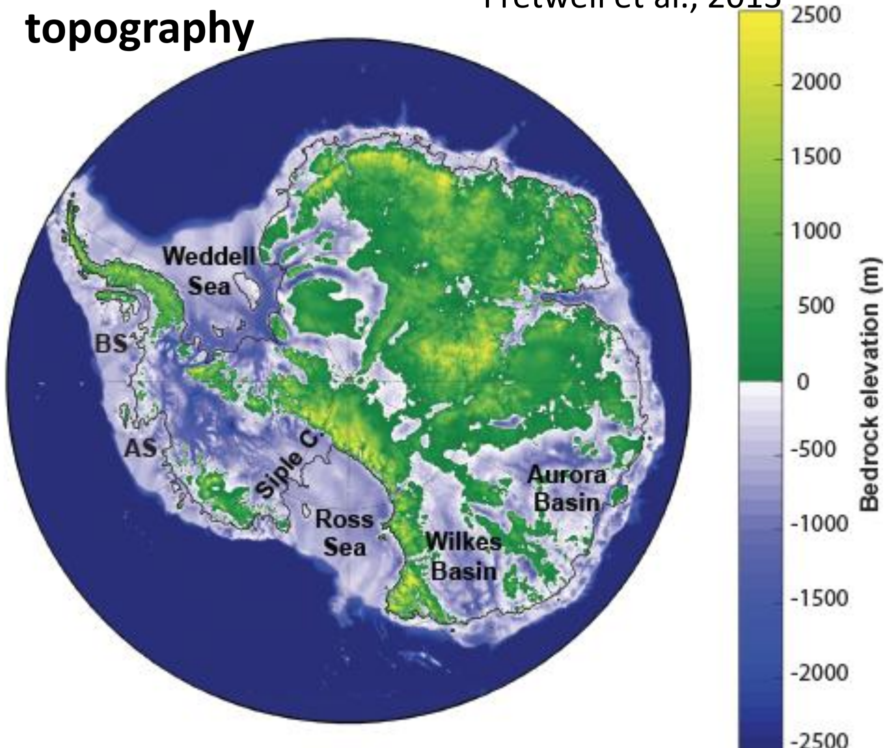


Morhlighem et al., 2017

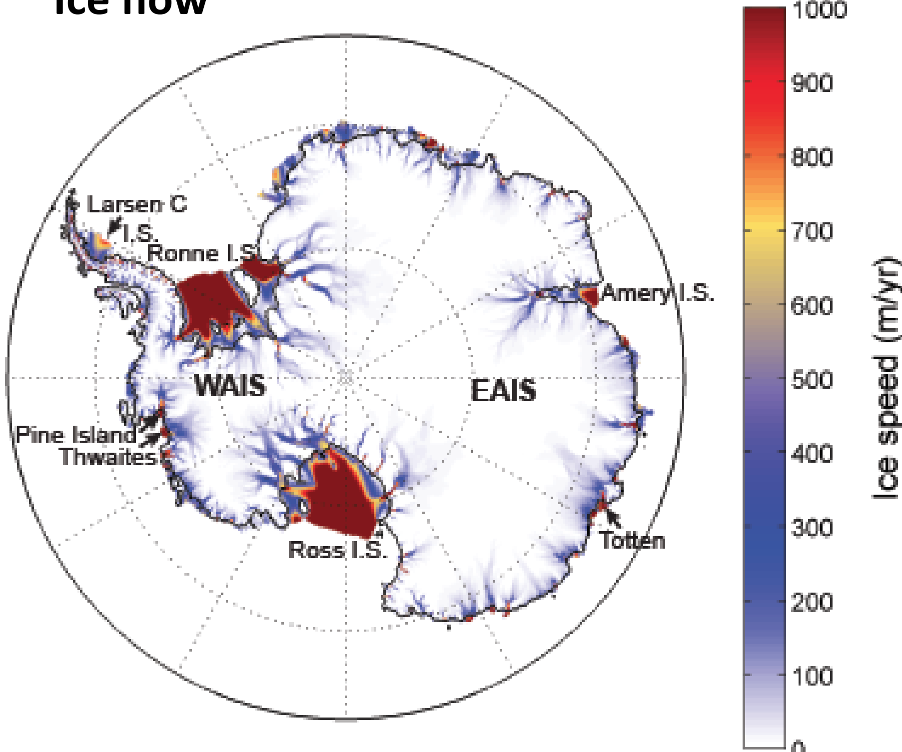


Bed topography

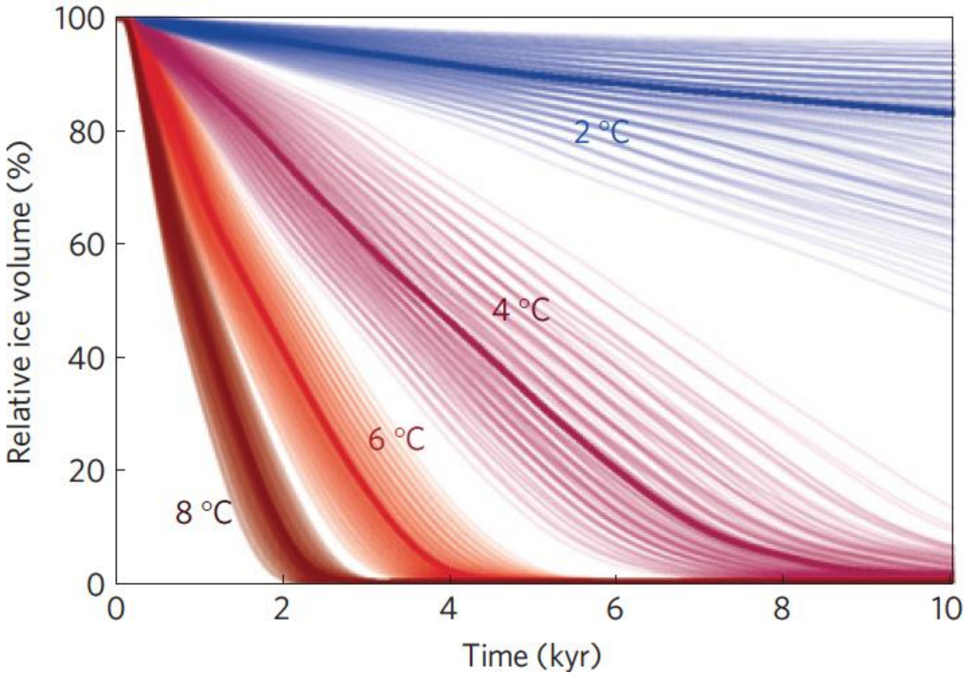
Fretwell et al., 2013



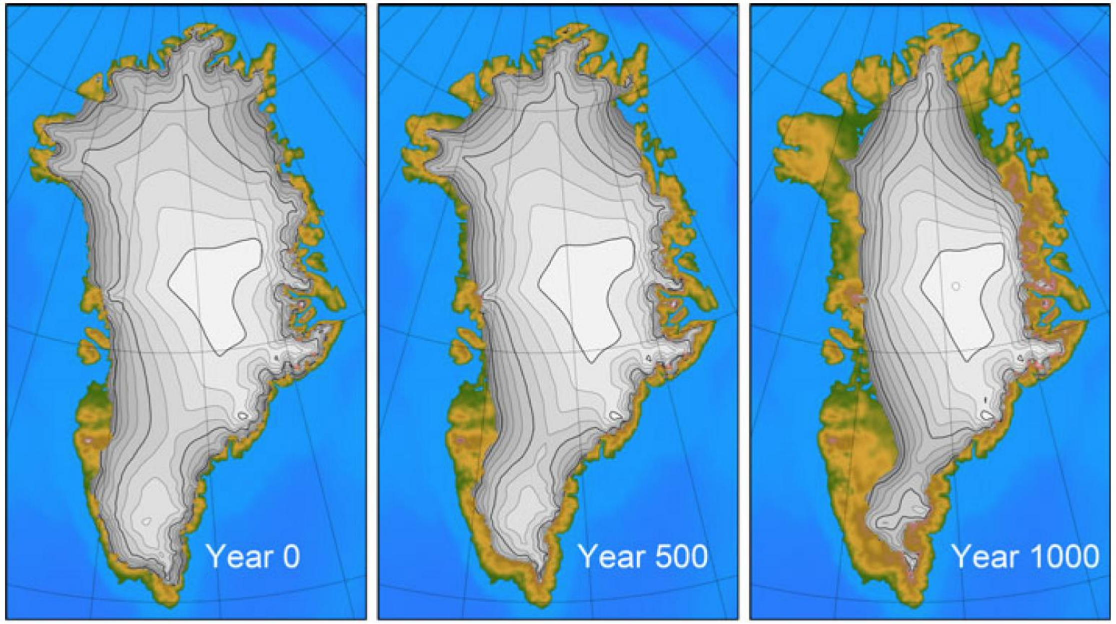
Ice flow



Model simulations of future Greenland retreat



Robinson et al., 2012

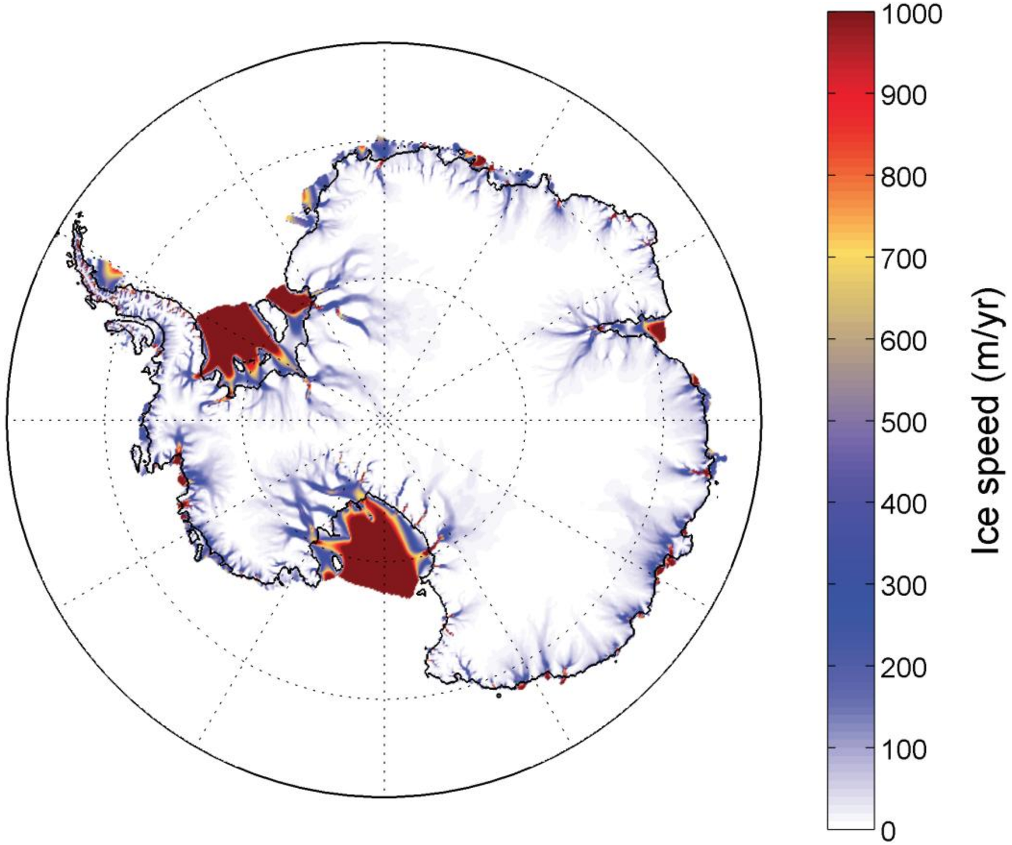


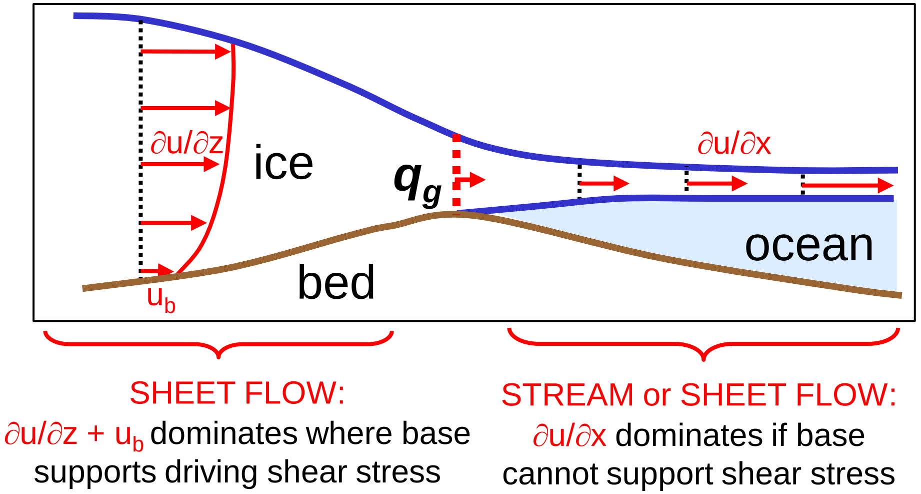
Huybrechs et al., 2012

Note the substantial jump in the rate of Greenland ice loss, with summer warming >2ºC (left).
Also note the millennial timescale for Greenland Ice Sheet retreat, even with 6-8 ºC summer warming.

Ice Sheet-Shelf Model

Pollard and DeConto, 2007; 2009; 2012, 2013; DeConto et al., 2012; Pollard et al., 2015; DeConto and Pollard, 2016





Hybrid (SIA+SSA) ice sheet-shelf model

Heuristic combination of the scaled equations for shearing (grounded interior) and stretching (floating/stream) ice flow, nominal resolution is 10km, with nesting capability (1 km)

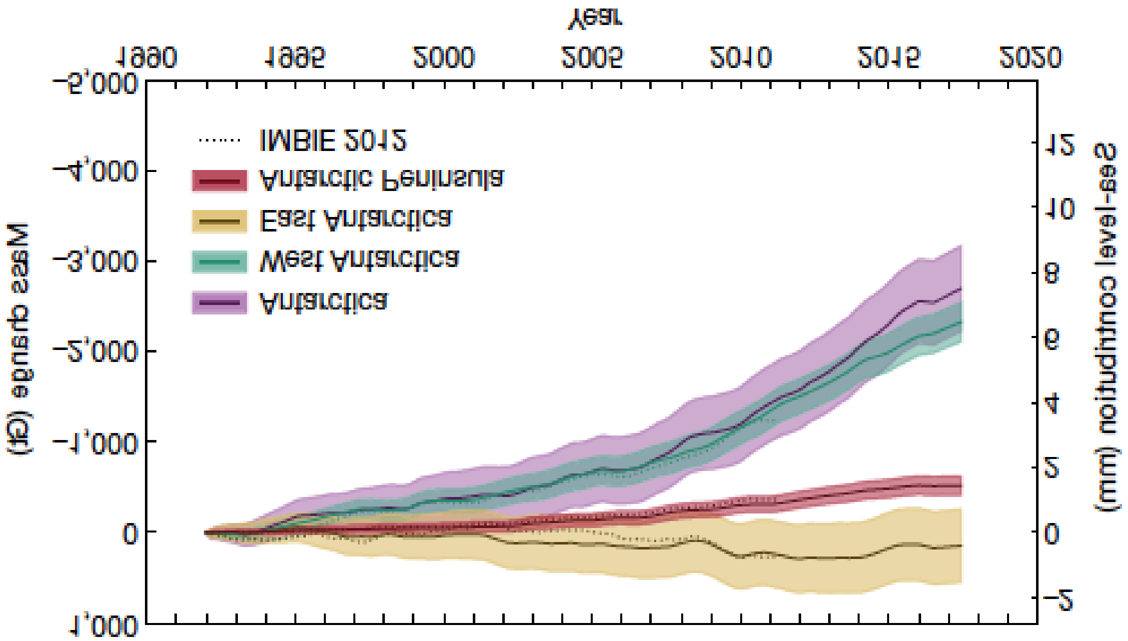
Parameterization of ice flux across grounding lines (q_g) after Schoof (2007) allowing free grounding-line migration and effects of ice-shelf buttressing including pinning points and side shear

$$\boxed{q_g = u_g h_g = A\, h_g^{\left(\frac{m+n+3}{m+1}\right)}}$$

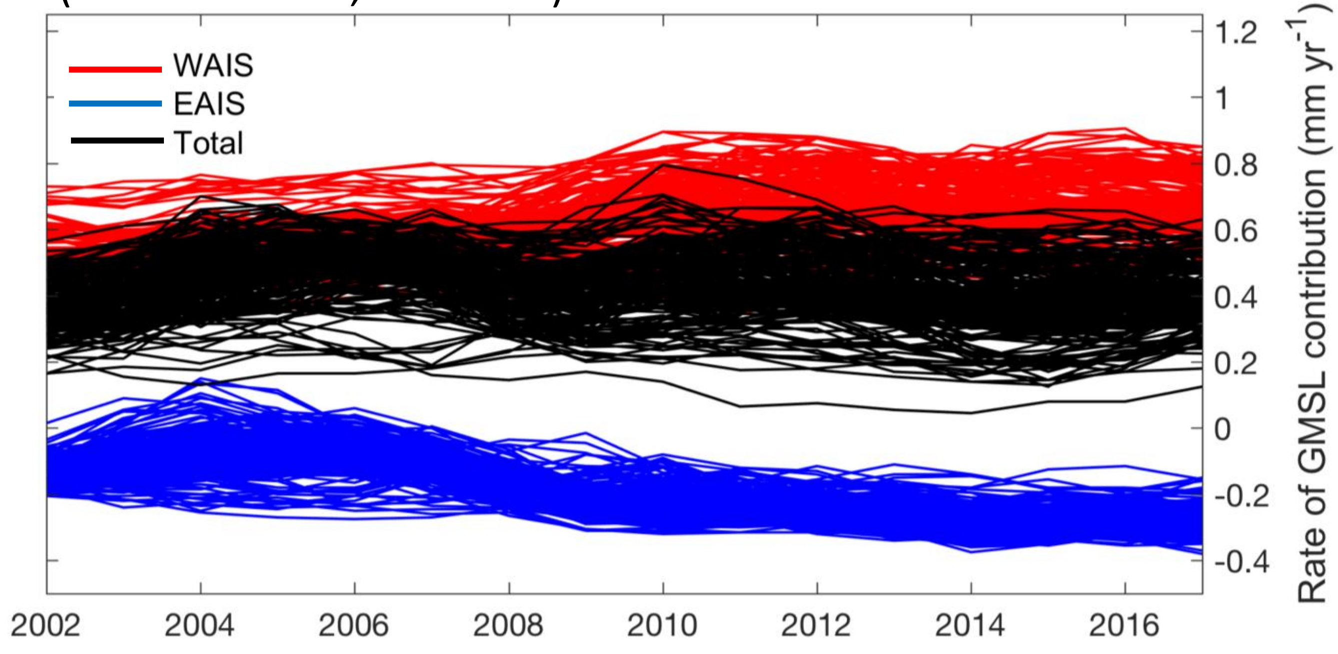
h_g = thickness, u_g = velocity, q_g = flux

Mass balance of the Antarctic Ice Sheet from 1992 to 2017

The IMBIE team*



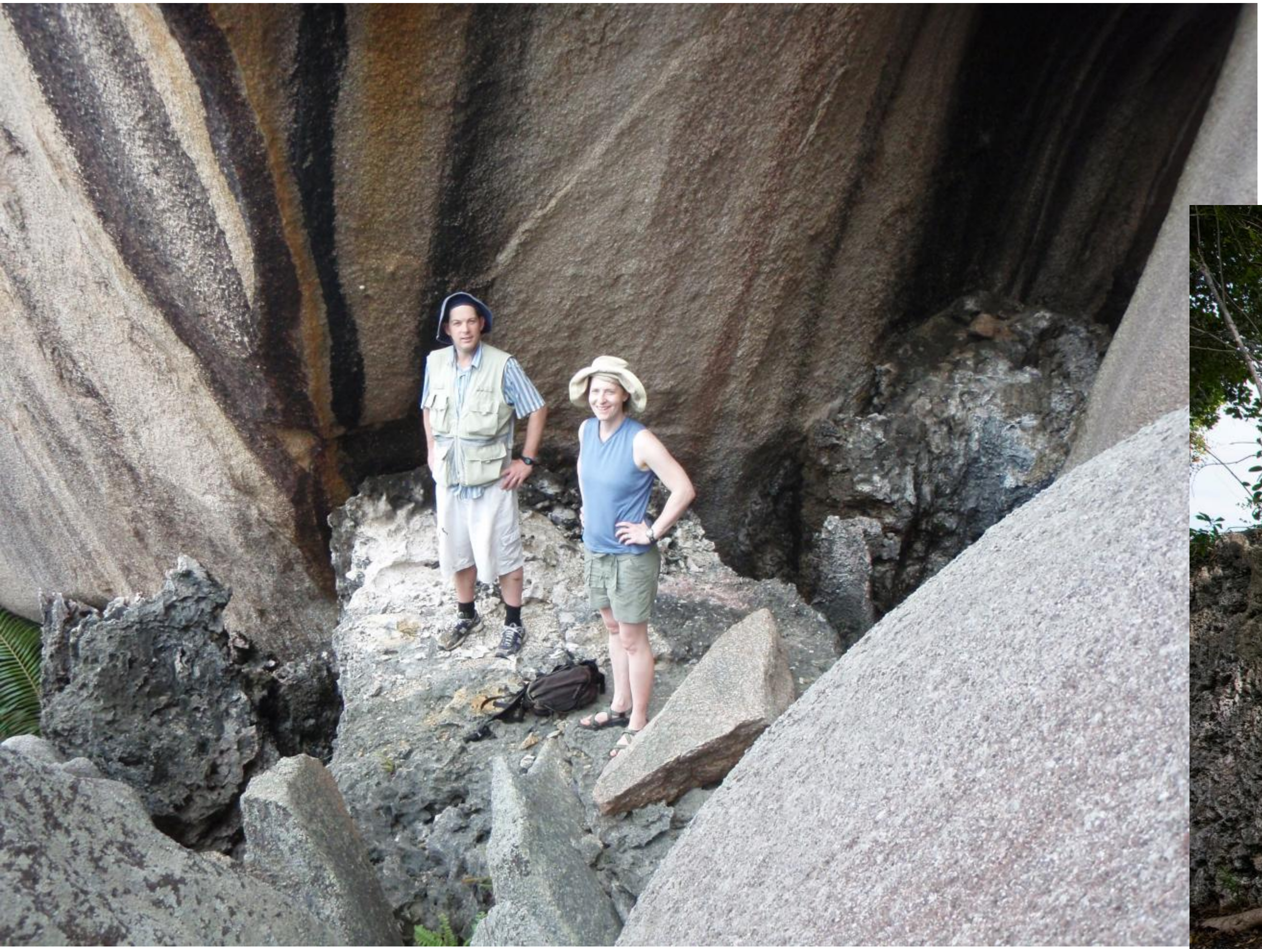
Model ice sheet mass change (sea-level equivalent)
(DeConto et al., in review)



Modern observations offer limited guidance on model performance

Last Interglacial reefs ~8 meters higher than modern sea level

Andrea Dutton, Univ. of Florida



Last Interglacial Reef, 8m above today's sea level
(Seychelles, Indian Ocean)

Last Interglacial Reef, 8m above today's sea level
(Florida Keys)

Estimates of Pliocene sea-level: +6 to ~30m

(e.g., Raymo et al., 2010; Miller et al., 2012; Rovere et al., 2014; Dutton et al., 2015; Grant et al., in review)

PLIOMAX

www.pliomax.org

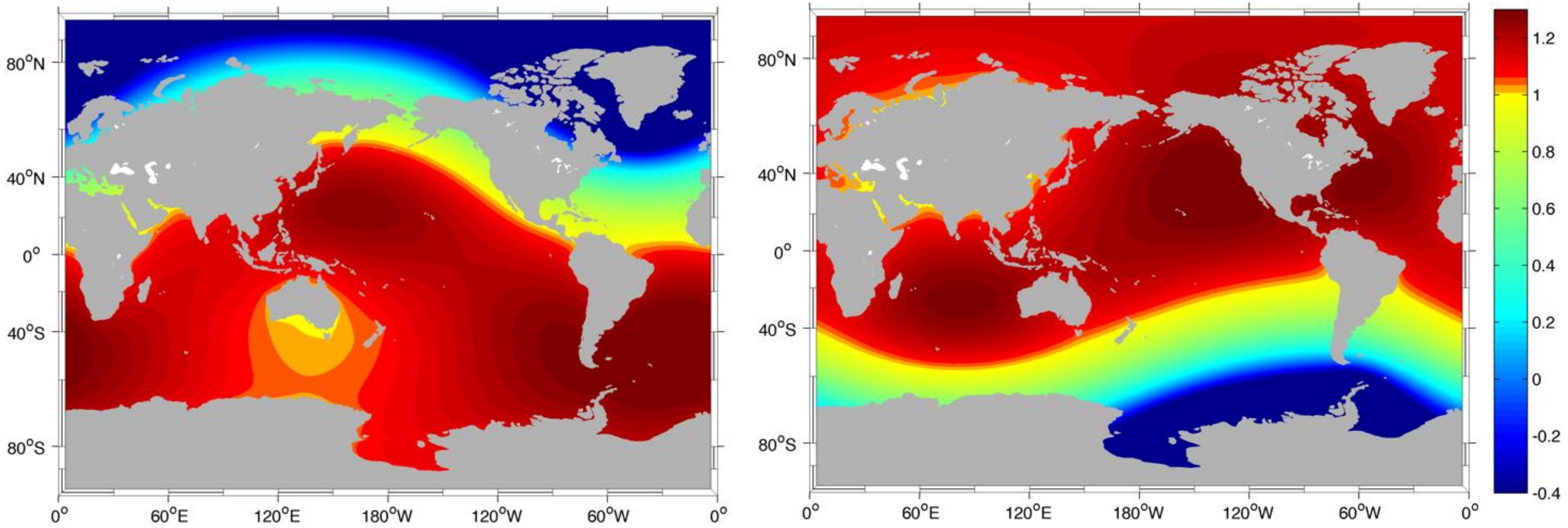
3 Ma barnacles and oysters on boulders at +22m, S. Africa *Photos: M. Raymo; M. O'Leary*

Why is Pliocene sea level so hard to reconstruct?

3 Ma barnacles and oysters on boulders at +22m, S. Africa *Photos: M. Raymo; M. O'Leary*

- Gravitational influence of ice sheets on ocean surface
- Glacio-isostatic adjustment of land surface
- Tectonics (vertical motion)
- Dynamic topography (vertical motion)

Sea level "fingerprints"



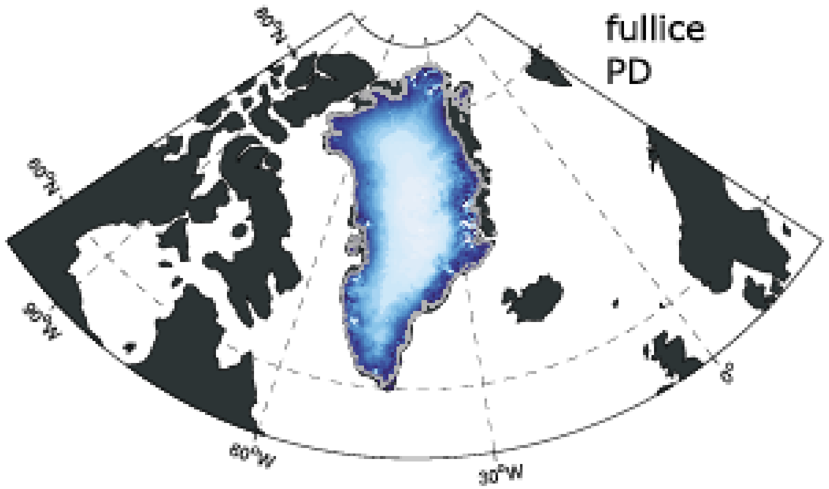
Thanks to Carling Hay; Mitrovica et al. 2011

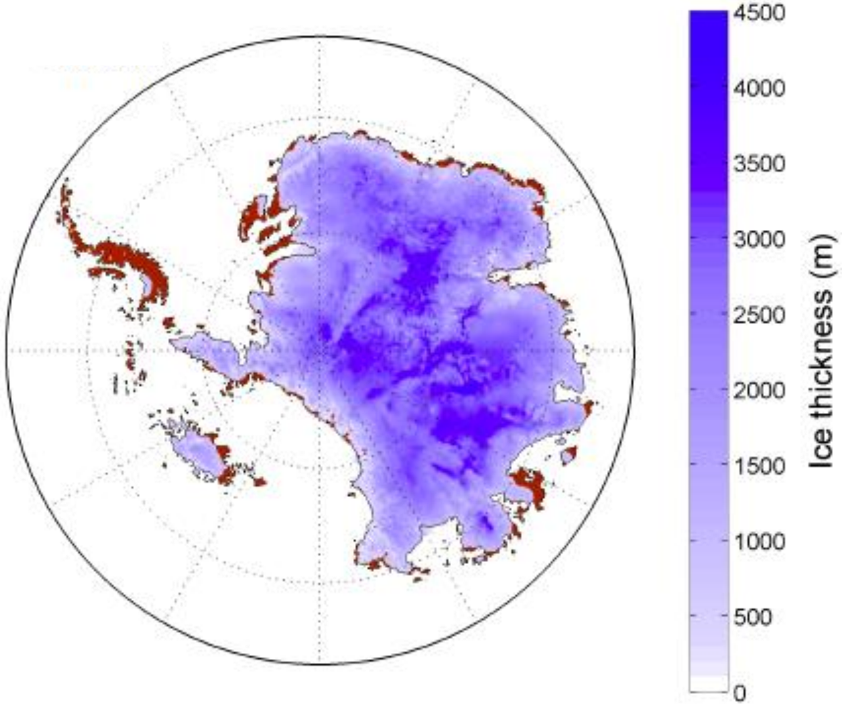
Gravitational and Earth rotational effects on relative sea level, caused by an equivalent ice mass loss from Greenland (left) or West Antarctica (right).

Pliocene inter-hemispheric antiphasing of ice volume “hides” sea level rise from Antarctica

Impact of reduced Arctic sea ice on Greenland ice sheet variability in a warmer than present climate

S. J. Koenig[1], R. M. DeConto[1], and D. Pollard[2]

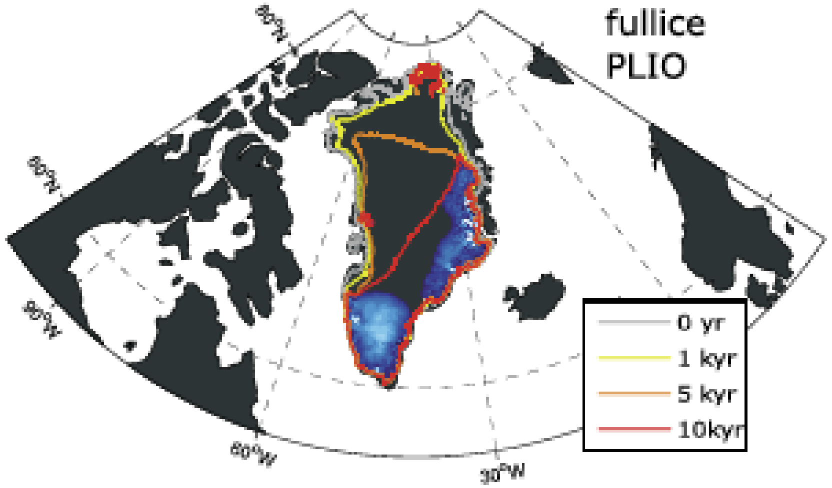


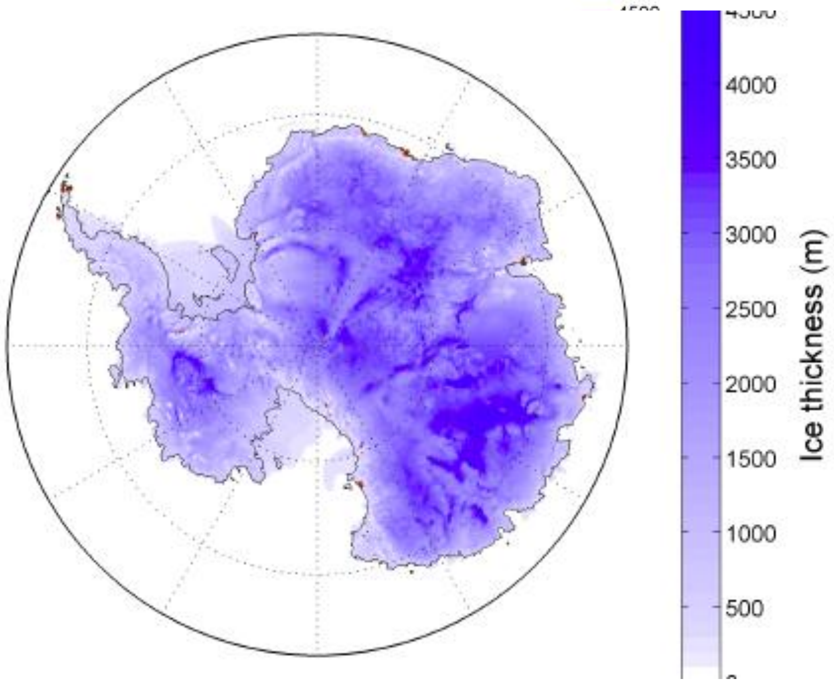


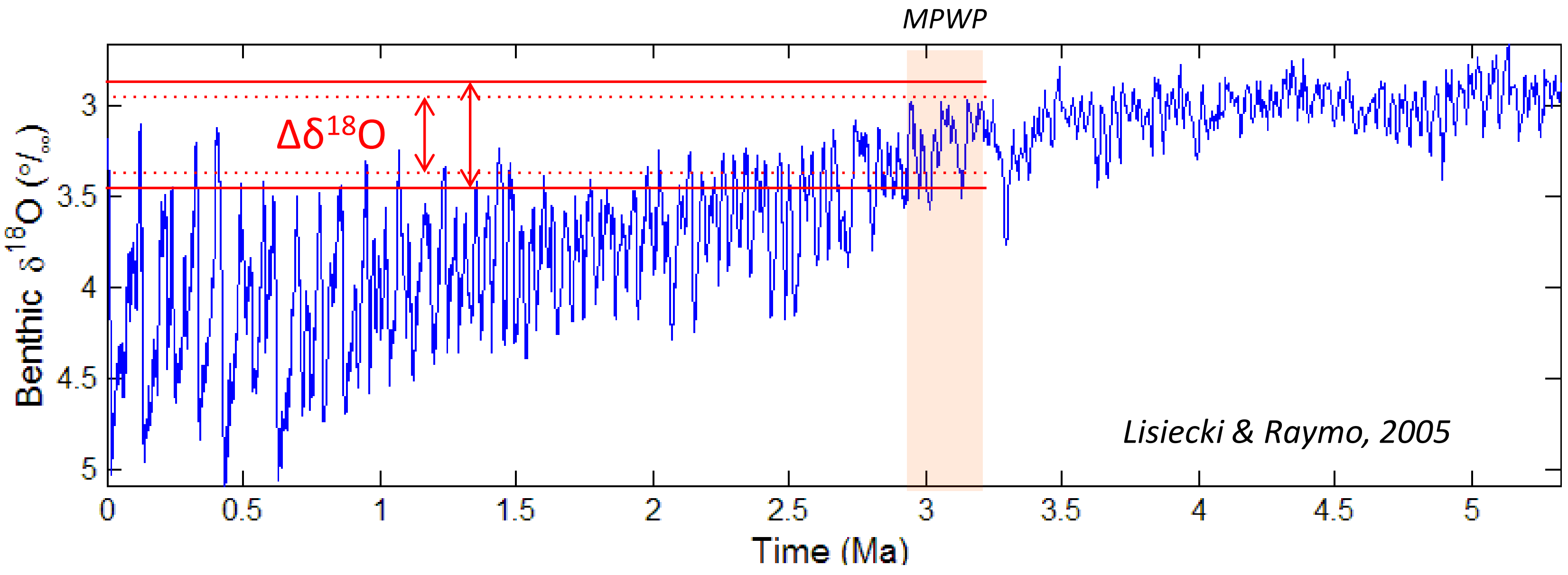
Pliocene inter-hemispheric antiphasing of ice volume “hides” sea level rise from Antarctica

Impact of reduced Arctic sea ice on Greenland ice sheet variability in a warmer than present climate

S. J. Koenig[1], R. M. DeConto[1], and D. Pollard[2]







$$M_O i_O + M_{GIS} i_{GIS} + M_{WAIS} i_{WAIS} + M_{EAIS} i_{EAIS} = M_{PlioO} i_{PlioO} + M_{PlioGIS} i_{PlioGIS} + M_{PlioWAIS} i_{PlioWAIS} + M_{PlioEAIS} i_{PlioEAIS}$$

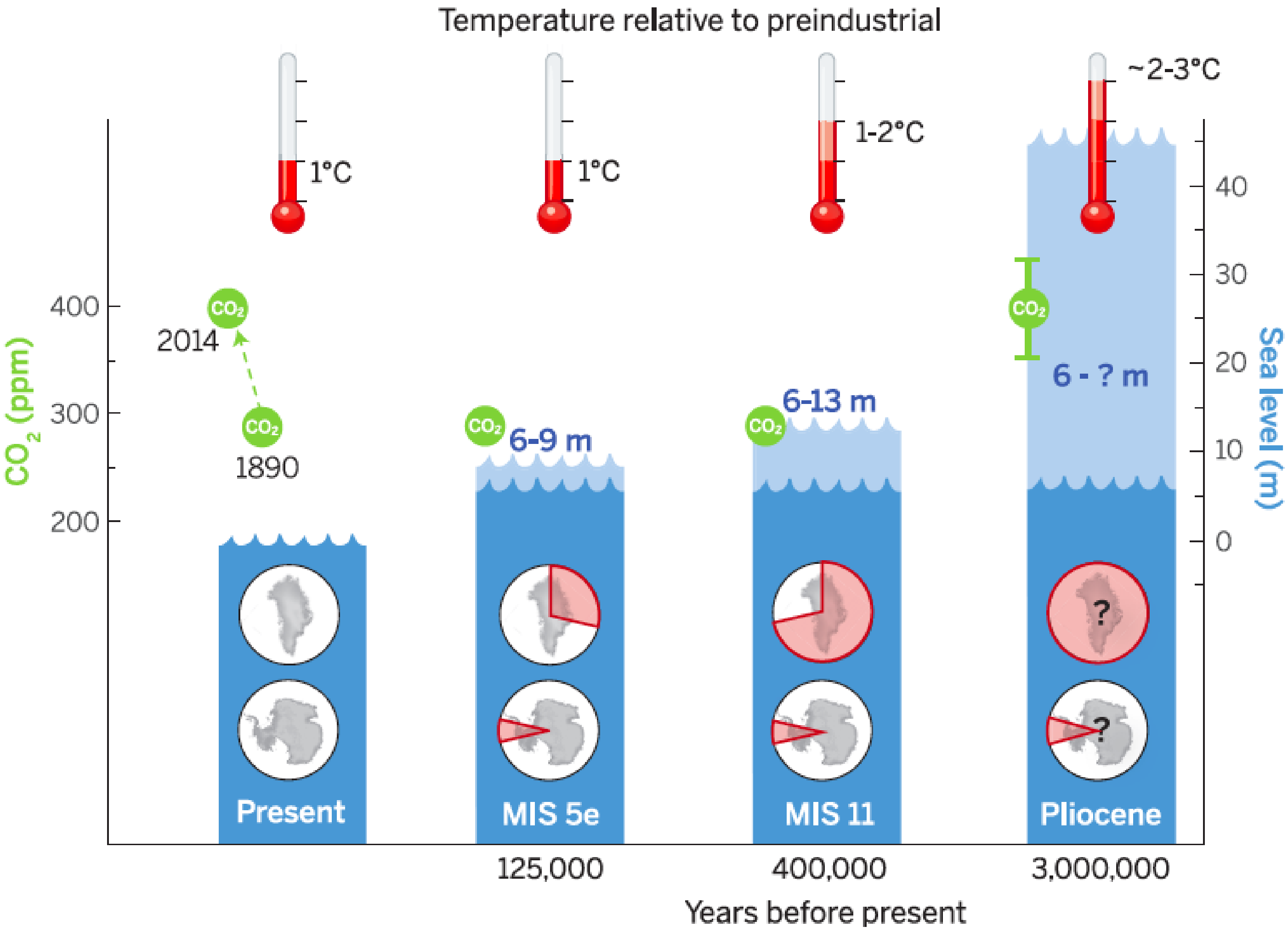
Isotope mass balance approach assumes some $\Delta\delta^{18}O$ temperature effect on i_O *(Miller et al., 2012) and* ***isotopic composition of ice sheets in the Pliocene vs Pleistocene (Winnick and Caves, 2015)***

$\Delta\delta^{18}O$: 0.3‰ ~ 9-13m
$\Delta\delta^{18}O$: 0.4‰ ~15-25m
$\Delta\delta^{18}O$: >0.4%? >25m?

Naish and Wilson, 2009	30m
Dwyer and Chandler, 2009	30m
Miller et al., 2012	22 ±10
Rowley et al., 2013	0-25m
Winnick and Caves, 2015	9-13.5m
Gasson et al., 2017	up to 13 m

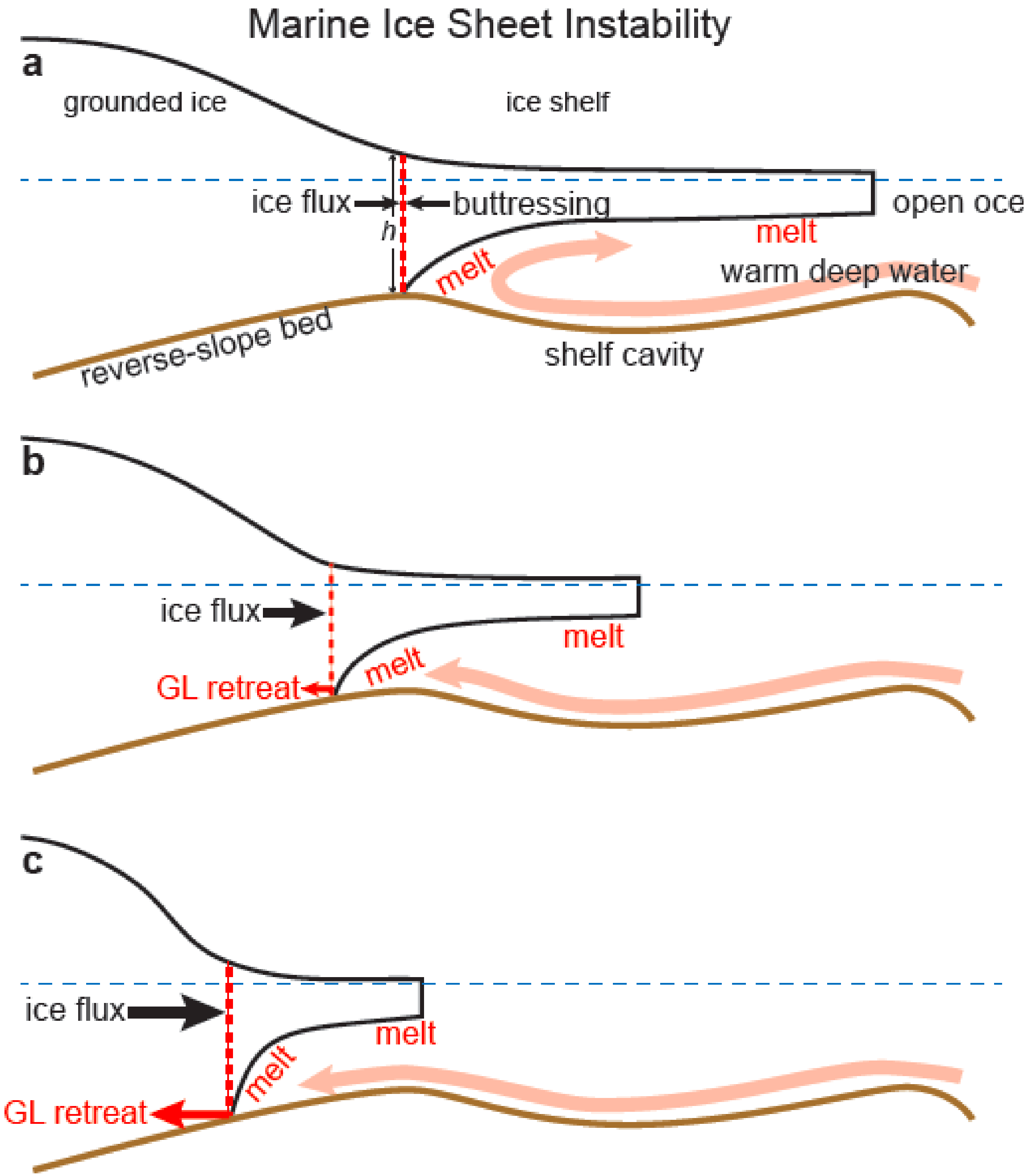
Sea-level rise due to polar ice-sheet mass loss during past warm periods

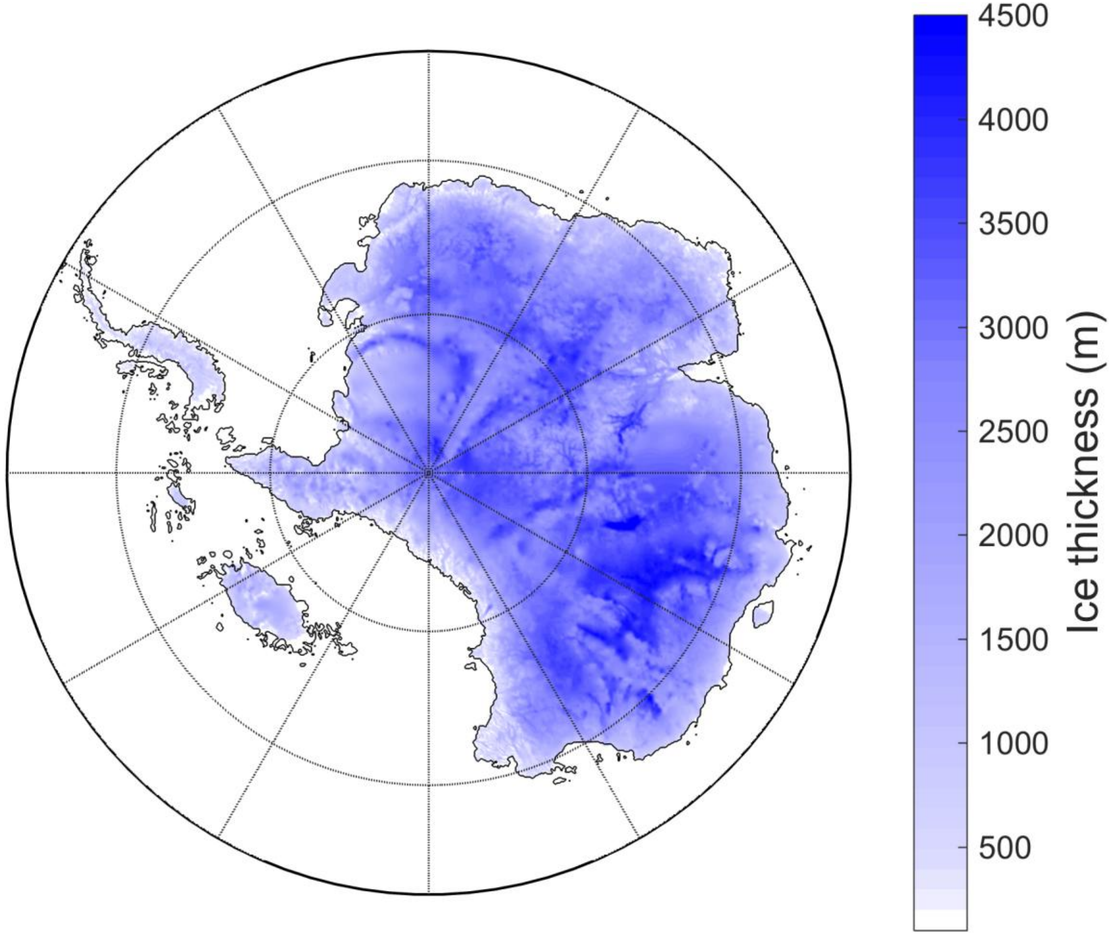
A. Dutton,* A. E. Carlson, A. J. Long, G. A. Milne, P. U. Clark, R. DeConto, B. P. Horton, S. Rahmstorf, M. E. Raymo



Dutton et al., 2015, *Science*

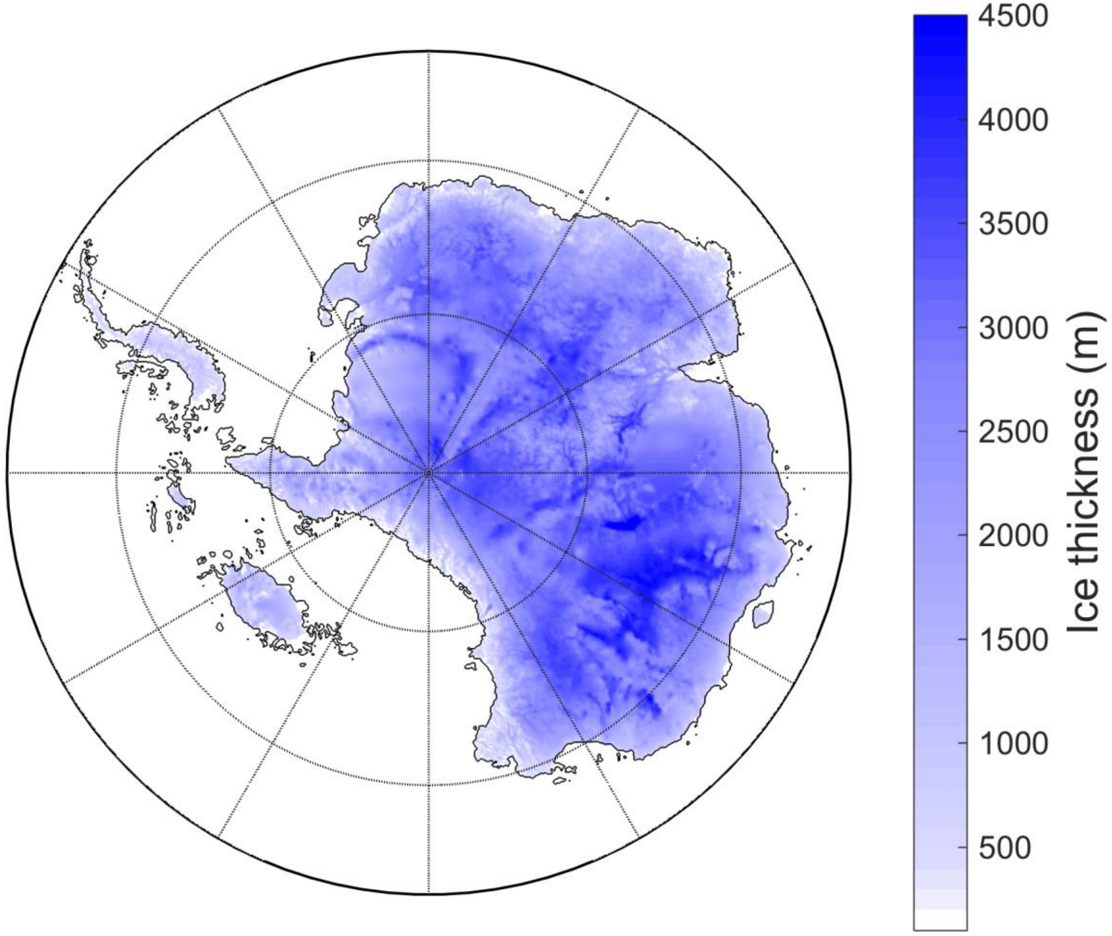
Previous Pliocene ice sheet modeling including MISI



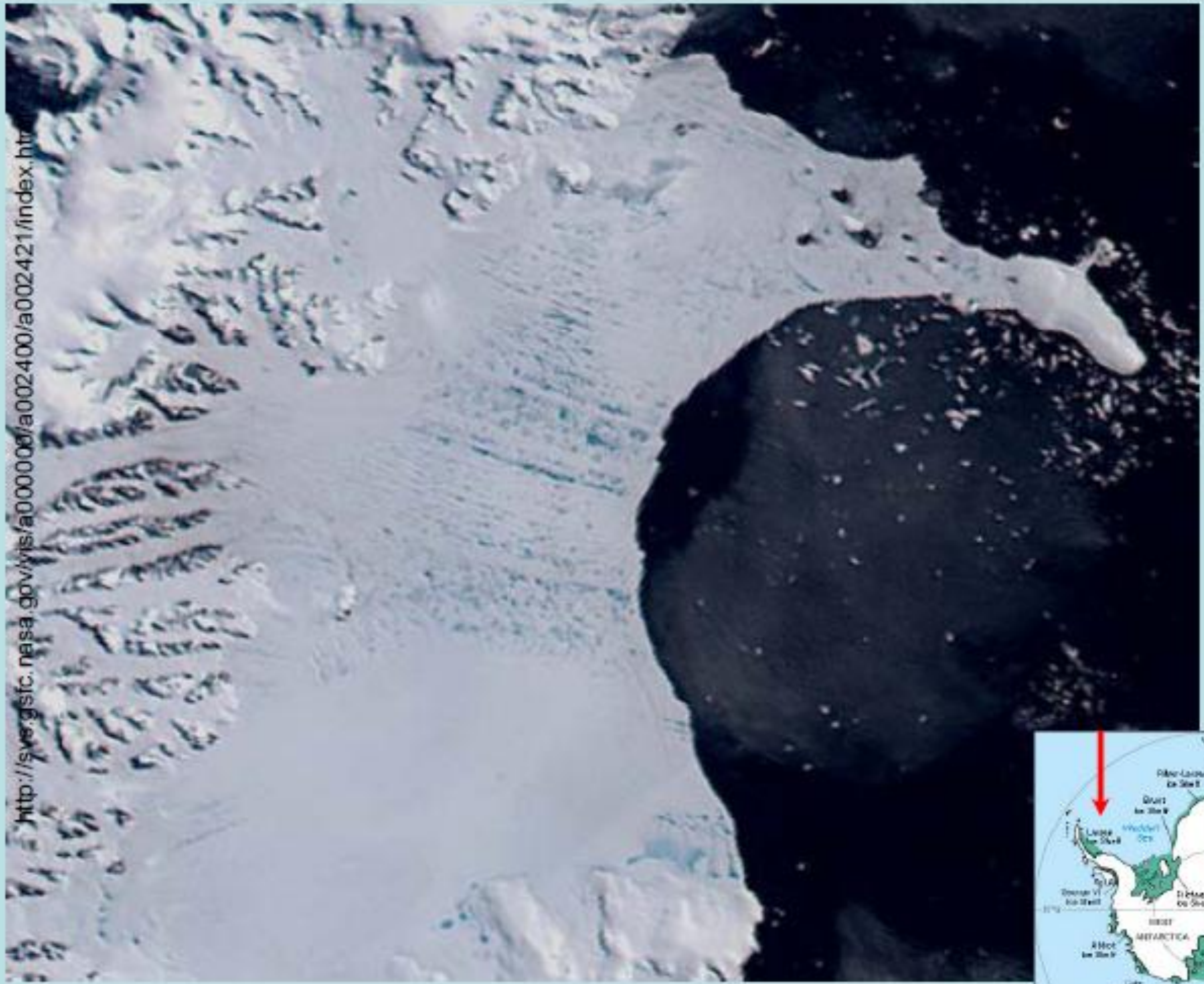


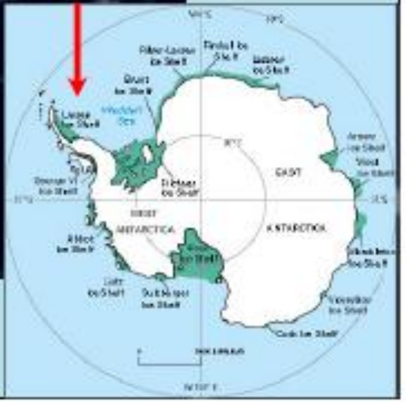
Pollard et al., 2015; DeConto and Pollard, 2016, *Nature*

Pliocene ice sheet simulations (1.5 m sea-level rise from Antarctica)? What's wrong with the model?

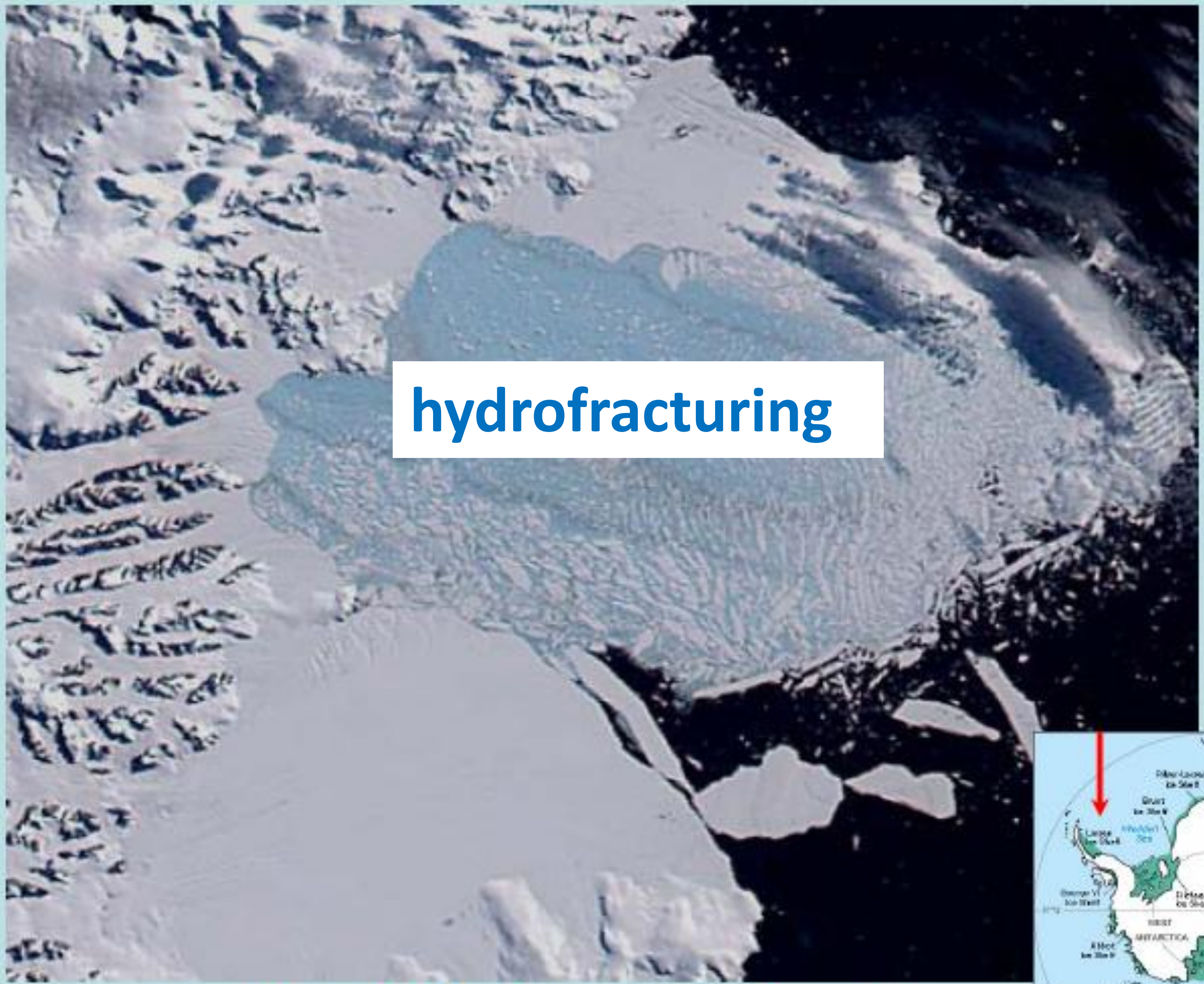


Pollard, DeConto, Alley; 2015; DeConto et al., 2016



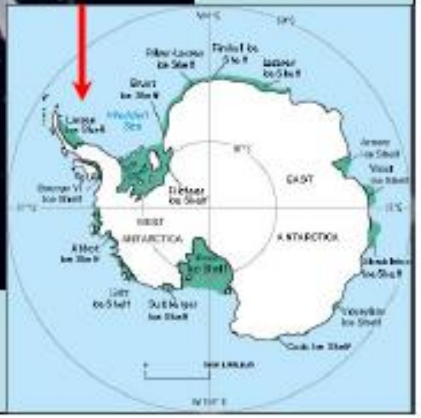


January 31, 2002



12 mi

20 km



March 7, 2002. **Then tributary sped up 8x.**

Source, Earth Observatory, NASA; Scambos et al., 2011

Glacial ice flowing into the ocean usually ends in a cliff

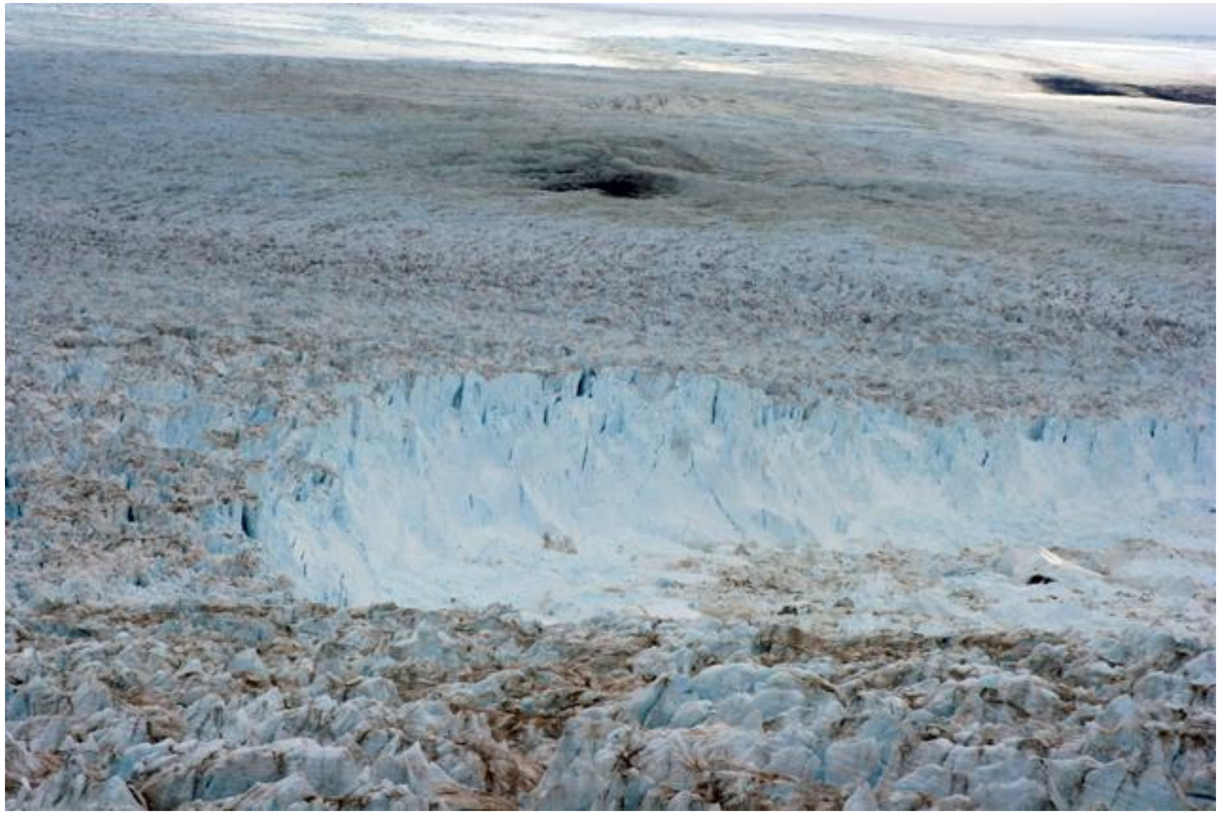
US National Parks Service, www.nps.gov

NASA, photo Jim Yungle

NASA, photo Dick Ewers

Helheim Glacier, SE Greenland
(Photo, Knut Christianson)

Jakobhsavn, W Greenland
(Photo, Richard Alley)



Swansea University
Prifysgol Abertawe

Helheim Glacier, South East Greenland

July 12, 2010 Calving Event

10 second time-lapse
18:40 - 20:10 GMT (1.5 hours) in 537 images

Dr Timothy James
Glaciology Group, Swansea University, United Kingdom
www.swansea.ac.uk/glaciology
@arctic_mit and @SUGlaciology YouTube SwanseaGlaciology

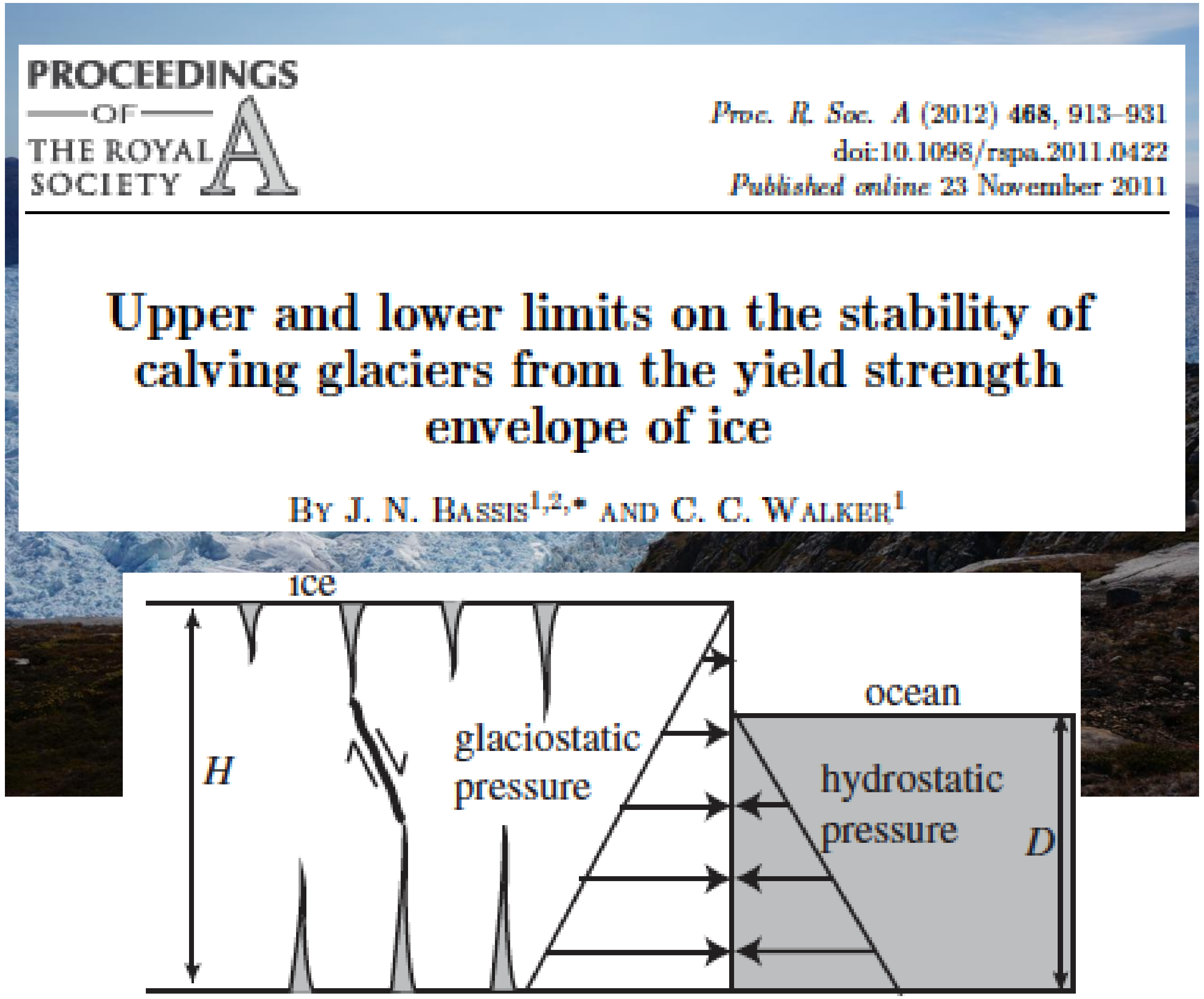
Climate Change Consortium of Wales
Consortiwm Newid Hinsawdd Cymru

Royal Geographical Society with IBG

The Leverhulme Trust

Swansea University GLIMPSE Greenland Ice Sheet Project www.greenlandice.org

Helheim Glacier, SE Greenland
(Photo, Knut Christianson)

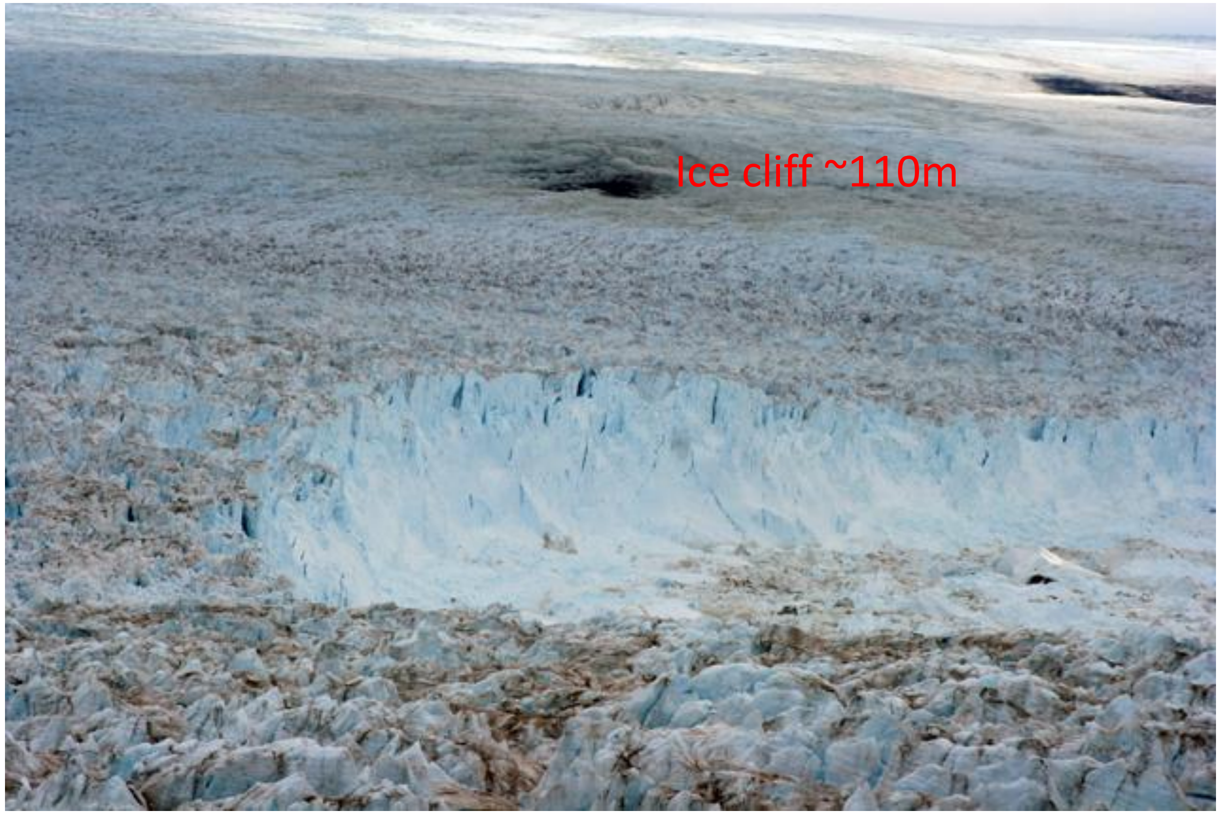

PROCEEDINGS OF THE ROYAL SOCIETY A

Proc. R. Soc. A (2012) 468, 913–931
doi:10.1098/rspa.2011.0422
Published online 23 November 2011

Upper and lower limits on the stability of calving glaciers from the yield strength envelope of ice

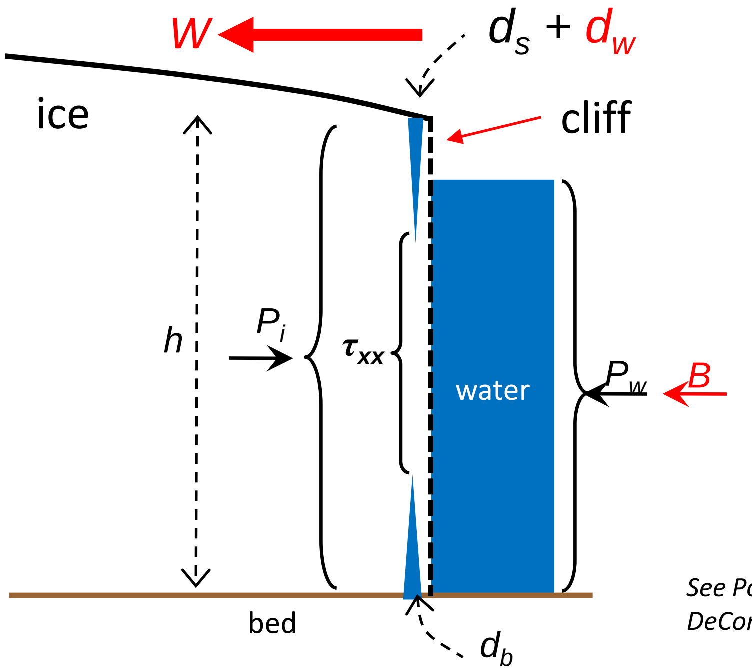
By J. N. Bassis[1,2,*] and C. C. Walker[1]

Jakobhsavn, W Greenland
(Photo, Richard Alley)



Marine-terminating ice cliff failure

Force-balance terms at ice cliff/grounding line



after Bassis and Walker (2012):

P_i = ice pressure

P_w = water pressure

τ_{xx} = longitudinal stress $(\partial u/\partial x)$

d = crevasse depth, f (h)

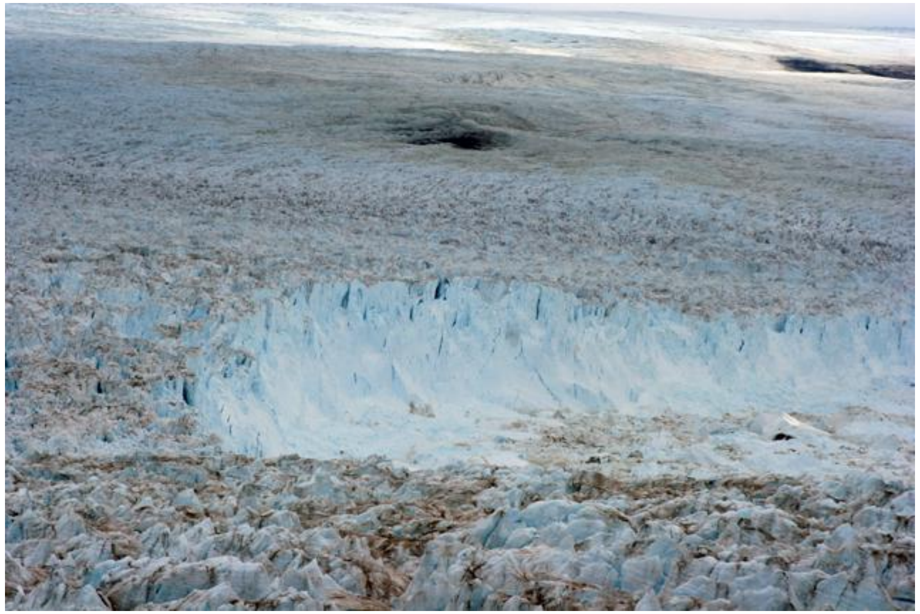
$$\boxed{\tau_{xx} = h\,(P_i - P_w - B)\,/\,(h - d - d_w)}$$

B = back stress

d = f $(h, B) + d_w$

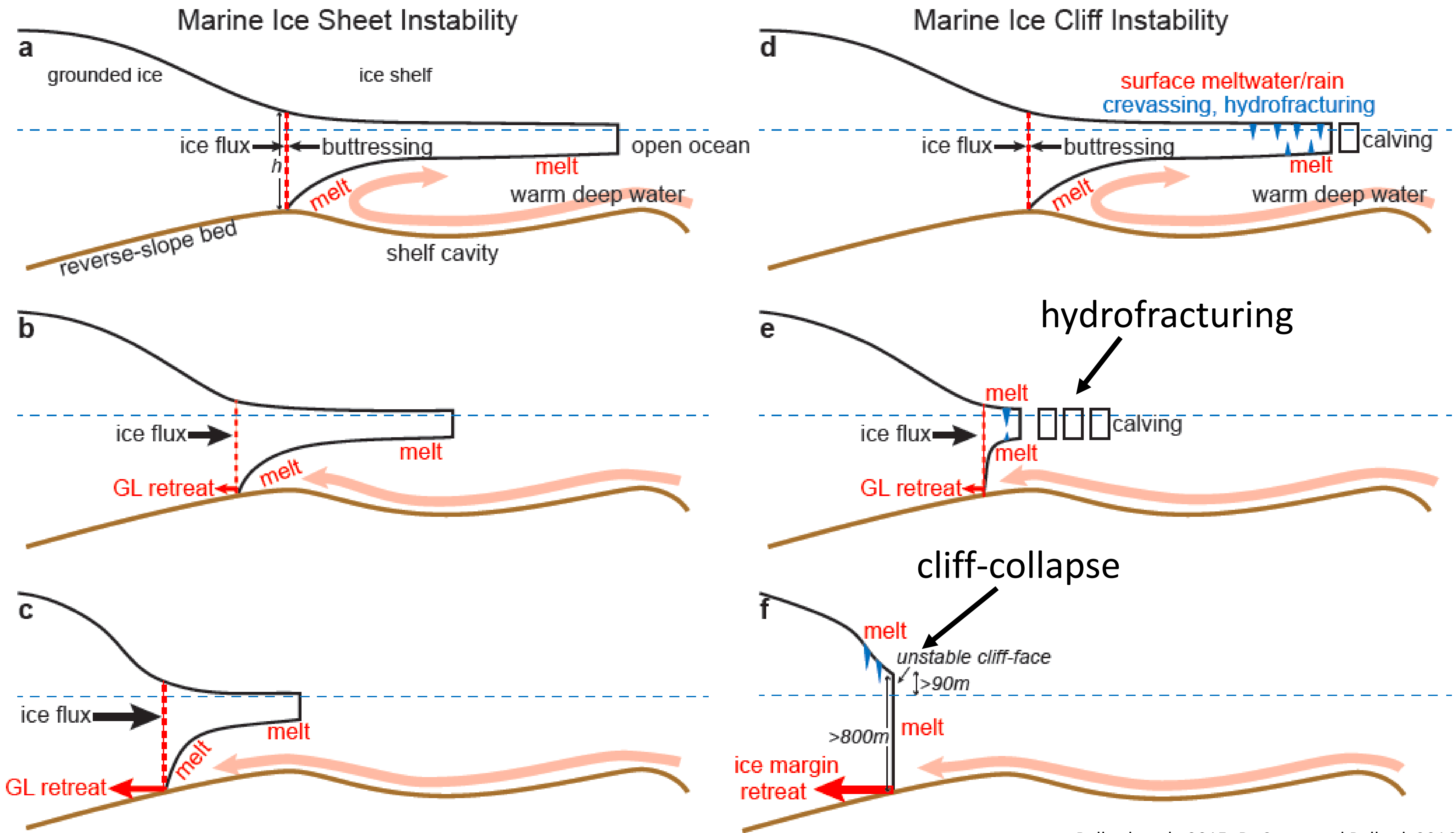
See Pollard, DeConto and Alley, 2015 and DeConto and Pollard, 2016 for complete formulation

W at Jakobshavn ~13 km yr^{-1}



- Cliff failure occurs if longitudinal stress τ_{xx} exceeds yield strength (~1 MPa)
- τ_{xx} increases as the vertical extent of intact ice *(h-d)* is reduced by crevassing
- maximum cliff size is reduced by surface crevassing (d_w) due to meltwater+rain

(Smaller effects due to back stress *B* if ice shelf or mélange provides some buttressing)

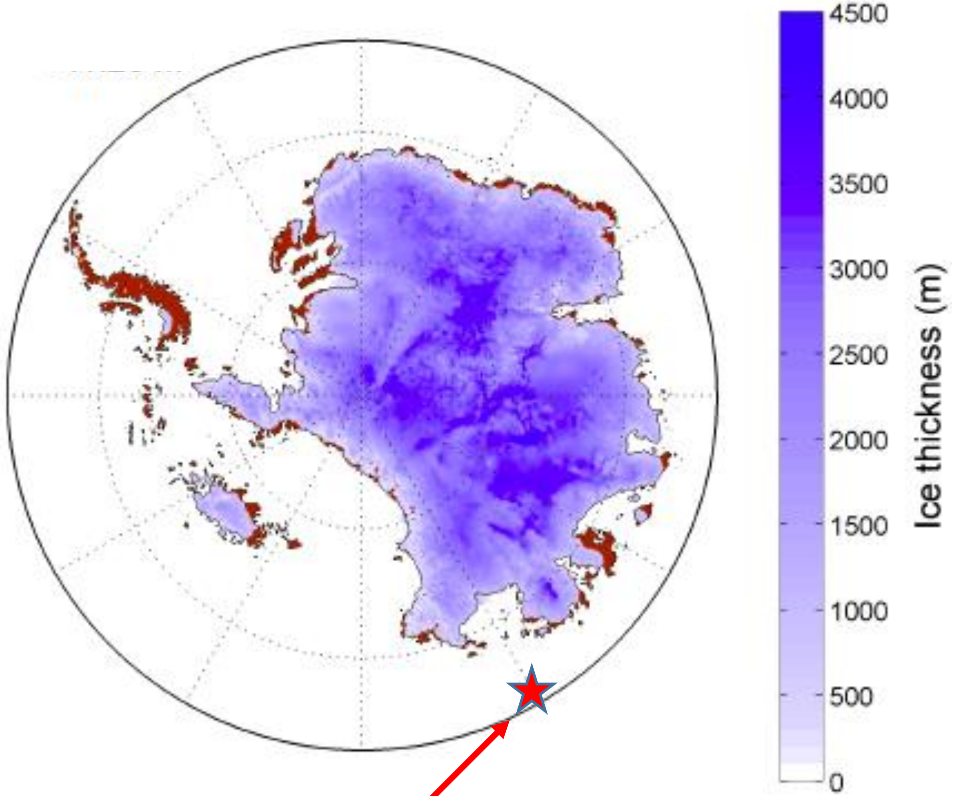


Pollard et al., 2015; DeConto and Pollard, 2016, *Nature*

Modeling the oxygen isotope composition of the Antarctic ice sheet and its significance to Pliocene sea level   Geology, 2016

Edward Gasson[1,2], Robert M. DeConto[1], and David Pollard[3]

Pliocene model with new brittle processes ~11m sea level



Cook et al., 2013

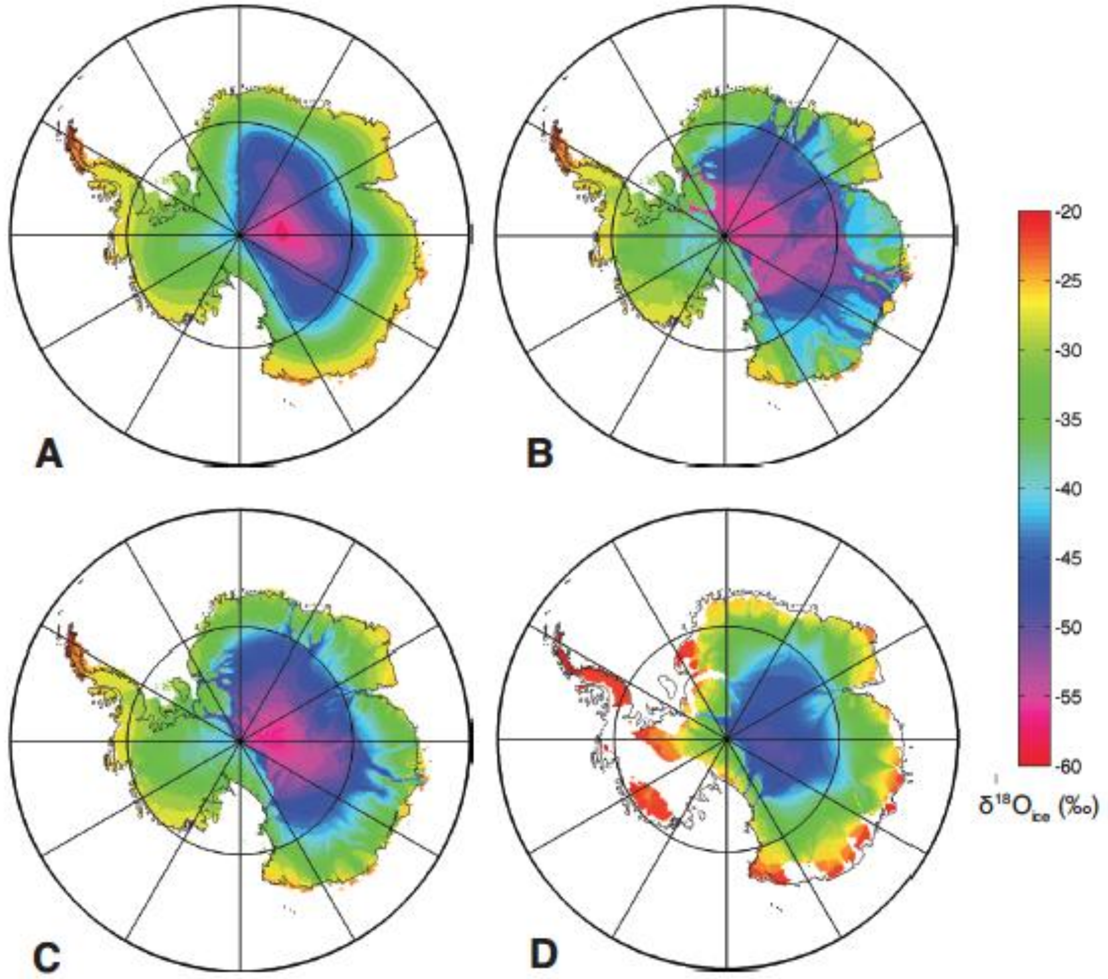
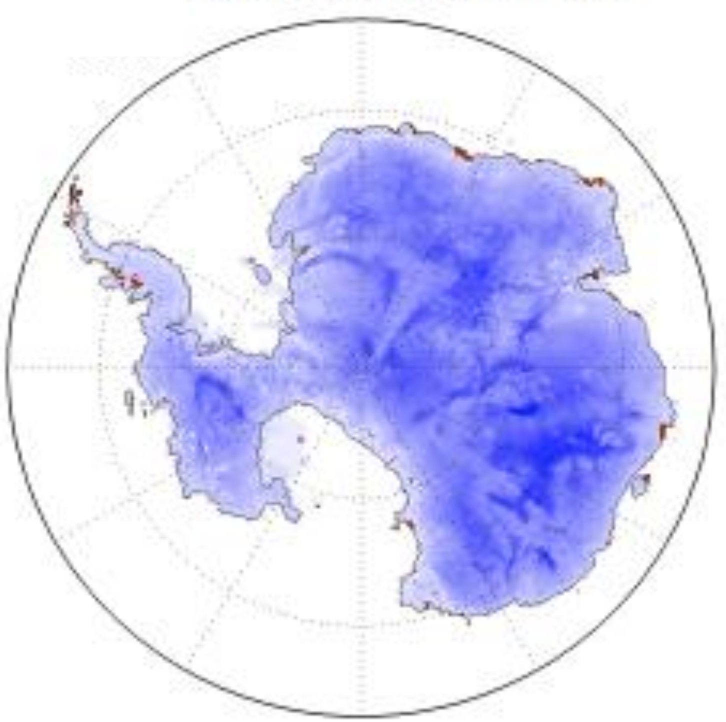


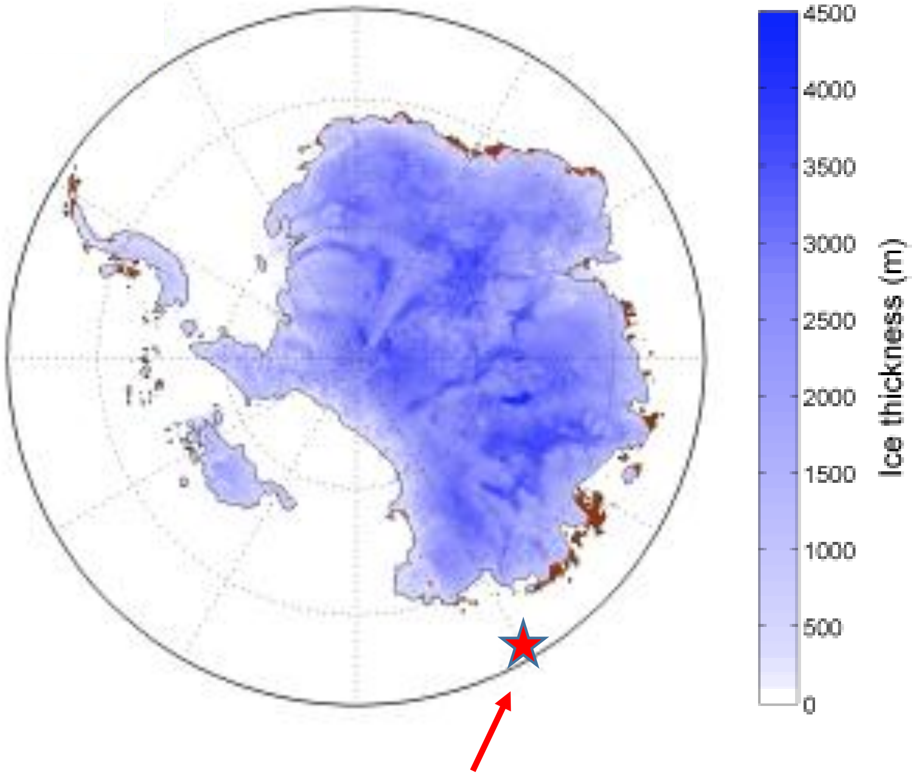
Figure 1. Simulated oxygen isotope composition of Antarctic ice sheets ($\delta^{18}O_{ice}$) at different ice depths. A: Modern ice surface layer. B: Modern ice basal layer. C: Modern depth-averaged. D: Pliocene depth-averaged (DeConto and Pollard, 2016).

Last Interglacial simulations (3.1-6.1 m GMSL target)

no hydrofracturing and no cliff calving +1m sea level



hydrofracturing and cliff calving +4m sea level



Wilson et al., 2018

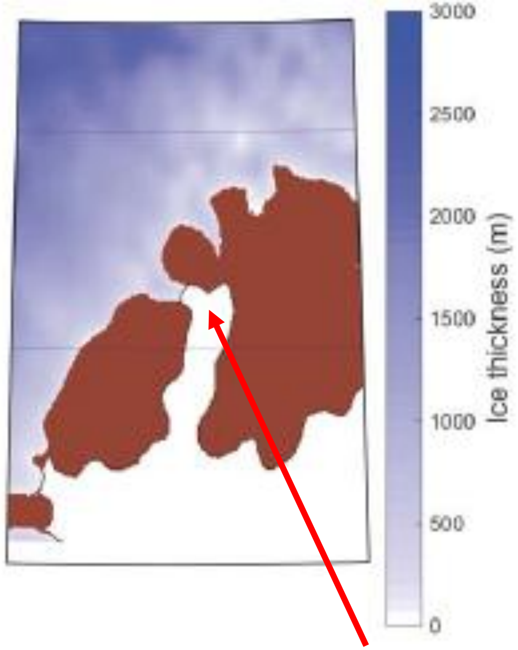
Ice loss from the East Antarctic Ice Sheet during late Pleistocene interglacials

David J. Wilson[1,2*], Rachel A. Bertram[1,2], Emma F. Needham[1], Tina van de Flierdt[1,2], Kevin J. Welsh[3], Robert M. McKay[4], Anannya Mazumder[3], Christina R. Riesselman[5,6], Francisco J. Jimenez-Espejo[7,8] & Carlota Escutia[8]

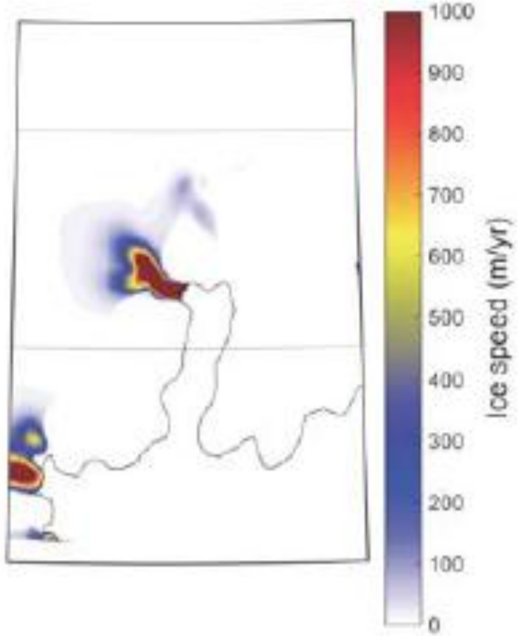
DeConto et al., in review

testing ice-cliff model physics in individual embayments
Helheim Glacier SE Greenland (1-km resolution)

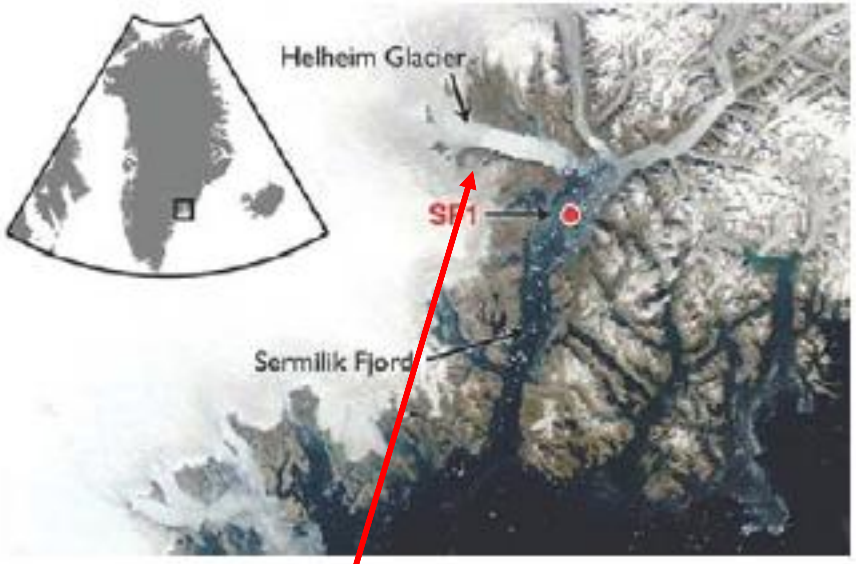
model ice thickness



model ice speed



observed cliff terminus



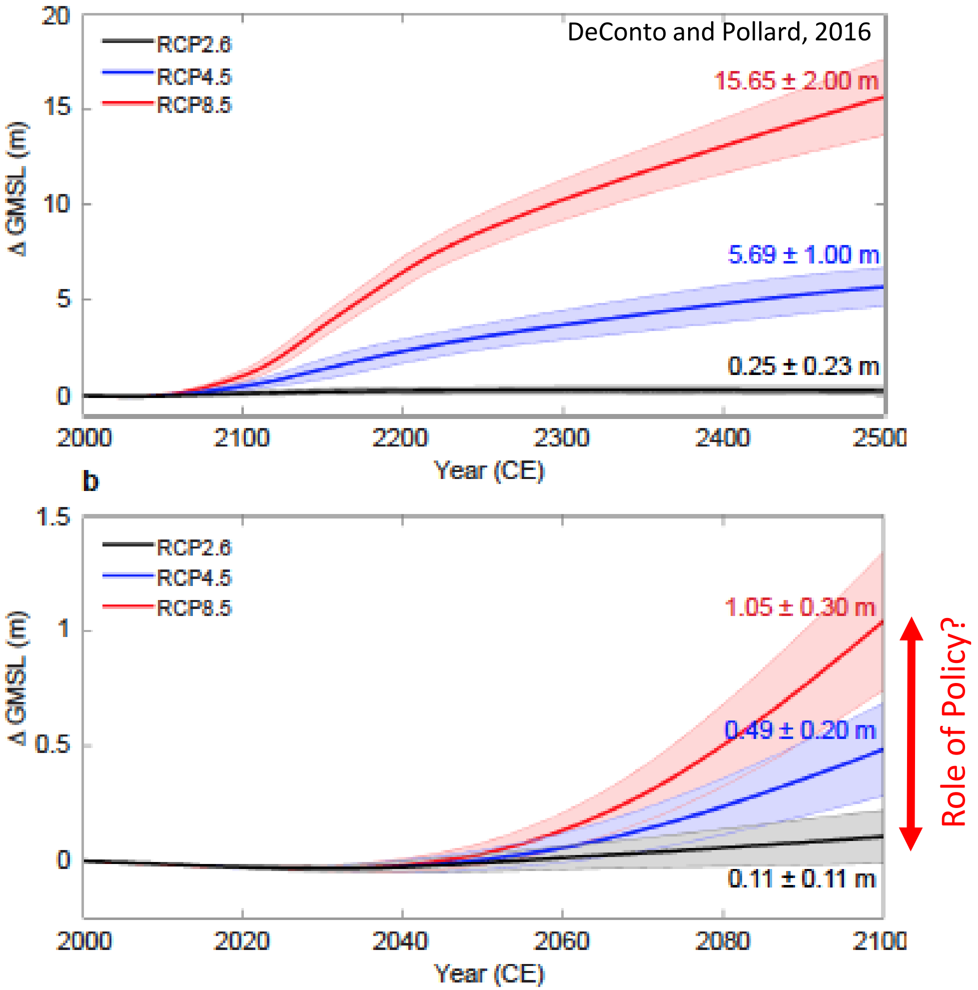
simulated cliff terminus

Observed cliff terminus

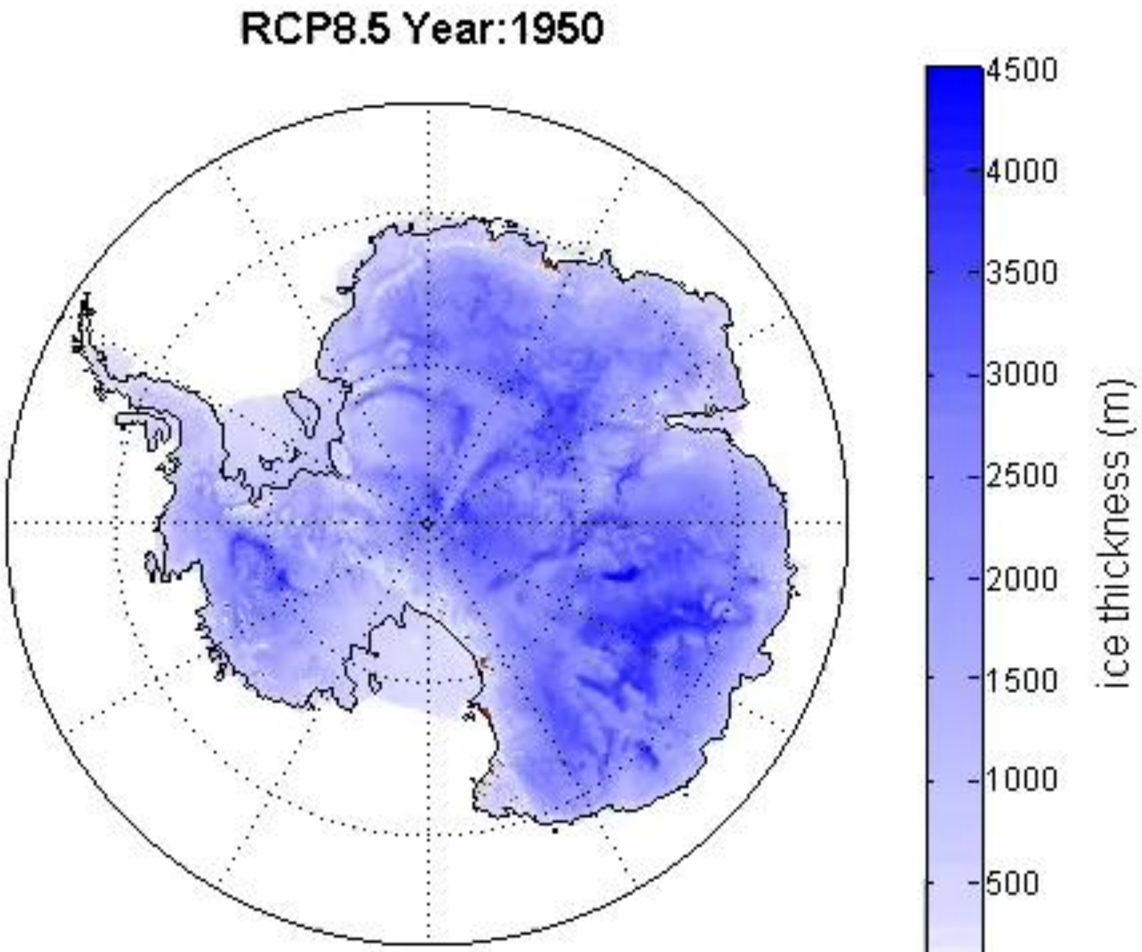
NASA

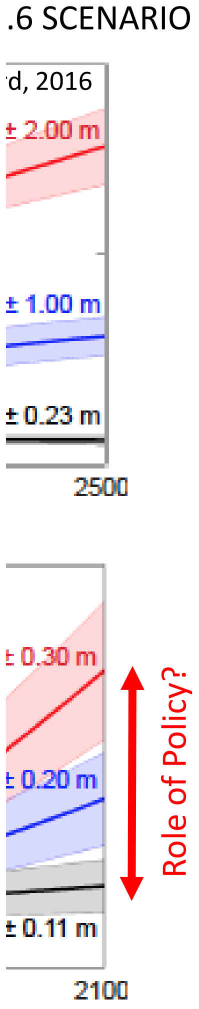
DeConto et al., in prep.

NOTE THE MAJOR REDUCTION IN RISK IN THE RCP2.6 SCENARIO



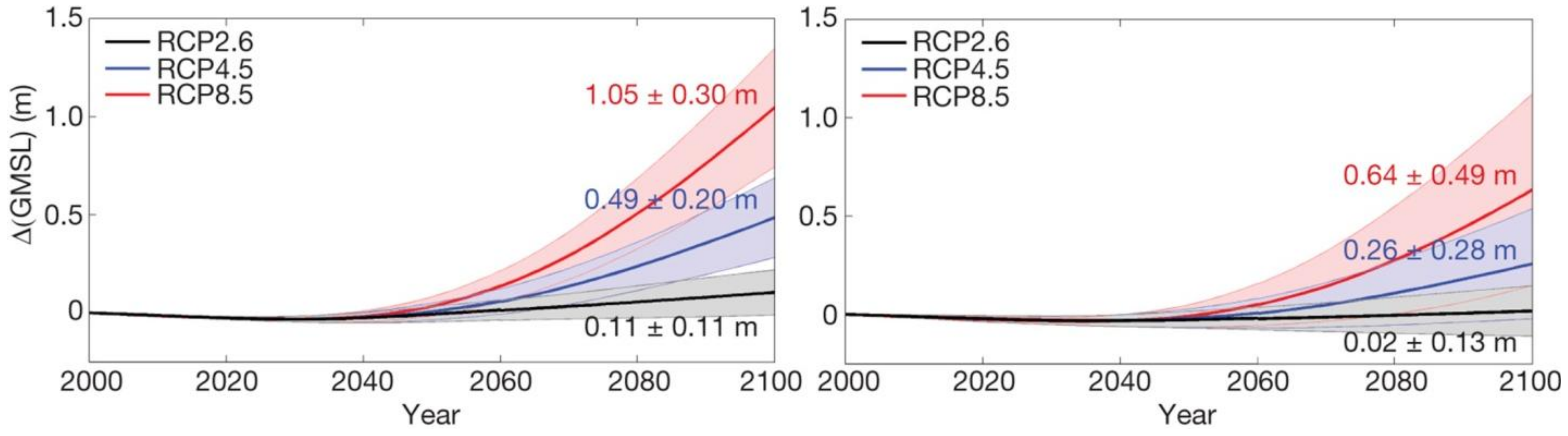

PARTICLE ACCELERA
NIGHT
AND DA
Twenty-four hours
of a synchrotro
PAGE 564


RCP8.5 Year:1950
4500
4000
3500
3000
2500
2000
1500
1000
500
0
ice thickness (m)


.6 SCENARIO
'd, 2016
± 2.00 m
± 1.00 m
± 0.23 m
2500
± 0.30 m
± 0.20 m
± 0.11 m
2100
Role of Policy?

Ensemble model analyses of future Antarctic contributions sea level

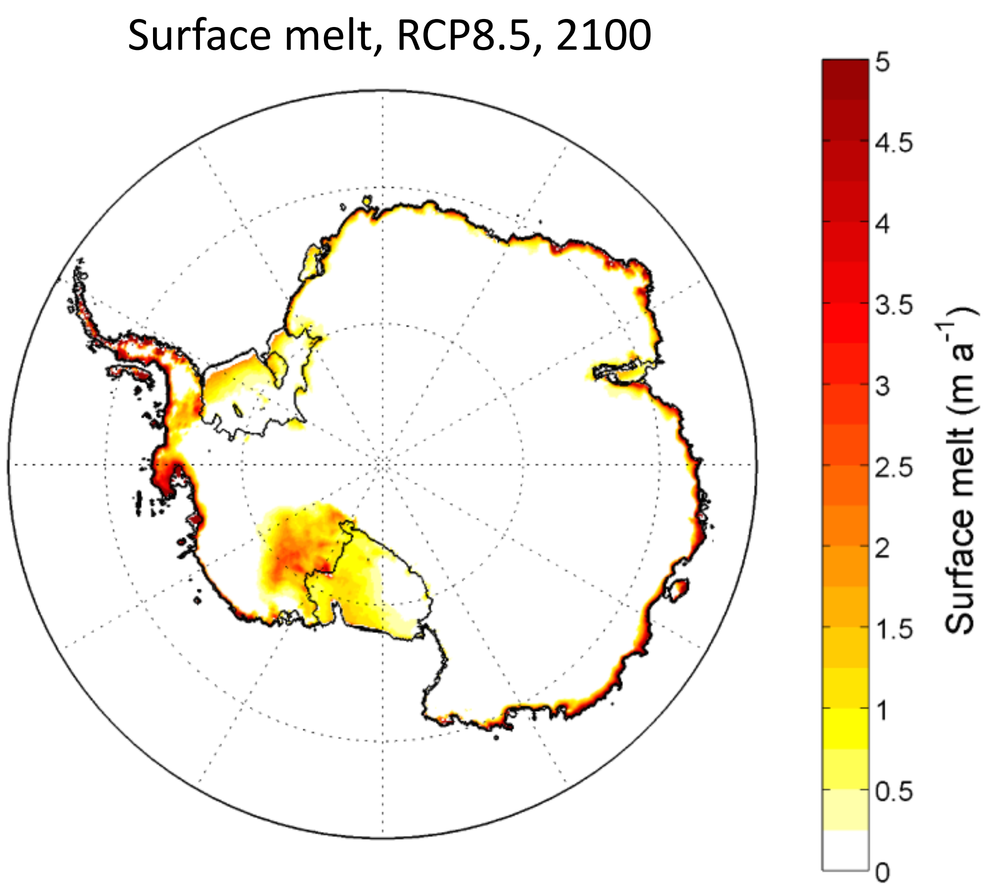
Model calibrated with +5-15 m Pliocene sea level Model calibrated with +10-20 m Pliocene sea level

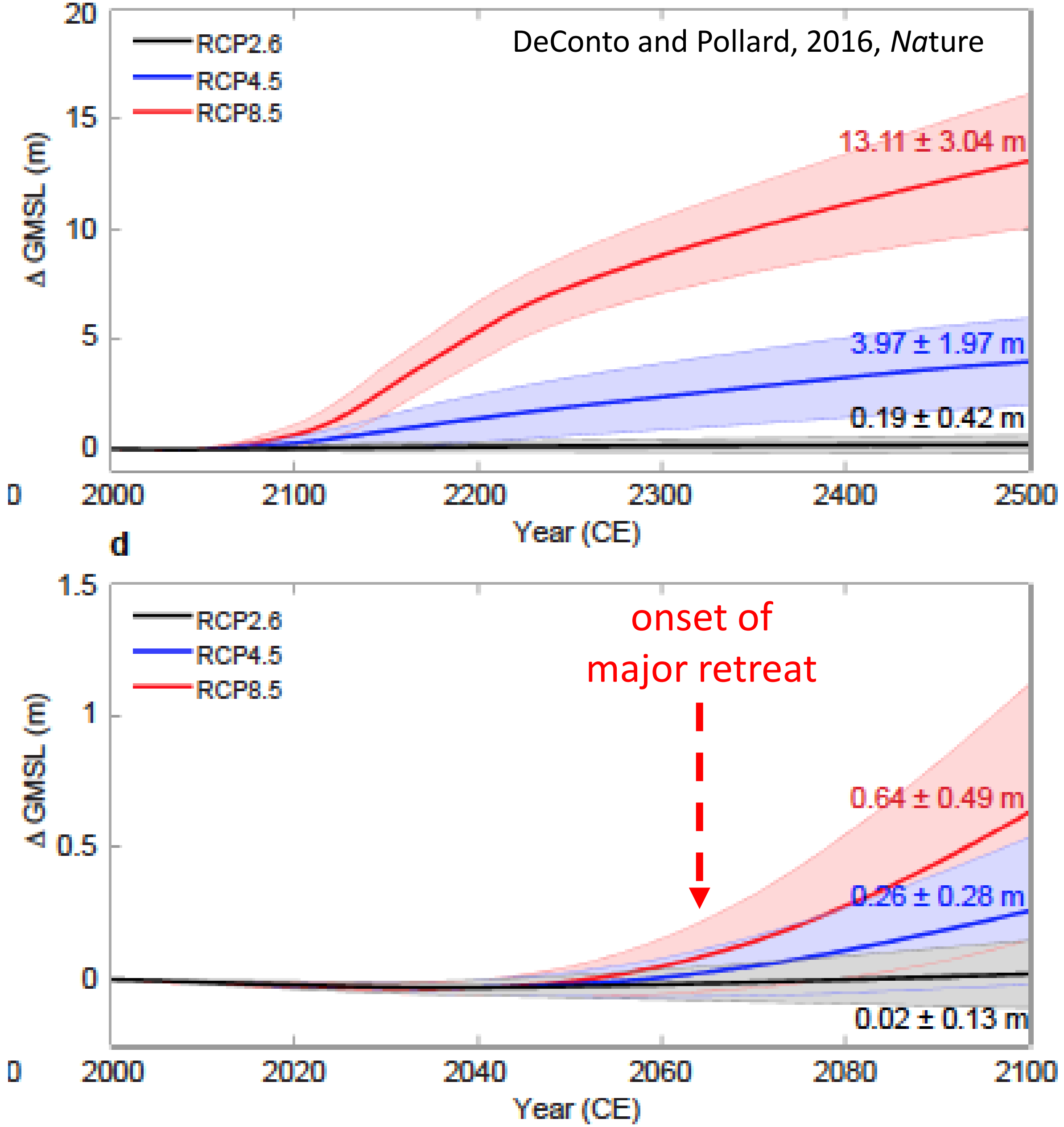


R M DeConto *et al. Nature* **531,** 591–597 (2016) doi:10.1038/nature17145

nature

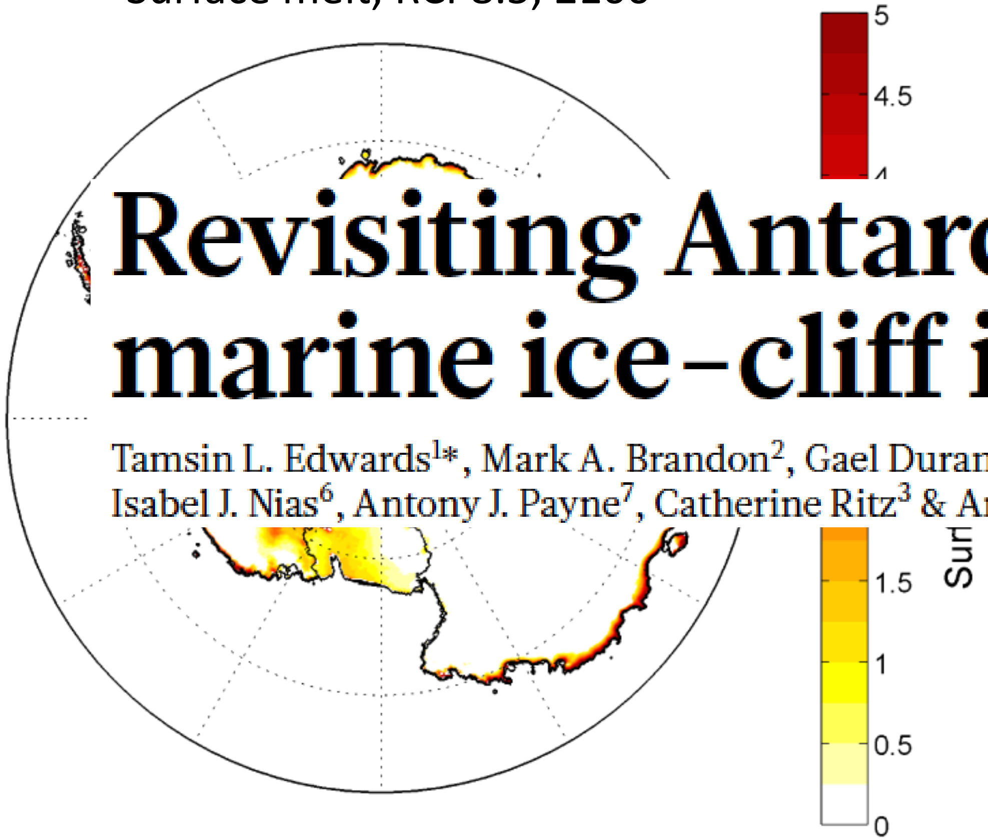
Future RCP ensembles with paleo-calibrated model physics

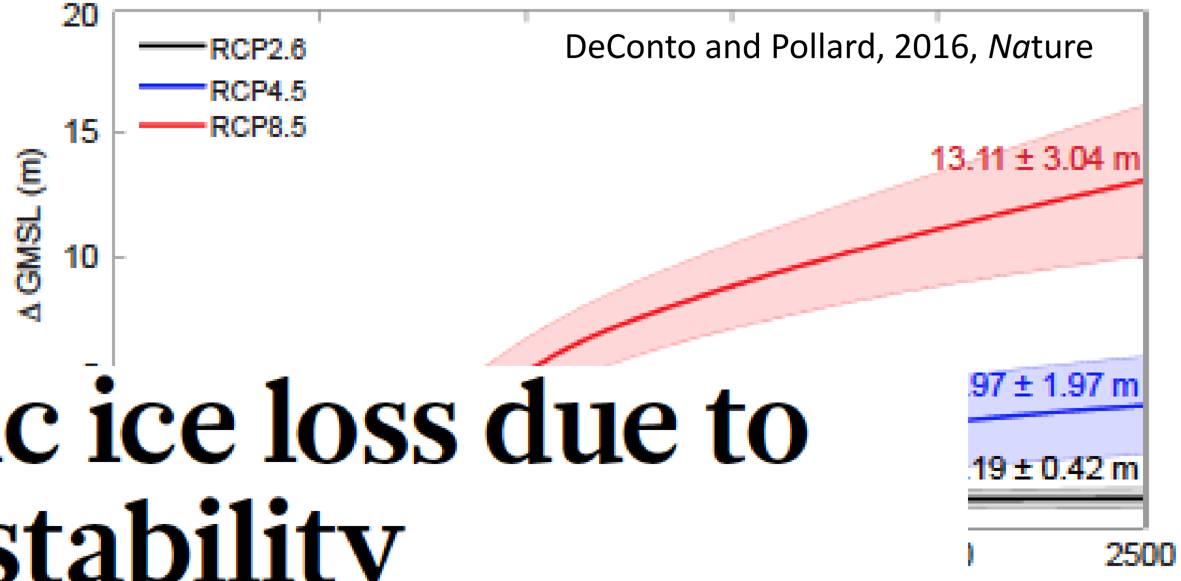




Future RCP ensembles with paleo-calibrated model physics

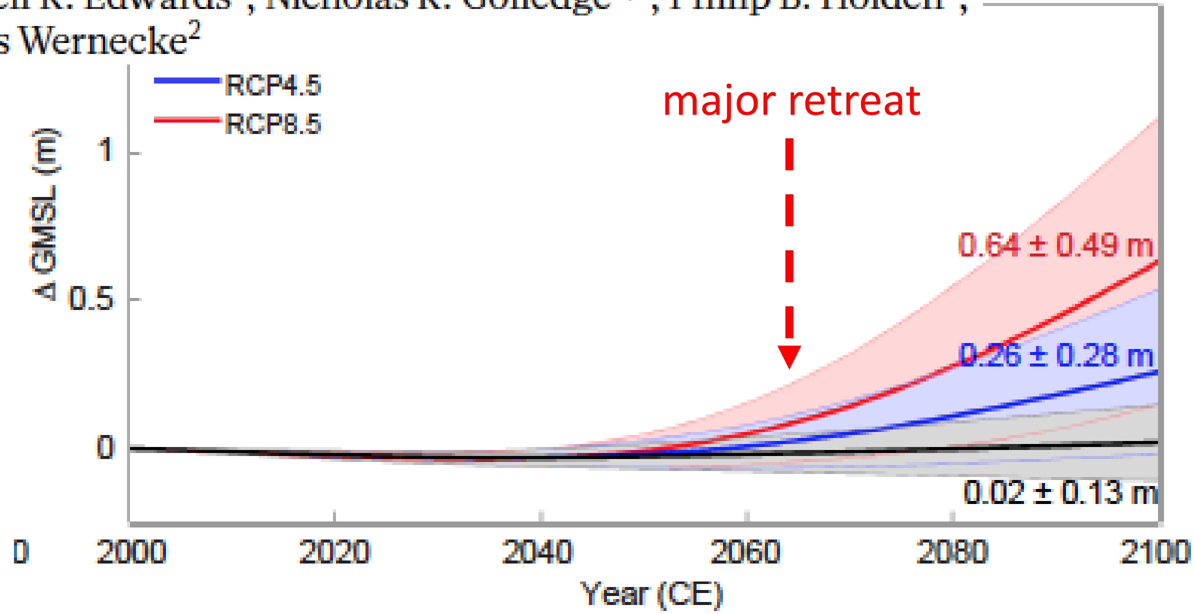
Surface melt, RCP8.5, 2100



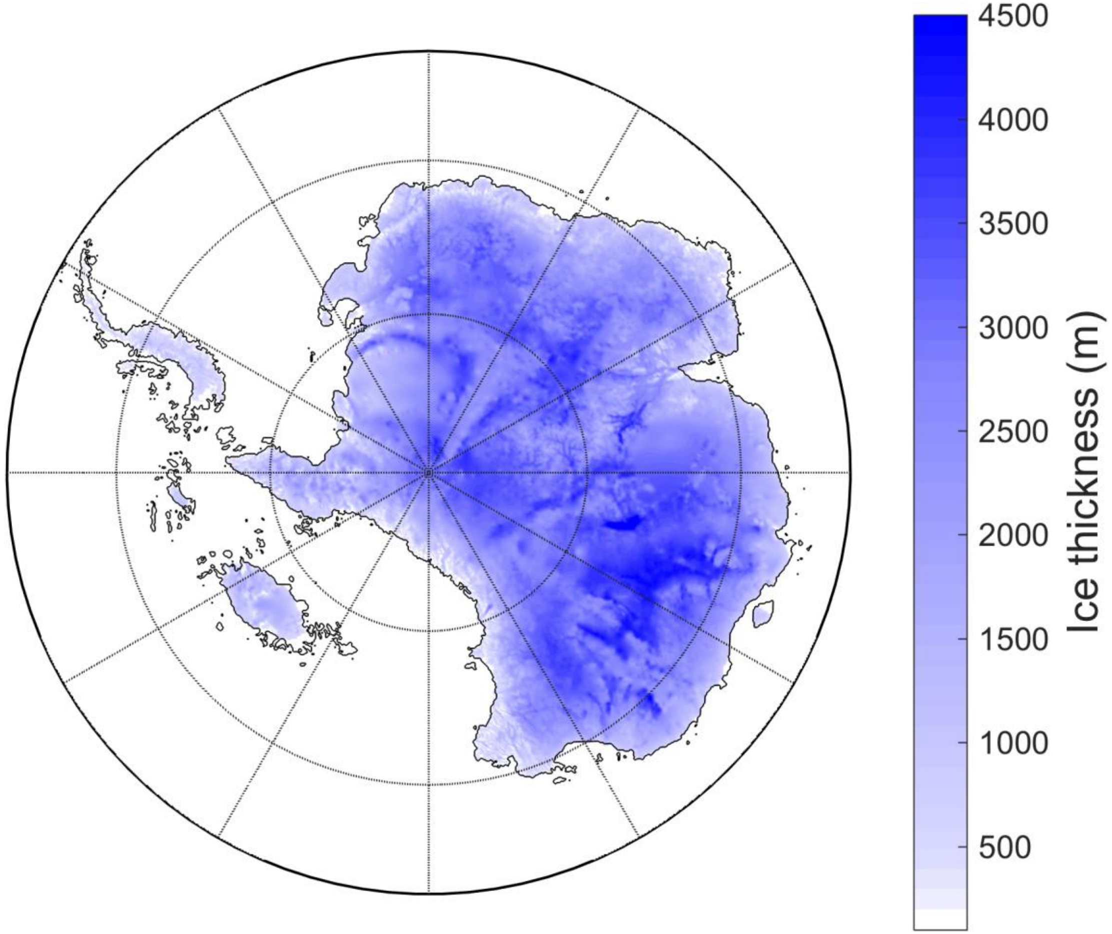


Revisiting Antarctic ice loss due to marine ice-cliff instability

Tamsin L. Edwards[1*], Mark A. Brandon[2], Gael Durand[3], Neil R. Edwards[2], Nicholas R. Golledge[4,5], Philip B. Holden[2], Isabel J. Nias[6], Antony J. Payne[7], Catherine Ritz[3] & Andreas Wernecke[2]



Pliocene ice sheet simulations without brittle fracture processes included

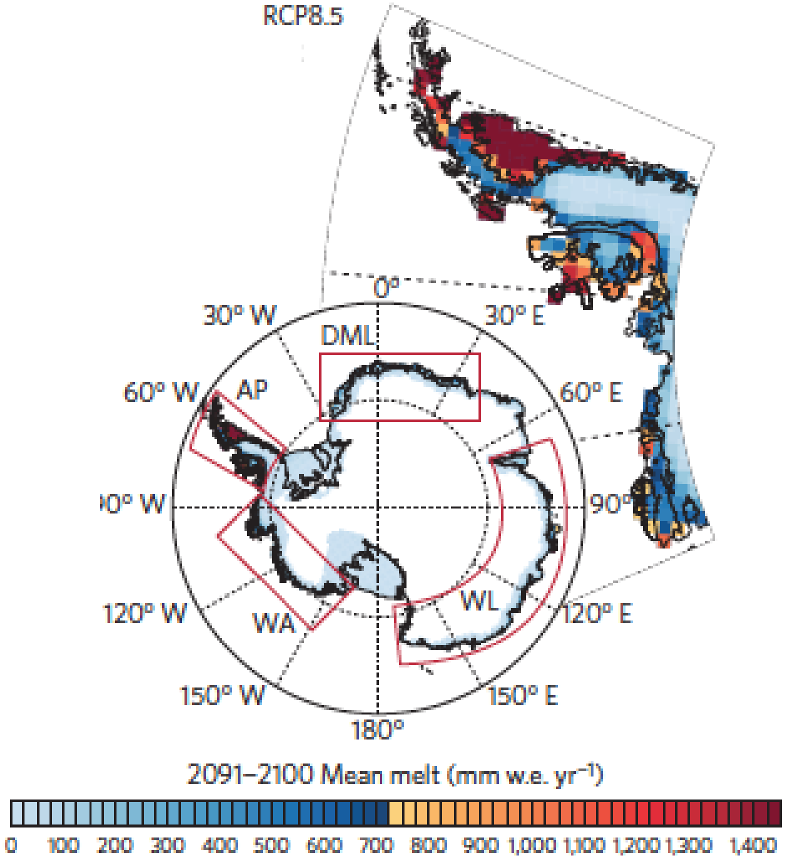


DeConto et al., in review

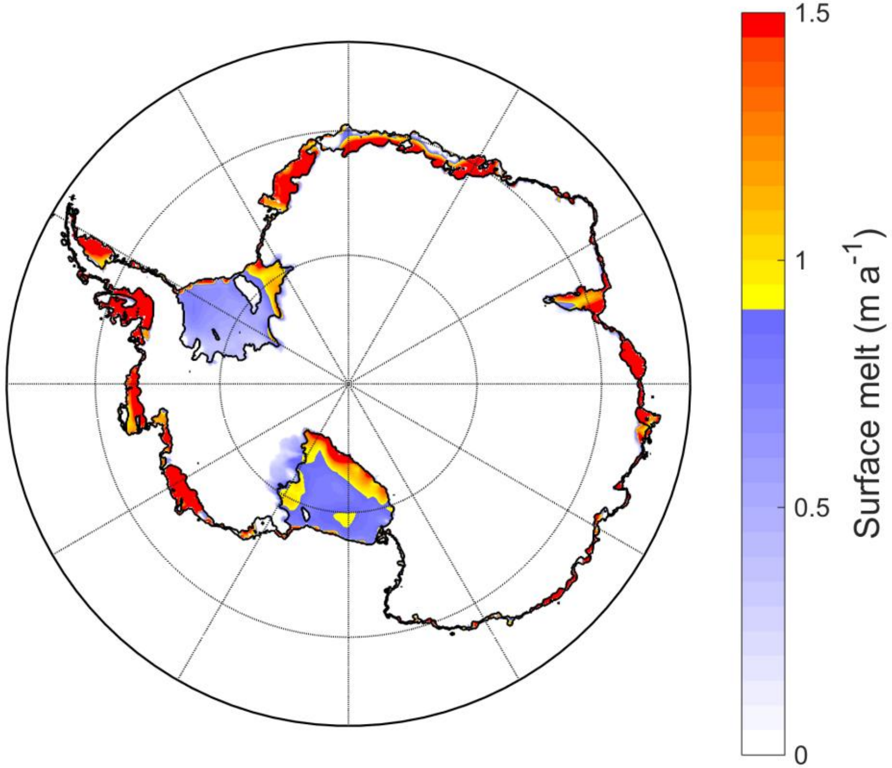
Time-evolving RCM atmospheric forcing (surface melt+rain water)

Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios

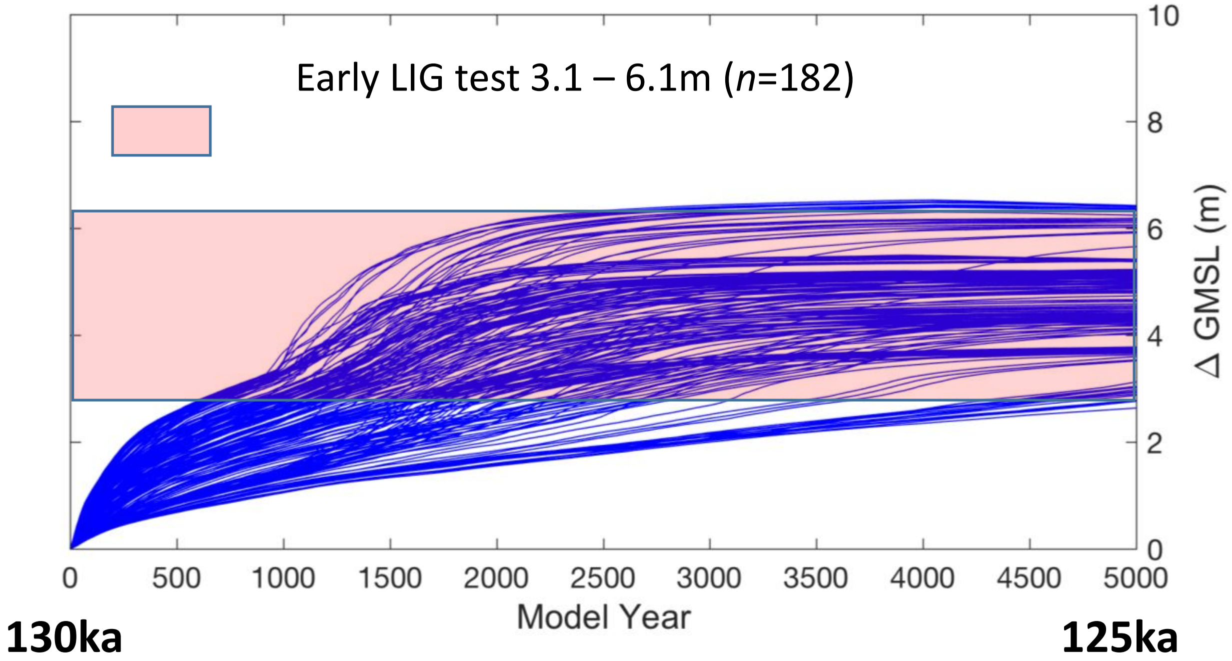
Luke D. Trusel[1,2*], Karen E. Frey[2], Sarah B. Das[1], Kristopher B. Karnauskas[1], Peter Kuipers Munneke[3,4], Erik van Meijgaard[5] and Michiel R. van den Broeke[3]

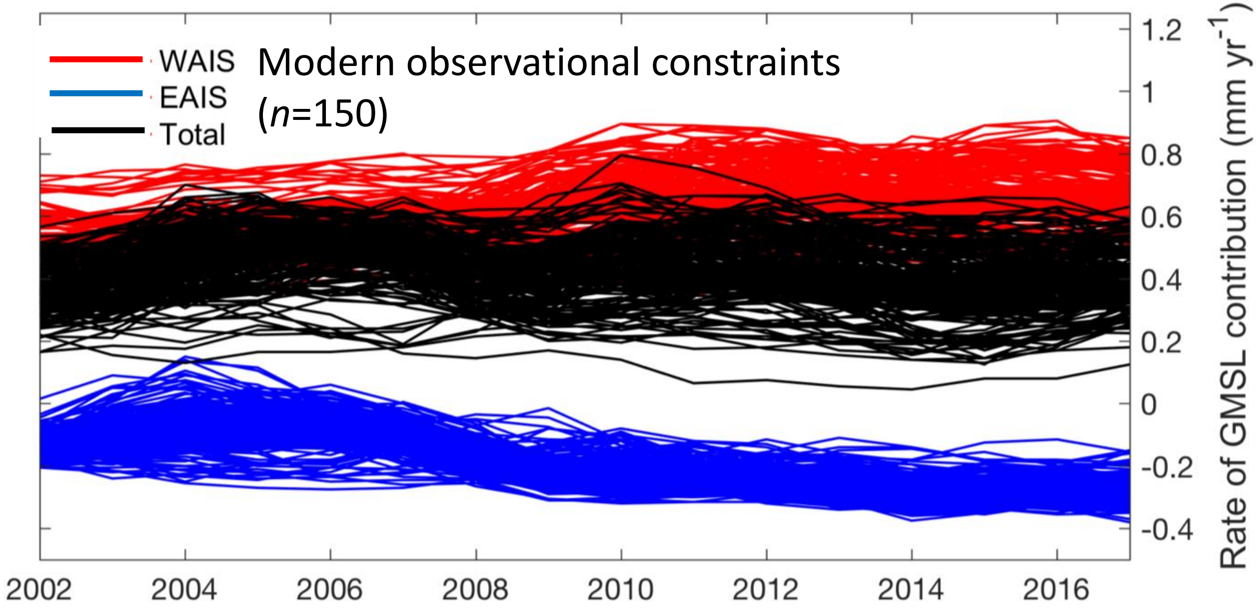


Surface meltwater production RCP8.5, 2100 CE



Last Interglacial raw ensemble (*n*=196)



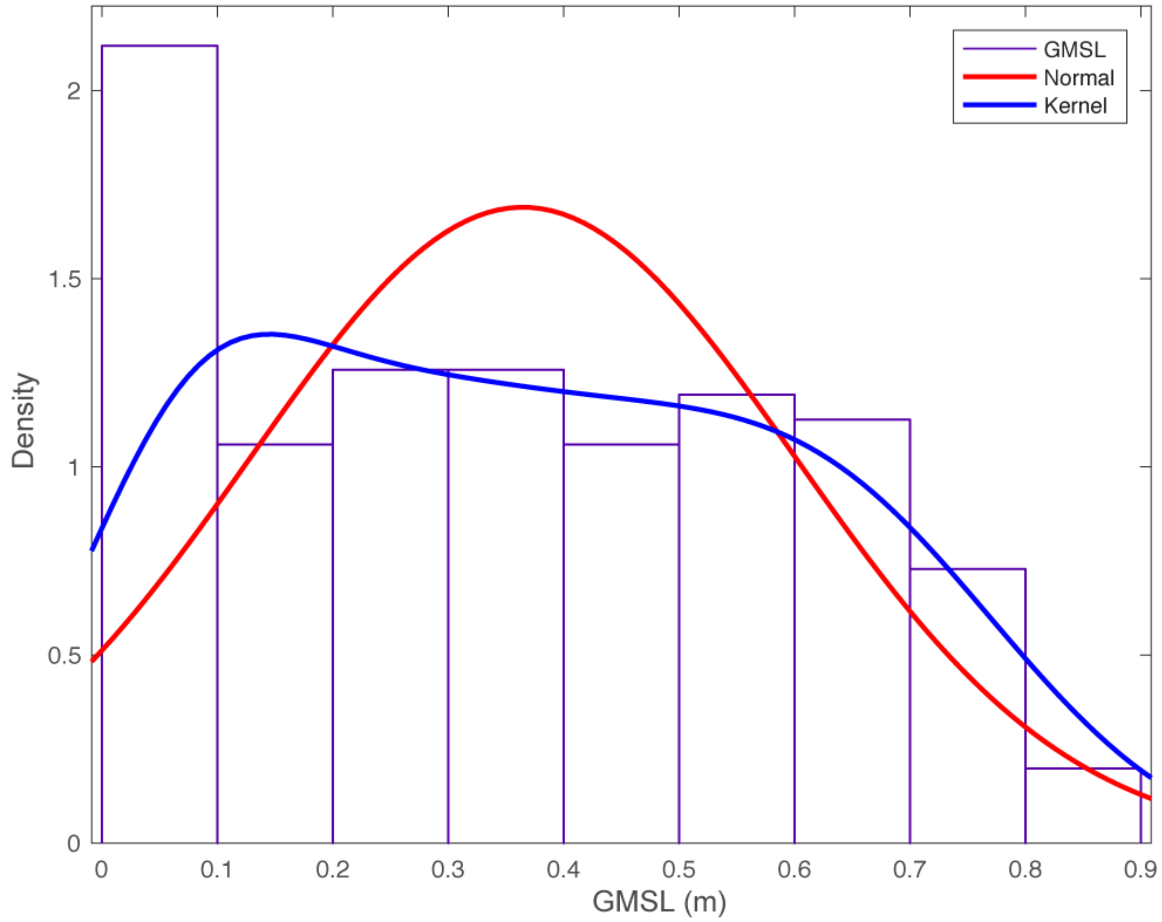


DeConto et al., in review

Implications of having better paleo-constraints

RCP8.5 GMSL contribution from Antarctica in 2100

3.1-6.1 LIG sea level from Antarctica



DeConto et al., in review

Implications of having better paleo-constraints

RCP8.5 GMSL contribution from Antarctica in 2100

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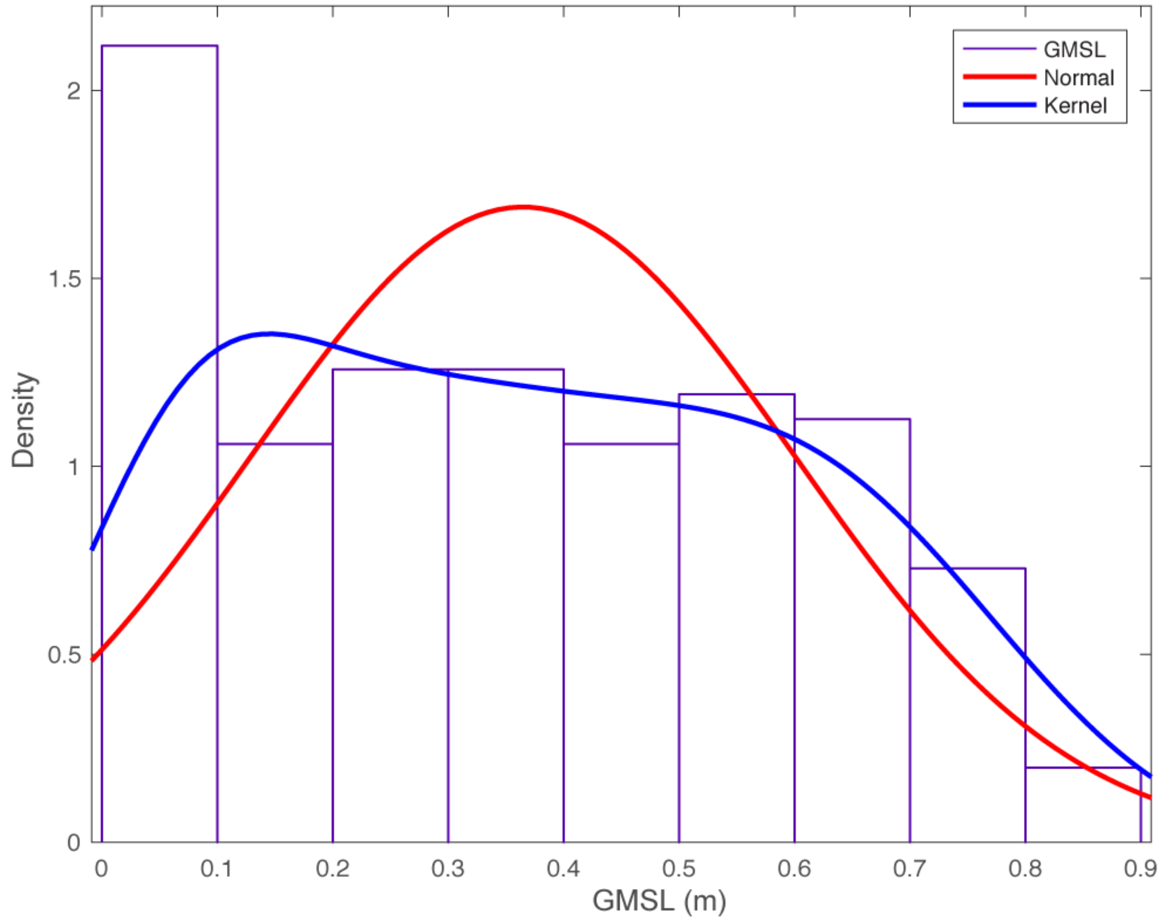
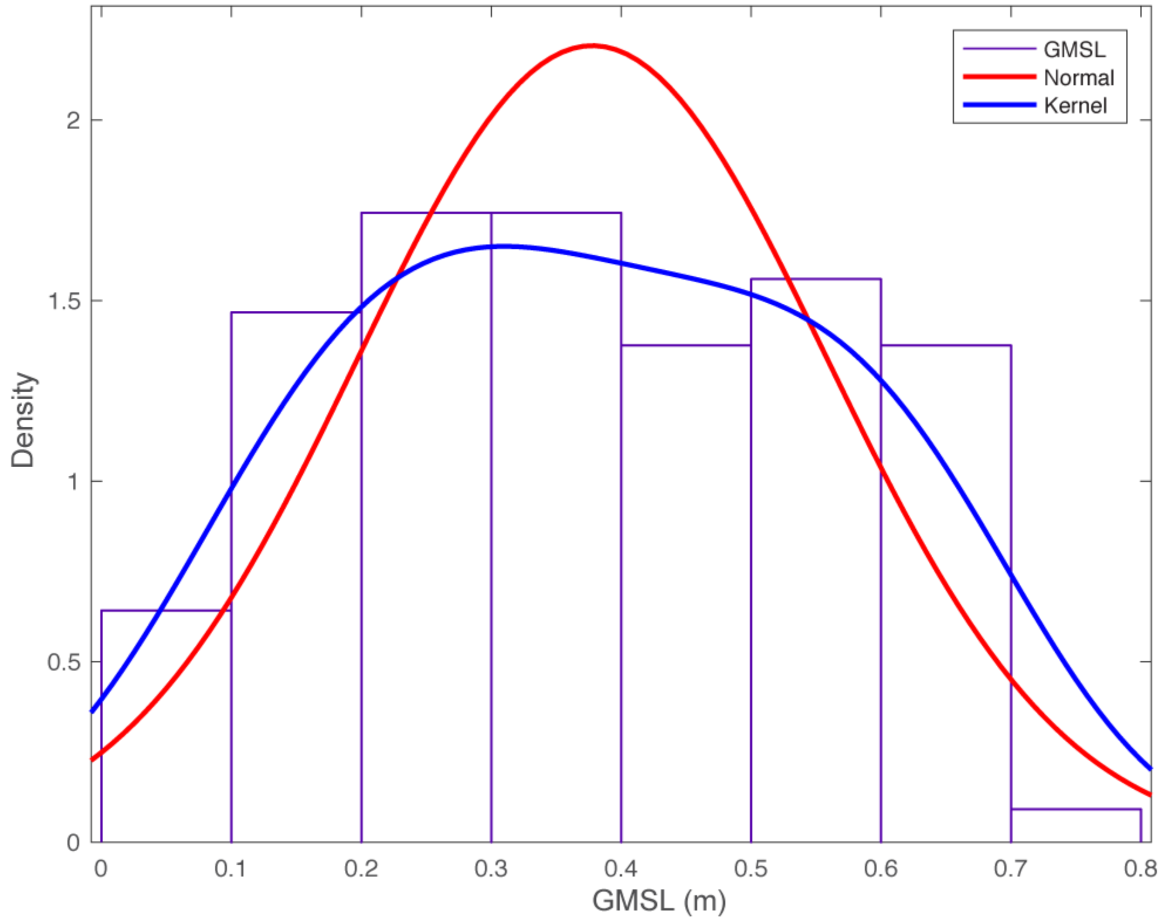
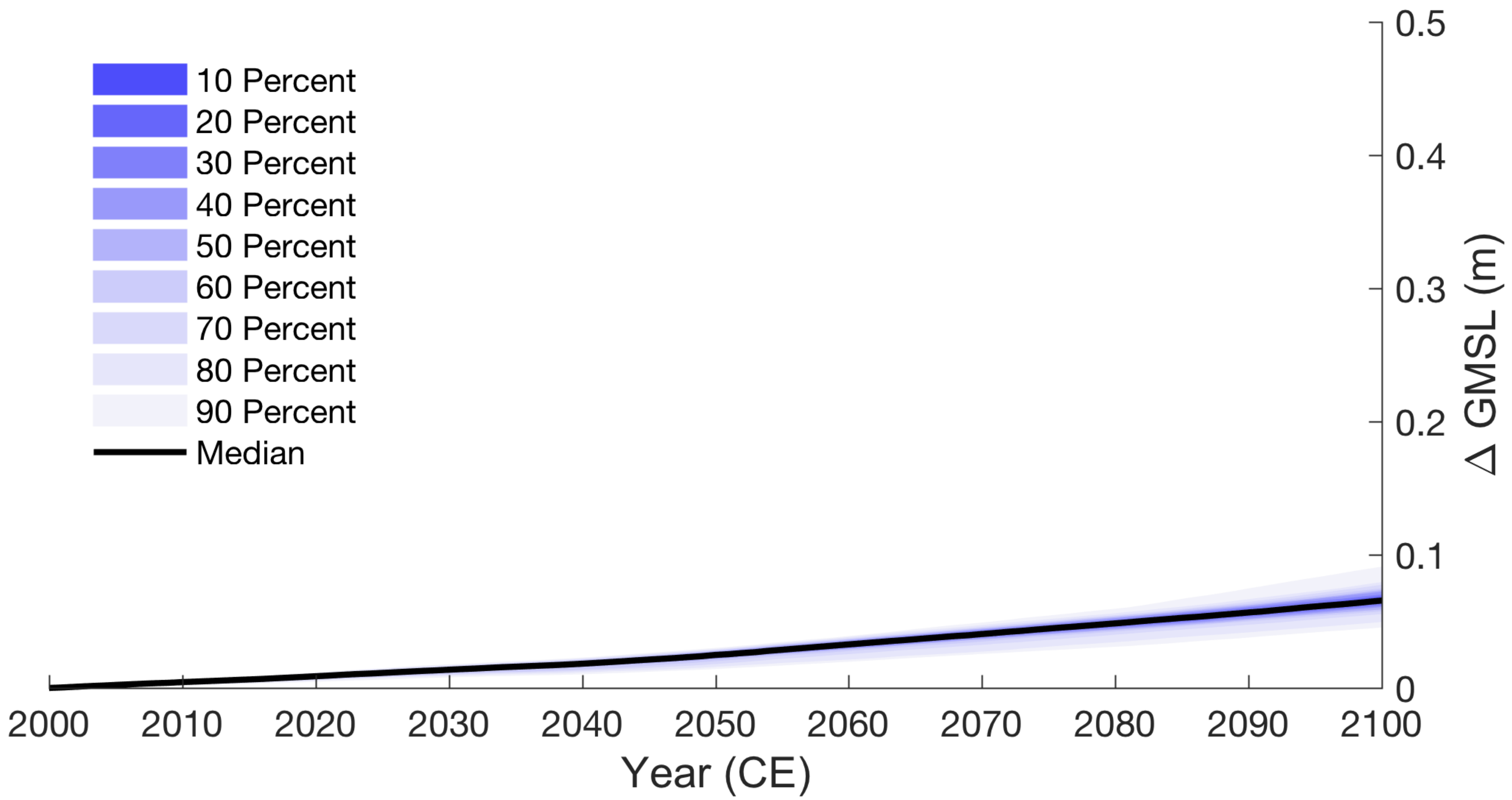


3.6-5.6 LIG sea level from Antarctica



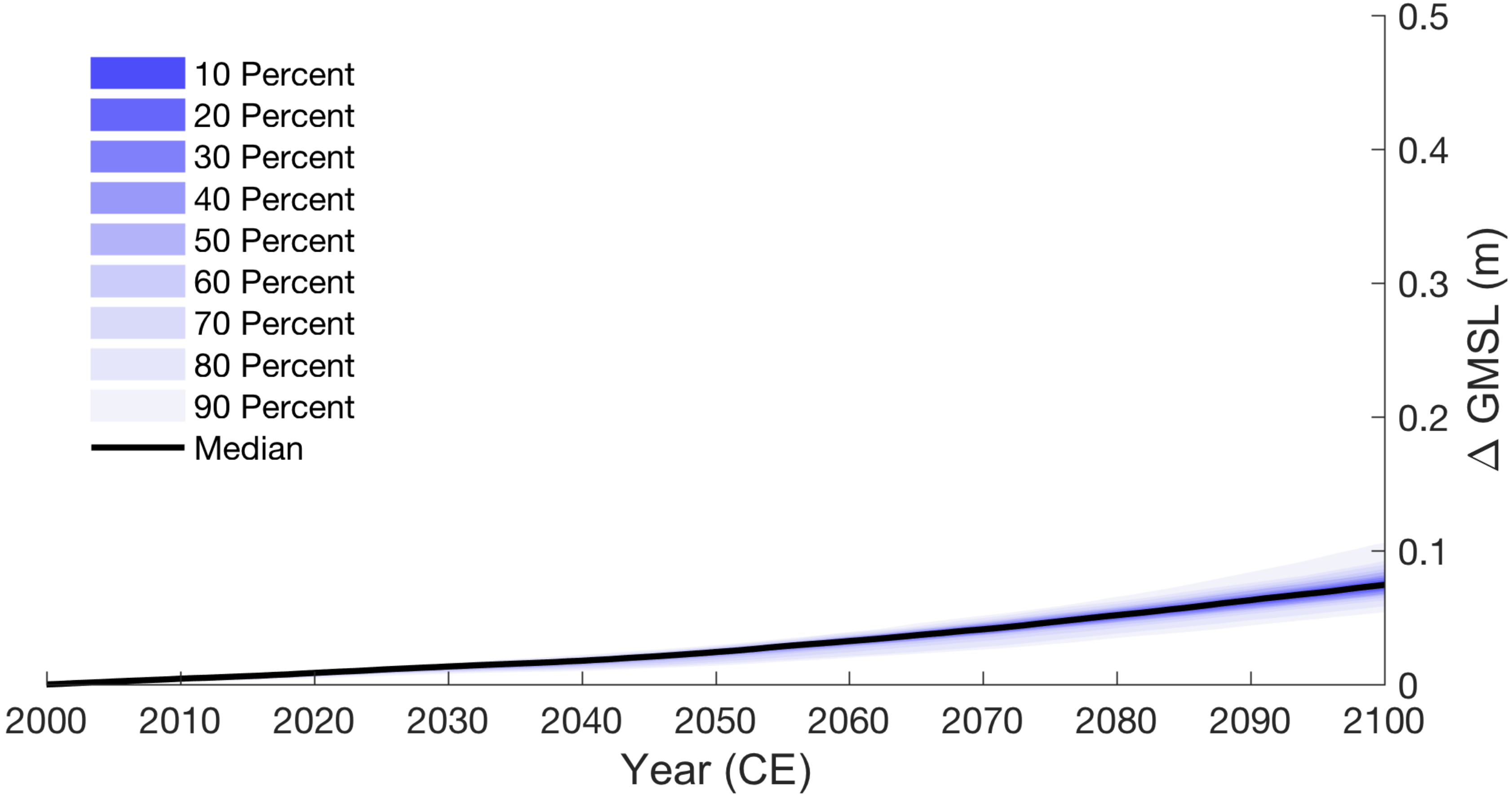
DeConto et al., in review

+1.5ºC global mean warming limit



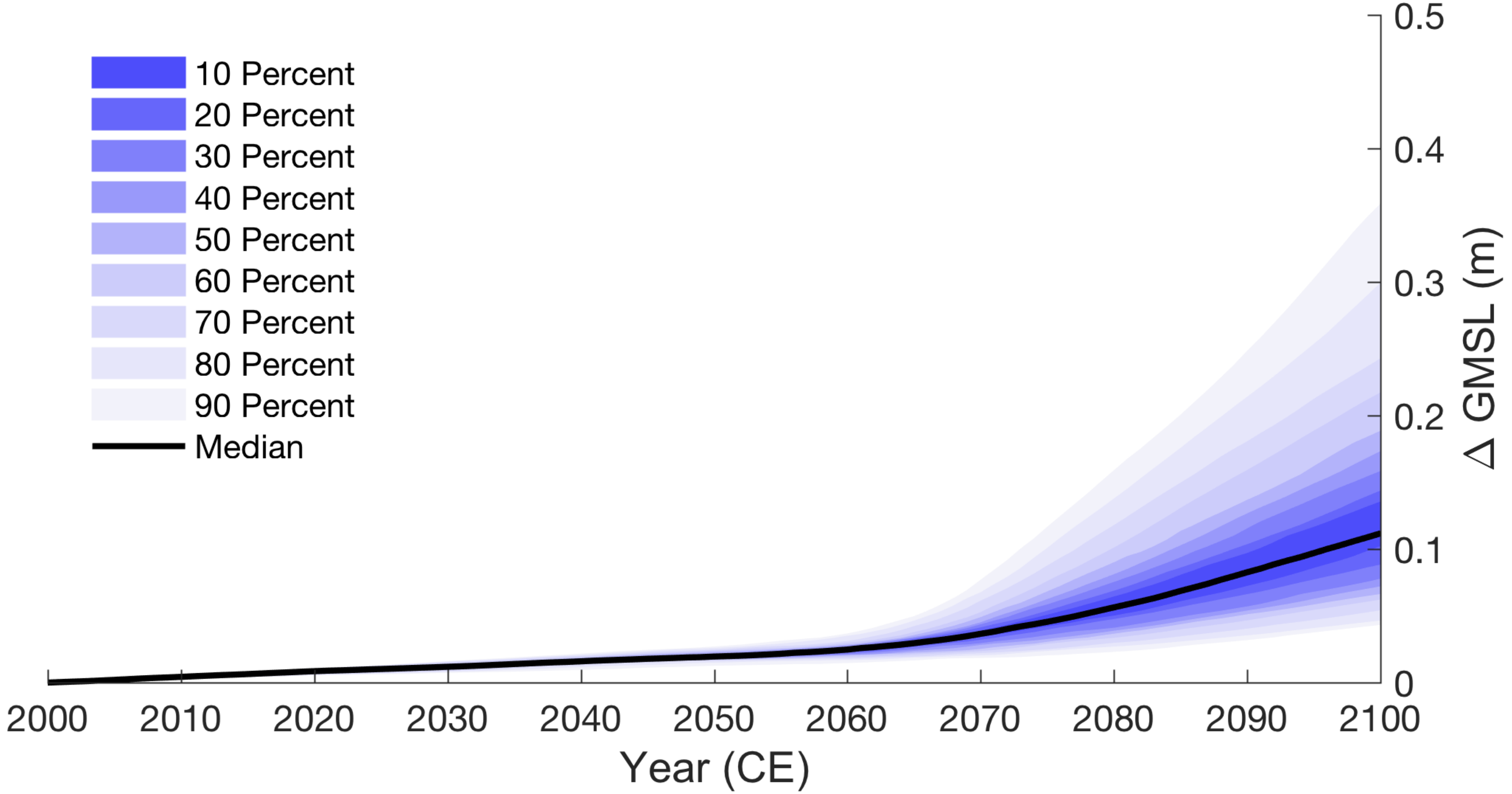
DeConto et al., in review

+2.0ºC global mean warming limit



DeConto et al., in review

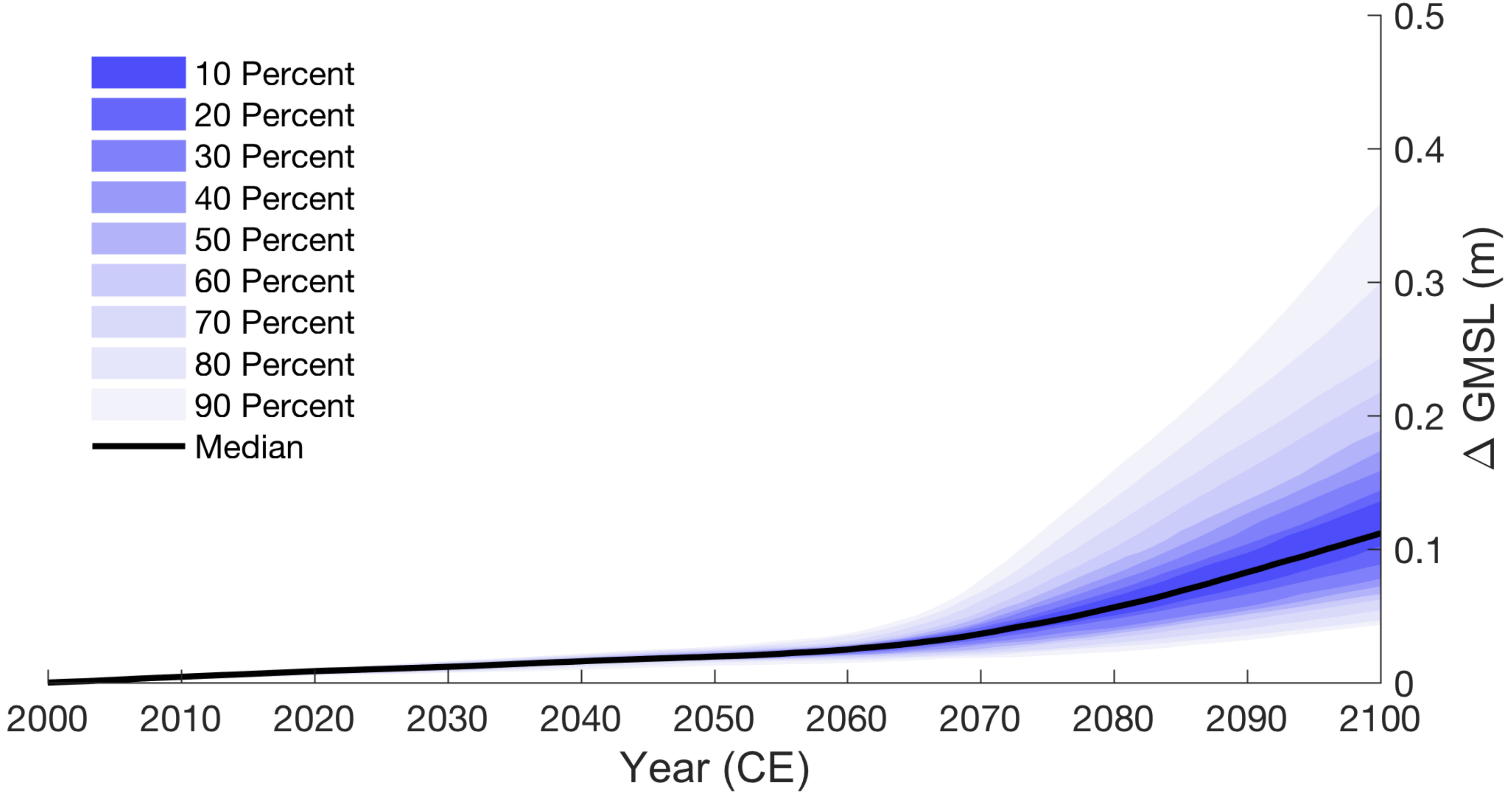
+3.0ºC global mean warming limit



DeConto et al., in review

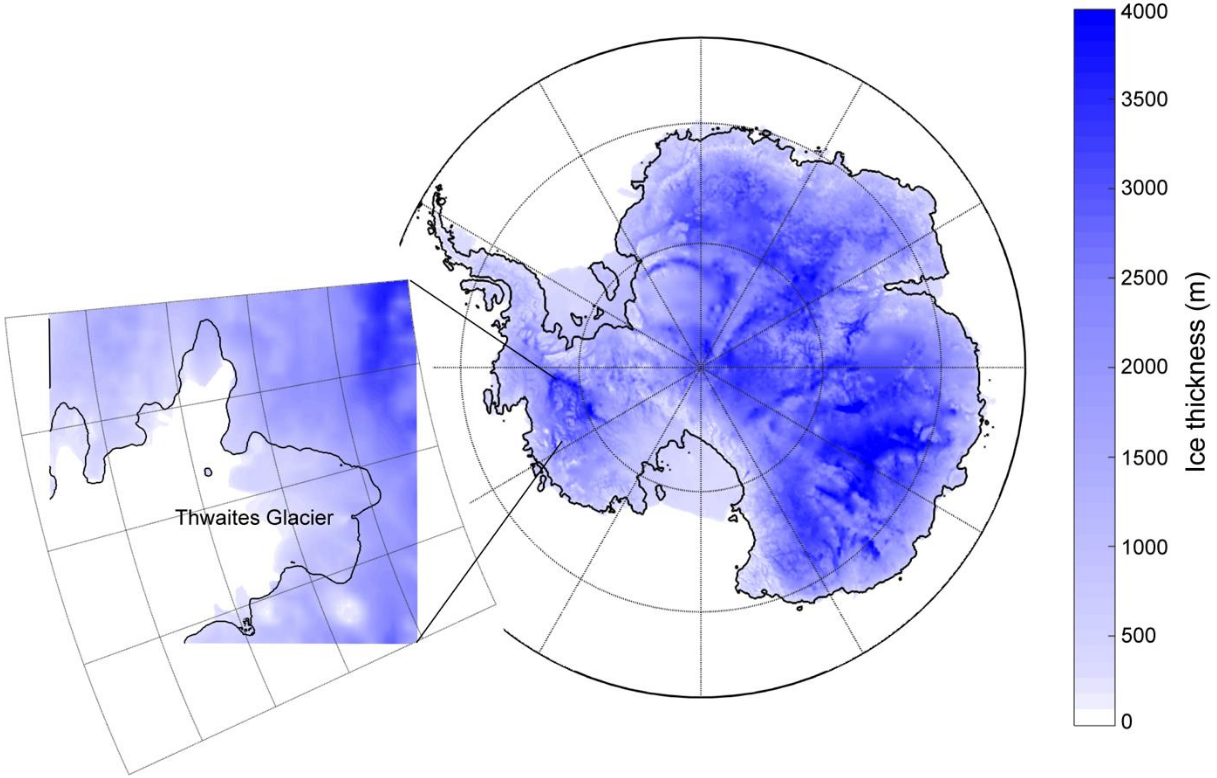
+3.0ºC global mean warming limit

Is this a real threshold?



DeConto et al., in review

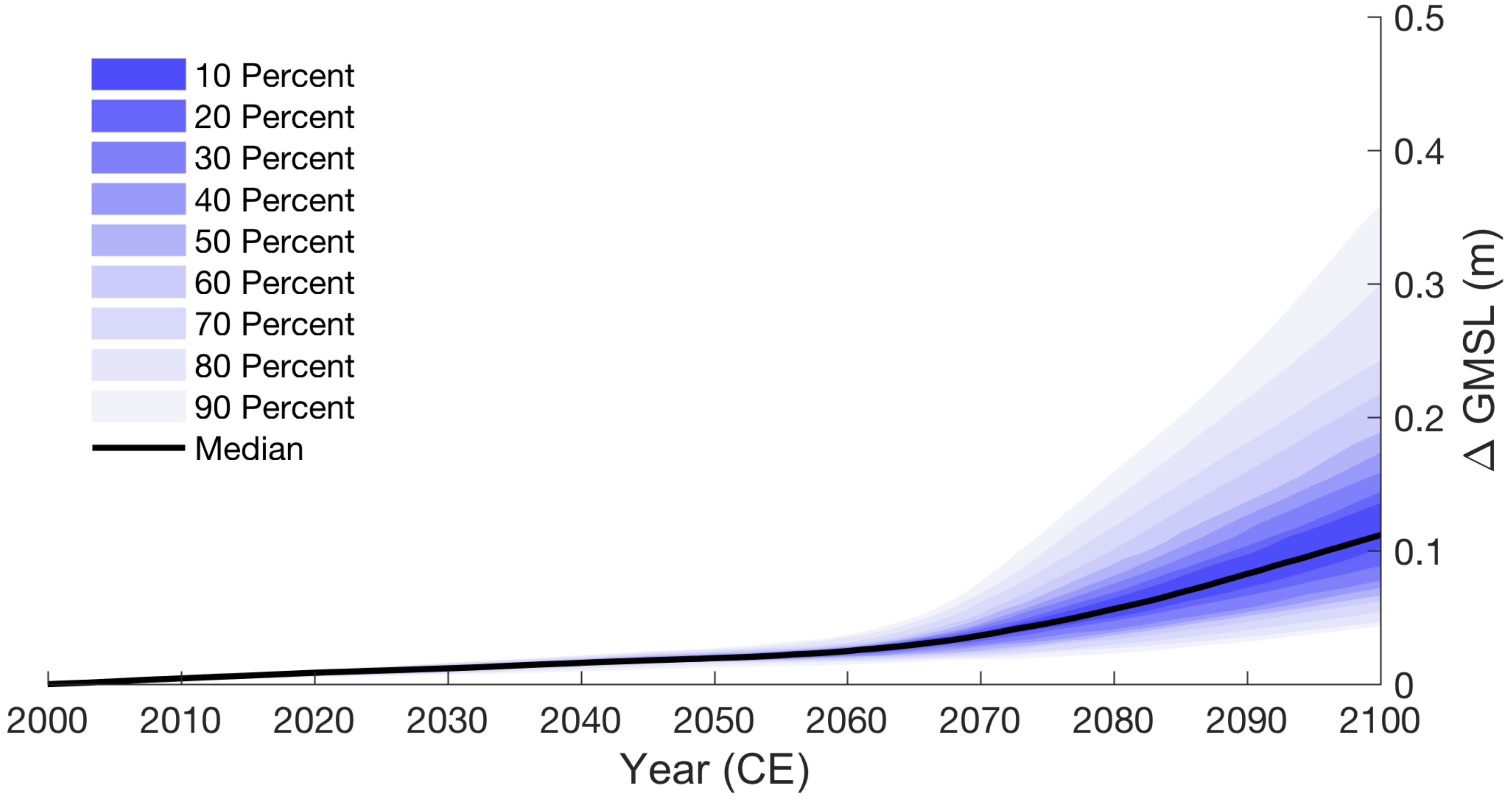
Antarctic retreat in 2100, with ice-cliff calving limited to Greenland-like rates (1 km resolution)



DeConto et al., in review

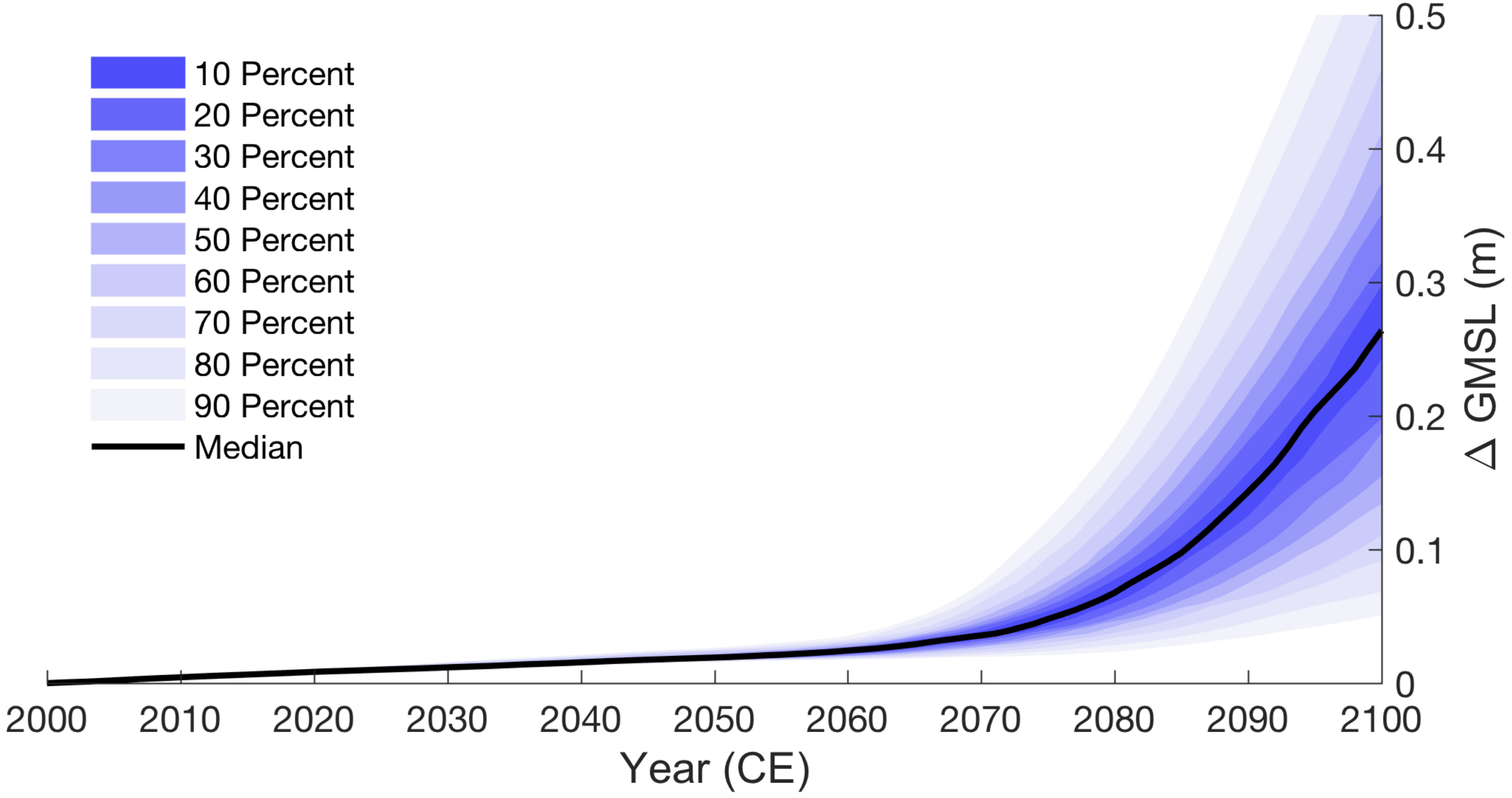
+3.0ºC global mean warming limit

Is this a real threshold?



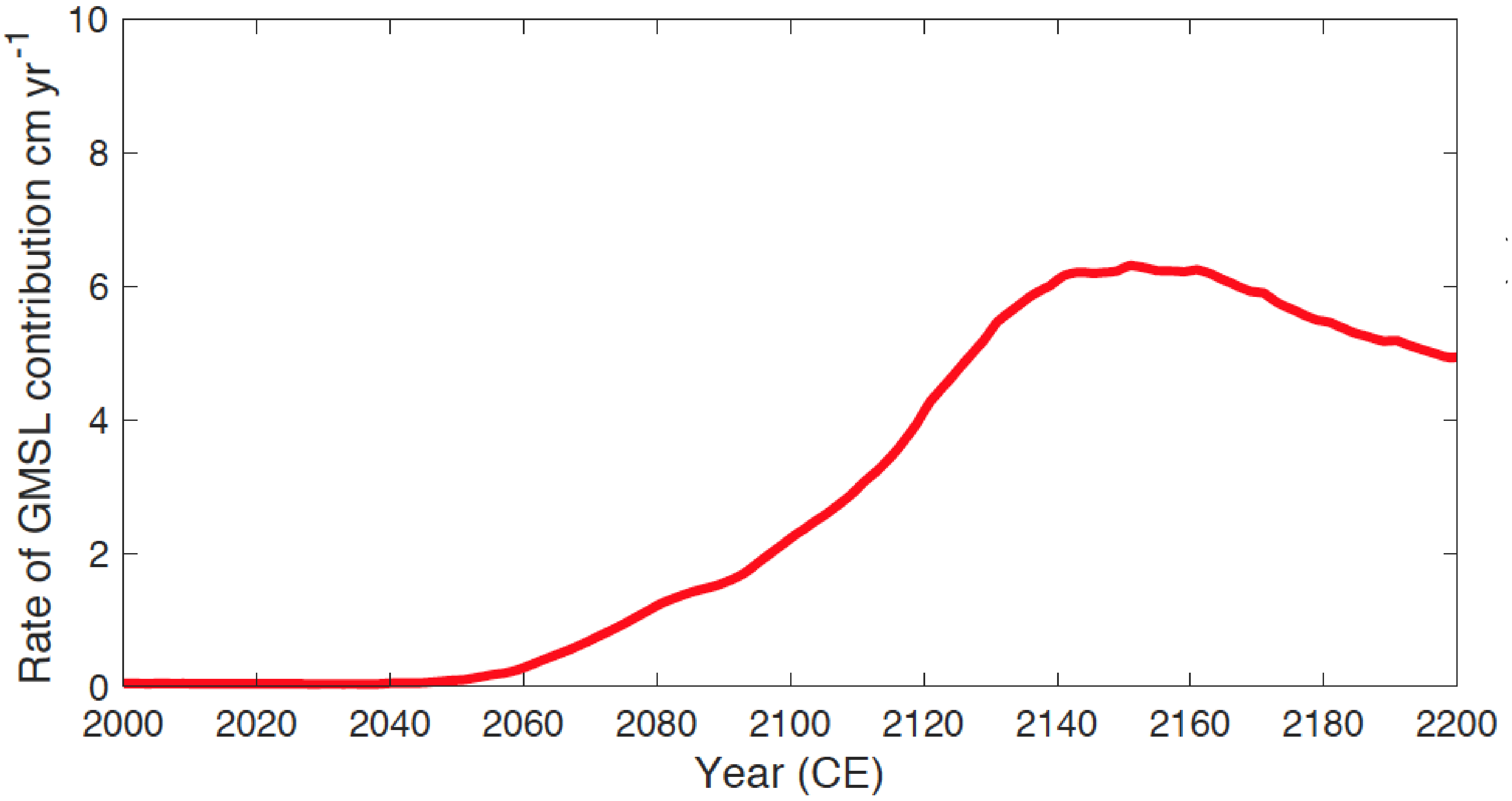
DeConto et al., in review

RCP8.5



DeConto et al., in review

RCP8.5 rate of sea-level rise from Antarctica limited to Greenland-like calving rates



DeConto et al., in review

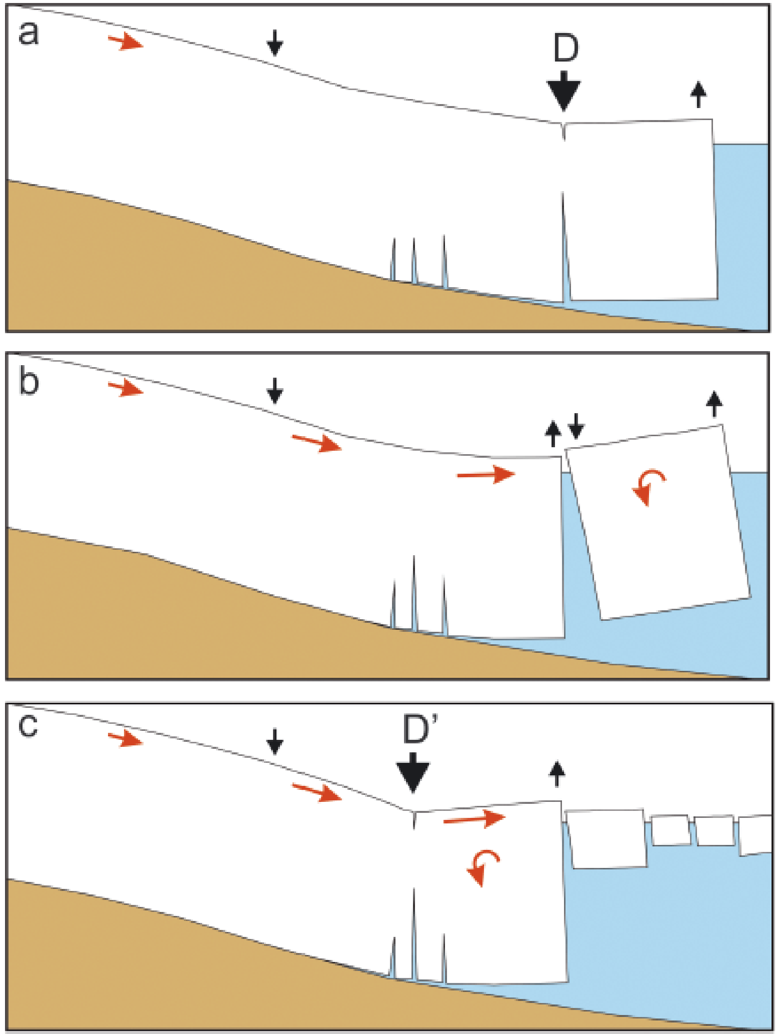
Helheim Glacier, SE Greenland

(Photo, Knut Christianson)

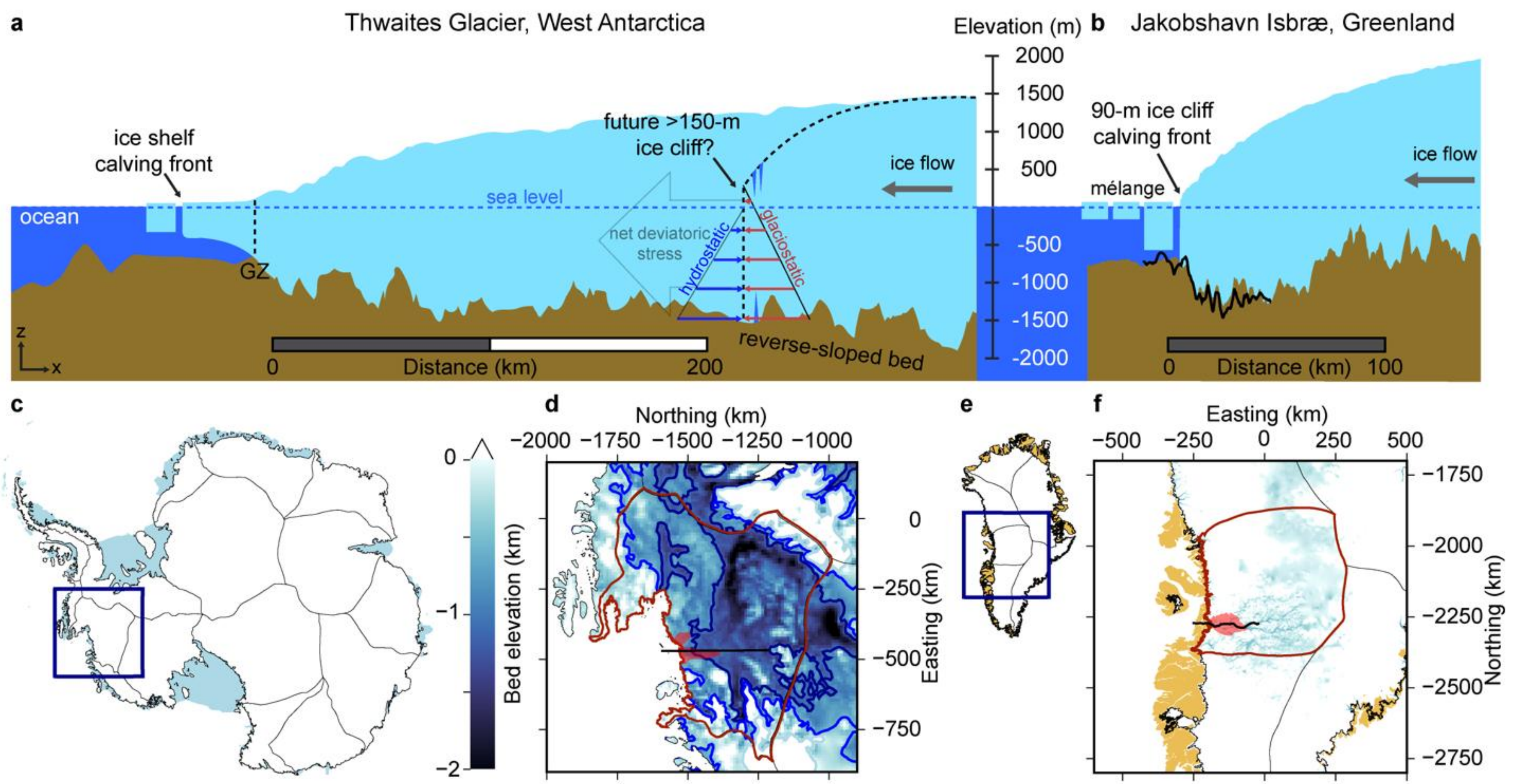
Dynamics of glacier calving at the ungrounded margin of Helheim Glacier, southeast Greenland

Tavi Murray[1], Nick Selmes[1], Timothy D. James[1], Stuart Edwards[2], Ian Martin[2], Timothy O'Farrell[3], Robin Aspey[3], Ian Rutt[1], Meredith Nettles[4], and Tim Baugé[5]

JGR, 2015

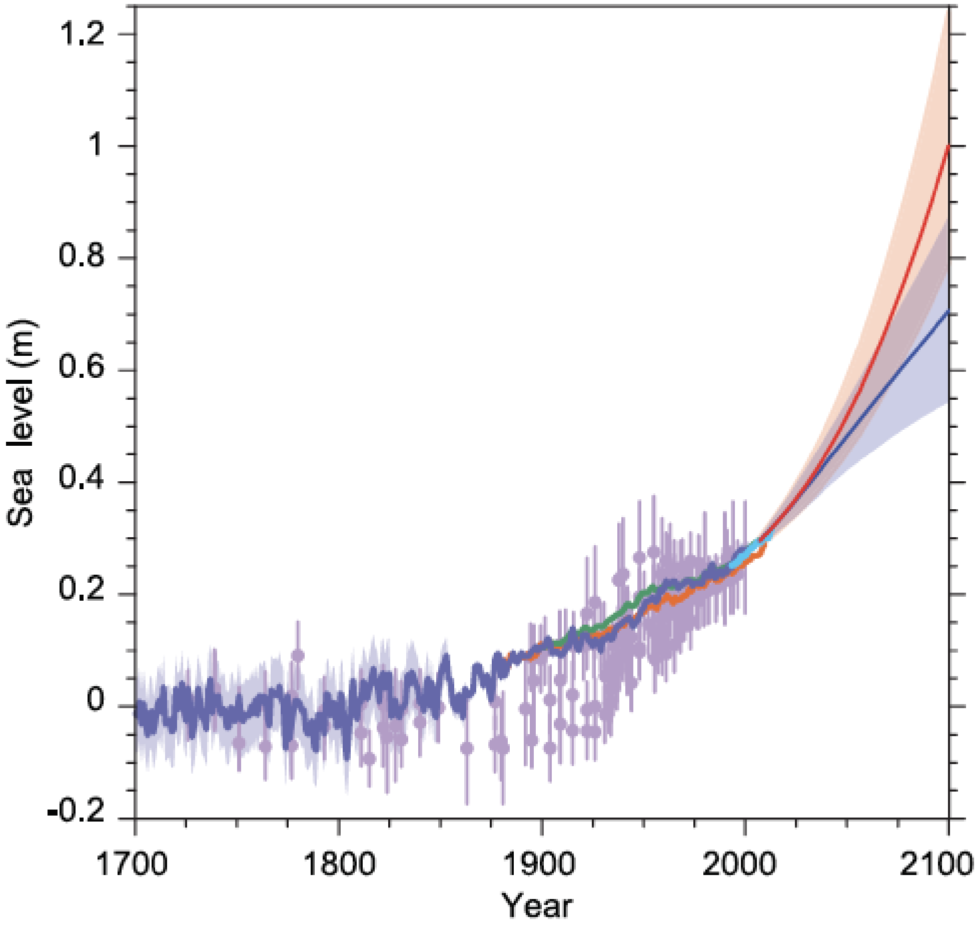


Could we still be underestimating the potential rate of retreat in Antarctica?



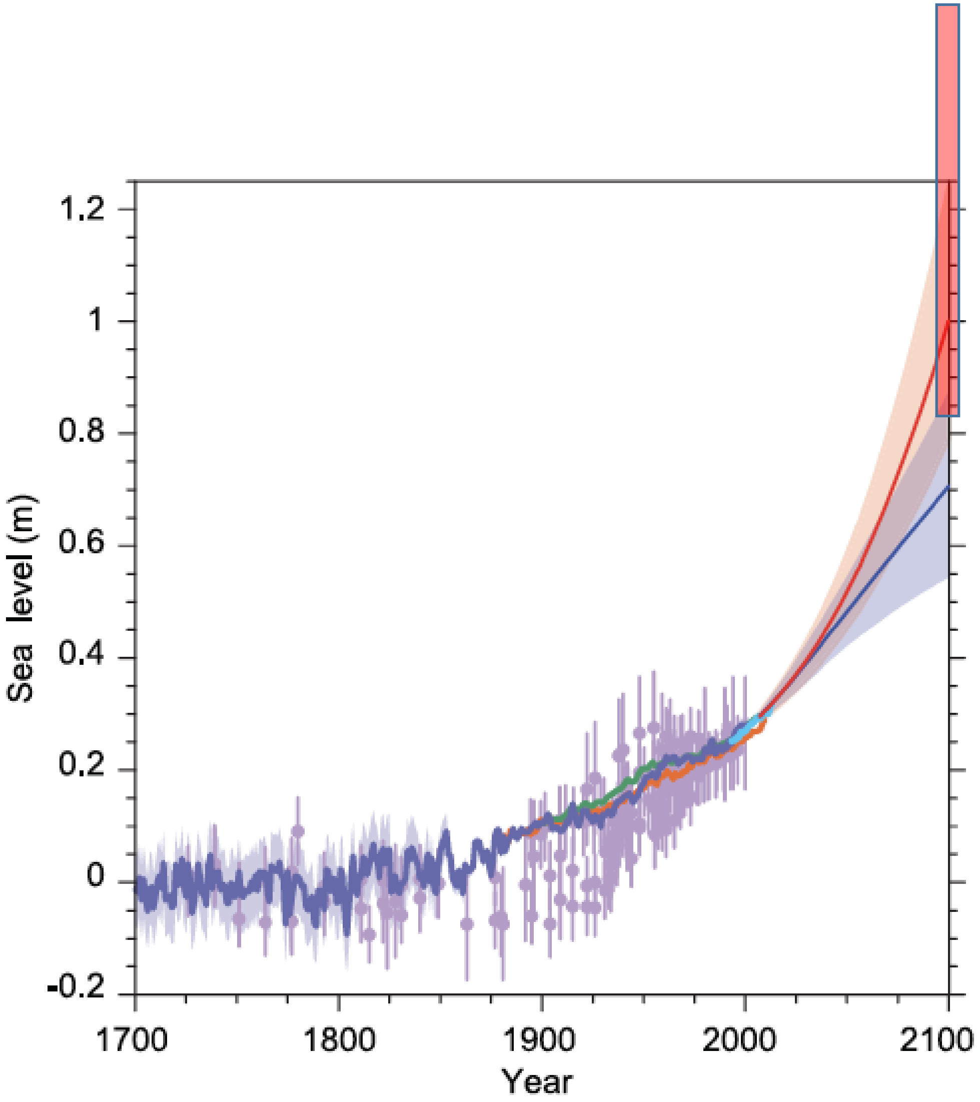
DeConto et al., submitted

Possible implications for future projections?



IPCC AR5 2013

Possible implications for future projections?



with new paleo-calibrated Antarctic modeling

IPCC AR5 2013

AGU PUBLICATIONS

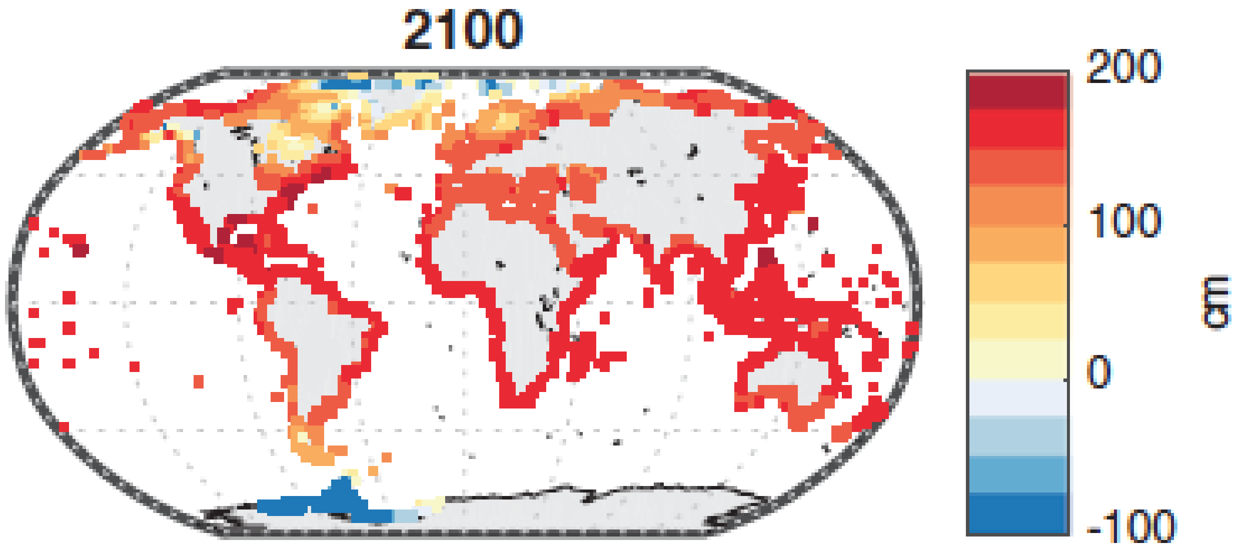
Earth's Future

RESEARCH ARTICLE

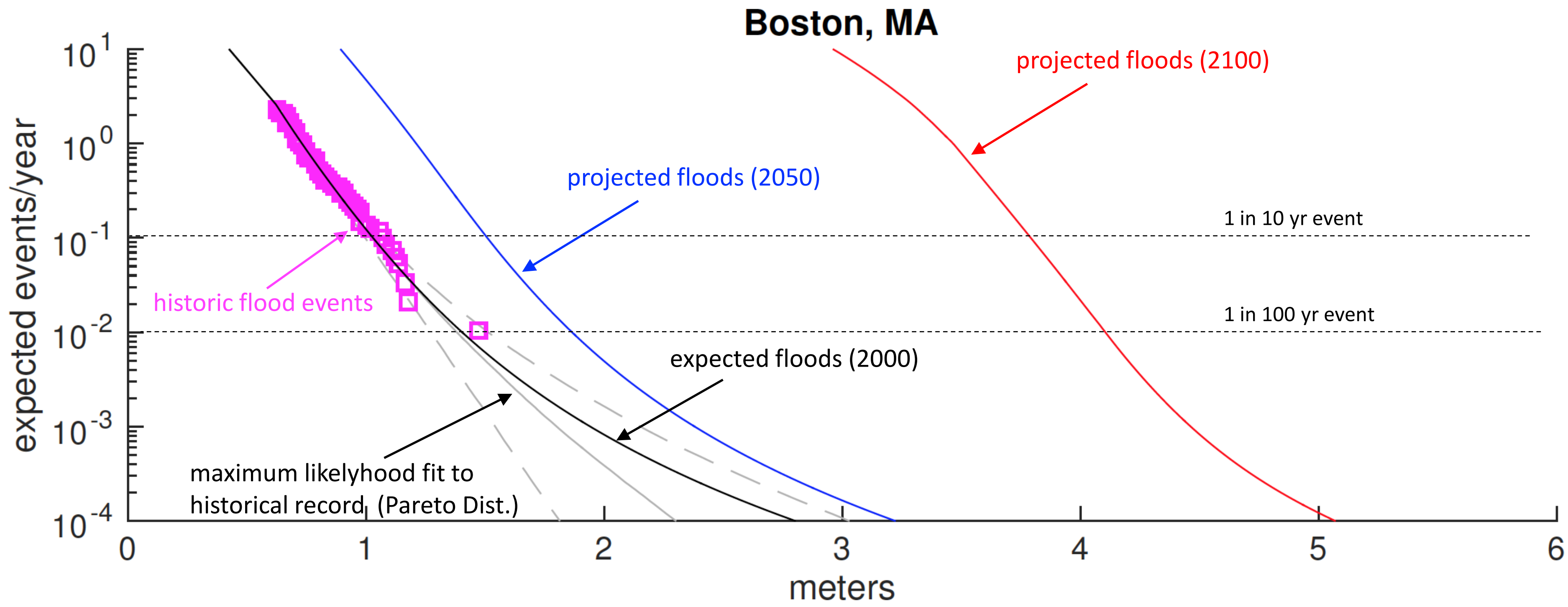
10.1002/2017EF000663

Evolving Understanding of Antarctic Ice-Sheet Physics and Ambiguity in Probabilistic Sea-Level Projections

Robert E. Kopp[1], Robert M. DeConto[2], Daniel A. Bader[3], Carling C. Hay[1,4,5], Radley M. Horton[3,6], Scott Kulp[7], Michael Oppenheimer[8], David Pollard[9], and Benjamin H. Strauss[7]



Projected flood recurrences RCP8.5

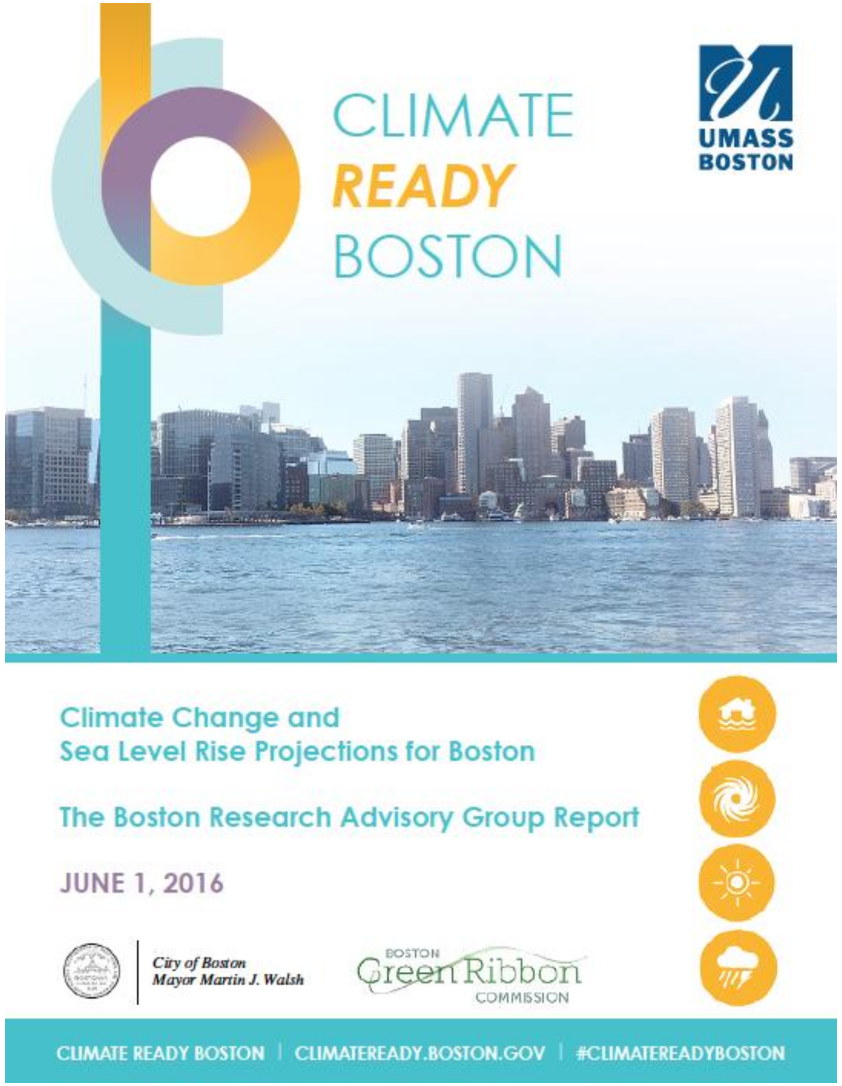


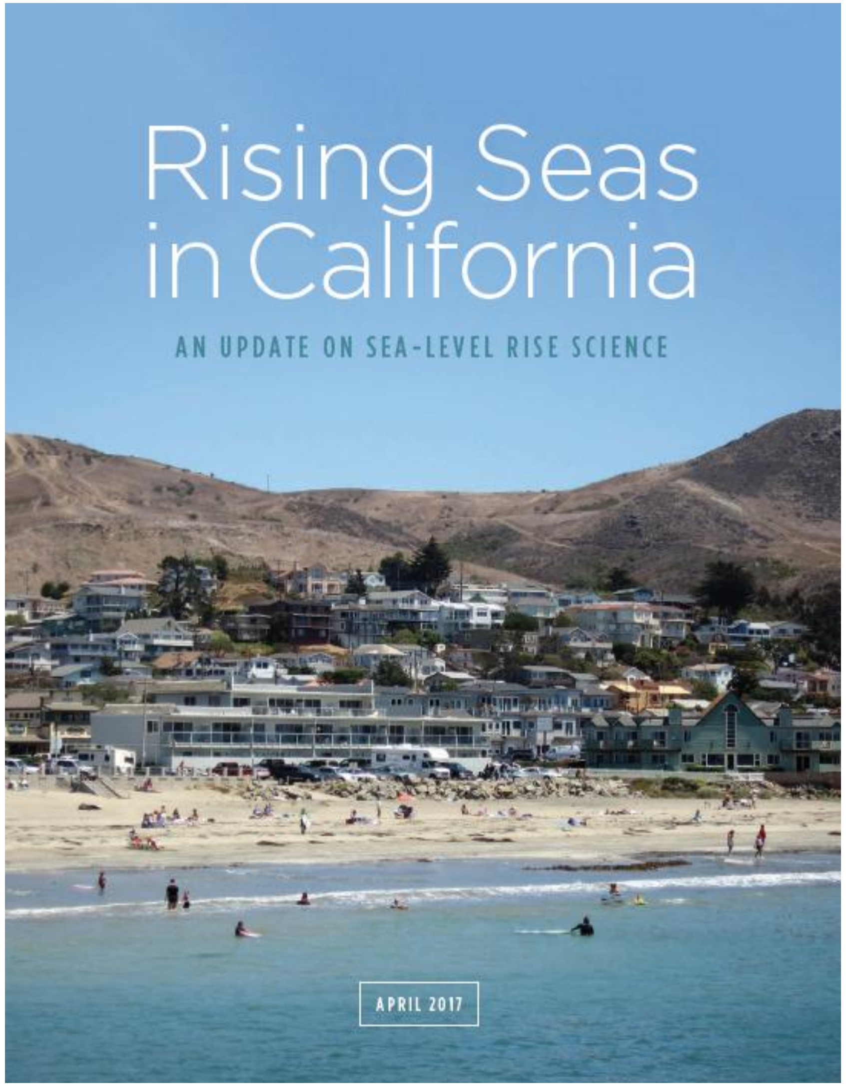
Recurrence frequencies for Boston tide gauge

after Buchanan et al., (2016)

NECSC Northeast Climate Science Center

UMASS AMHERST





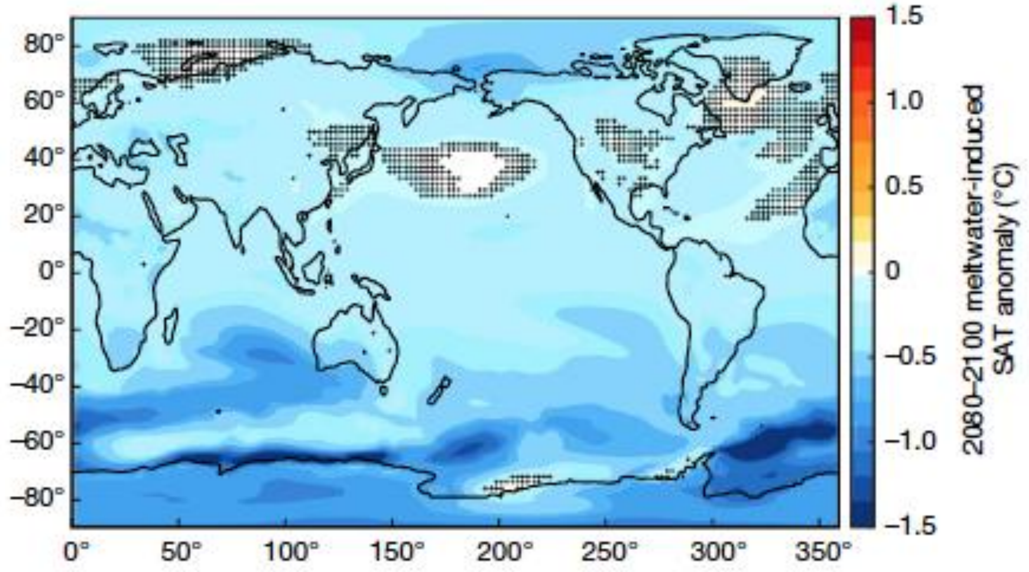
UMASS
AMHERST

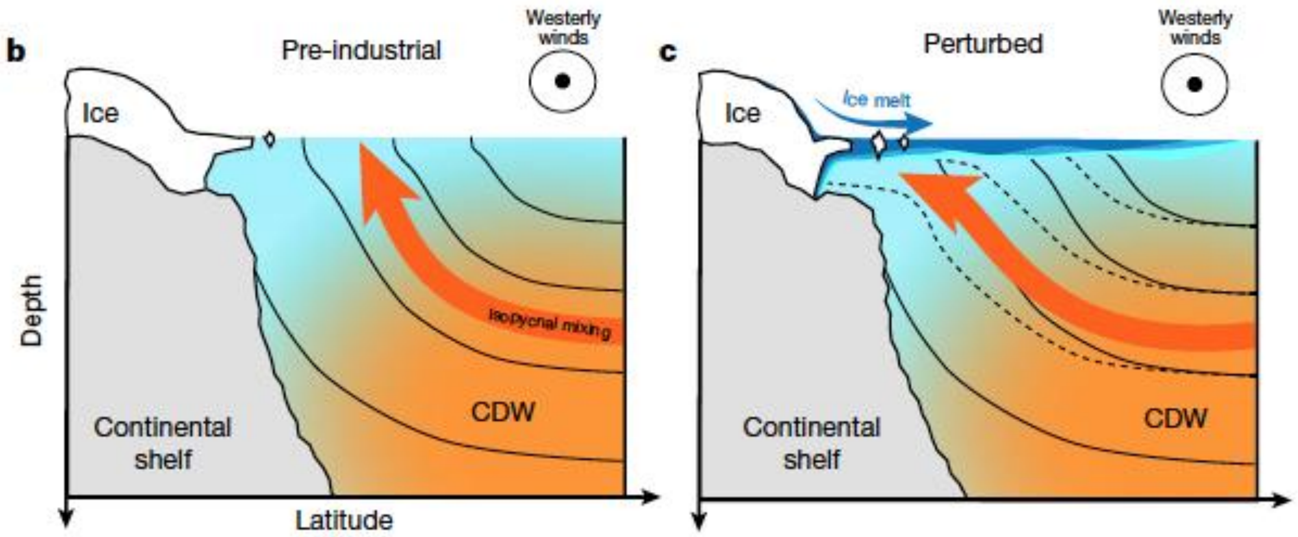
ARTICLE

https://doi.org/10.1038/s41586-018-0712-z

Change in future climate due to Antarctic meltwater

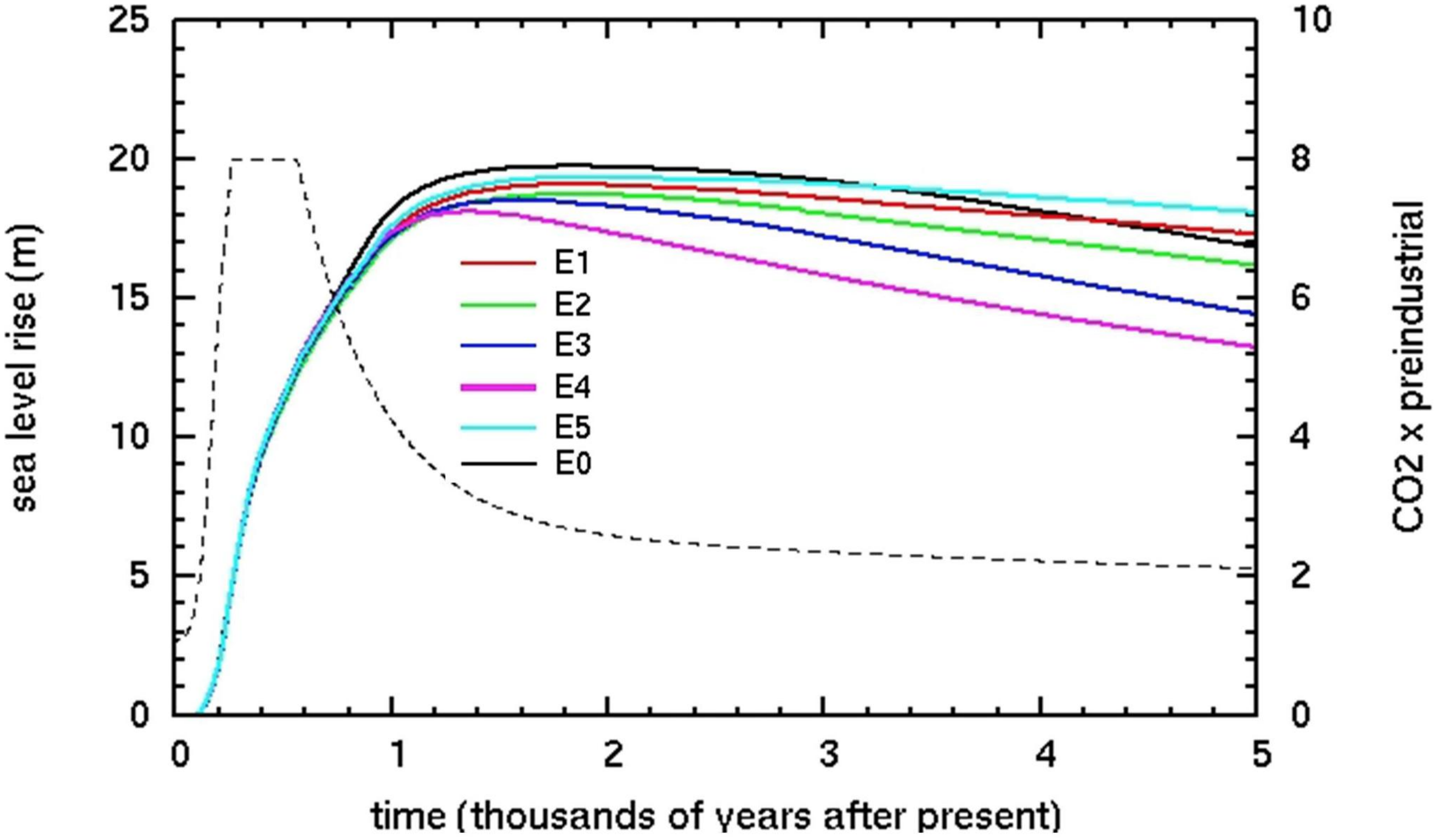
Ben Bronselaer[1,2,3*], Michael Winton[2], Stephen M. Griffies[2,3], William J. Hurlin[2], Keith B. Rodgers[3], Olga V. Sergienko[2,3], Ronald J. Stouffer[1,2] & Joellen L. Russell[1]





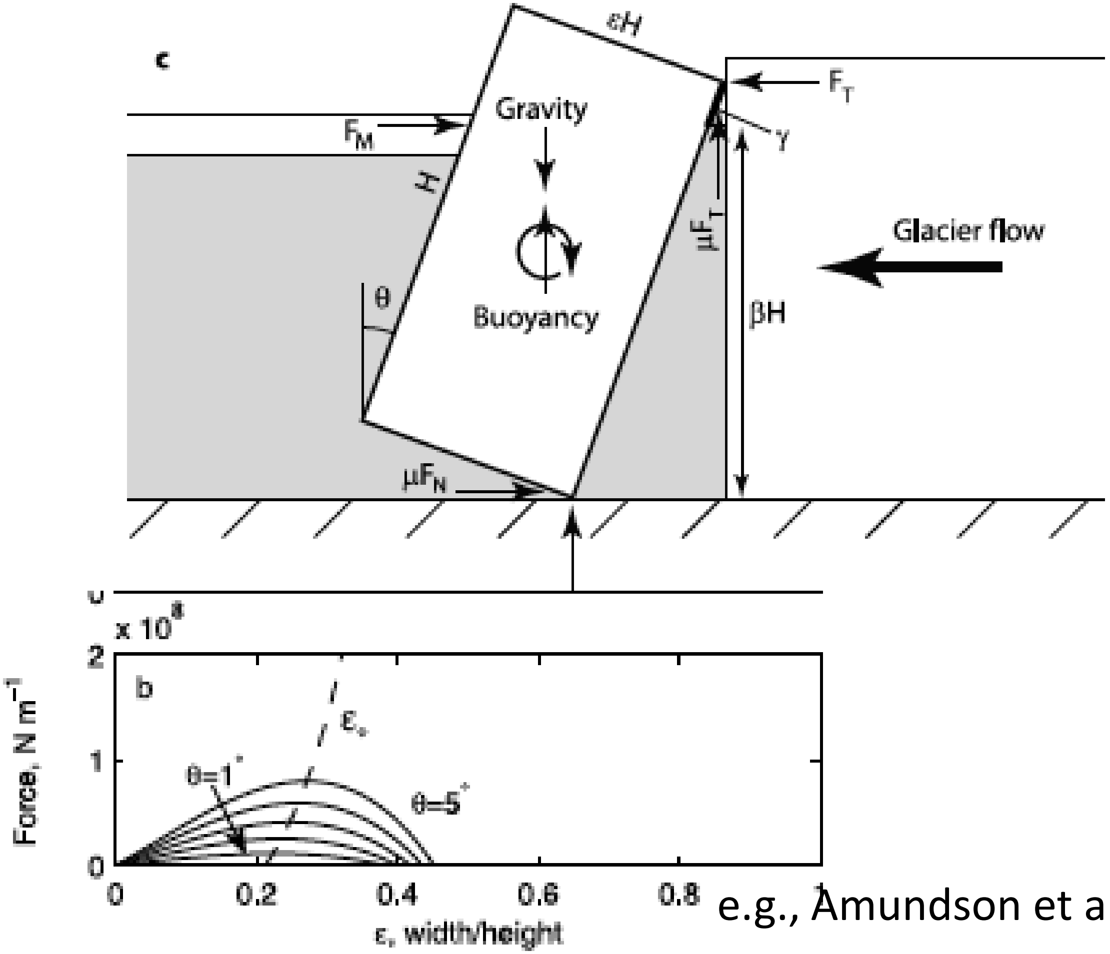
atmospheric cooling versus **sub-surface ocean warming**

Will self-gravitation and a soft mantle save the Antarctic Ice Sheet? Probably not in the short term.



Pollard, Gomez, DeConto, JGR, 2017

Role of mélange during ice-cliff retreat?



e.g., Amundson et al., 2010

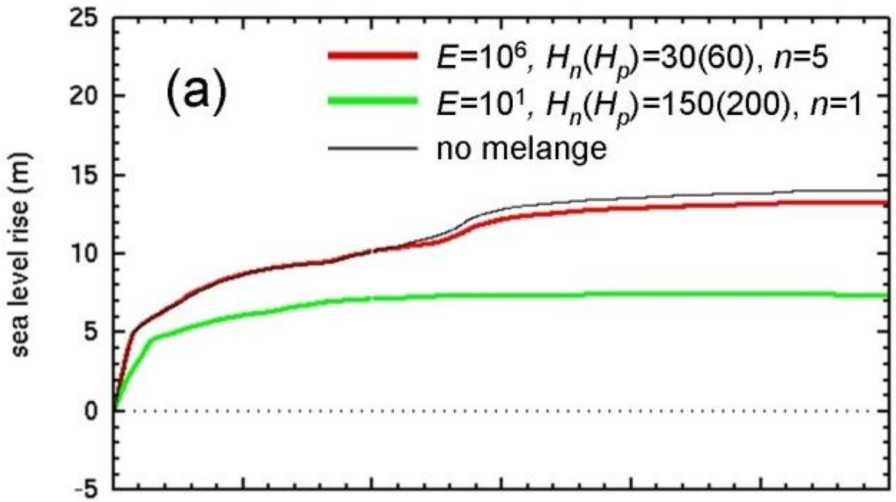
Probably not.

$$\tau' = 2\eta \begin{pmatrix} f\dfrac{\partial u}{\partial x} & \dfrac{1}{2}\left(\dfrac{\partial u}{\partial y}+\dfrac{\partial v}{\partial x}\right) & \dfrac{1}{2}\left(\dfrac{\partial u}{\partial z}+\dfrac{\partial w}{\partial x}\right) \\ \dfrac{1}{2}\left(\dfrac{\partial u}{\partial y}+\dfrac{\partial v}{\partial x}\right) & f\dfrac{\partial v}{\partial y} & \dfrac{1}{2}\left(\dfrac{\partial v}{\partial z}+\dfrac{\partial w}{\partial y}\right) \\ \dfrac{1}{2}\left(\dfrac{\partial u}{\partial z}+\dfrac{\partial w}{\partial x}\right) & \dfrac{1}{2}\left(\dfrac{\partial v}{\partial z}+\dfrac{\partial w}{\partial y}\right) & f\dfrac{\partial w}{\partial z} \end{pmatrix}$$

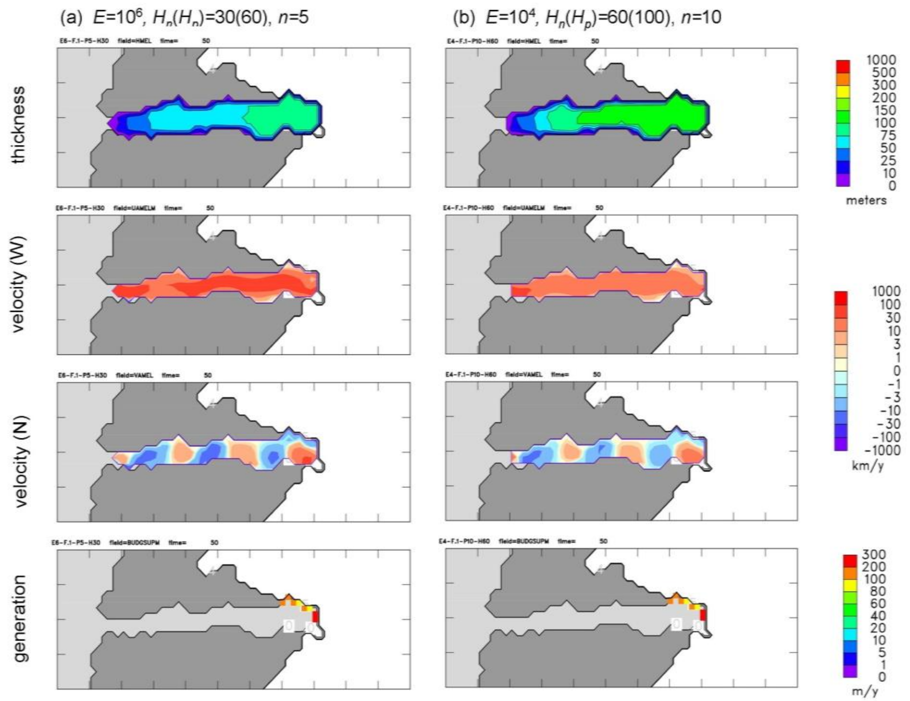
where η is the effective viscosity

$$\eta = \tfrac{1}{2}(EA)^{-1/n}\,\dot{\varepsilon}^{(1-n)/n}$$

- Assume mélange driven by hydrostatic gradients
- Use SSA scaling (n=3), modified to allow
    - No resistance to divergence
    - Limited resistance to convergence
    - Resistance to shear



Model physics (*E, n)* tuned to Jakobshavn



Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-28
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 13 March 2018

A continuum model of ice mélange and its role during retreat of the Antarctic Ice Sheet

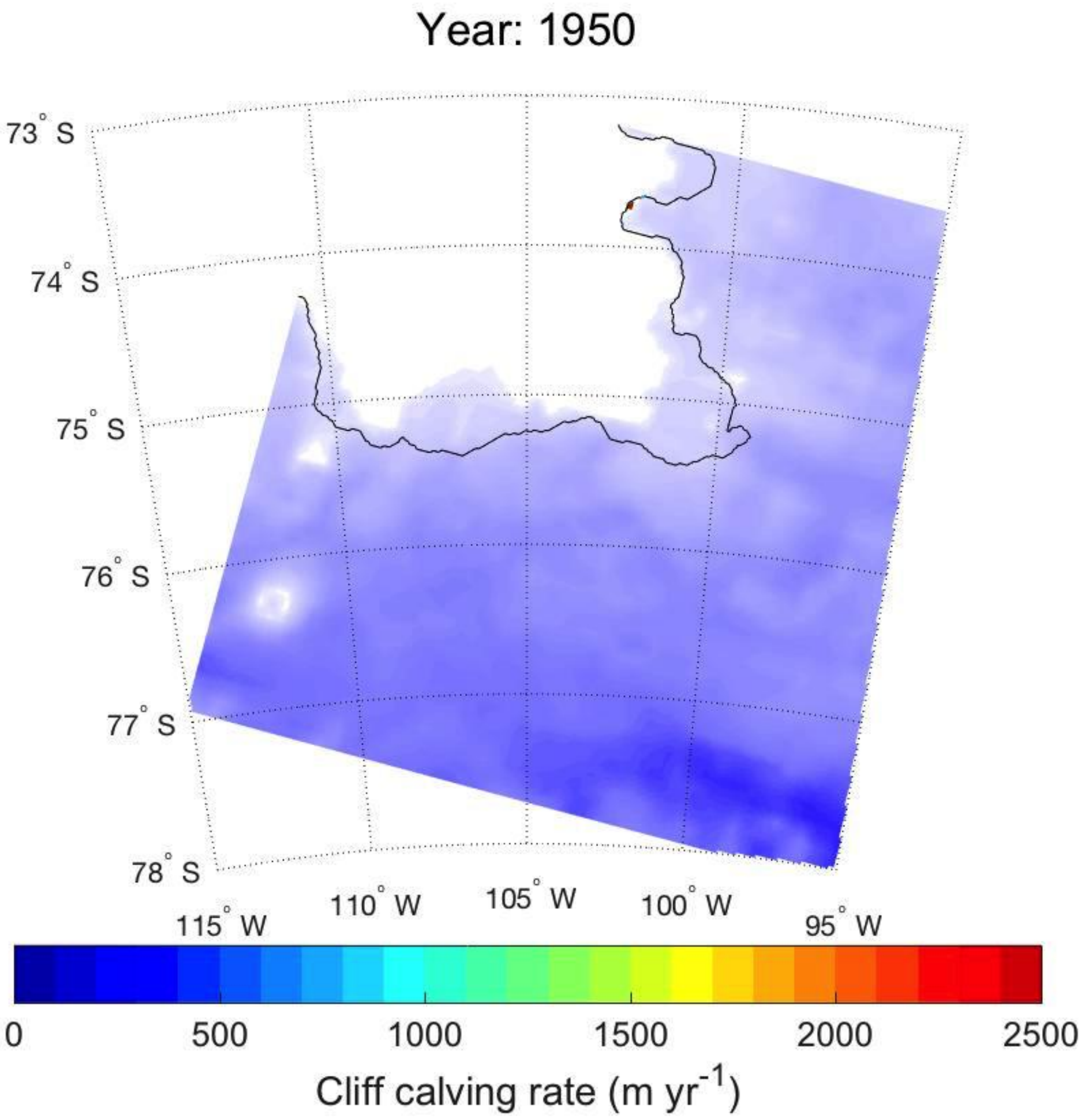
David Pollard[1], Robert M. DeConto[2], Richard B. Alley[1,3]

[1]Earth and Environmental Systems Institute, Pennsylvania State University, University Park, PA 16802, USA
[2]Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA
[3]Department of Geosciences, Pennsylvania State University, University Park, PA 16802, USA

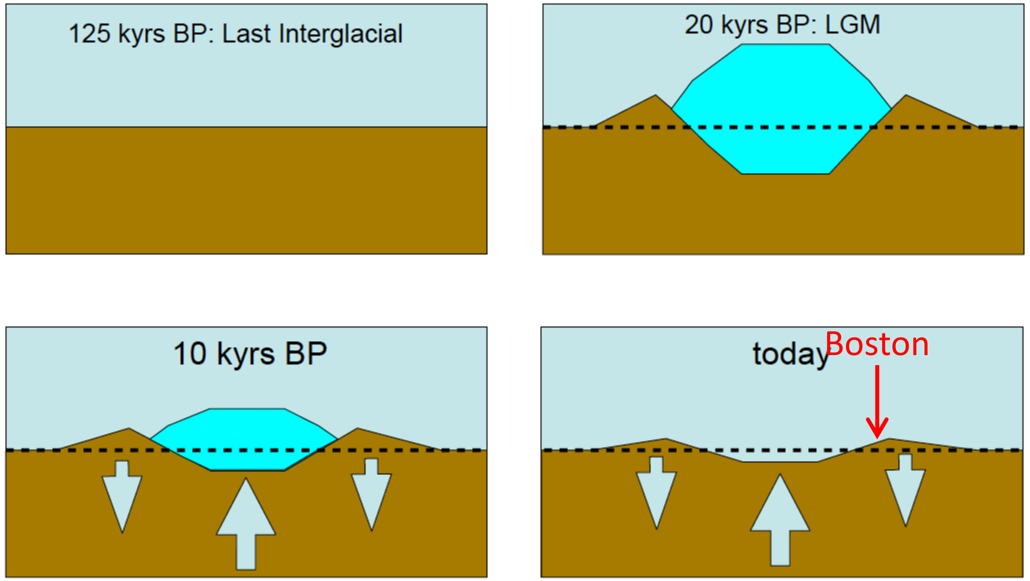
Correspondence to: David Pollard (pollard@essc.psu.edu)

Pollard, DeConto, Alley , 2018

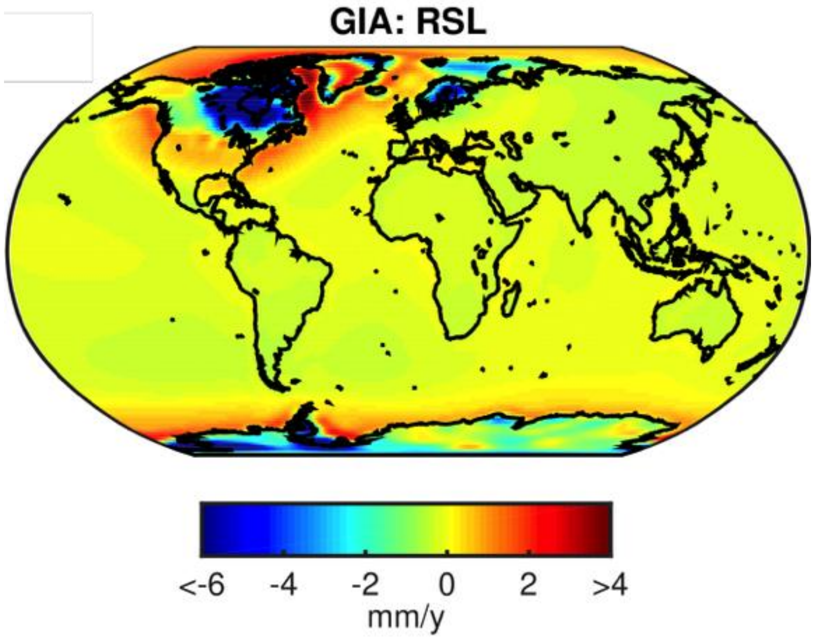
+3ºC global mean warming



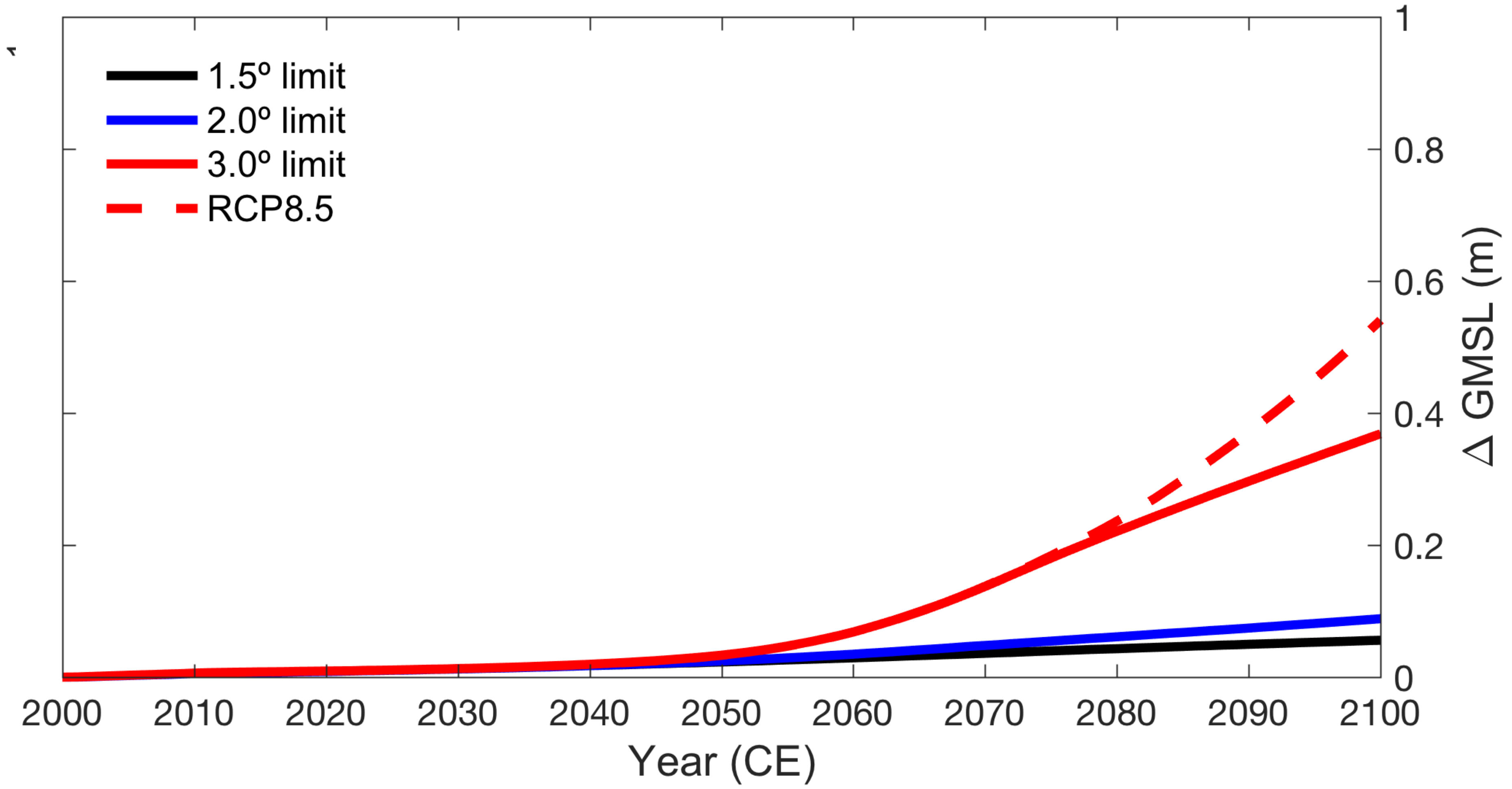
Glacio-Isostatic Adjustment (GIA)



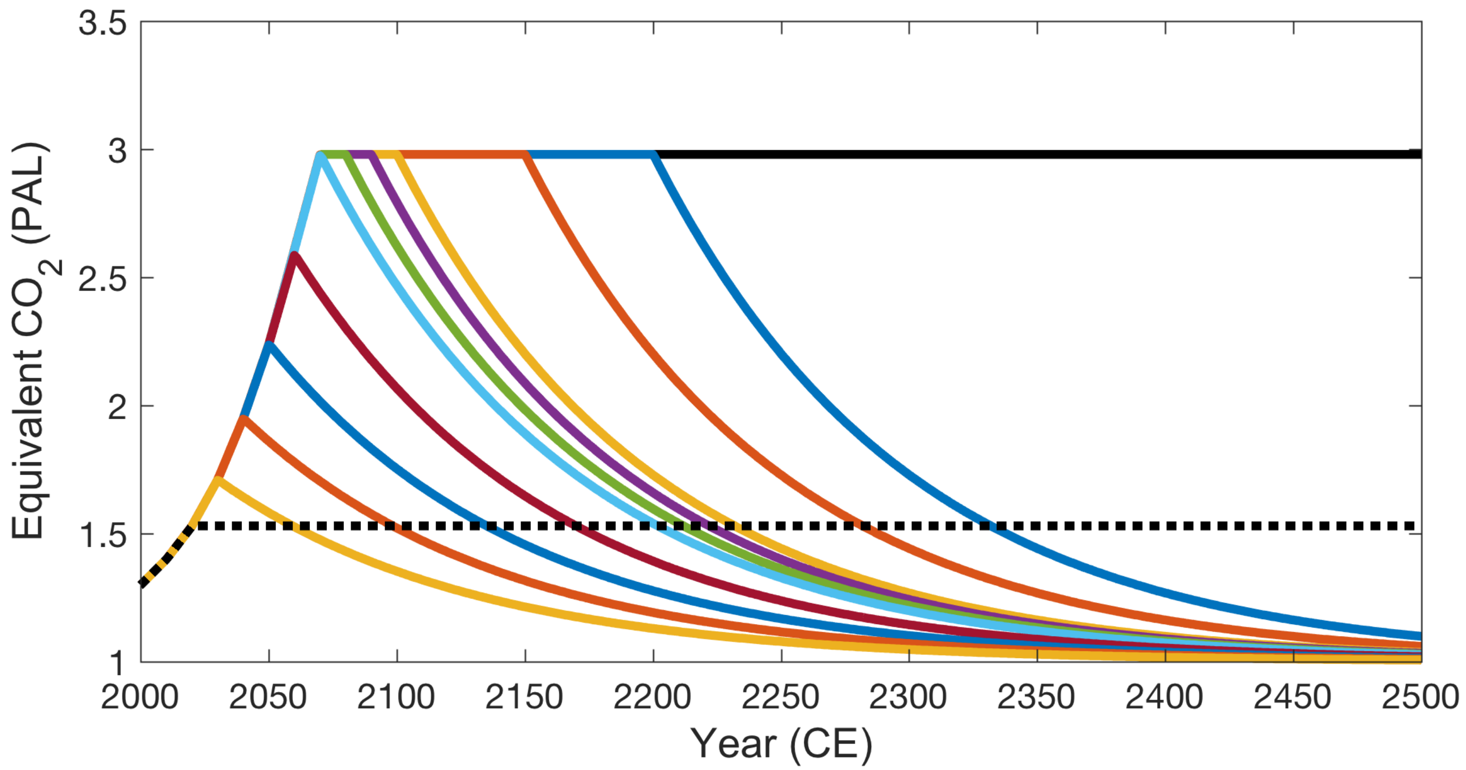
Compliments, Paolo Stocchi



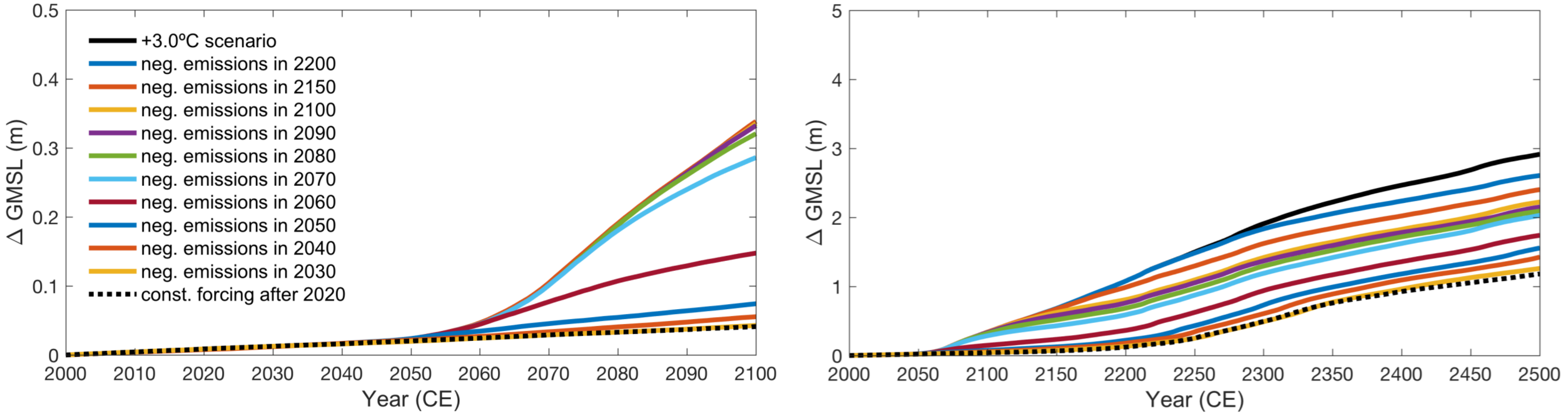
Summary: LIG and GRACE constrained ensembles



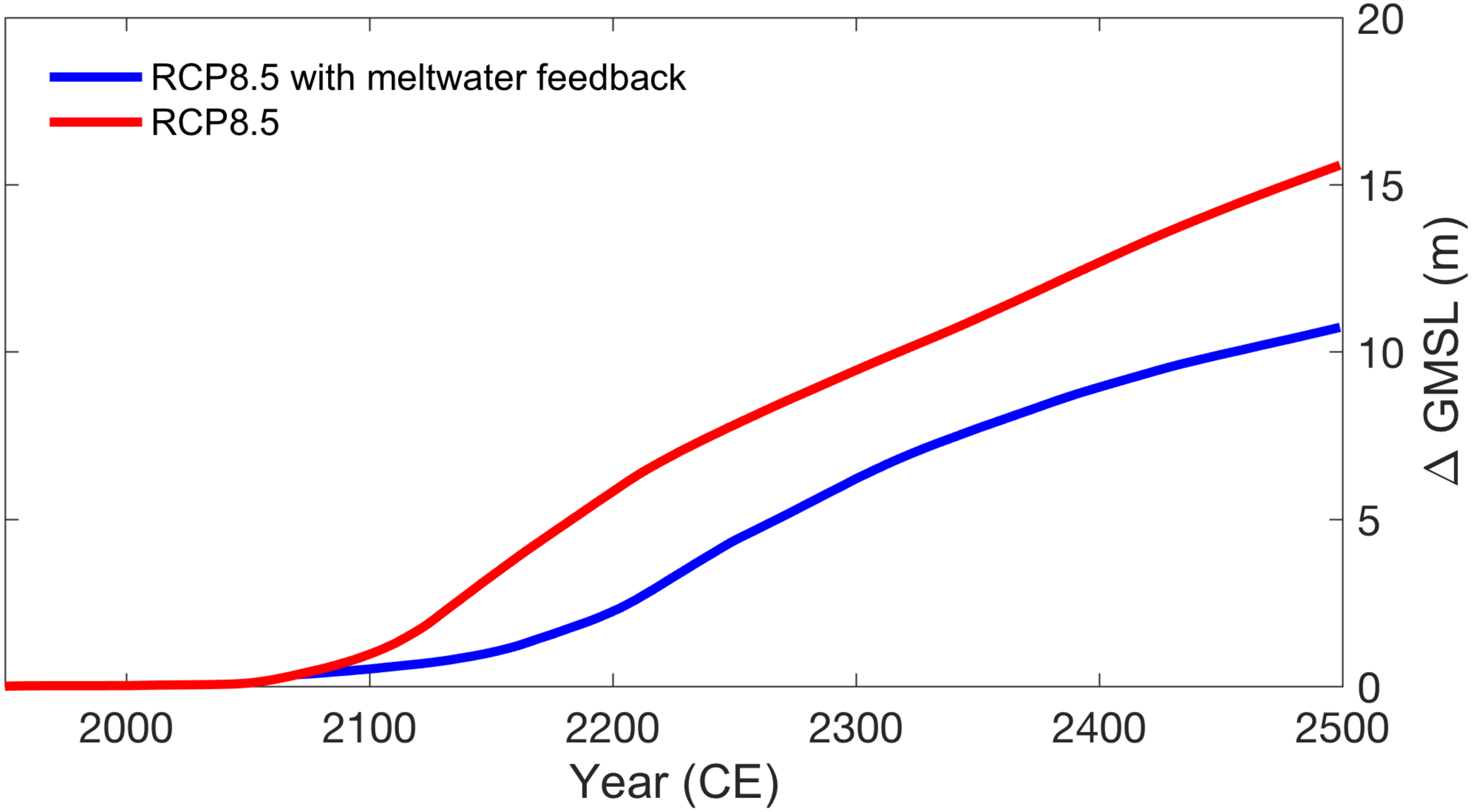
Ocean and atmospheric forcing representing “CO_2 overshoots” INDC emissions with negative emissions beginning in year X



Ocean and atmospheric forcing representing "CO_2 overshoots" INDC emissions with negative emissions beginning in year X

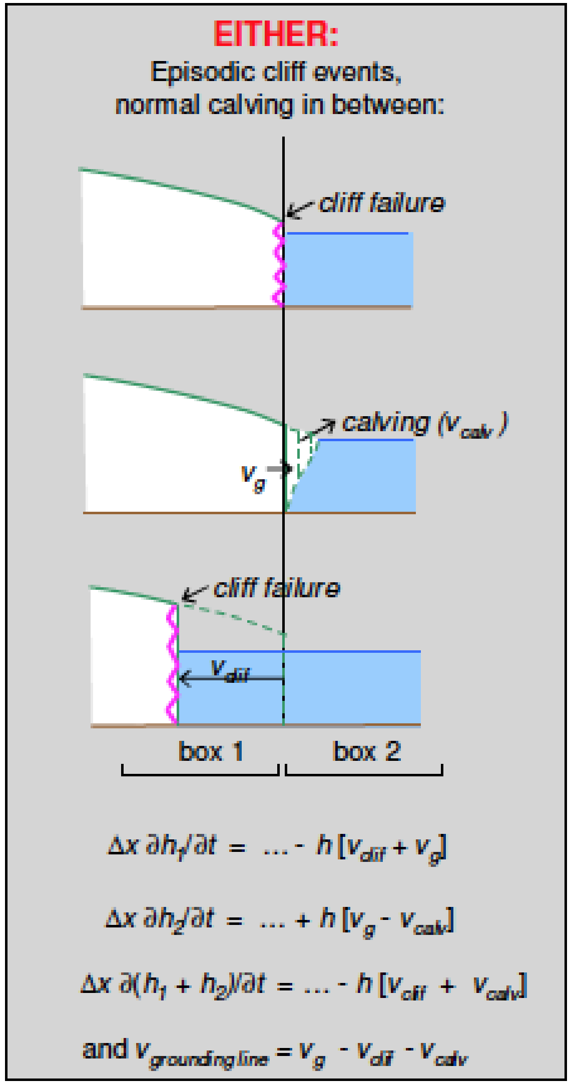


RCP 8.5 with meltwater feedback

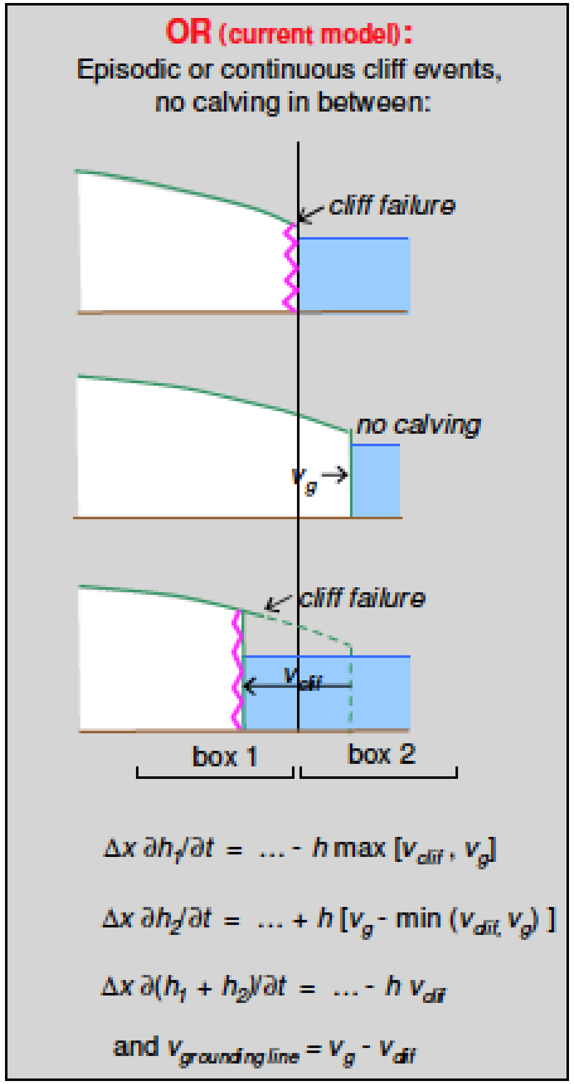


numerics of ice removal must conserve mass

$V_{grounding\ line} = V_g - V_{cliff} - V_{calving}$



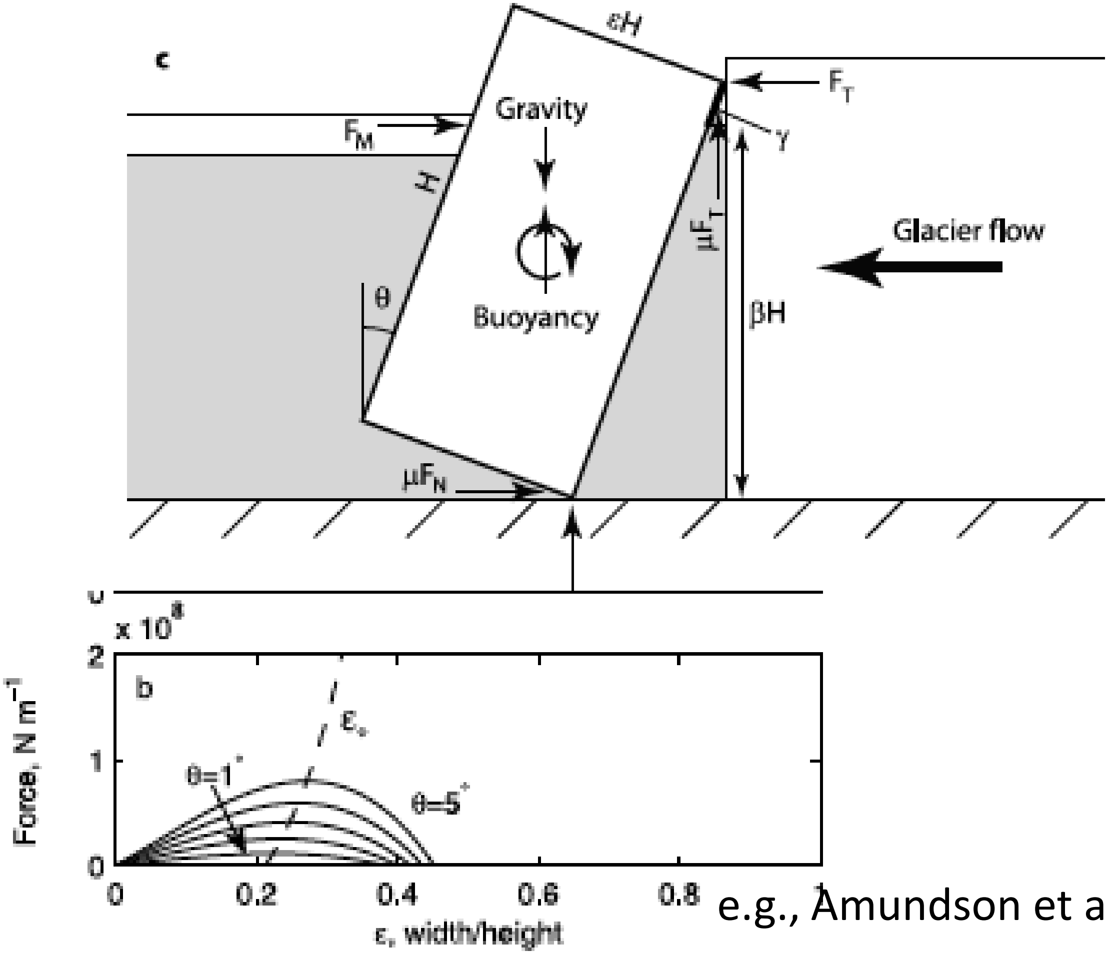
$V_{grounding\ line} = V_g - V_{cliff}$



Pollard and DeConto, EGU 2014

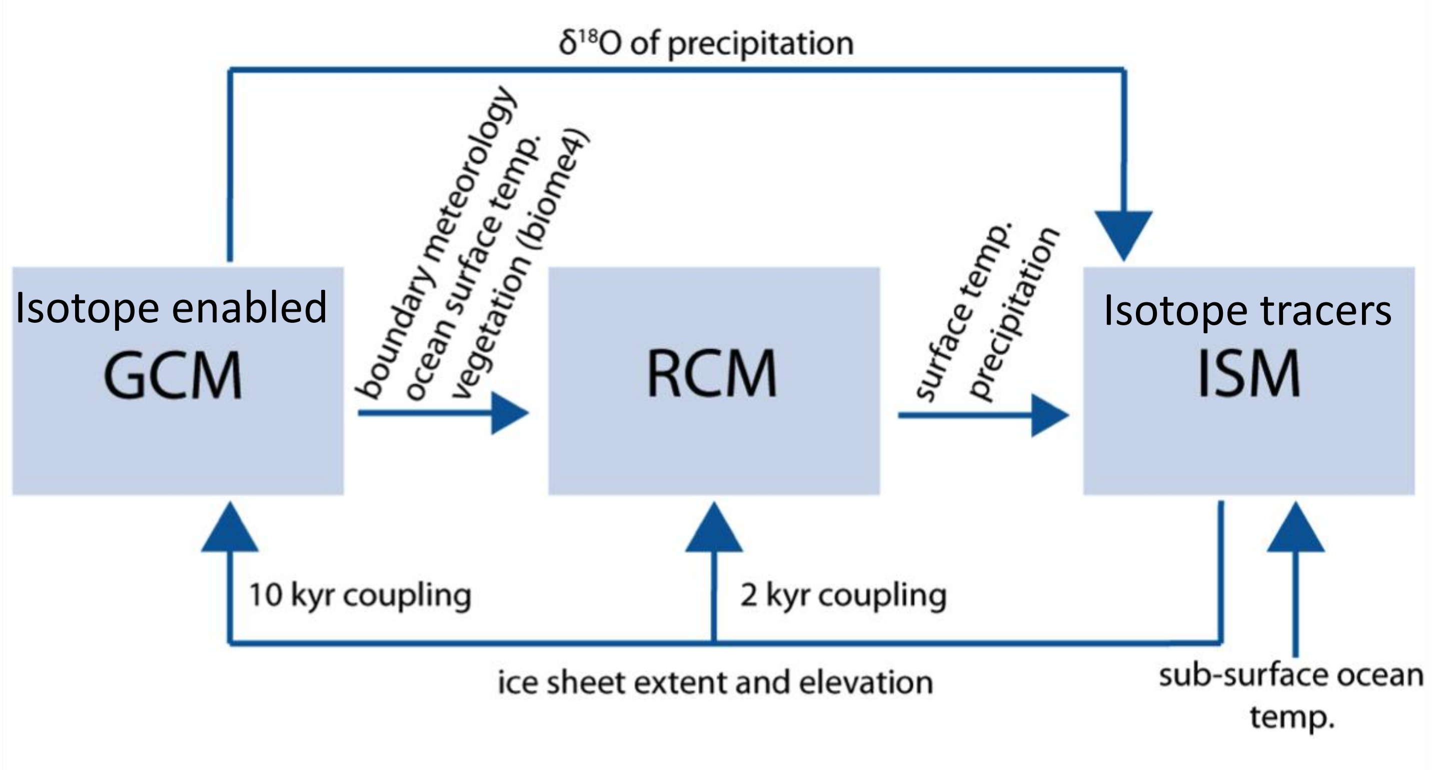
- All dynamic ice flux across the g.l. must be lost to cliff collapse or hydrofracturing, before cliff failure can attack grounded grid cells.
- Implicit ice velocities at g.l. via Schoof (~1-2km a^{-1}) are << ice loss from cliff collapse (up to 13km a^{-1})
- We make the conservative assumption that mass loss due to ice-cliff failure and “normal” calving are exclusive, rather than additive. i.e., there is no shelf loss, between cliff-calving events, allowing the g.l. to advance where allowed.

Role of mélange during ice-cliff retreat?



e.g., Amundson et al., 2010

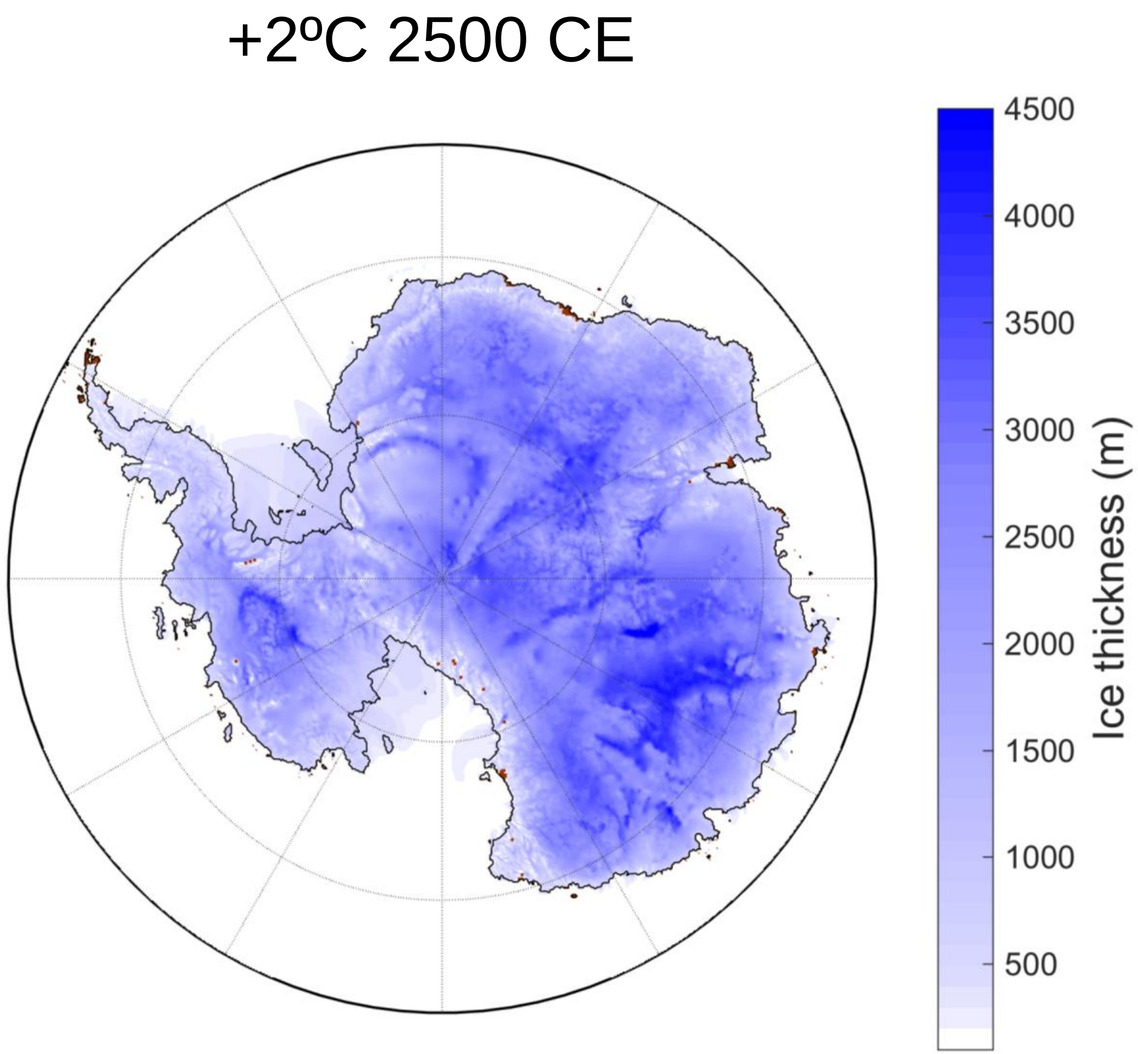
climate-ice sheet isotope modeling



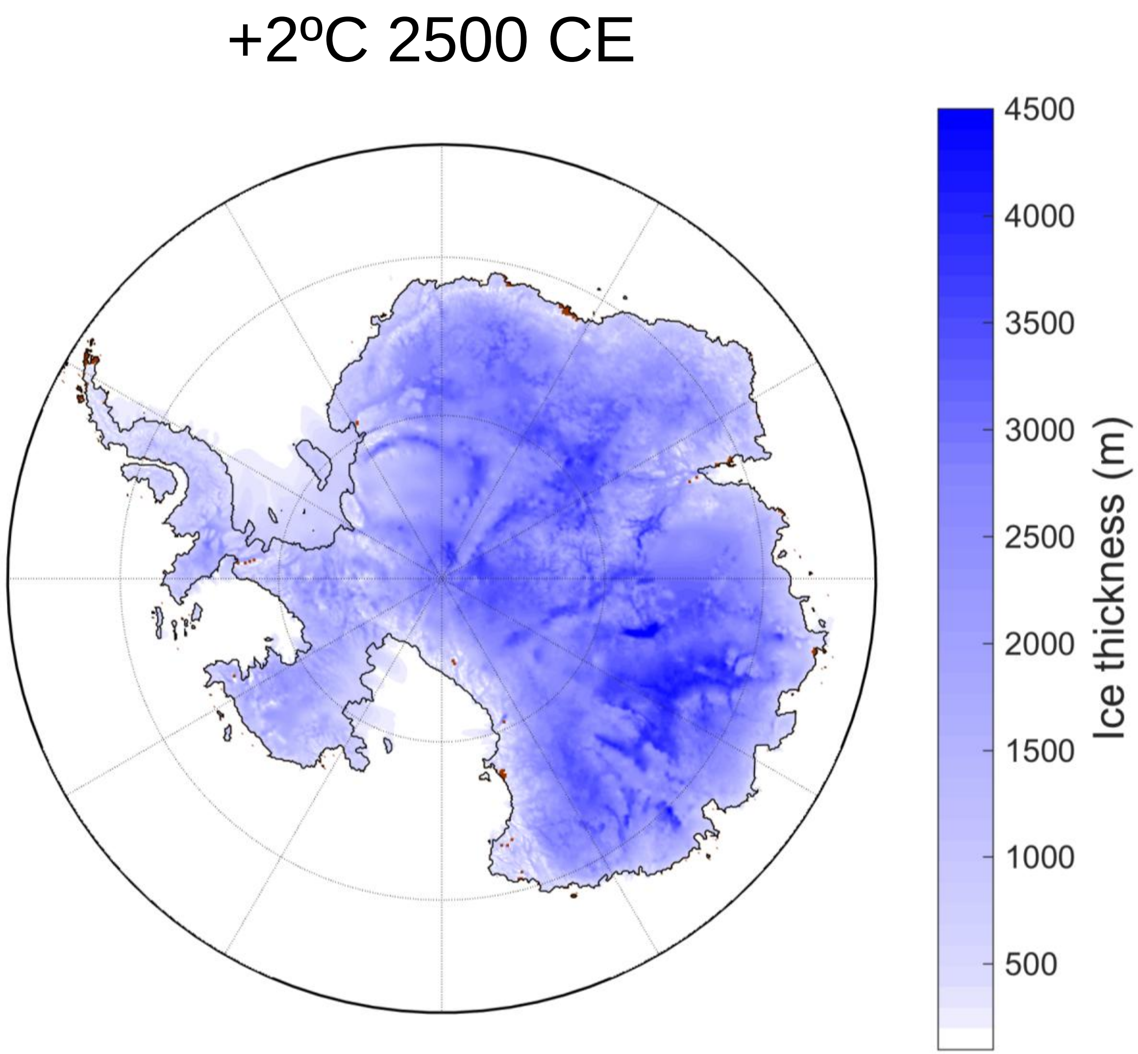
fully accounts for the climate and basin effects on $\delta^{18}O_{sw}$

Gasson et al., 2015; 2016

Effect of uncertain basal boundary conditions on results



Effect of uncertain basal boundary conditions on results



Two tests of ensemble members

1. Paleo:

LIG contribution to SL at 125ka (3.1-6.1m)

Total	4.5-7.5 m (Dutton et al., 2015)
Greenland	1 m (NEEM, 2013, Goelzer et al., 2016)
Thermosteric	0.4 m (McKay et al., 2014)

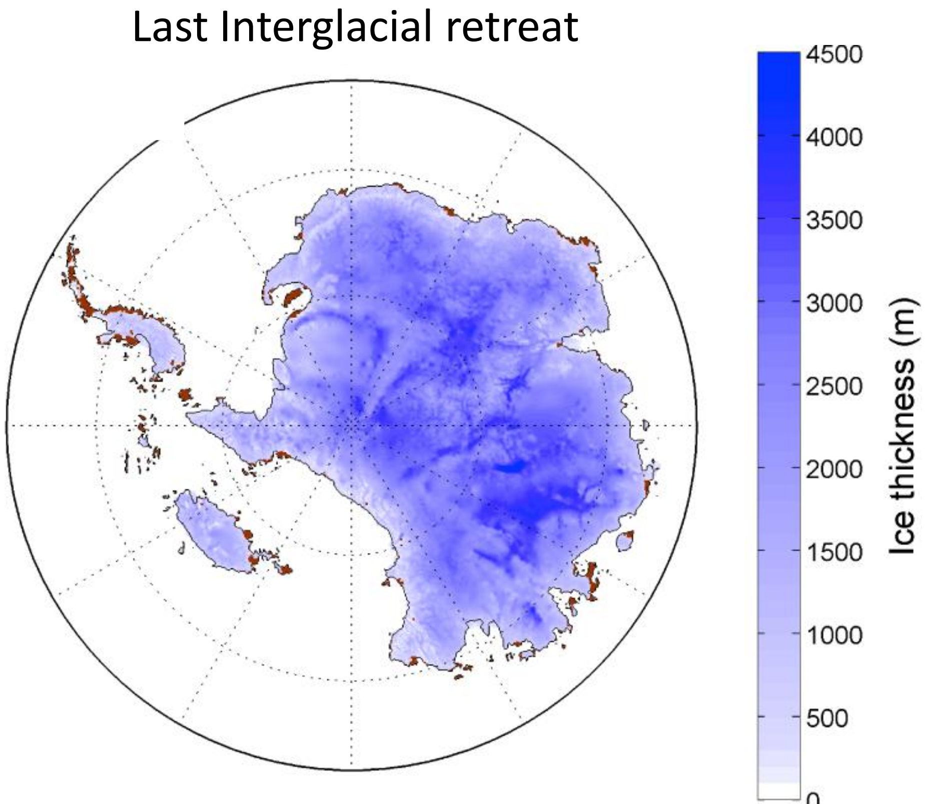
2. Modern:

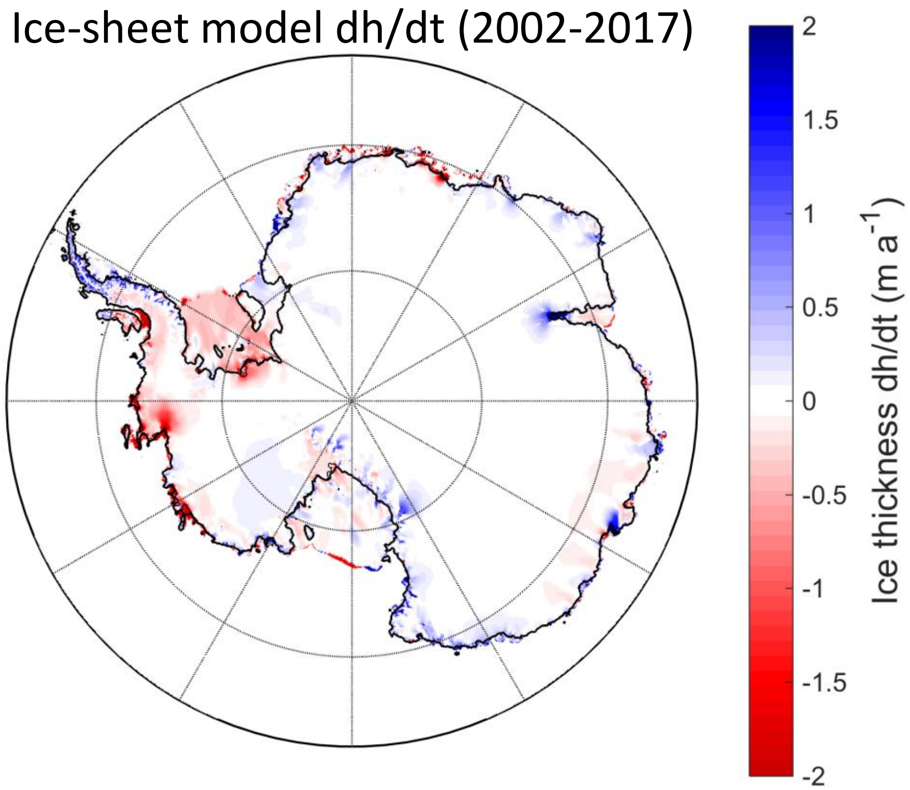
GRACE (2002-2017): 0.20-0.54 mm/yr

*best GRACE (2002-2017): 0.39-0.53 mm/yr

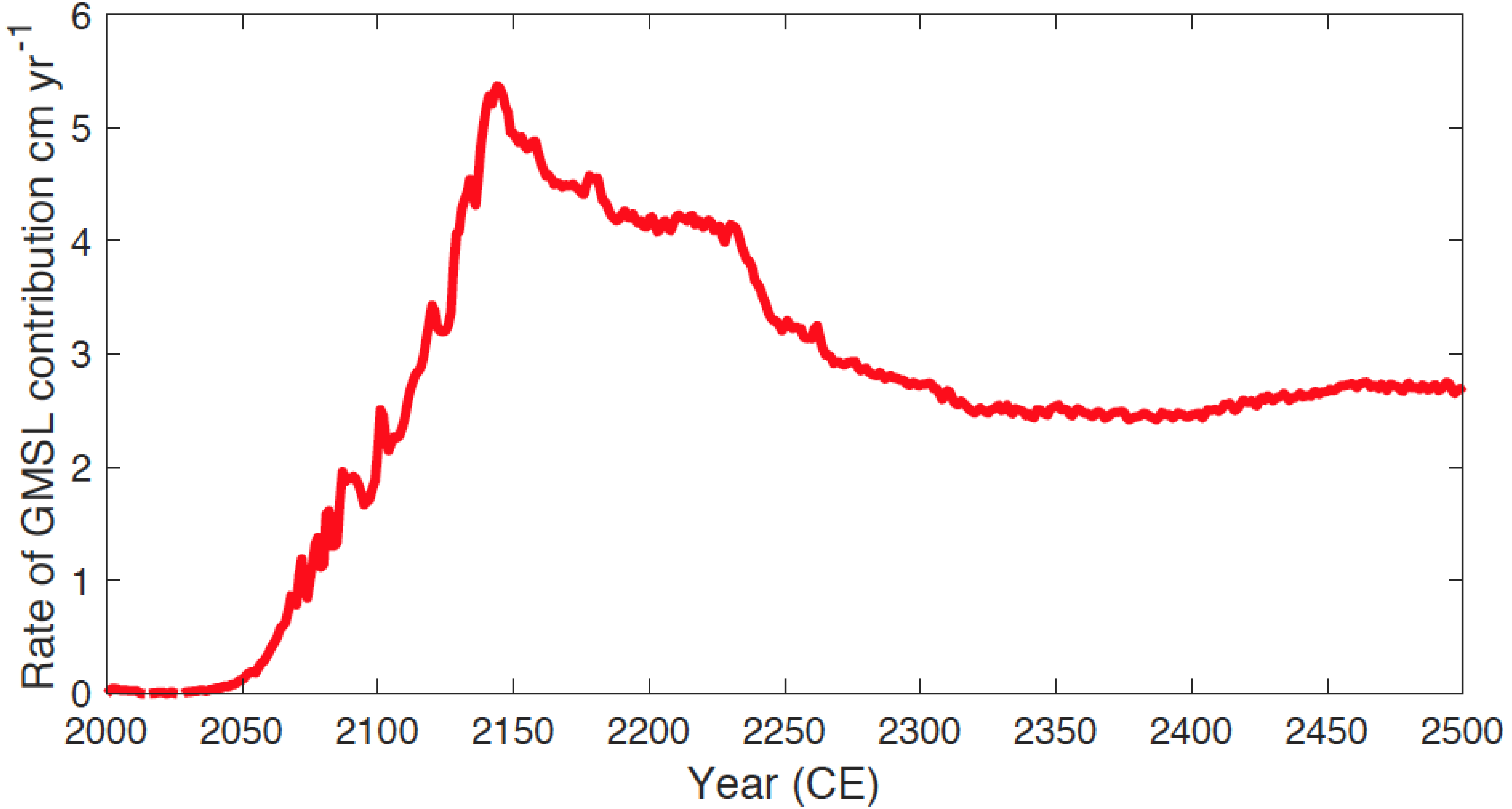
Updated from Velicogna et al., (2014)

IMBIE2 (1992-2017): 0.15-0.46 mm/yr





RCP8.5 n=47 (mean rate of GMSL rise)



new physics: meltwater-enhanced calving

see: *Pollard, DeConto and Alley, 2015; DeConto and Pollard, 2016*

- Crevasse penetration depth *d* dependent on divergence (e.g., Nick et al., 2010; 2013)

$$\dot{\varepsilon} = \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \qquad d_s = \frac{2}{\rho_i g}\left(\frac{\dot{\varepsilon}}{A}\right)^{\frac{1}{n}}$$

$$\dot{\varepsilon} = 4\left(\frac{\rho_i g h}{4}\right)^{n} \qquad d_b = \left(\frac{\rho_i}{\rho_o - \rho_i}\right)\frac{2}{\rho_i g}\left(\frac{\dot{\varepsilon}}{A}\right)^{\frac{1}{n}}$$

- Additional crevasse penetration d_a dependent on accumulated strain

$$\int \frac{\partial u}{\partial x}\,dt$$

Substituting *dt=dx/(dx/dt)=dx/u*

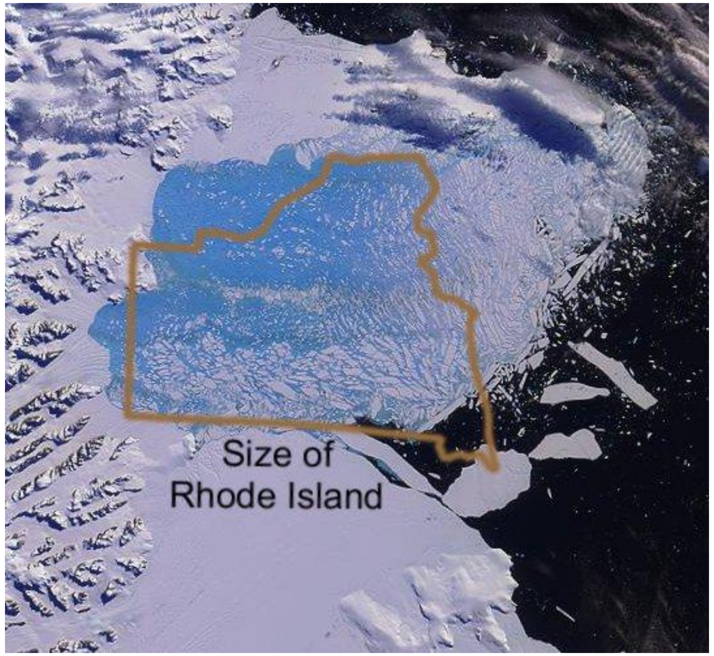
$$\int \frac{\partial \ln(u)}{\partial x}\,dx = \ln(u_2 / u_1)$$

$$d_a = h\max\left[0, \ln(u/1600)\right] / \ln(1.2)$$

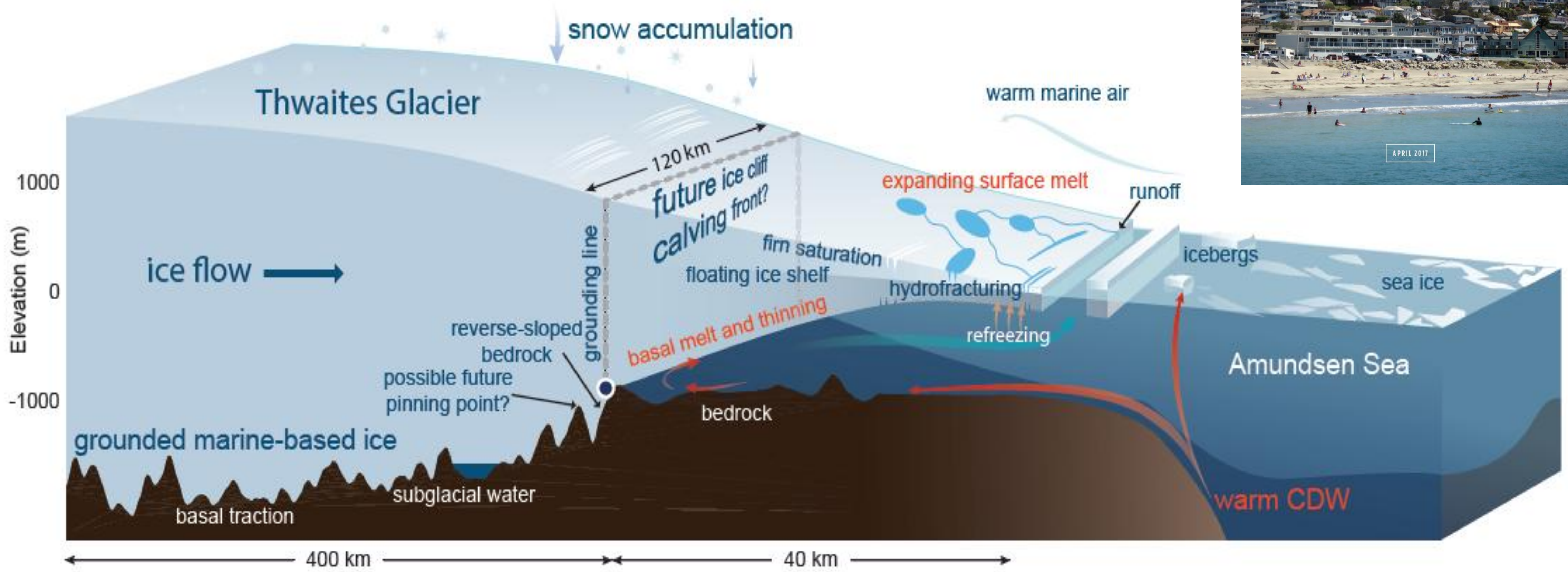
$$d_w = 100R^2$$

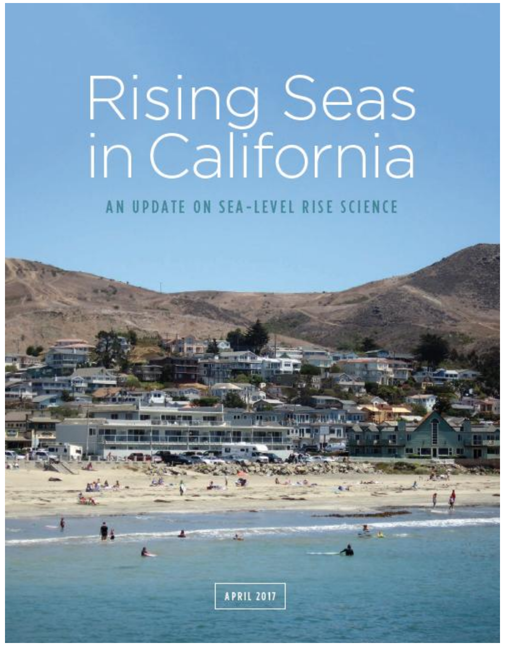
$$C = 3000\max\left[0, \min\left[1, (r - r_c)/1 - r_c)\right]\right]$$

Calving rate *C* (m/yr), where r is ratio of total crevasse penetration to ice thickness. Critical value is 0.75.



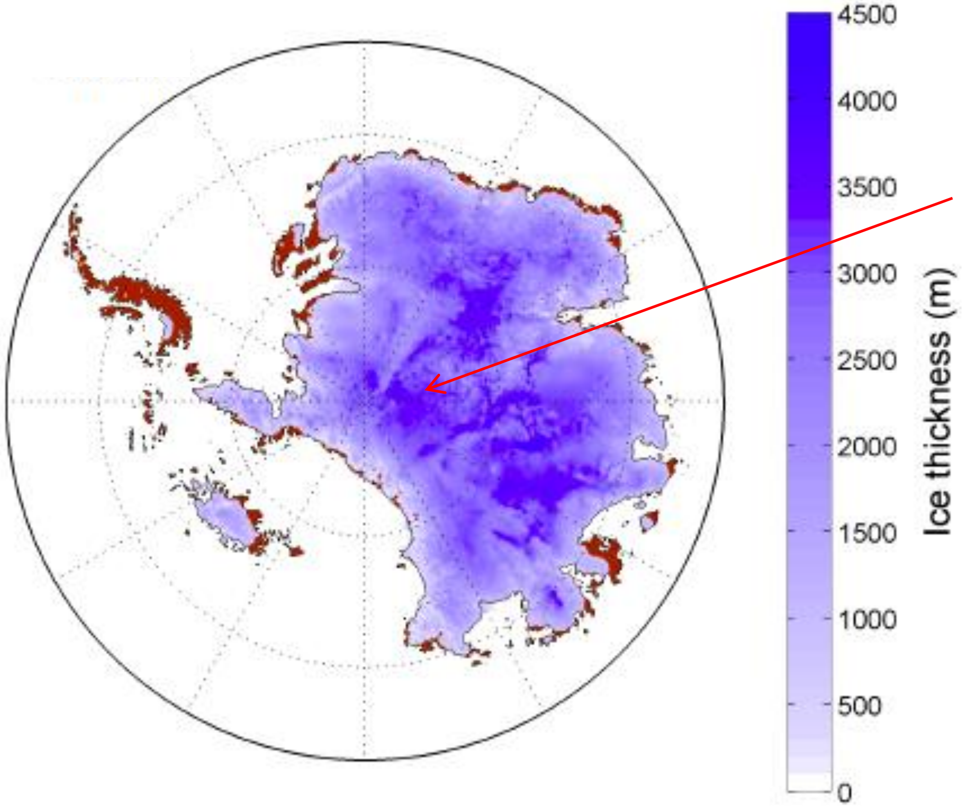
Thwaites Glacier, Antarctica





Compliments, Helen Fricker, Scipps/UCSD

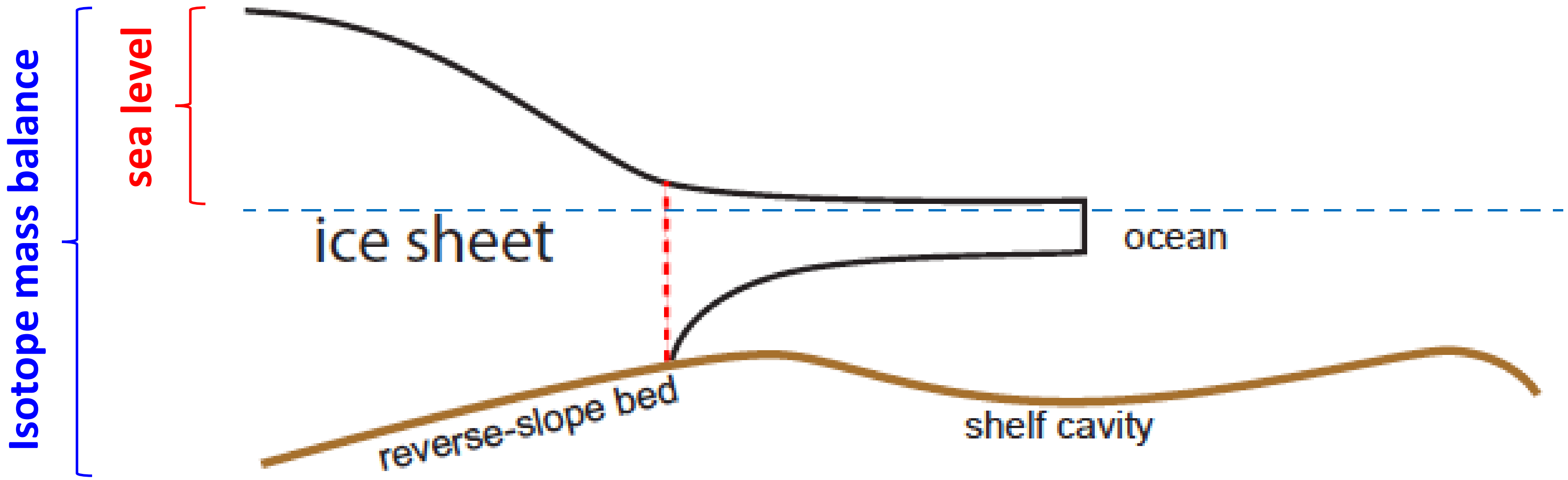
Pliocene isotopic distillation effect



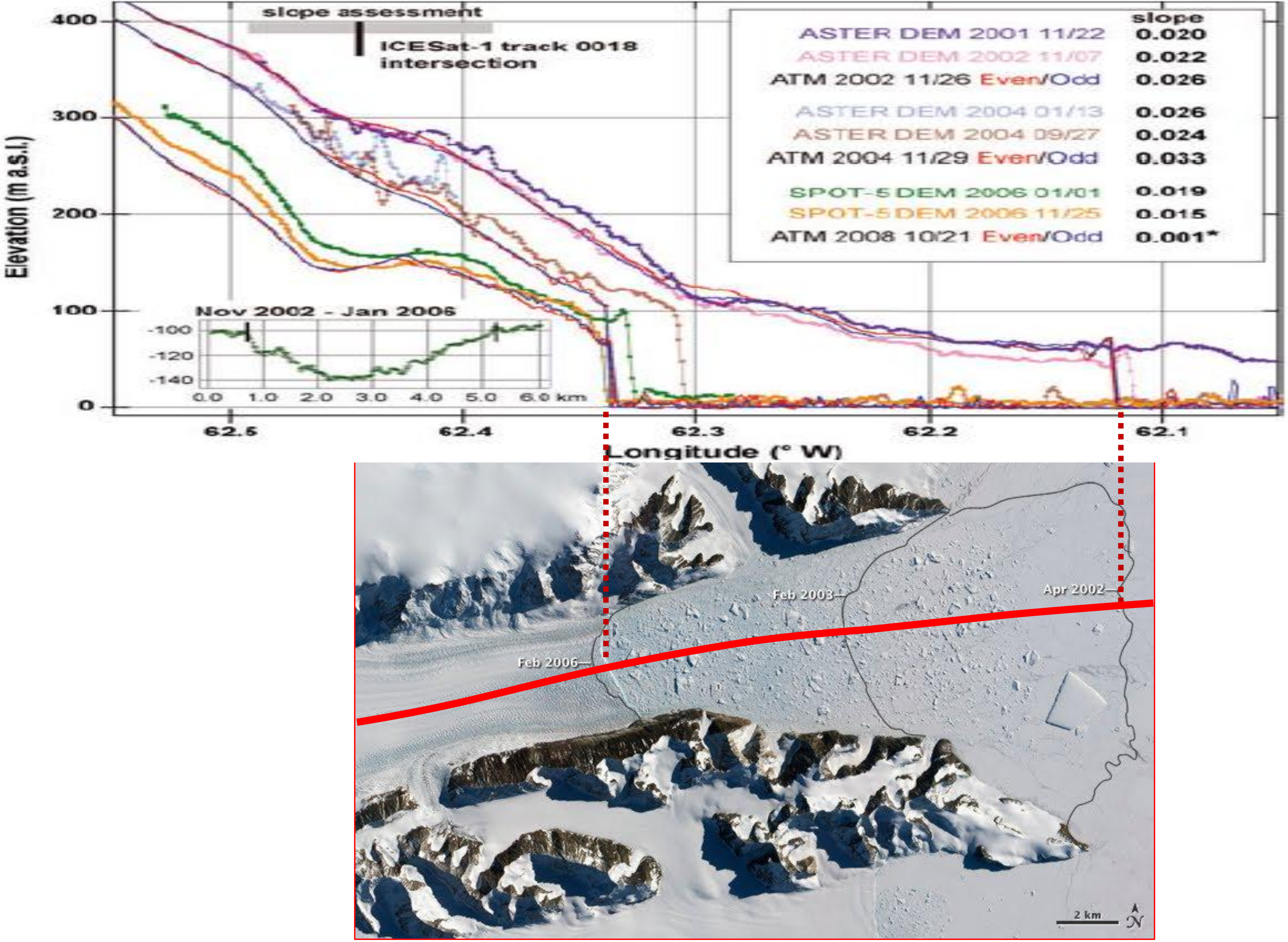
From DeConto and Pollard, 2016

interior accumulation zone pushes the ice sheet toward lighter values of $\delta^{18}O$, despite a warmer overall climate (Gasson, DeConto, and Pollard, 2016)

sea level – isotope ‘deep basin’ effect



Relating a mean ocean $\delta^{18}O$ change to ancient sea level doesn’t work for Antarctica!



Source, Earth Observatory, NASA; Scambos et al., 2011

meltwater-enhanced calving

see: *Pollard, DeConto and Alley, 2015; DeConto and Pollard, 2016*

Crevasse penetration depth *d* dependent on:

- divergence (e.g., Nick et al., 2010; 2013)

$$\dot{\varepsilon} = \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$$

$$d_s = \frac{2}{\rho_i g}\left(\frac{\dot{\varepsilon}}{A}\right)^{\frac{1}{n}} + d_w$$

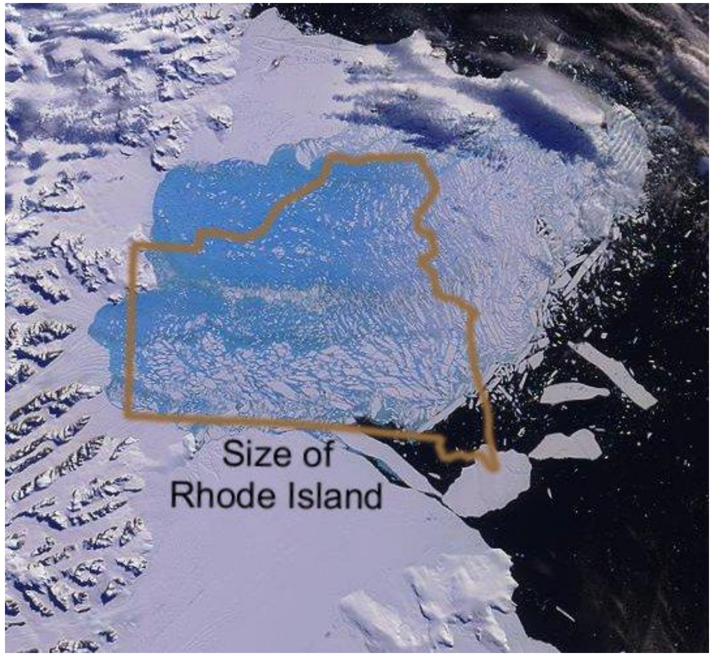
$$\dot{\varepsilon} = 4\left(\frac{\rho_i g h}{4}\right)^{n}$$

$$d_b = \left(\frac{\rho_i}{\rho_o - \rho_i}\right)\frac{2}{\rho_i g}\left(\frac{\dot{\varepsilon}}{A}\right)^{\frac{1}{n}}$$

- Additional deepening d_w *in meters* from

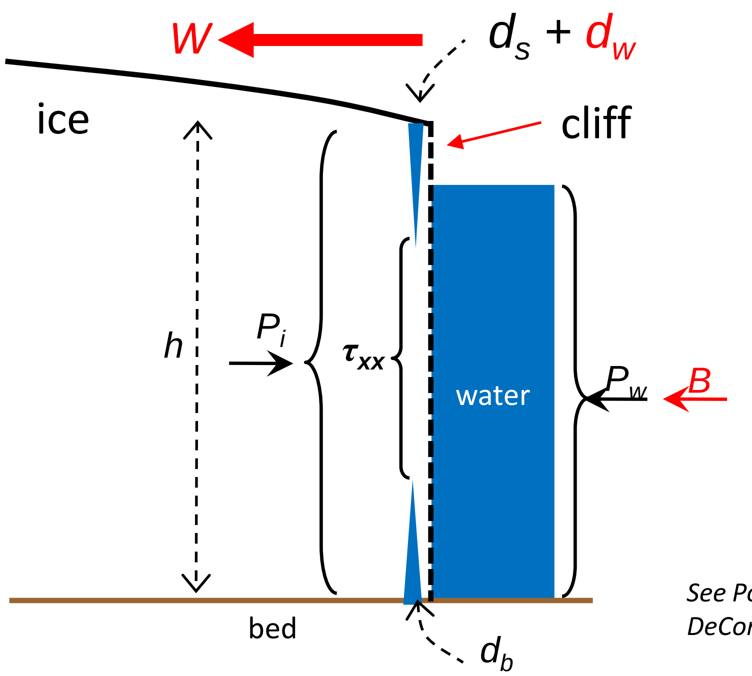
$$C = 3000 \max\left[0, \min\left[1, (r - r_c)/1 - r_c\right]\right]$$

Calving rate *C* (m/yr), where r is ratio of total crevasse penetration to ice thickness. Critical value is 0.75



Marine-terminating ice cliff failure

Force-balance terms at ice cliff/grounding line



after Bassis and Walker (2012):

P_i = ice pressure

P_w = water pressure

τ_{xx} = longitudinal stress ($\partial u/\partial x$)

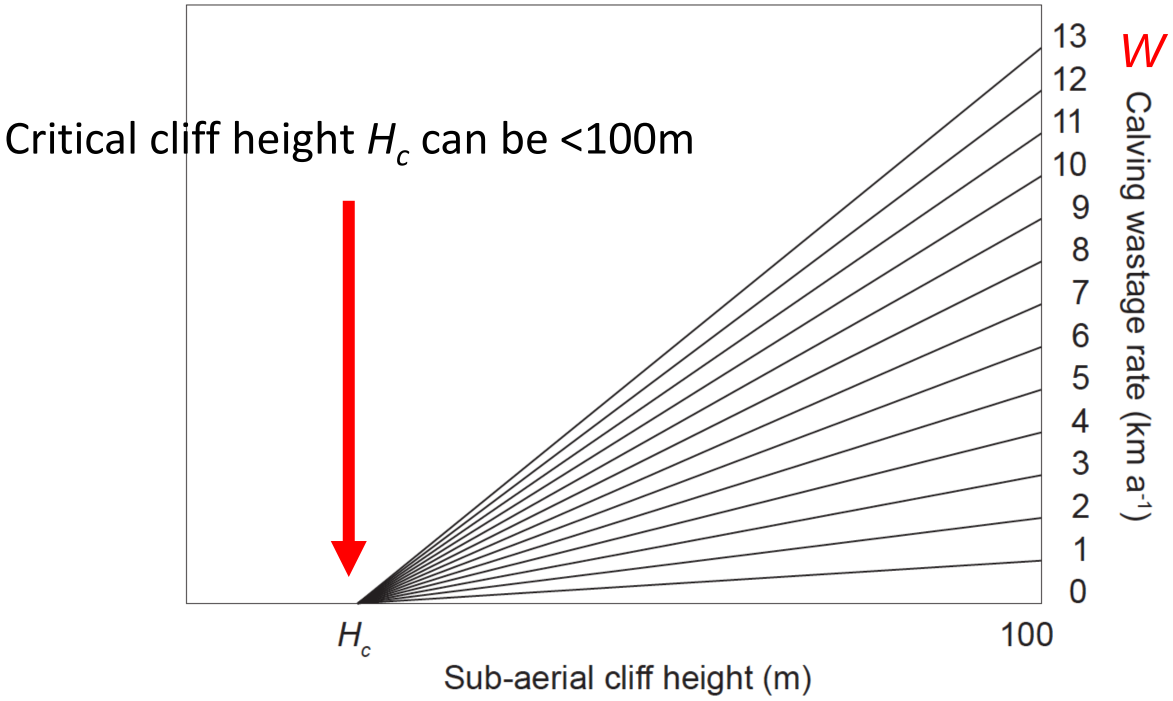
d = crevasse depth, f (h)

$$\boxed{\tau_{xx} = h\,(P_i - P_w - B)\,/\,(h - d - d_w)}$$

B = back stress

d = f (h, B) + d_w

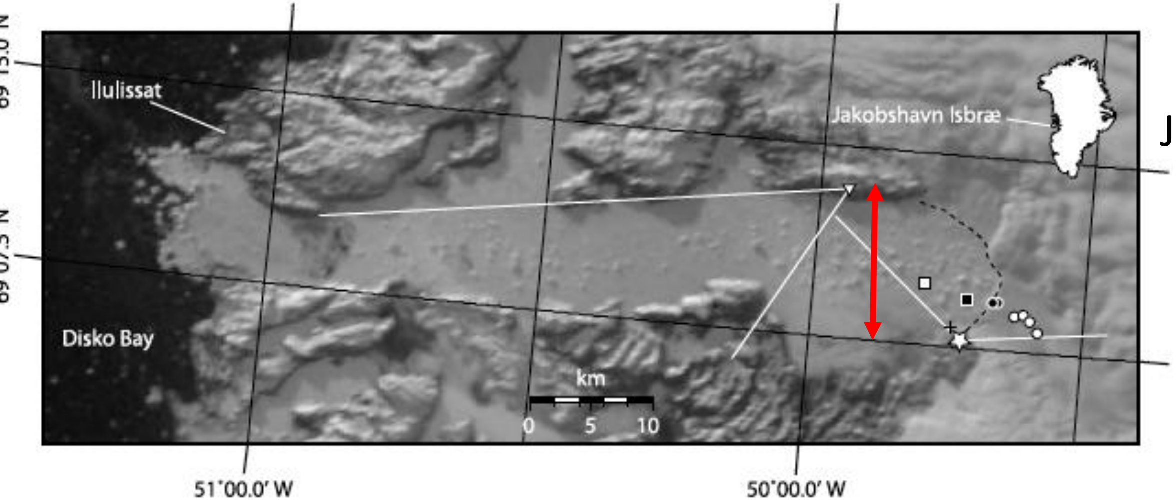
See Pollard, DeConto and Alley, 2015 and DeConto and Pollard, 2016 for complete formulation



W at Jakobshavn ~13 km yr^{-1}

- Cliff failure occurs if longitudinal stress τ_{xx} exceeds yield strength (~1 MPa)
- τ_{xx} increases as the vertical extent of intact ice (h-d) is reduced by crevassing
- maximum cliff size is reduced by surface crevassing (d_w) due to meltwater+rain

(Smaller effects due to back stress B if ice shelf or mélange provides some buttressing)



Jakobshavn

~10 km

MODIS image, Amundson et al., 2010

~120 km

Thwaites

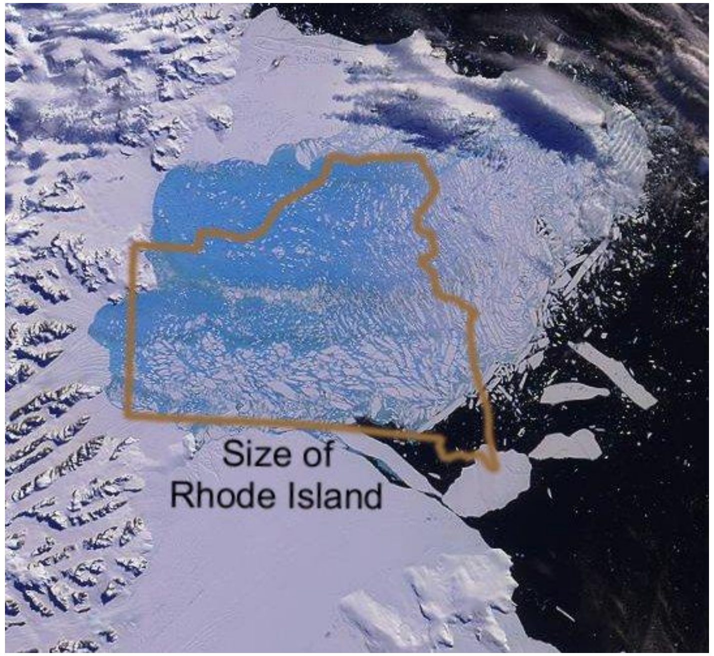
Perturbed physics ensemble (n=196)

maximum cliff-failure rate in ensembles: 0-13 km/yrc	Sensitivity of surface crevasse depth to meltwater production $d_w = 90R^2$
0 km yr^{-1}	0
1 km yr^{-1}	15
2 km yr^{-1}	30
3 km yr^{-1}	45
4 km yr^{-1}	60
5 km yr^{-1}	75
6 km yr^{-1}	90
7 km yr^{-1}	105
8 km yr^{-1}	120
9 km yr^{-1}	135
10 km yr^{-1}	150
11 km yr^{-1}	165
12 km yr^{-1}	180
13 km yr^{-1}	195

Widespread movement of meltwater onto and across Antarctic ice shelves

Jonathan Kingslake[1], Jeremy C. Ely[2], Indrani Das[1] & Robin E. Bell[1]

Photo: Wong Sang Lee/Korea University of Science and Technology



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