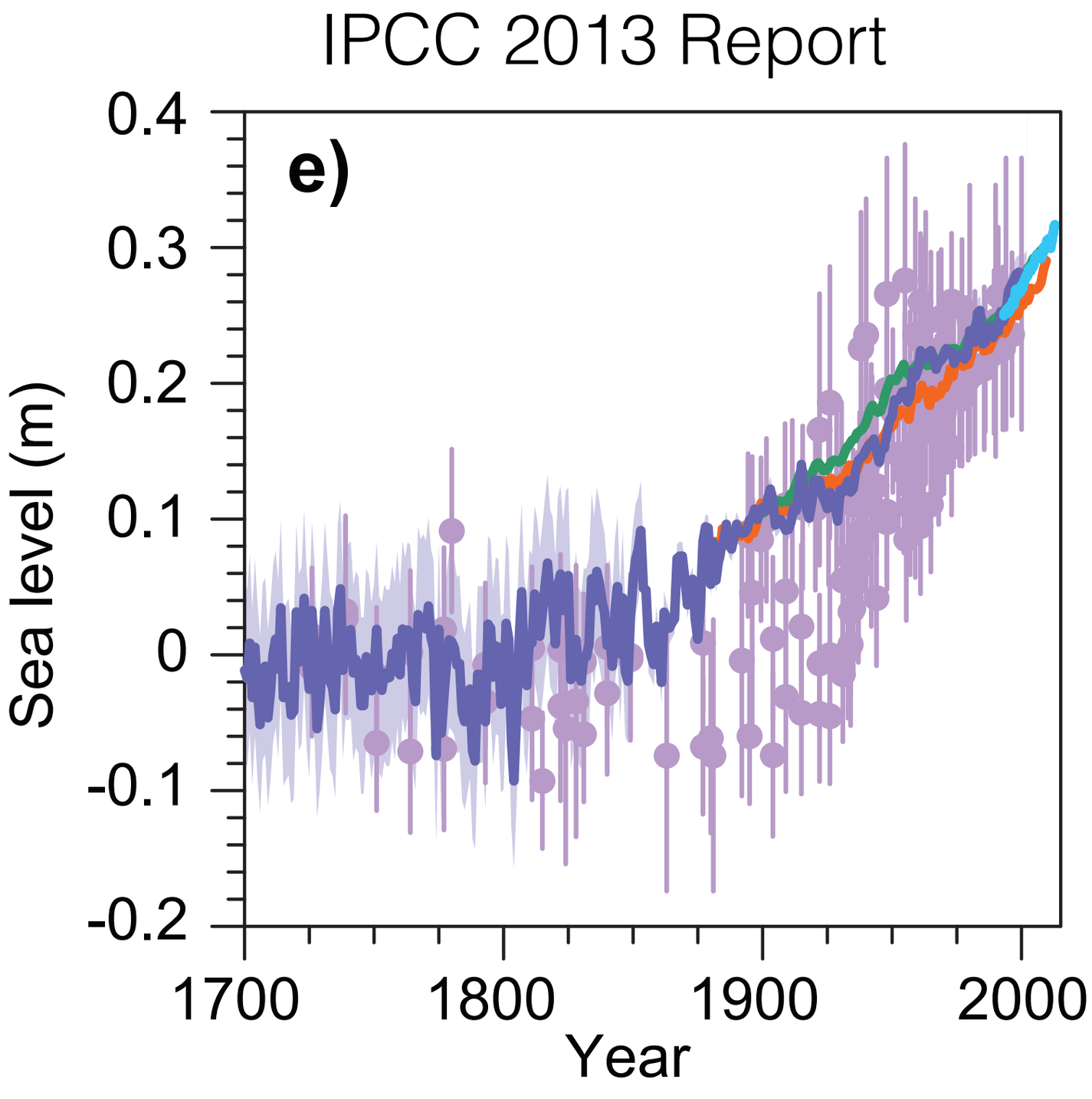
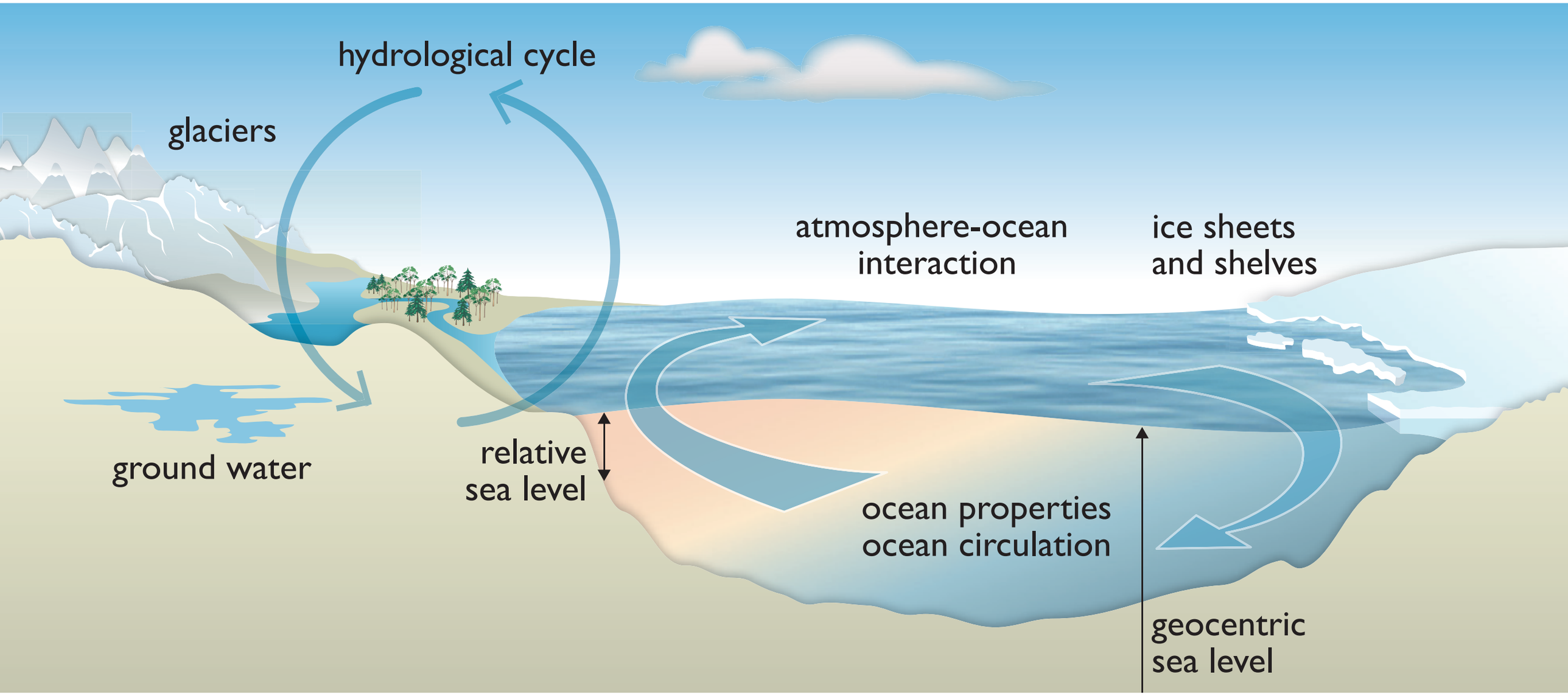
Global Drivers of Modern Sea Level Change

Modern changes



Where does modern sea level rise come from?

What causes sea level change?



The sea level budget

Source	1901–1990	1971–2010	1993–2010
Observed contributions to global mean sea level (GMSL) rise			
Thermal expansion	–	0.8 [0.5 to 1.1]	1.1 [0.8 to 1.4]
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Greenland ice sheet	–	–	0.33 [0.25 to 0.41]
Antarctic ice sheet	–	–	0.27 [0.16 to 0.38]
Land water storage	–0.11 [–0.16 to –0.06]	0.12 [0.03 to 0.22]	0.38 [0.26 to 0.49]
Total of contributions	–	–	**2.8 [2.3 to 3.4]**
Observed GMSL rise	**1.5 [1.3 to 1.7]**	**2.0 [1.7 to 2.3]**	**3.2 [2.8 to 3.6]**

IPCC AR4 Report

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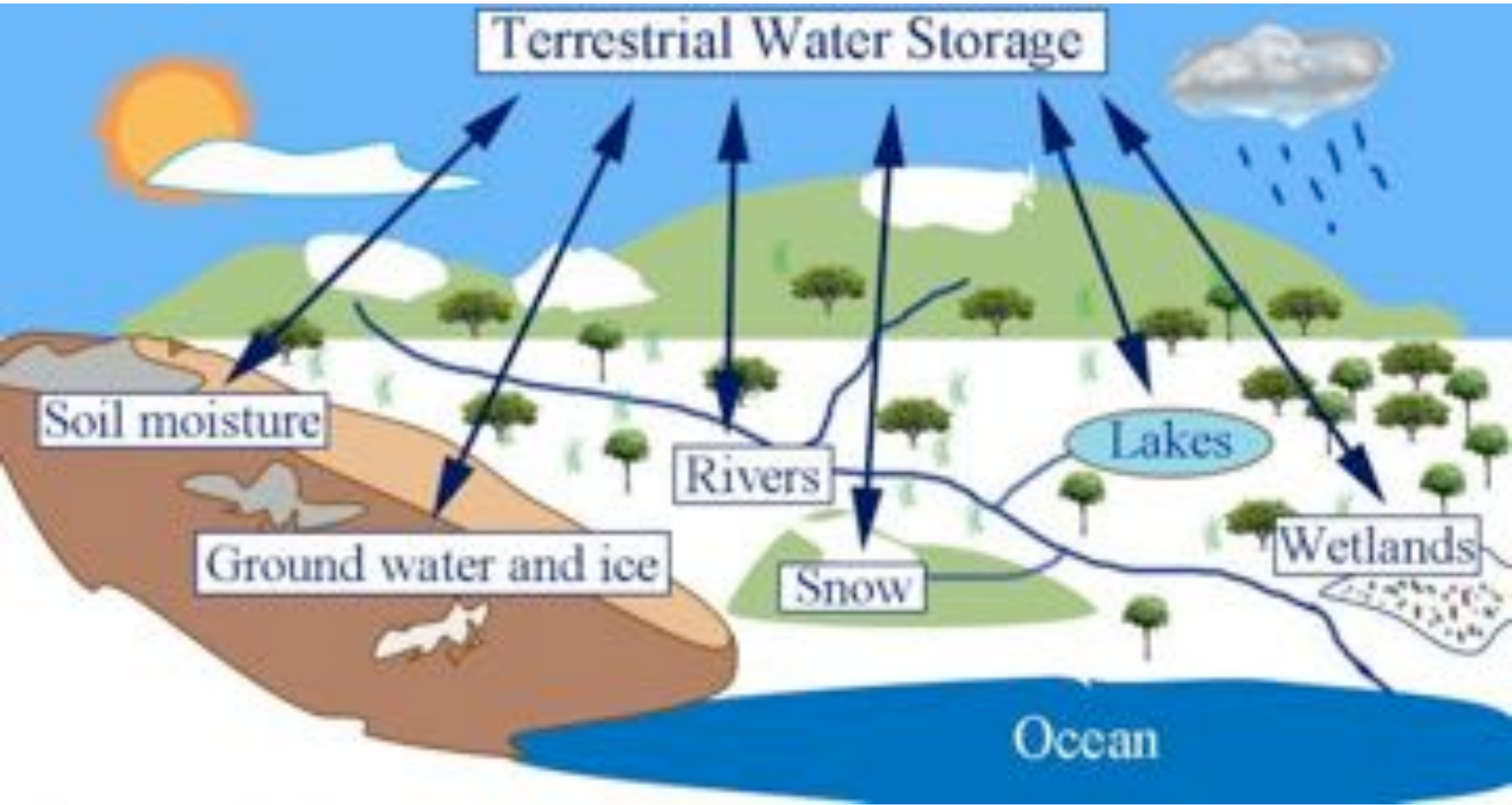
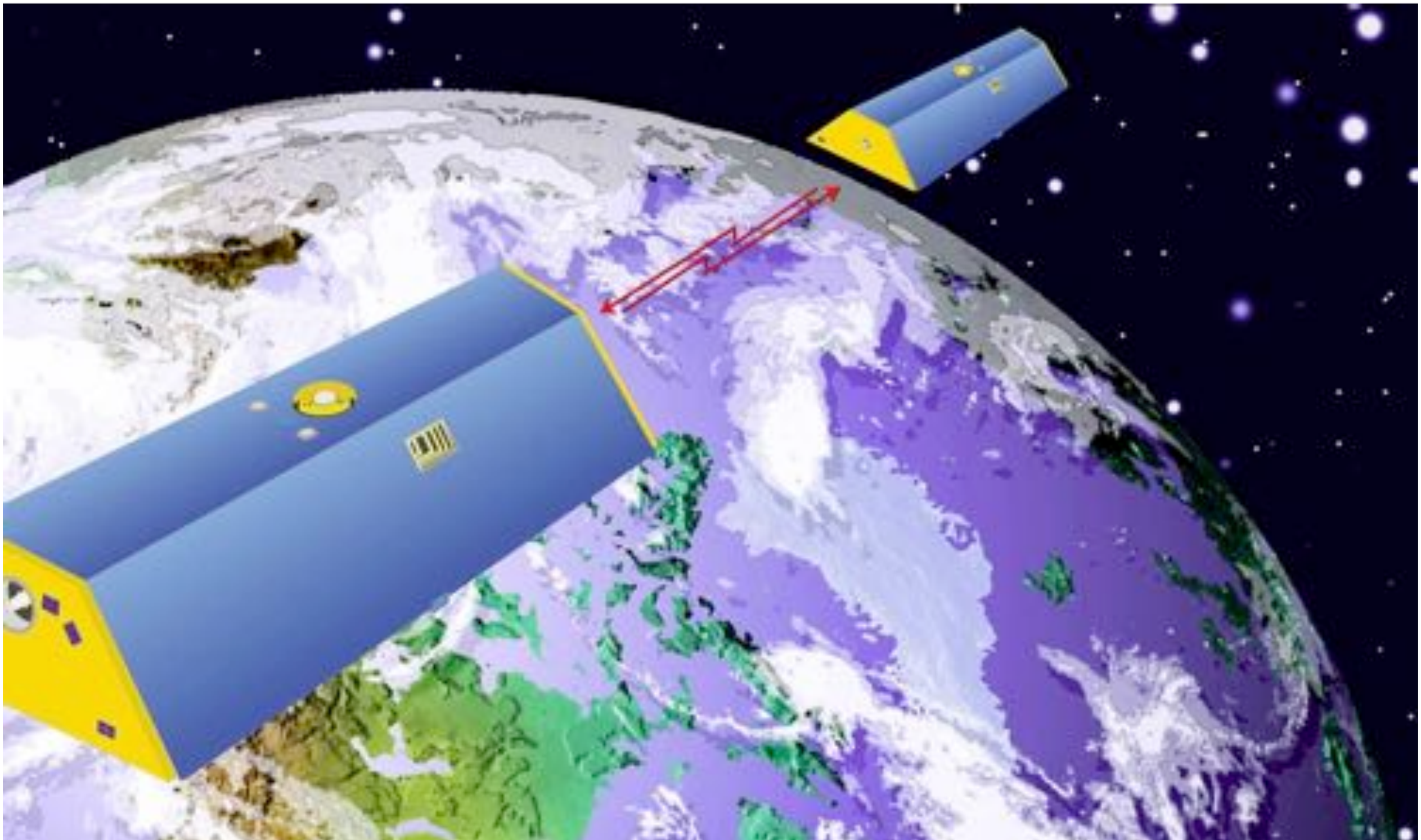
However, in the last 10-15 years the contribution from Greenland and Antarctica has greatly increased

Terrestrial Water Storage/ Discharge

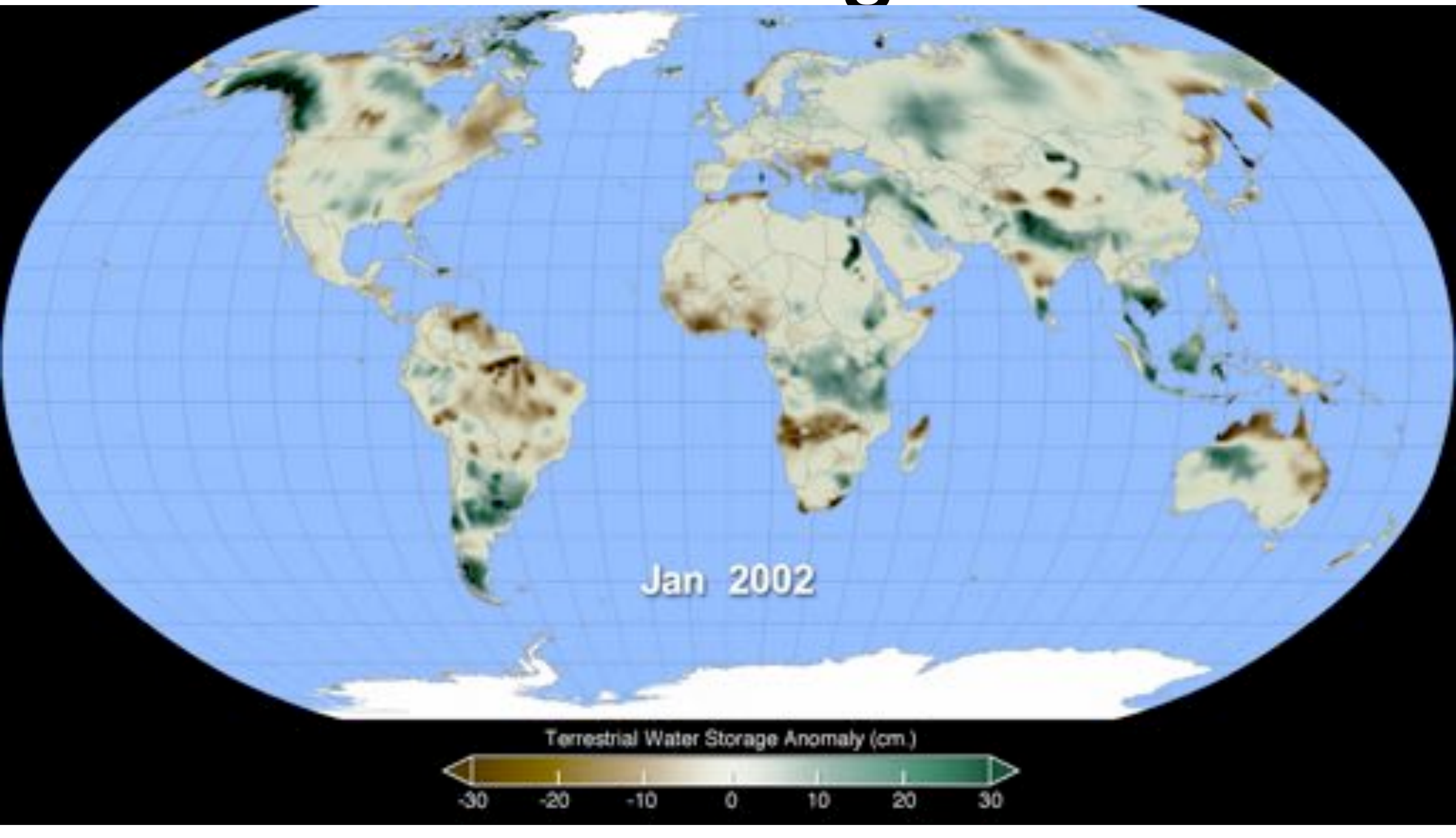
What is terrestrial water storage?



GRACE satellites measure changing gravity anomalies at Earth's surface



Terrestrial Water Storage/ Discharge



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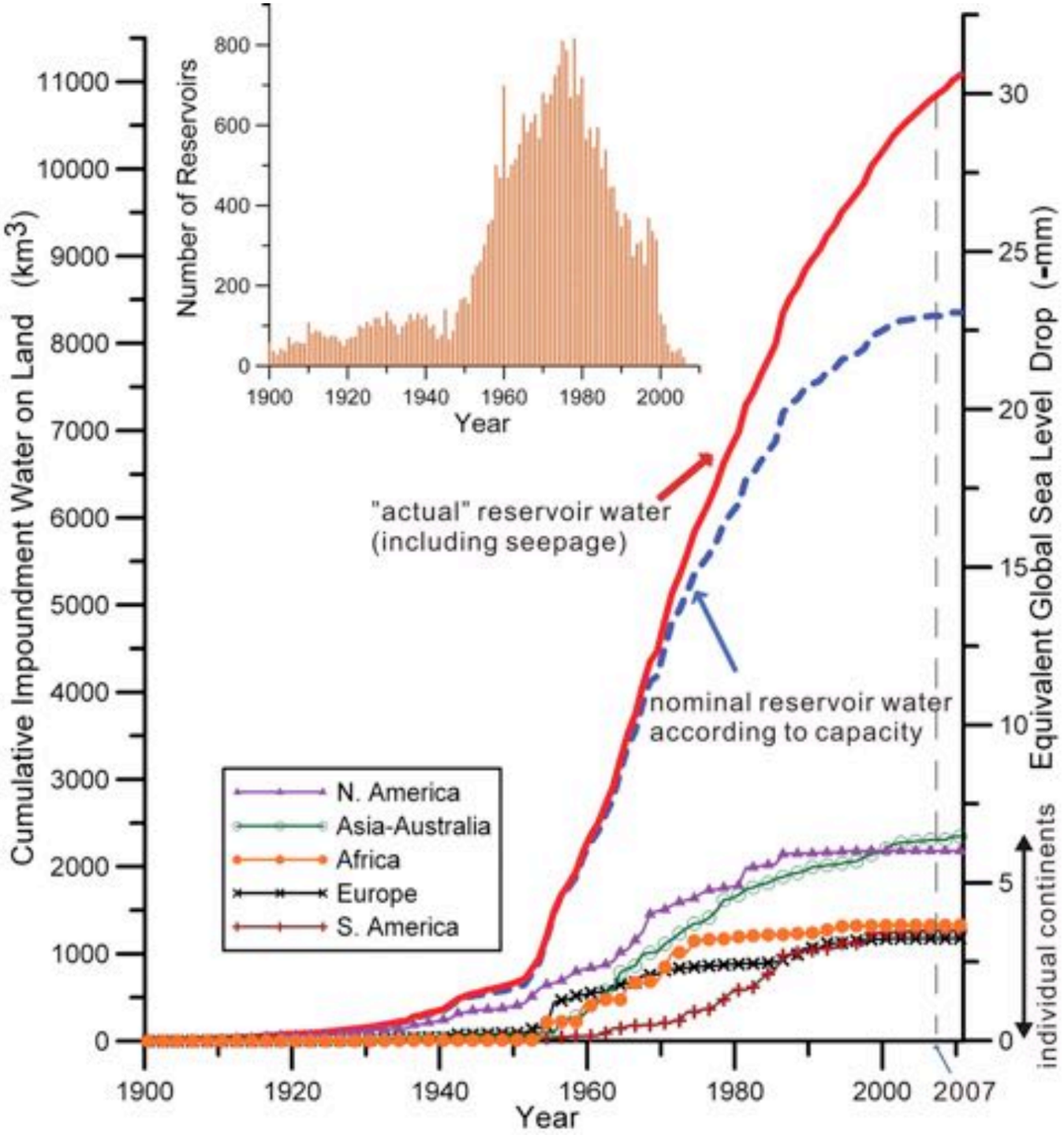


Chao et al. 2008

Terrestrial Water Storage/ Discharge

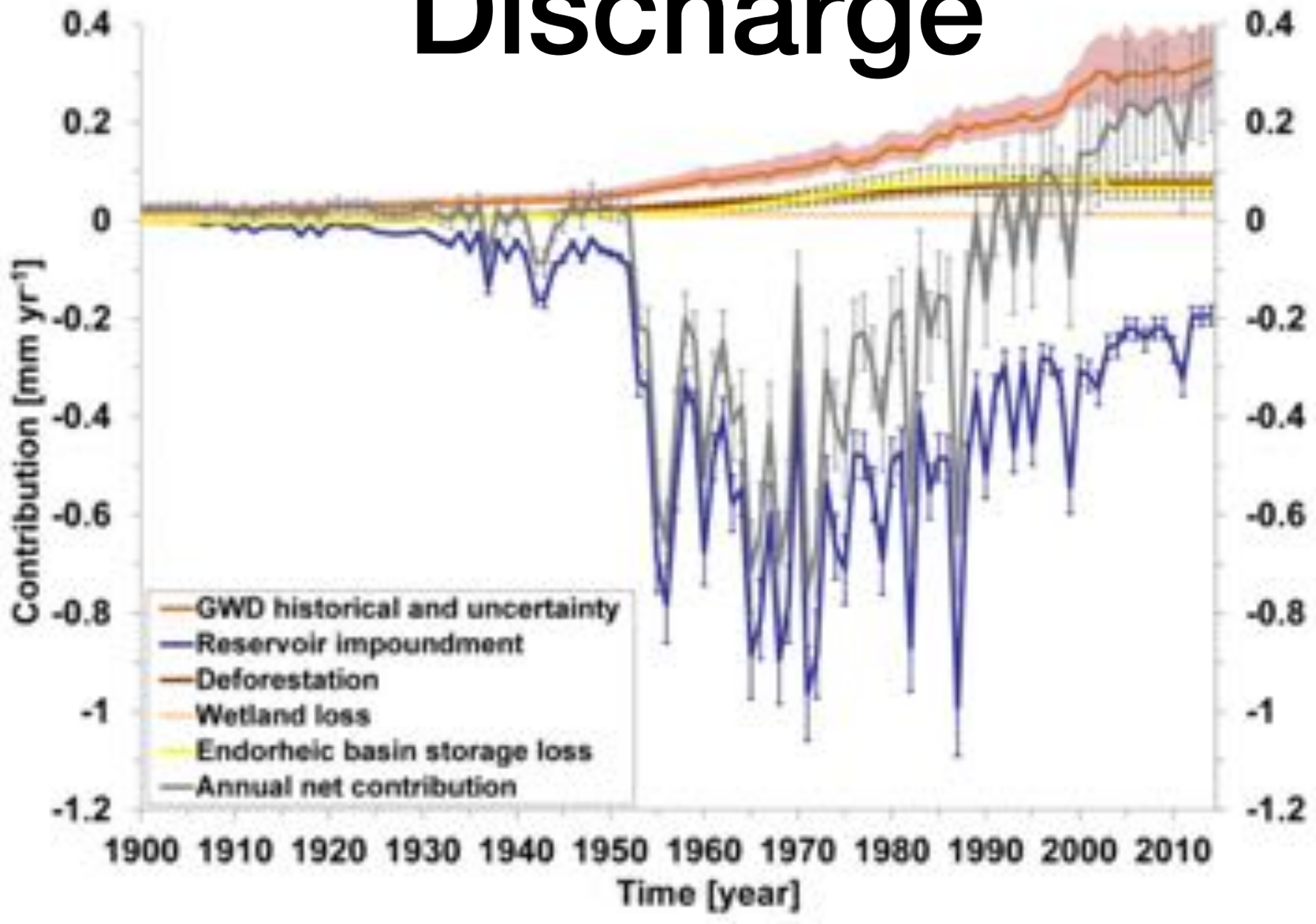


Figure 11: Time series of the estimated annual contribution of terrestrial water storage change to global sea-level over the period 1900-2014 (rates in mm yr^{-1} SLE) (modified from Wada et al., 2016).

Thermal expansion of seawater

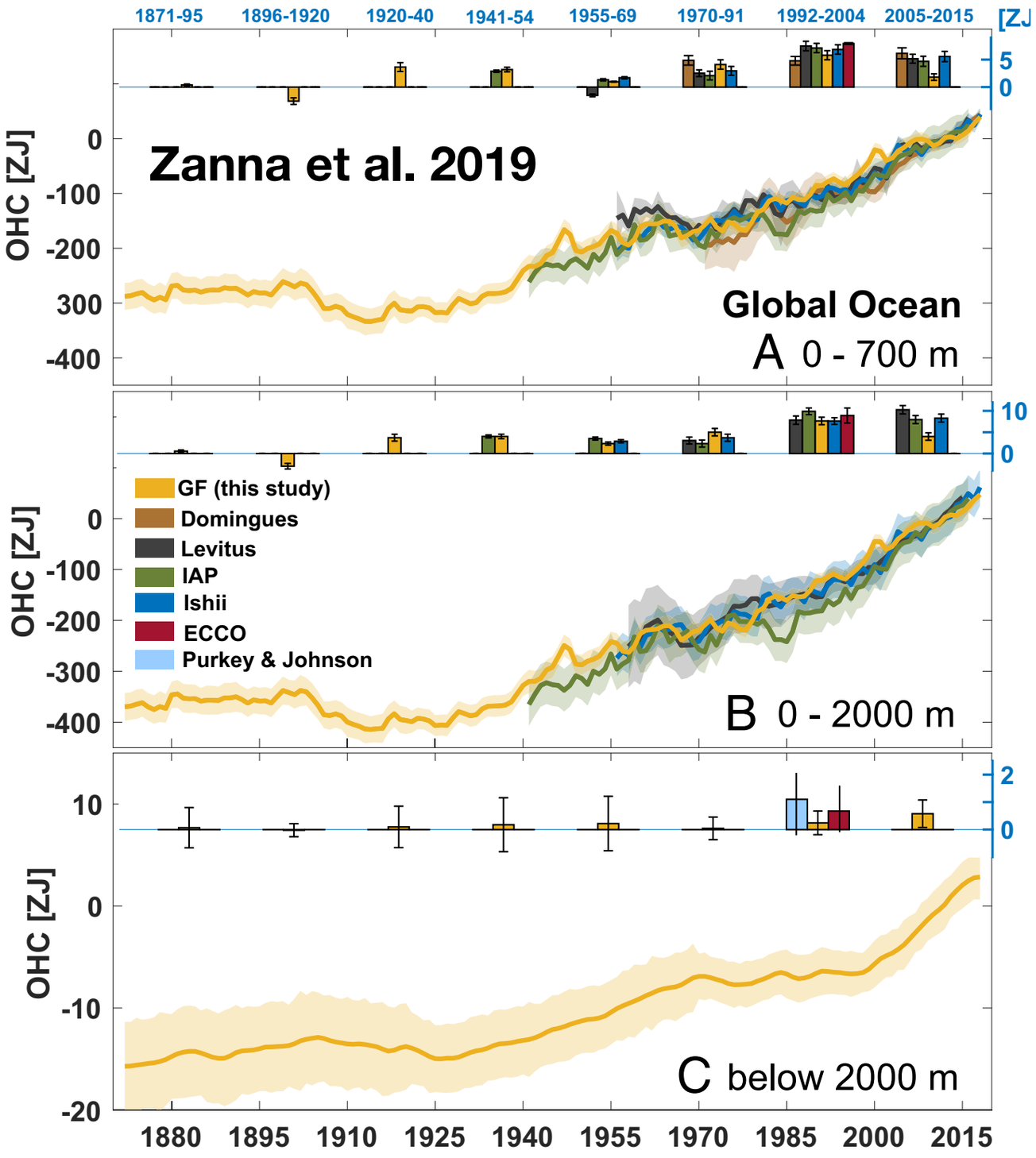
An easy science experiment

Thermal Expansion of Water: Demonstration and Explanation

Thermal Expansion of Water: Demonstration and Explanation

https://youtu.be/IHhvaUdWfDI?t=69

Ocean heat uptake

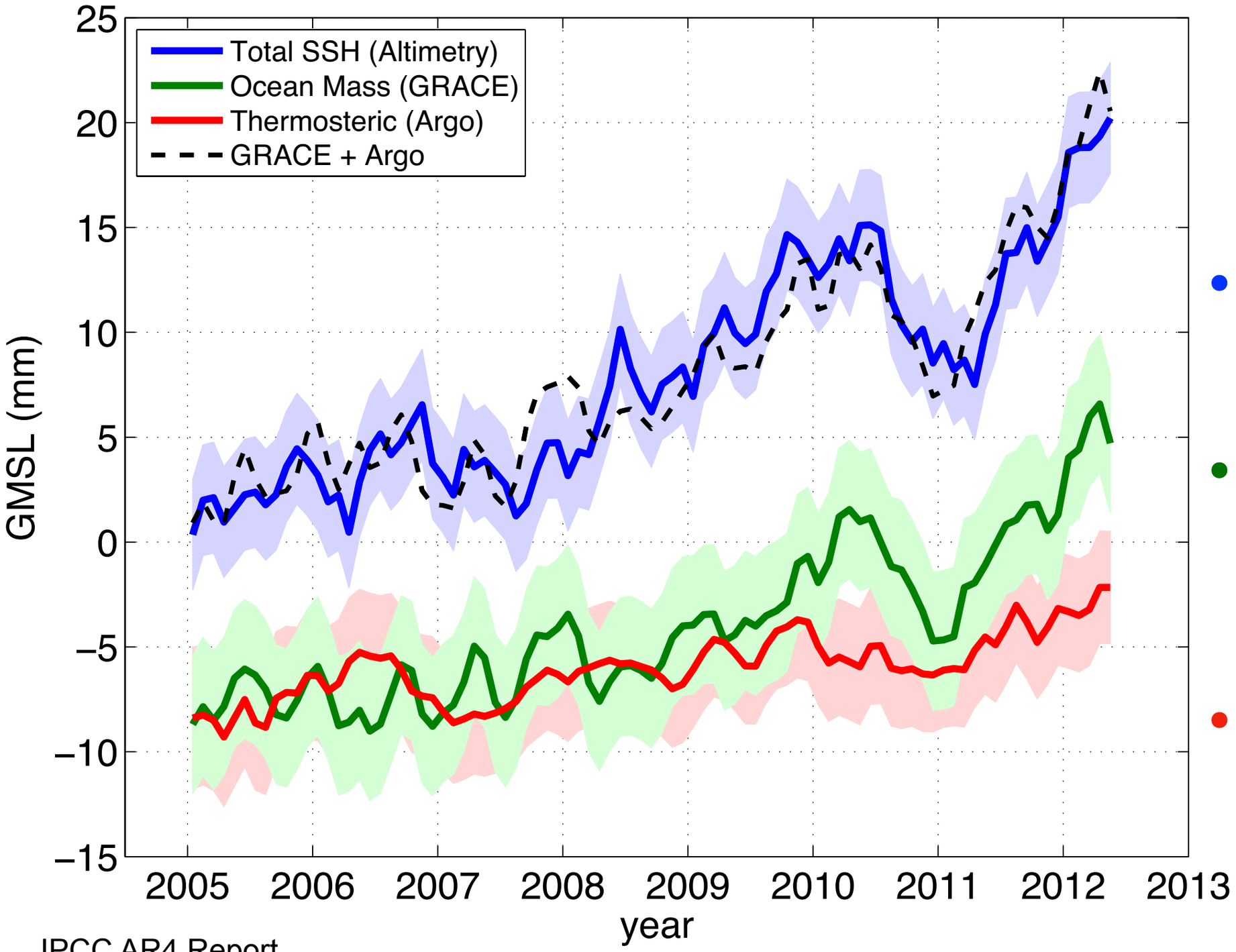


~90% of all extra heat retained in the atmosphere by increased greenhouse gas emissions has been taken up by the ocean

[ZJ = 10^{21} J]

(0.5 ZJ = global annual energy use)

How to distinguish thermal expansion from other things



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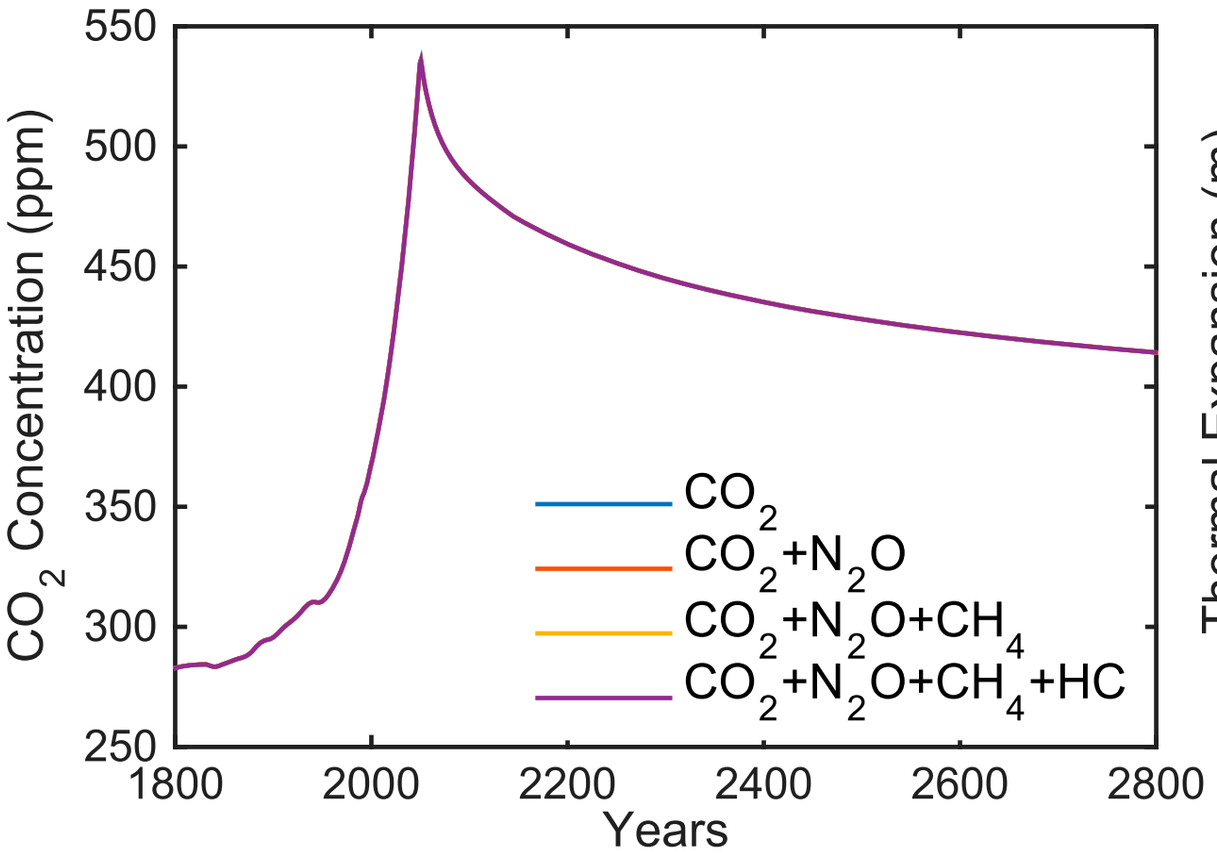
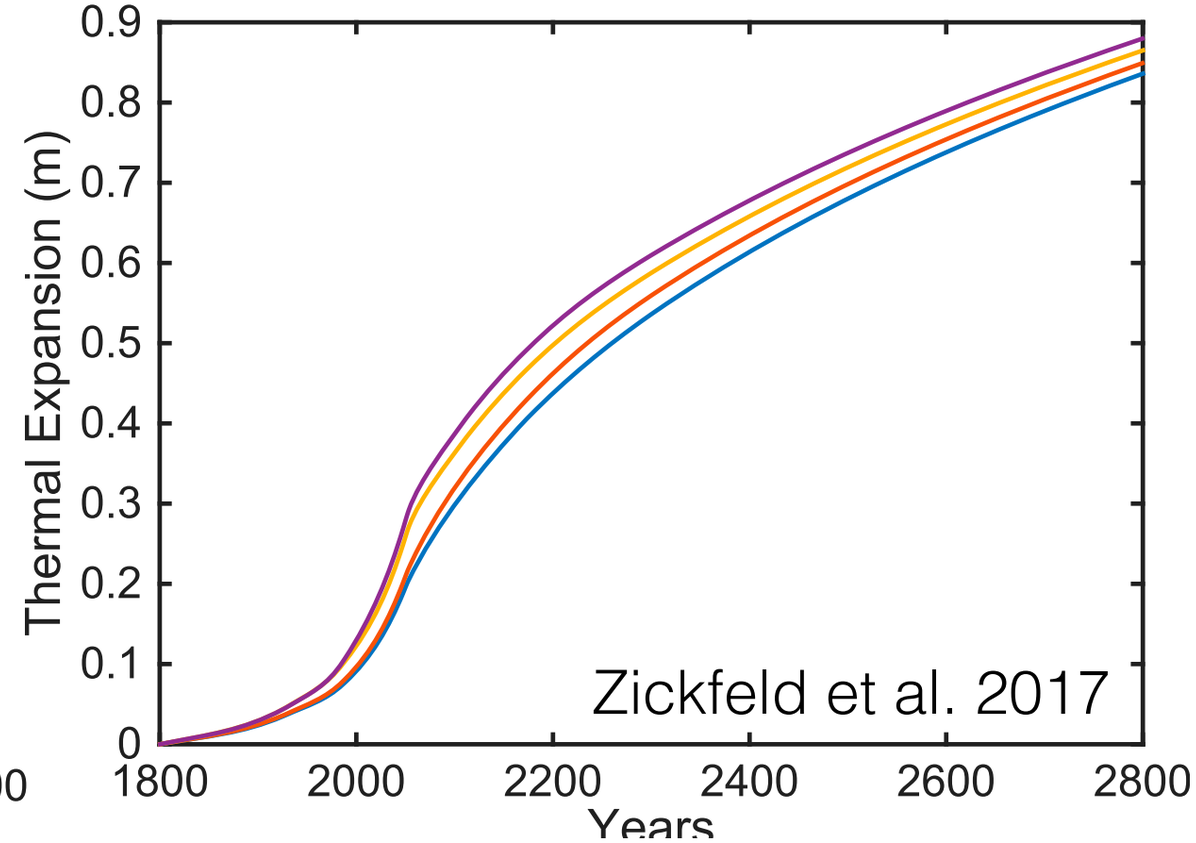
Three independent measurements

- **Satellite altimeters measure sea surface heights**
- **Satellite gravimeters measure the ocean mass**
- **Ocean floats measure density of the ocean**

The delayed reaction of the ocean to increased atmospheric temperatures





Even if we stop emitting greenhouse gases today, the ocean would continue to slowly absorb heat and expand for hundreds of years

Ice

Where is ice

Mountain glaciers: 0.4 m SLE
Greenland Ice Sheet: 7.4 m SLE
Antarctic Ice Sheet: 58.3 m SLE

Glacier vs. Ice Sheet vs. Ice Cap vs. Ice Stream vs. Sea Ice

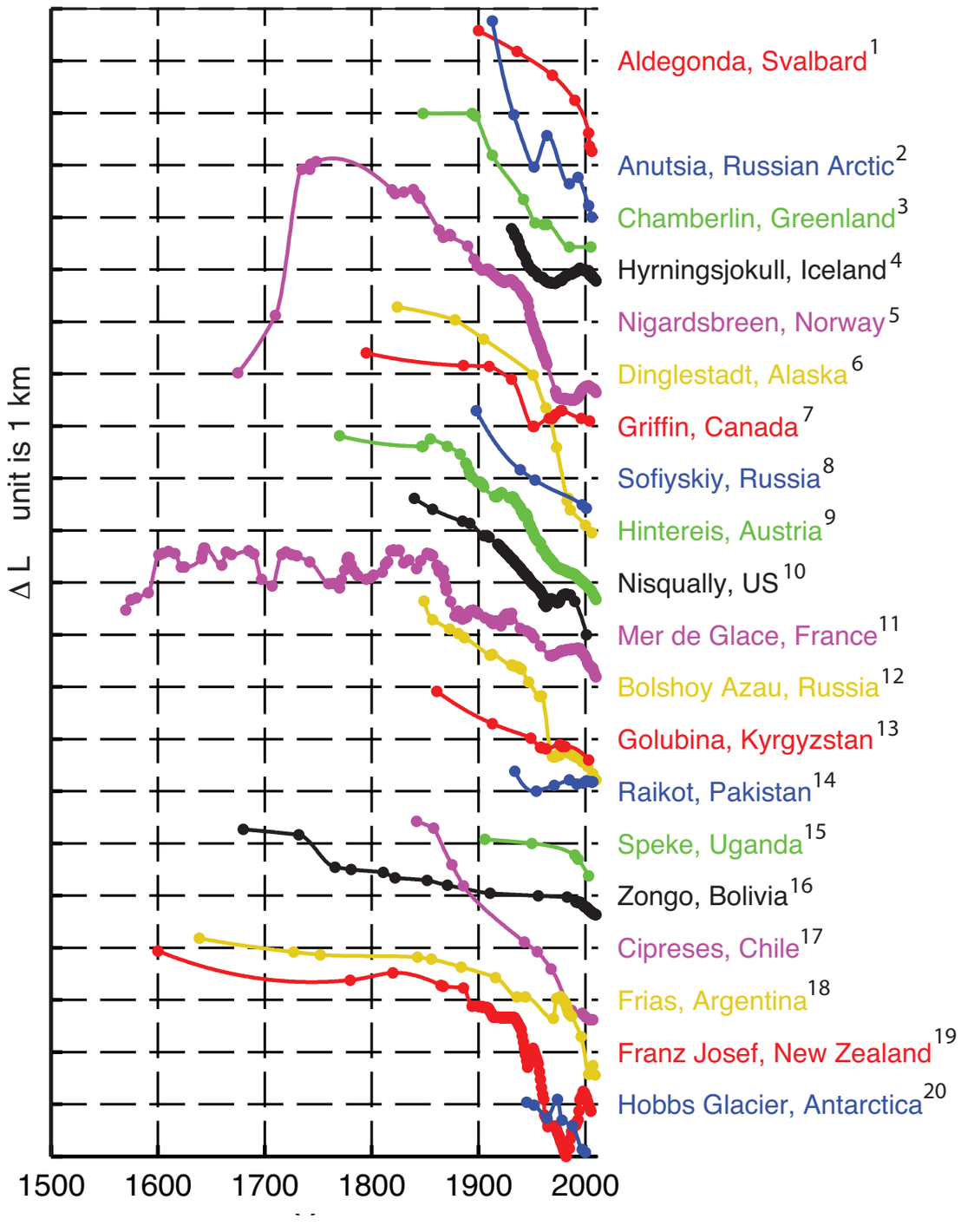
Mountain Glaciers

Trift Glacier, Switzerland, has retreated by 1.17 km (0.7 miles) between 2006 (left) and 2015 (right) James Balog and the Extreme Ice Survey

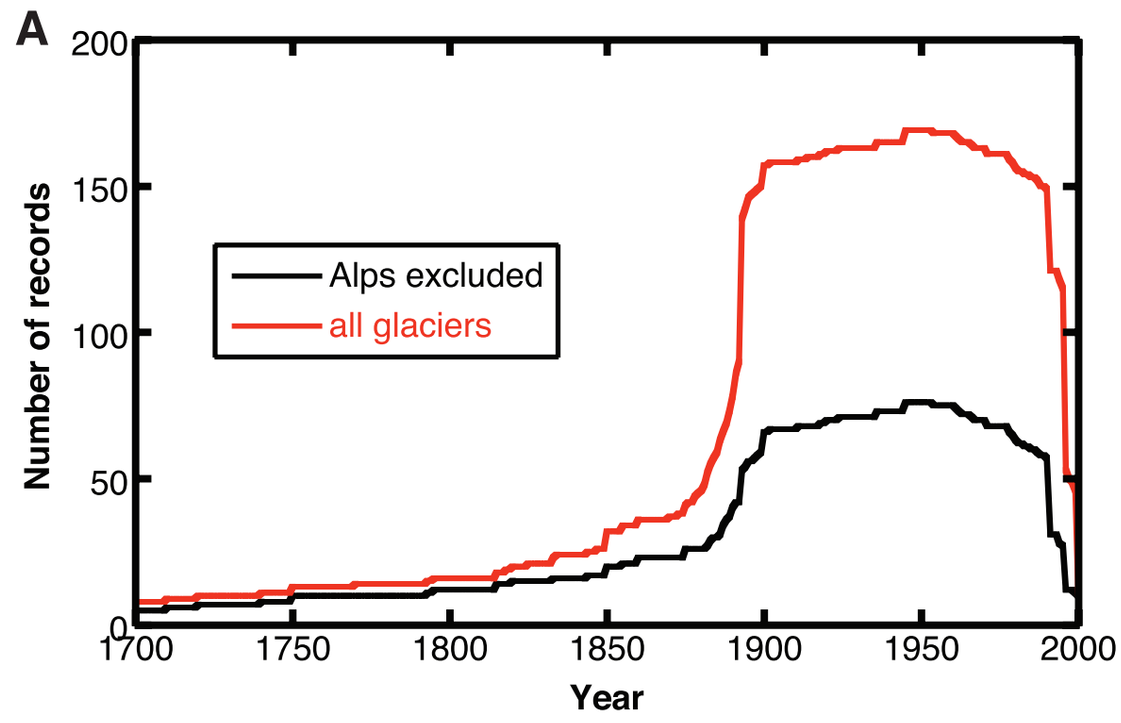
Columbia Glacier, Alaska, has retreated by 6.5 km (4 miles) between 2009 (left) and 2015 (right) James Balog and the Extreme Ice Survey

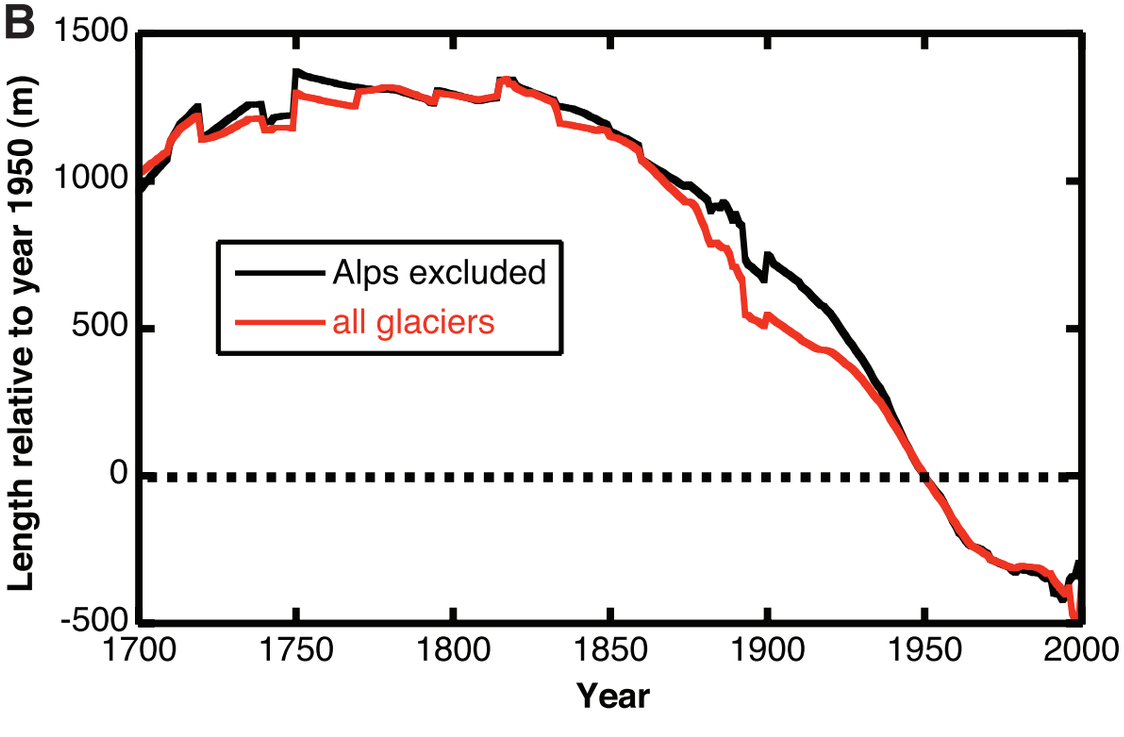
Stein Glacier, Switzerland, has retreated by 550 m (1,800 ft) between 2006 (left) and 2015 (right) James Balog and the Extreme Ice Survey

Mountain glaciers



Leclercq et al. 2014





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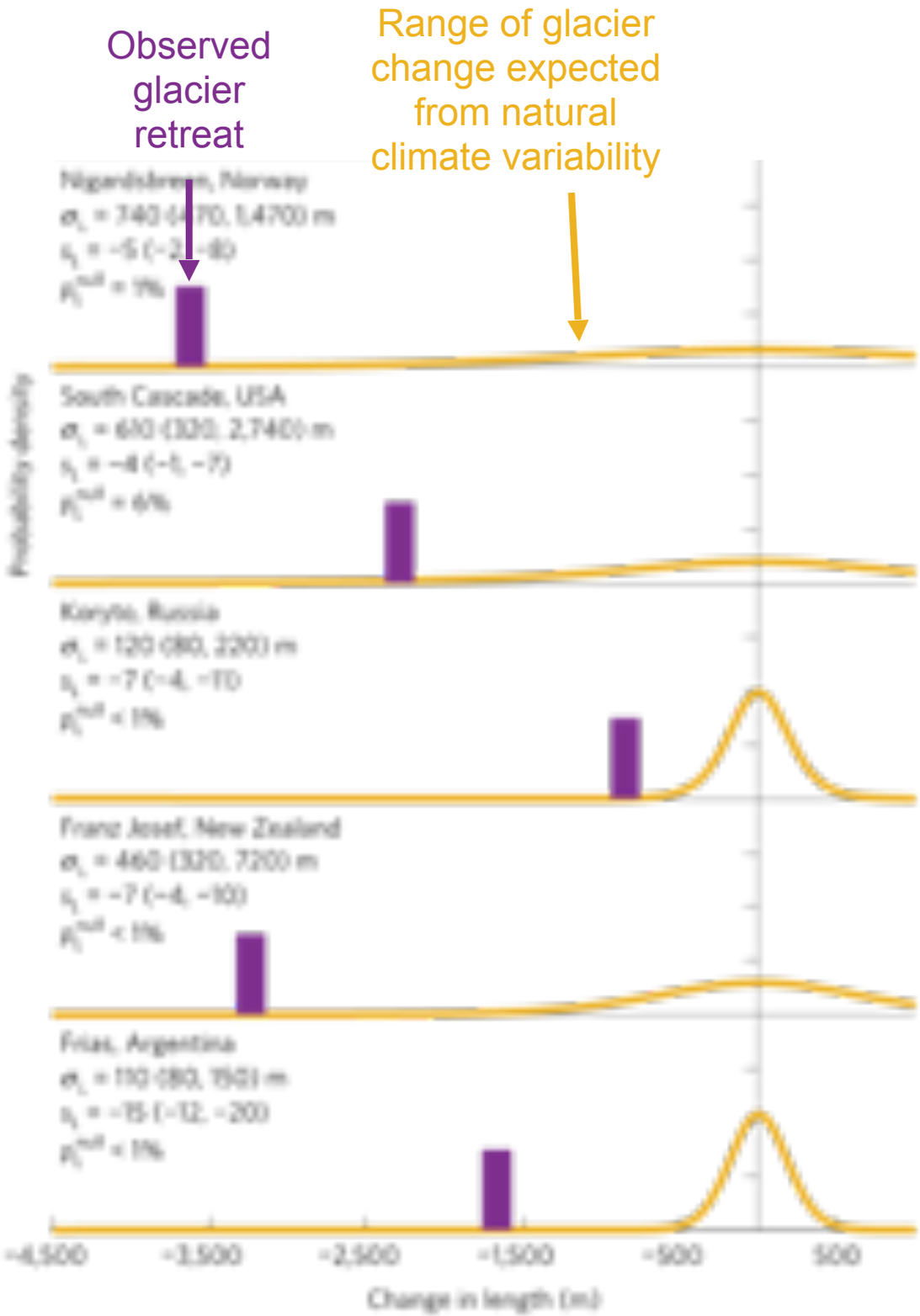

nature geoscience

ARTICLES

PUBLISHED ONLINE: 12 DECEMBER 2016 | DOI: 10.1038/NGEO2863

Centennial glacier retreat as categorical evidence of regional climate change

Gerard H. Roe[1]*, Marcia B. Baker[1] and Florian Herla[2]

"…observed retreats of individual glaciers represent some of the highest signal-to-noise ratios of climate change yet documented."

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IPCC AR4 Report

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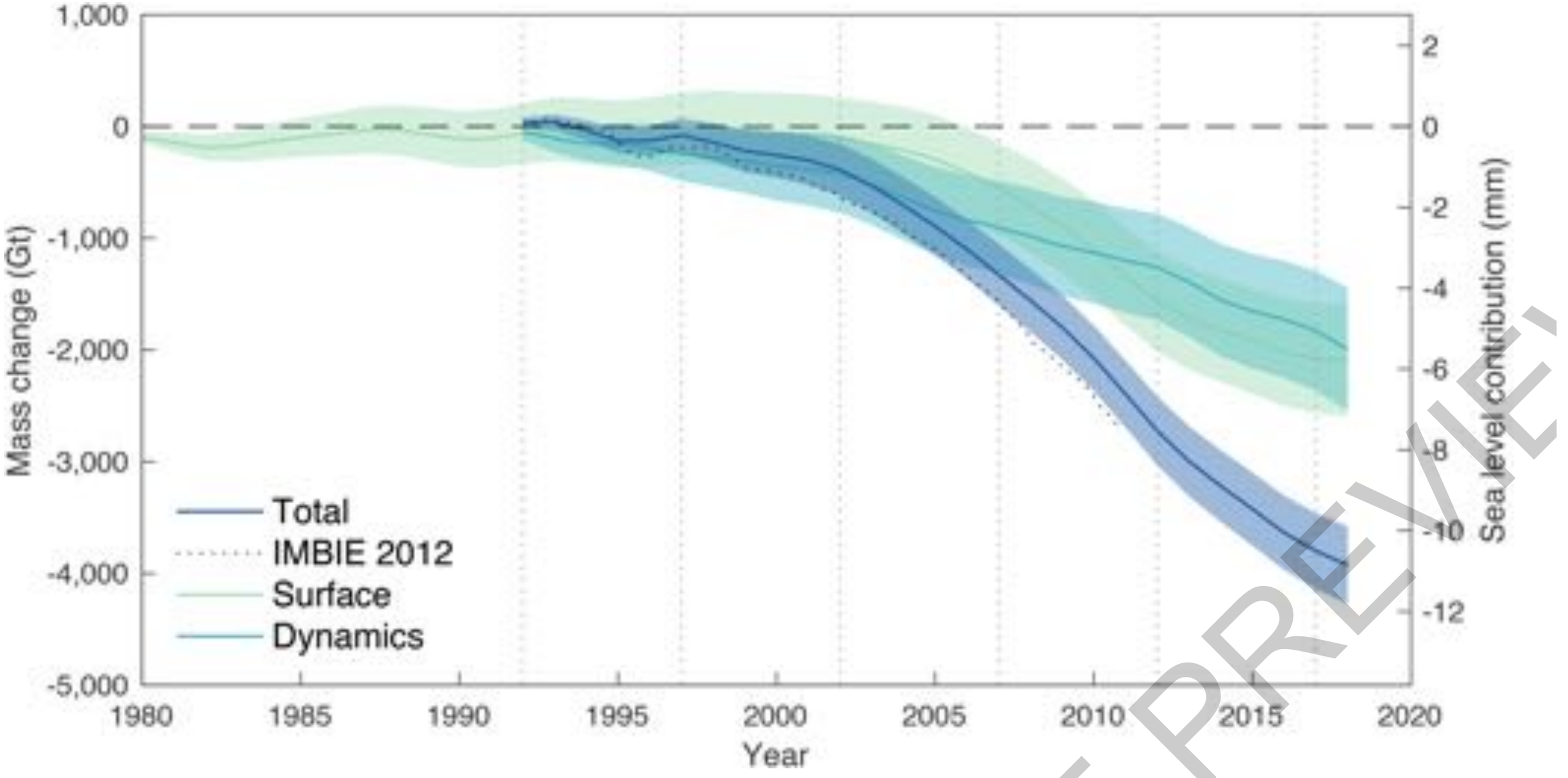
Ice sheets

Greenland Ice Sheet



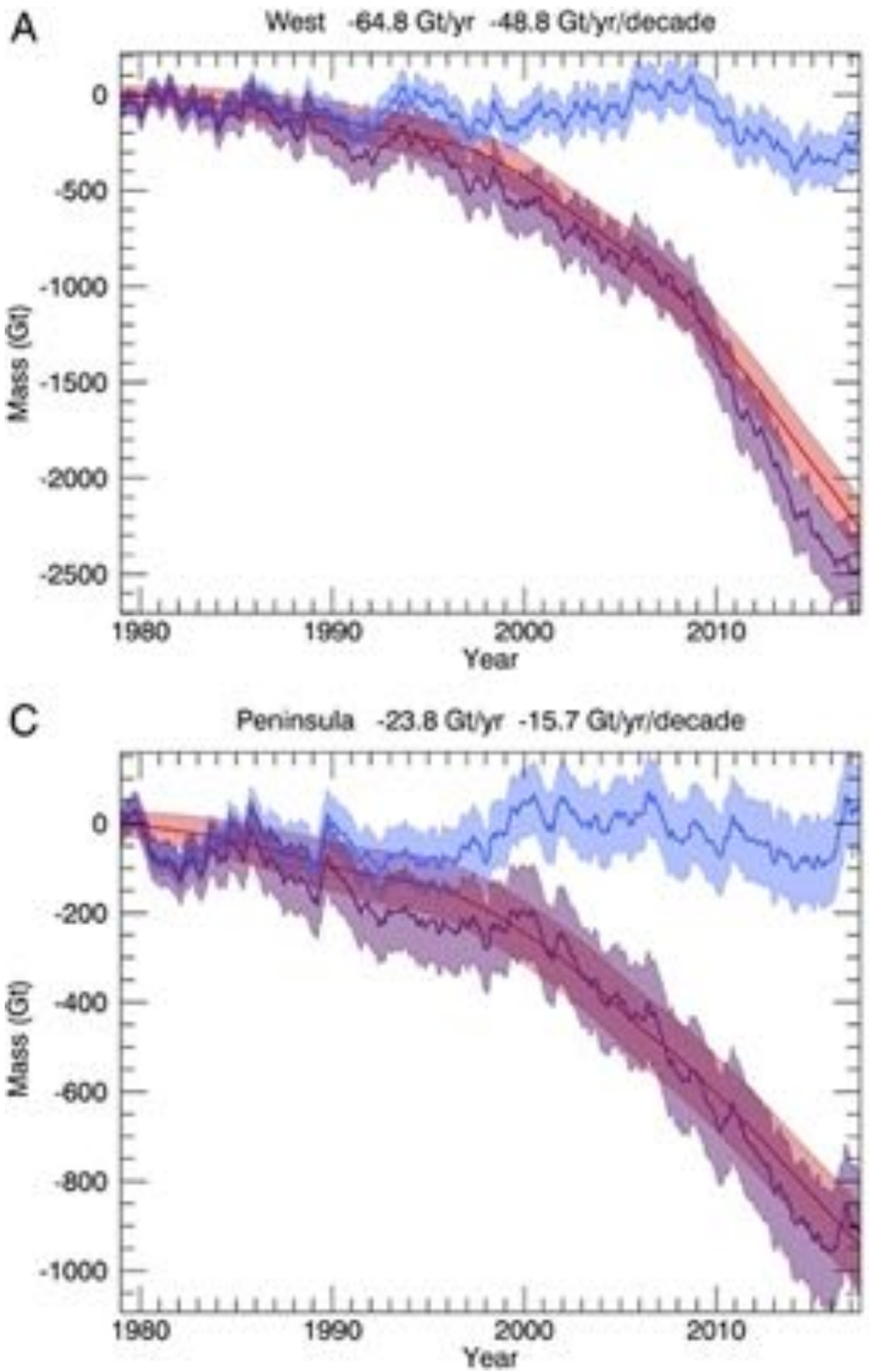
Satellite-based measurements of ice mass loss from the Greenland Ice Sheet

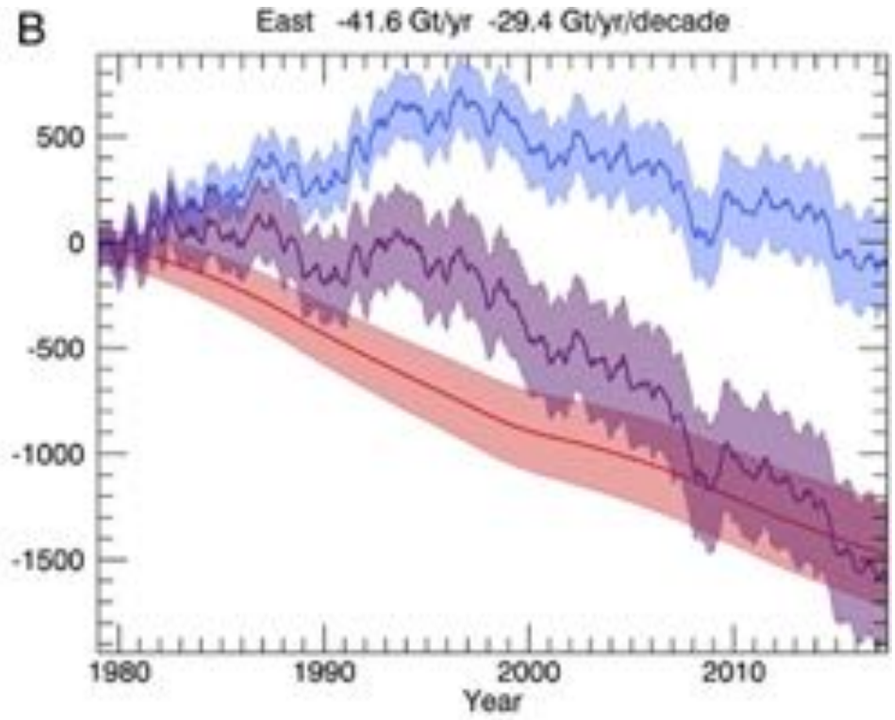
- Ice in/out from snowfall/melt on ice sheet
- Ice out from melt and iceberg calving
- Total "mass balance"

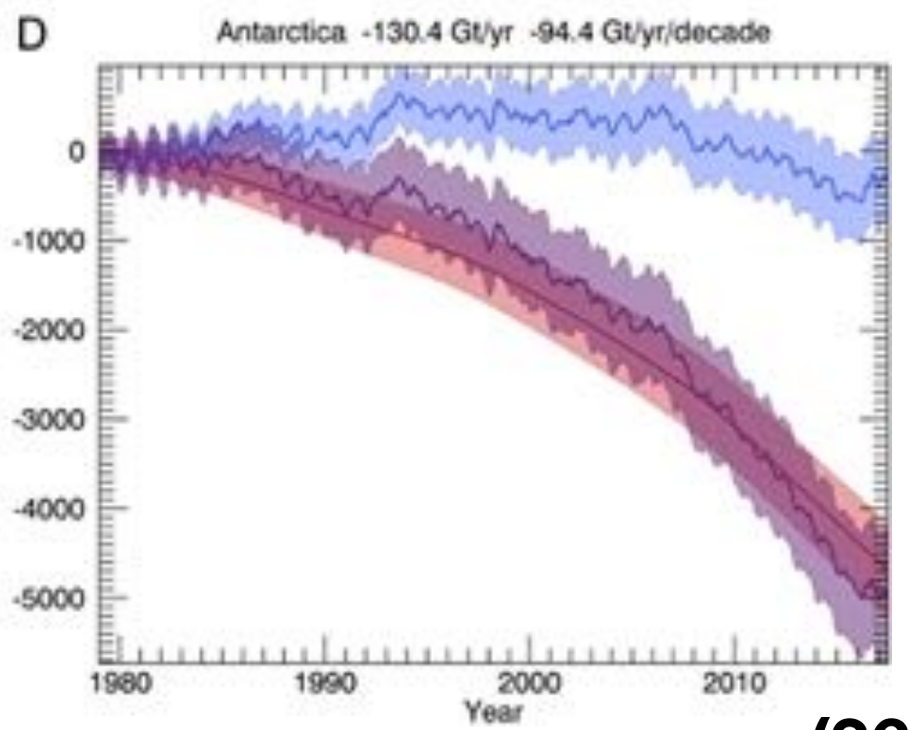
(IMBIE Team 2019)

(365 Gt = 1 mm SLR)

Antarctic Ice Sheet







<u>Satellite-based measurements of ice mass loss from the Antarctic Ice Sheet</u>

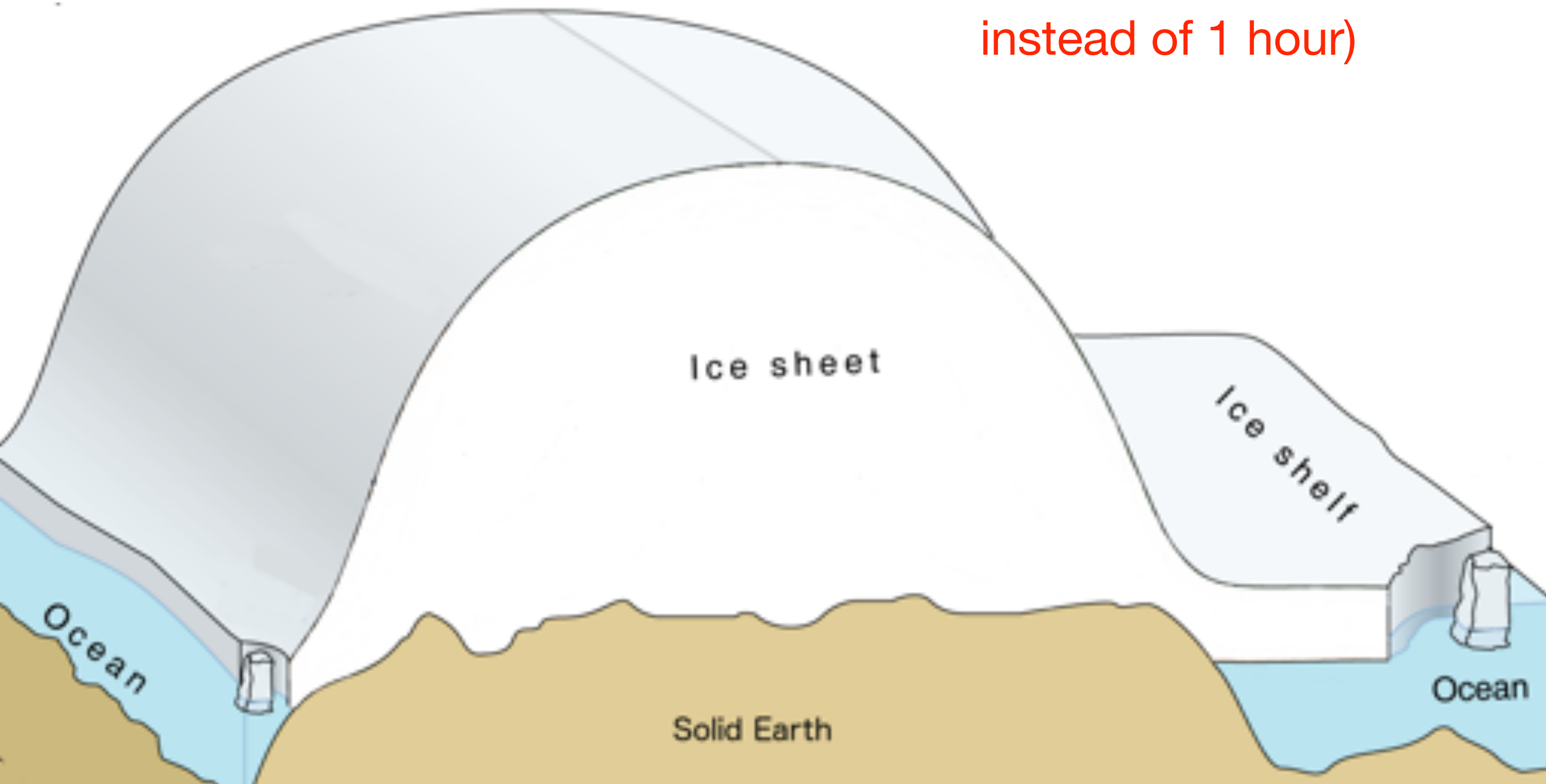
- **Ice in from snowfall on ice sheet**
- **Ice out from melt and iceberg calving**
- **Total "mass balance"**

(Rignot et al. 2019)

(365 Gt = 1 mm SLR)

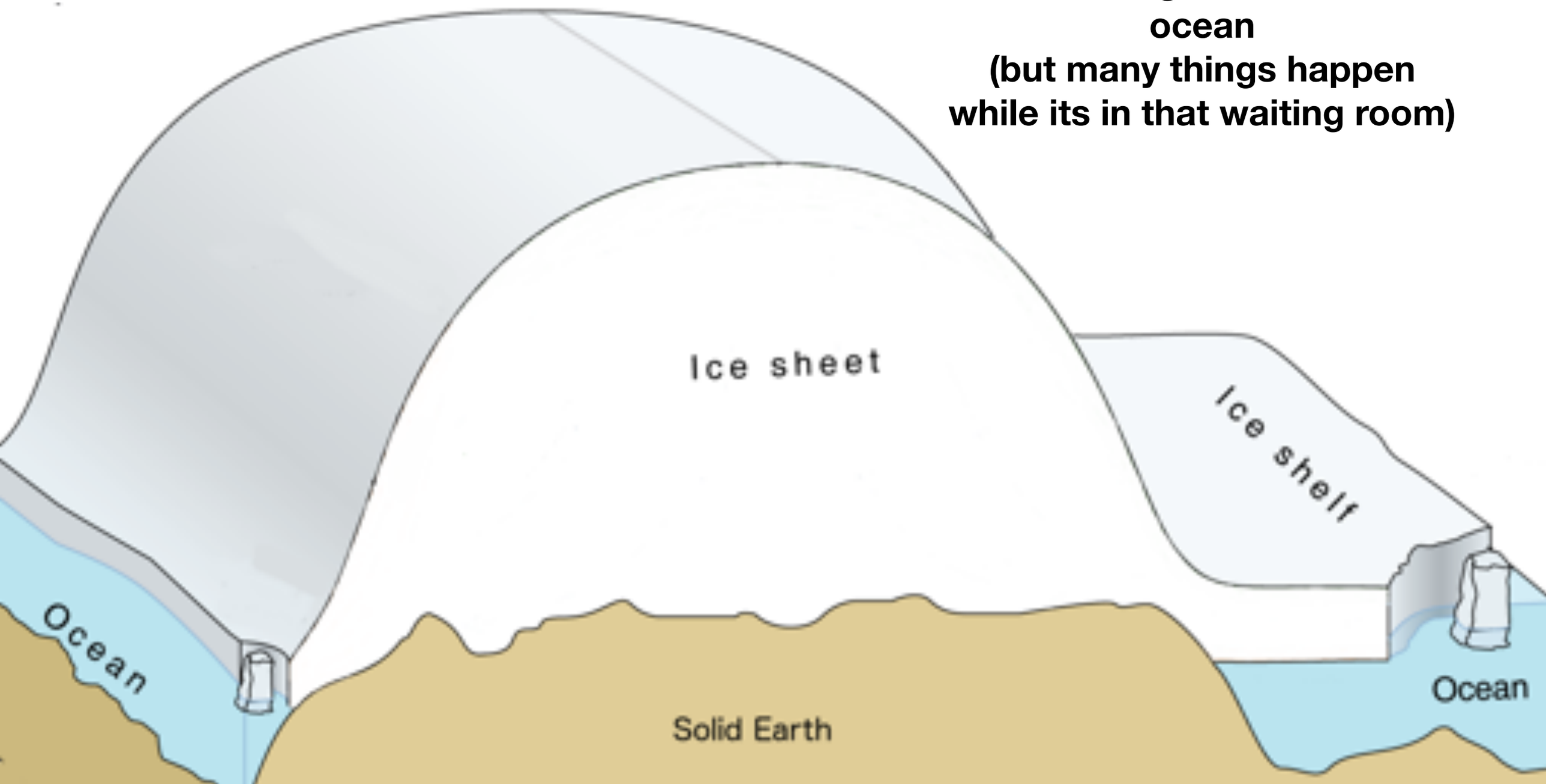
Crash course in glacier and ice sheet dynamics

(Take EAS 4803/8803 if you want to learn this over 15 weeks instead of 1 hour)



So what is a glacier/ice sheet?

For the purpose of this class:
a glacier is the "waiting room" in between water falling on land in cold places before being returned in the ocean
(but many things happen while its in that waiting room)



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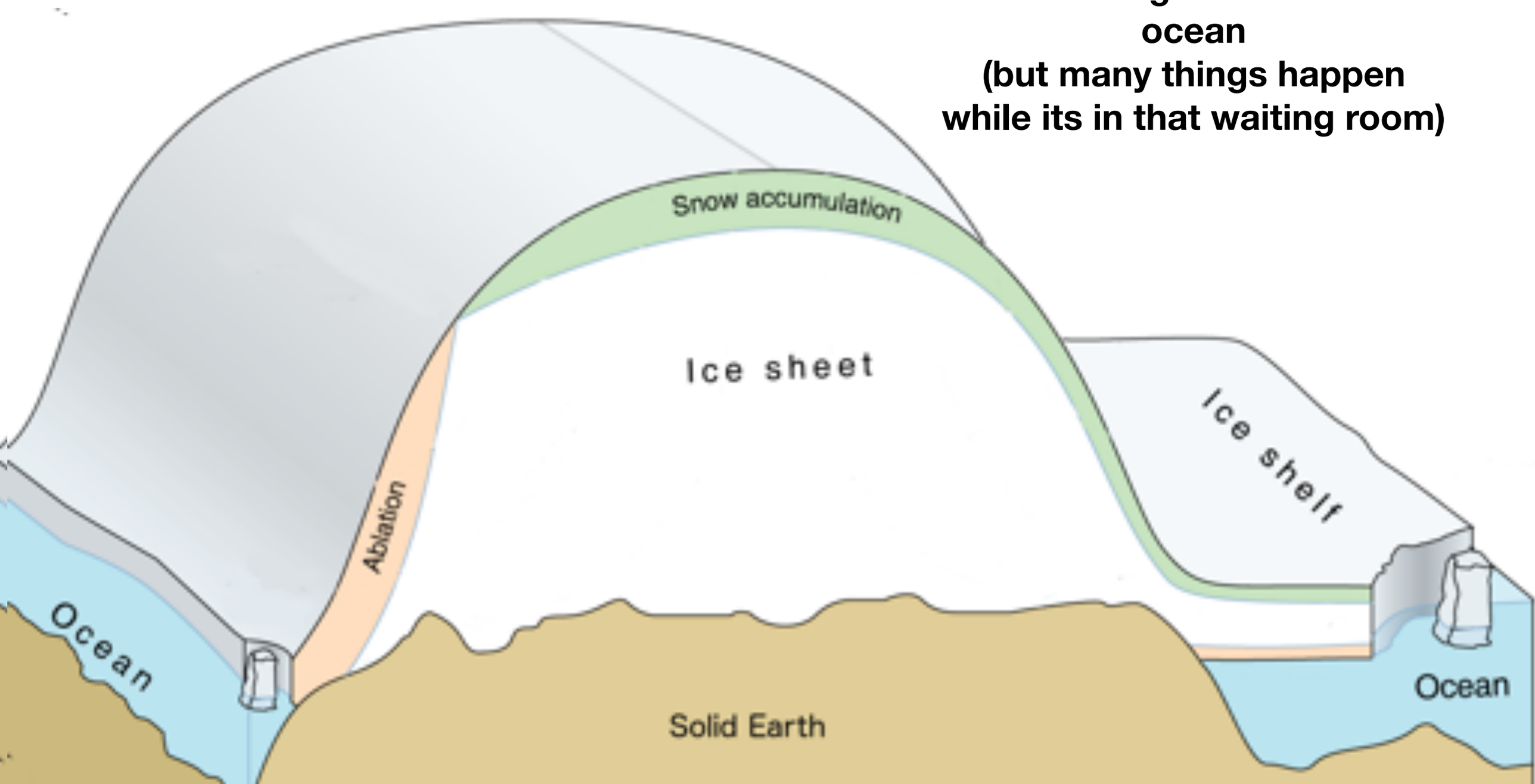

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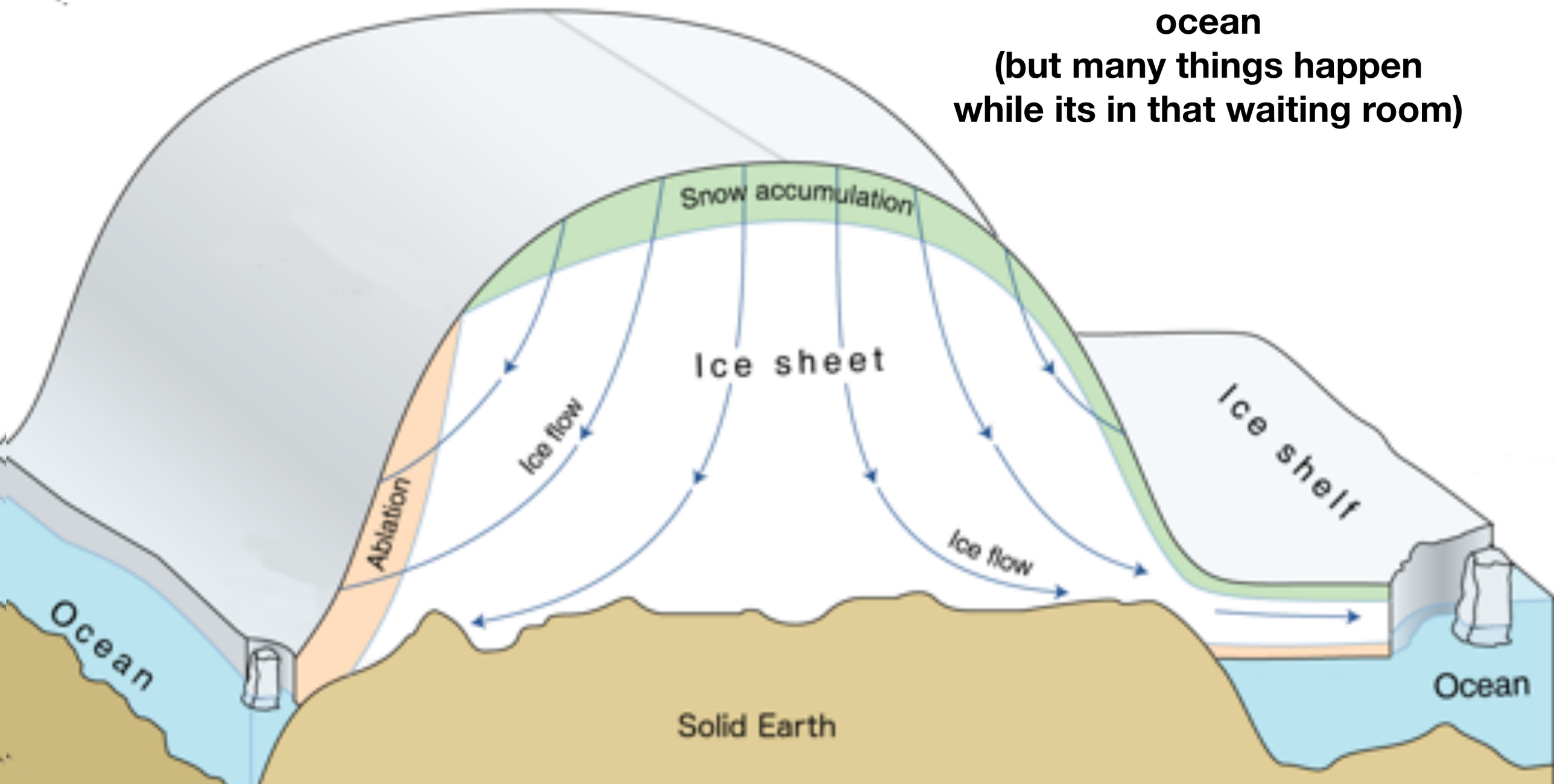
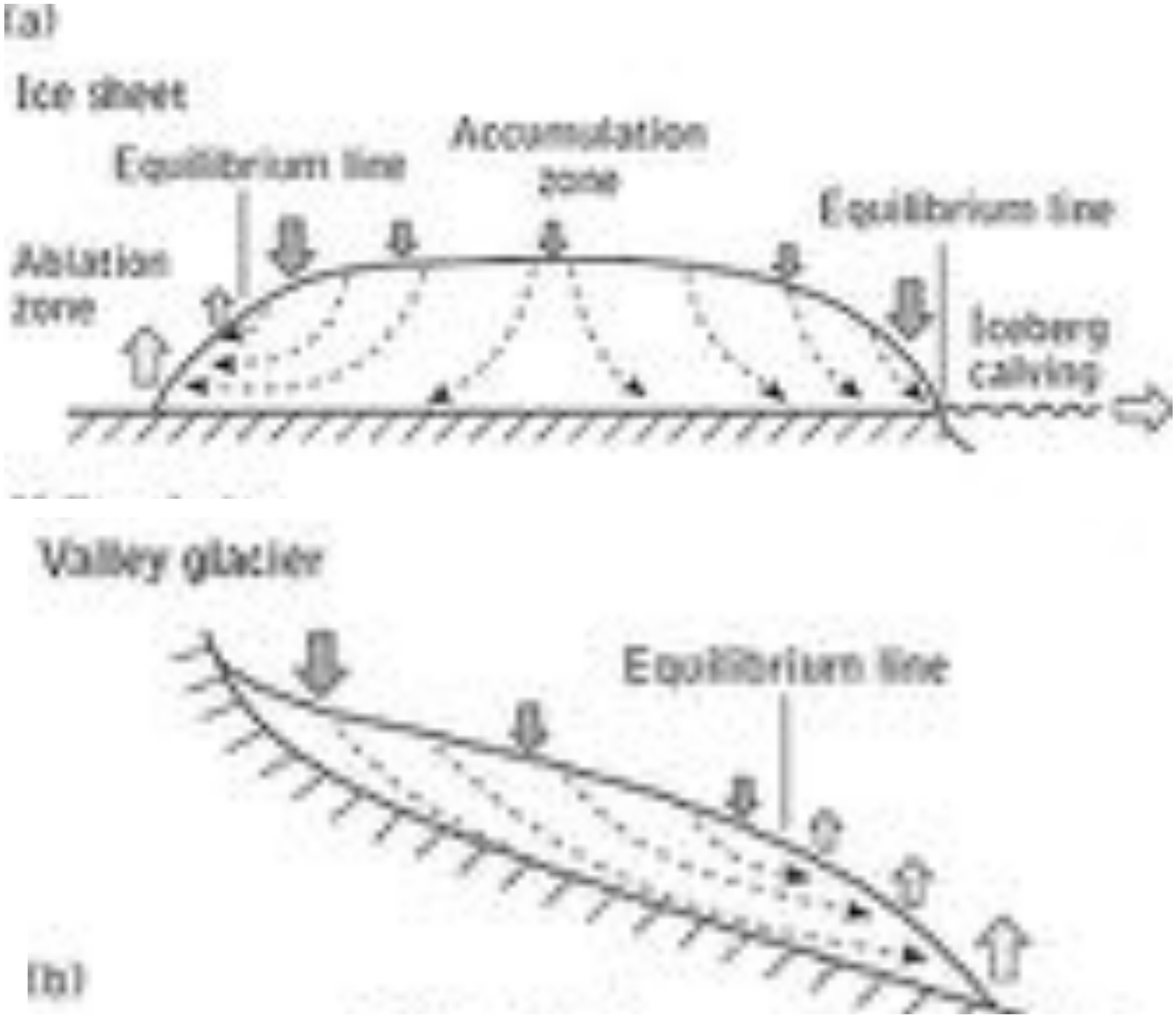
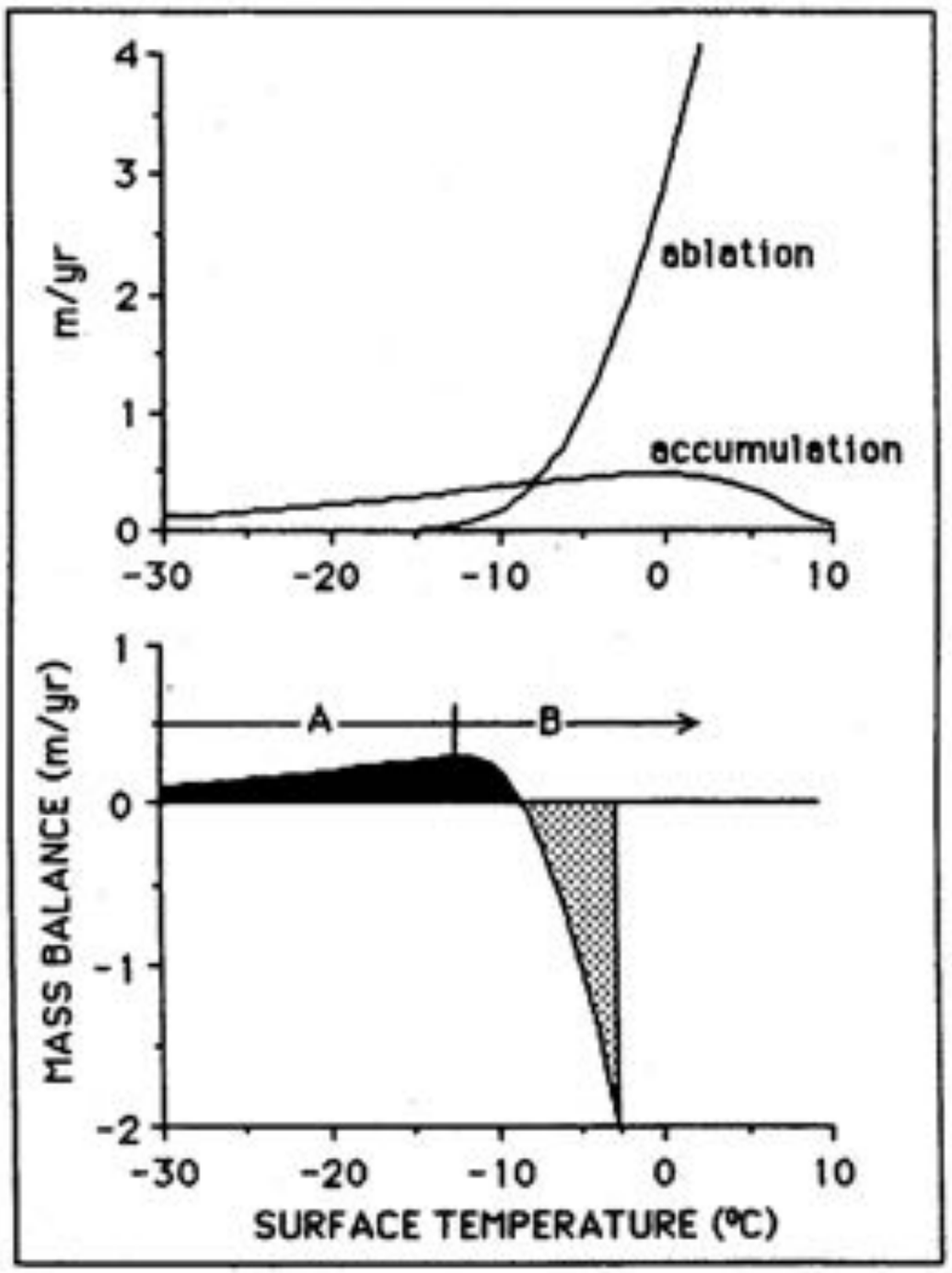
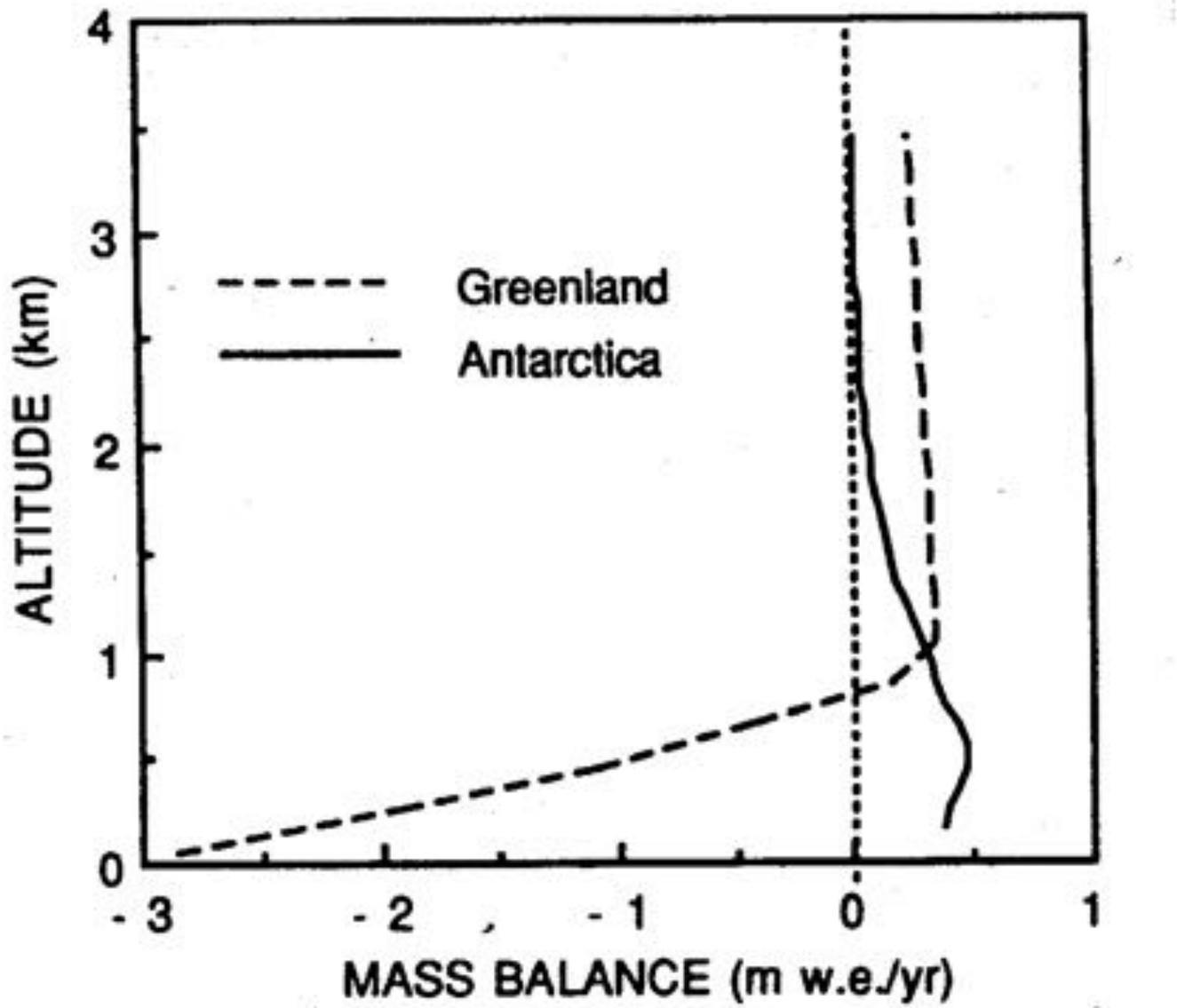


The top


(a)
Ice sheet
Equilibrium line
Accumulation zone
Equilibrium line
Ablation zone
Iceberg calving
Valley glacier
Equilibrium line
(b)

Surface mass balance (net source or sink of ice at the surface of the glacier/ice sheet) tends to increase with decreasing temperature, which means increase with elevation





Can lead to a runaway “small ice sheet instability” where:

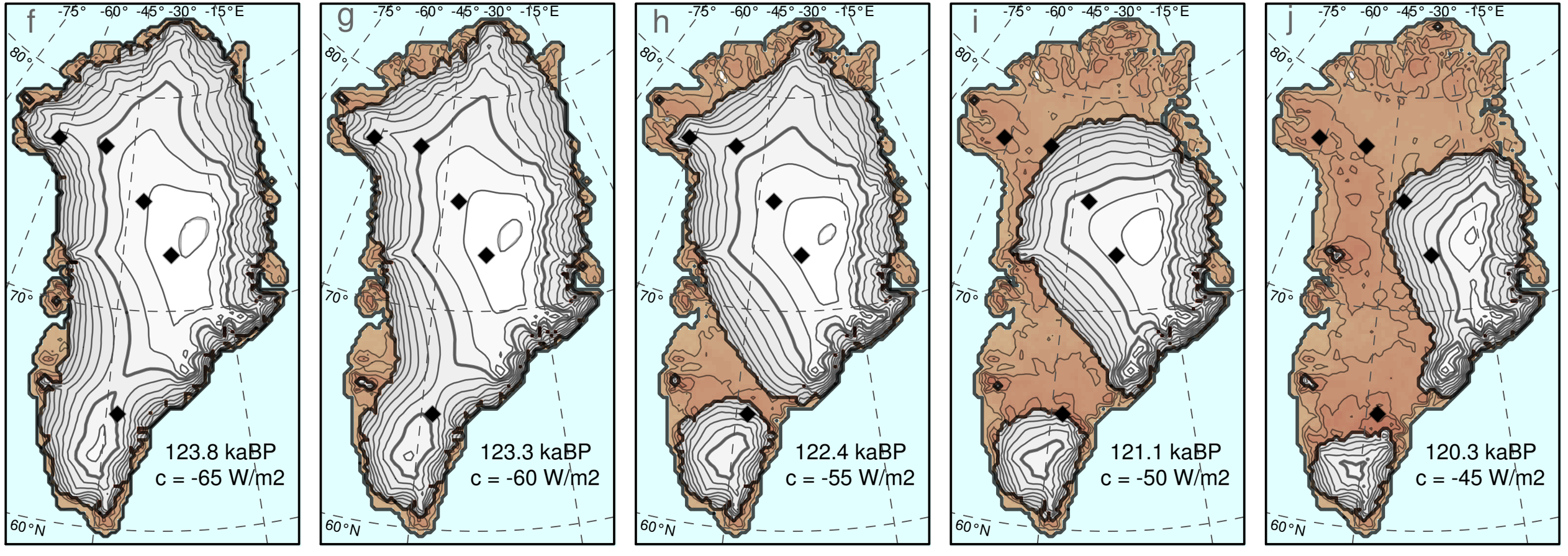
Ice sheet thins

↓

More of the ice sheet is at low elevation

↓

More of the ice sheet experiences melting



Greenland Ice Sheet simulations for the Last Interglacial - Robinson et al. 2011

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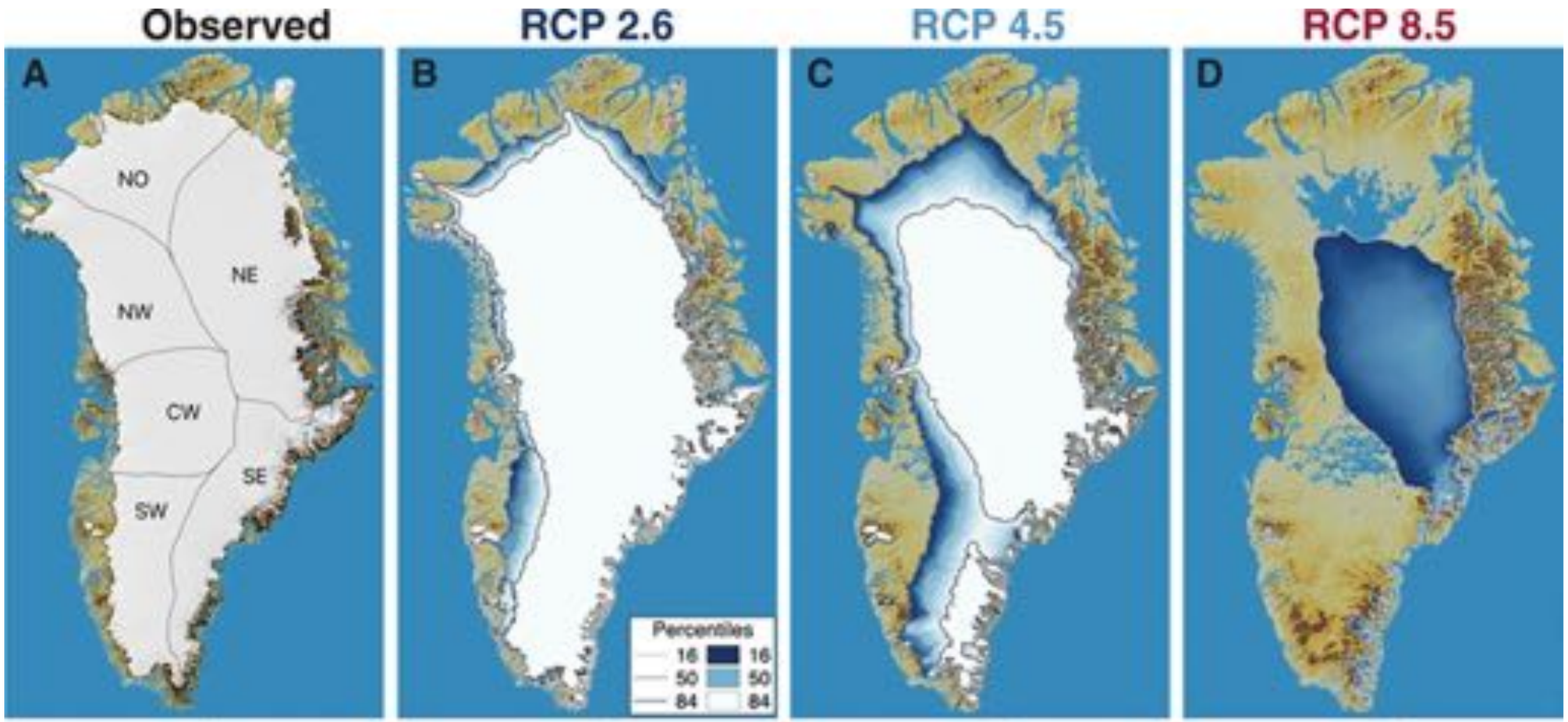
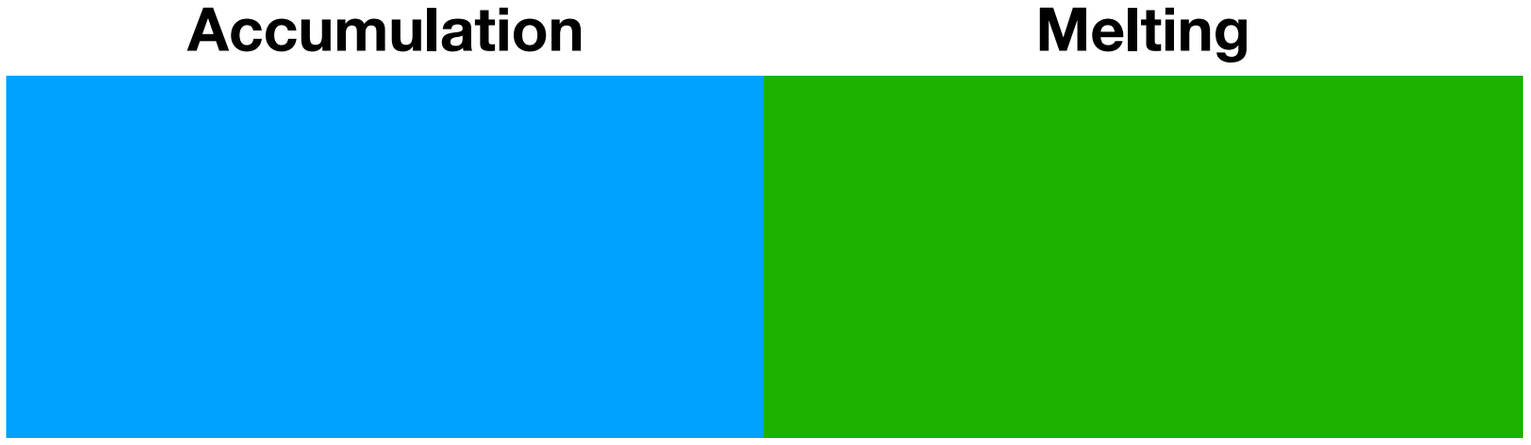


Greenland Ice Sheet simulations for the next 1000 years - Aschwanden et al. 2019

If ice didn’t move

This



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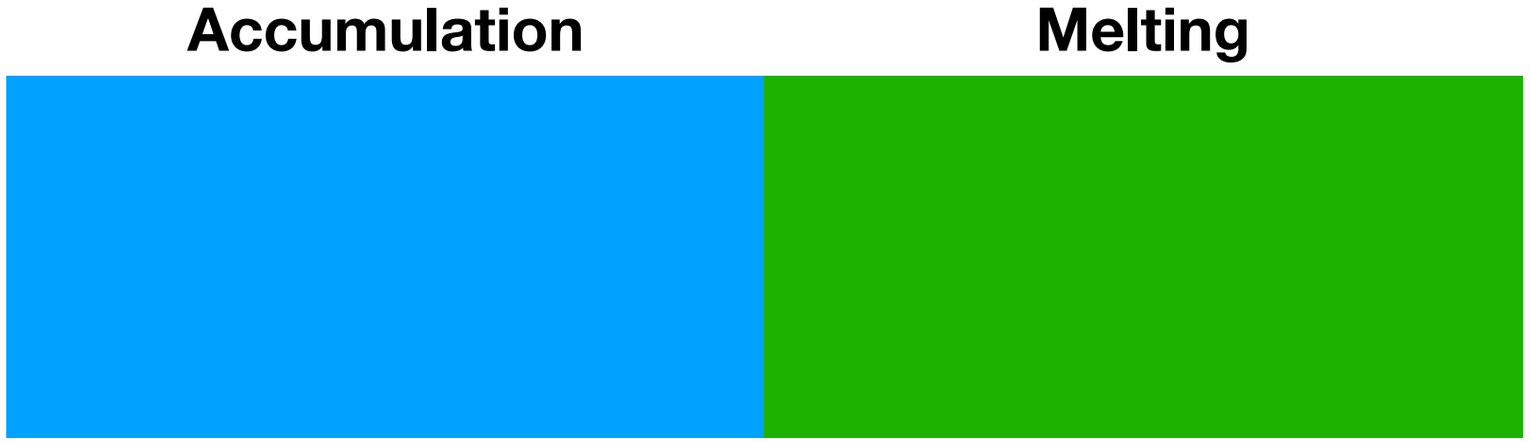
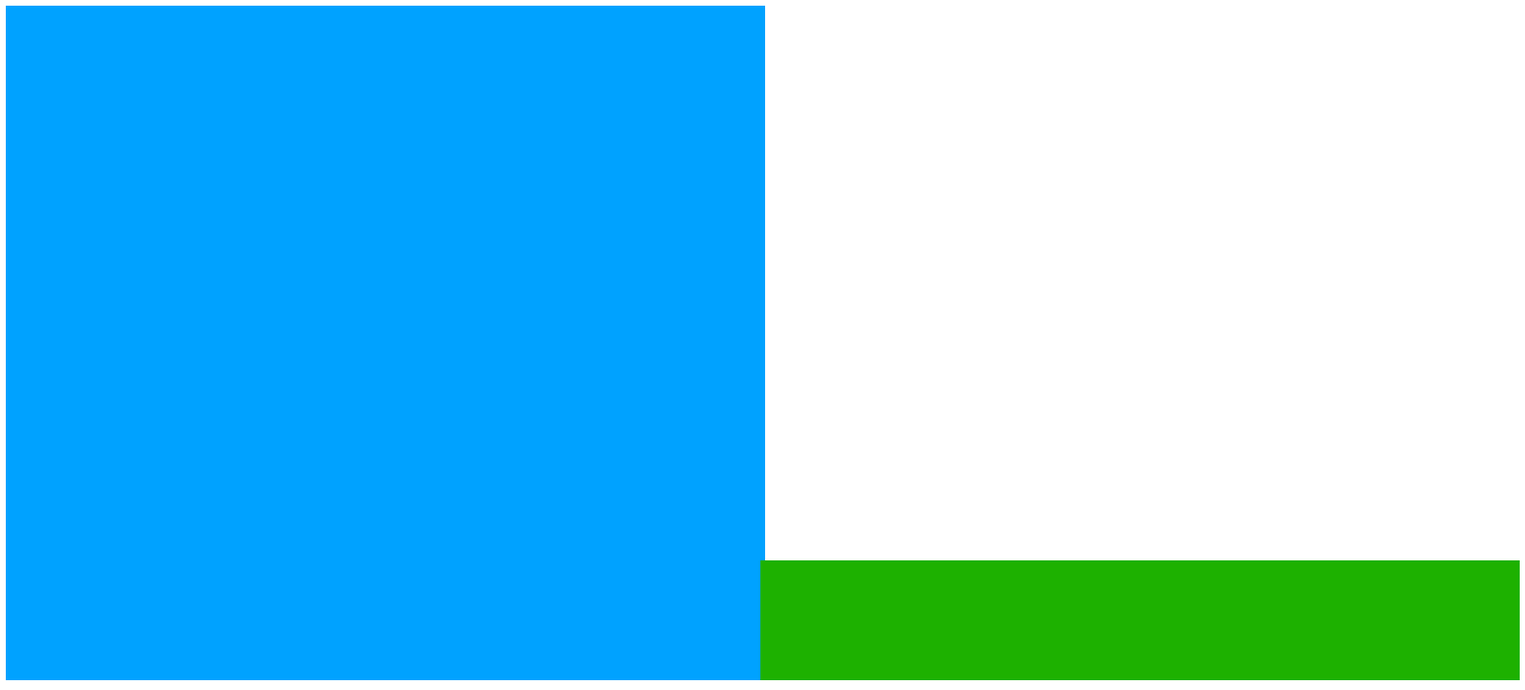
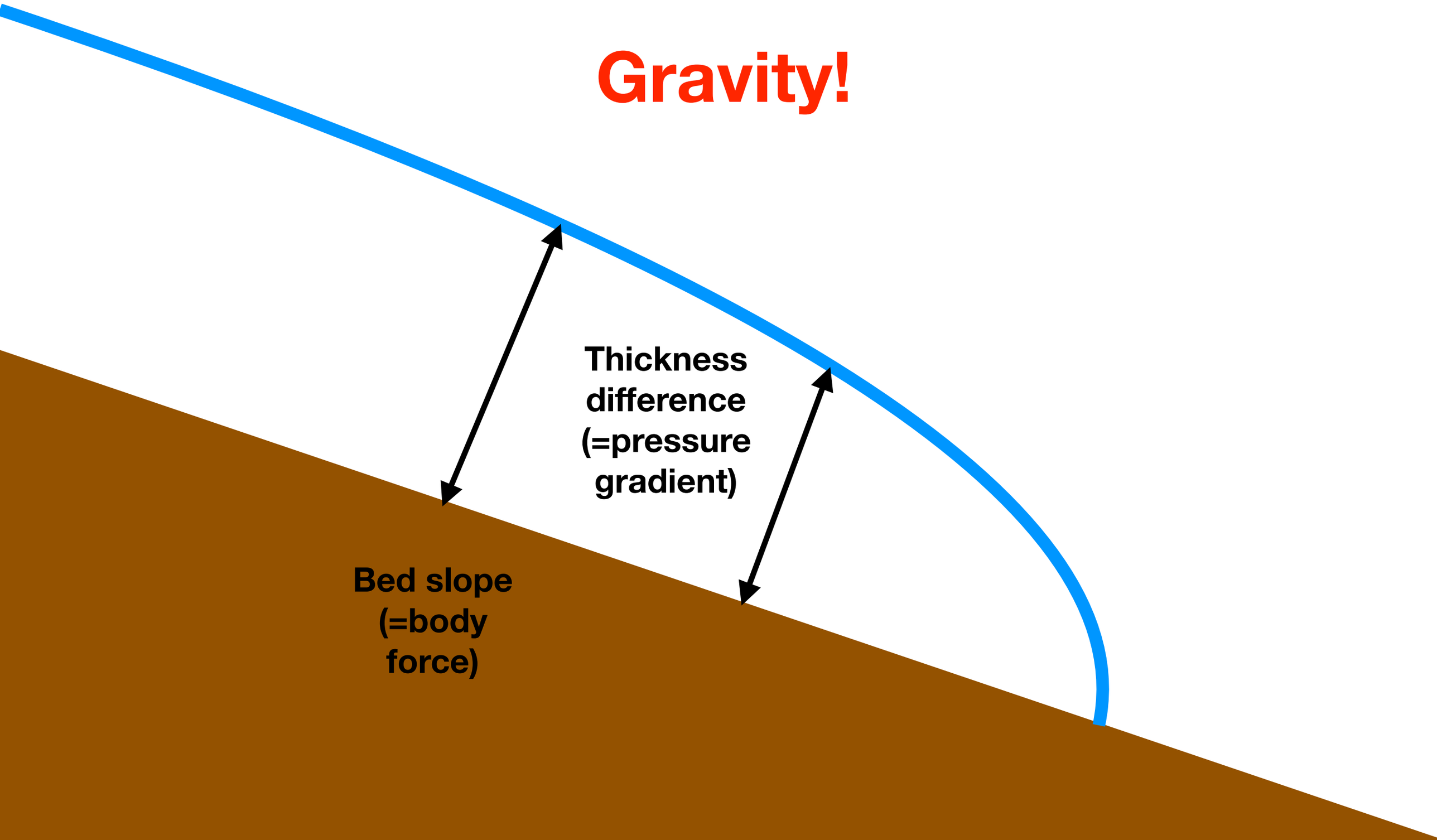


Would turn into this

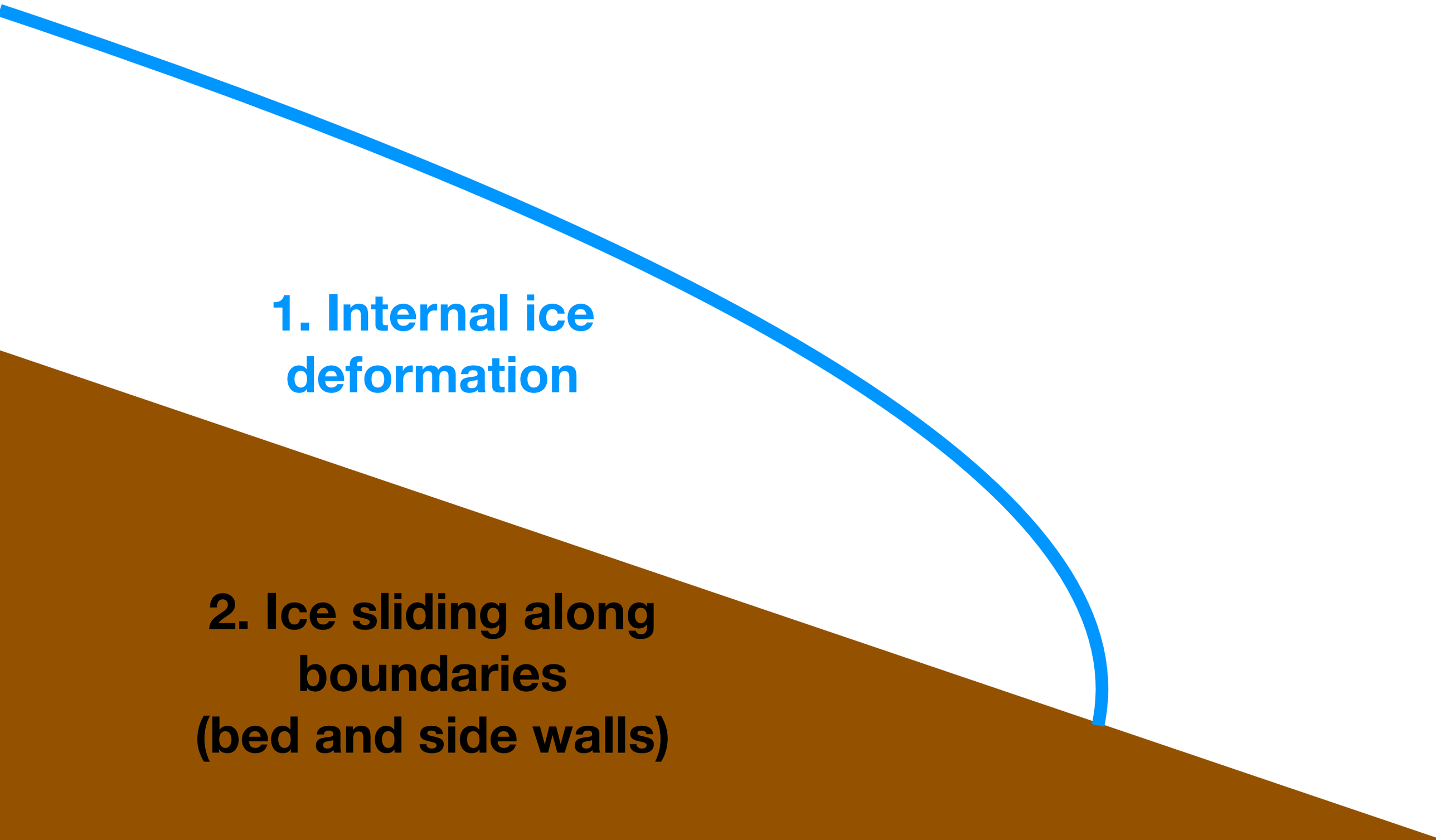


Why does ice move/flow?

Gravity!

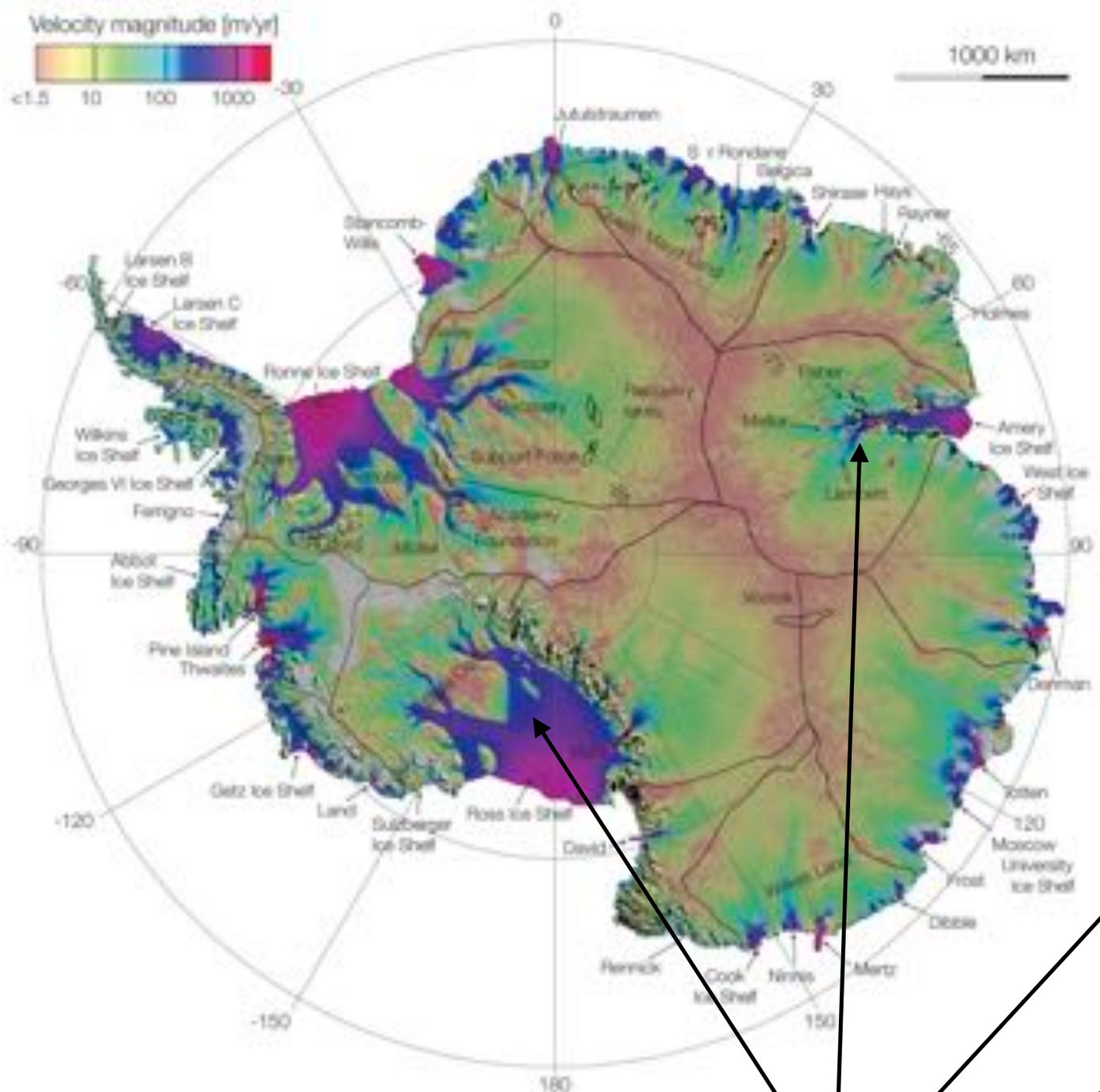


How is flow accommodated?

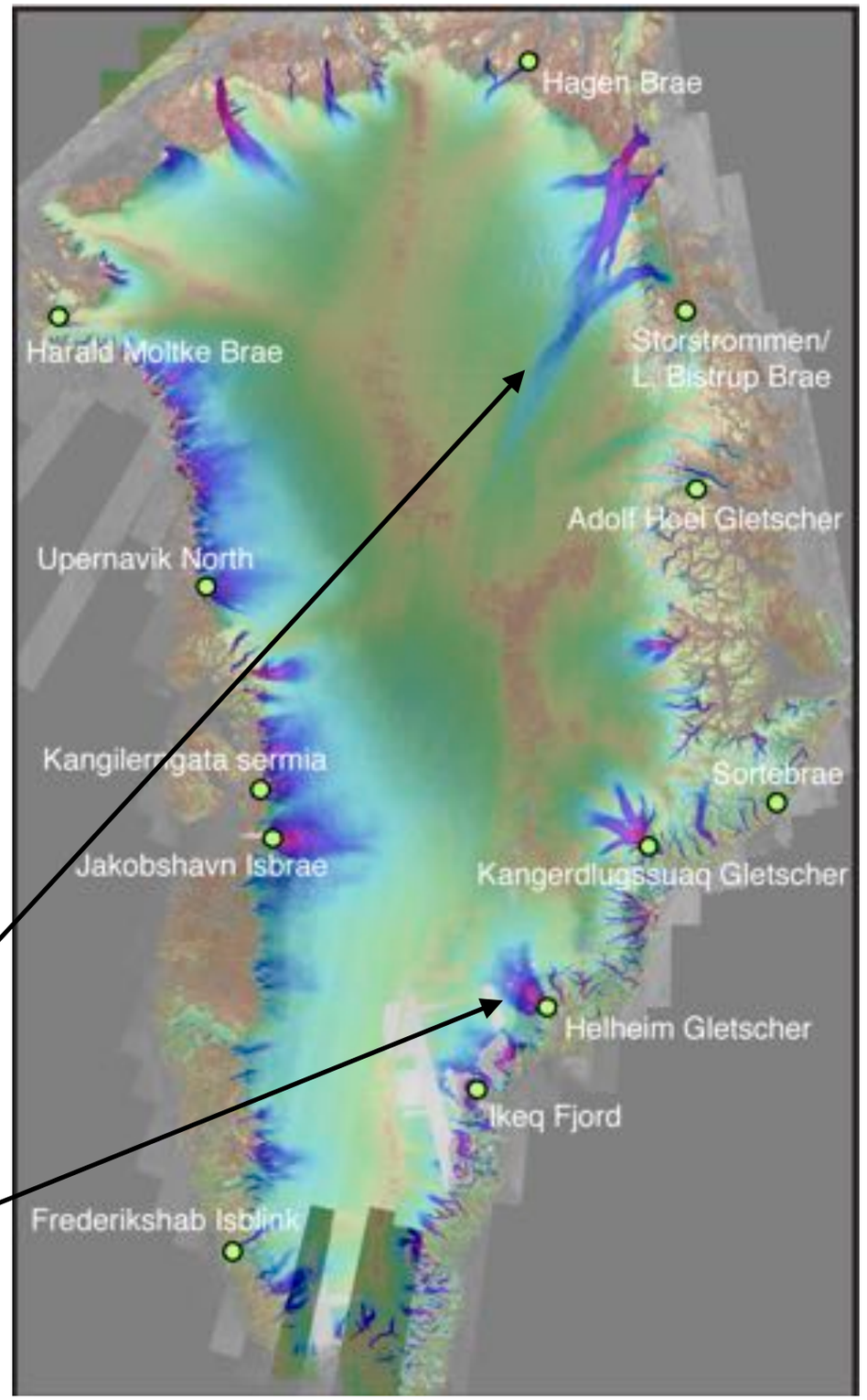


Ice flow redistributes mass from accumulation region to ablation region

Antarctic Ice Sheet



Greenland Ice Sheet

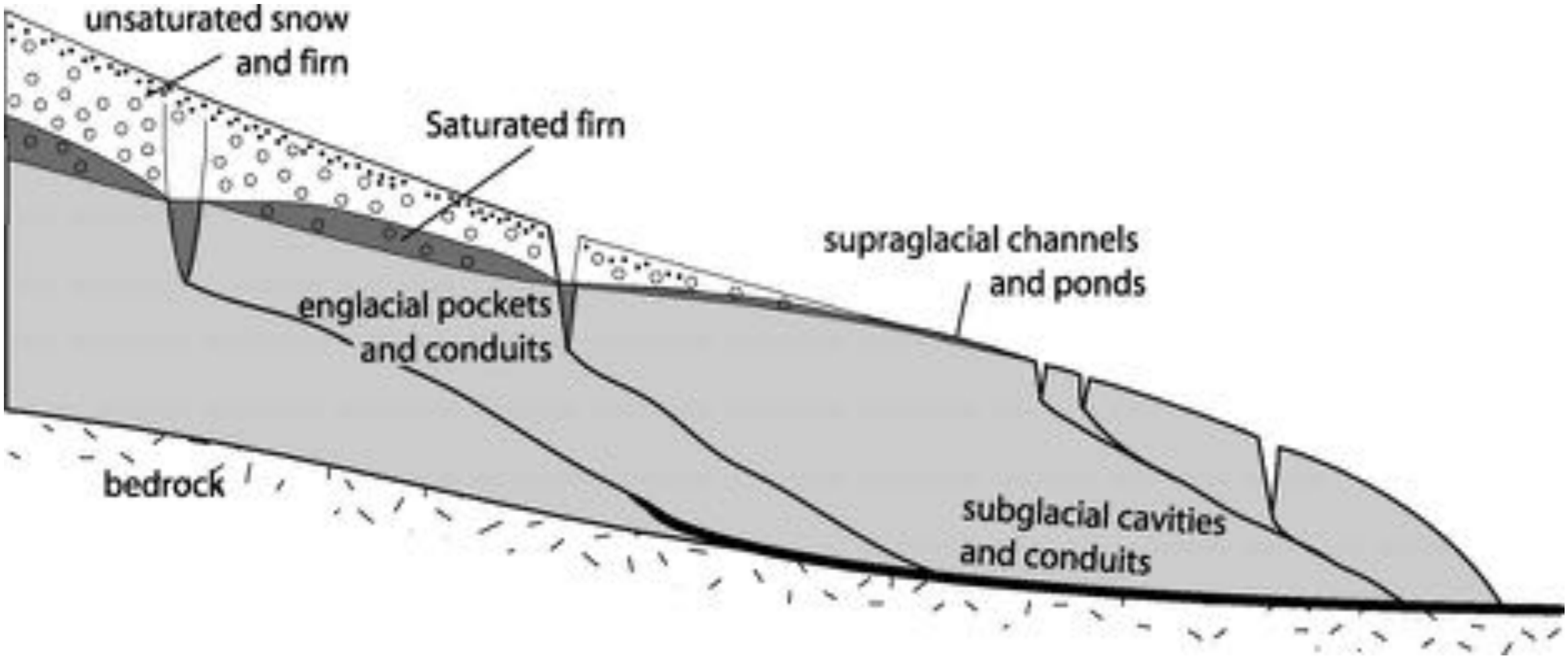


Most ice flow occurs through these.
What are they? Why are they?

Where does the meltwater go?

accumulation area

ablation area



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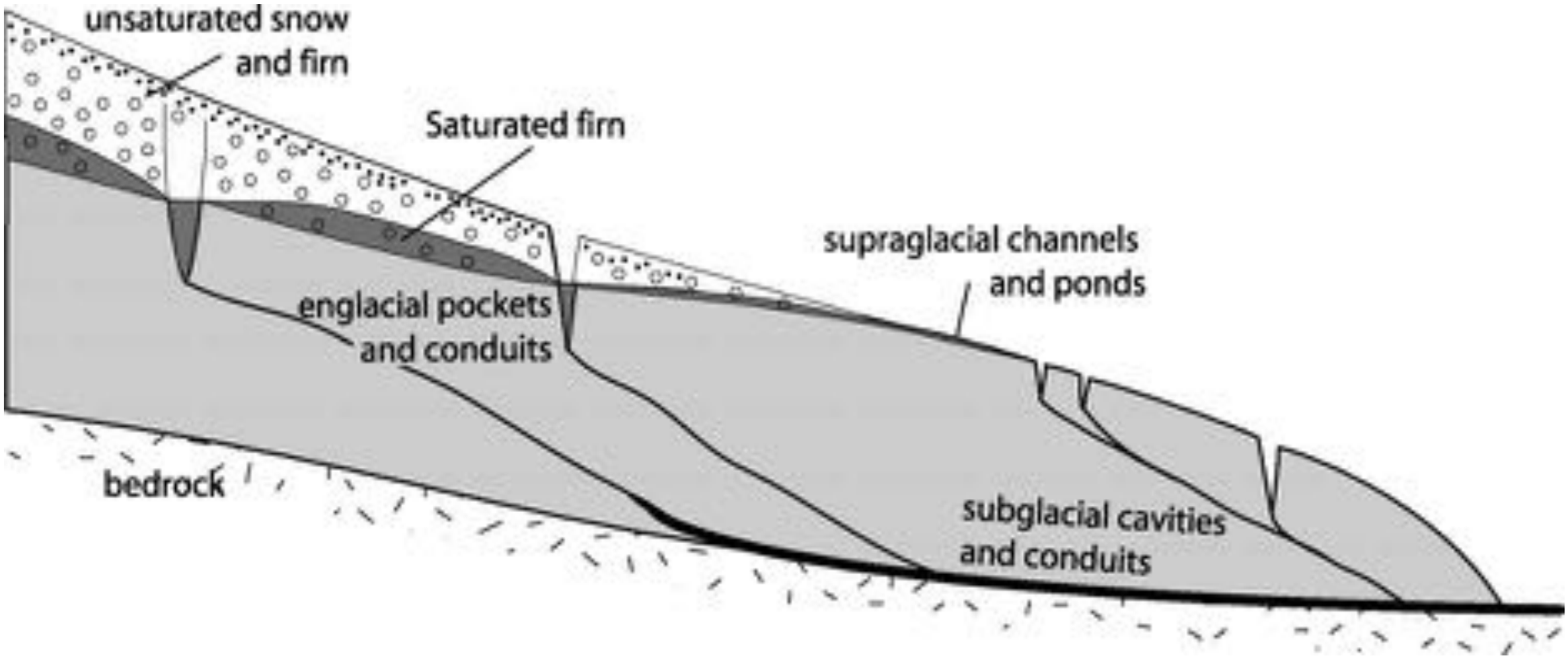
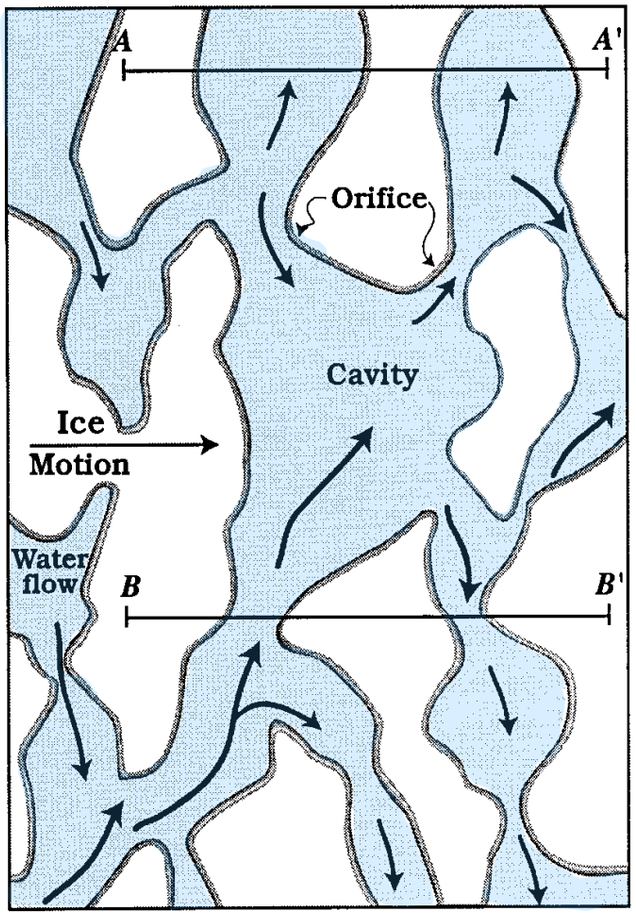


Where does the meltwater go?

Sometimes the water goes through fractures in the ice all the way to the bottom of the ice sheet

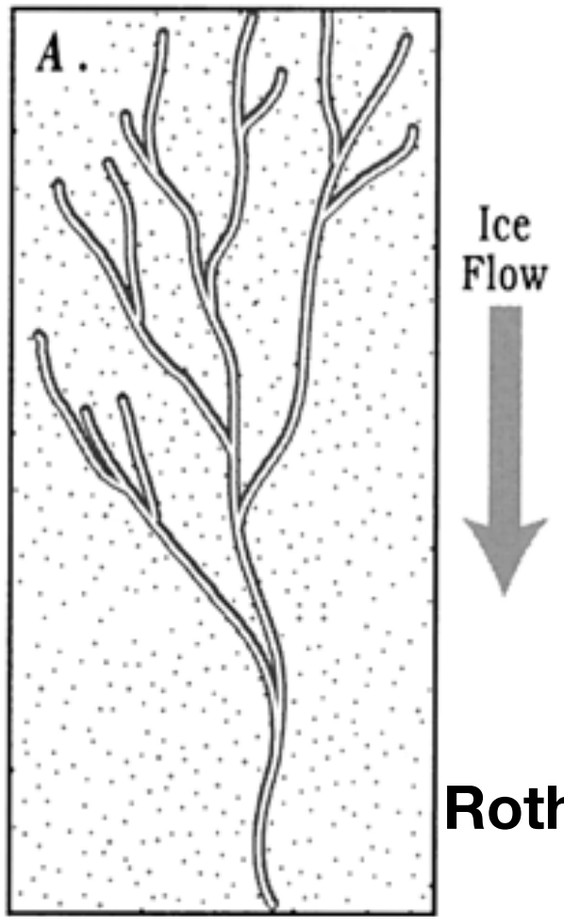
What happens when the water gets to the bed?

Linked Cavities

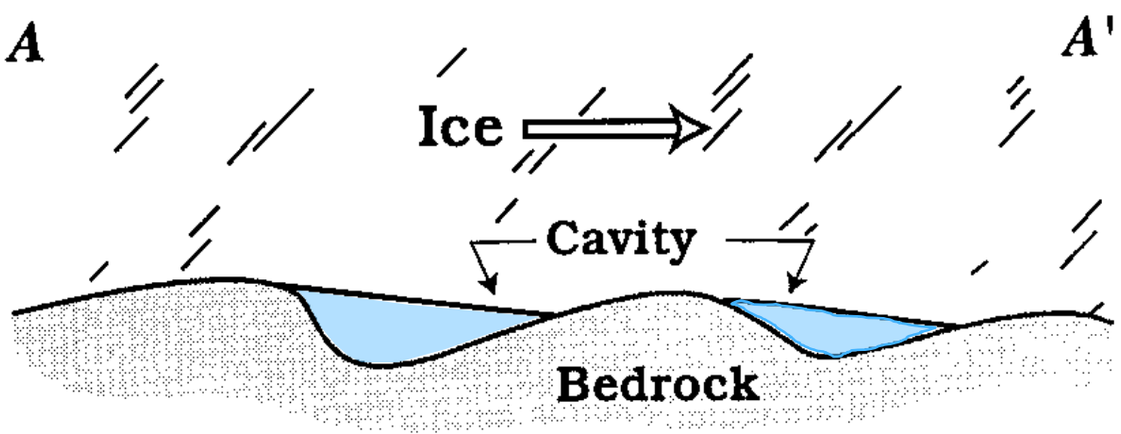


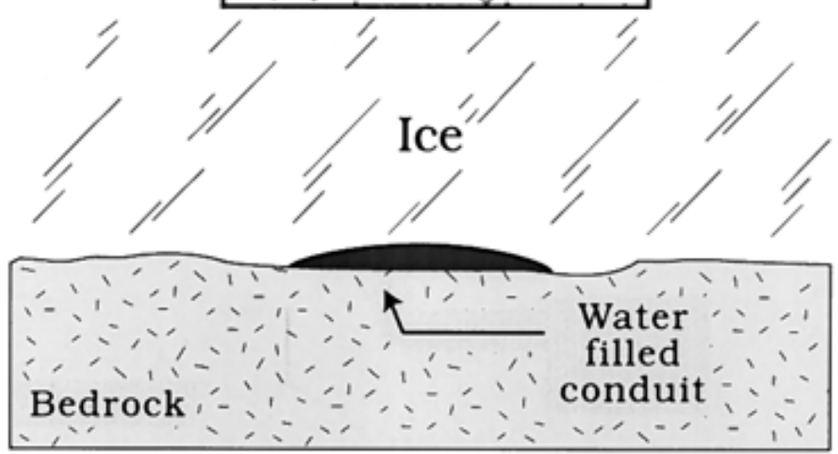
Walder and Fowler 1994

Subglacial Channels



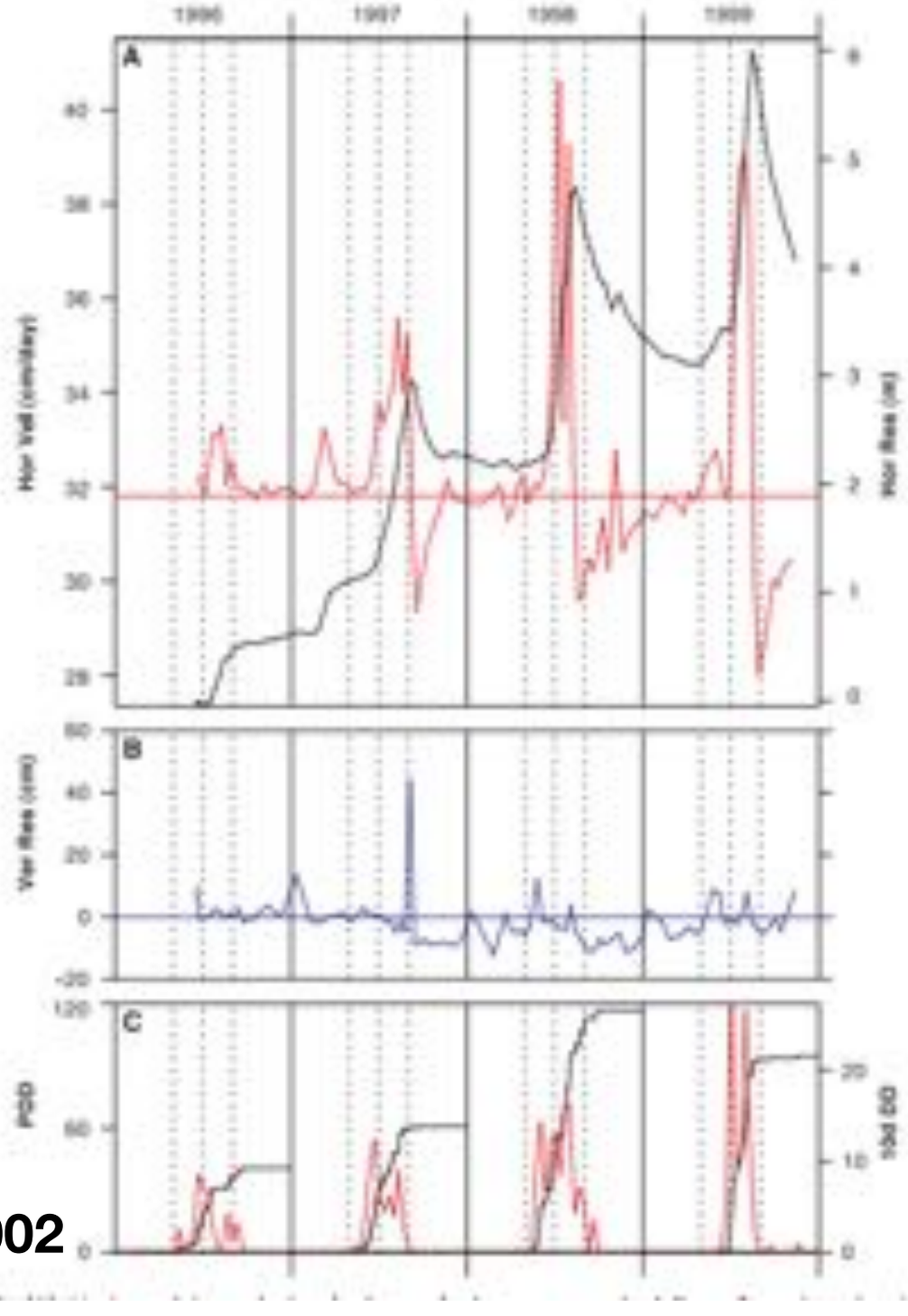
Rothlisberger 1972





Does ice velocity go up or down with increased water supply?

Water lubricates ice flow?



Zwally et al. 2002

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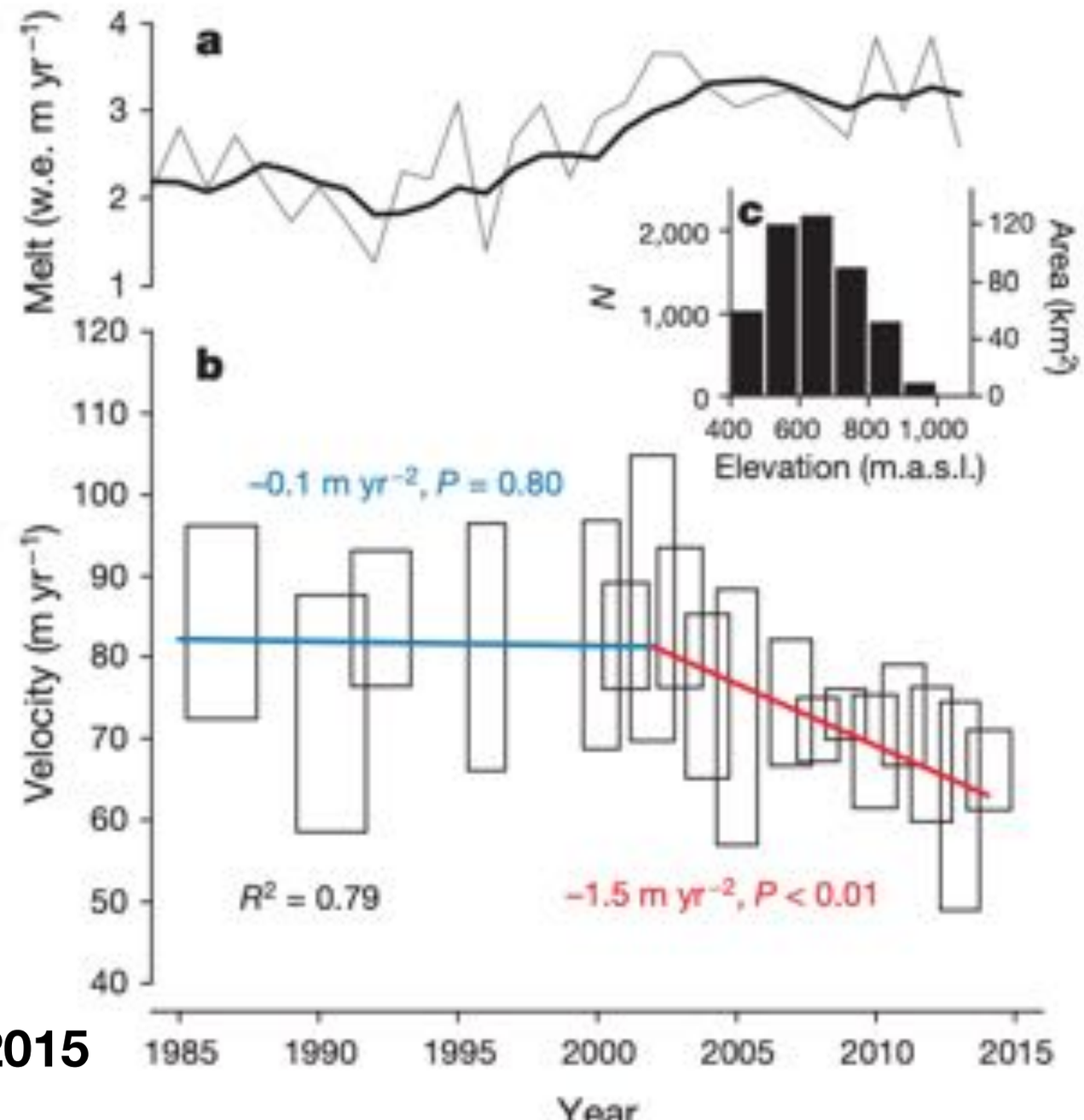
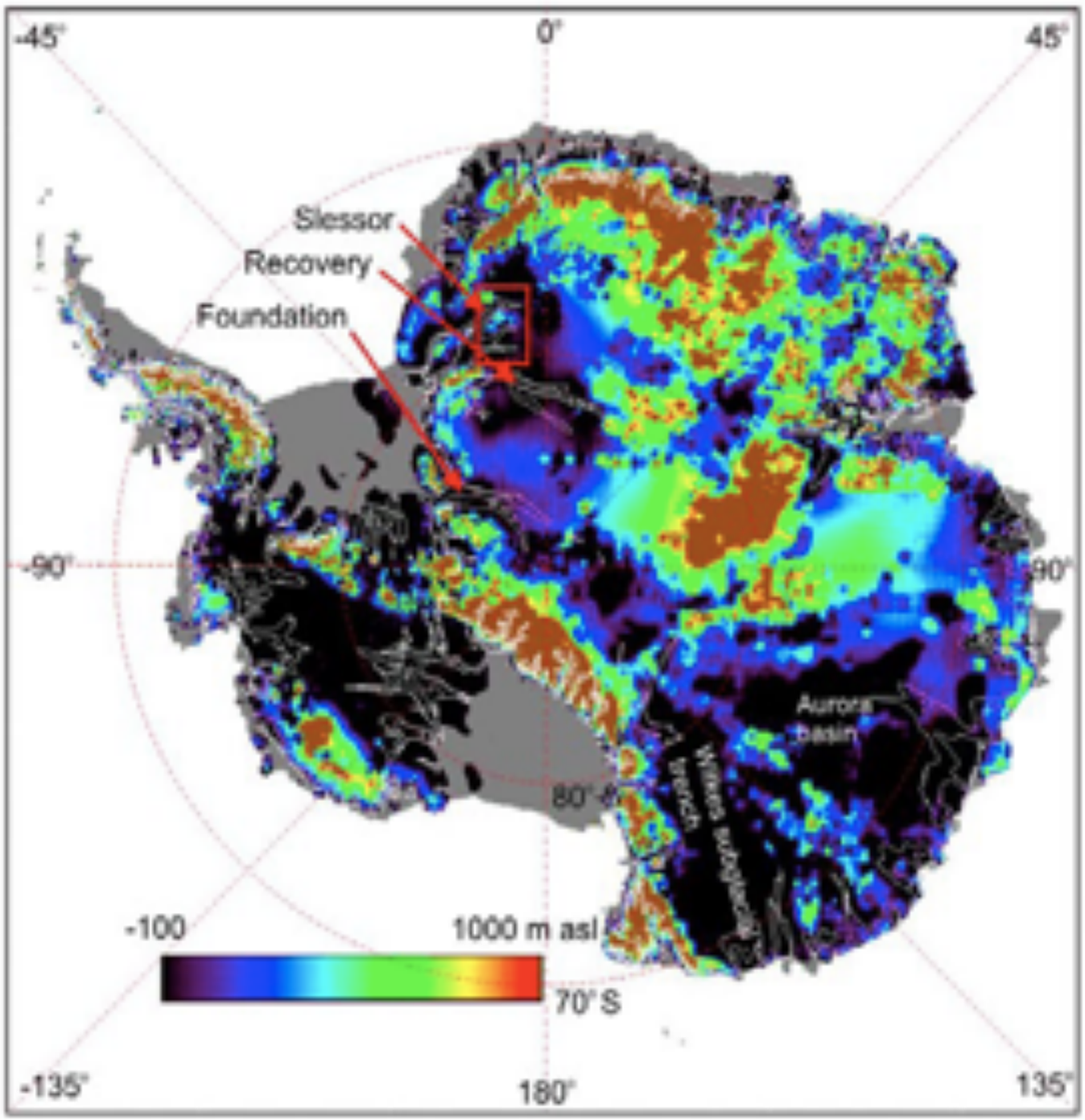
Water organizes drainage, reducing ice flow?



Tedstone et al. 2015

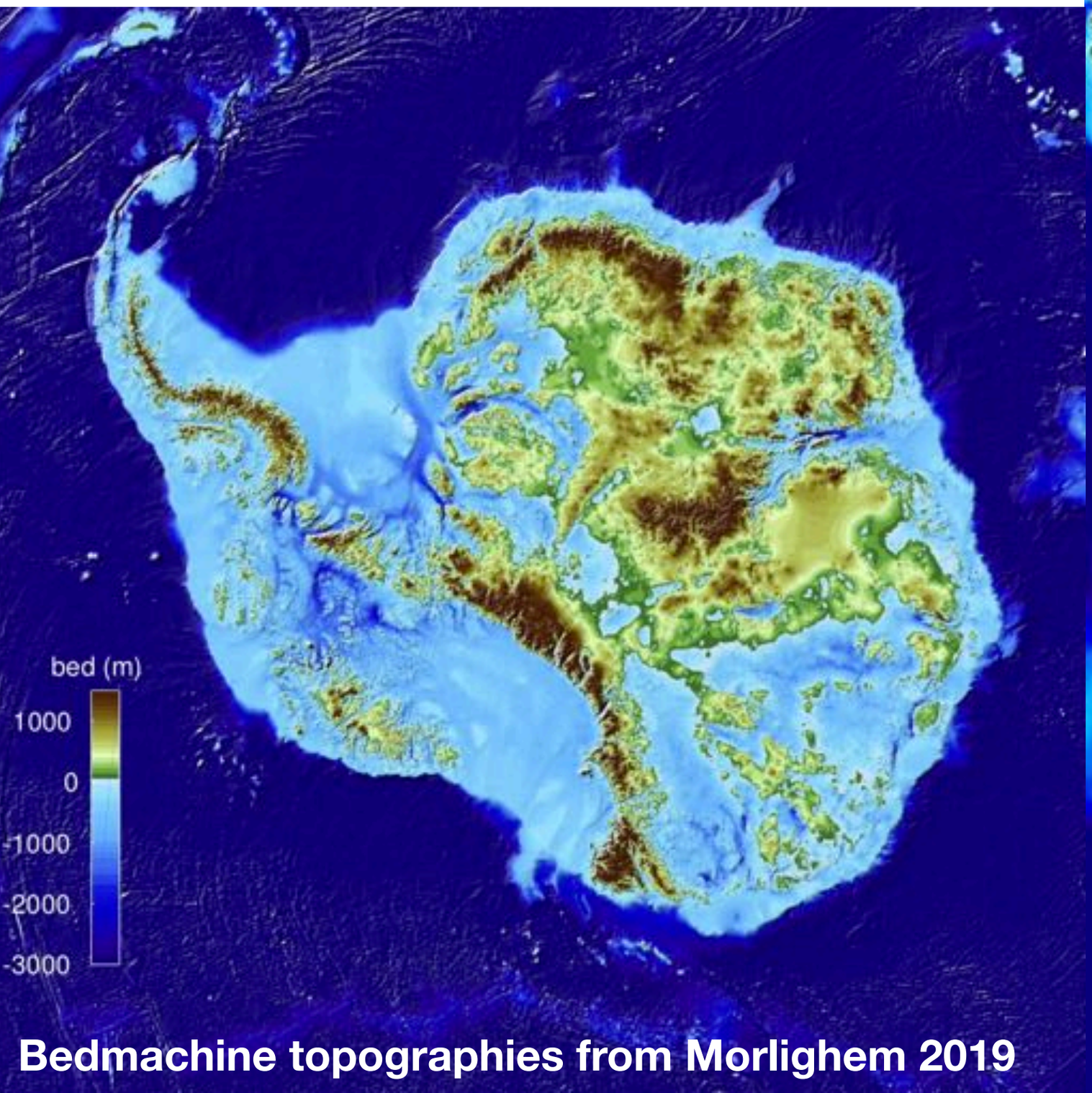
Ice stream beds are very slippery

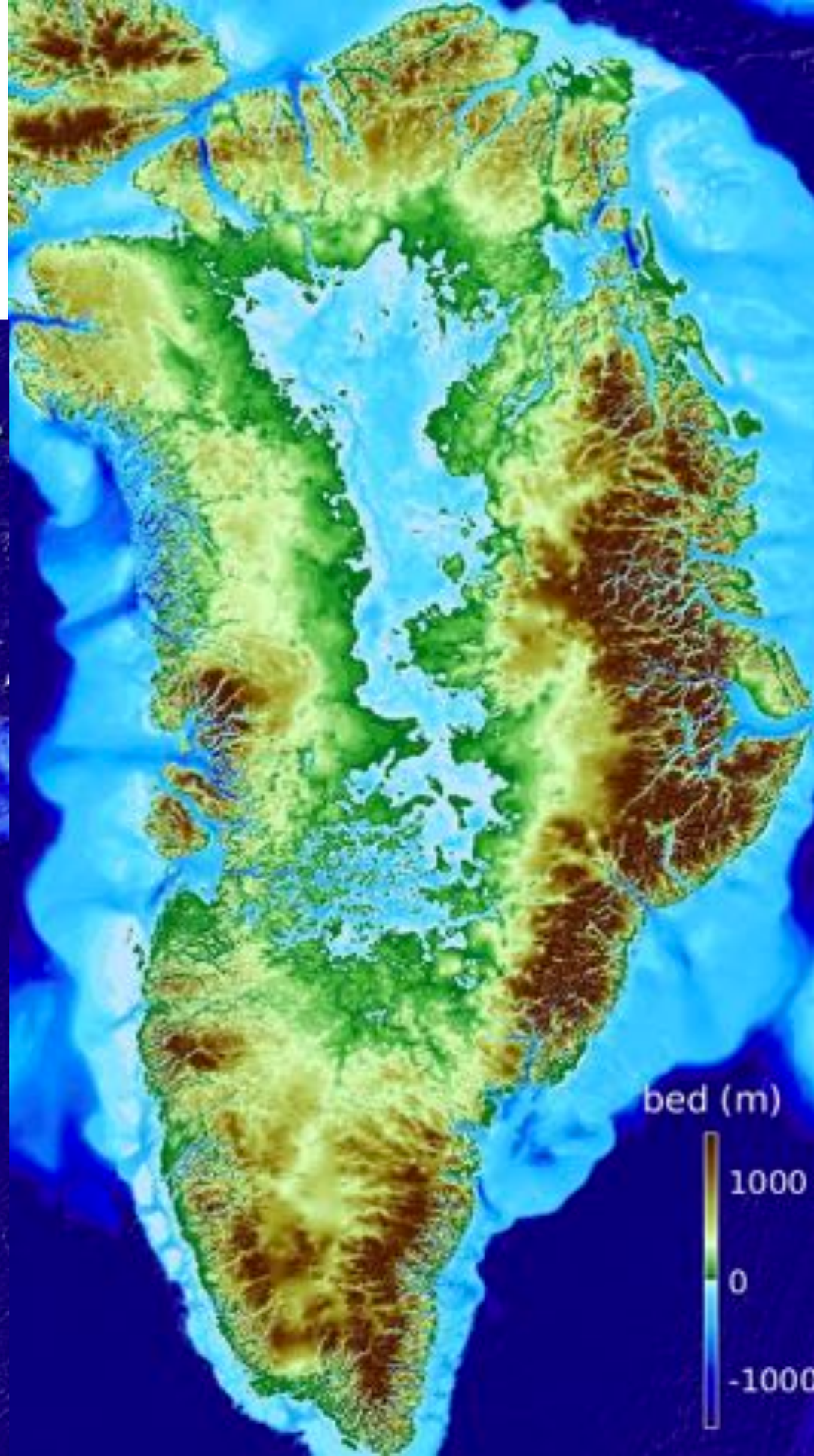


Parts of Antarctic Ice Sheet that are below sea level (black on plot to the left) have been covered by ocean in the past when the ice sheet was much smaller and so there are lots of marine sediments

Some ice streams flow through subglacial valleys

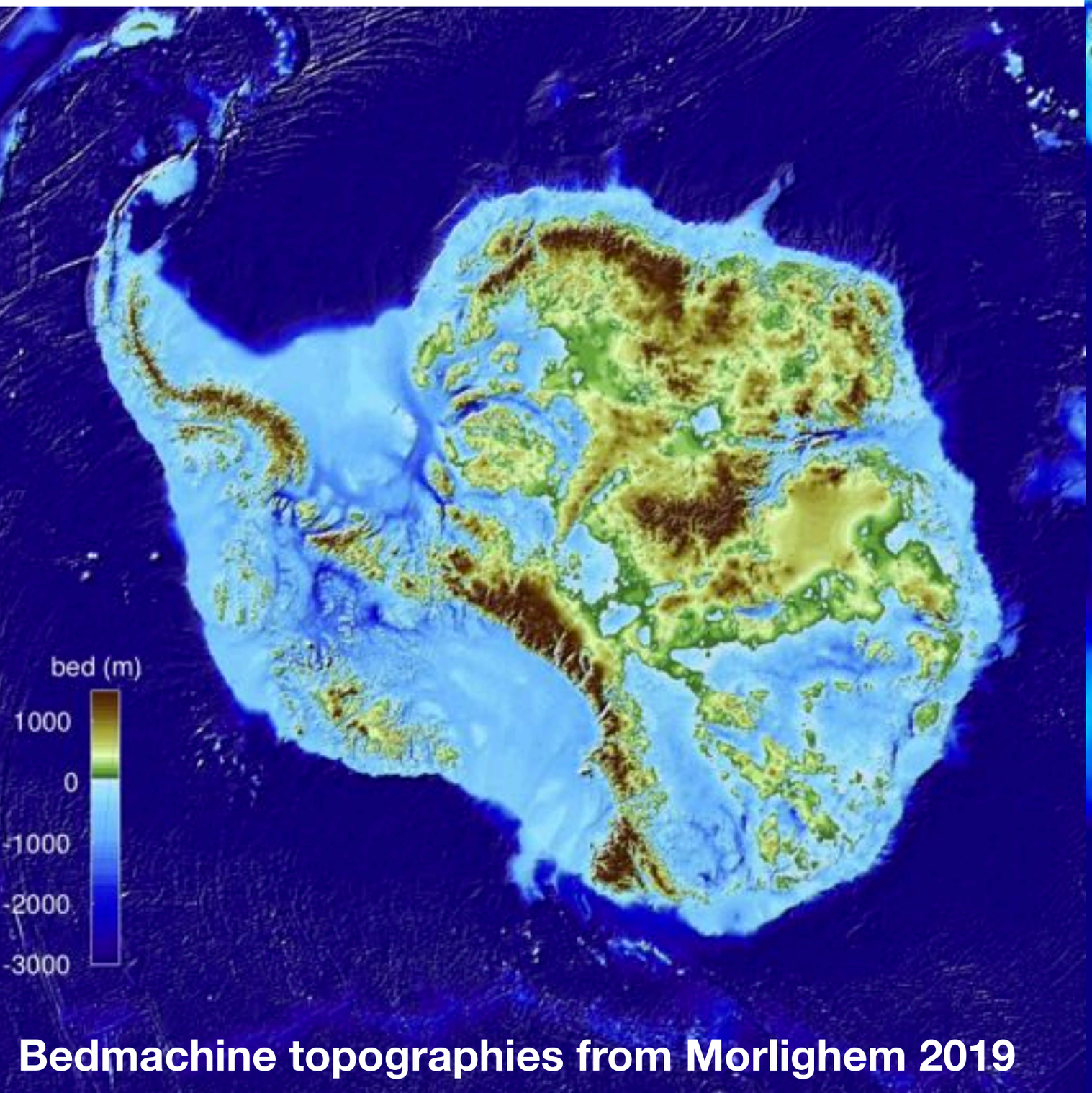
(including the deepest valley in the world in Antarctica!)

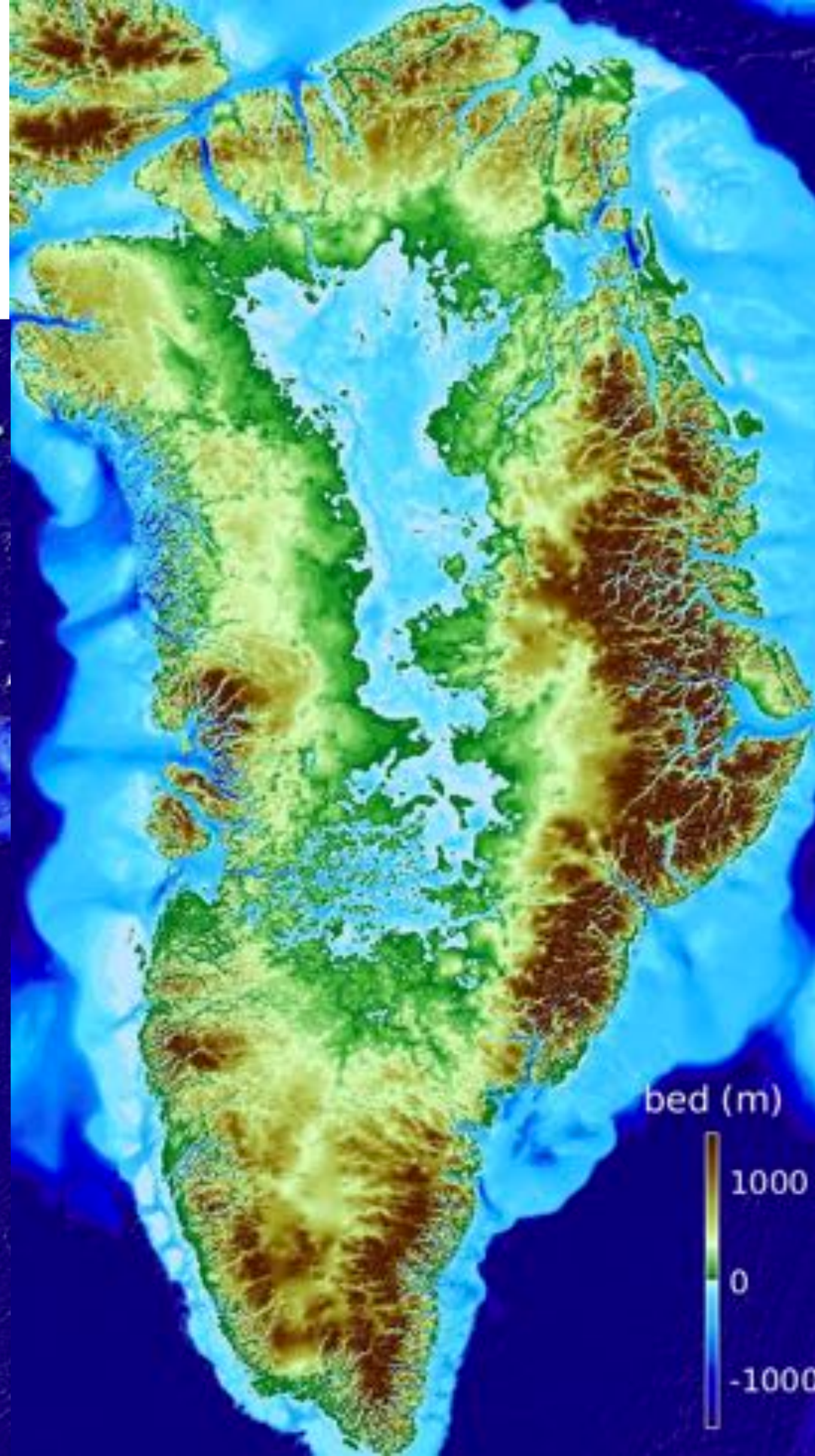




Bedmachine topographies from Morlighem 2019

Marine ice sheets have significant portions of their bed beneath sea level (blue below)





Bedmachine topographies from Morlighem 2019

Why do we care about marine ice sheets?

John Mercer, grizzled coffee drinker

Nature Vol. 271 26 January 1978 321

West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster

J. H. Mercer

Institute of Polar Studies, The Ohio State University, Columbus, Ohio 43210

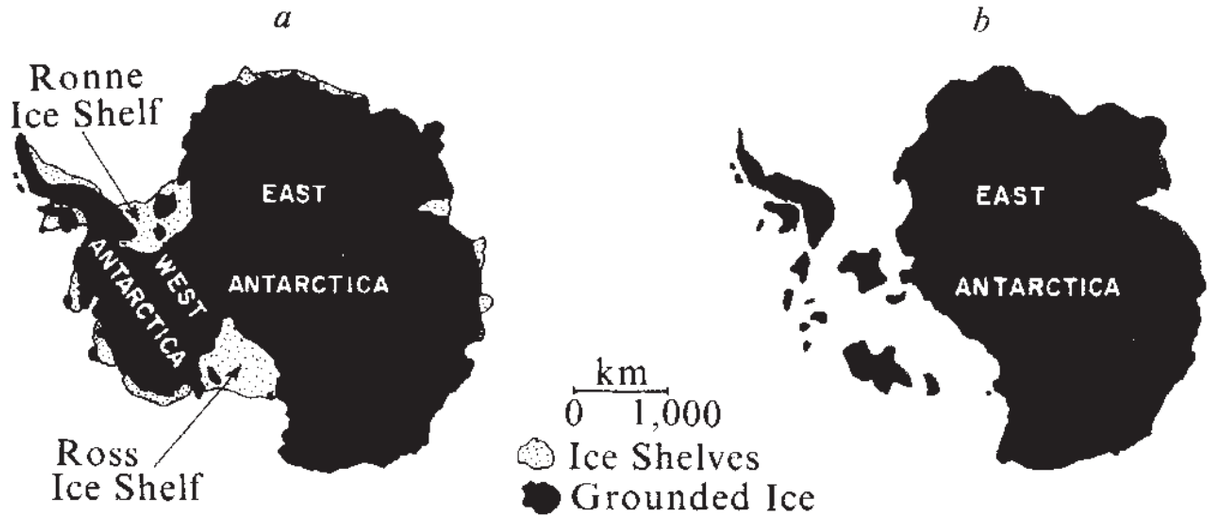
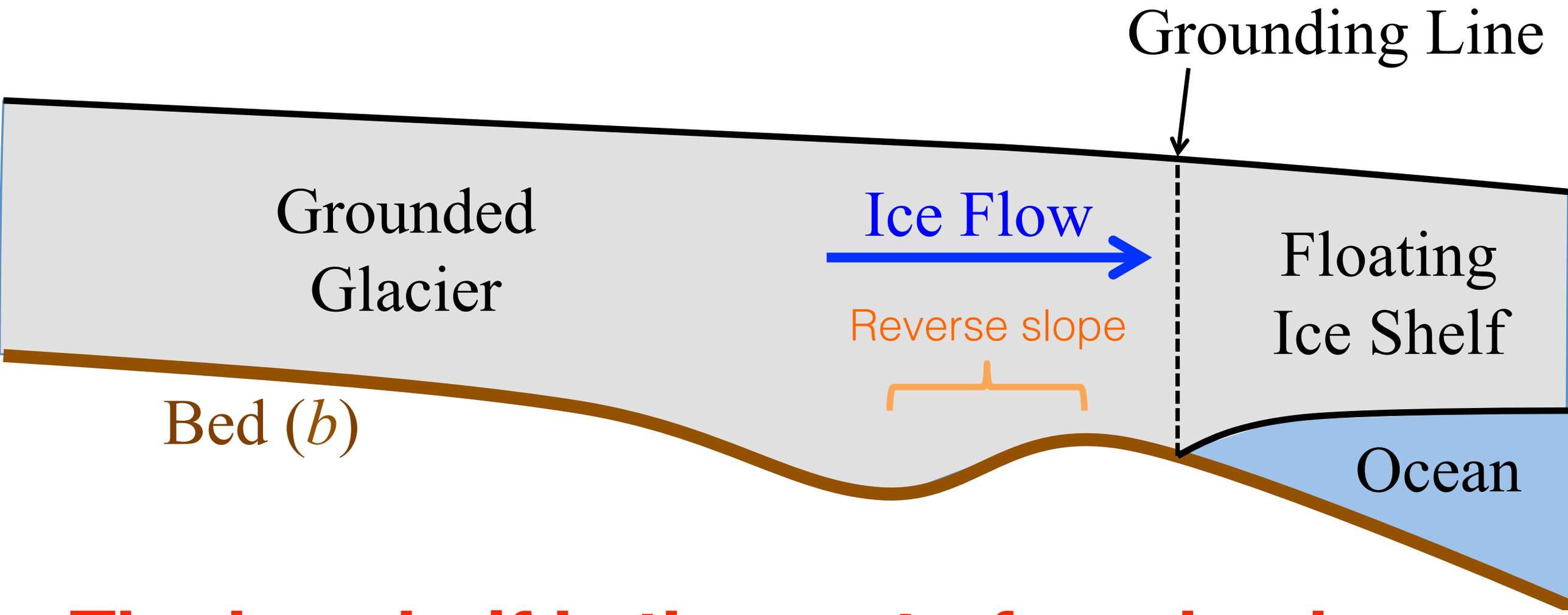
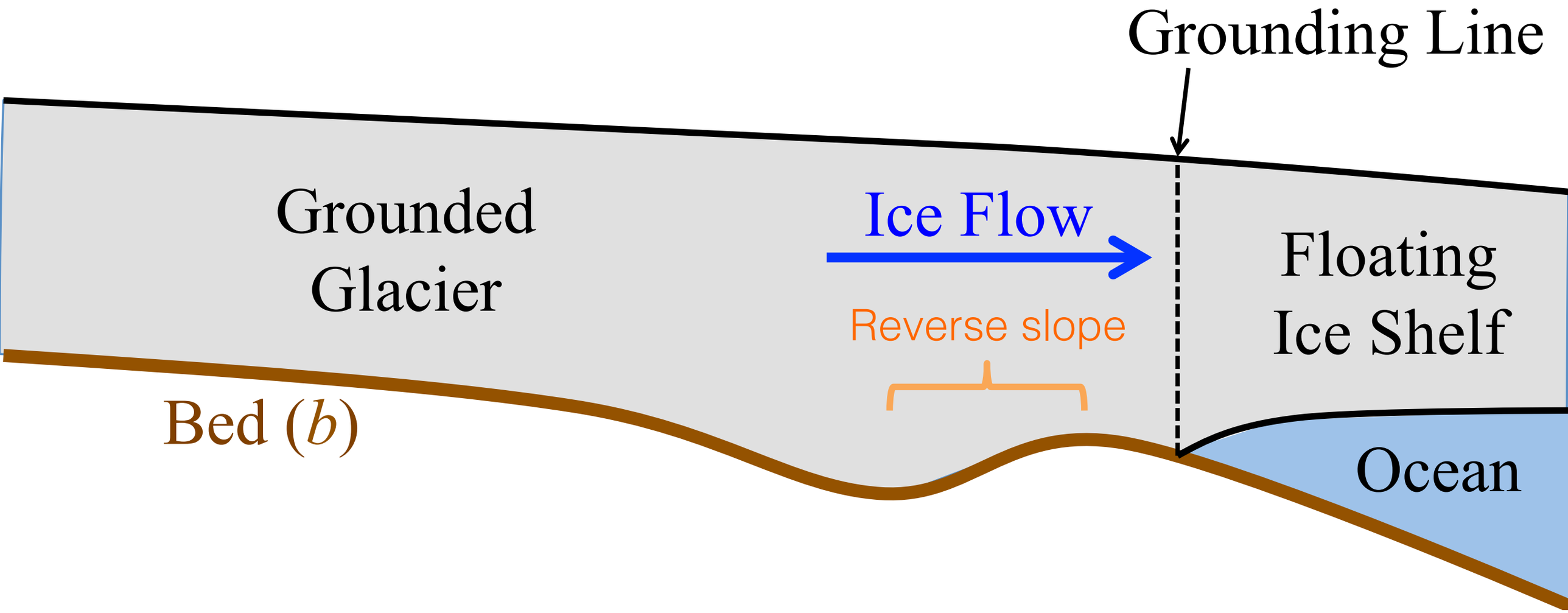


Fig. 3 *a*, Antarctic ice cover today, and *b*, after a 5–10 °C warming.

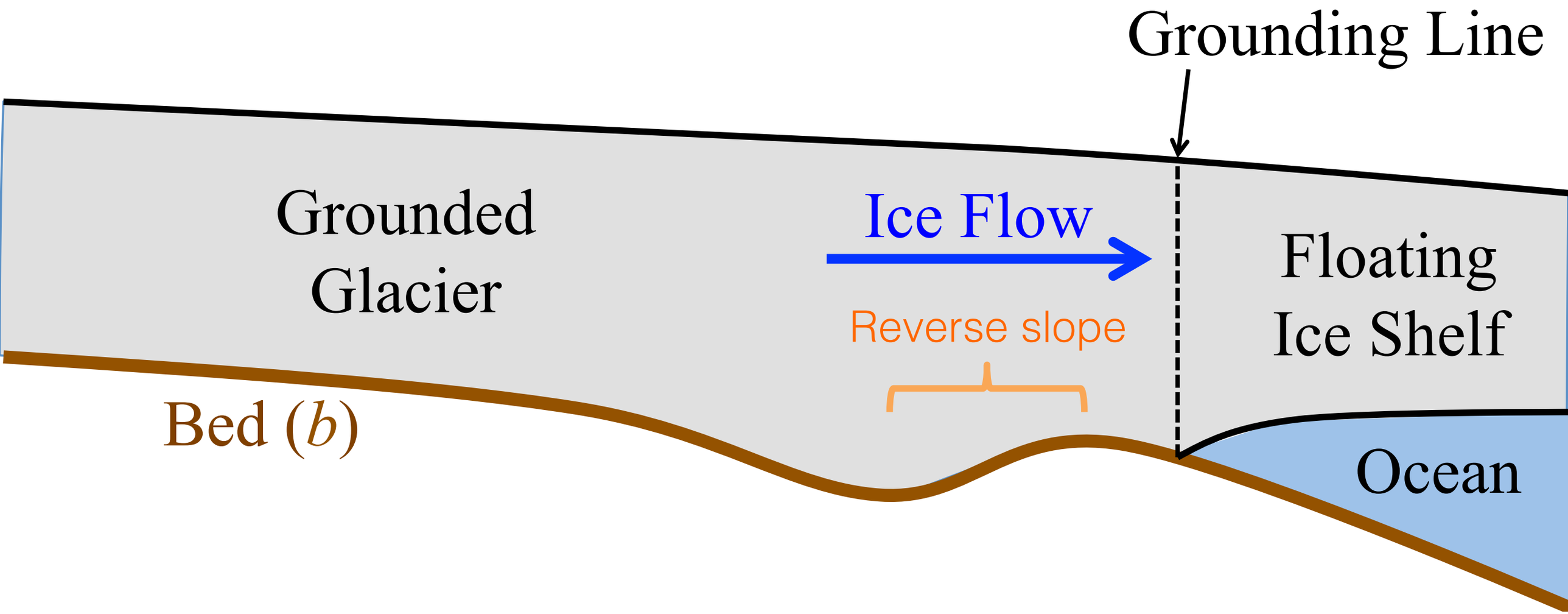
The continued contact of marine ice sheets with the ocean makes them especially susceptible to melting due to changes in climate



The ice shelf is the part of marine ice sheets where the ice is thin enough to float in seawater



The grounding line is the place where ice is last in contact with the bed (in theory)



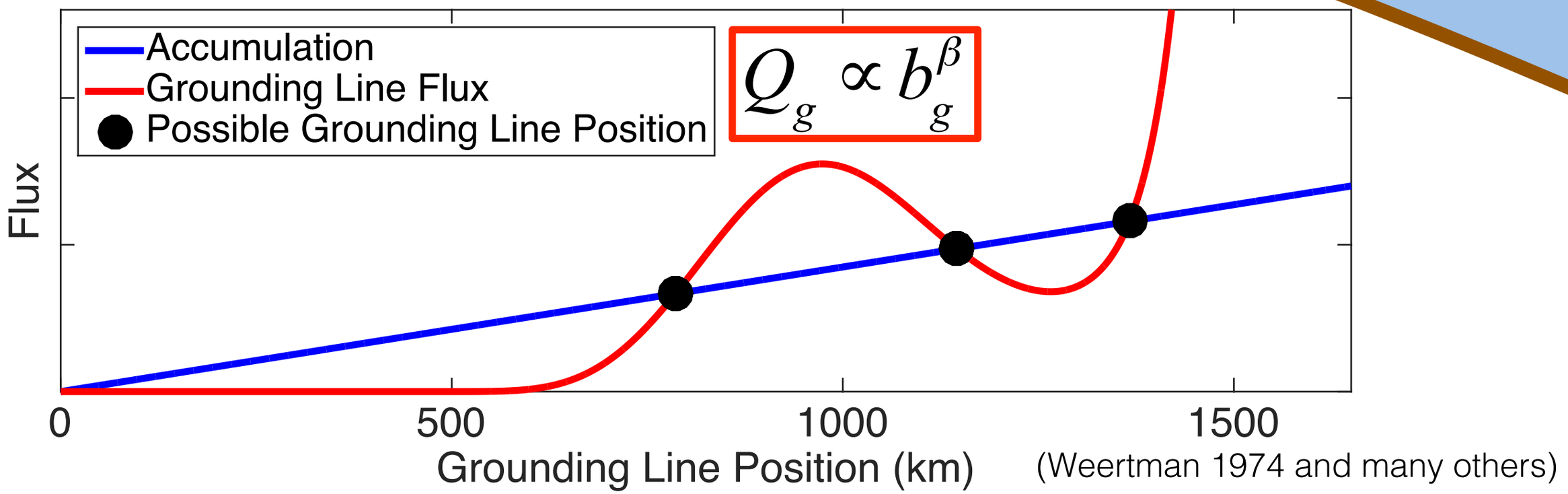
Once ice goes through the grounding line, it either becomes part of the floating ice shelf or calves as an iceberg, and so it begins to contribute to global sea level (buoyancy is compensated by ocean)

Marine ice sheet instability

Snow Accumulation (P)

Grounding line flux (Q_g)

Bed (b)



(Weertman 1974 and many others)

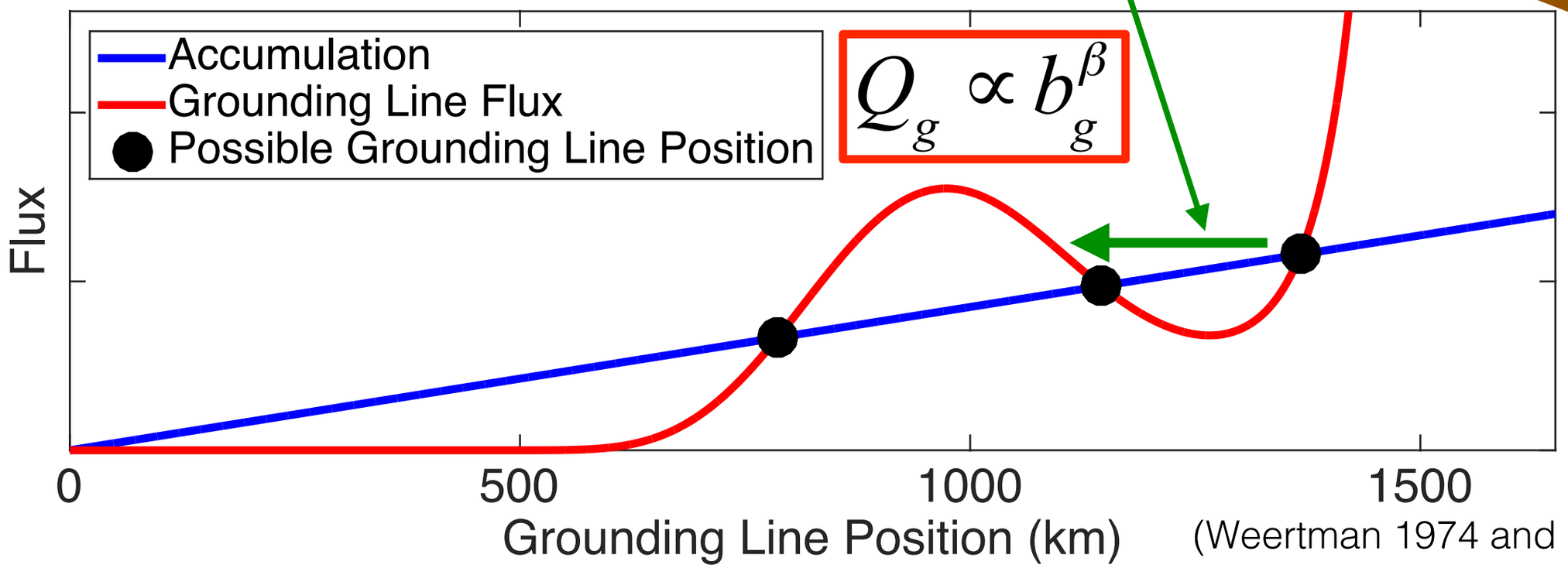
Marine ice sheet instability

Snow Accumulation (P)

Grounding line flux (Q_g)

Possibility: ocean melt perturbs you away from a steady state

Bed (b)



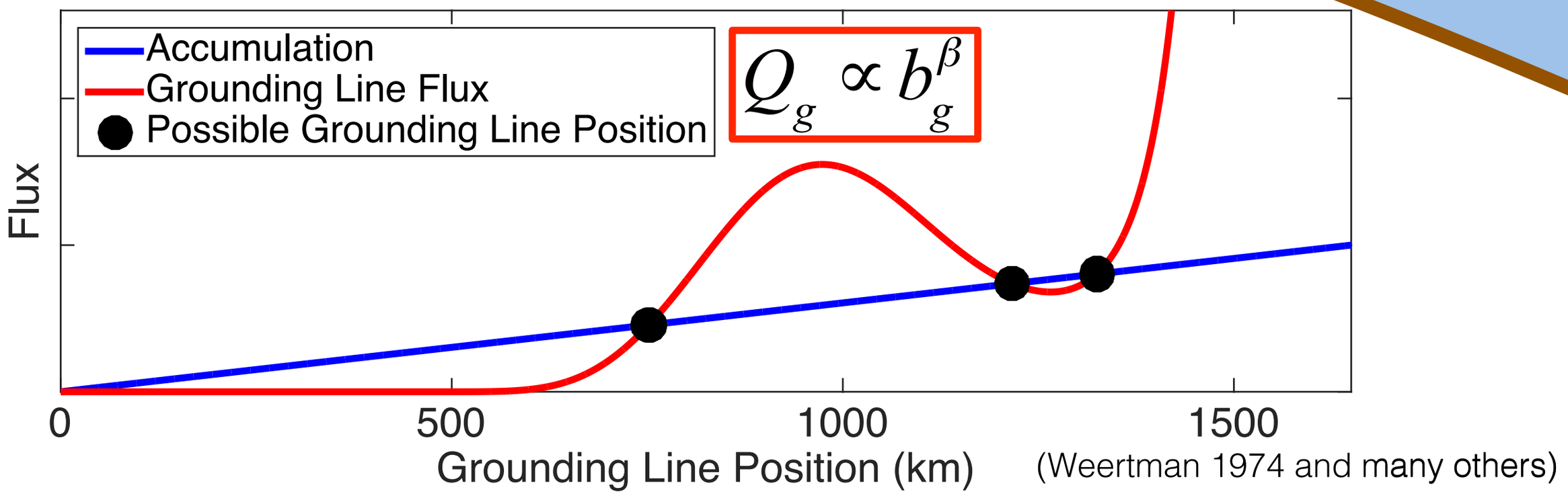
(Weertman 1974 and many others)

Marine ice sheet instability

Snow Accumulation (P)

Grounding line flux (Q_g)

Bed (b)



(Weertman 1974 and many others)

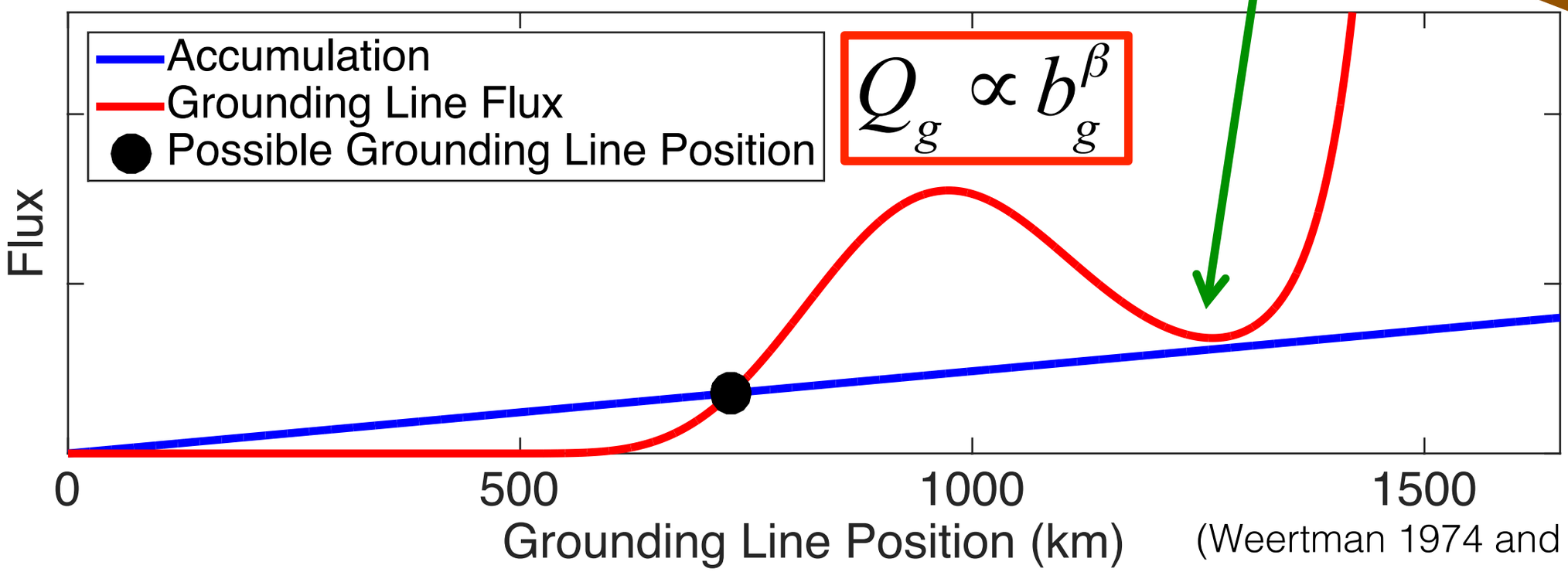
Marine ice sheet instability

Snow Accumulation (P)

This is popularly called
"ice sheet collapse"

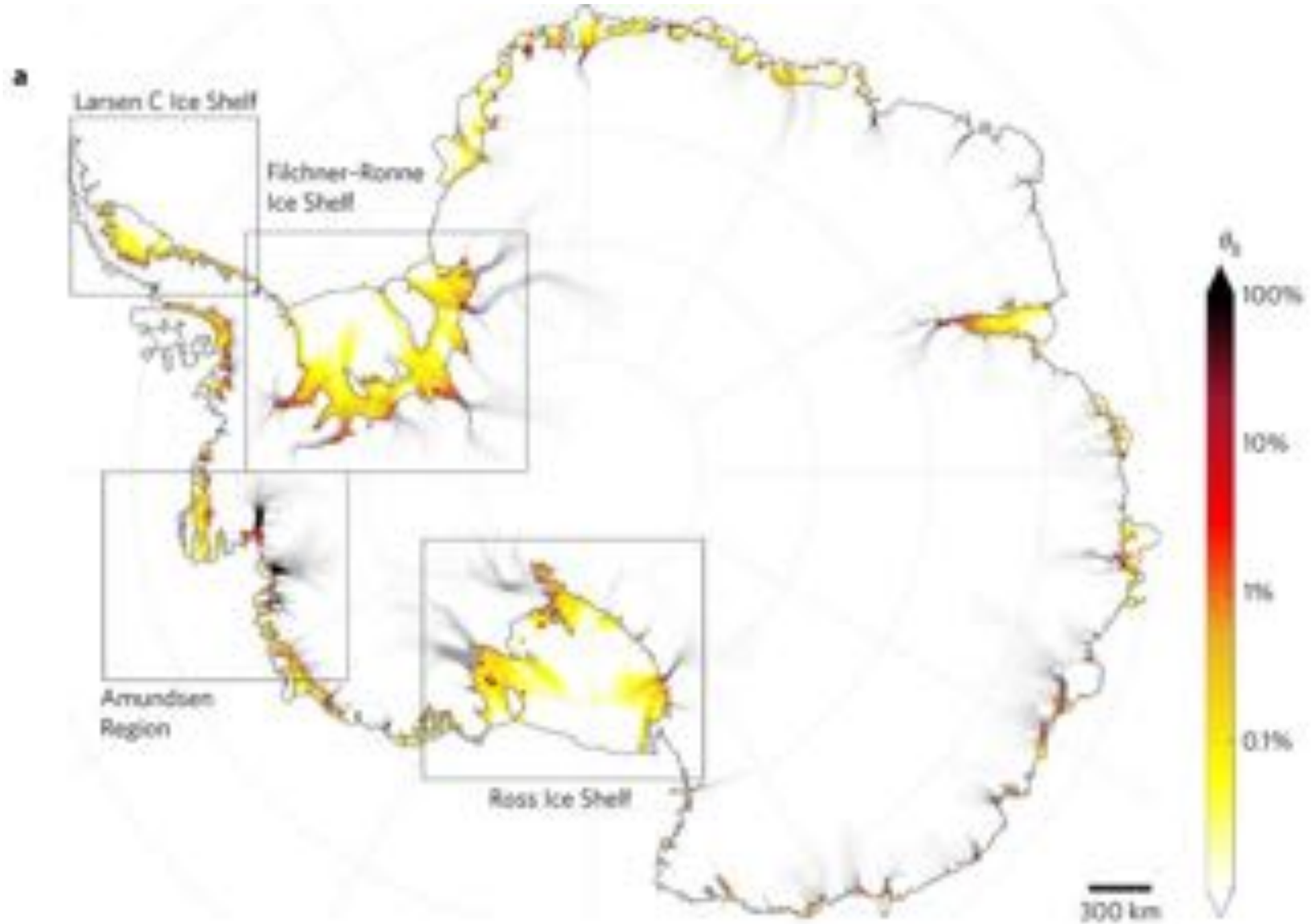
Grounding
line flux (Q_g)

Bed (b)



(Weertman 1974 and many others)

Ice shelf buttressing



Reese et al. 2017

Ice shelf buttressing

When ice sheet dynamics makes it into the New York Times

The New York Times

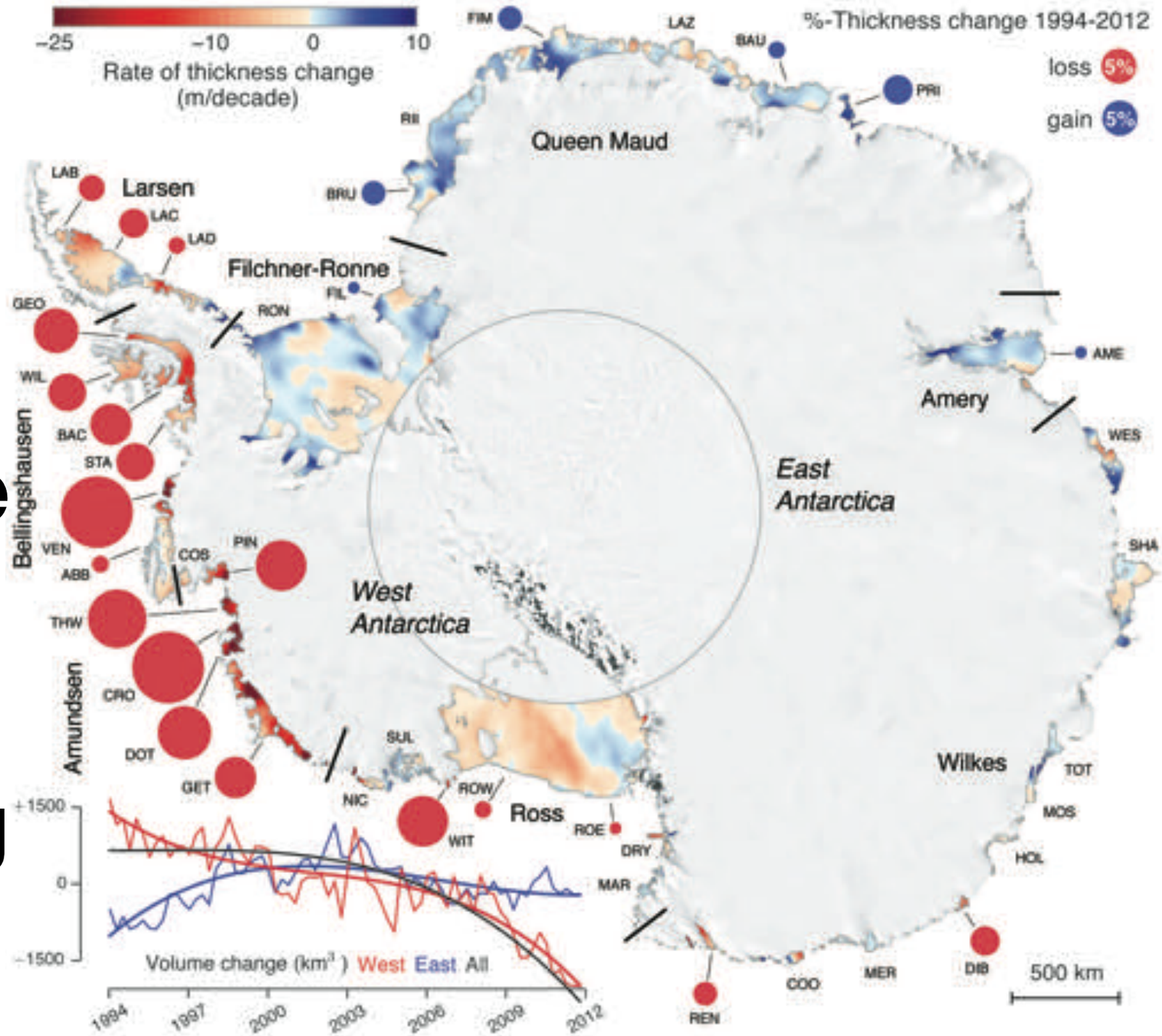
A Crack in an Antarctic Ice Shelf Grew 17 Miles in the Last Two Months

By JUGAL K. PATEL FEB. 7, 2017

A rapidly advancing crack in Antarctica's fourth-largest ice shelf has scientists concerned that it is getting close to a full break. The rift has accelerated this year in an area already vulnerable to warming temperatures. Since December, the crack has grown by the length of about five football fields each day. RELATED ARTICLE

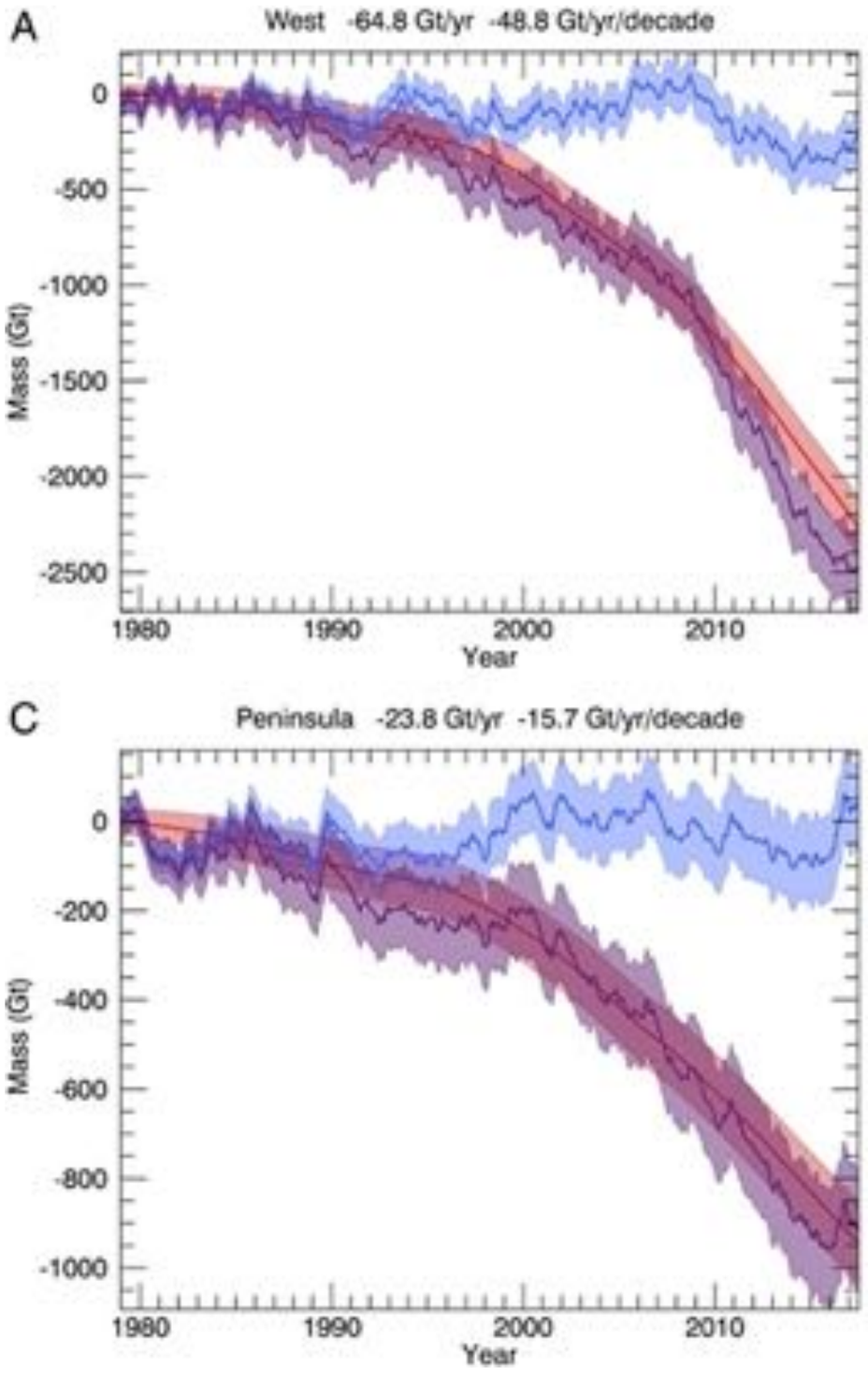
Ice Shelves and the Ocean

The most significant changes in ice thickness in Antarctica have occurred due to ocean melting floating ice shelves



Paolo et al. 2015

Antarctic Ice Sheet



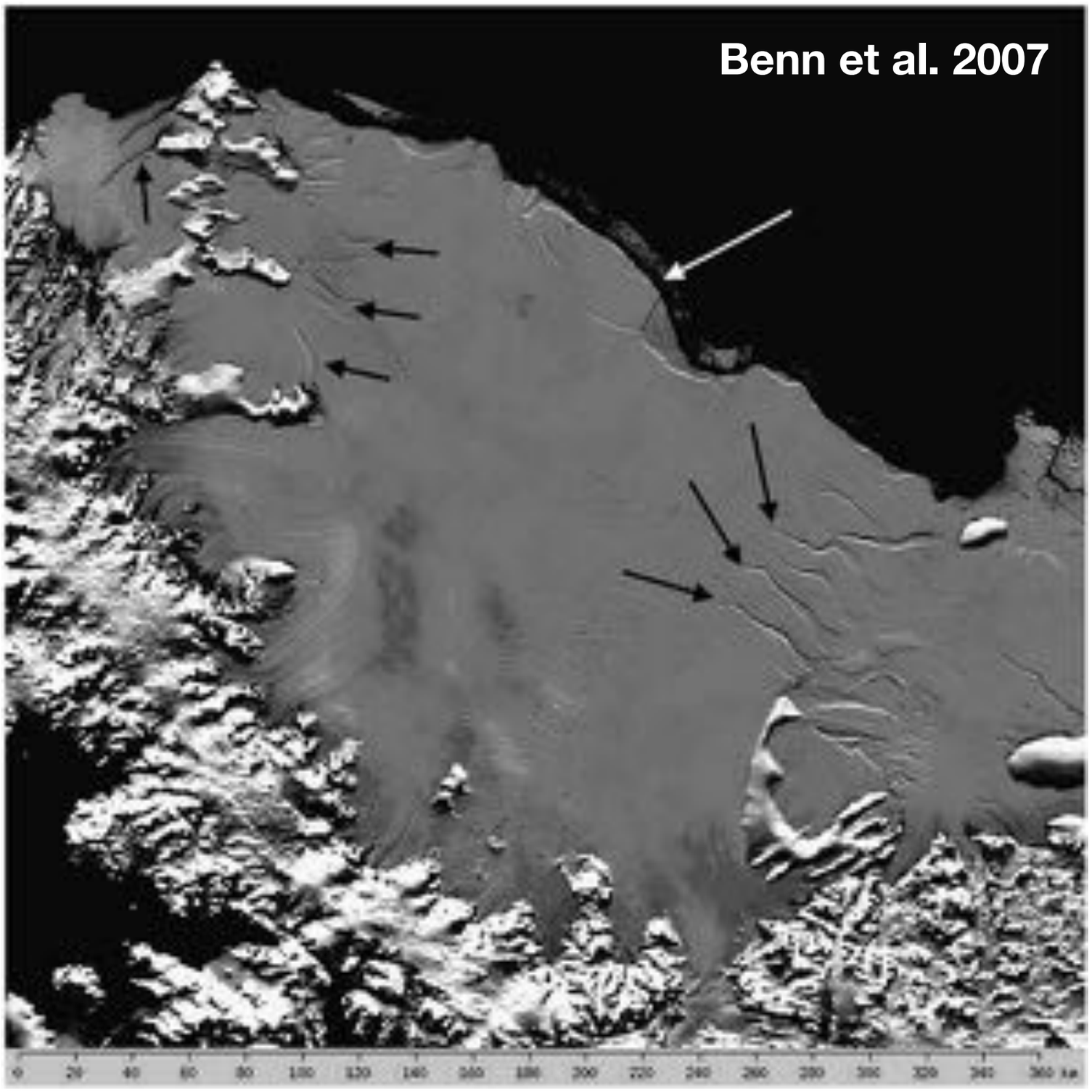
Most of this acceleration in discharge from the Antarctic Ice Sheet (and accelerating contribution to sea level rise) come from places where the grounding line is retreating on deepening beds

Iceberg calving

Benn et al. 2007

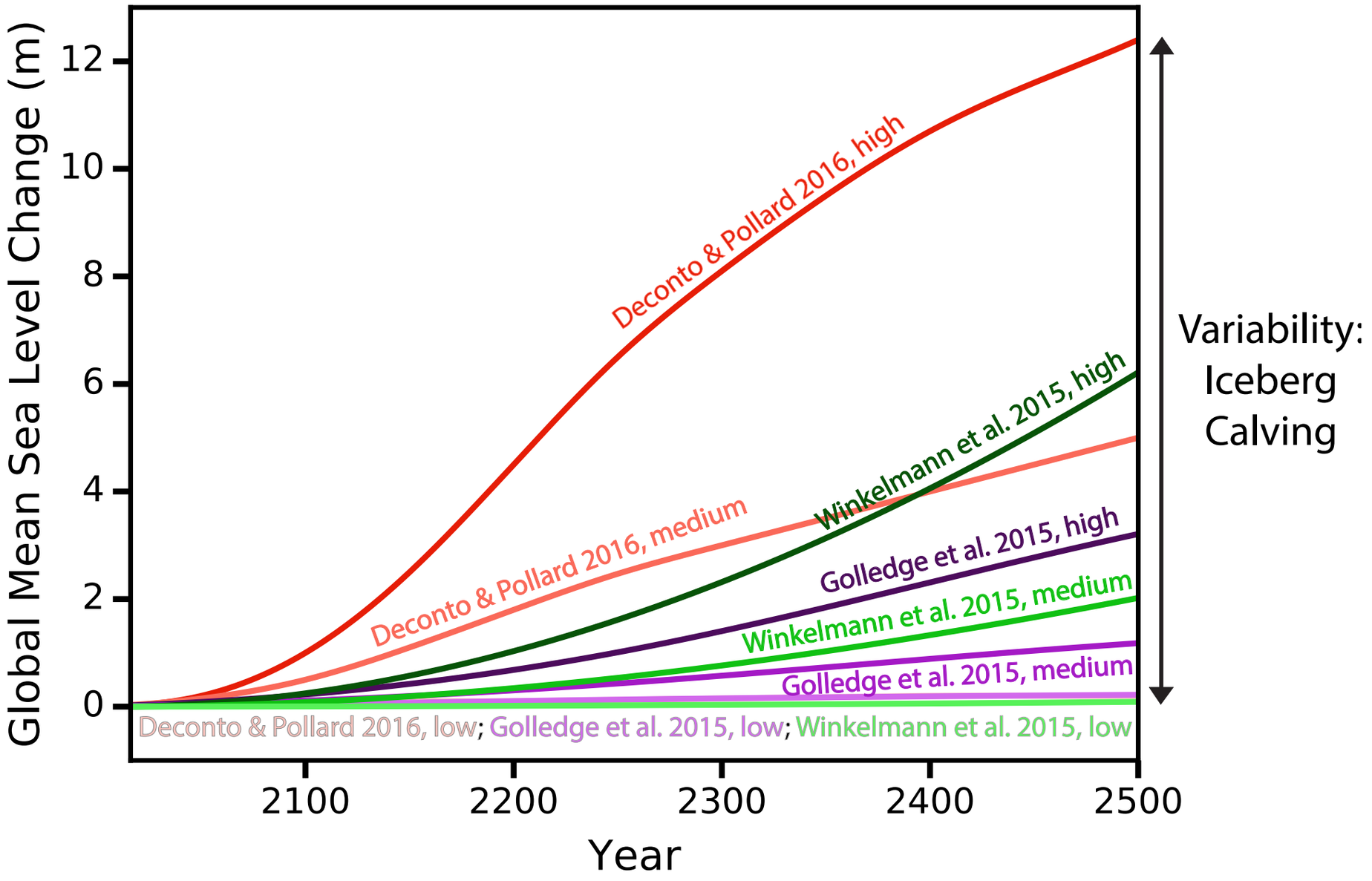
Fractures that penetrate all the way to the base and all the way through the width of a glacier near the glacier terminus in the ocean lead to iceberg *calving*

Iceberg calving



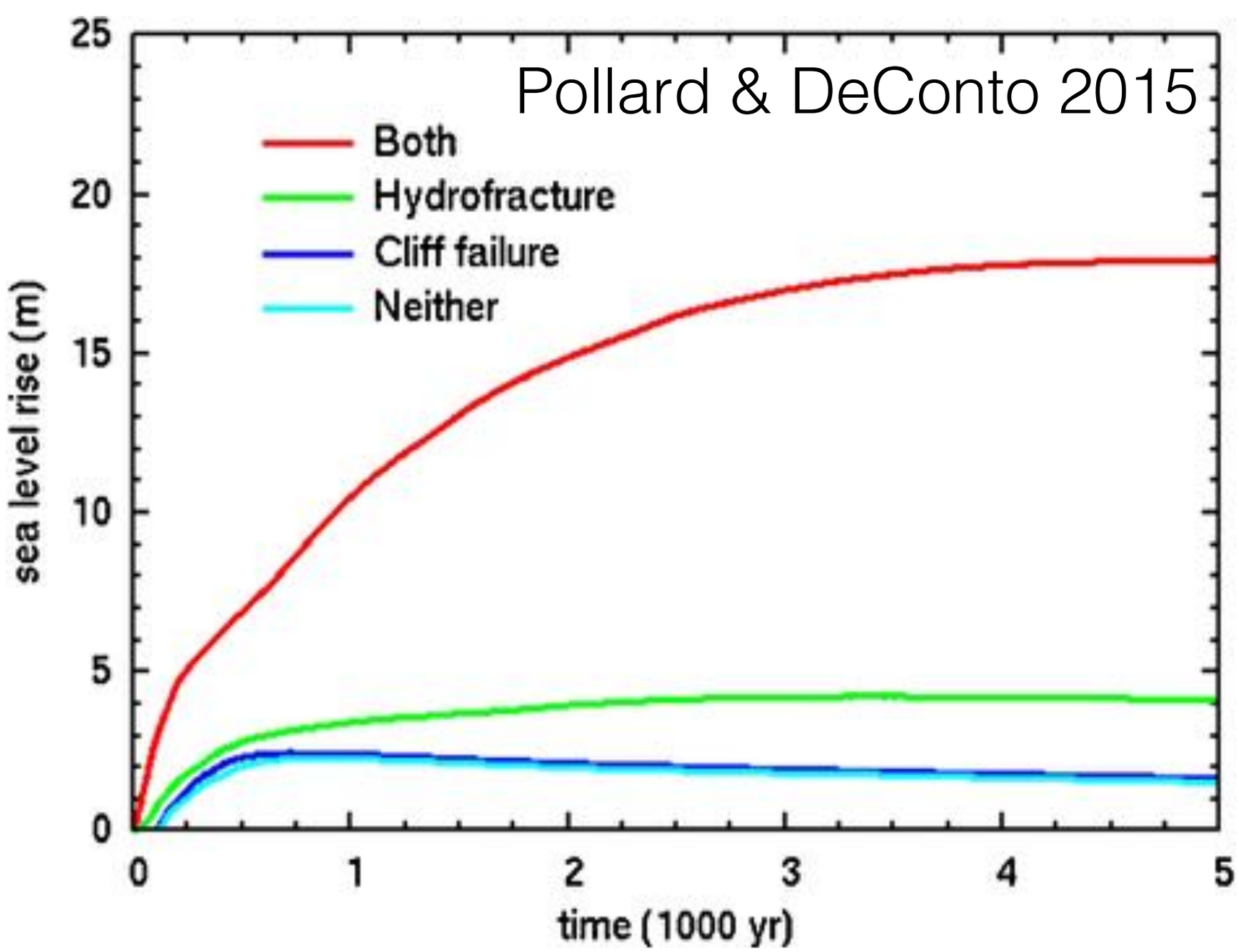
For marine ice sheets, calving can be the most important way in which ice is lost from the glacier (compared to surface/ocean melt)

Iceberg calving



Calving is also one of the biggest unknowns in ice sheet models and the reason why there are large differences in sea level rise prediction between ice sheet models

Ice Cliffs



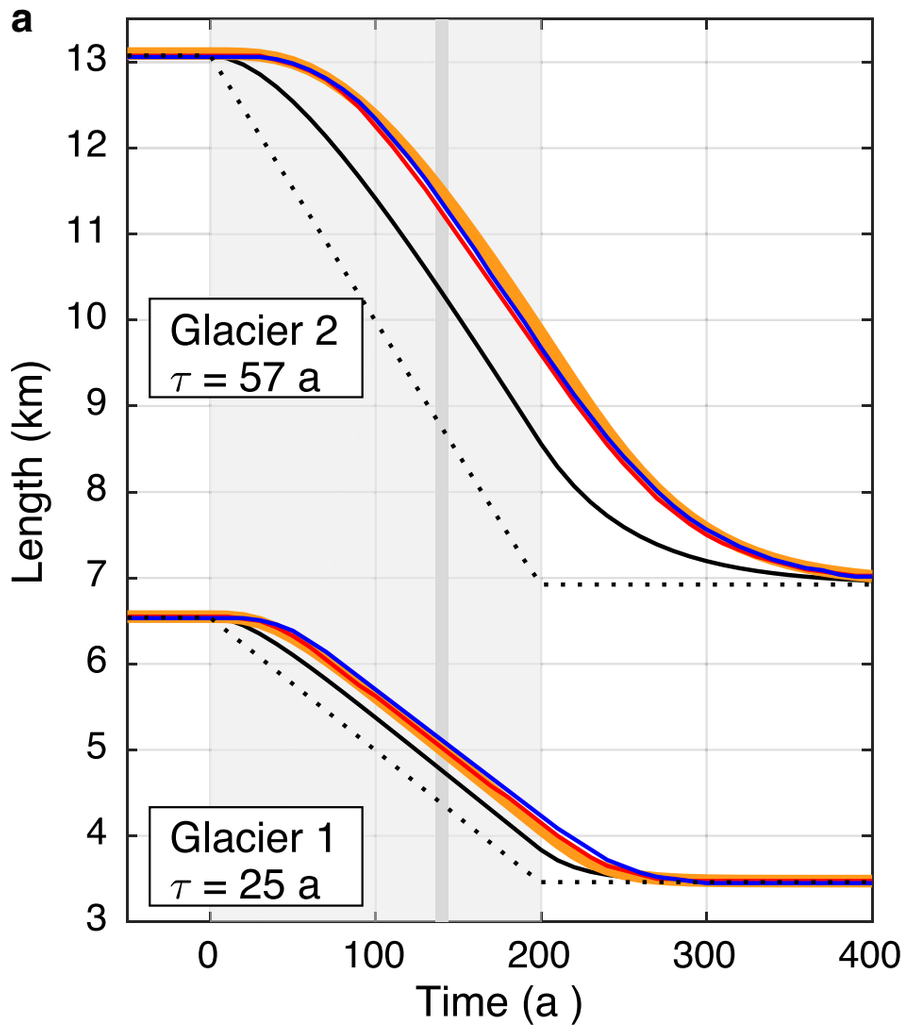
In recent years there has been intense debate over the possibility of rapid calving from tall ice cliffs in Antarctica and whether this could produce much more sea level rise than previously was though possible over a period of a few centuries

You are driving on a rainy bridge, going 70 MPH. Suddenly, you lose control and start skidding towards a truck stopped in front of you. What do you do?

If you know that you are going to hit the truck for sure, would you do anything differently?

Sea Level Commitment: Earth's runaway car

Mountain glaciers: A Toyota Prius with brand-new brake pads

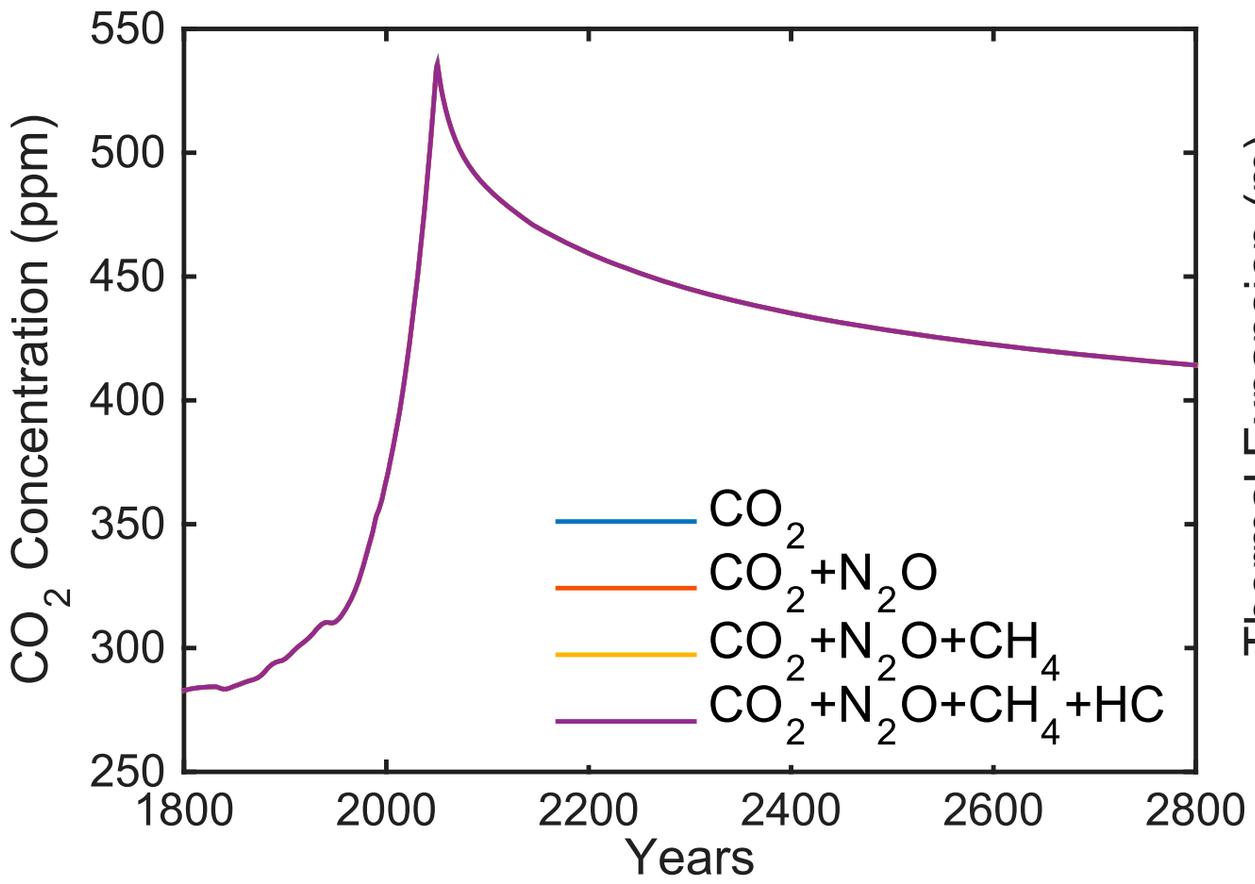


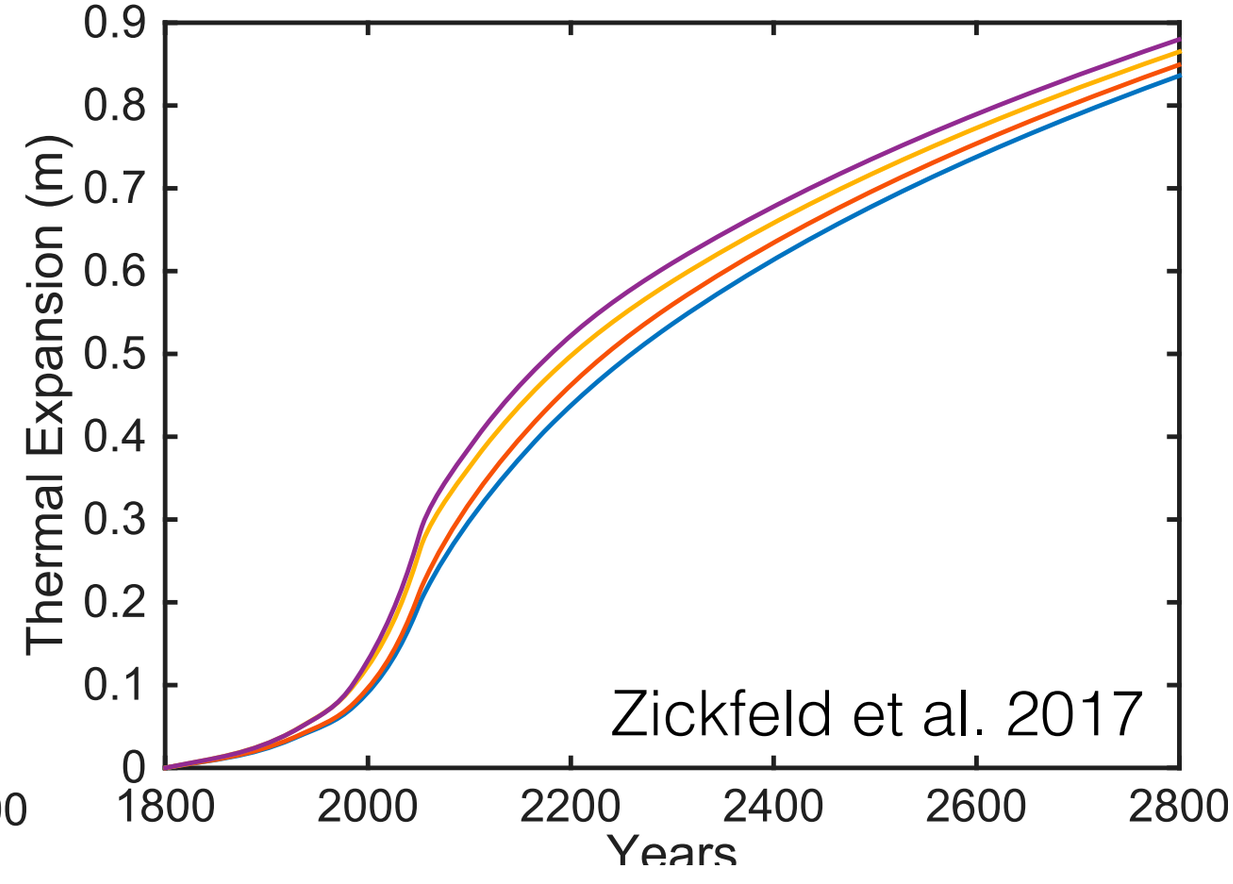
Christian et al. 2018

Even if we stop emitting greenhouse gases today, mountain glaciers would continue to melt for a few decades (and some are definitely going to disappear)

Sea Level Commitment: Earth's runaway car

Thermal expansion: A minivan that's due for maintainance

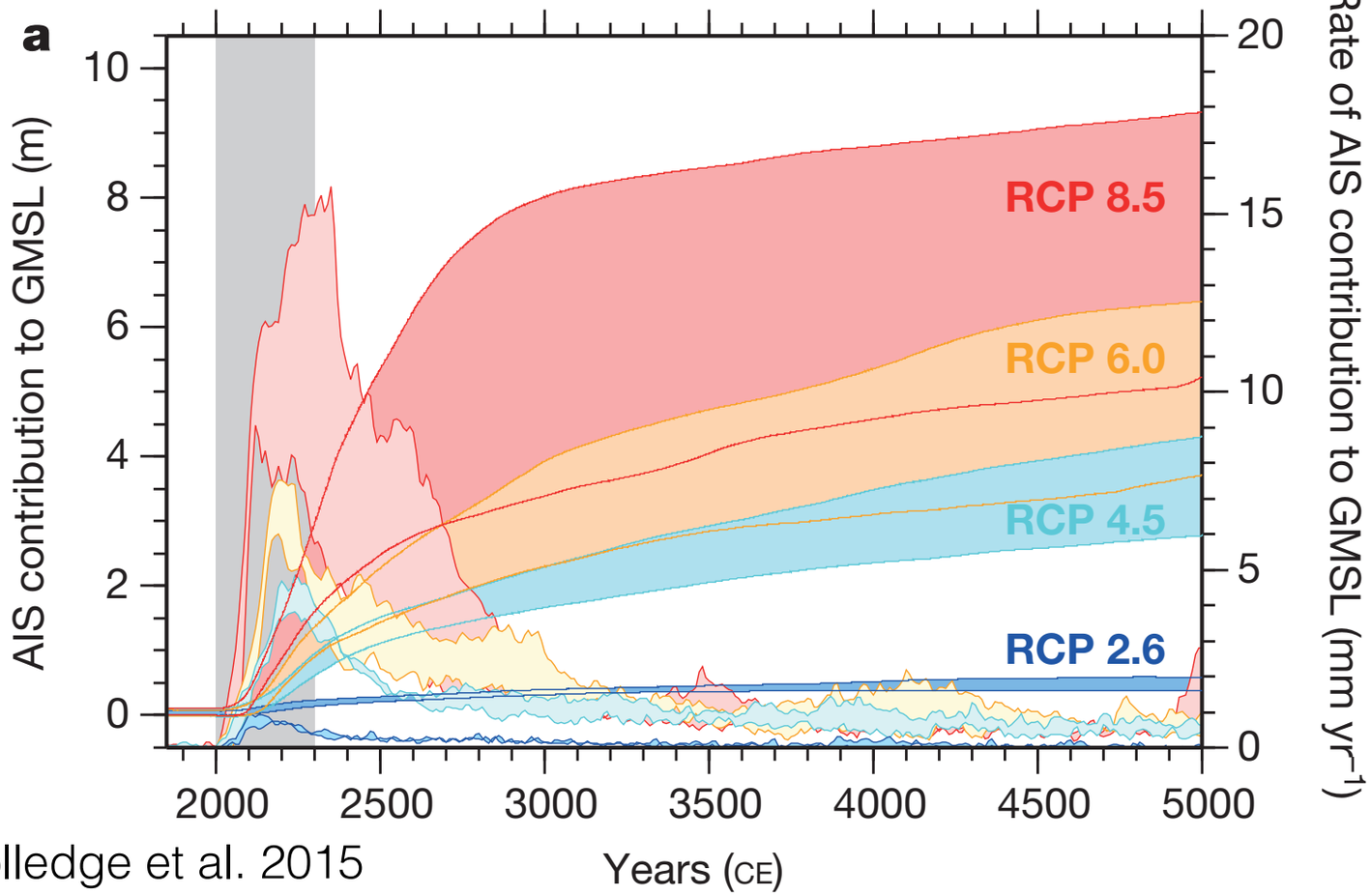




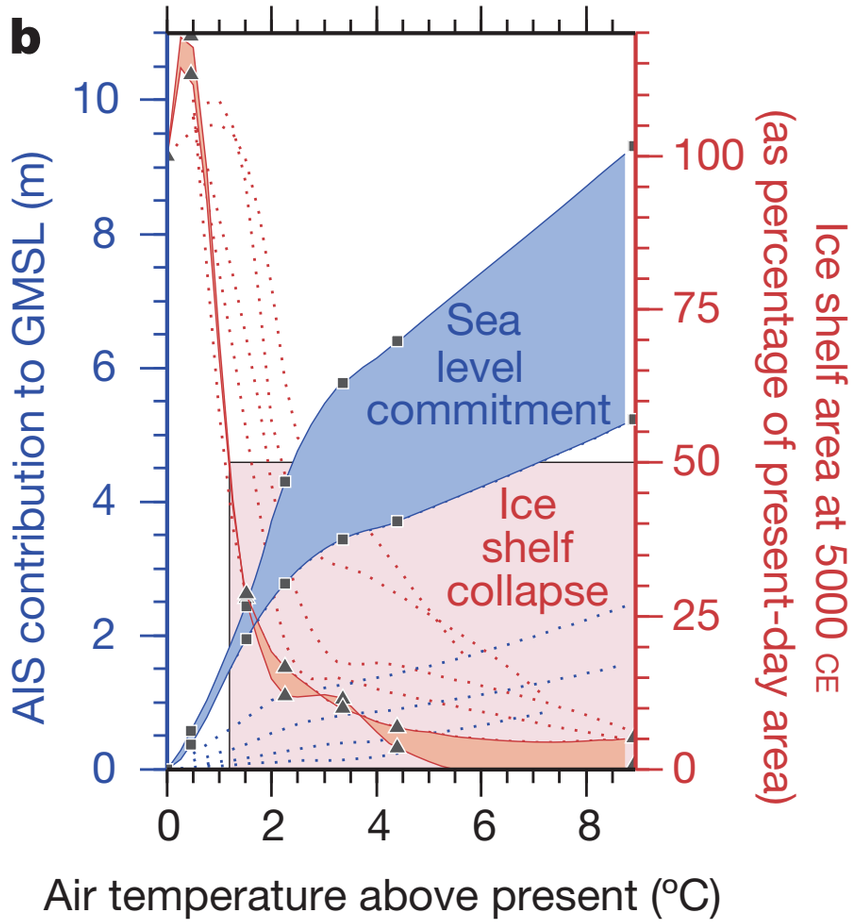
Even if we stop emitting greenhouse gases today, the ocean would continue to slowly absorb heat and expand for hundreds of years

Sea Level Commitment: Earth's runaway car

The Antarctic Ice Sheet: A poorly-maintained 18-wheeler



Golledge et al. 2015



Antarctic melt contributes to sea level for 1000's of years even if we stop emitting greenhouse gases today.

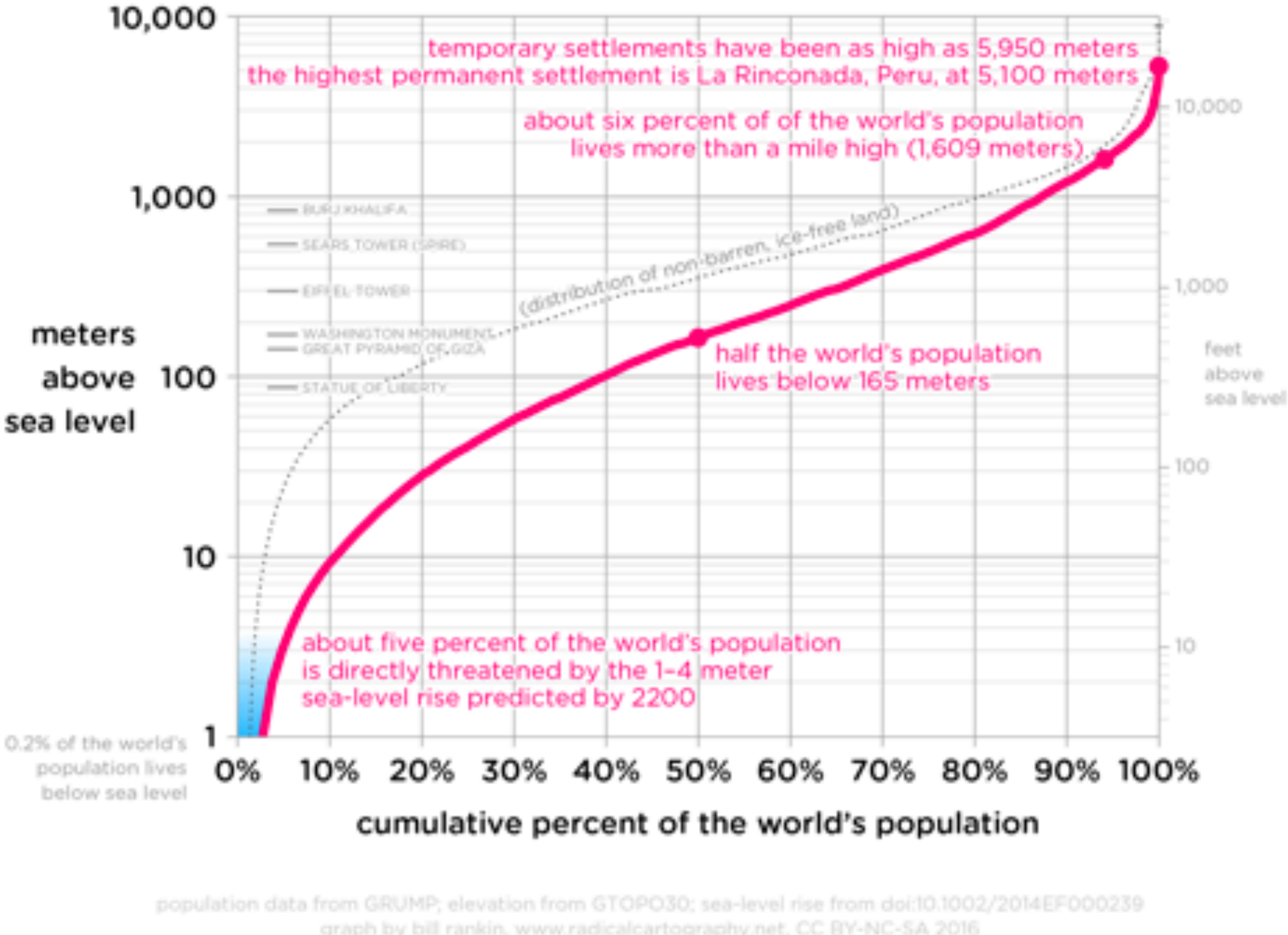
Sea level "commitment" depends on total climate change

Why the committed response?

- The car: it takes time to slow down the current inertia based on the car's size and effectiveness of brakes

- Glaciers: their "inertia" (time to adjust to climate changes) depends on their size too
  - Mountain glaciers (100s feet of ice): decades
  - Antarctic/Greenland glaciers (1000s feet of ice): centuries/millennia

Why it still makes sense to hit the brakes



Every 1 cm of additional sea level rise, threatens an additional 1 million people