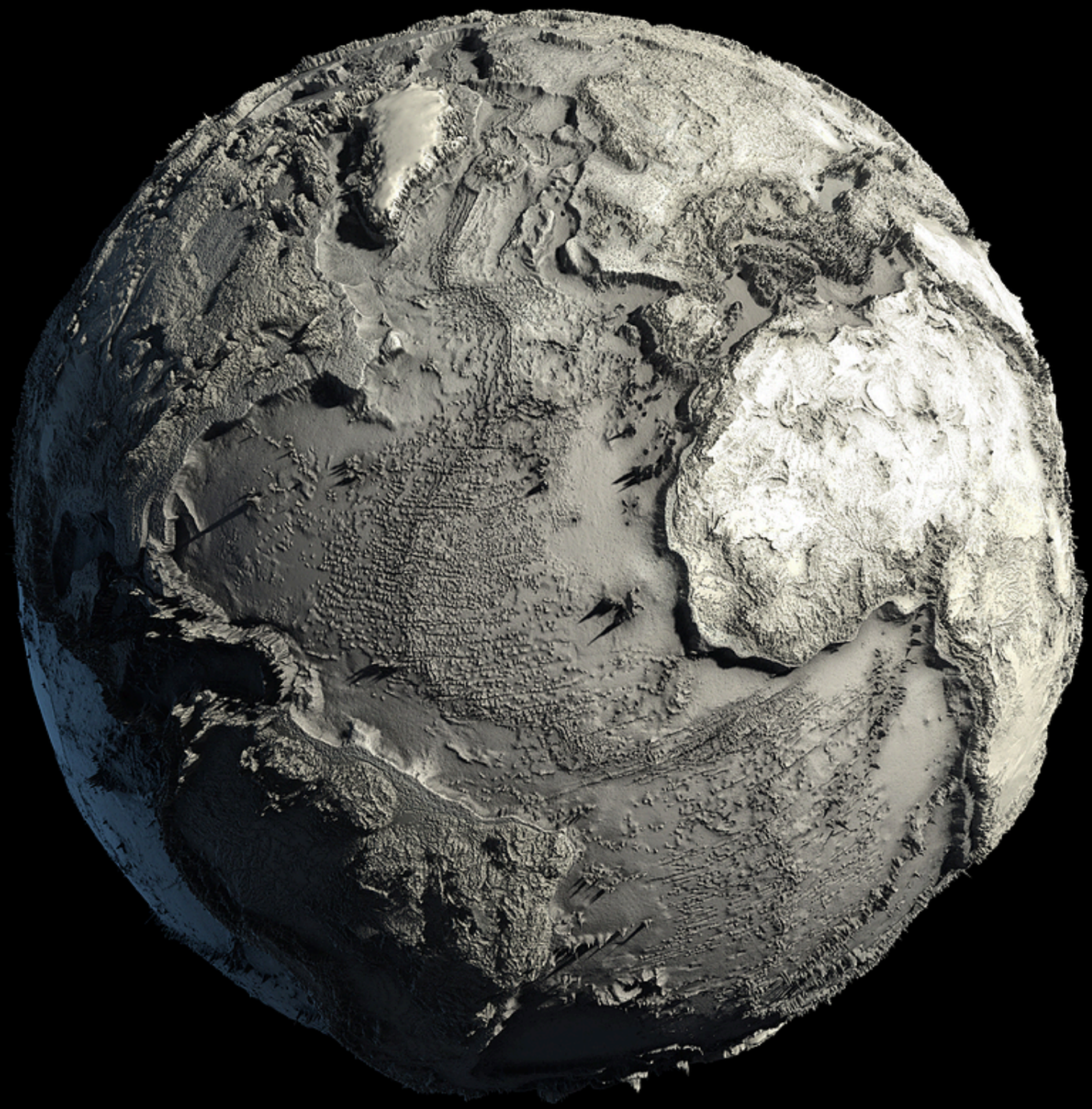
What is sea level?

Imagine you were at the coast…

Where is sea level?

The Earth without oceans - what happens when you drop a lot of water on this sphere(oid)? Why?



Sea level is local

Tide gauge station

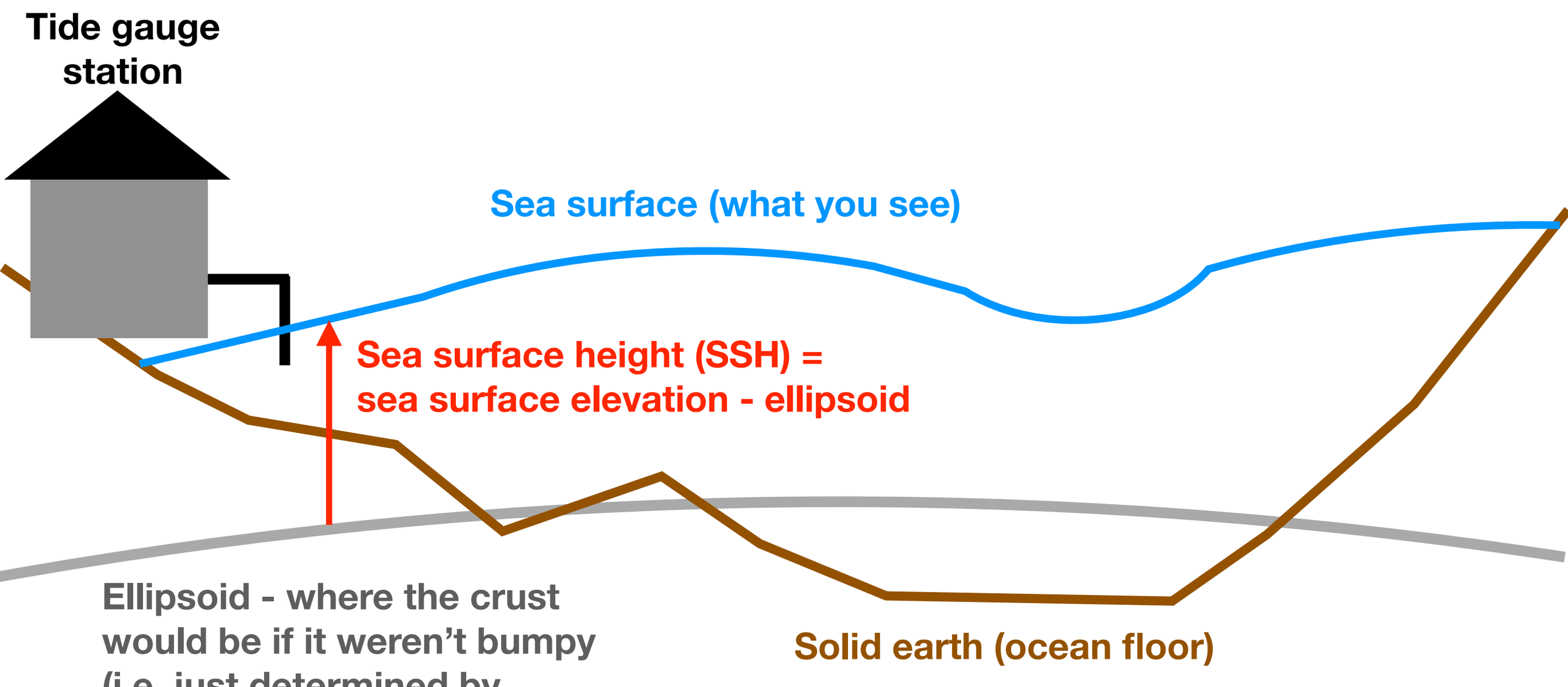
Sea surface (what you see)

Relative sea level (RSL) =
sea surface elevation - crust elevation

Solid earth (ocean floor)

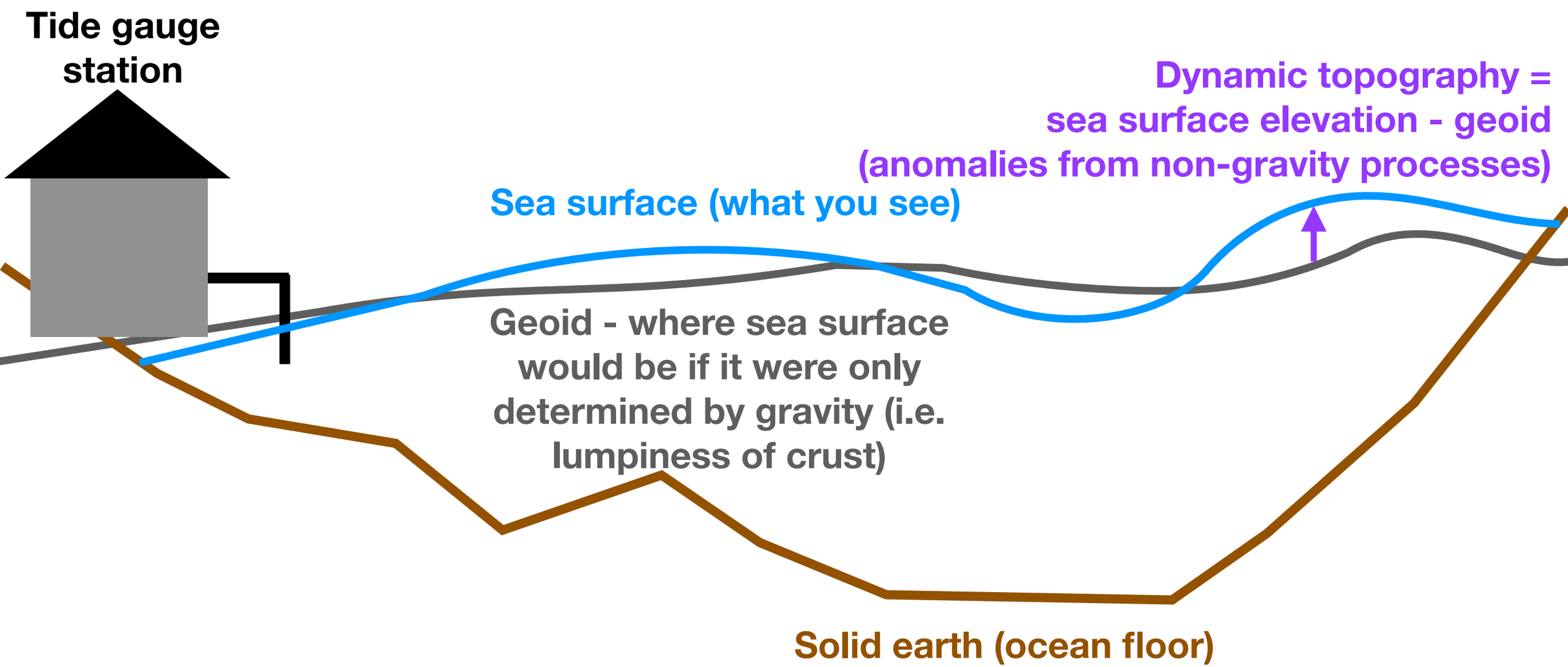
Schematic adapted from Tamisea et al. 2014

Sea level is local



Schematic adapted from Tamisea et al. 2014

Sea level is local and reference-dependent



Schematic adapted from Tamisea et al. 2014

Why the location of the solid earth matters just as much as the location of sea level

- The solid earth can change
- But also because we live and build things on the solid earth, the relative position of the sea surface to the coastal land surface (i.e. RSL) is what matters for flooding

ARTICLE

https://doi.org/10.1038/s41467-019-12808-z OPEN

New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding

Scott A. Kulp[1]* & Benjamin H. Strauss[1]

CLIMATE

The New York Times

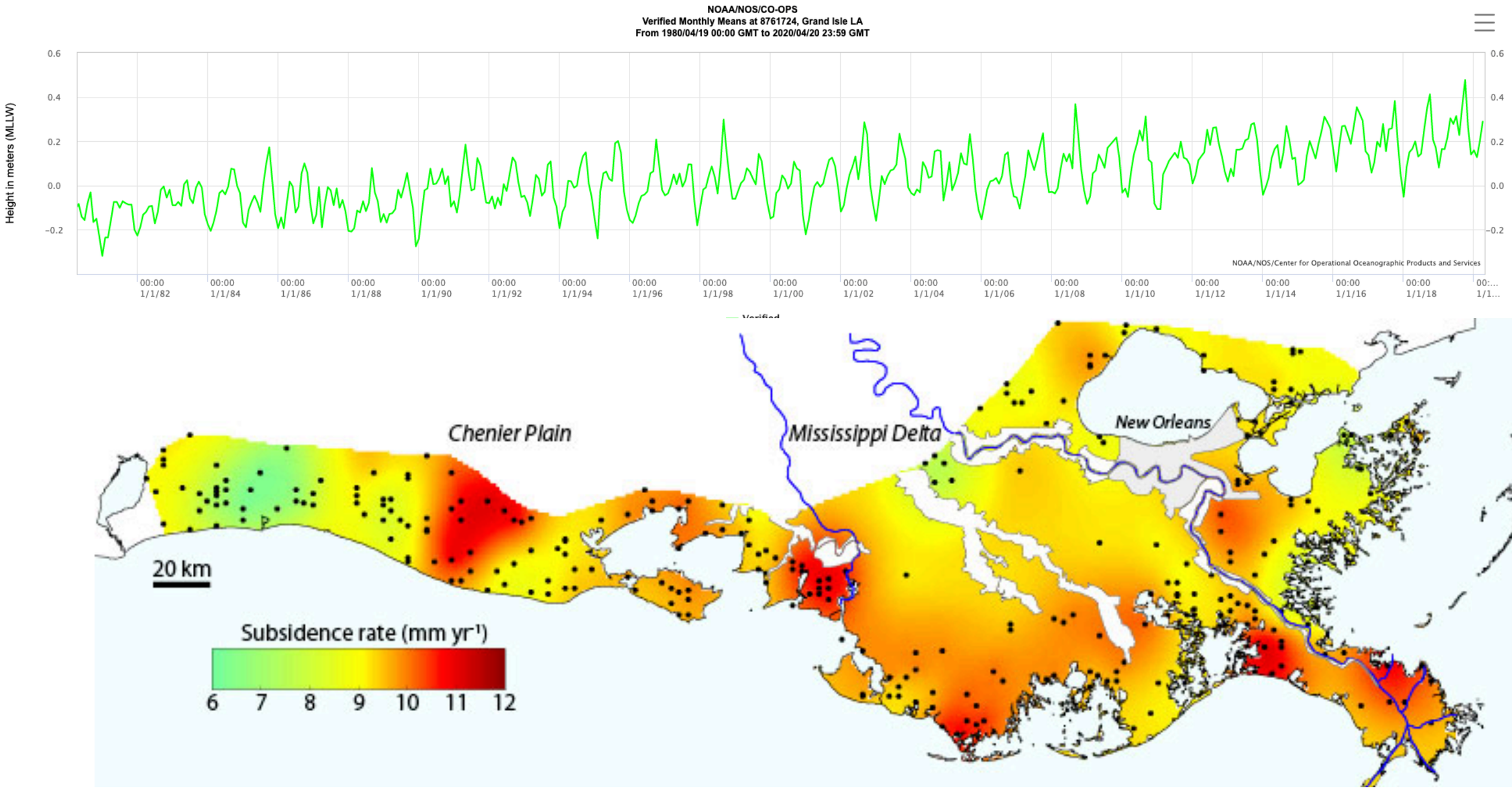
Rising Seas Will Erase More Cities by 2050, New Research Shows

By Denise Lu and Christopher Flavelle Oct. 29, 2019

KidsPost

More of the world's population will face flooding tied to climate change

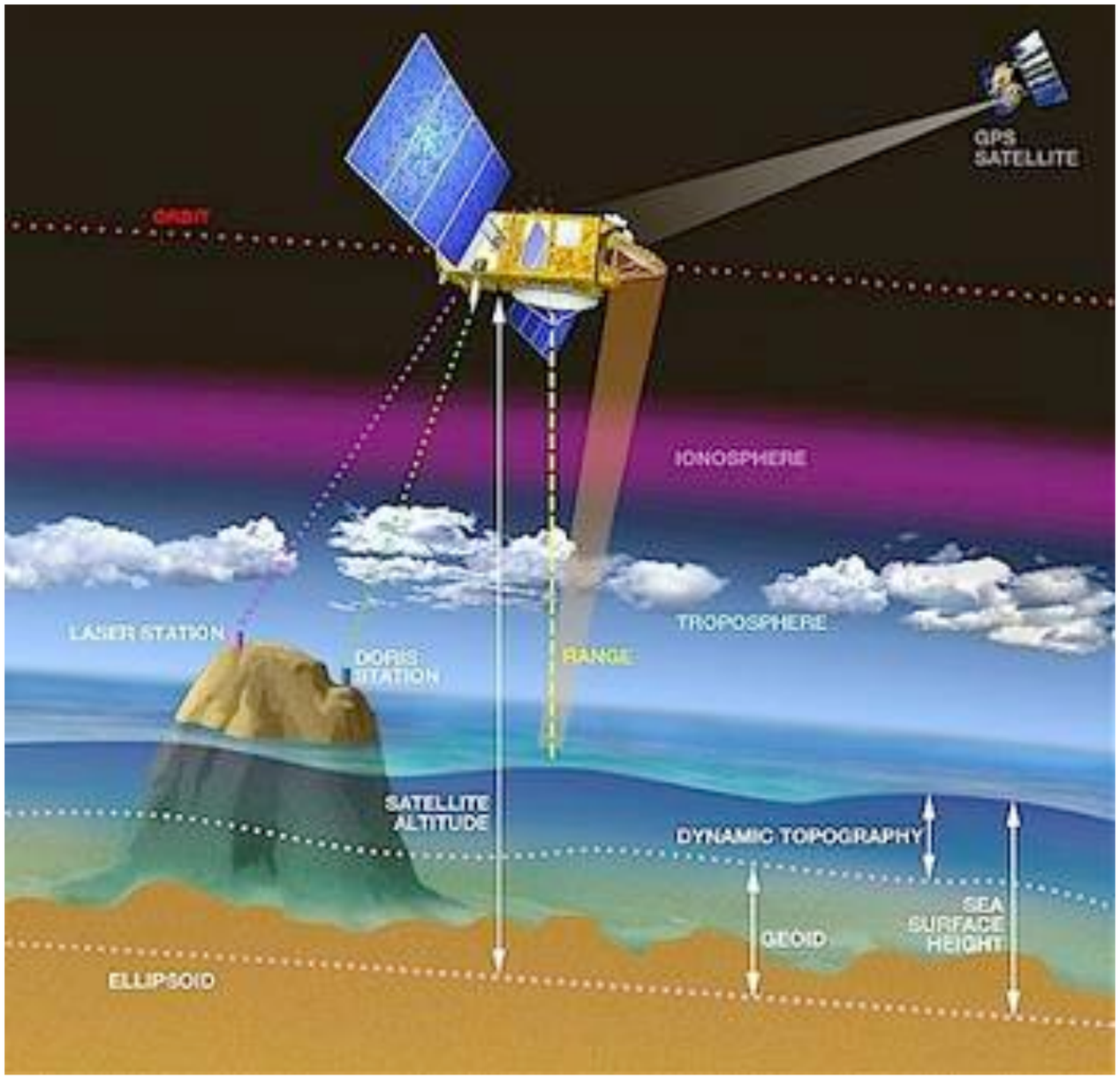
Why the location of the solid earth matters just as much as the location of sea level



Nienhuis et al. 2017

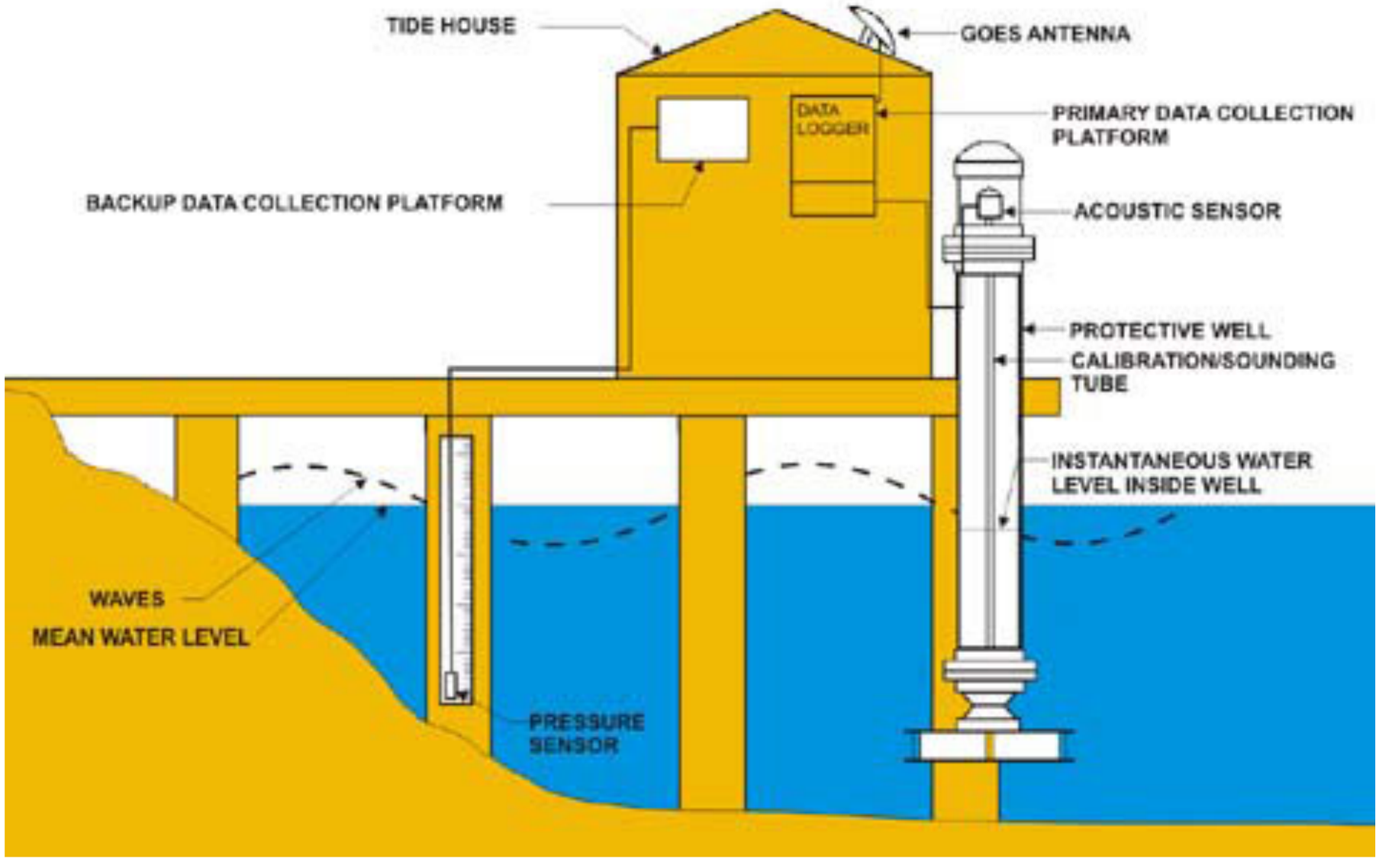
Measuring Sea Level

How do we measure sea level?

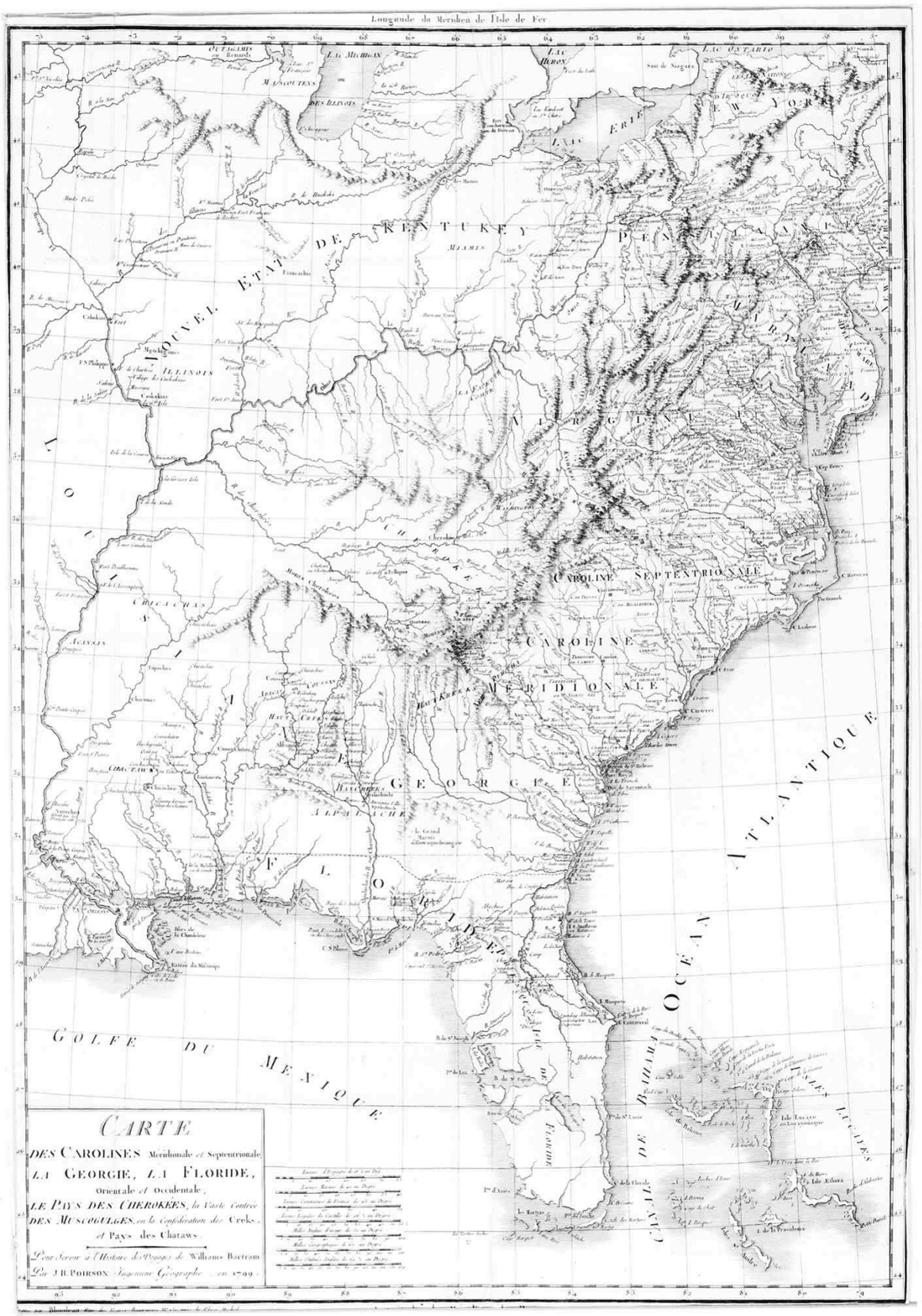


Altimeter measures distance from satellite to ocean surface based on return time of a radar or laser signal - great spatial coverage, poor resolution near coast

How do we measure sea level?



Tide gauges measure the distance from a reference position to the ocean surface inside a well at a coastal site - great precision, temporal resolution, poor spatial coverage



A typical map of the SE US coast around 1800 - meh

Tide gauges in the US

The earliest tide gauges in the US were installed to facilitate more detailed mapping of the US coastline at the behest of Thomas Jefferson in 1807.

How do we measure sea level?

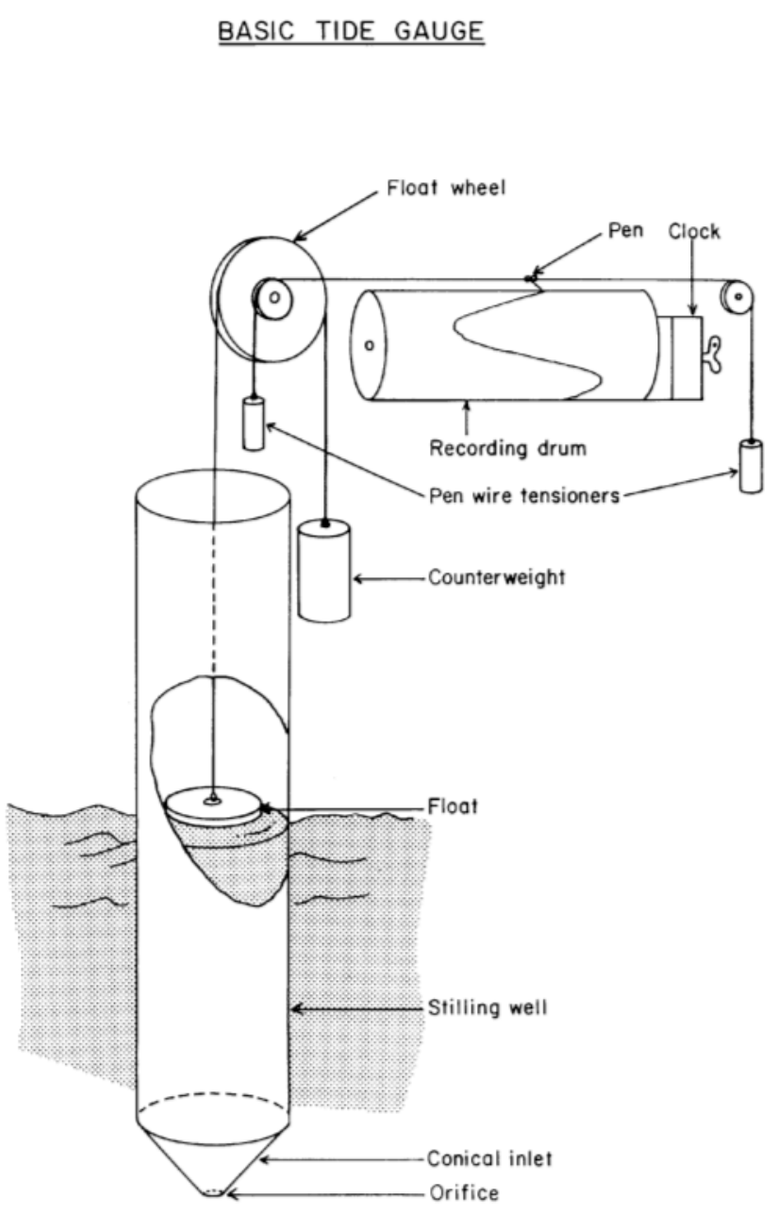


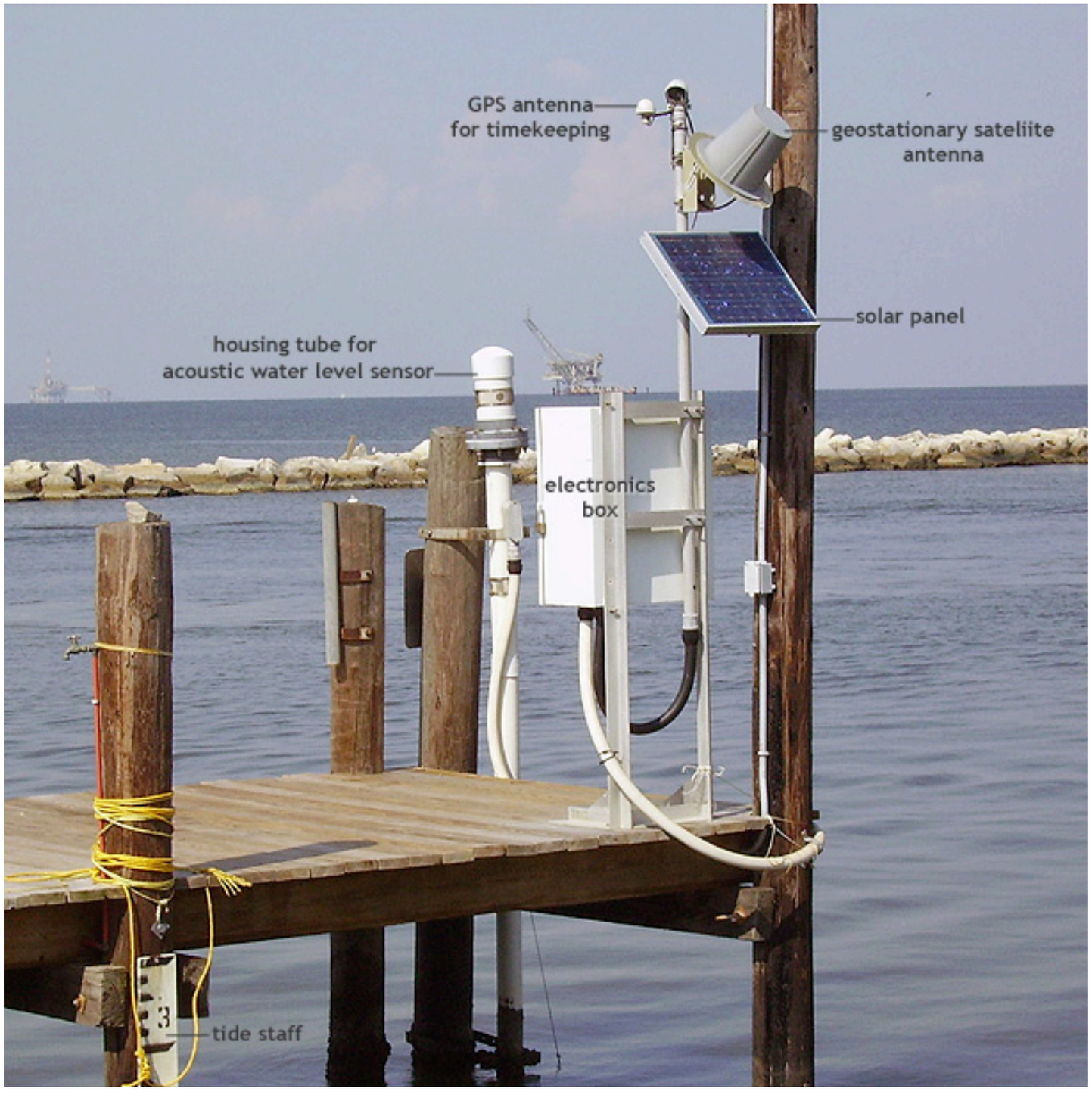
Figure 3.1

“Old school” tide gauge - a float and pulley system

How do we measure sea level?

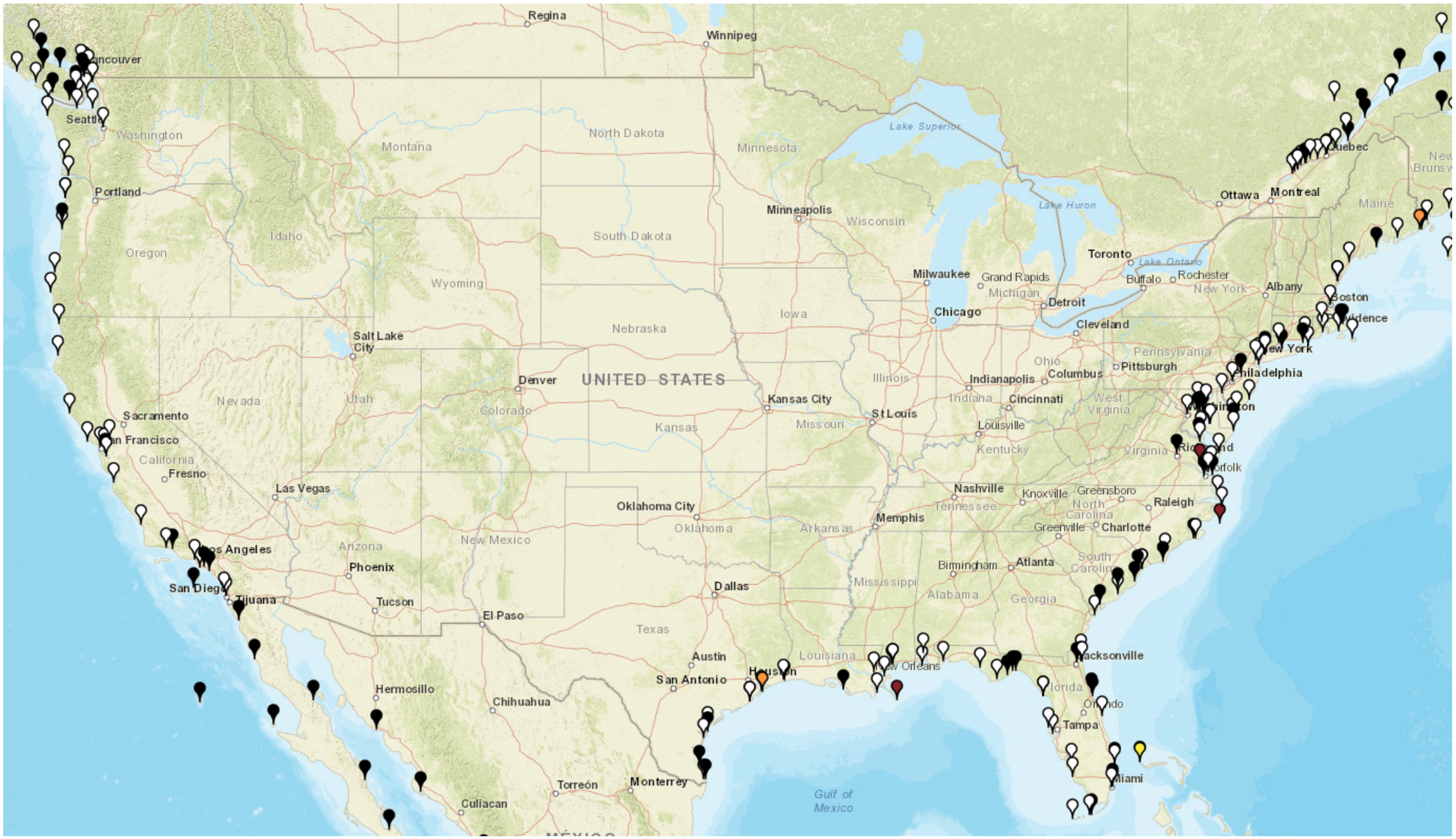
“New school” - a microwave sensor

How do we measure sea level?



“New school”
- an acoustic sensor

How do we measure sea level?



Long-running tide gauges in US (one in GA) - installed over last century

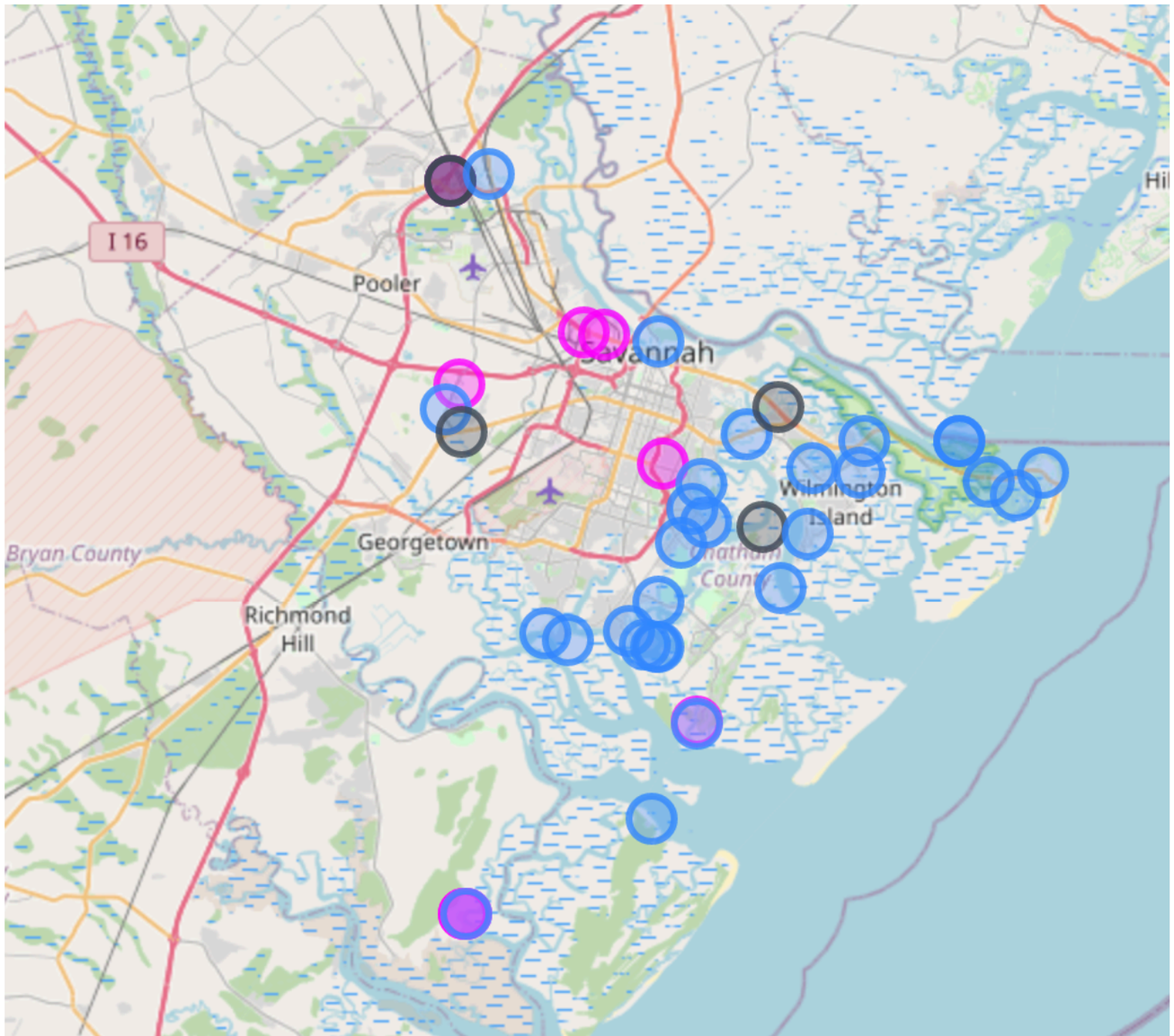
How do we measure sea level?

SMART
SEA LEVEL SENSORS

GT Project to make very cheap internet-connected acoustic SL sensors that can be installed in many more locations than tide gauges

How do we measure sea level?

SMART
SEA LEVEL SENSORS



GT now runs the densest network of sea level sensors in the world

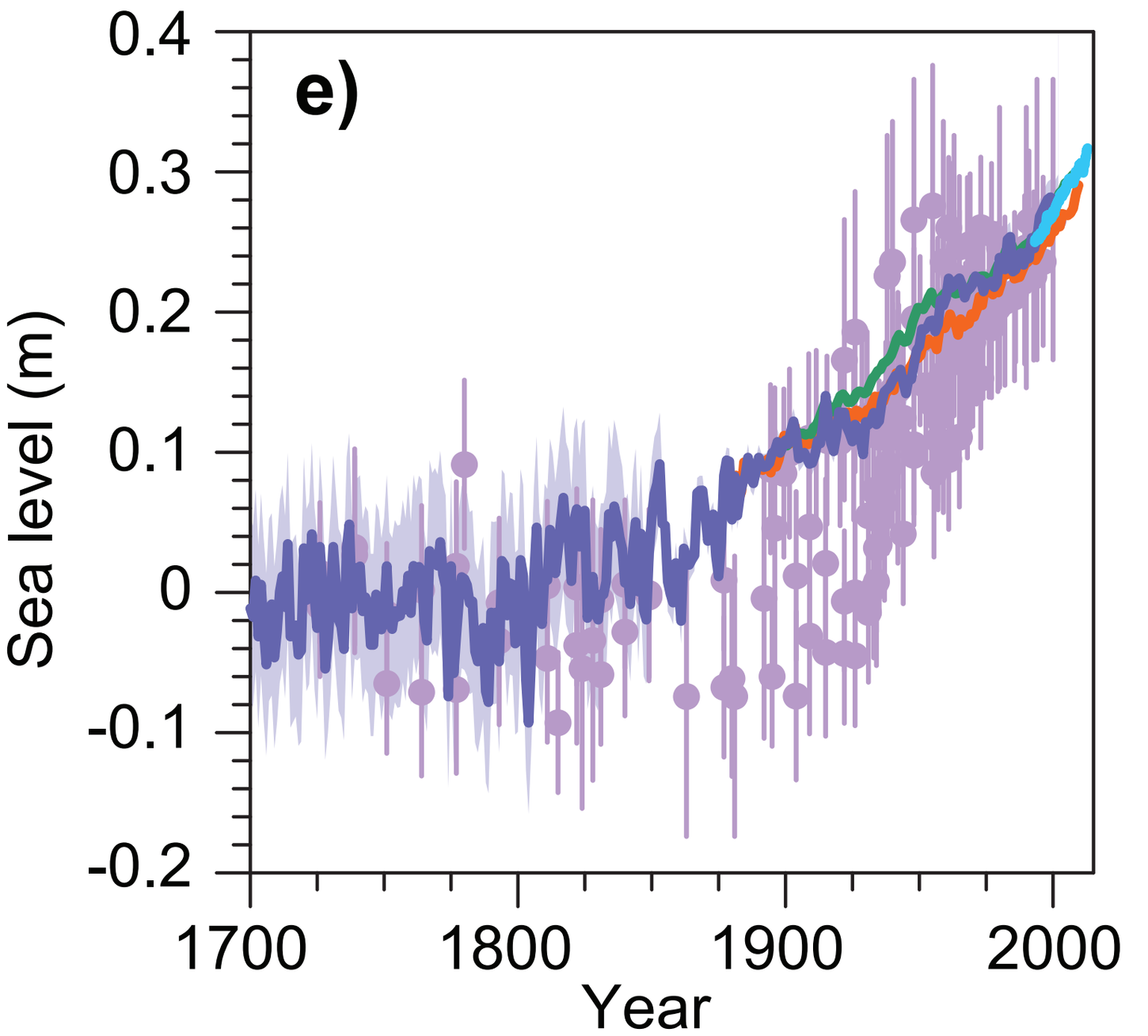
Activity!

- Breakout groups of two
- Go to PSMSL website
- Groups: pick a site with at least 50 years of mostly uninterrupted tide gauge data
- Have a quick look at data in the browser
- Then download monthly data and import to examine in MATLAB/Excel/Python
  - May require you to remove missing data
- 15 minutes!
- Answer these questions:
  - What is the trend?
  - Why do you think the trend has such a sign and magnitude?
  - What other variability seems important at your site?

Recent sea level change

Recent sea level change

IPCC 2013 Report



Averaged tide gauges (three different methods)
Altimetry

Since ~1900 global mean sea level has been increasing at a rate of 1.5-2 cm/ decade.

Recent sea level change

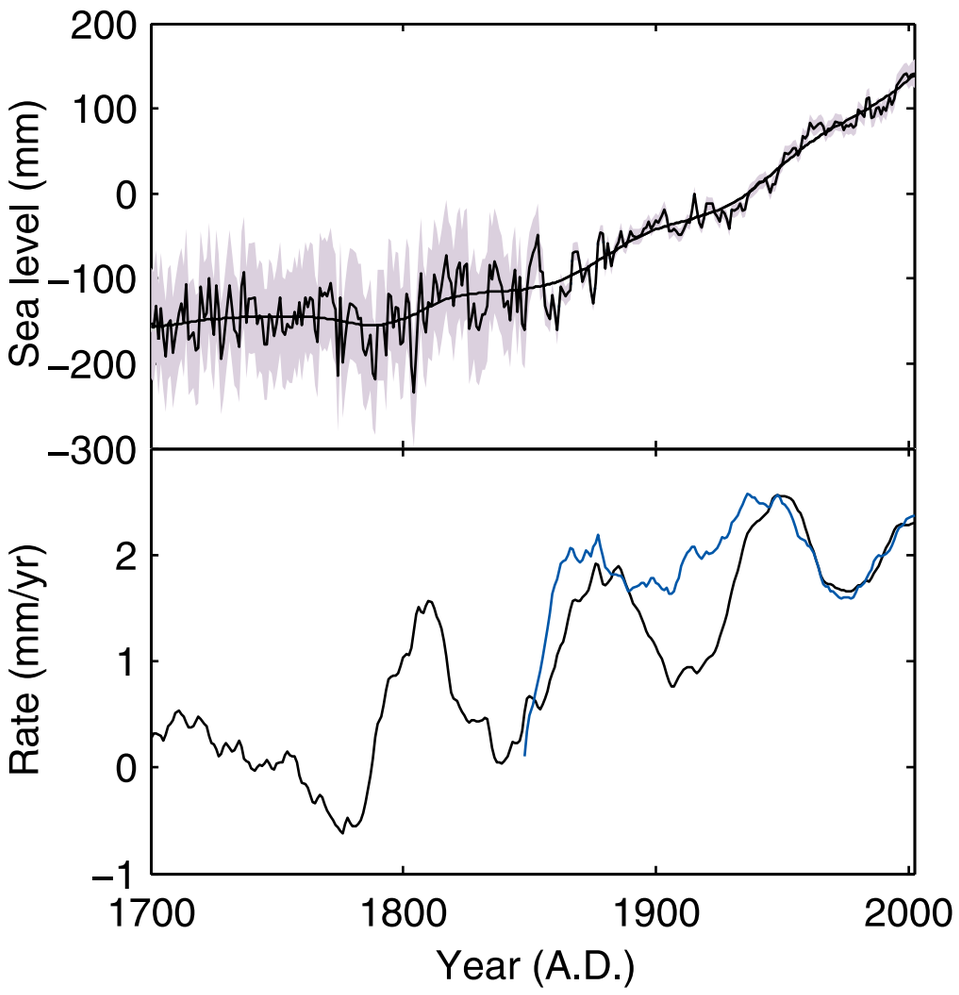
GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L08715, doi:10.1029/2008GL033611, 2008

Recent global sea level acceleration started over 200 years ago?

S. Jevrejeva,[1] J. C. Moore,[2,3] A. Grinsted,[2] and P. L. Woodworth[1]

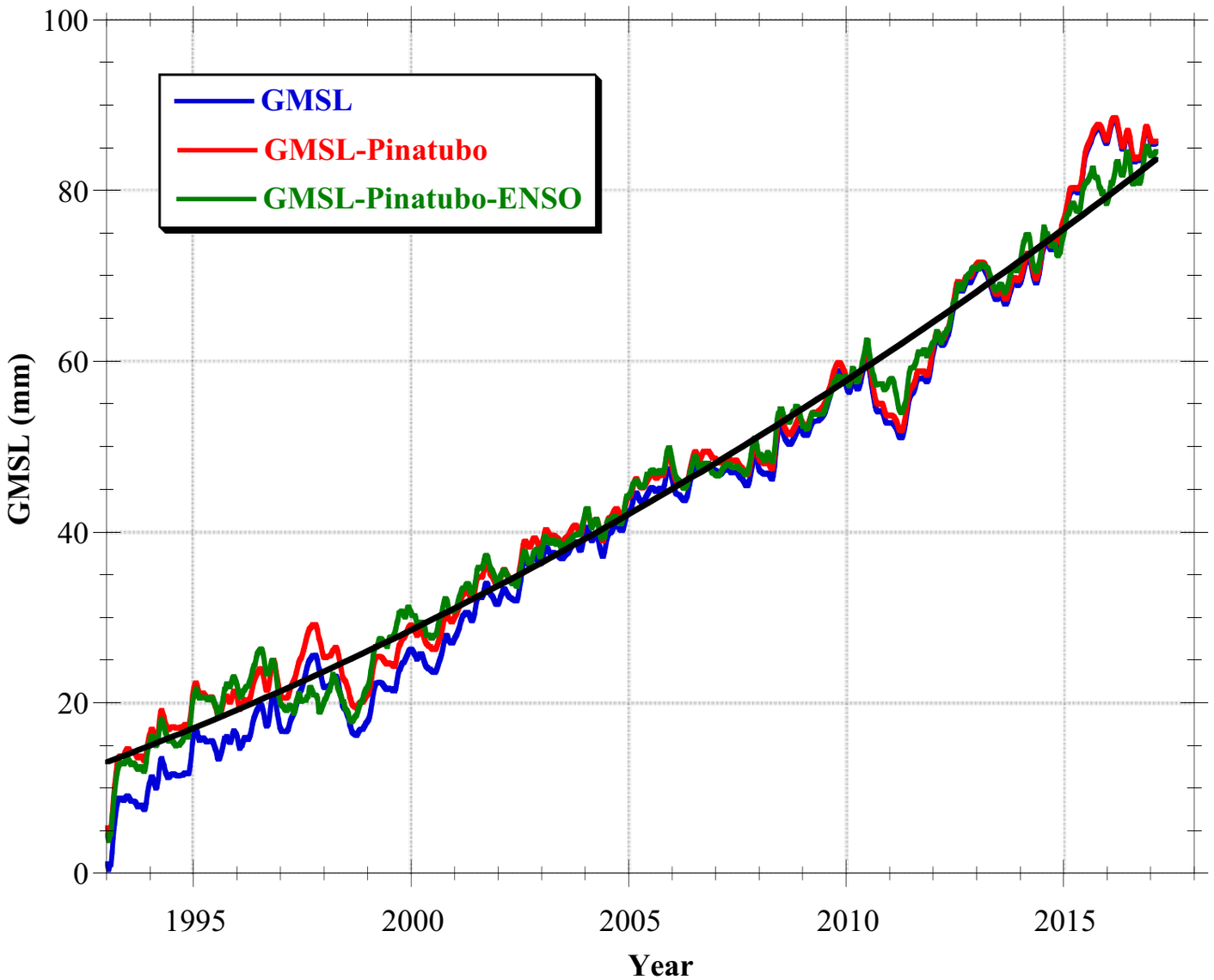
Received 12 February 2008; revised 19 March 2008; accepted 28 March 2008; published 30 April 2008.

(Dark blue line in previous slide)



Modern sea level rise probably started in the 1800s - as long as the climate has been changing, so has sea level.

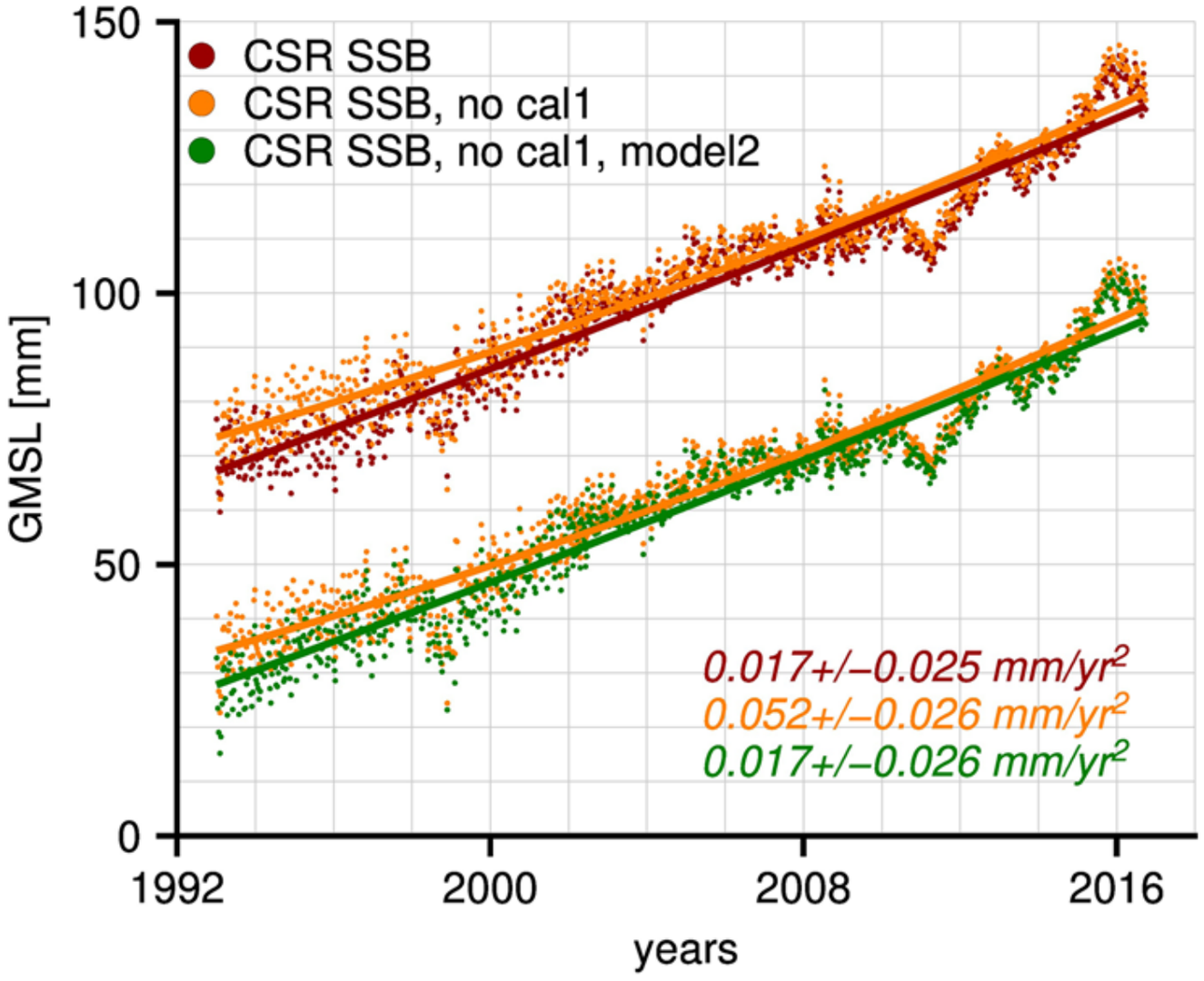
Recent sea level change



Nerem et al. 2018

Since ~1990 global mean sea level has been increasing at a rate of ~3 cm/ decade.

Recent sea level change

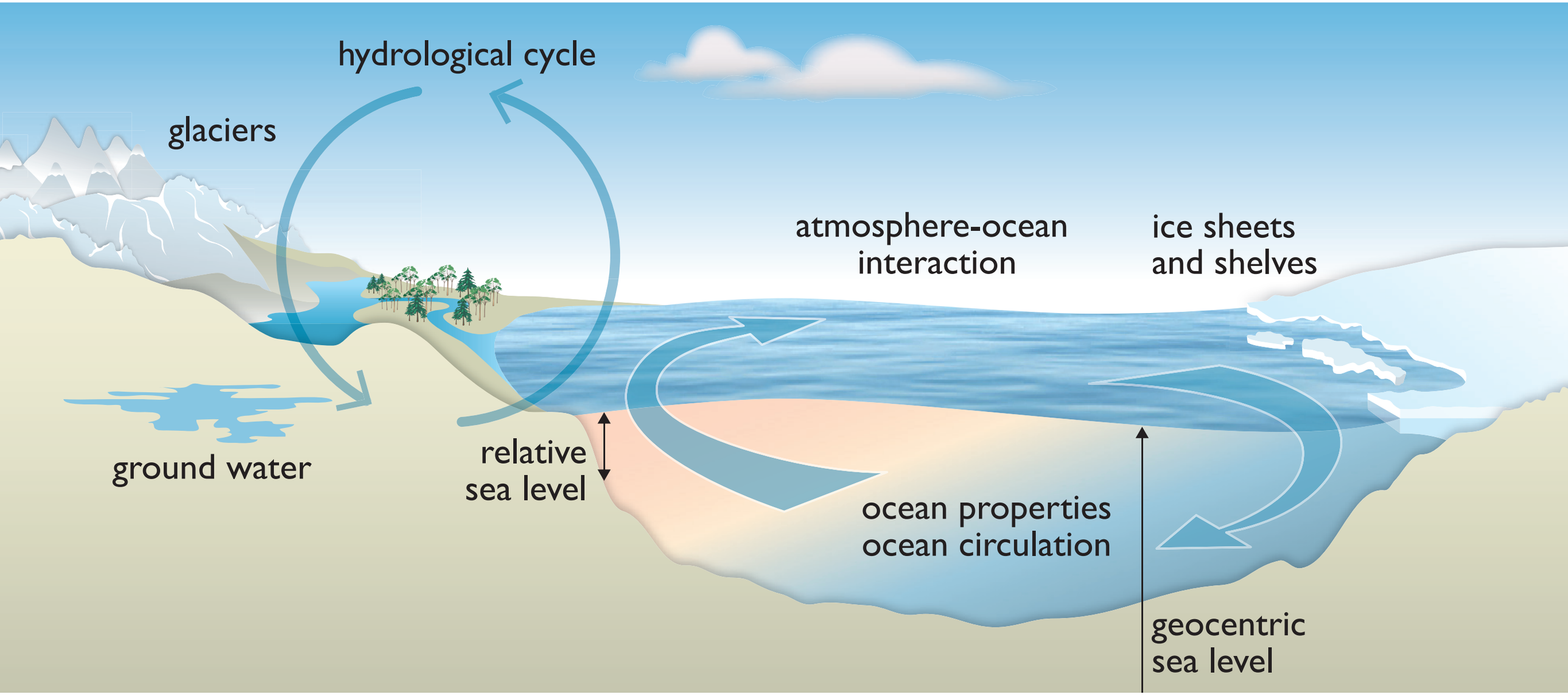


Kleinherenbrink et al. 2019

Or has it?

(wonky: when corrected for inter-mission altimeter bias)

What causes sea level change?



Recent sea level change

Table 2. Validation of acceleration estimate

Component	Time period	Rate, mm/y; Epoch 2005.0	Acceleration, mm/y^2
Greenland	2002.3–2017.0	0.66	0.0236
Antarctica	200.32–2017.0	0.19	0.0332
Mountain glaciers and small ice caps	2002.3–2017.0	0.51	0.0094
Thermosteric*	1993.0–2016.0	1.65	0.0076
Components total		3.01	0.074
Altimeter observed	1993.0–2017.0	3.1	0.097
Altimeter observed*	1993.0–2017.0	2.9	0.117
Altimeter observed†	1993.0–2017.0	2.9	0.084

*Corrected for Pinatubo.
†Corrected for Pinatubo and ENSO effects (climate-change–driven acceleration).

Nerem et al. 2018

Recent SLR is:

- **1/3 thermal expansion**
- **1/4 mountain glaciers (not in Greenland or Antarctica)**
- **1/4 Greenland + Antarctica**
- **+water discharge from land and other small sources**

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

Terrestrial Water Storage/ Discharge

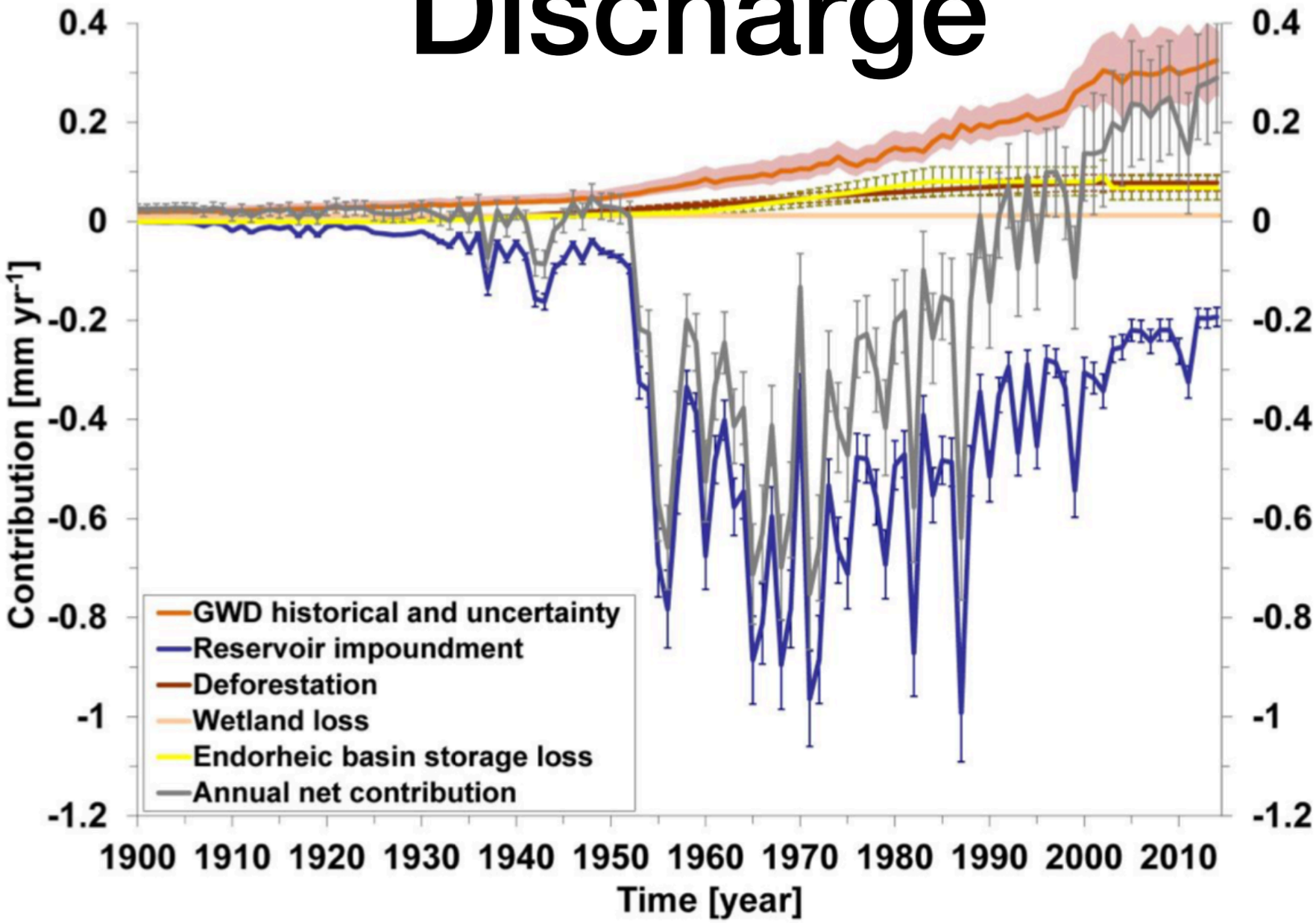
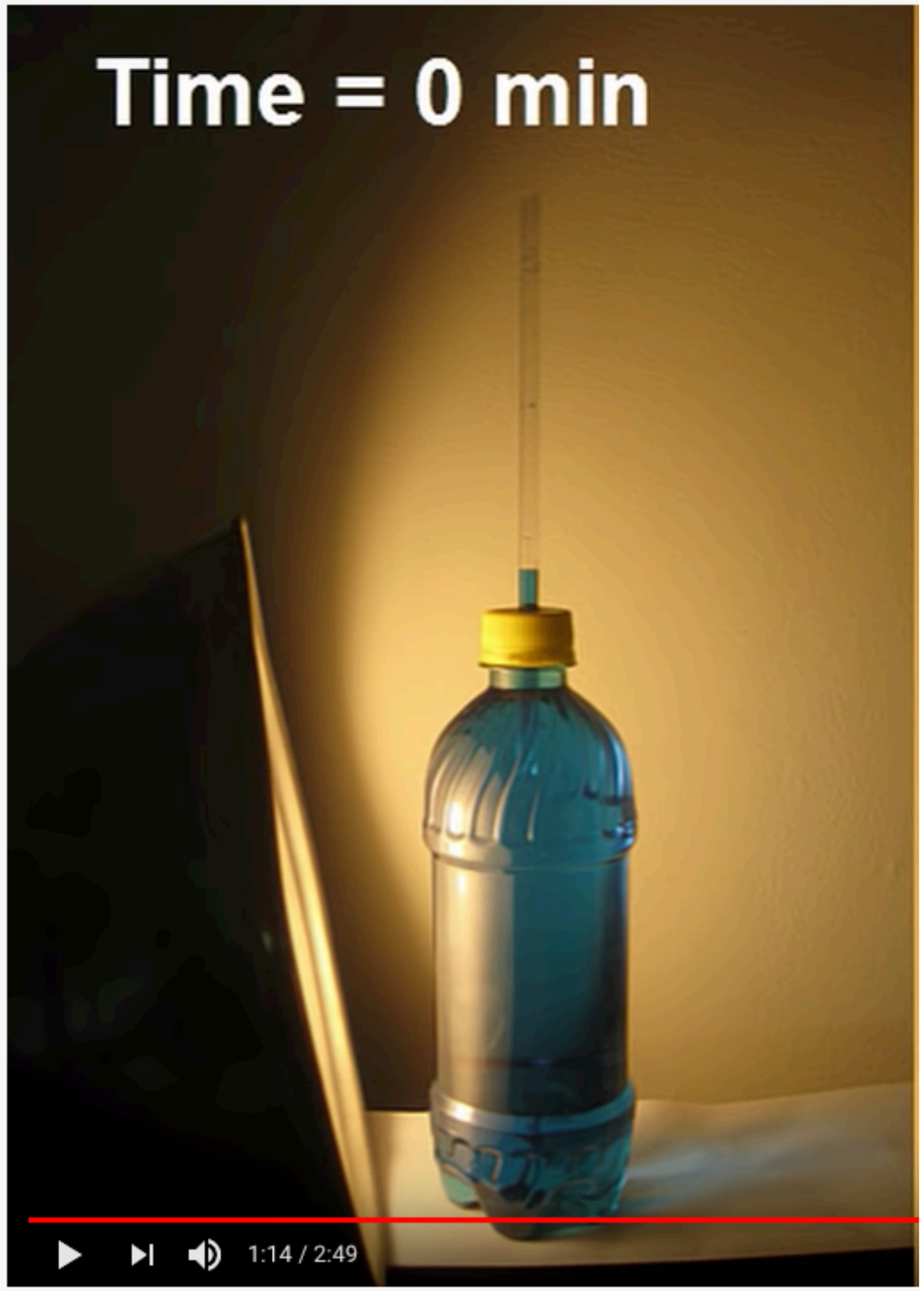
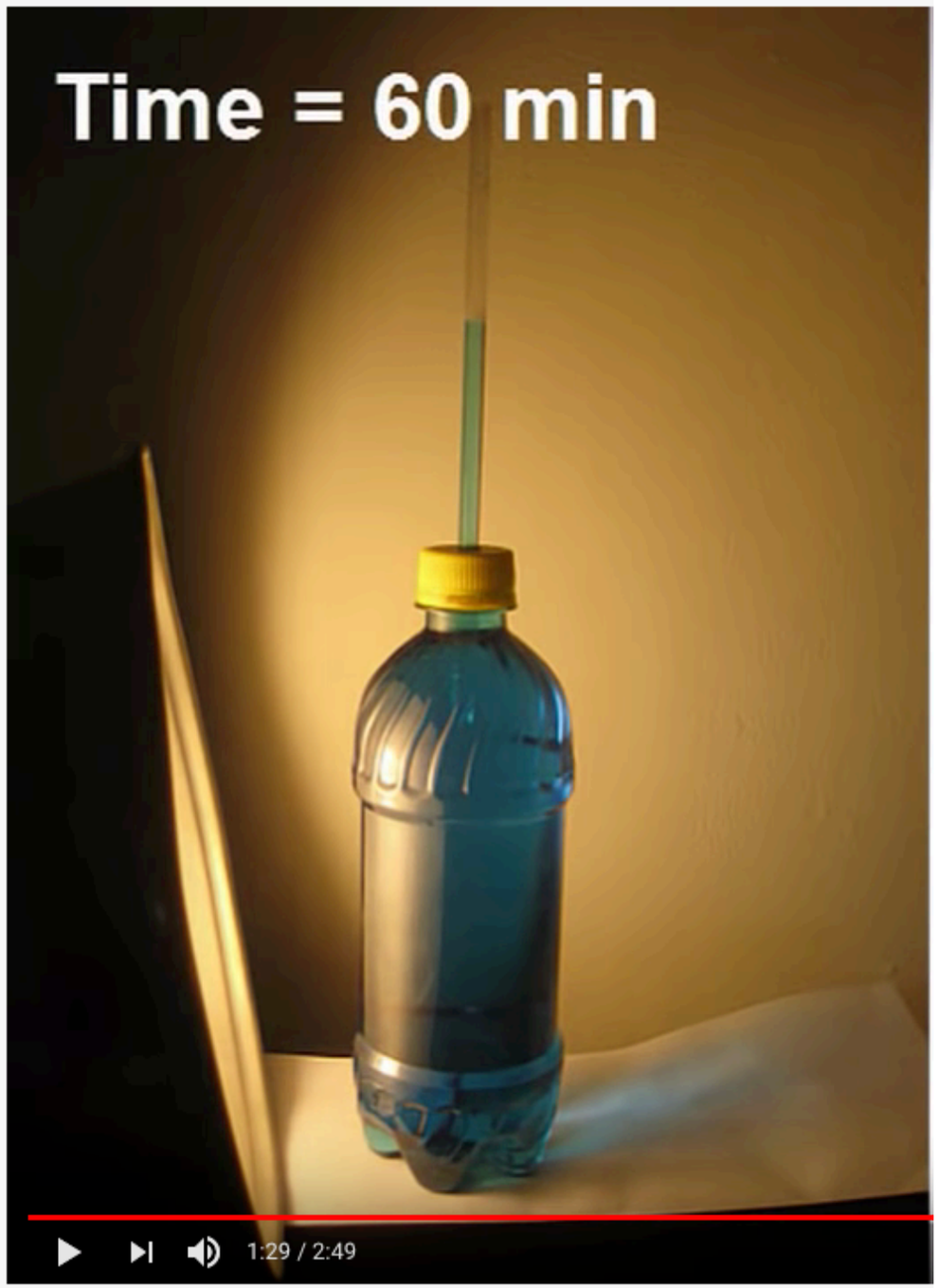


Figure 11: Time series of the estimated annual contribution of terrestrial water storage change to global sea-level over the period 1900-2014 (rates in mm yr^{-1} SLE) (modified from Wada et al., 2016).

Thermal expansion: a simple science experiment



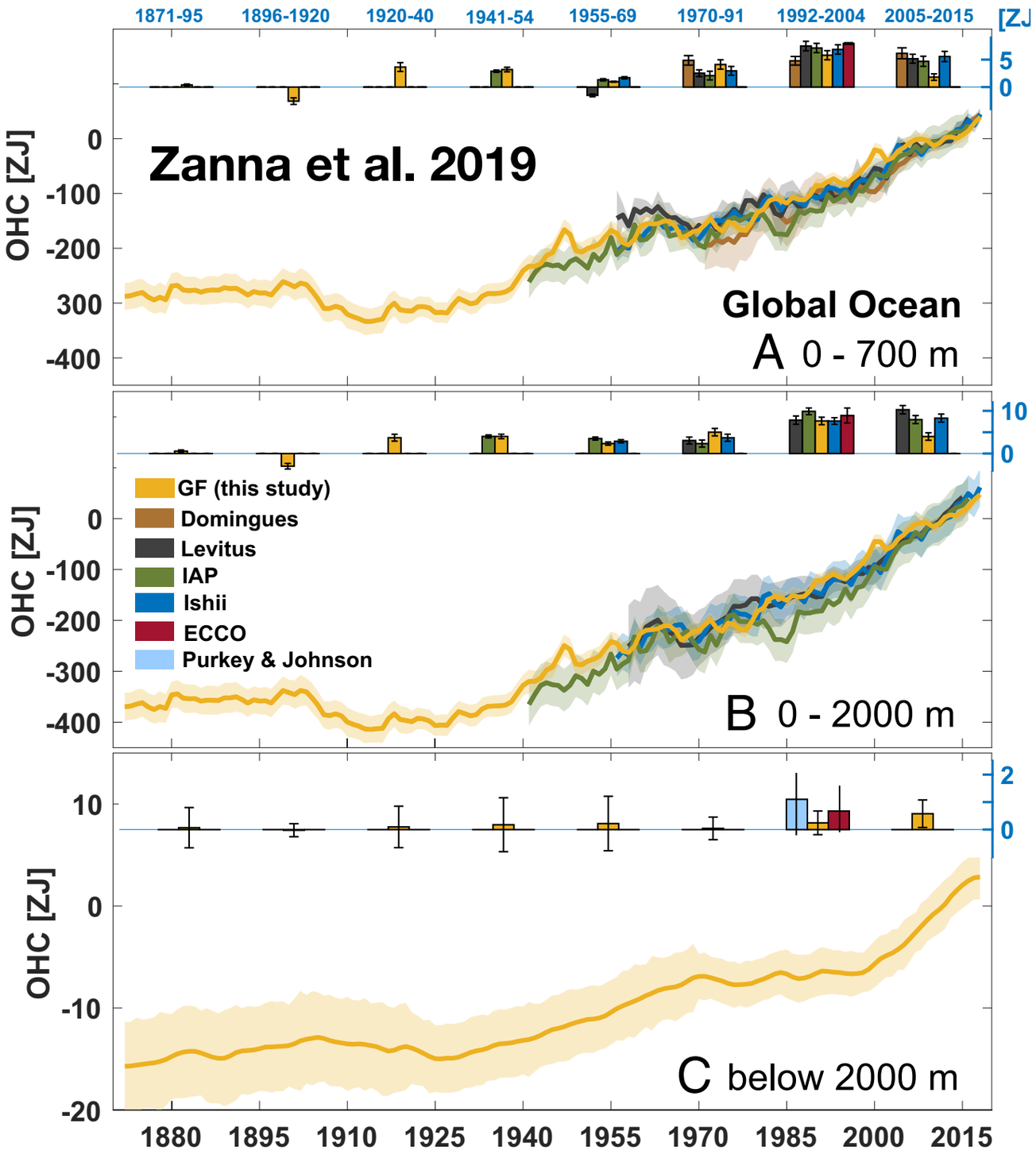
Thermal Expansion of Water: Demonstration and Explanation



Thermal Expansion of Water: Demonstration and Explanation

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

Ocean heat uptake

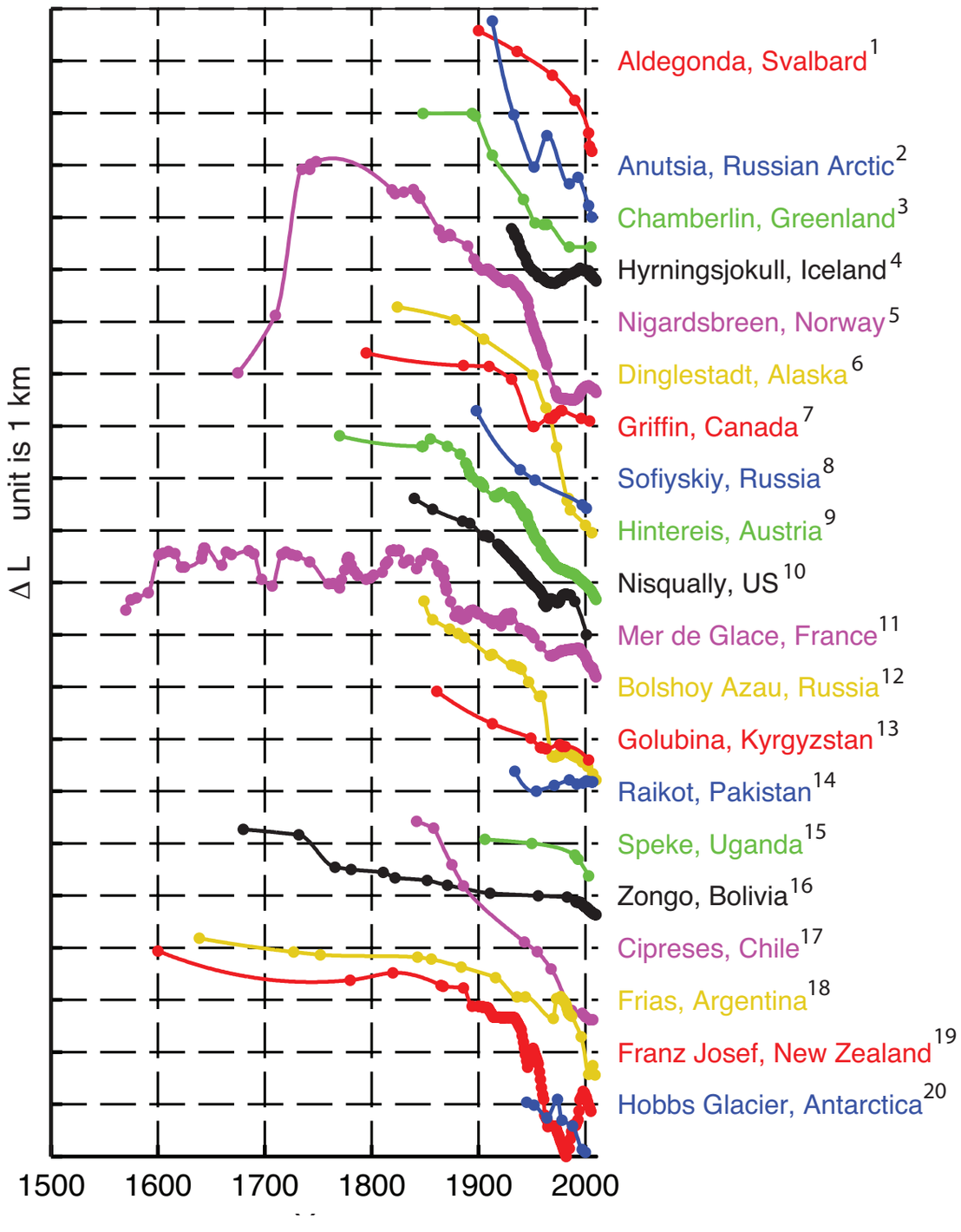


~90% of all extra heat retained in the atmosphere by increased greenhouse gas emissions has been taken up by the ocean

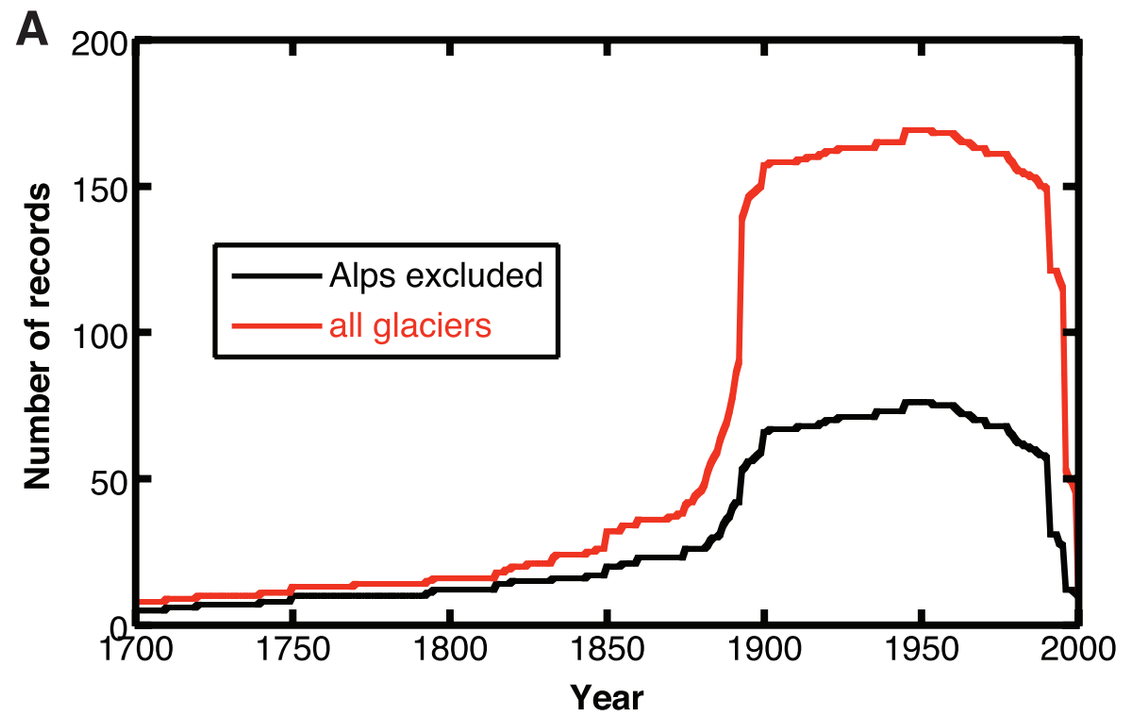
[ZJ = 10^{21} J]

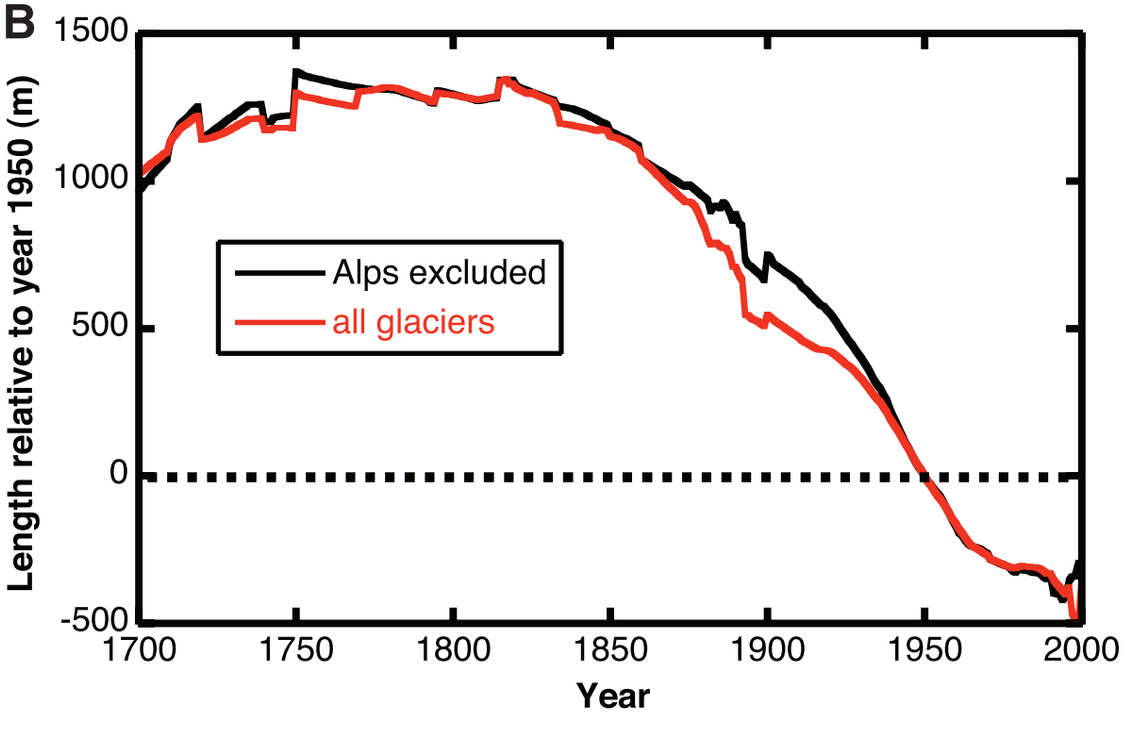
(0.5 ZJ = global annual energy use)

Mountain glaciers

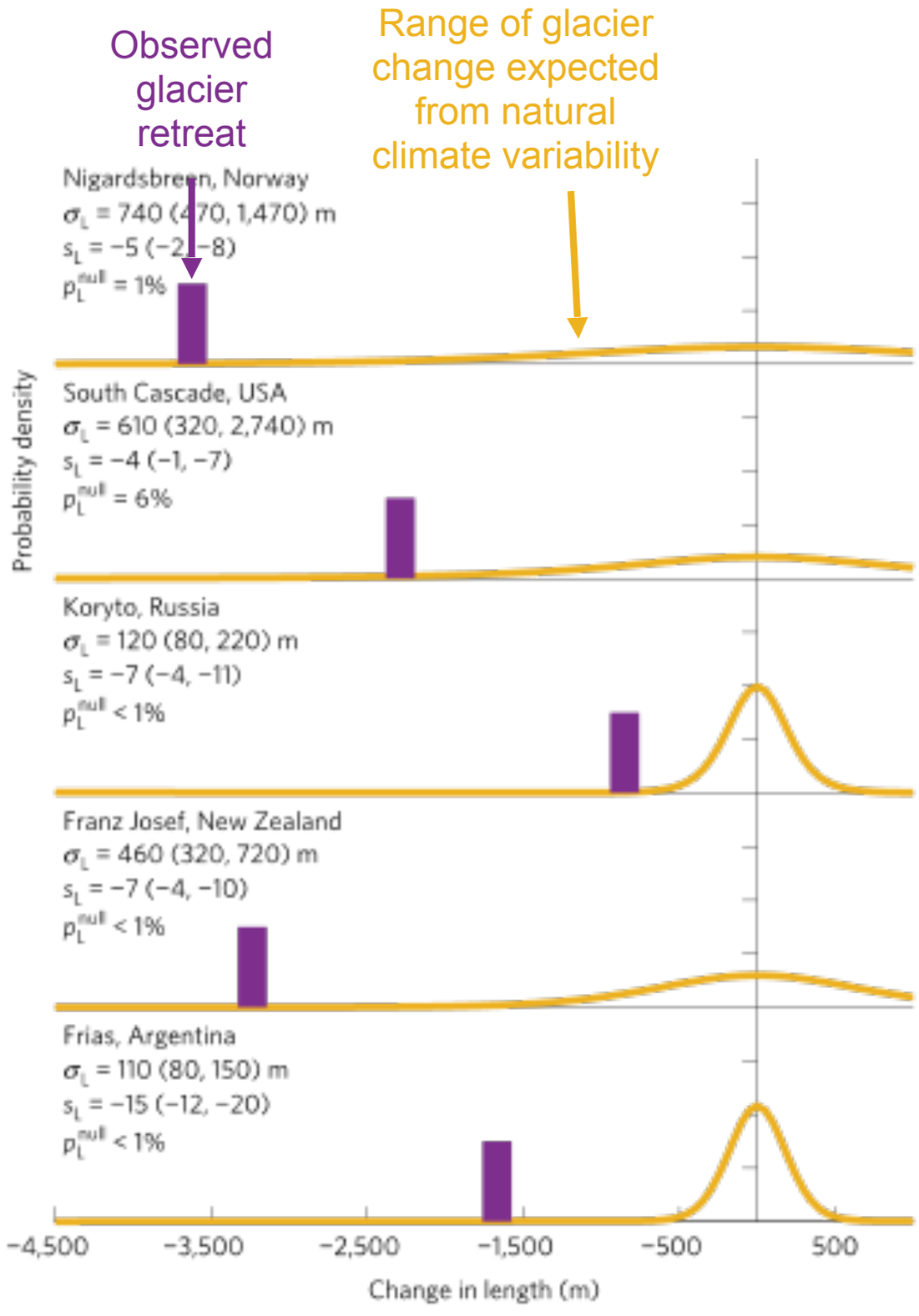


Leclercq et al. 2014





Mountain glaciers



nature geoscience

ARTICLES

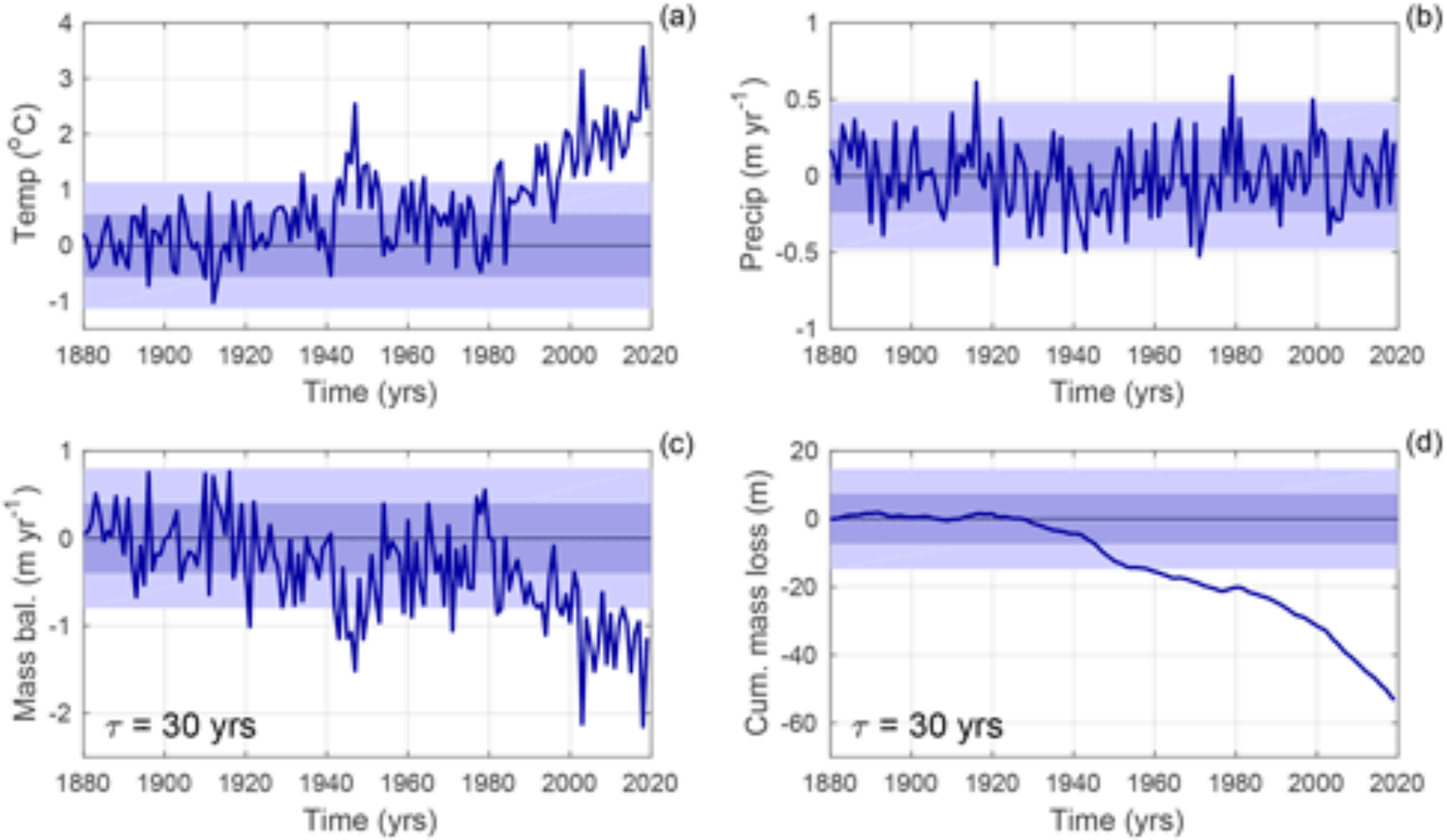
PUBLISHED ONLINE: 12 DECEMBER 2016 | DOI: 10.1038/NGEO2863

Centennial glacier retreat as categorical evidence of regional climate change

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

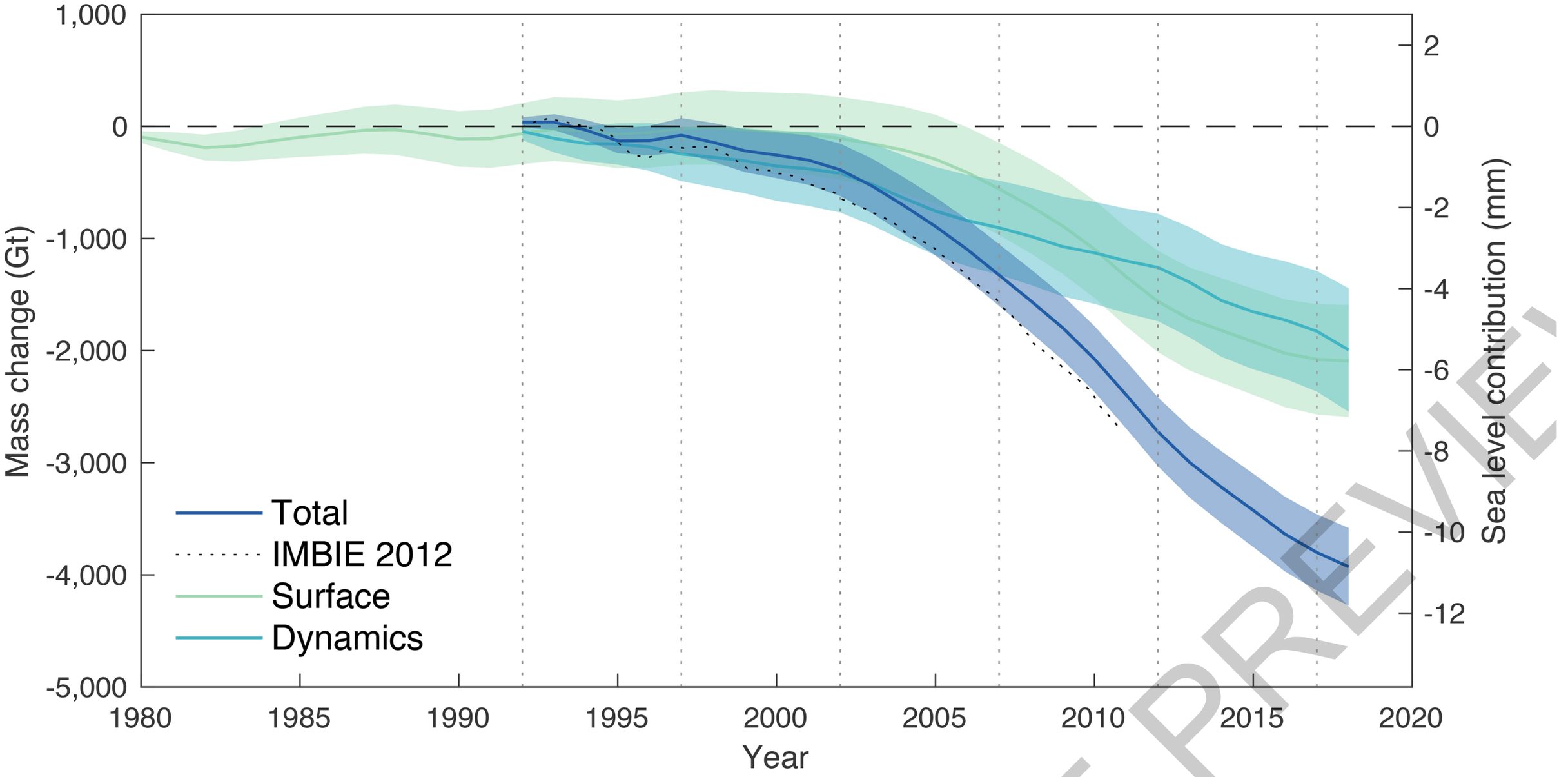
"…observed retreats of individual glaciers represent some of the highest signal-to-noise ratios of climate change yet documented."

Mountain glaciers



"…our calculations suggest that the central estimate of the anthropogenic mass loss of glaciers and small ice caps is essentially 100% of the observed mass loss. " (Roe et al. 2021)

Greenland Ice Sheet



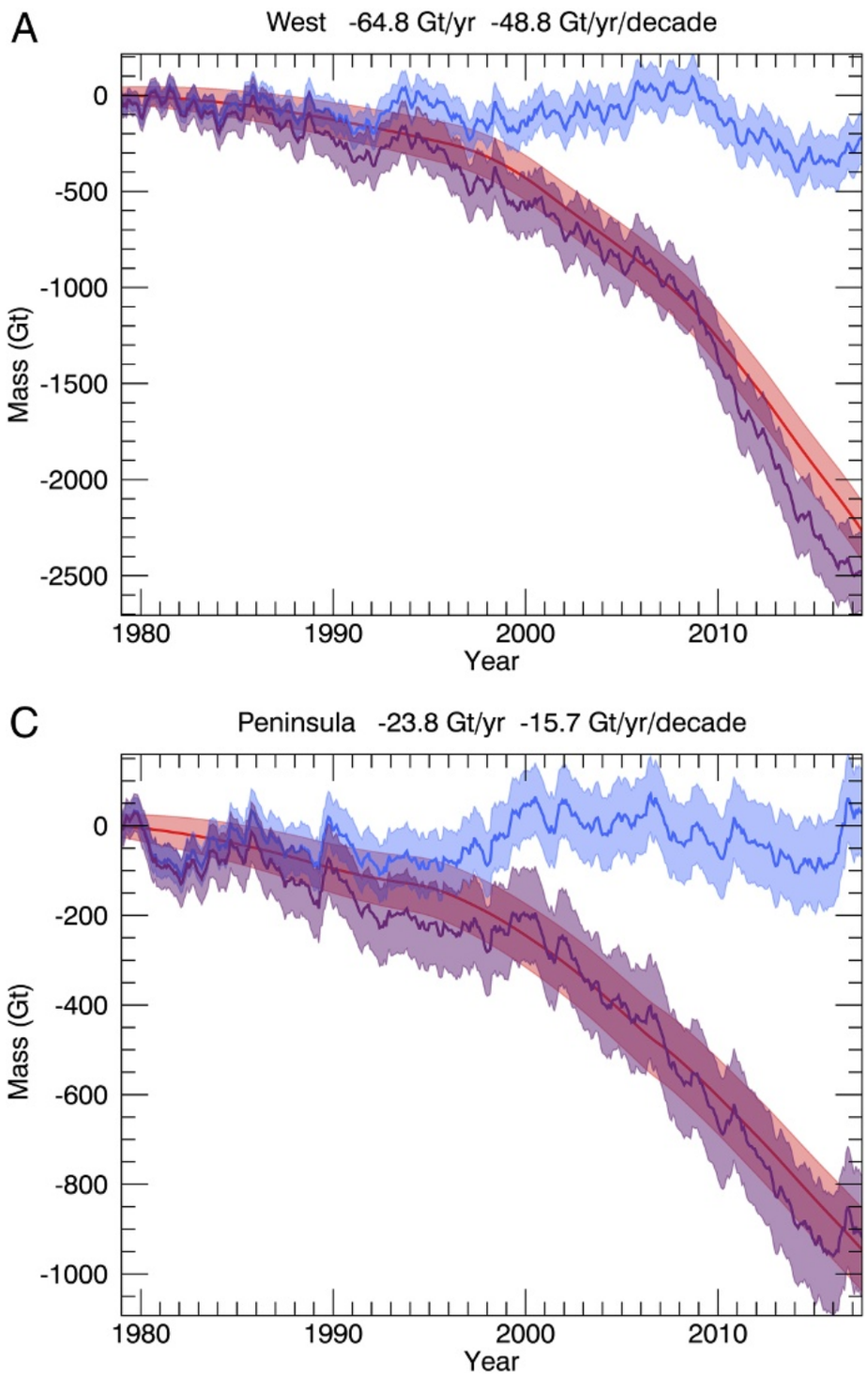
Satellite-based measurements of ice mass loss from the Greenland Ice Sheet

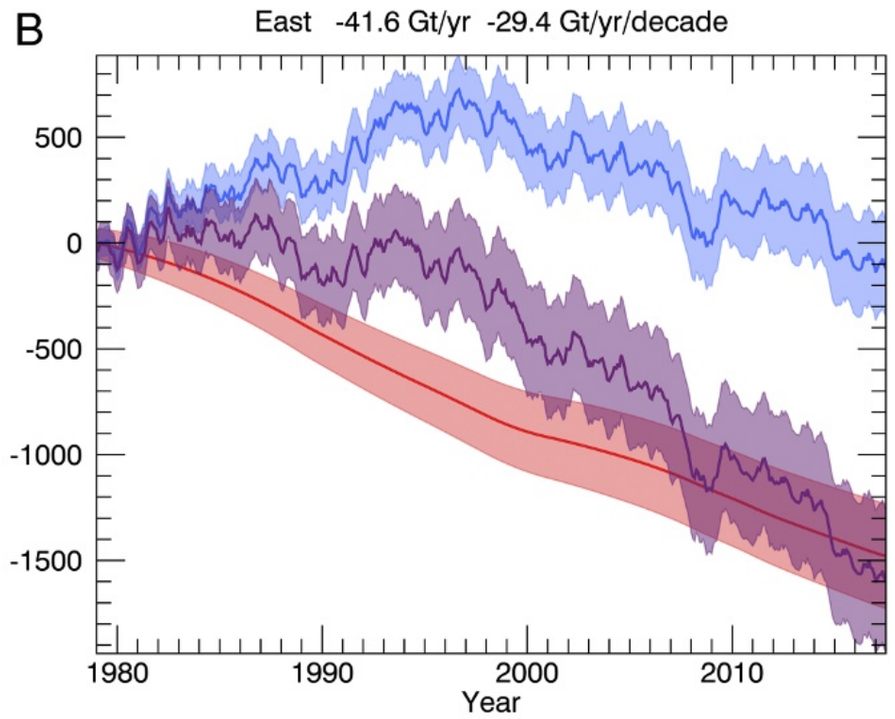
- Ice in/out from snowfall/melt on ice sheet
- Ice out from melt and iceberg calving
- Total "mass balance"

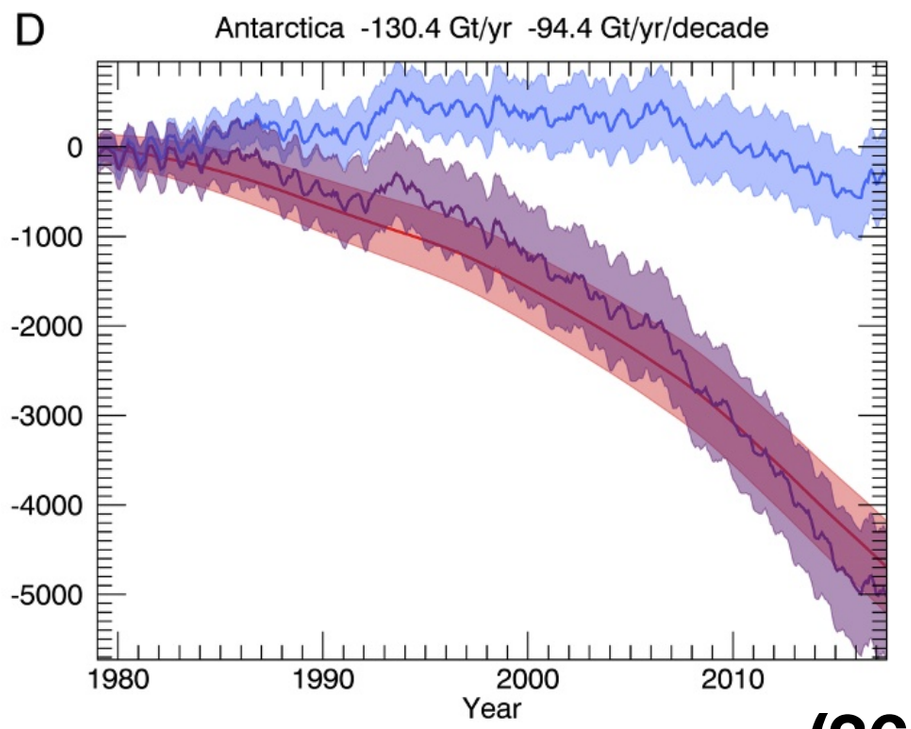
(IMBIE Team 2019)

(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"**

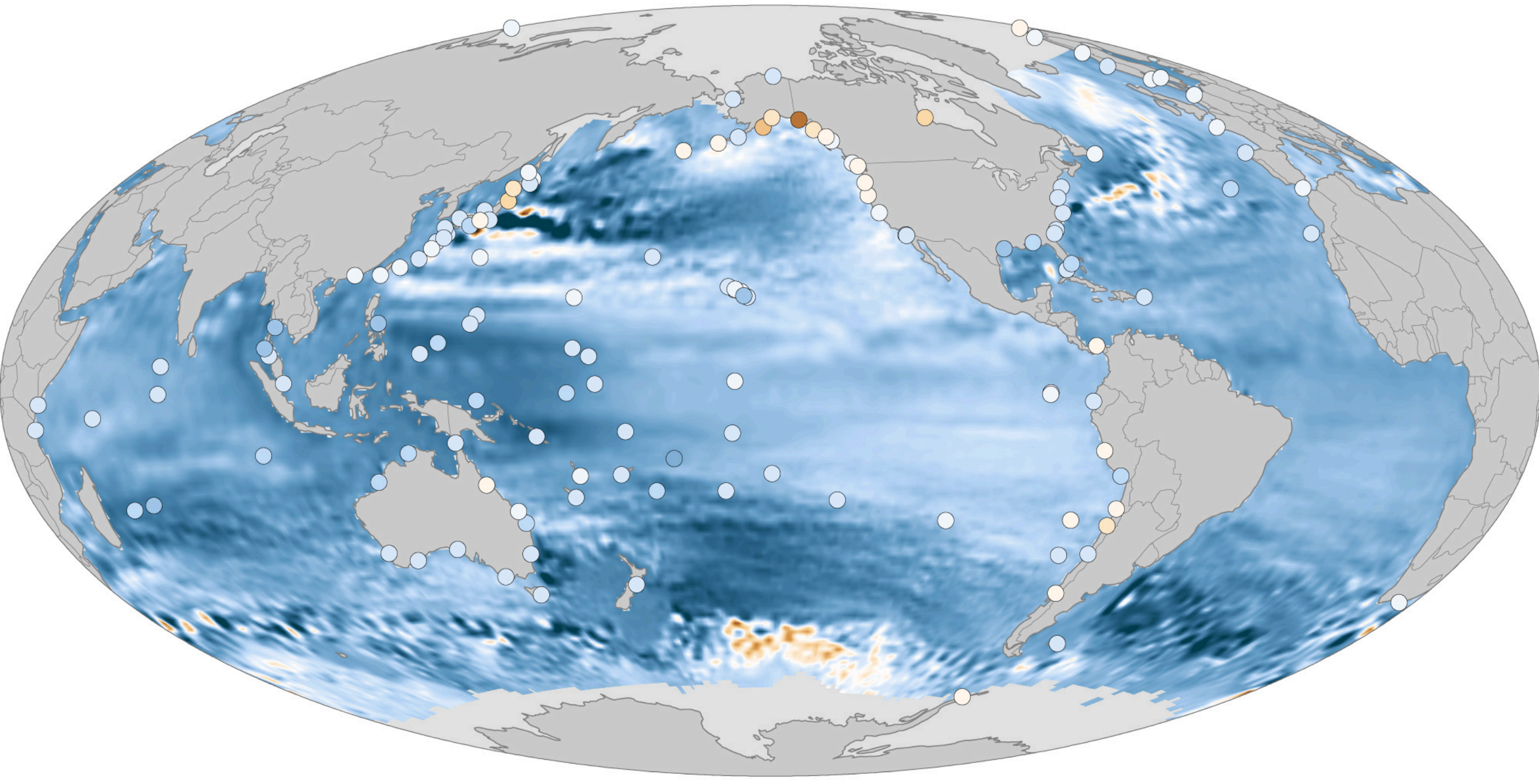
(Rignot et al. 2019)

(365 Gt = 1 mm SLR)

Local Sea Level

The Ocean is Not a Bathtub

Sea level change (1993-2018)



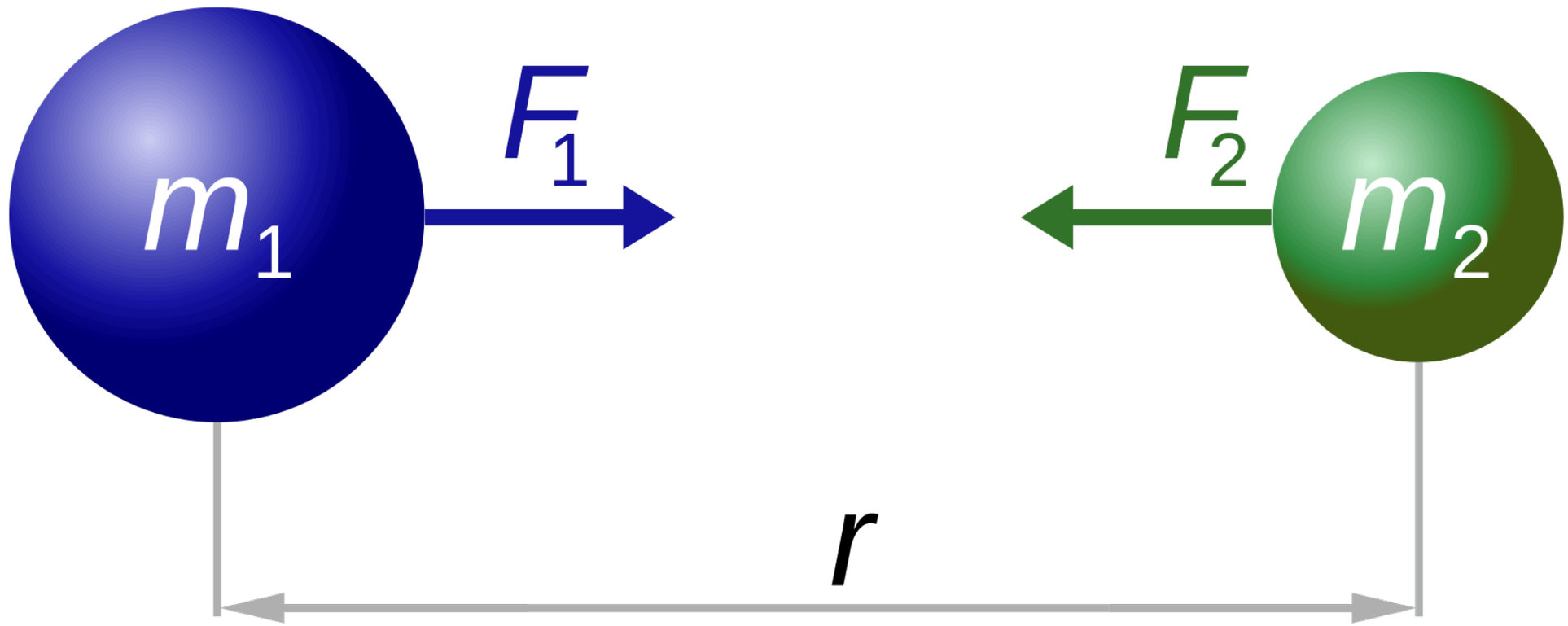
1993–2018

Change in sea level (cm)

-20 0 20

NOAA Climate.gov
Data: UHSLC

A reminder: how gravity works

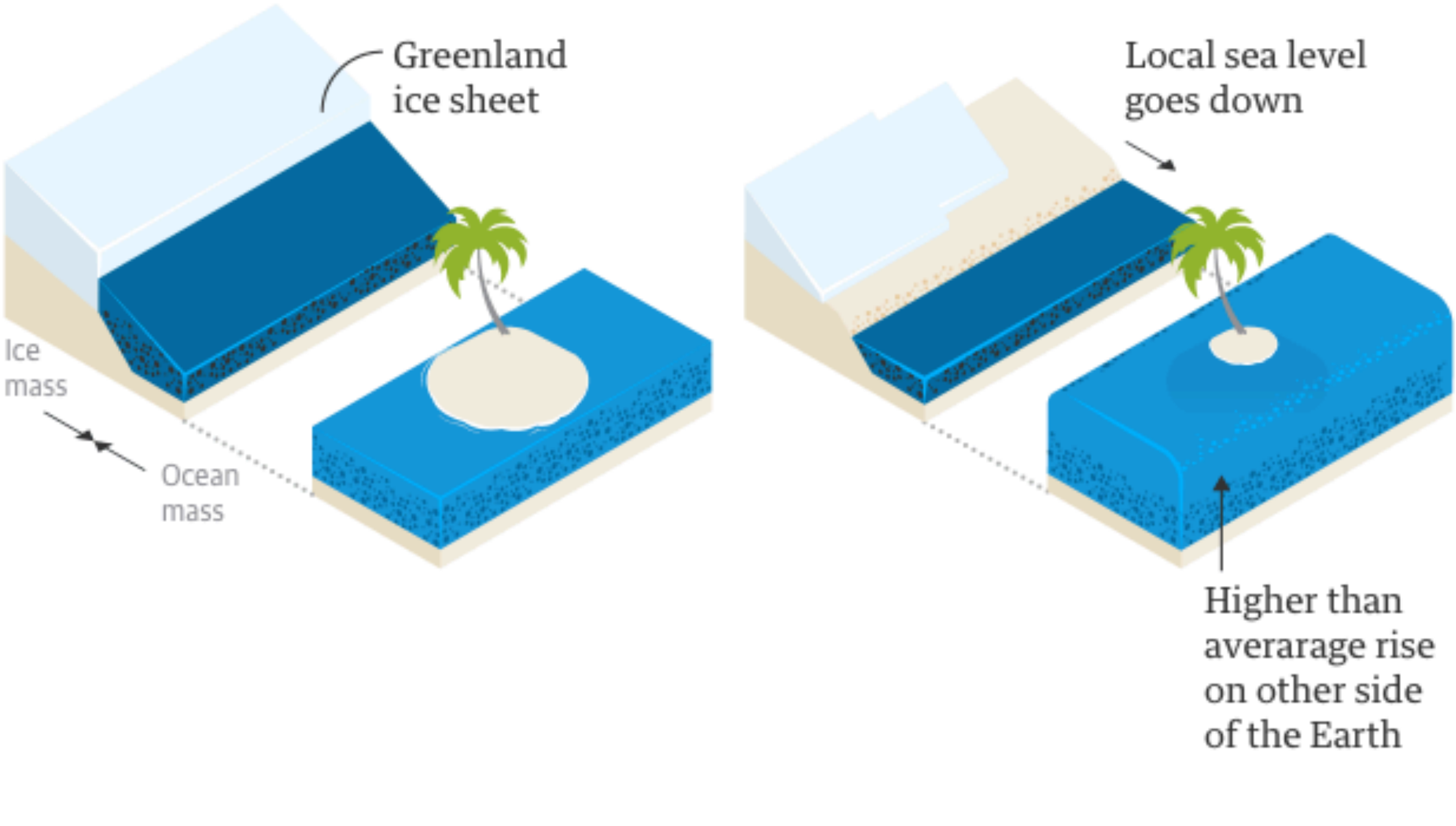


$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

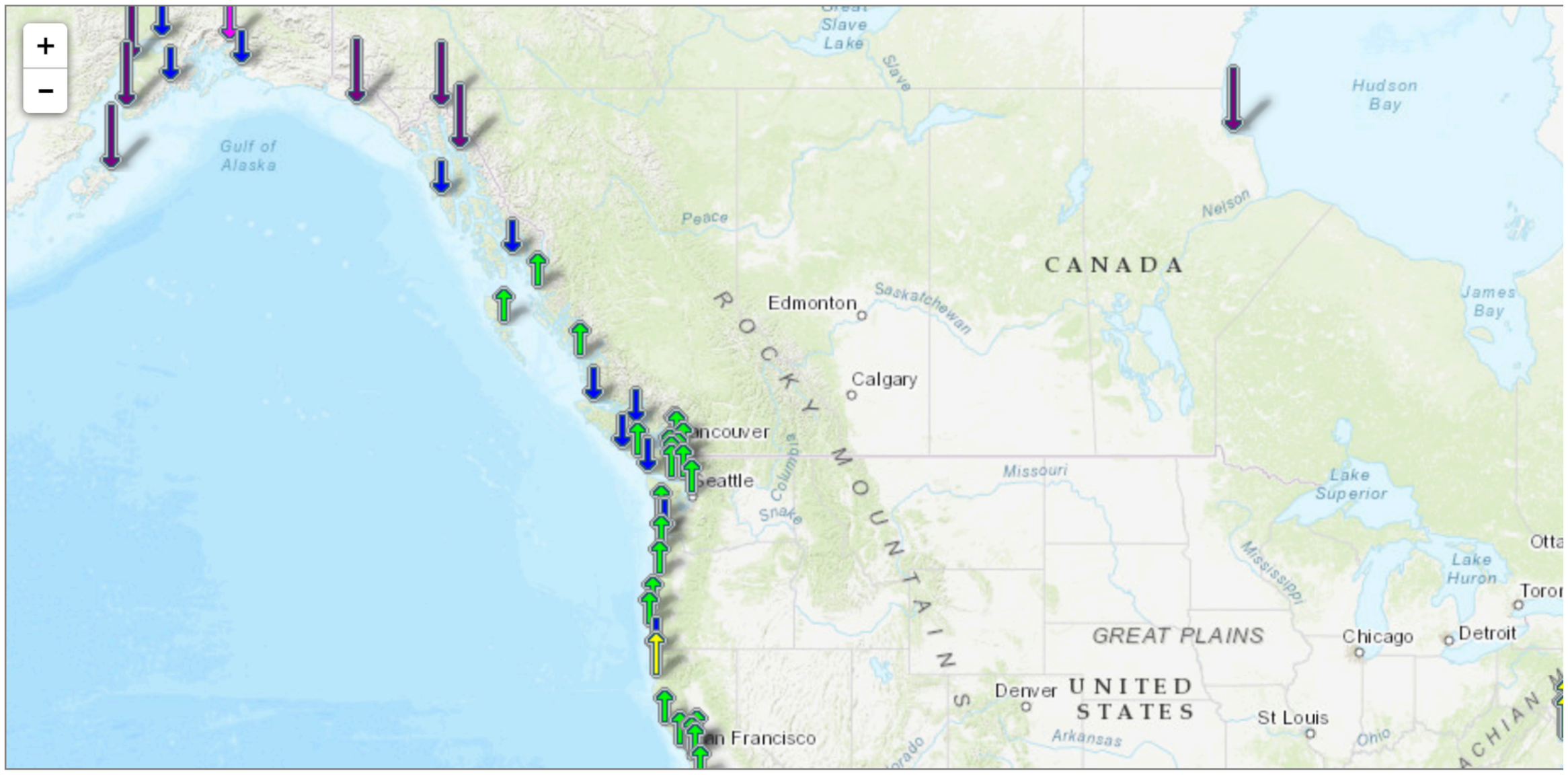
Gravity

Ice sheets attract water because of gravity

As their mass decreases, they have less gravitational pull. This makes water flow away



The gravitational effect of melting Alaska glaciers is visible in the time series of sea level change along the N. American West Coast



The map above illustrates relative sea level trends , with arrows representing the direction and magnitude of change. Click on an arrow to access addit

NOAA SL trends map:

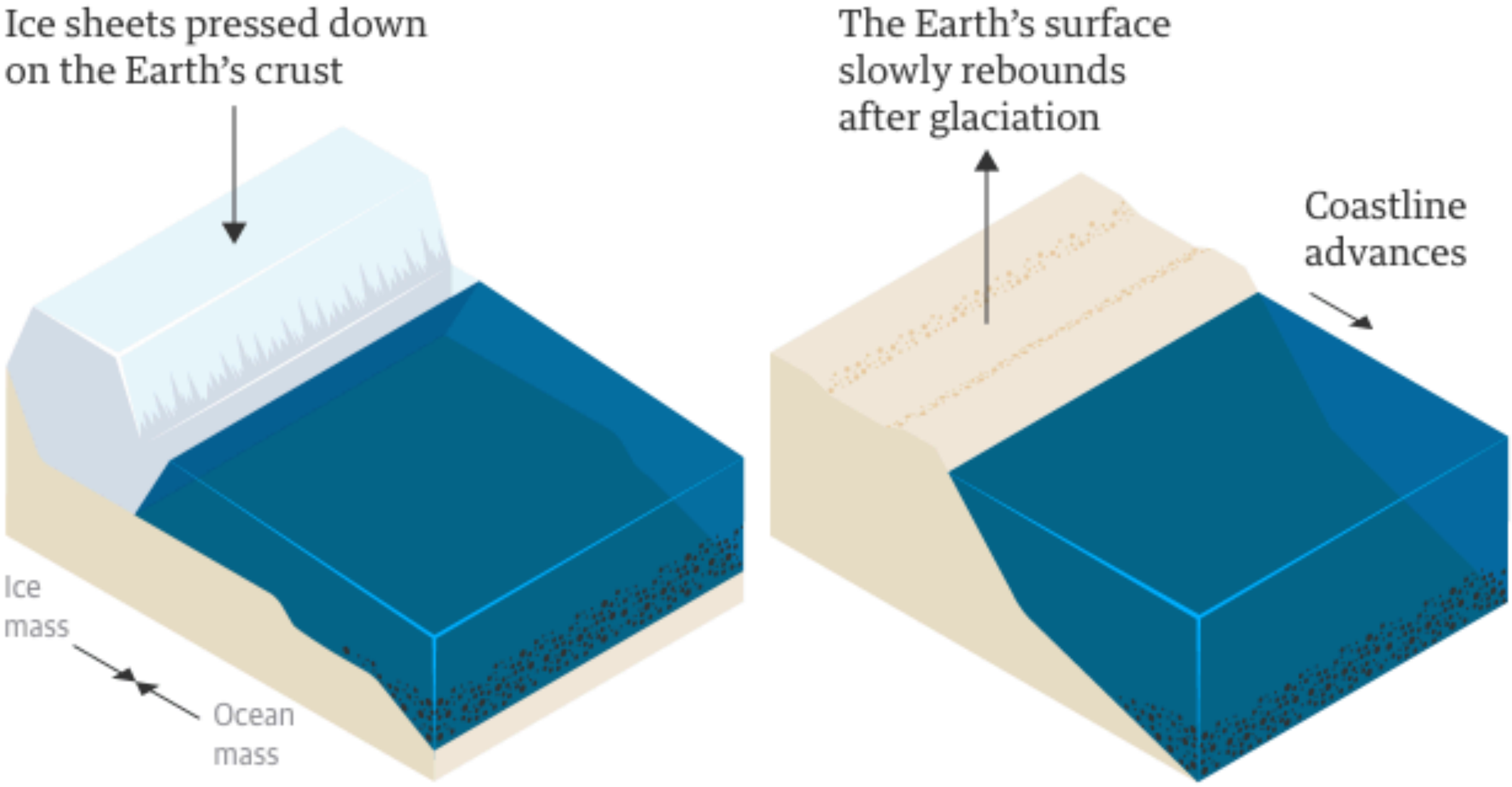
https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

Relative Sea Level Trends

mm/yr (feet/century)

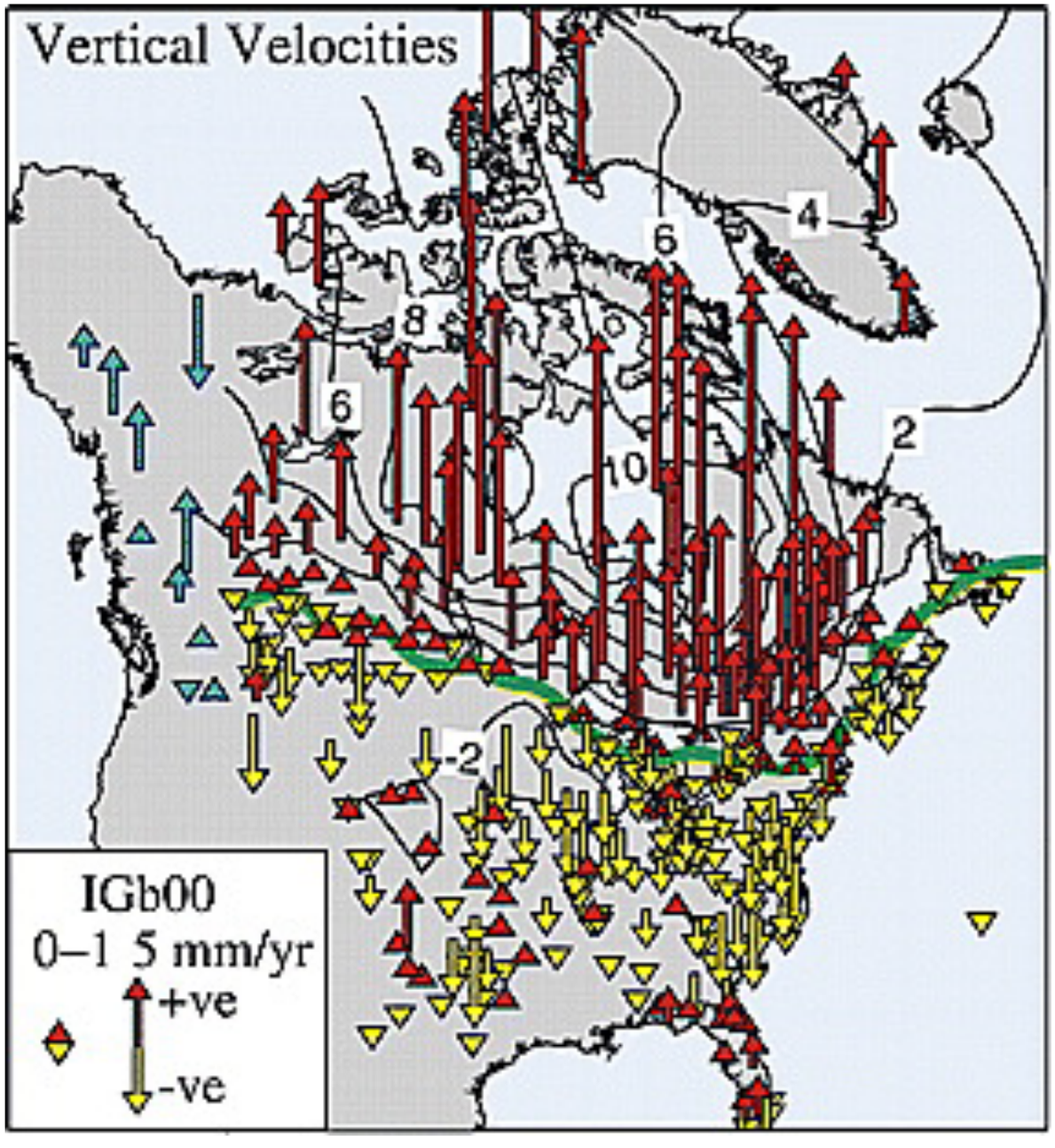
Above 9 (Above 3)	6 to 9 (2 to 3)	3 to 6 (1 to 2)	>0 to 3 (0 to 1)	-3 to 0 (-1 to 0)	-6 to -3 (-2 to -1)	-9 to -6 (-3 to -2)	Below -9 (Below -3)

Glacial rebound



Guardian graphic. Source: Dr Pippa L. Whitehouse

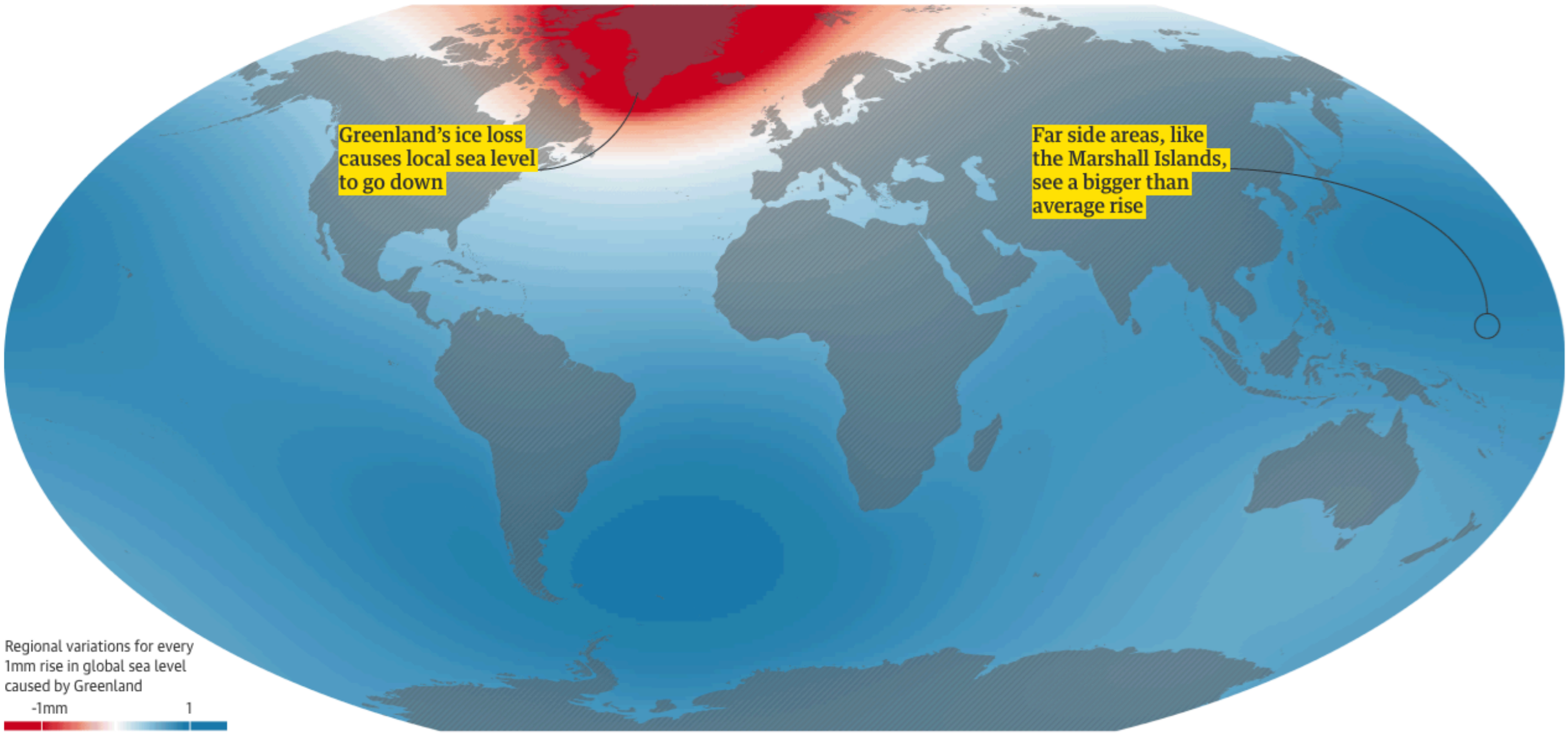
Glacial Isostatic Adjustment (GIA)



Sella et al. 2007

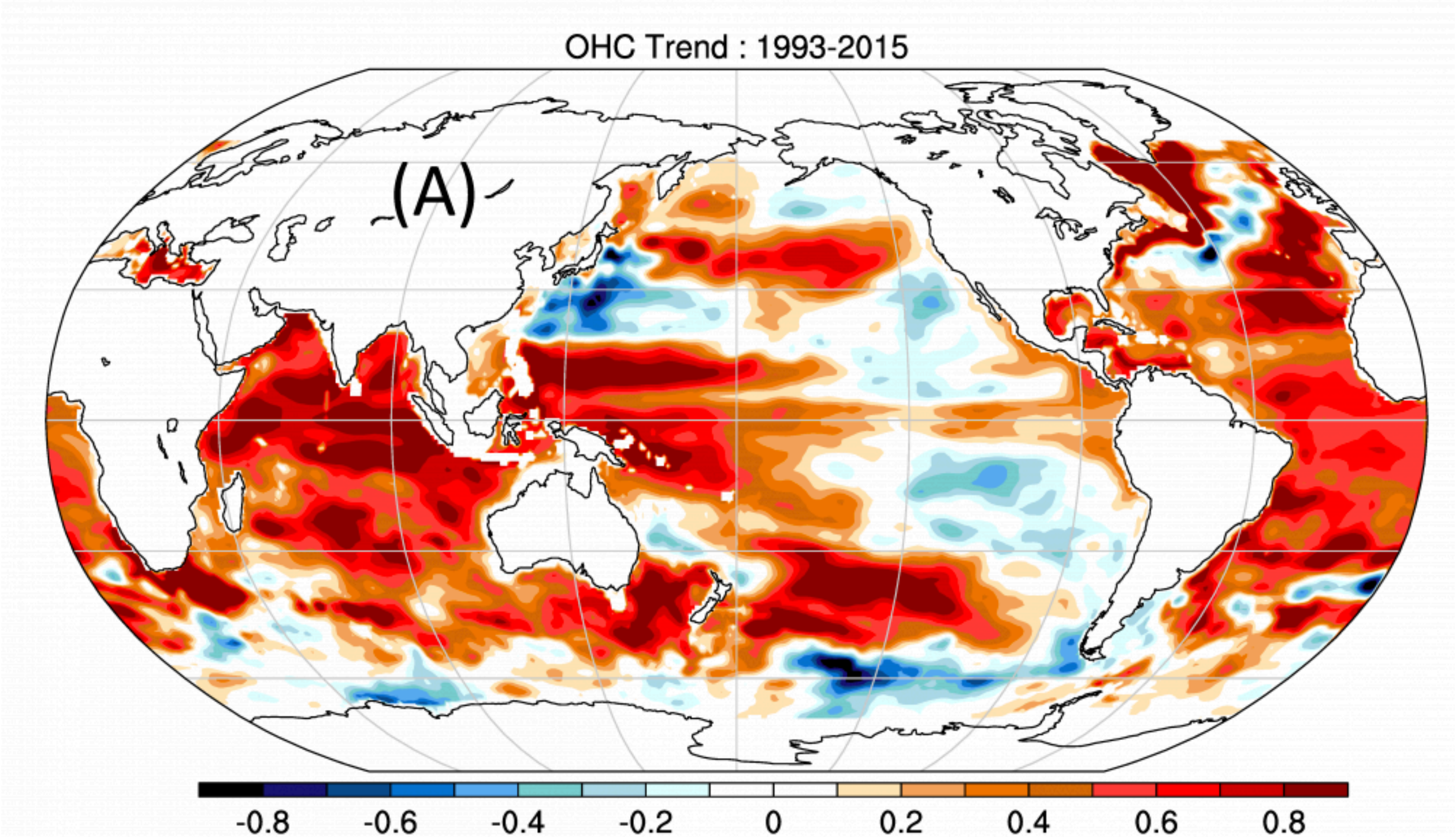
The result: Canada is moving up, the US is moving down (or not at all)

Accounting for gravity and glacial rebound, how much sea level would change if a layer of ice were melted from Greenland (1 mm of global mean SLR)



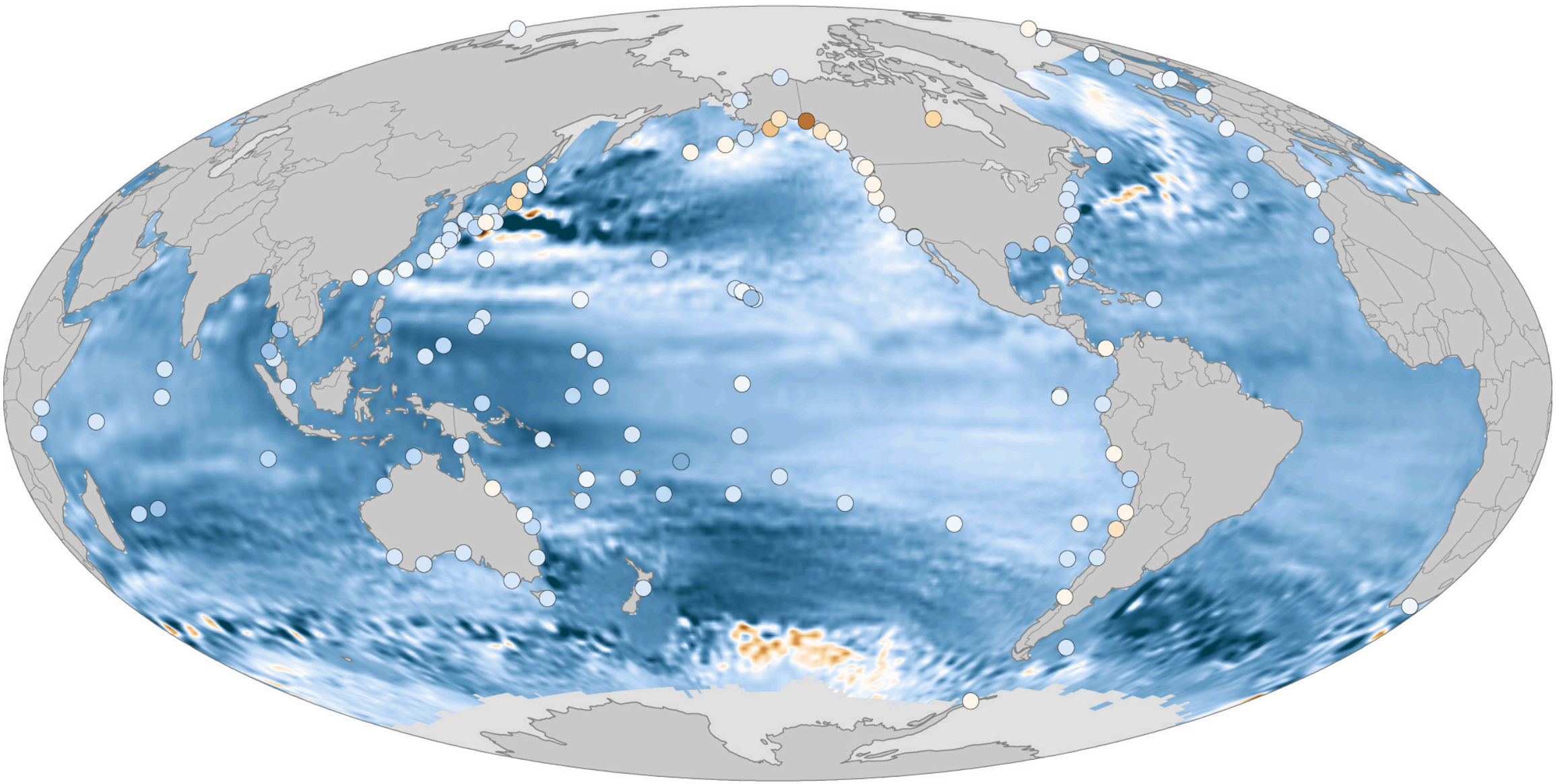
Gravitational fingerprint for Greenland's surface mass balance. Source: NIOZ Royal Netherlands Institute for Sea Research

Ocean heat uptake and therefore thermal expansion is not the same everywhere



Compare again to SLR map

Sea level change (1993-2018)



1993–2018

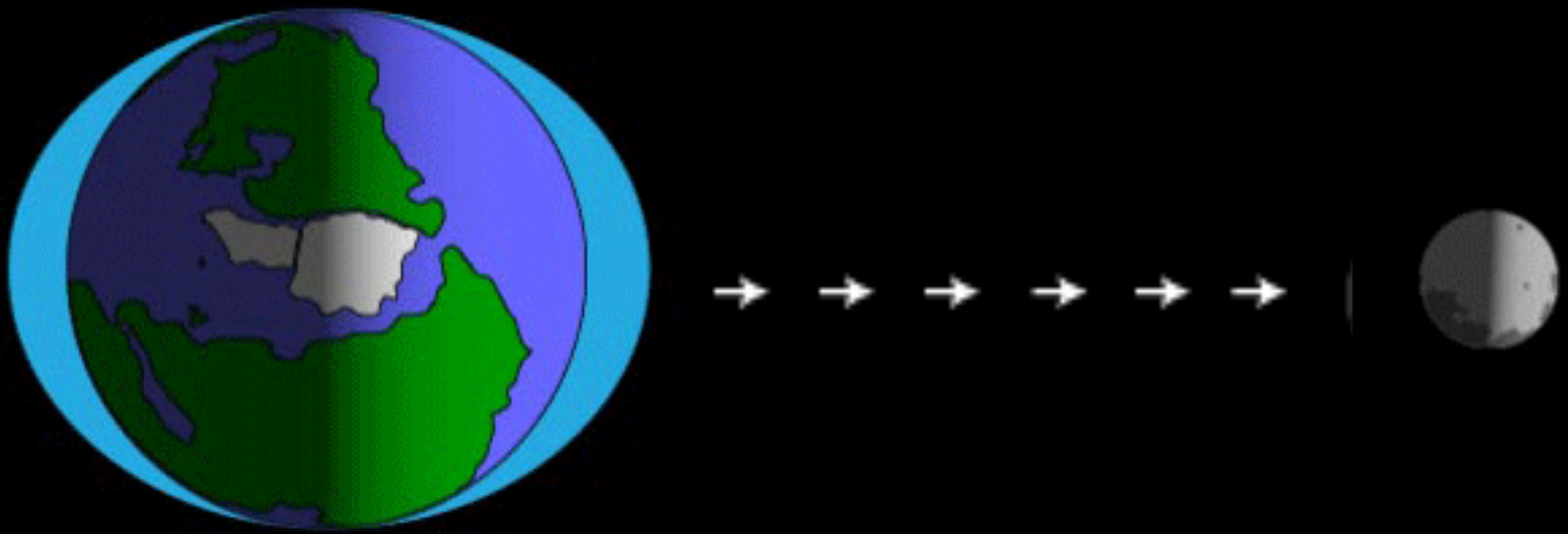
Change in sea level (cm)

-20 0 20

NOAA Climate.gov
Data: UHSLC

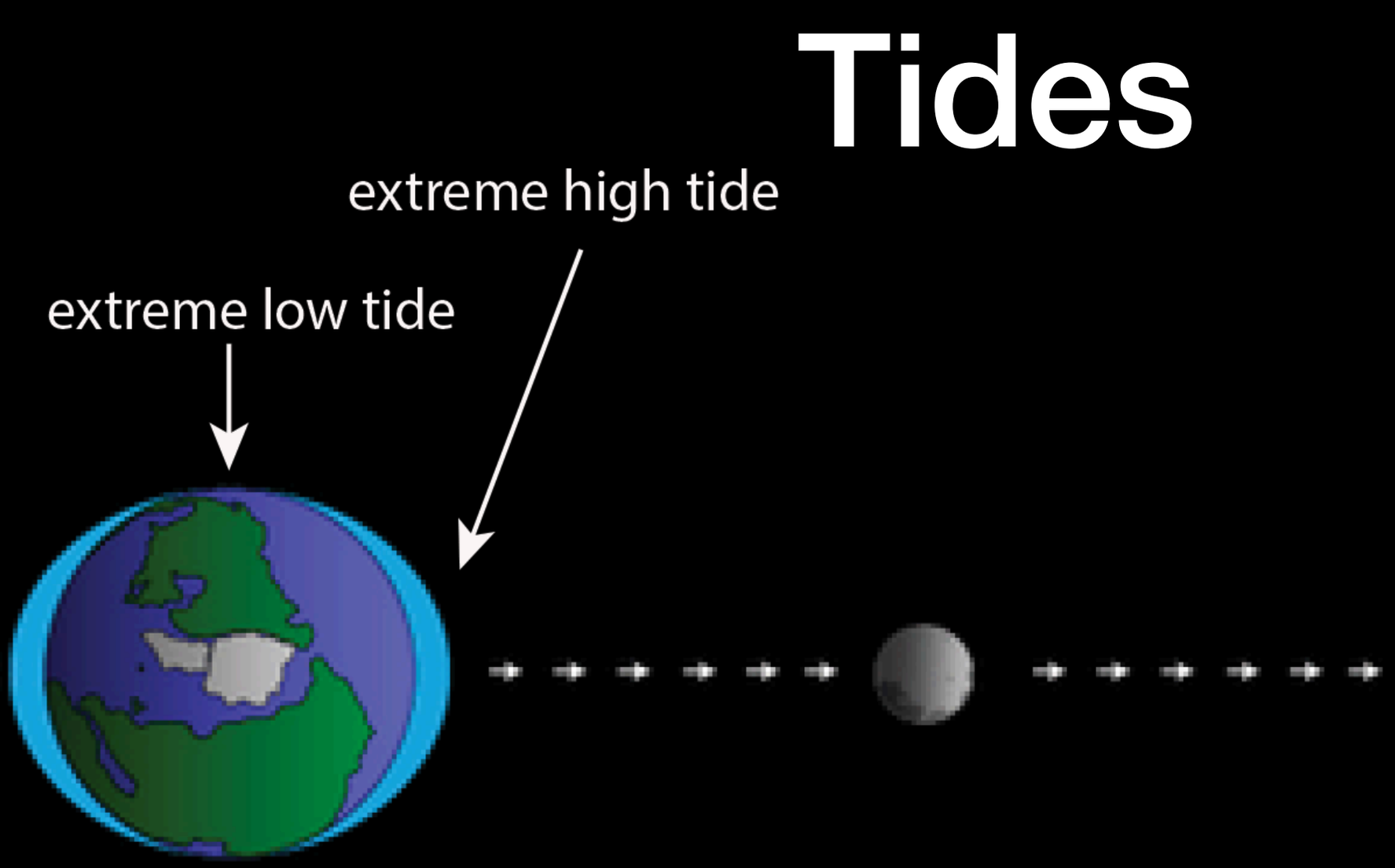
Sea level rise is already happening and disrupting our lives

Tides



There is a tidal bulge on both sides of the earth because the gravitational pull also effects the Earth's solid shape and so squashes the far side of the Earth, producing a second tide. However, water can't flow easily everywhere because of continents, so some places have only one high tides per day)

Tides



When the sun and moon are aligned on one side (spring) or on opposite sides (neap), the addition of both of their gravitational pulls causes extreme tides

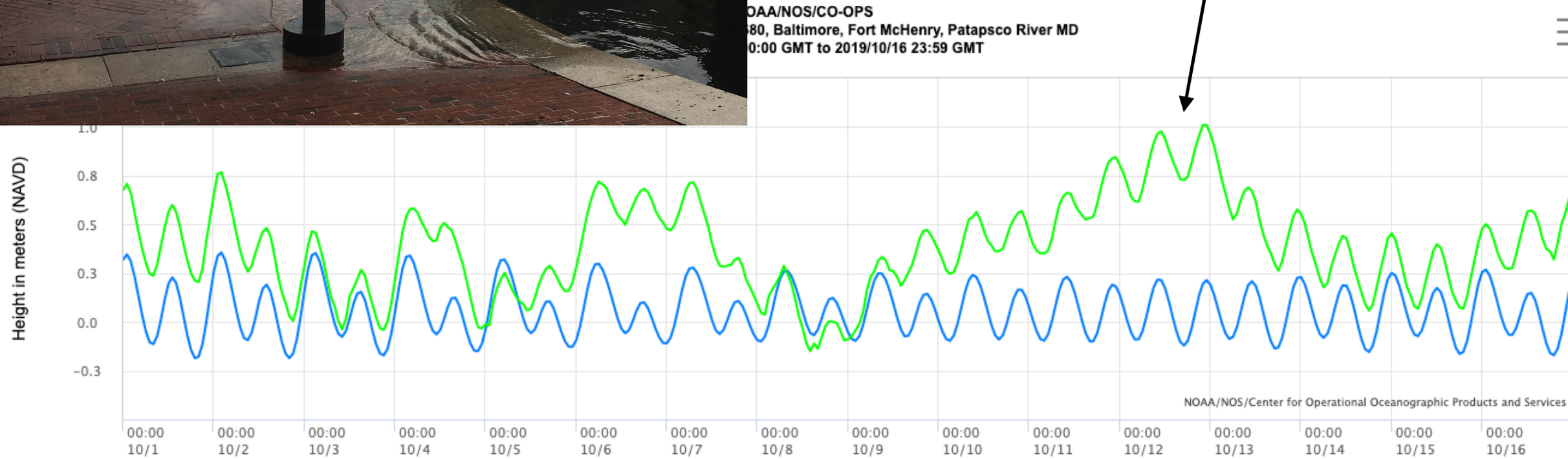
“Sunny-day” flooding

Downtown Miami on a sunny day

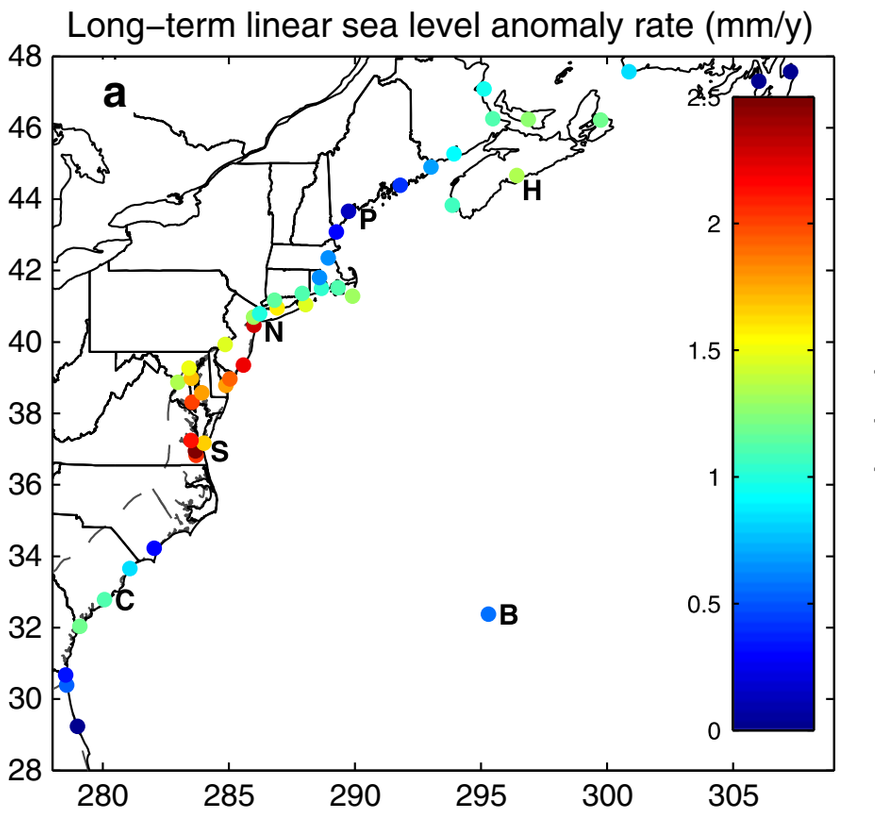
When average sea level at a location is slowly increasing, often the first major effect that is felt is “sunny-day” flooding, which might occur a few times a year during spring/king tides

“Sunny-day” flooding

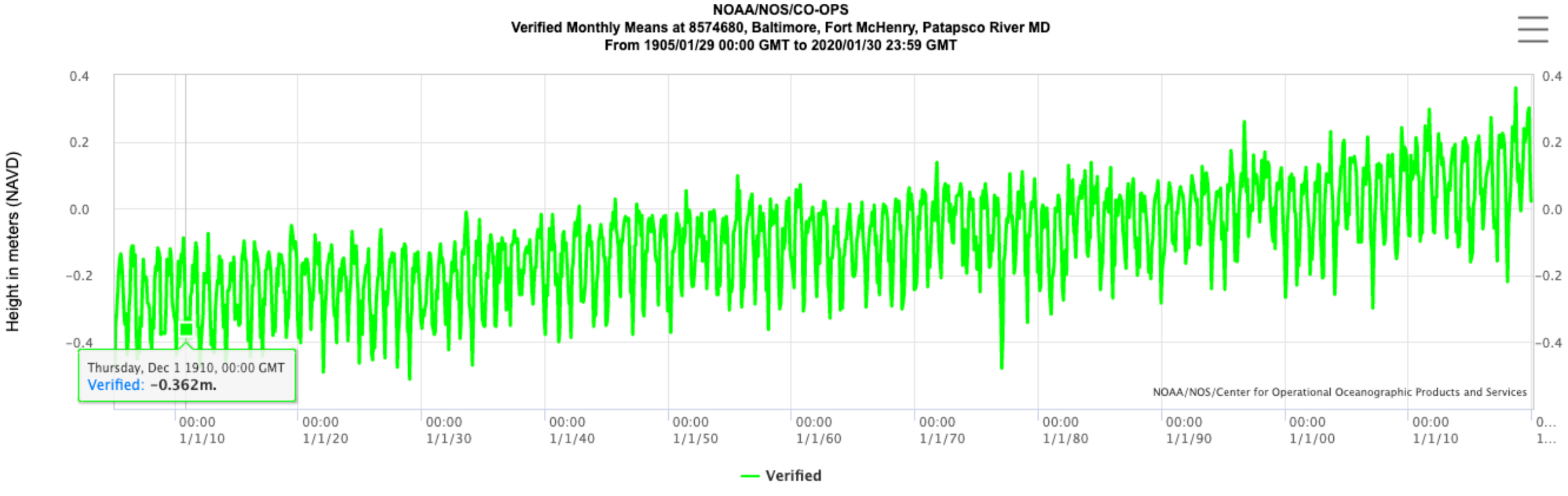
My not very good picture from Baltimore Harbor in October 2019 - not even high tide



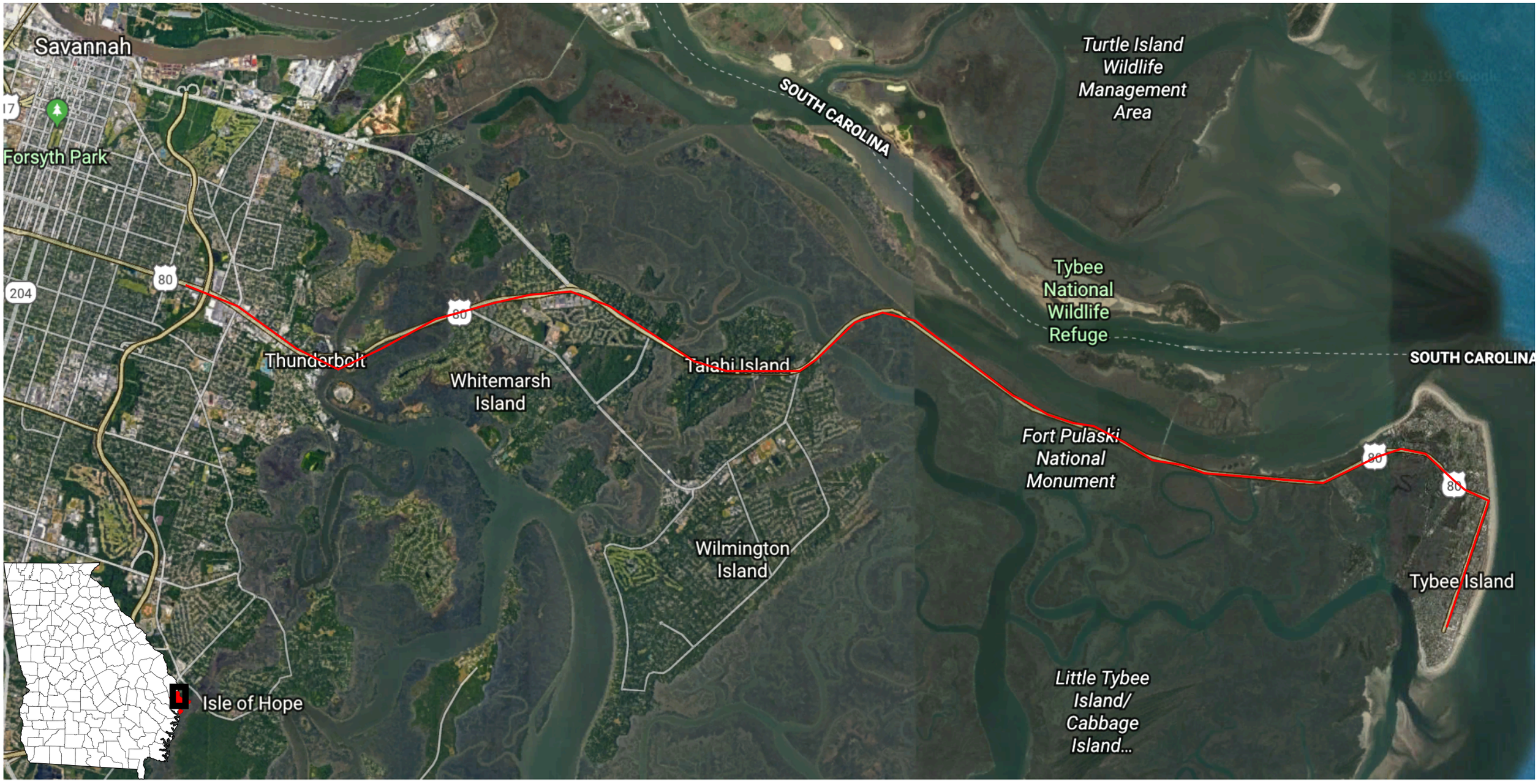
“Sunny-day” flooding



Baltimore Tide Gauge (running since almost 1900!)

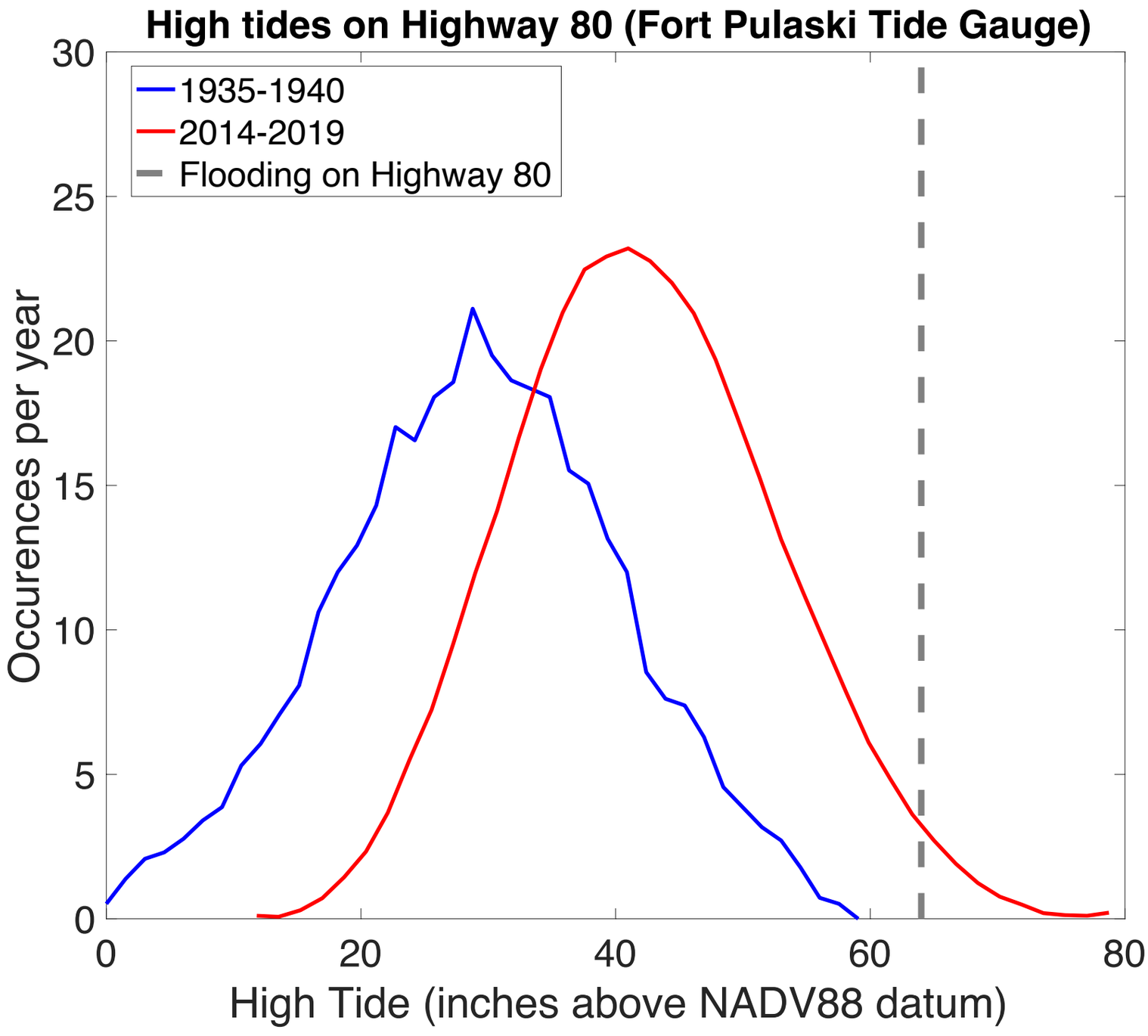


Highway 80 and Tybee Island



Highway 80 is the only connection from Savannah, GA to Tybee Island, a barrier island community with permanent population of 3000+

Highway 80 and Tybee Island



When Highway 80 was extended to Tybee Island in the 1930's, it was three feet above the typical high tide. Now it is just two feet above mean high tide, and floods a few times per year.

Highway 80 and Tybee Island

savannahnow
Savannah Morning News.

Low lying and narrow, U.S. 80 awaits improvements

BUY PHOTO ▲ HIDE CAPTION

Cars rush by on US 80 near areas that are prone to flooding. (Shelly Mobley/savannahnow.com)

By Mary Landers

Follow

Posted Apr 6, 2019 at 5:35 PM

This year: Georgia Dept. of Transportation raising lowest parts of Highway 80 8 inches to prevent some flooding at cost of $1.8 million – drop in the bucket, but this is just the start

Future Projections

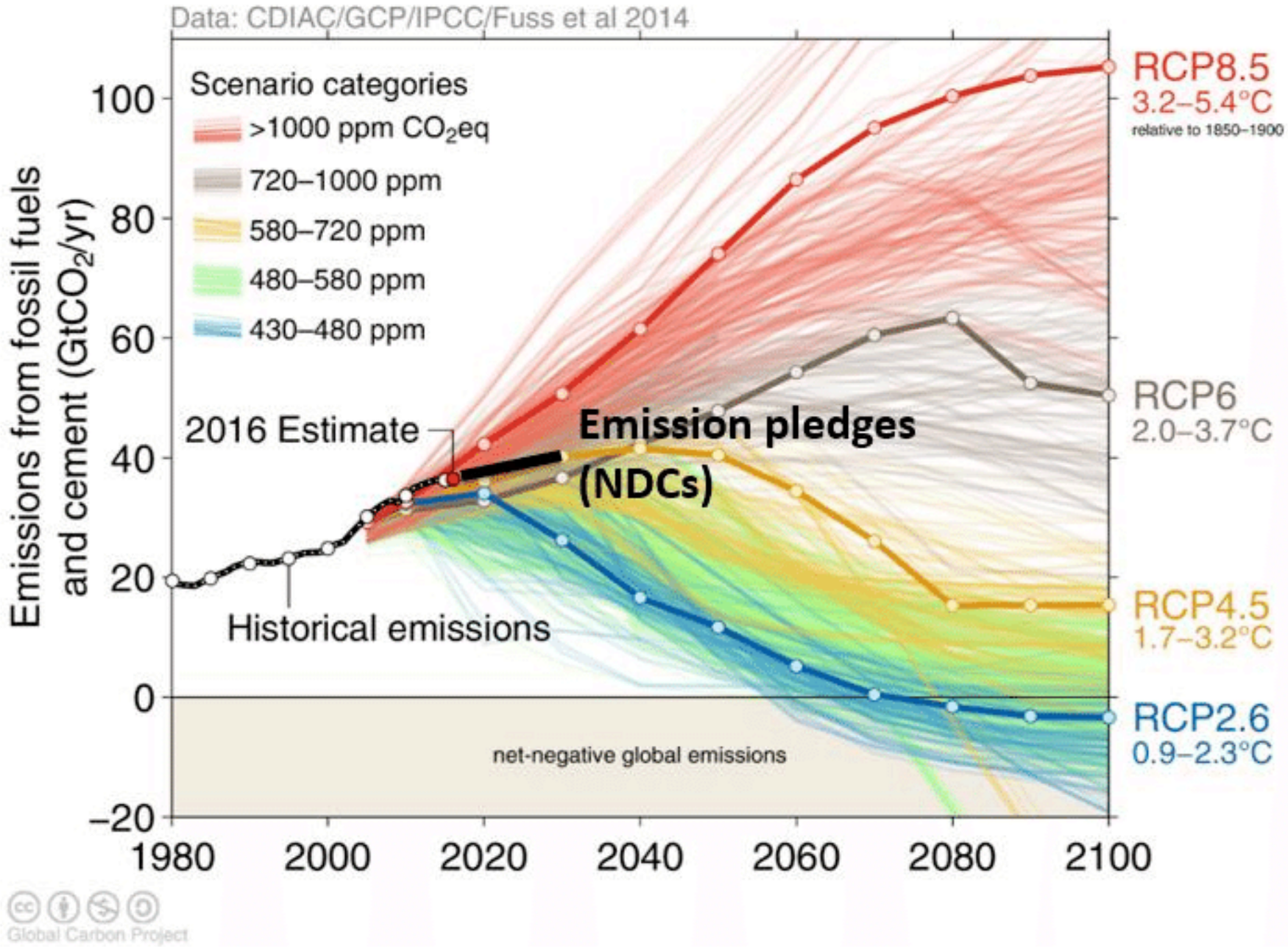
The three essential facts about future sea level rise

1. The rate of future sea level rise is highly uncertain, but we do know some things about it (**uncertainty**)

2. There will be some amount of continuing sea level rise for at least hundreds of years into the future (**commitment**)

3. The amount of future sea level rise depends sensitively on decisions we make about future emissions of greenhouse gases (**agency**)

What goes into a sea level projection?

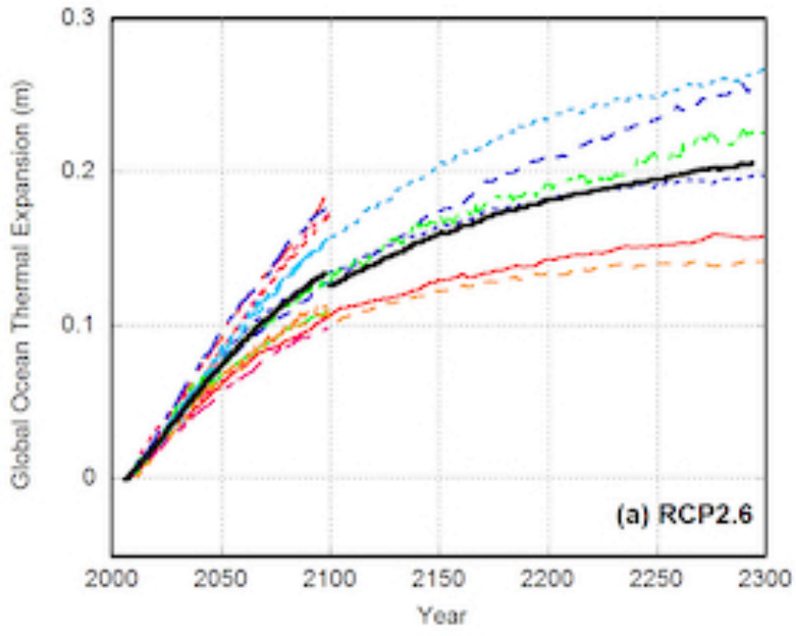


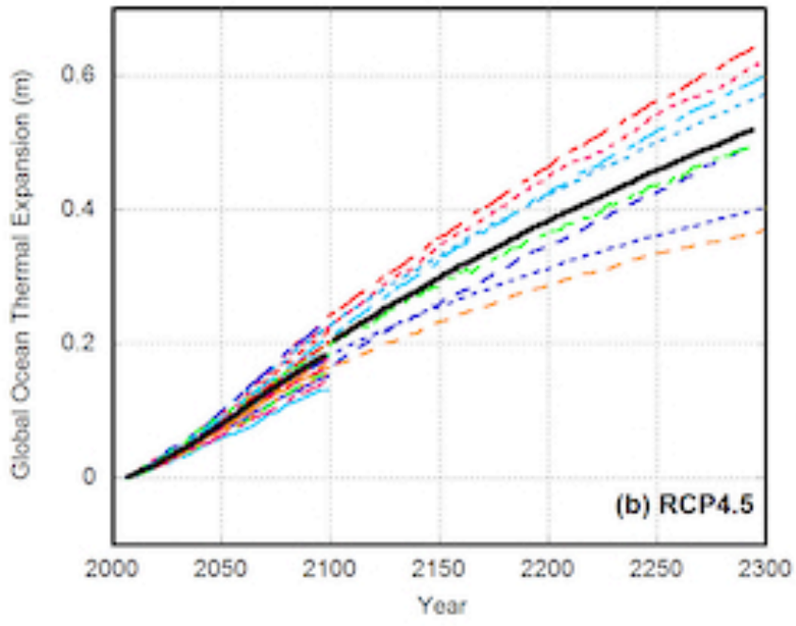
RCP = Representative Concentration Pathway (a potential scenario for how much greenhouse gas humans will emit in the future)

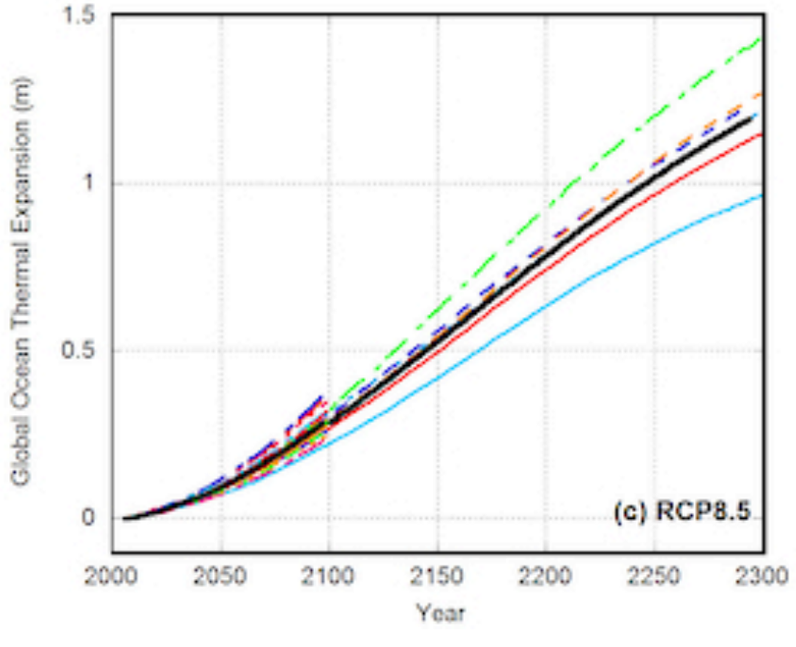
All projections are a conditional statement: "if this, then that"

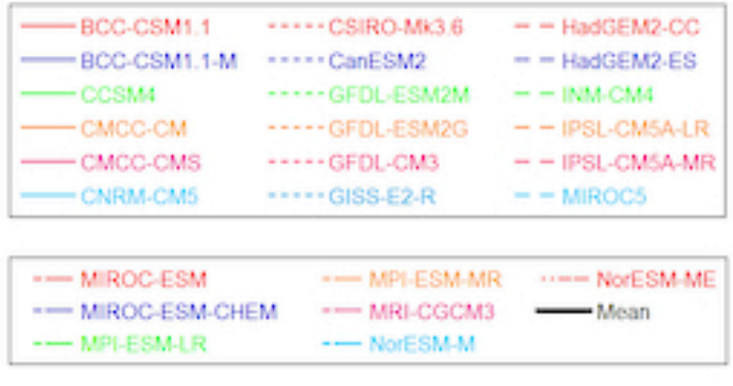
What goes into a sea level projection?

A climate model to estimate ocean heat uptake









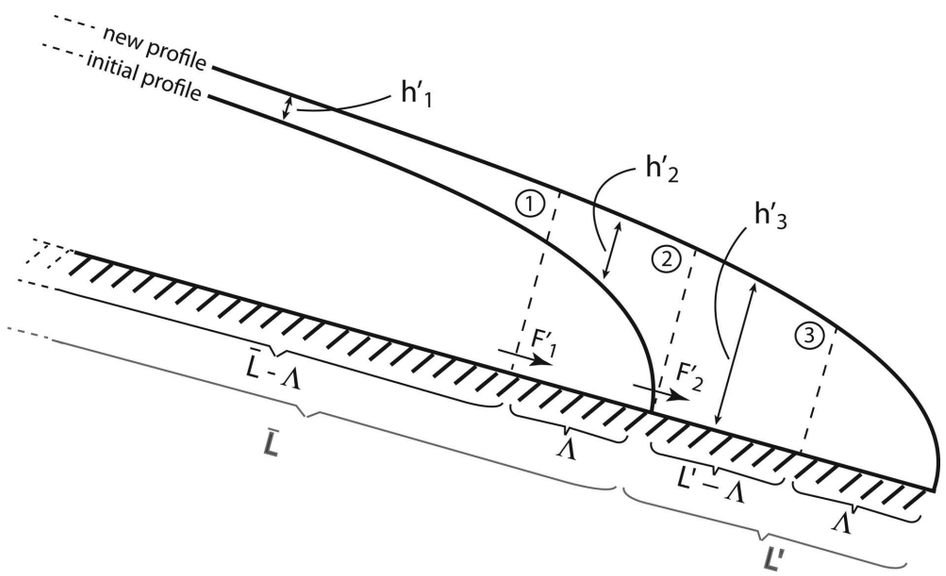
Yin 2012

There are many climate models, each which makes slightly different assumptions about how to describe the evolution of the climate system

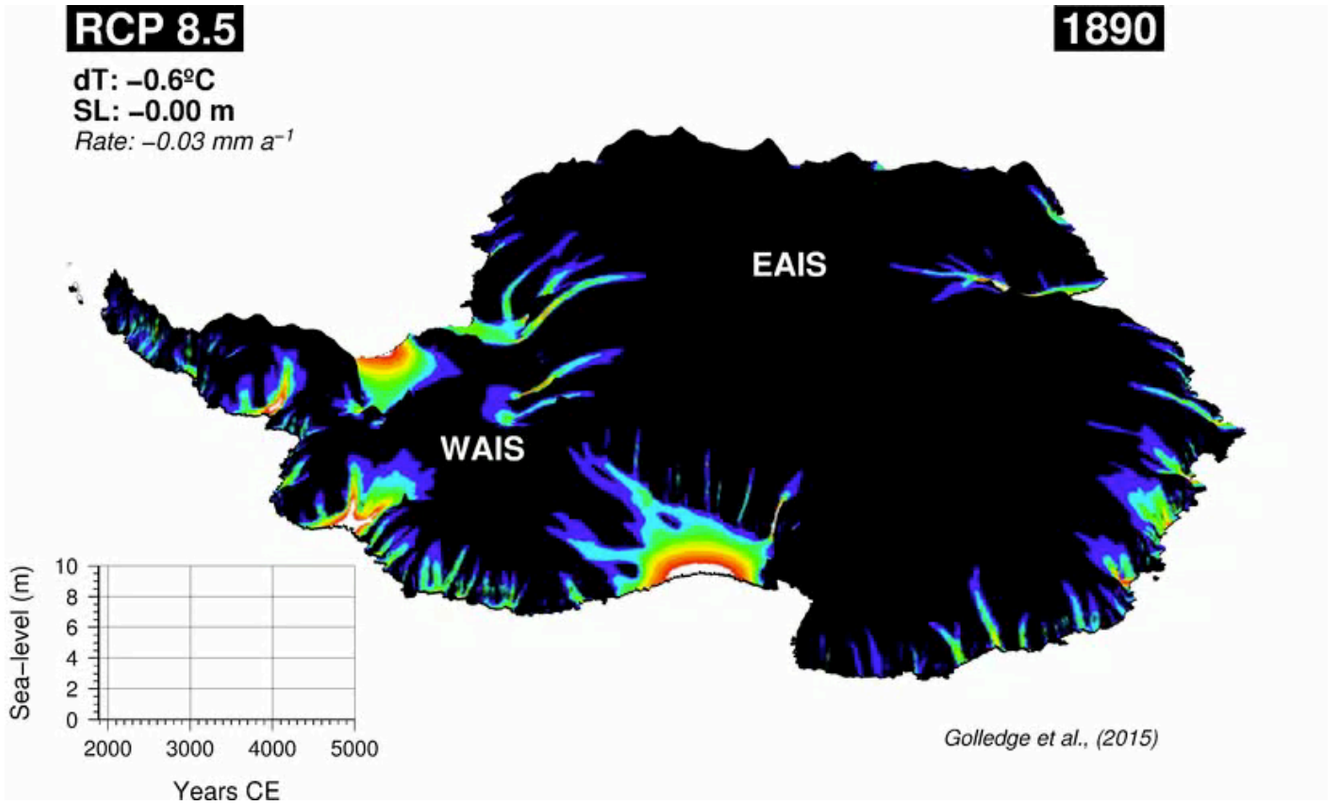
MIPs = model intercomparison project (all the major climate models are run with the same RCPs, and then compared)

What goes into a sea level projection?

A model of glaciers and/or ice sheets - which can come in many different forms



A very simple glacier model - 3 equations (Roe and Baker 2013)

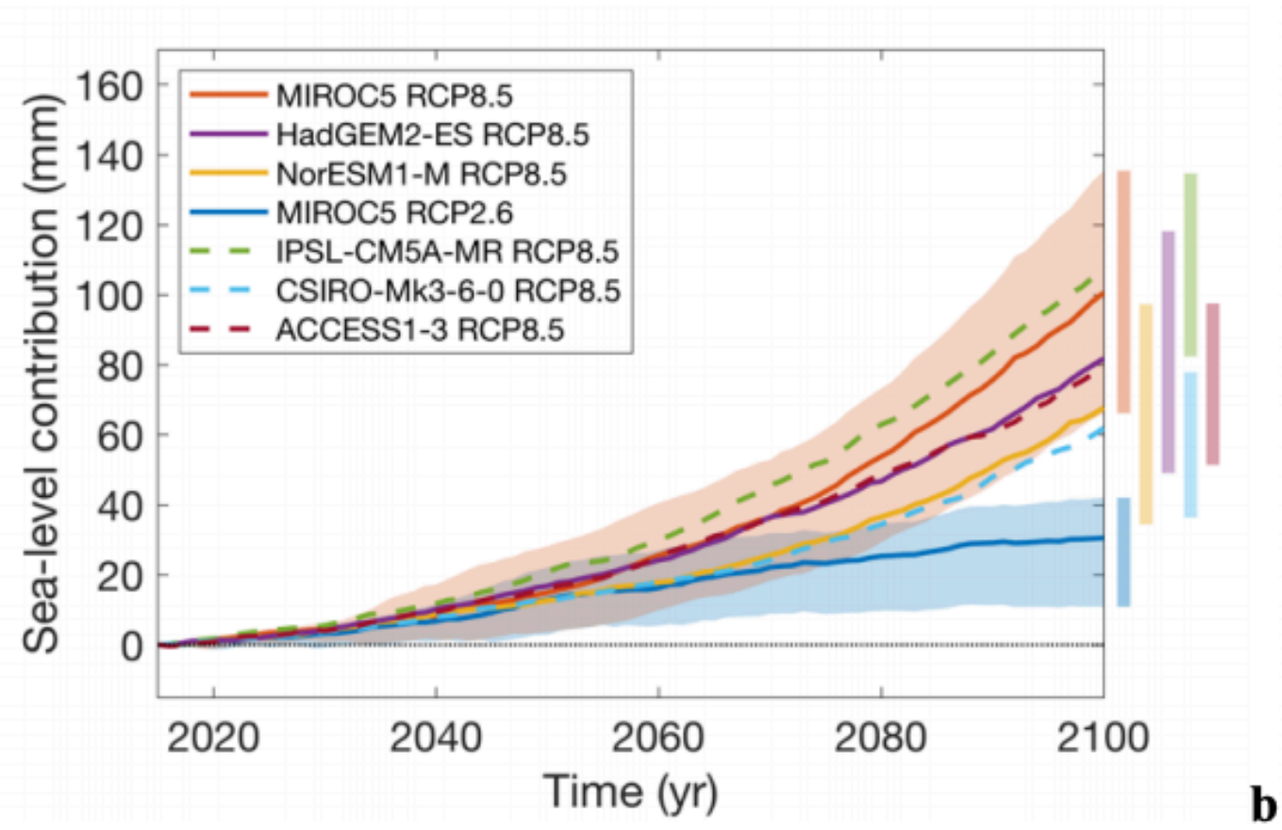


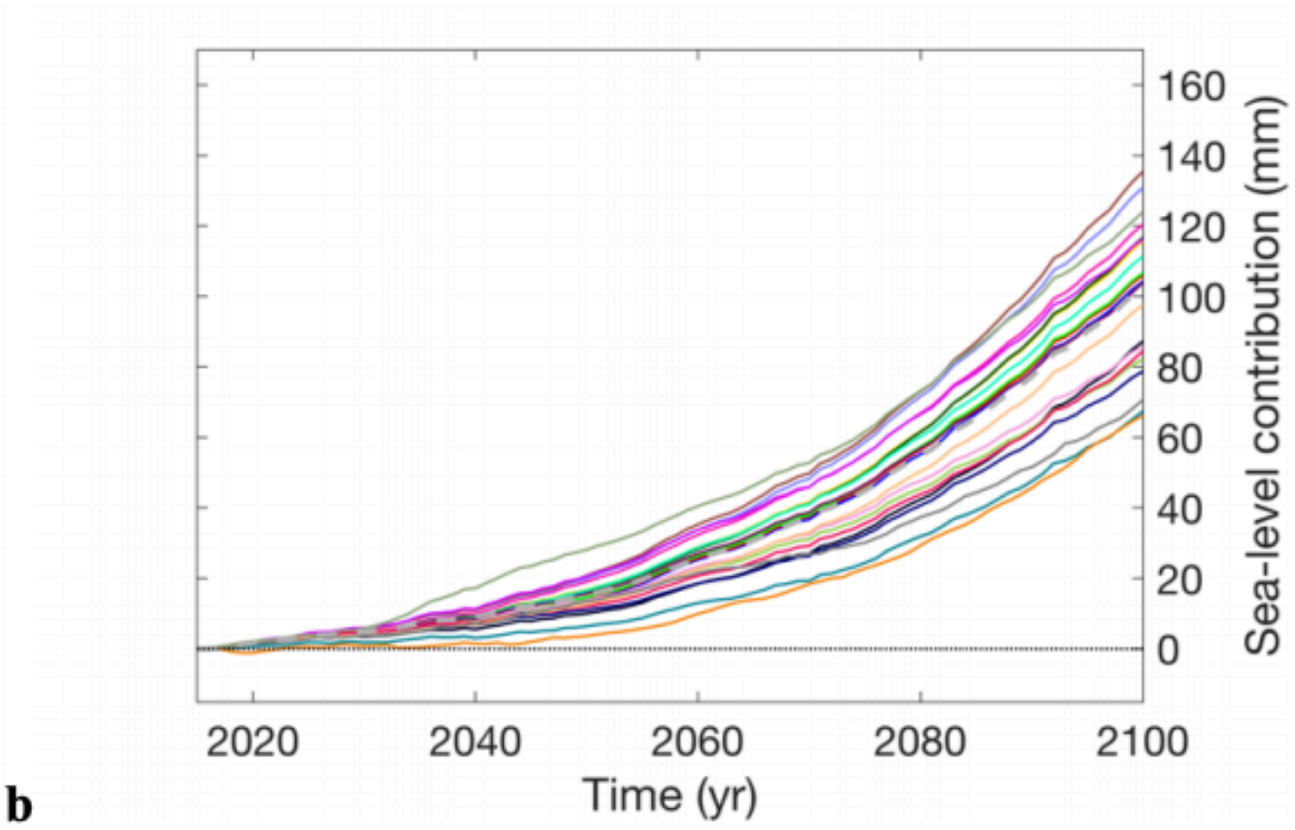
A complicated glacier model - millions of equations (PISM; UAlaska)

Ice sheet model projections

Different climate models, mean of difference Greenland ice sheet models

One climate model, different Greenland ice sheet models



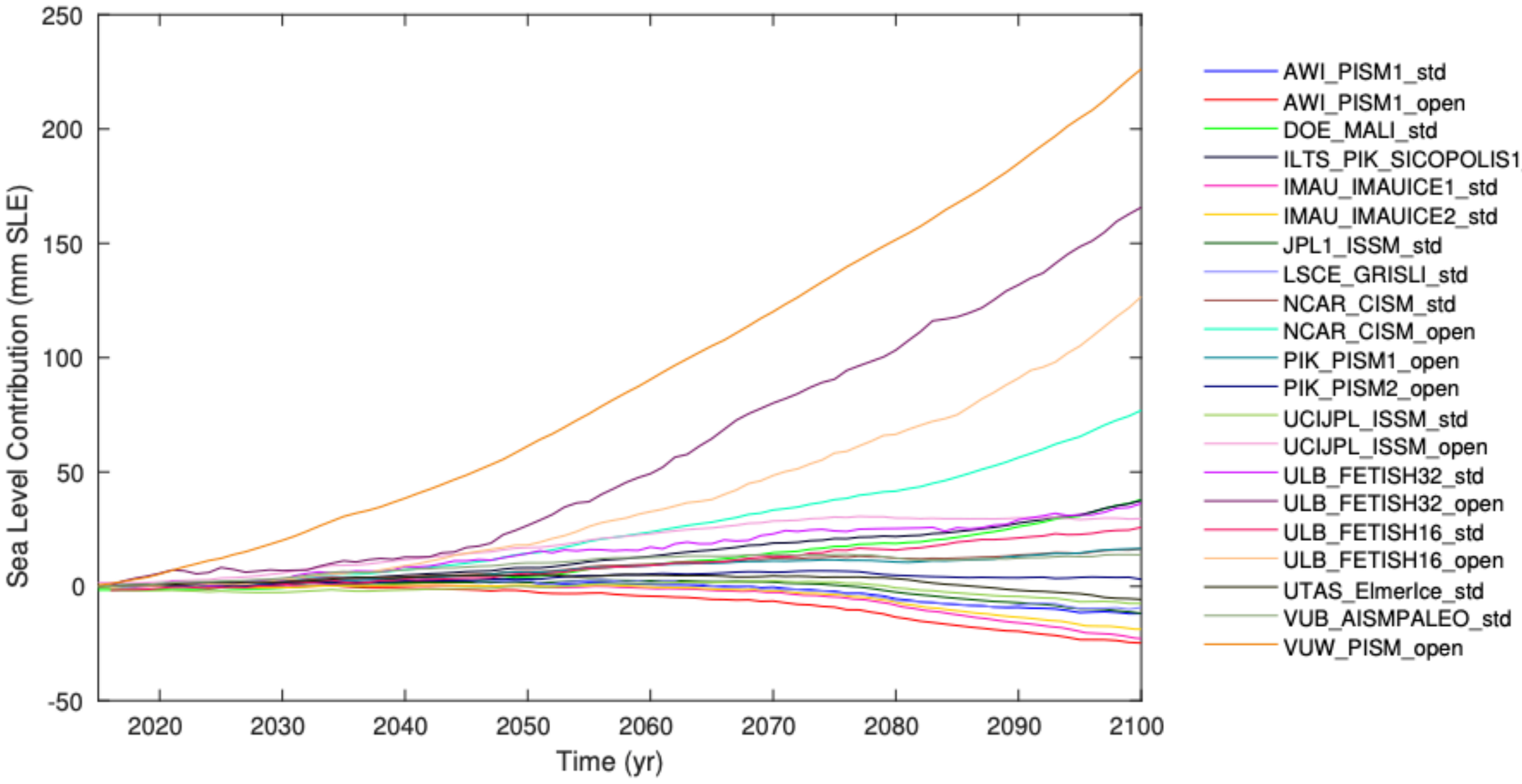


b

ISMIP6 - Goelzer et al. 2020

Ice sheet model projections

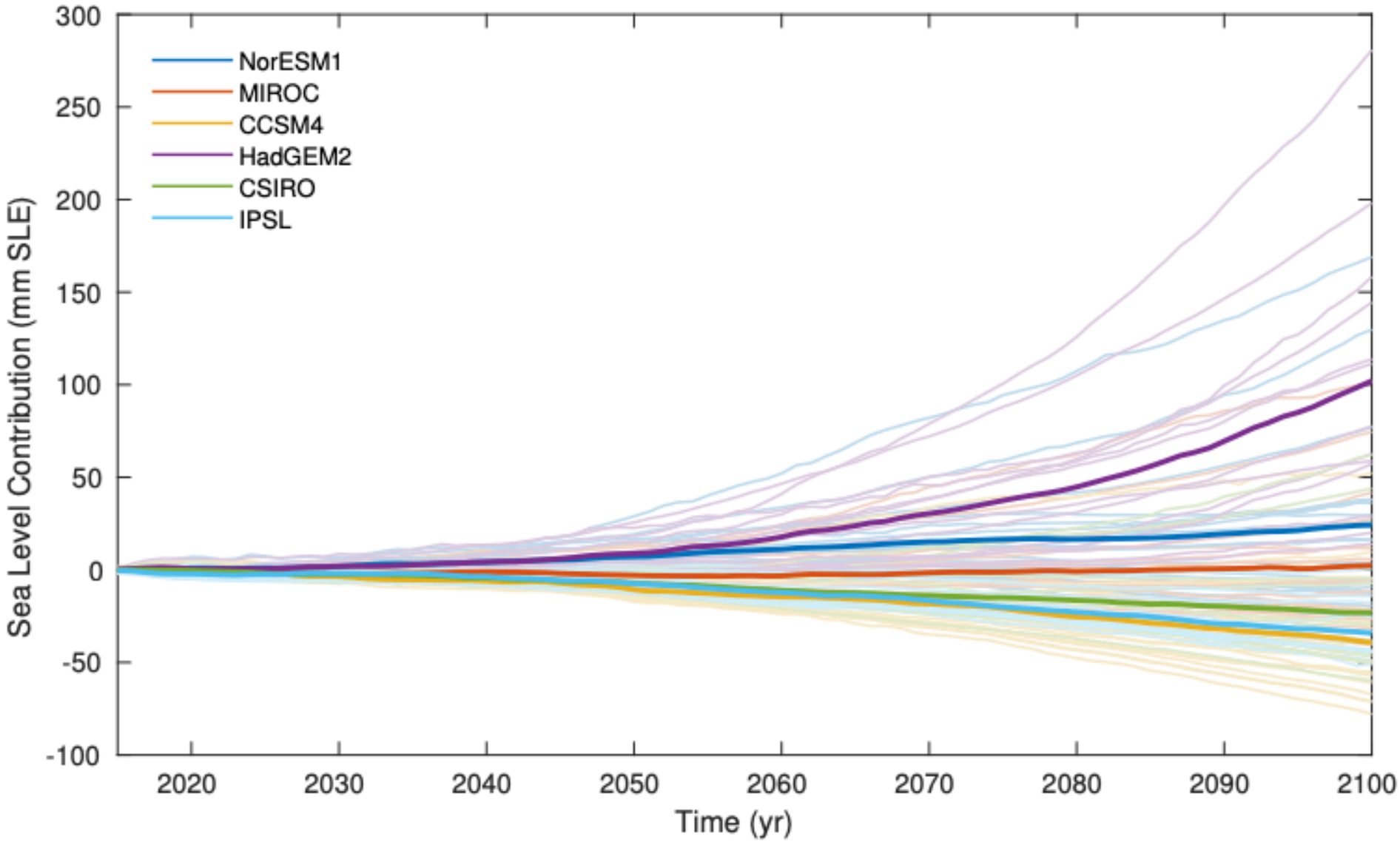
Same climate model, different Antarctic ice sheet models



ISMIP6 - Seroussi et al. 2020

Ice sheet model projections

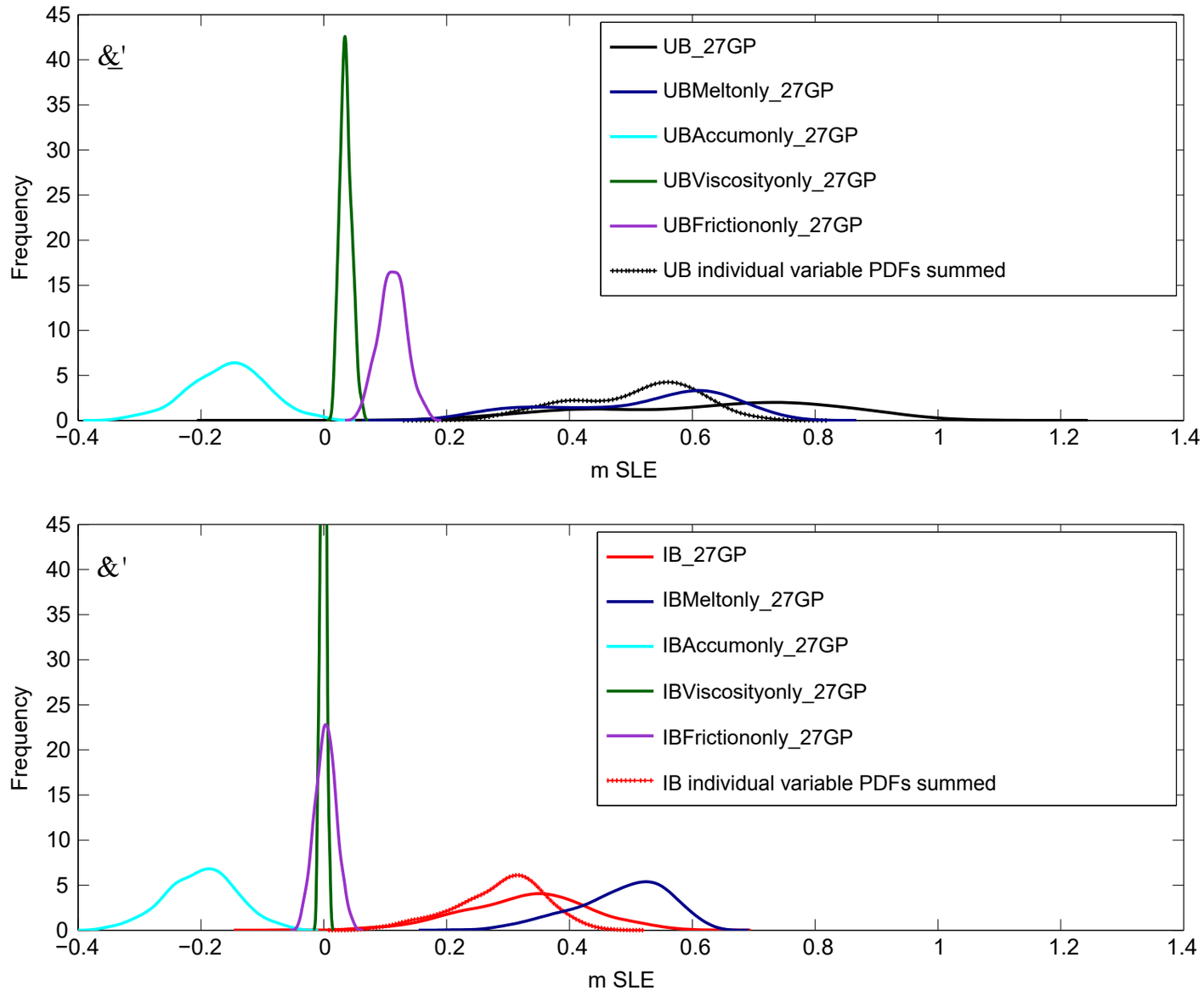
Different climate models (different colors), same Antarctic ice sheet models



ISMIP6 - Seroussi et al. 2020

Ice sheet model projections

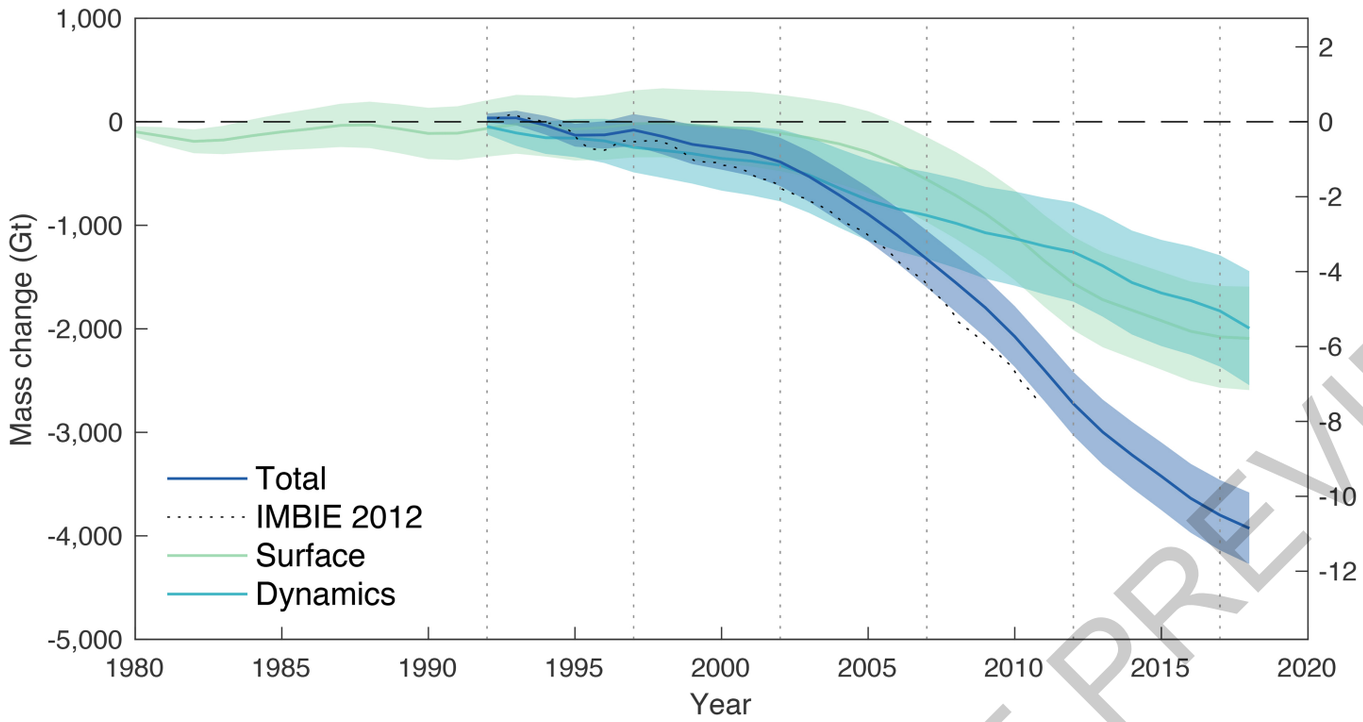
Same climate model, same Antarctic ice sheet model, many different parameter values selected in different ways



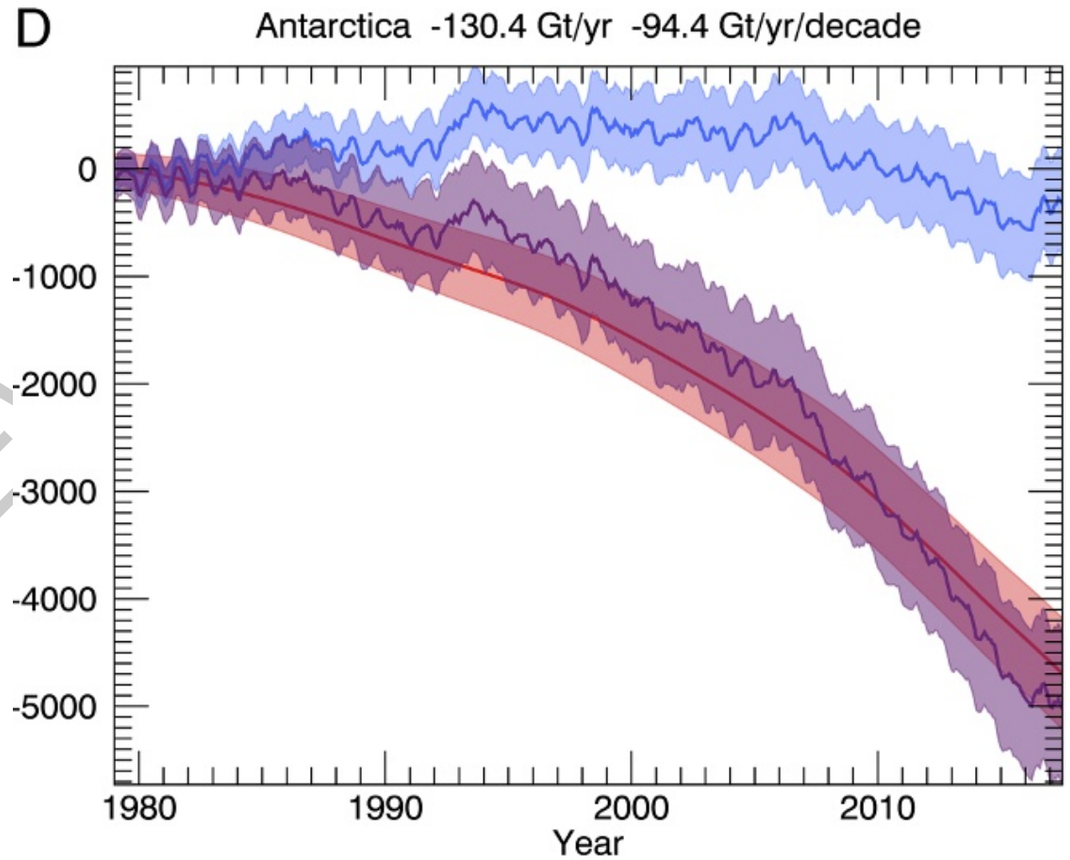
Schlegel et al. 2018

Why the difference between Greenland and Antarctica?

Future Greenland melt will likely continue to be dominated by surface melt, which is better understood than ice sheet flow dynamics



IMBIE Team 2019



Rignot et al. 2019

IPCC's Latest View

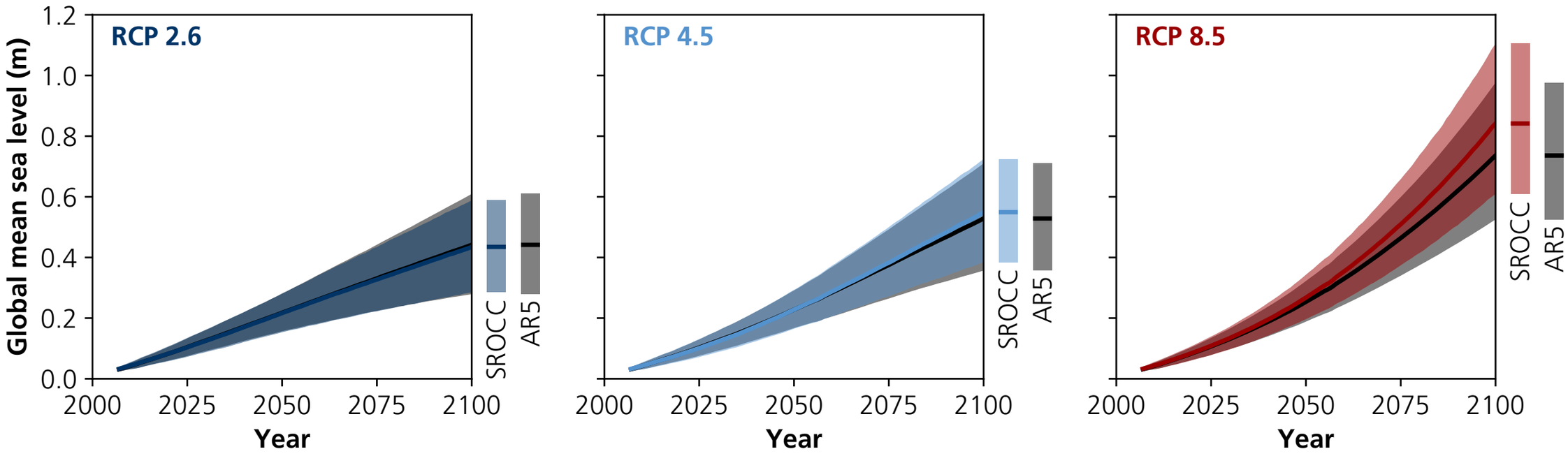


Figure 4.9: Time series of GMSL for RCP2.6, RCP4.5 and RCP8.5 as used in this report and, for reference the AR5 results (Church et al., 2013). Results are based on AR5 results for all components except the Antarctic contribution. Results for the Antarctic contribution in 2081–2100 are provided in Table 4.4. The shaded region should be considered as the *likely range*.

IPCC language tip: "likely" means 66% (+/-1 SD)

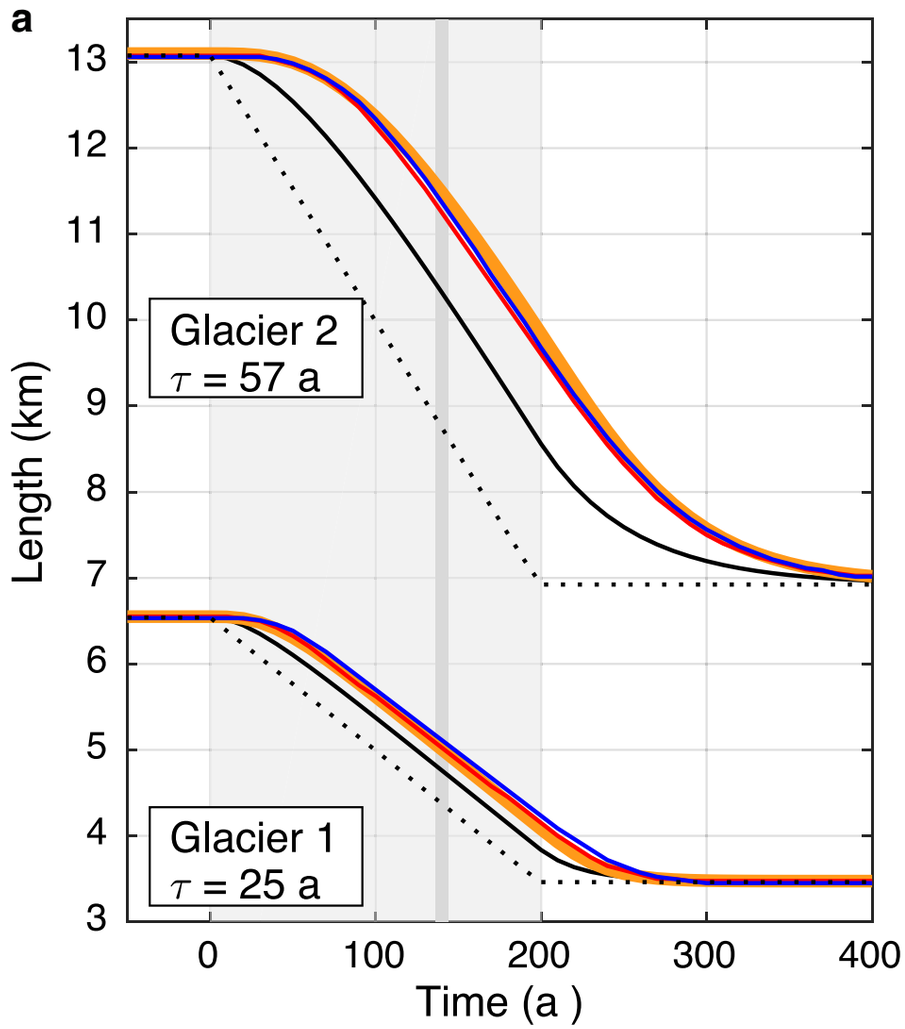
Group discussion

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

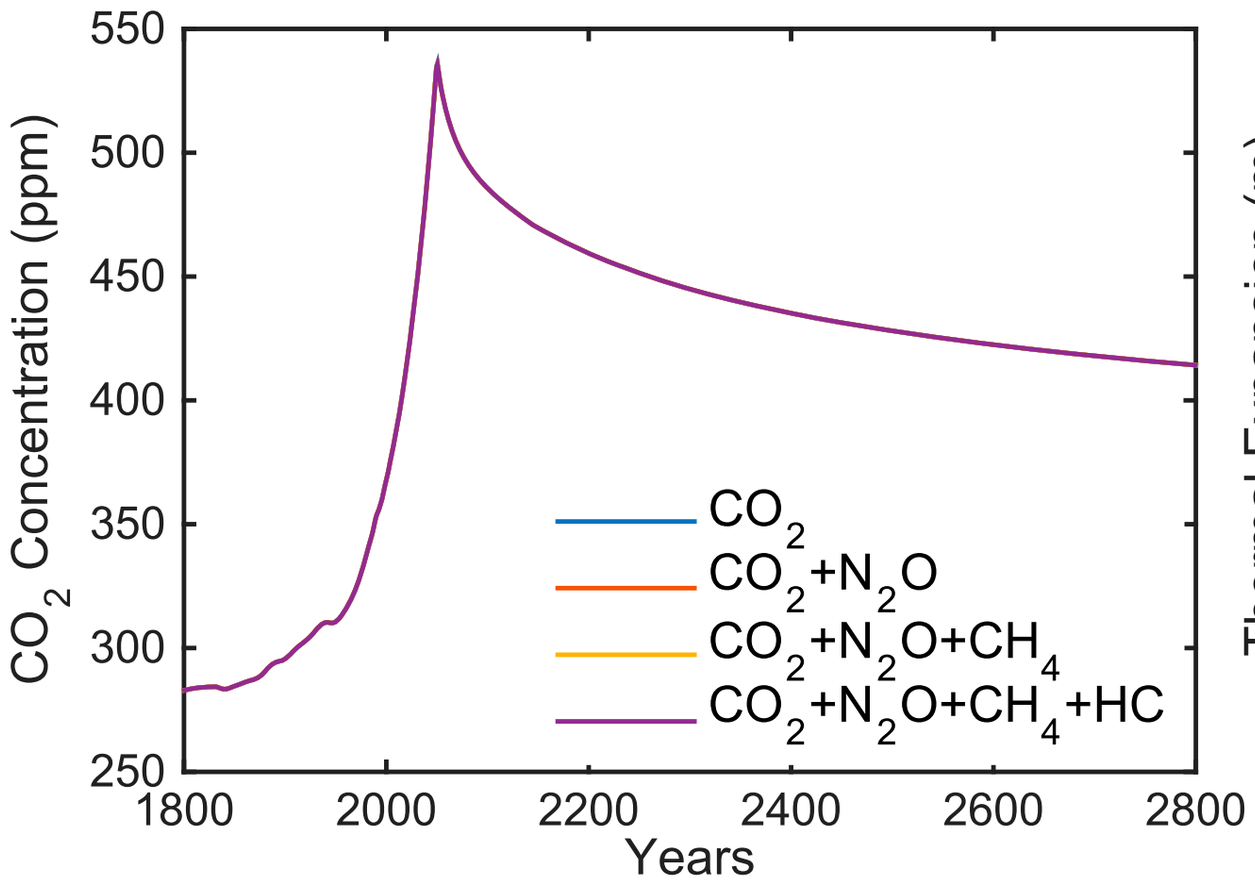


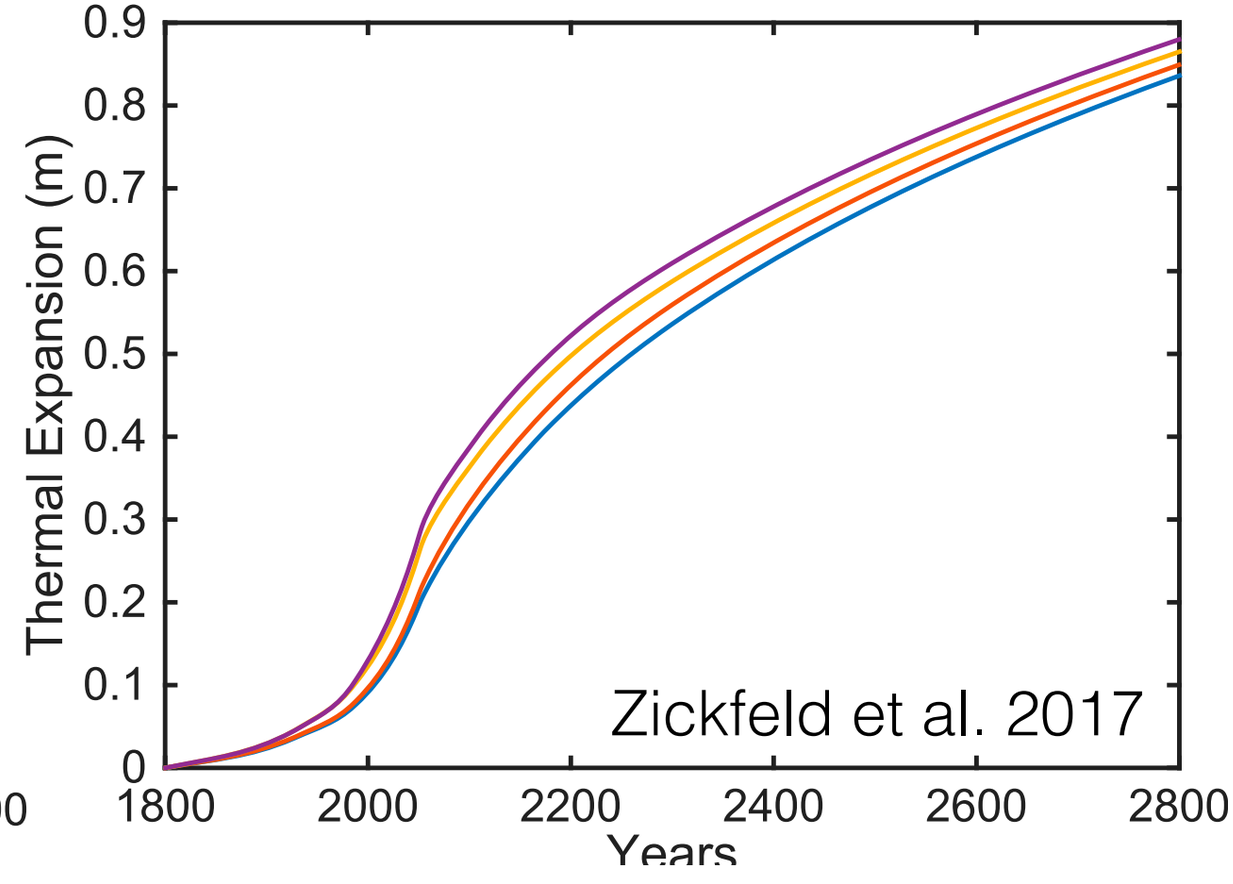
Christian et al. 2018

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

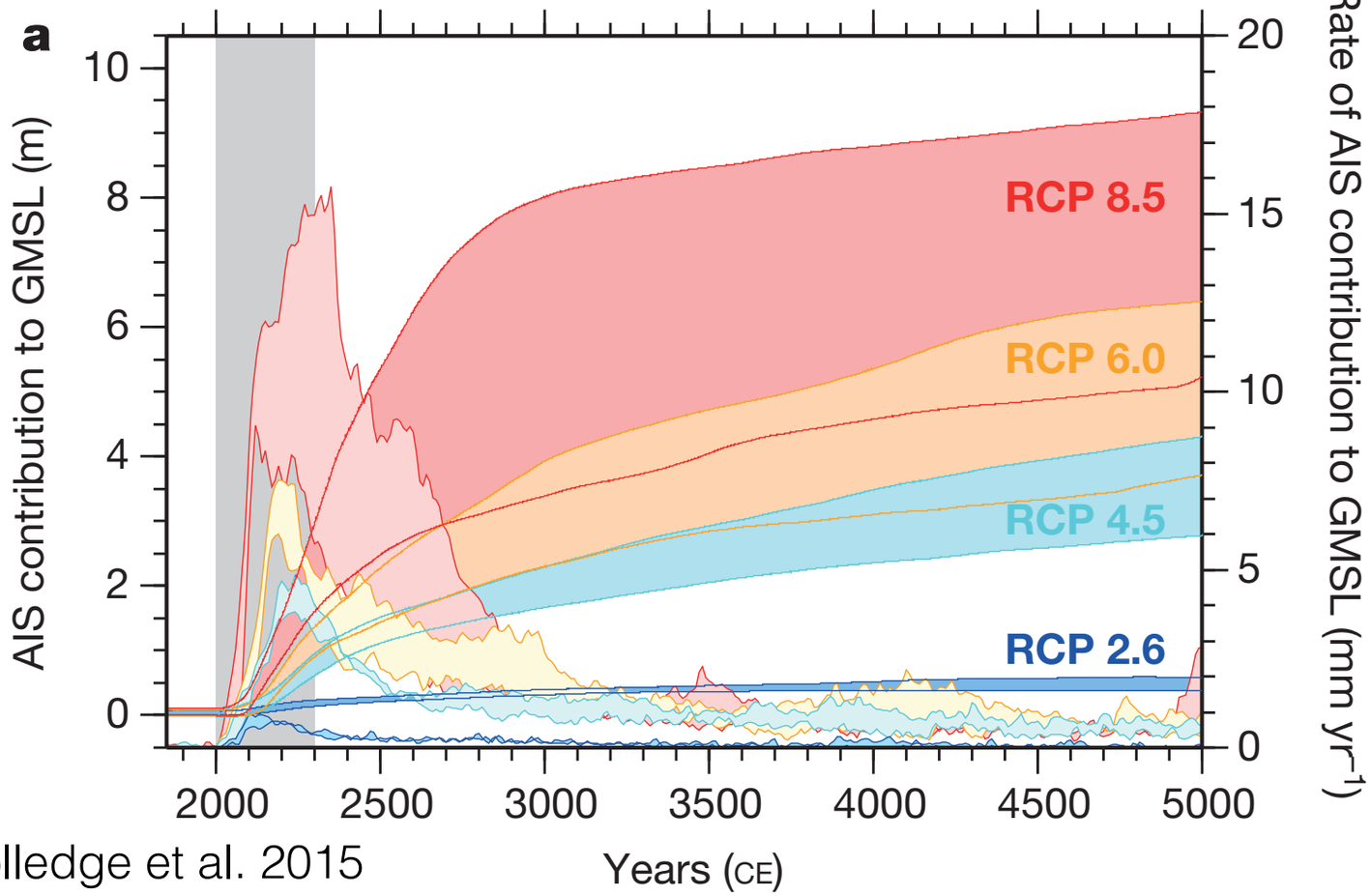




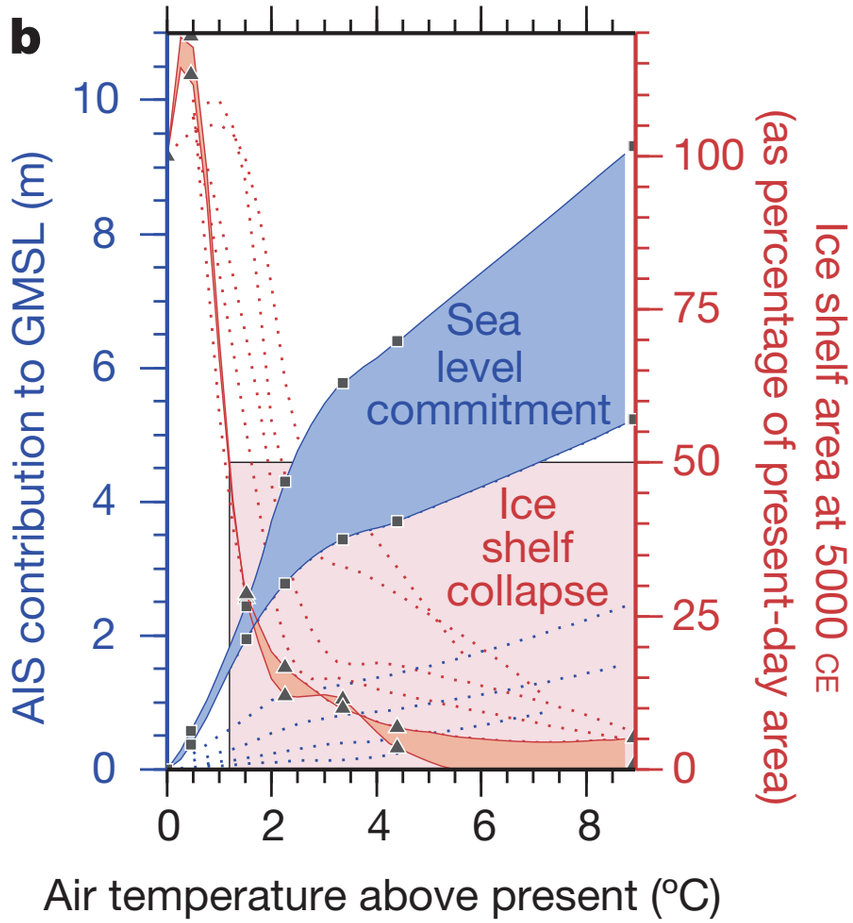
Even if we stop emitting greenhouse gases today, the ocean would continue to slowly absorb heat and expand for hundreds of years

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.

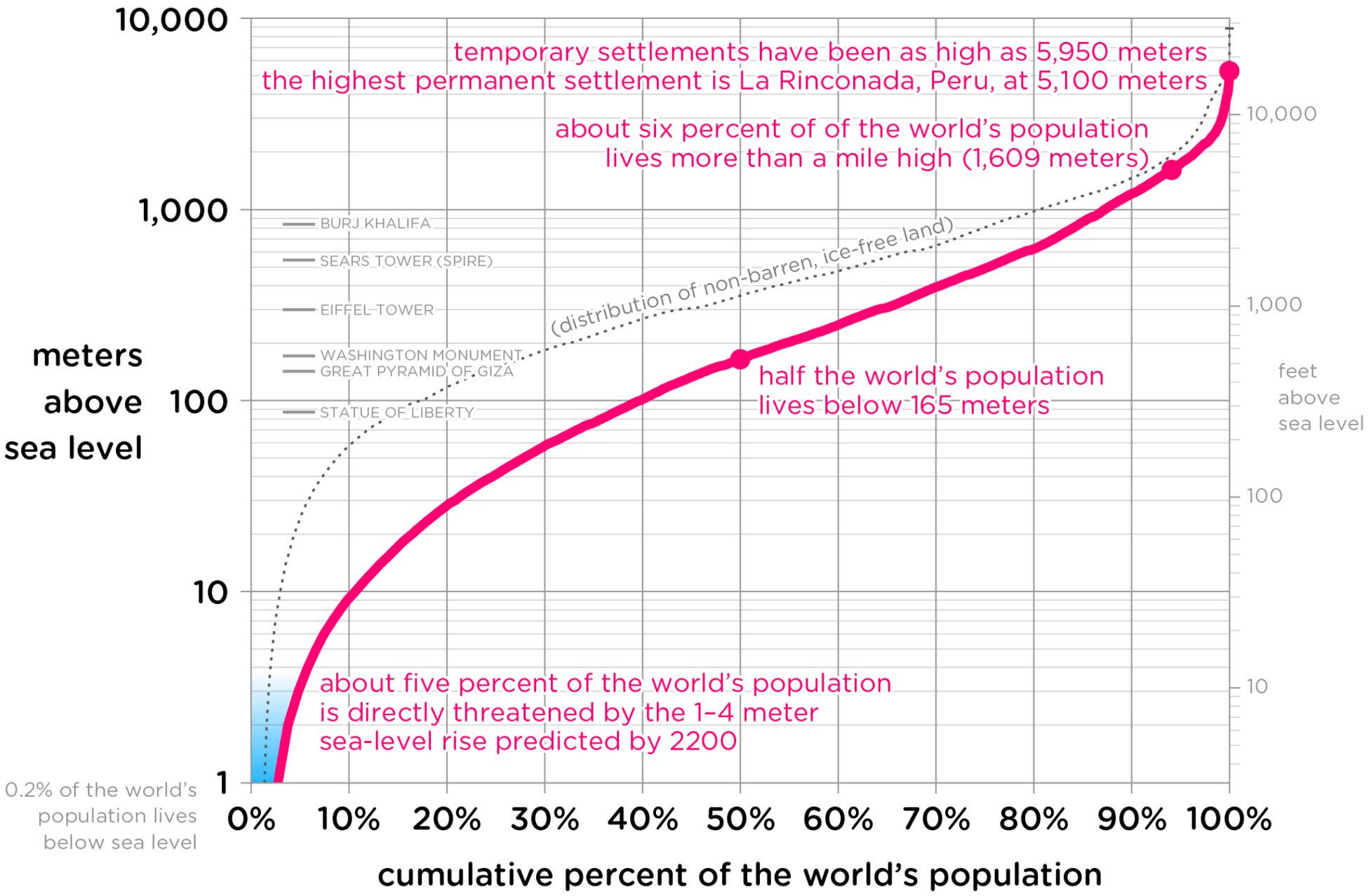
Sea level "commitment" depends on total climate change

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



population data from GRUMP; elevation from GTOPO30; sea-level rise from doi:10.1002/2014EF000239
graph by bill rankin, www.radicalcartography.net, CC BY-NC-SA 2016

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