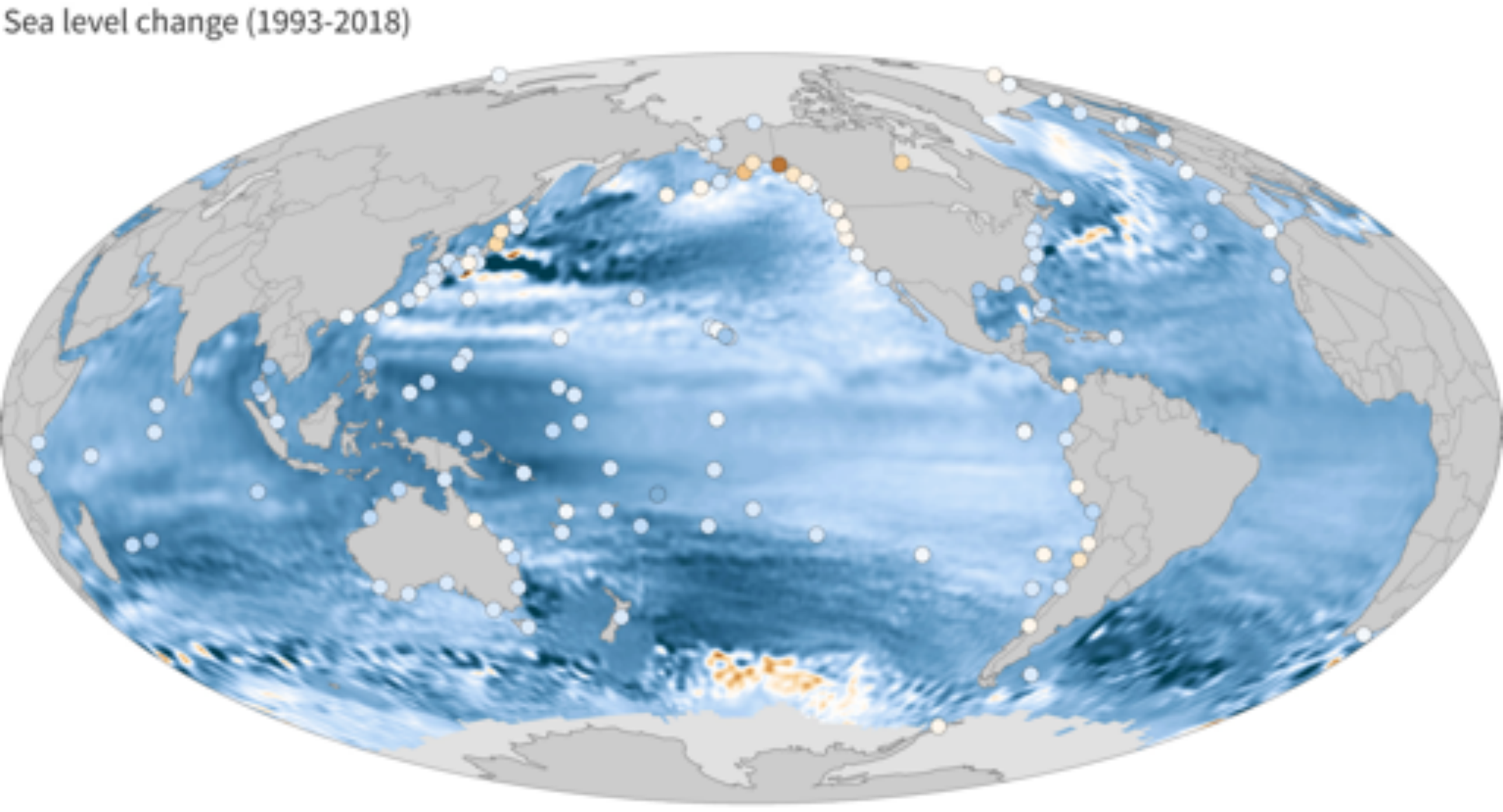
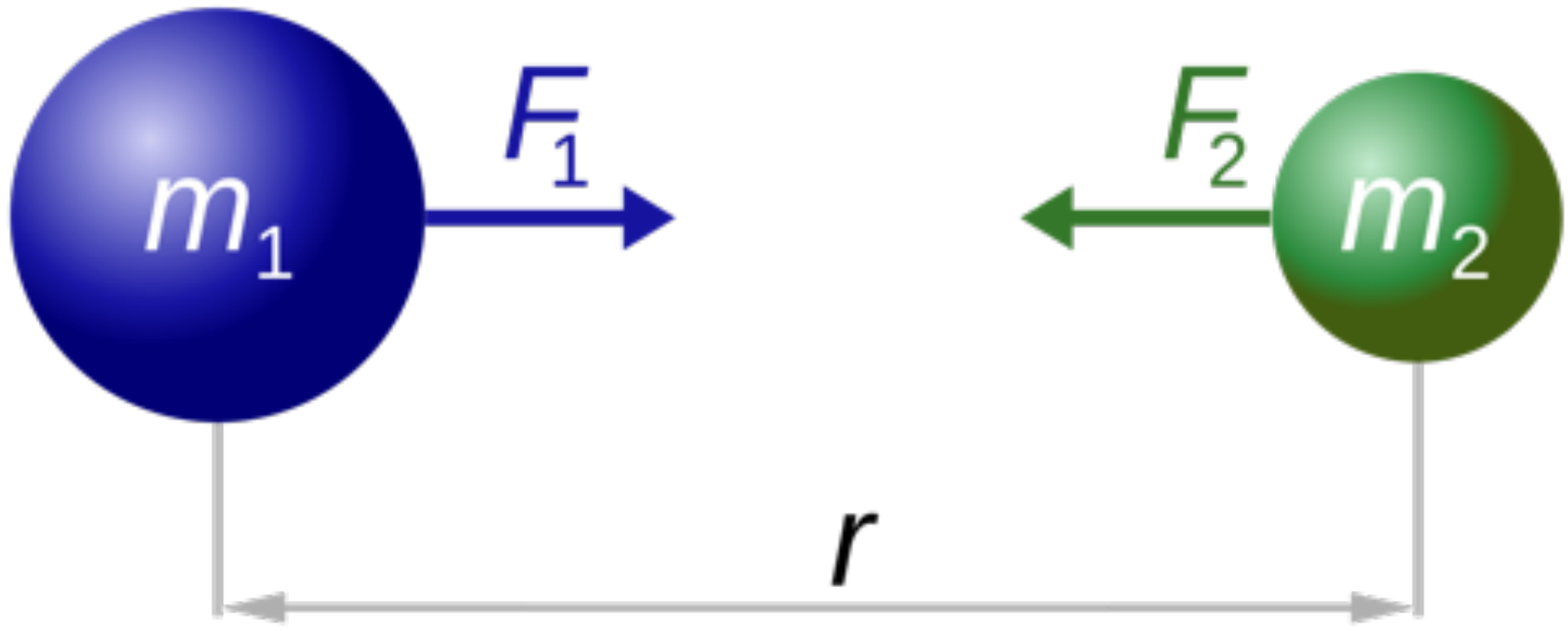
Regional and Local Drivers of Sea Level Change (beyond GMSL)

The Ocean is Not a Bathtub



A reminder: how gravity works

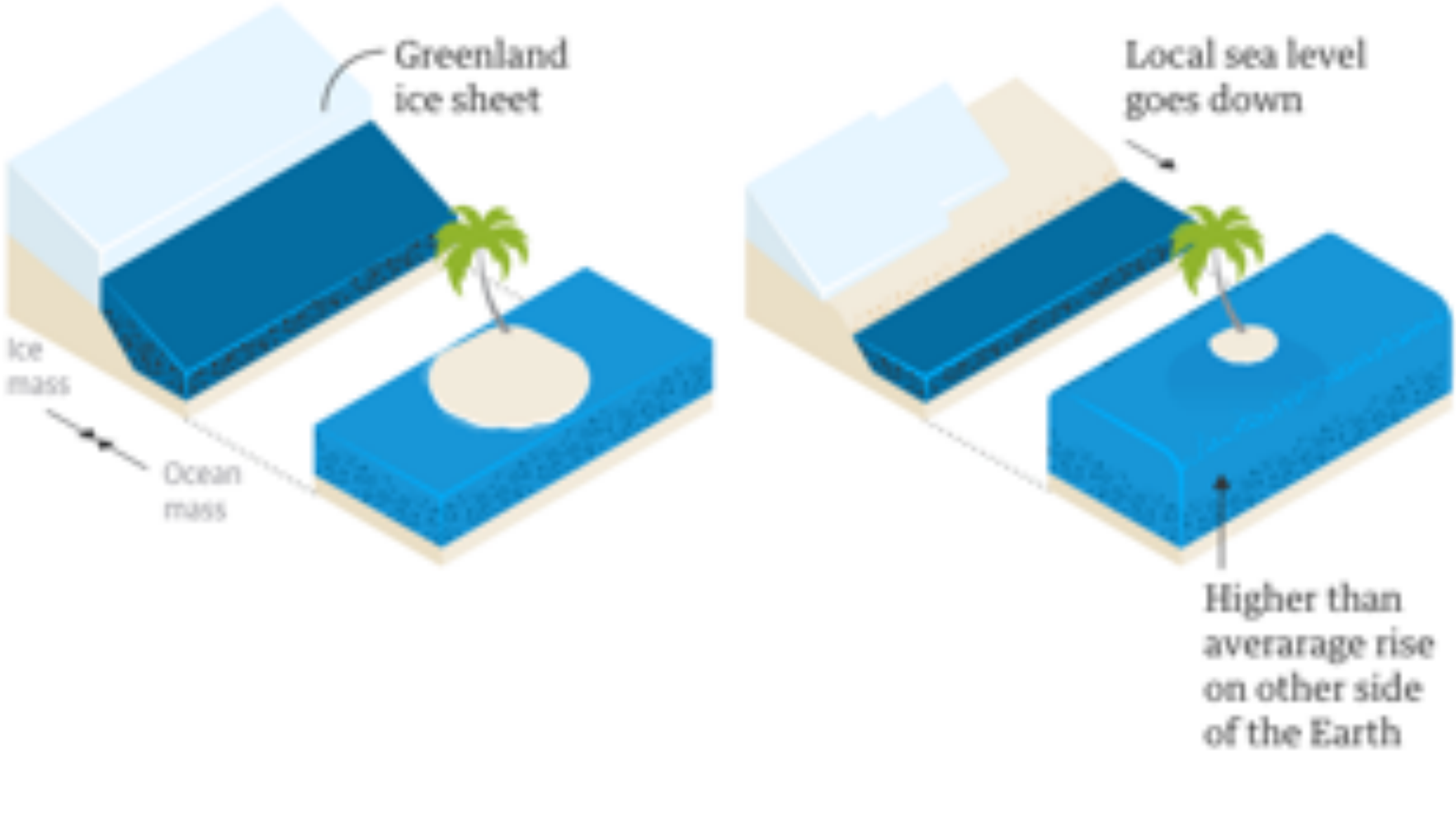


$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

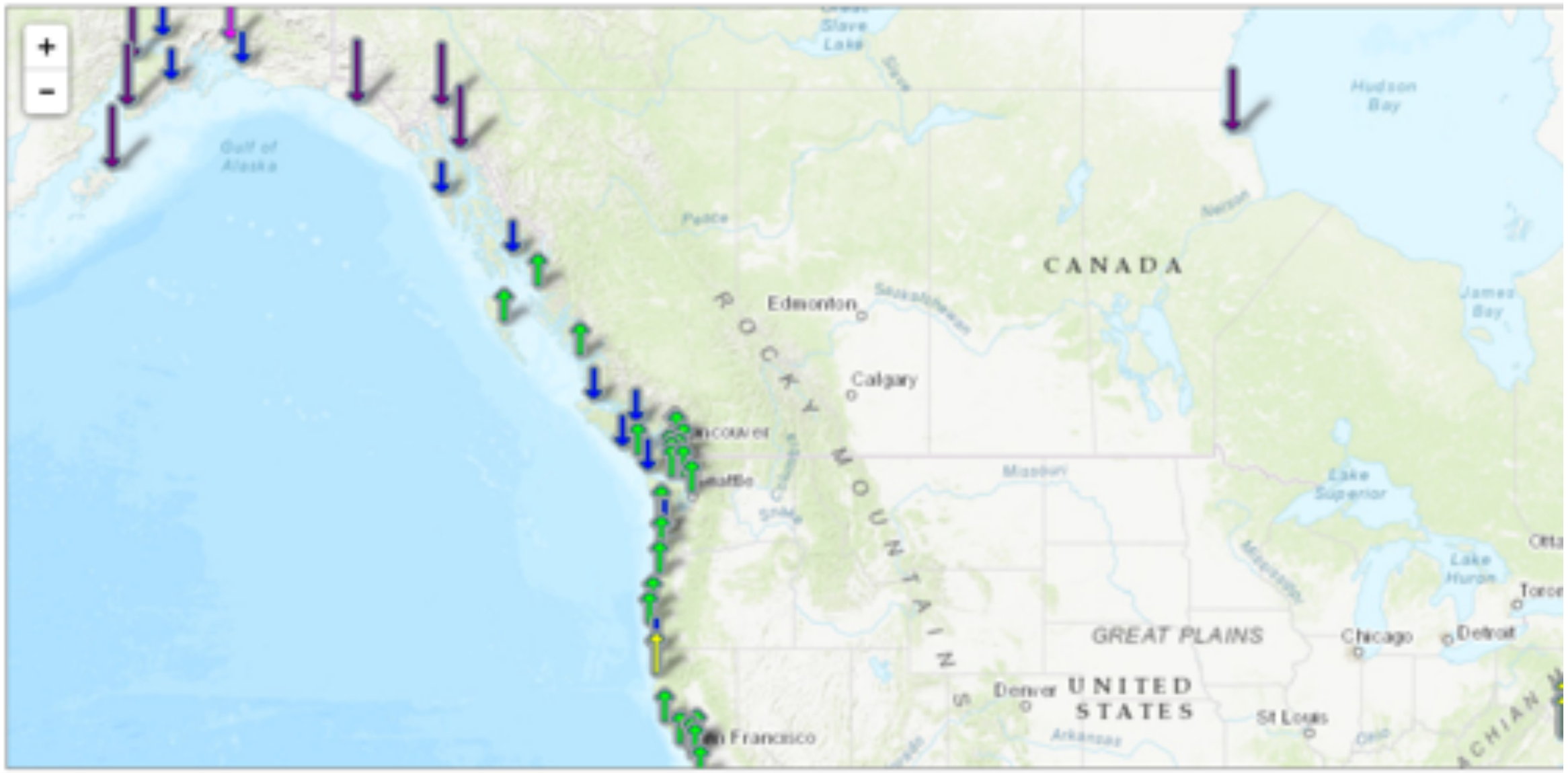
Gravity

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

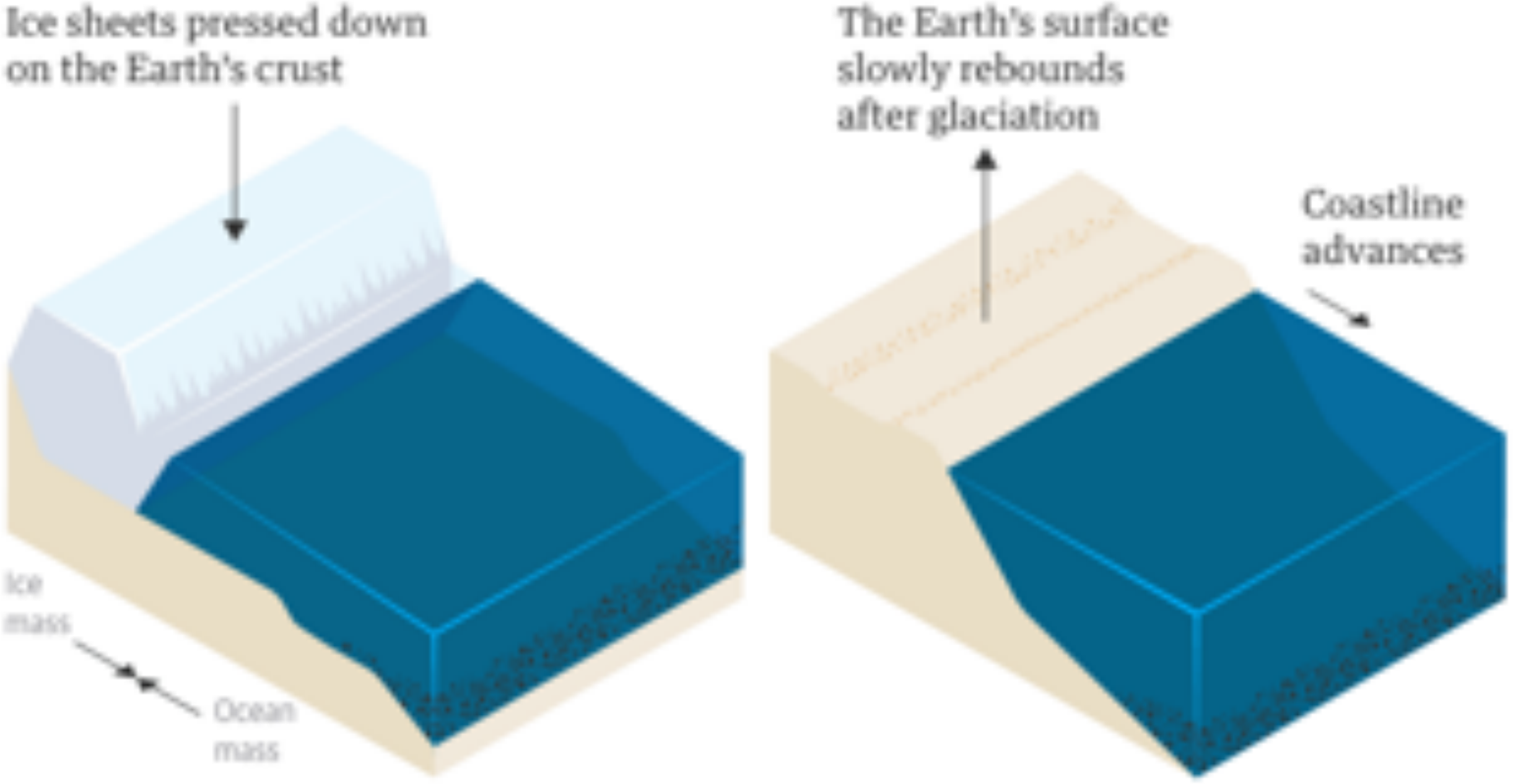


The map above illustrates relative sea level trends , with arrows representing the direction and magnitude of change. Click on an arrow to access addit

NOAA SL trends map:

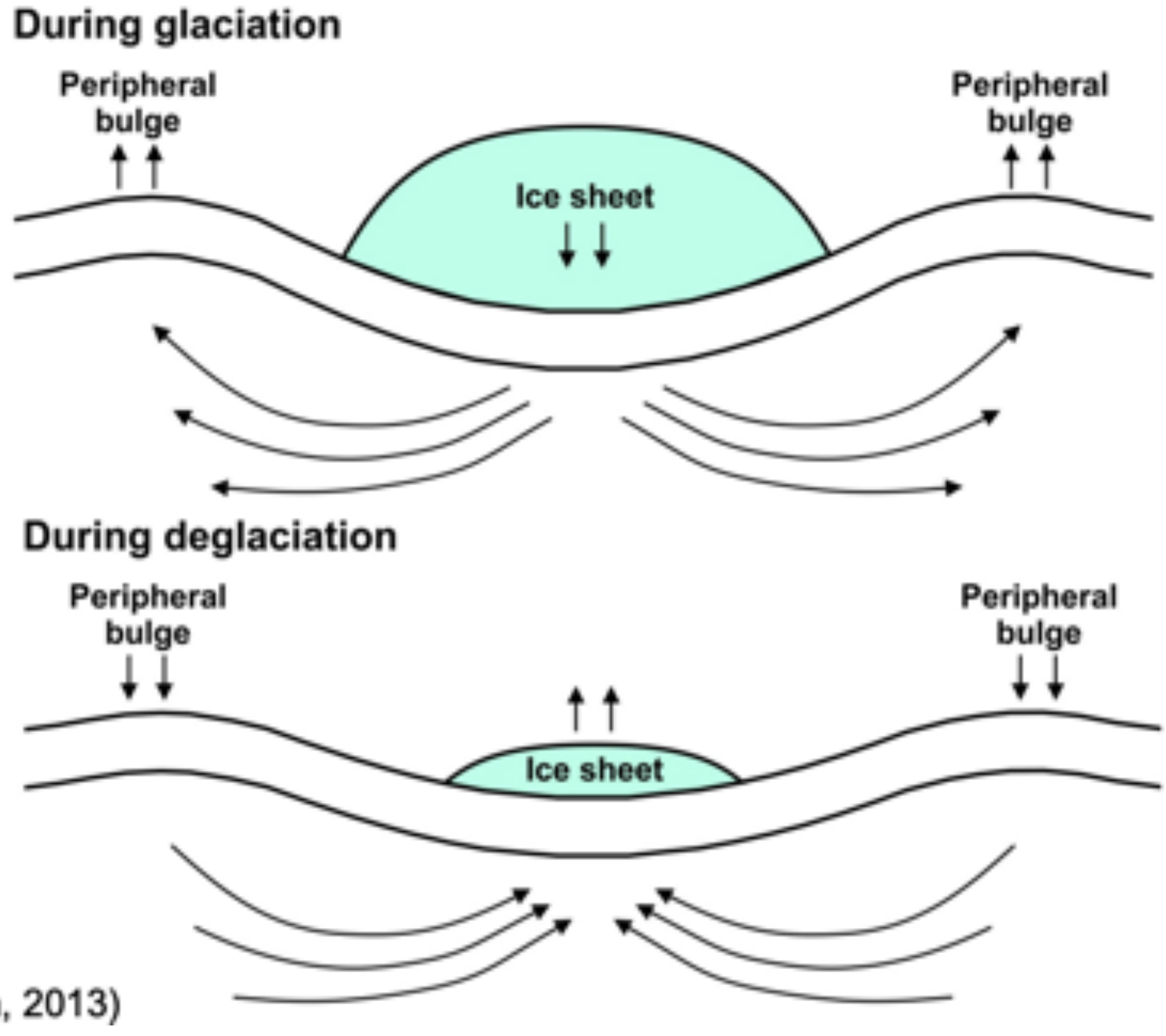
https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

Glacial rebound



Guardian graphic. Source: Dr Pippa L. Whitehouse

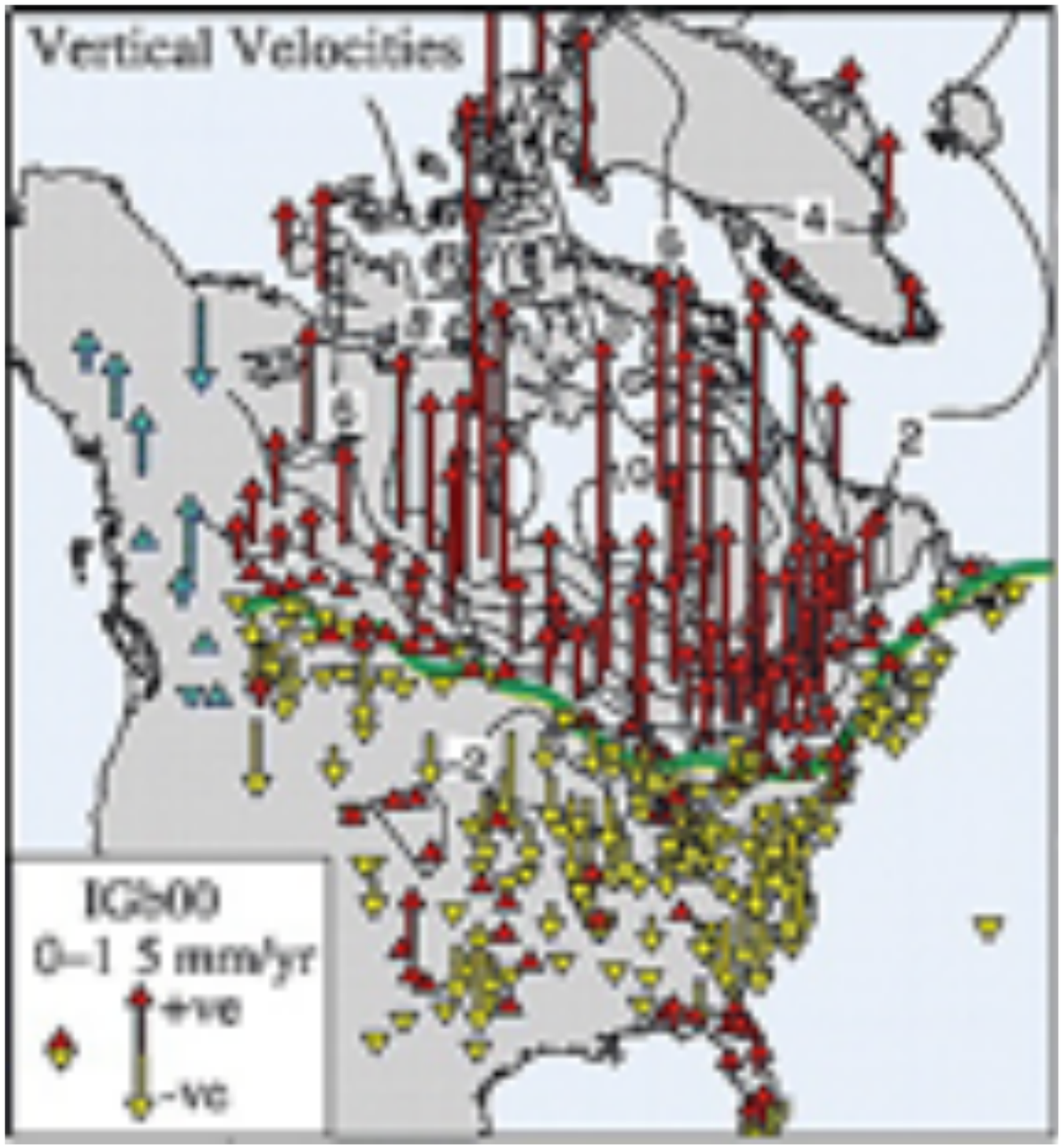
Glacial rebound



When the crustal load (ice sheet) is relaxed (deglaciated), the crust just under the former load moves up and the crust just adjacent to the former load (peripheral bulge) moves down

fen, 2013)

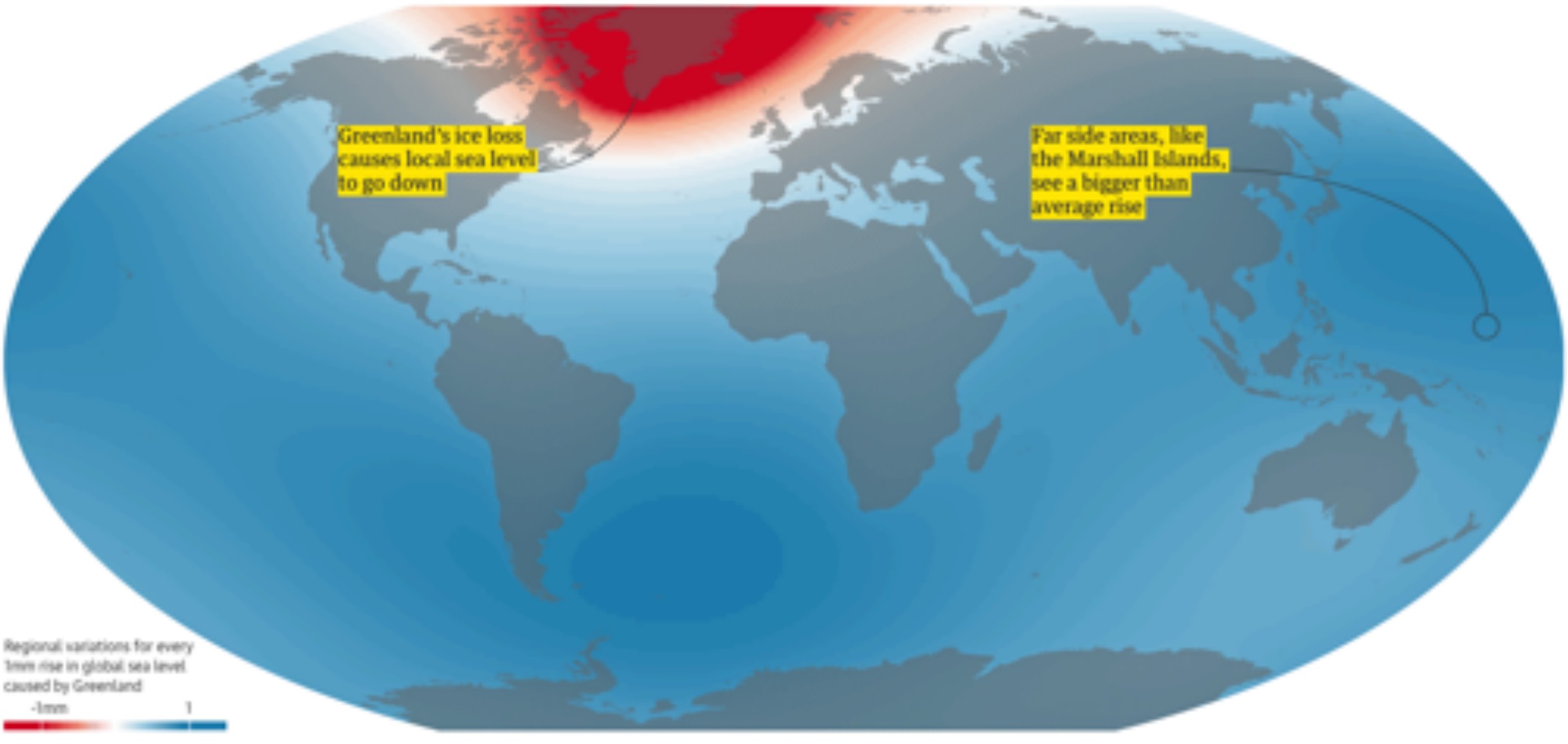
Glacial Isostatic Adjustment (GIA)



Sella et al. 2007

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

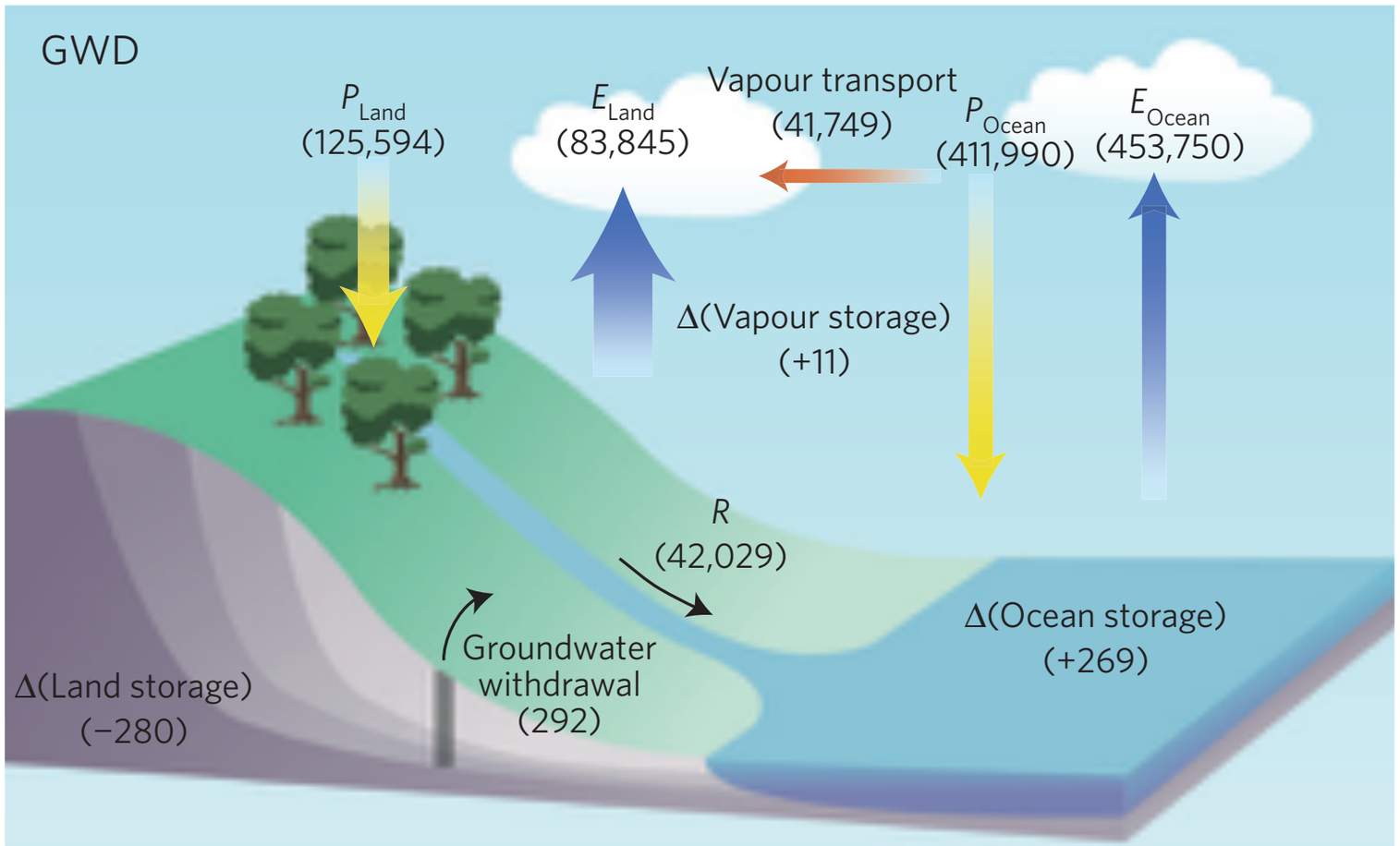
Accounting for gravity and glacial rebound, how much sea level would change if a layer of ice were melted from Greenland (1 mm of global mean SLR)



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

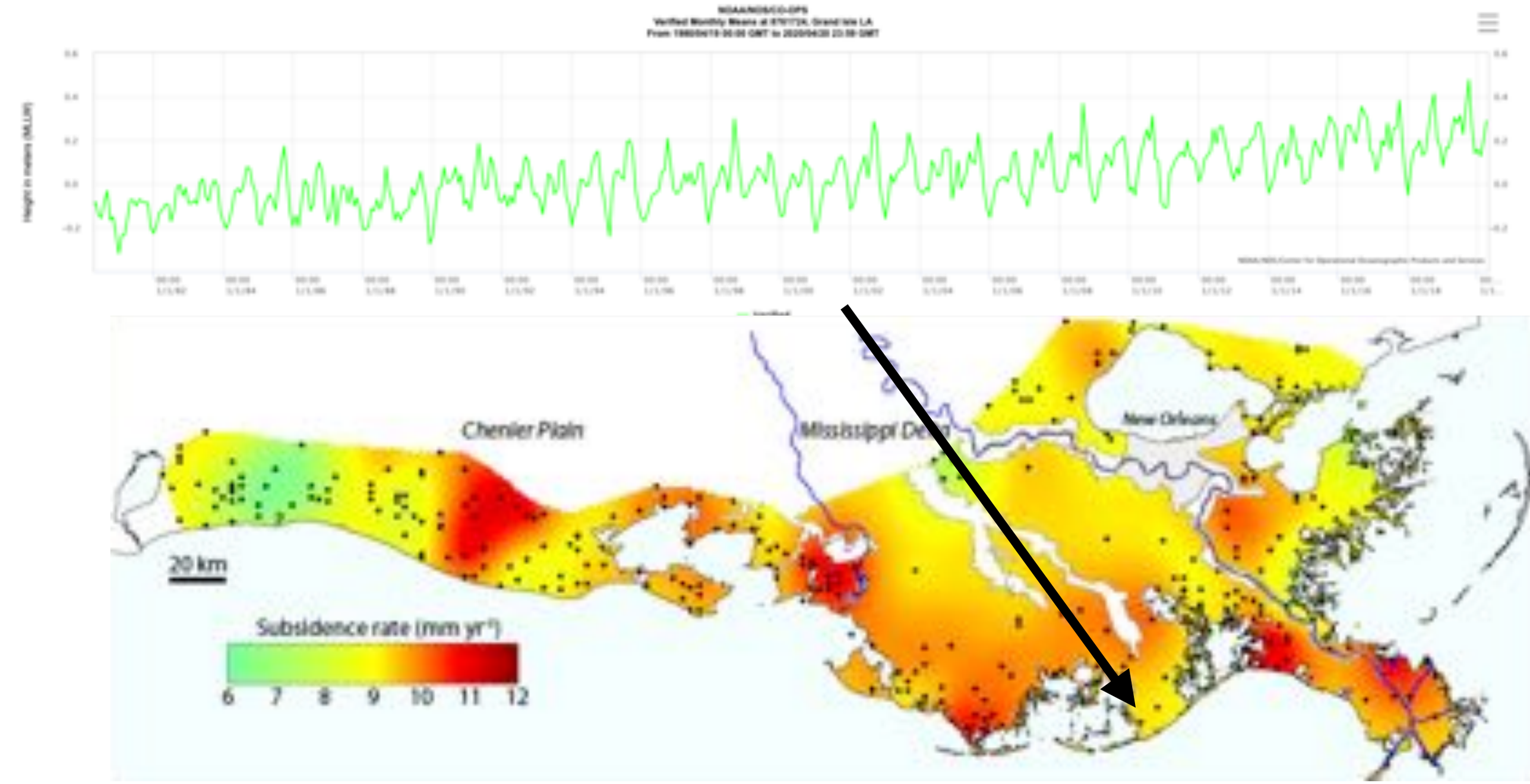
Sea level changes due to groundwater extraction

- **Water is pumped out of existing reservoirs, and then dumped in the ocean - global sea level rise**
- **Development of reservoirs leads to more water impoundment on land - global sea level fall**
- **However, the largest change is local and comes from land subsidence due to groundwater extraction**



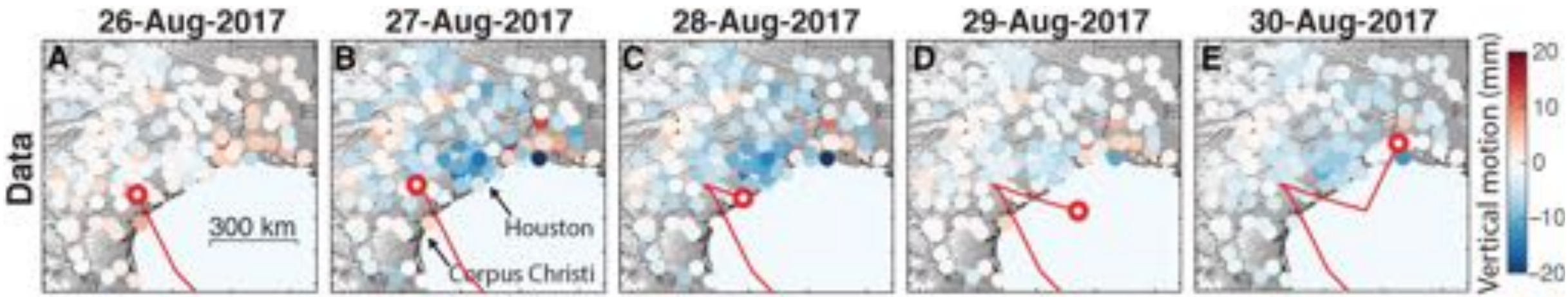
Wada et al. 2016

Sea level changes due to land subsidence



Nienhuis et al. 2017

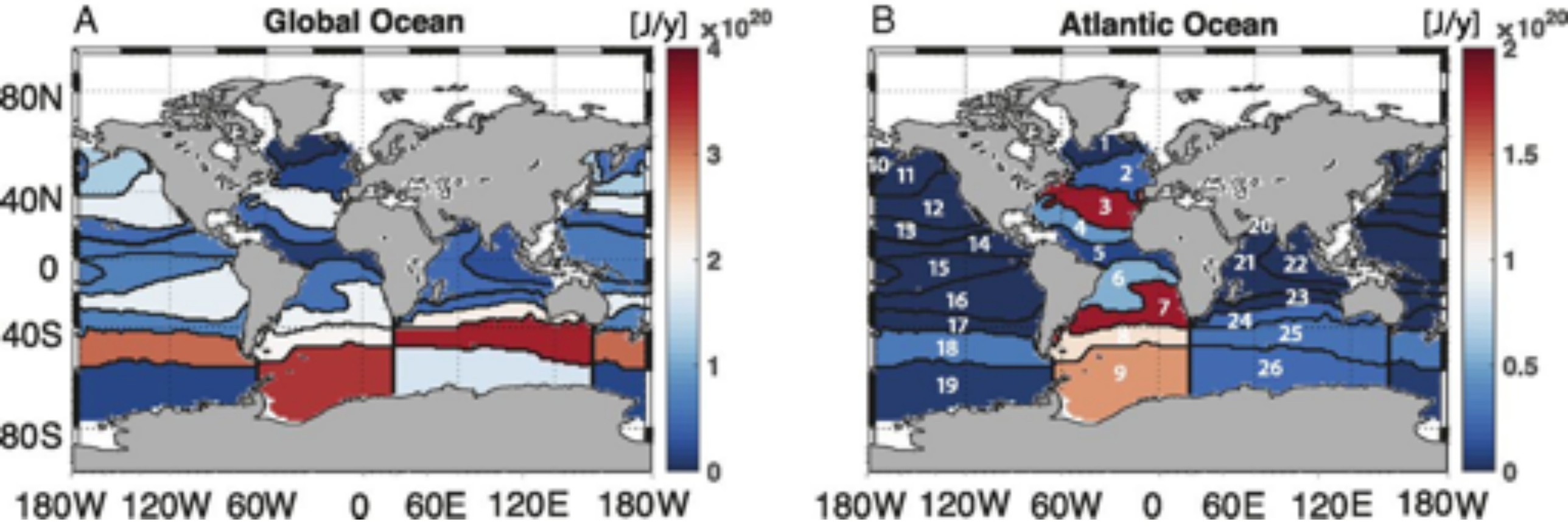
Relative sea level change due to the hydrologic cycle



Hurricane Harvey rainfall caused depression of the land surface in Texas by several cm (Milliner et al. 2017)

“Dynamic” effects

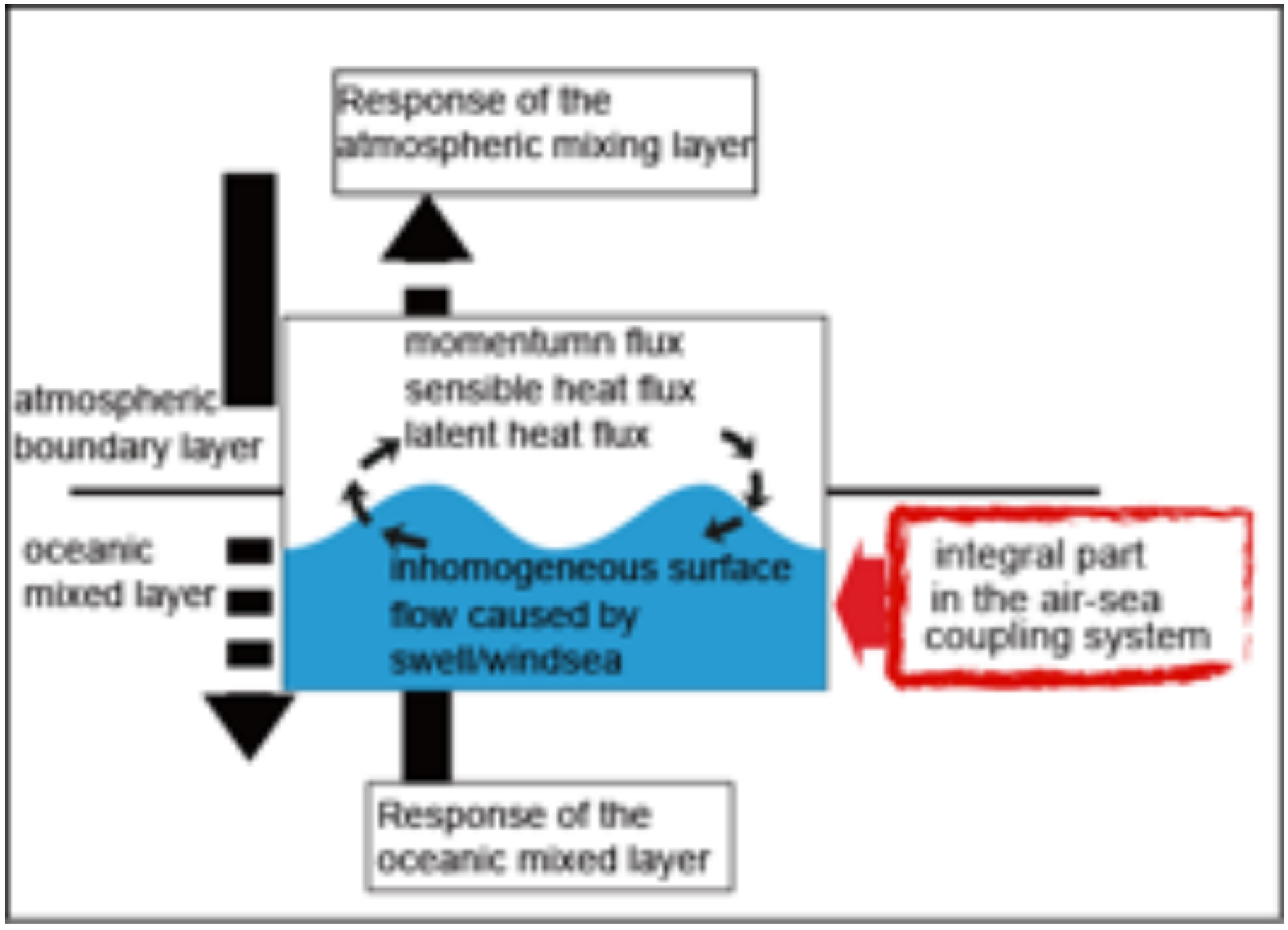
Ocean heat uptake



Zanne et al. 2019

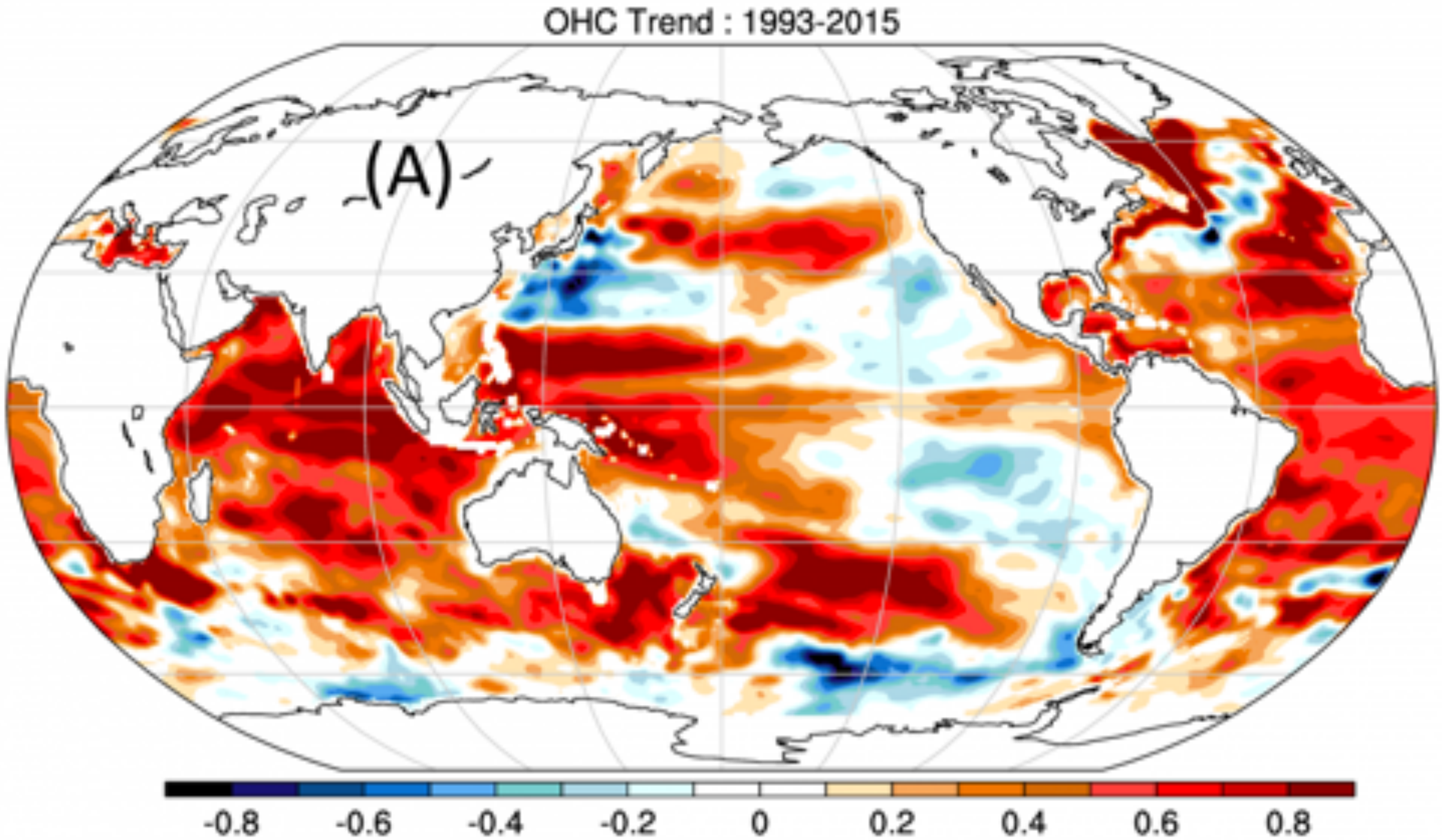
90% of the excess heat from a warming atmosphere has been captured by the ocean.

Ocean heat uptake

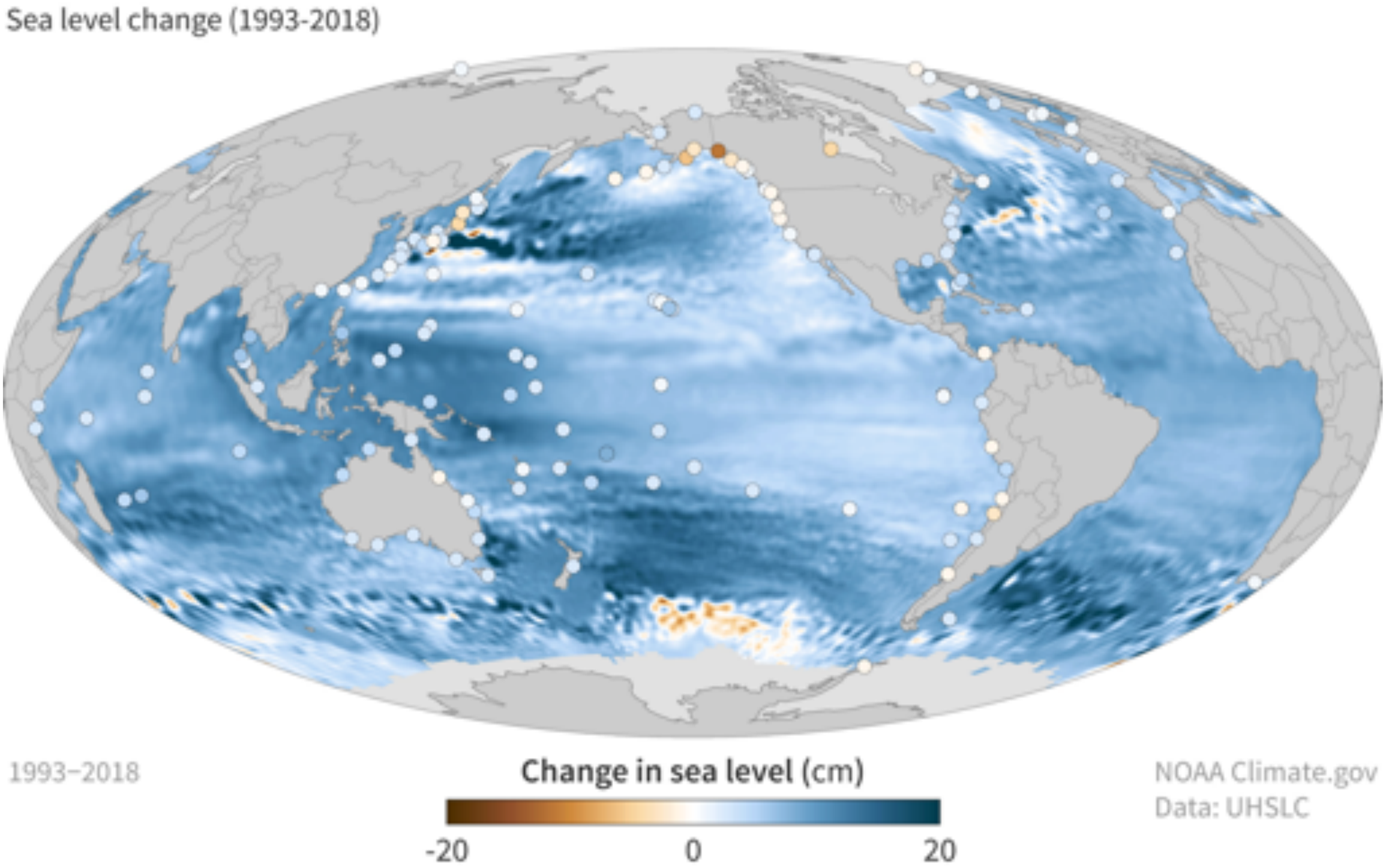


In places where the atmosphere and the ocean are different temperatures, the ocean will absorb or release heat from/to the atmosphere. The rate of heat uptake varies over space and time due to changing ocean currents and atmospheric variability.

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

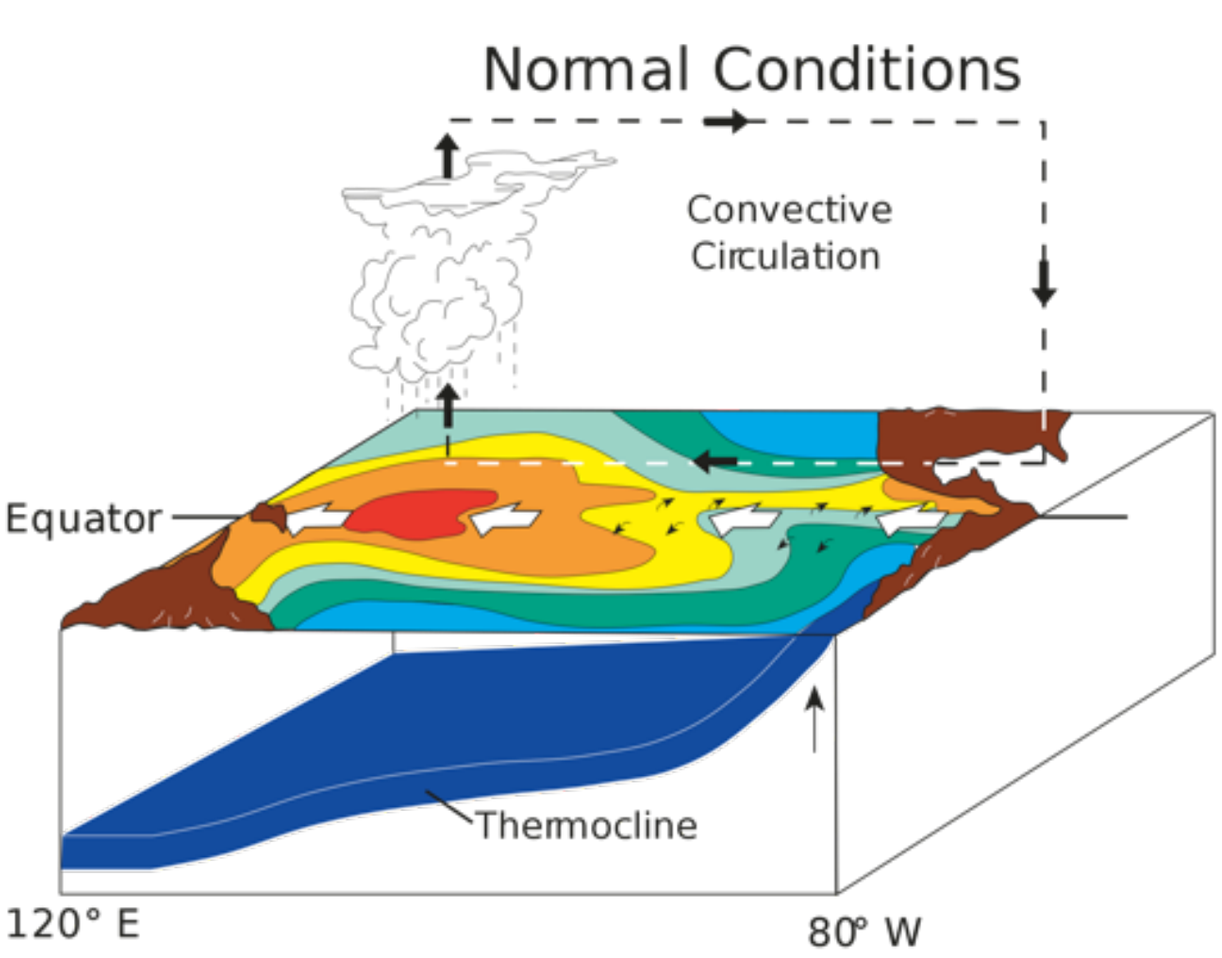


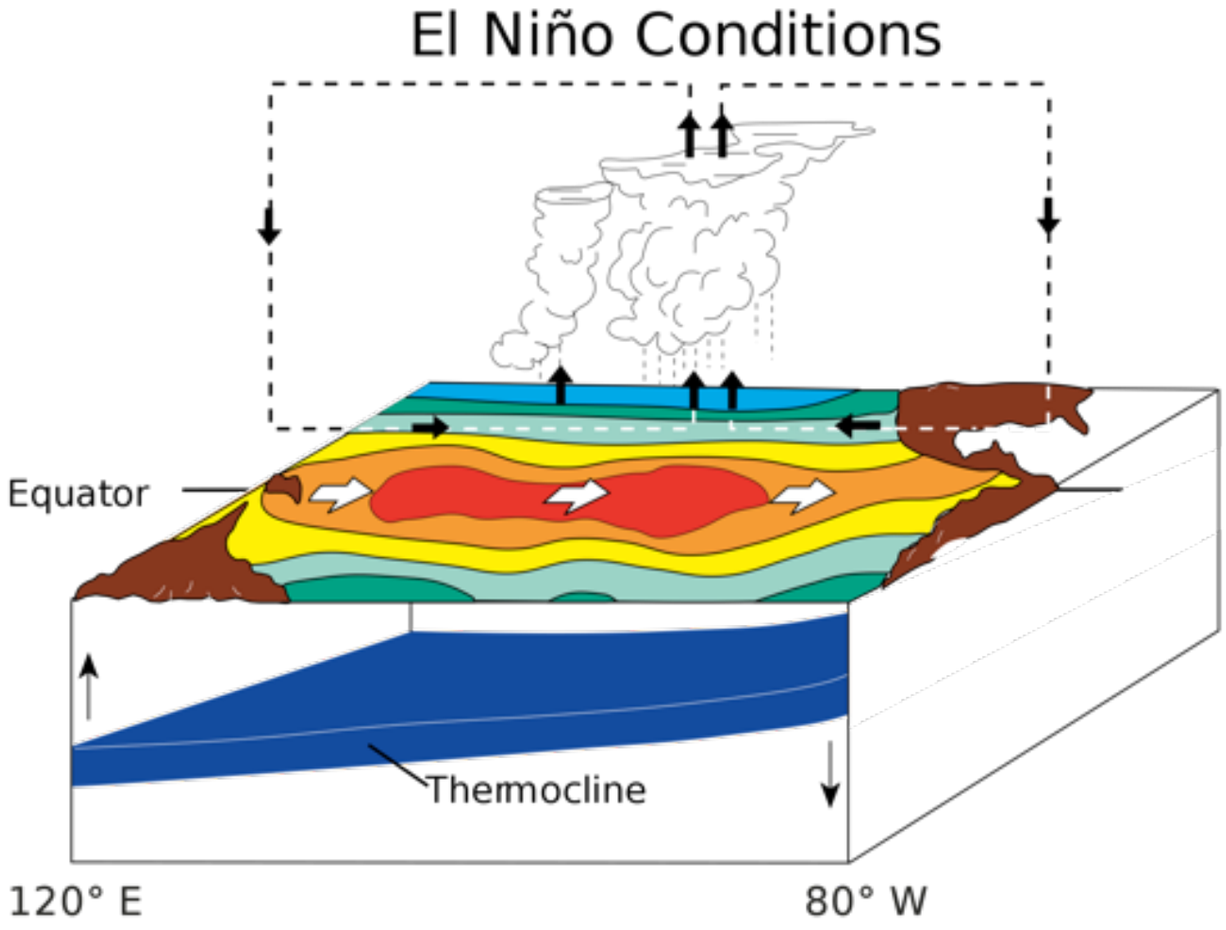
Compare again to SLR map



Temporal sea level variability

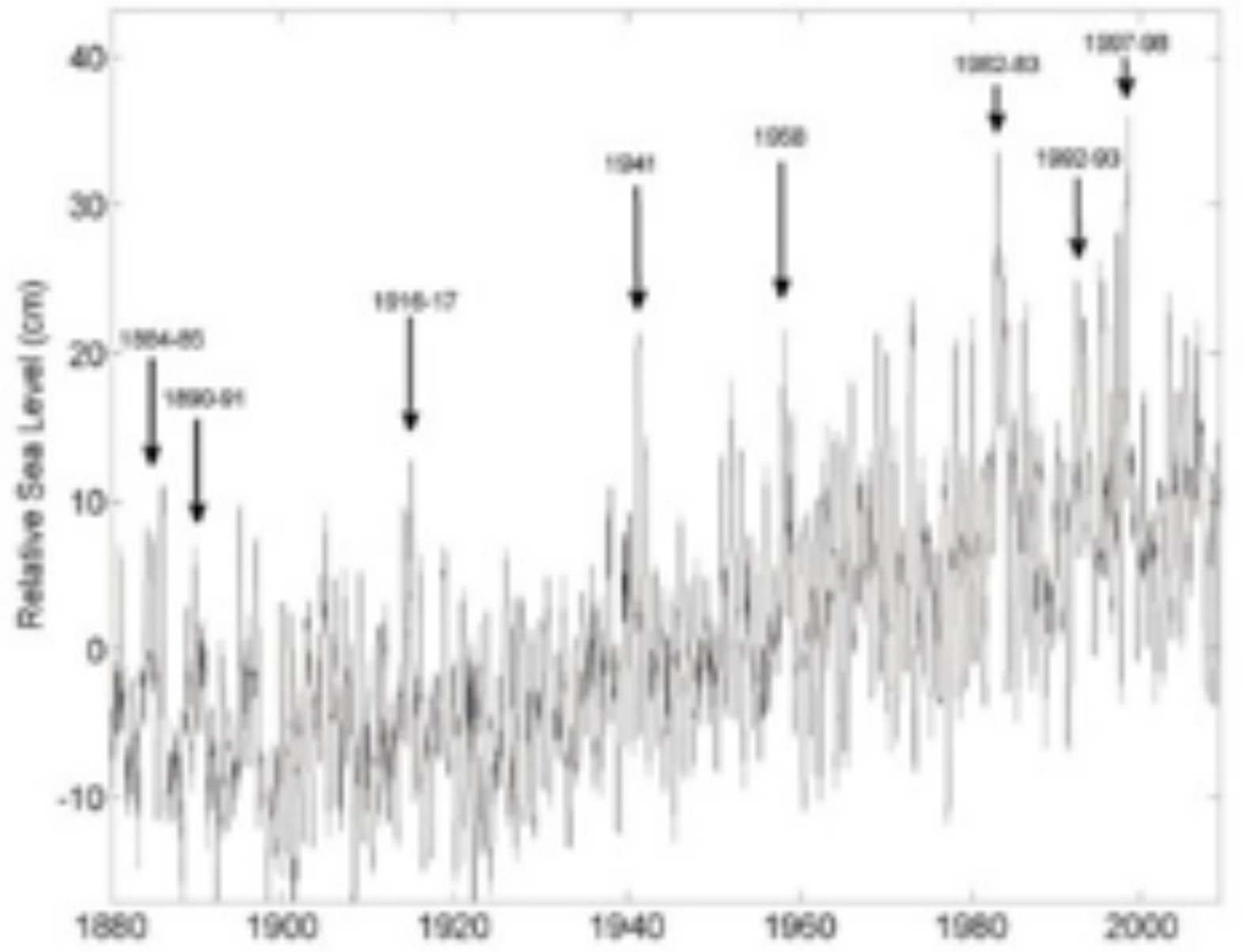
Recurring coupled ocean-atmosphere patterns and effects on sea level





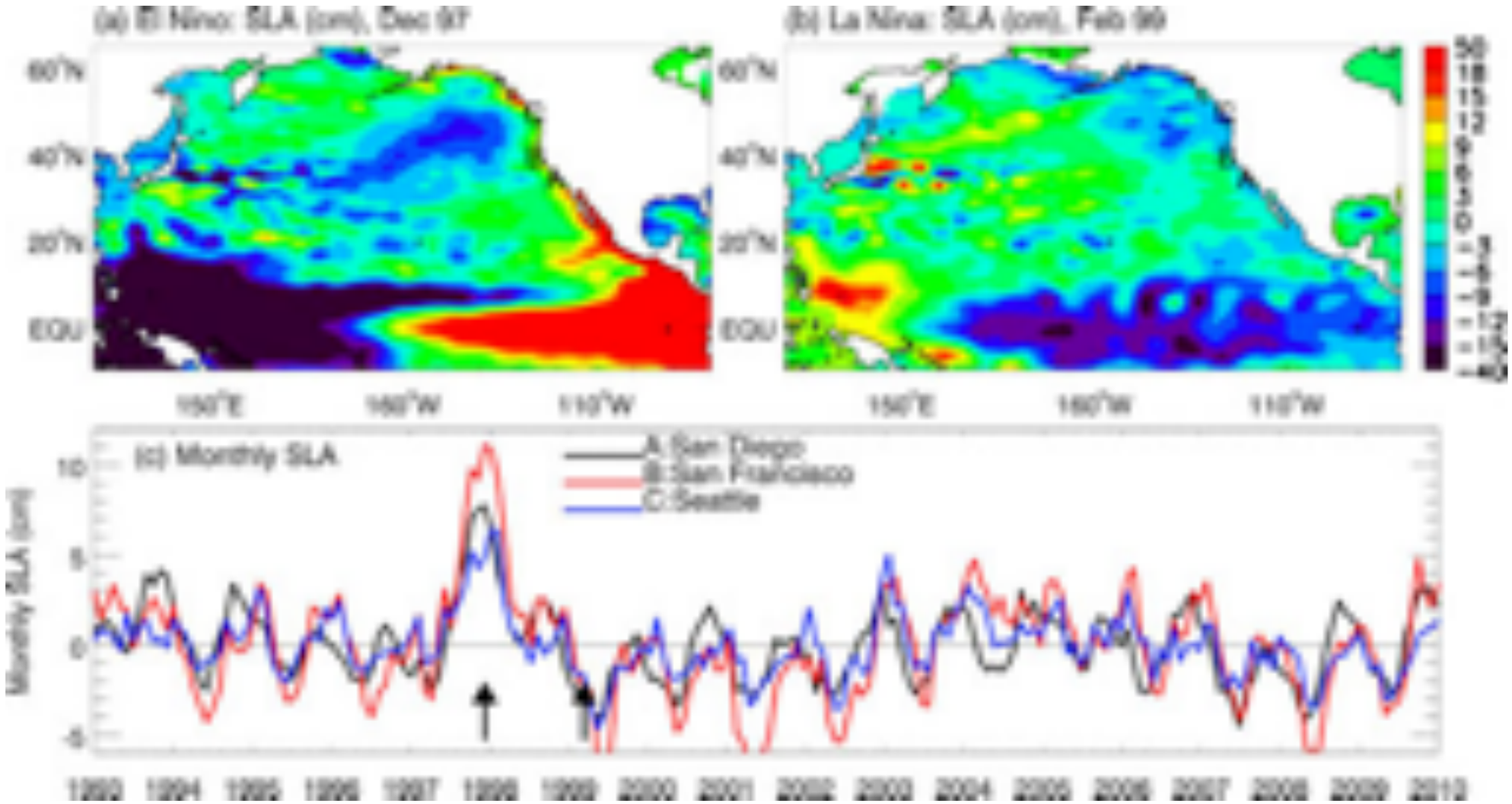
The El Nino - Southern Oscillation (ENSO) is a warming of the central/eastern Pacific ocean that occurs every 2-7 years. In many parts of the world (especially tropics/subtropics), ENSO is the single large signal of climate variability besides the seasonal cycle

Recurring coupled ocean-atmosphere patterns and effects on sea level



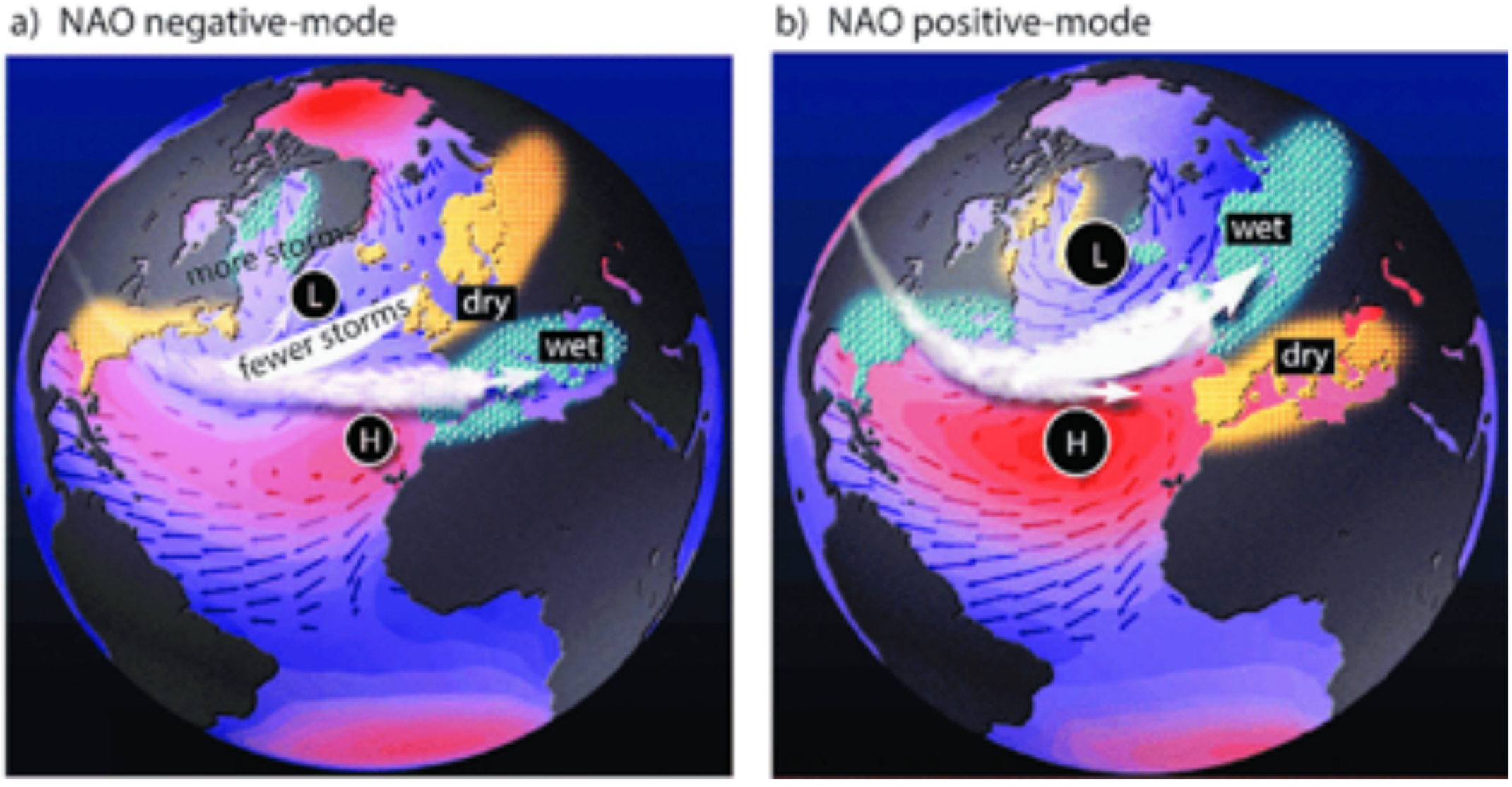
Tide gauge data from San Francisco shows that in addition to the long term SLR trend of ~15 cm/ century, ENSO can lead to large multi-annual sea level spikes of 20+ cm

Recurring coupled ocean-atmosphere patterns and effects on sea level



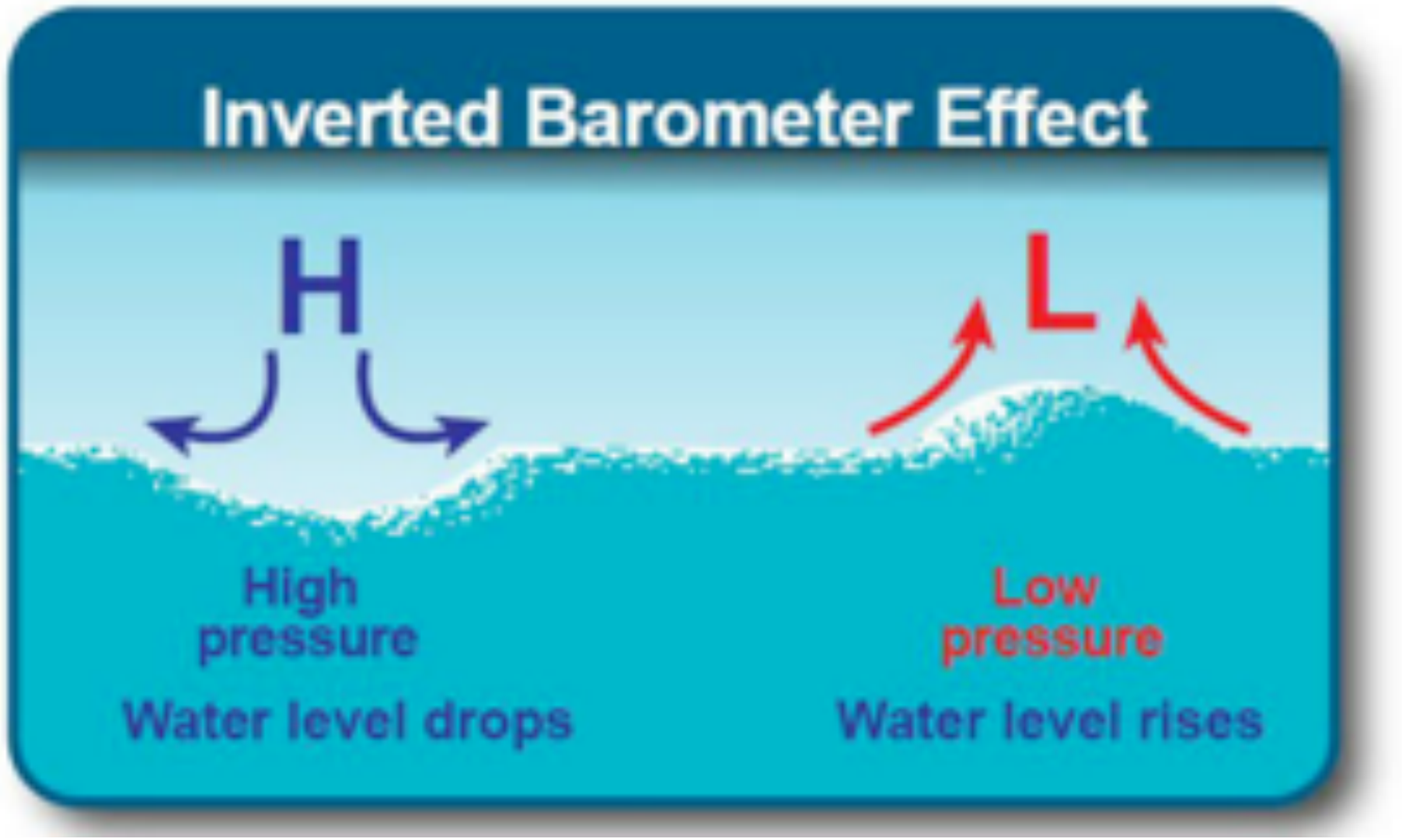
El Nino is probably the dominant sources of interannual sea level variability at coasts around the Pacific Ocean

Recurring coupled ocean-atmosphere patterns and effects on sea level

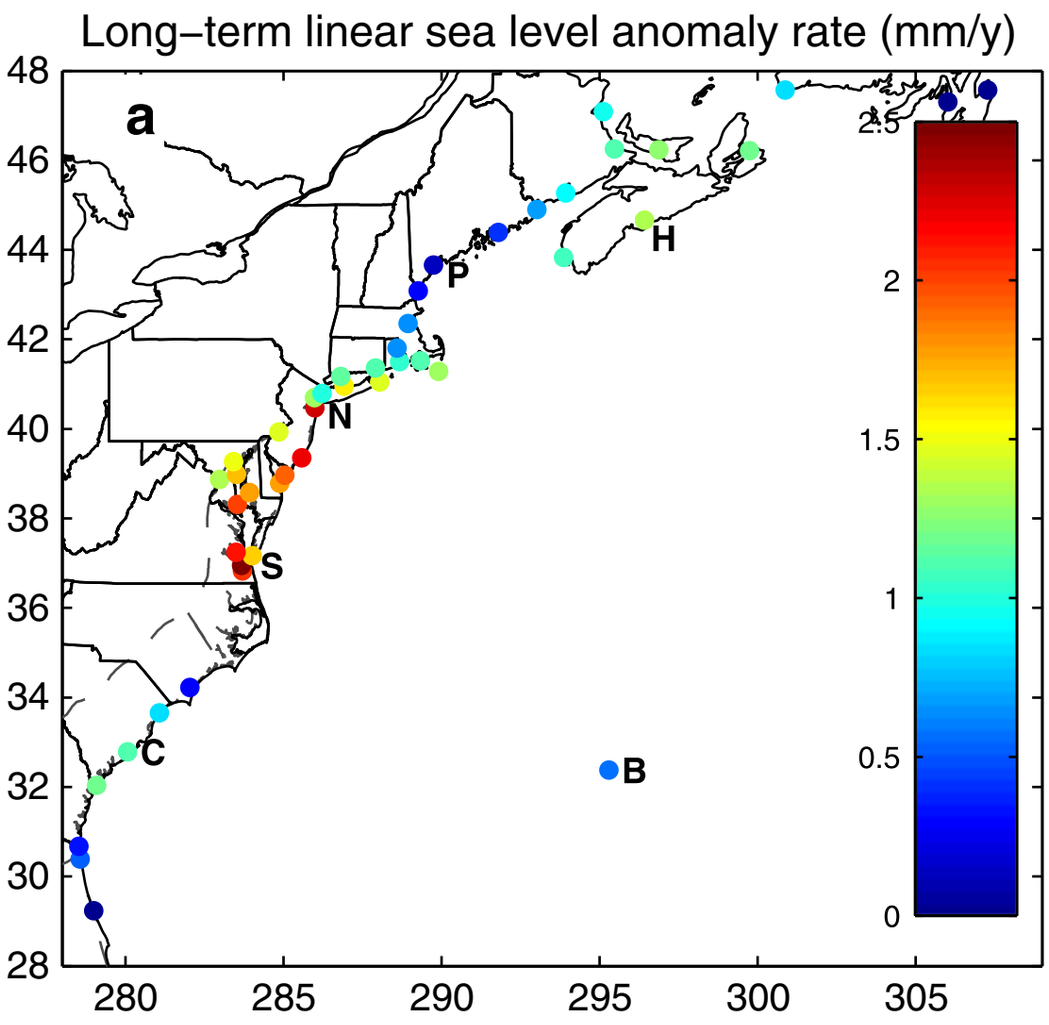


The North Atlantic Oscillation causing climatic variations over interannual to decadal time scales and is primarily distinguished by a variation in the Azores high pressure - the dominant high pressure system that sits over the Atlantic

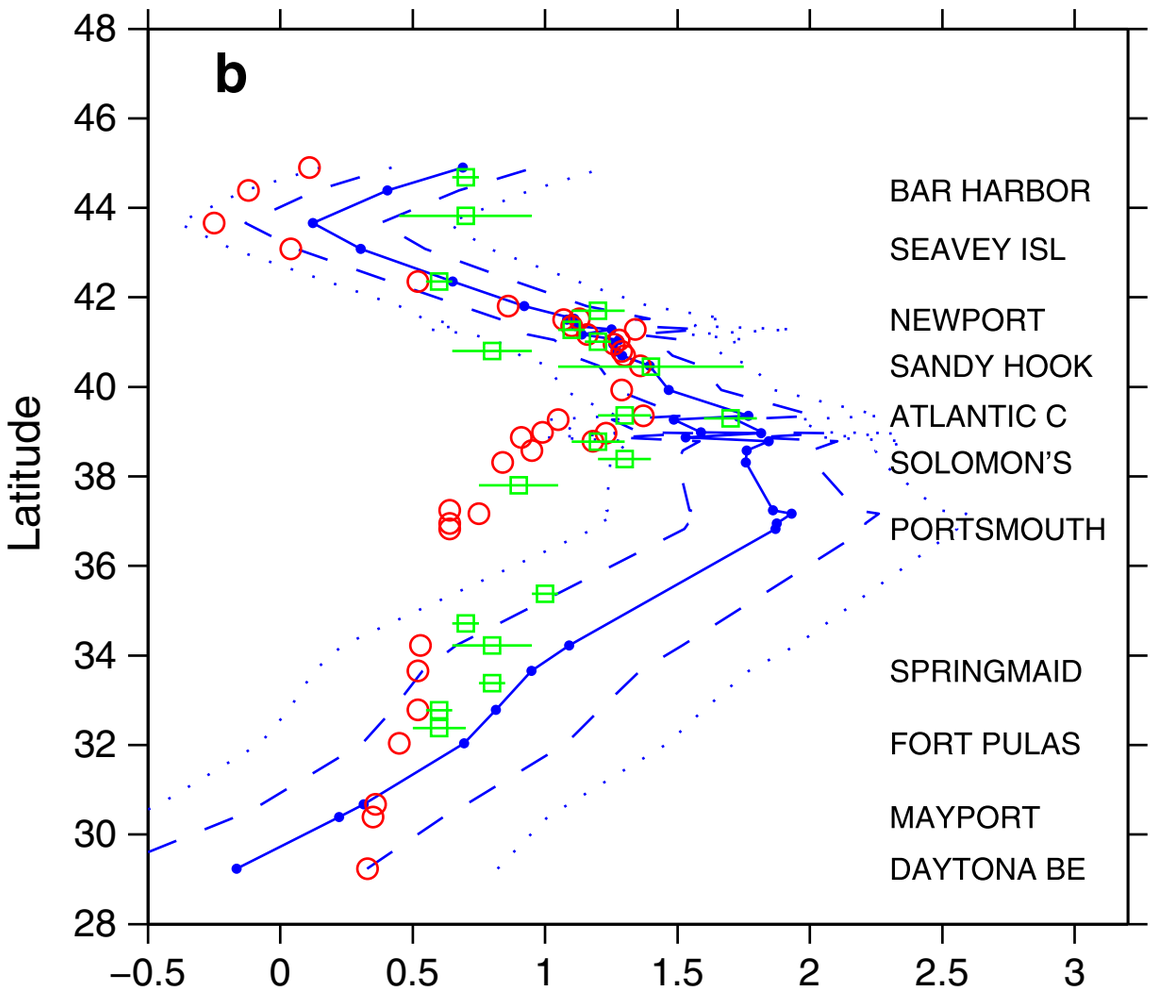
The inverse barometer effect



Recurring coupled ocean-atmosphere patterns and effects on sea level



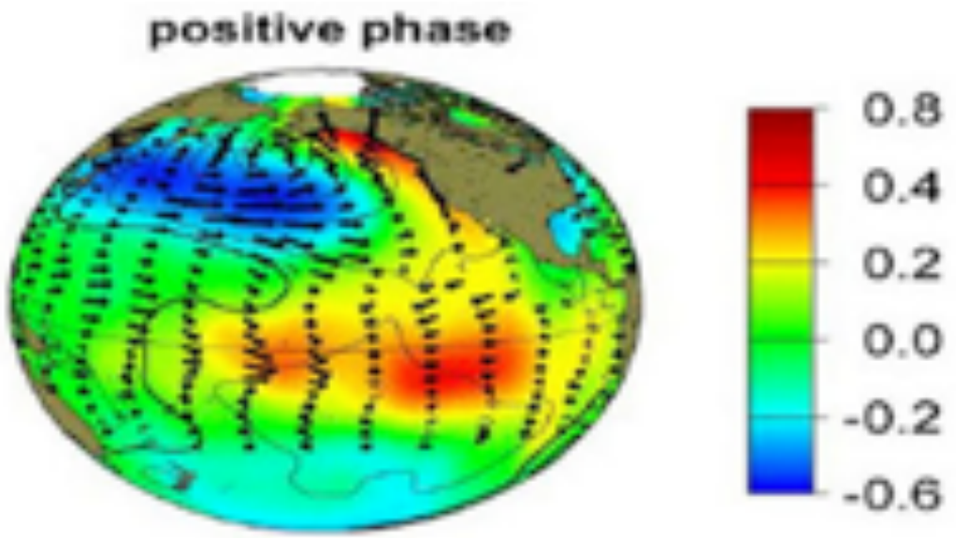
Kopp et al. 2013



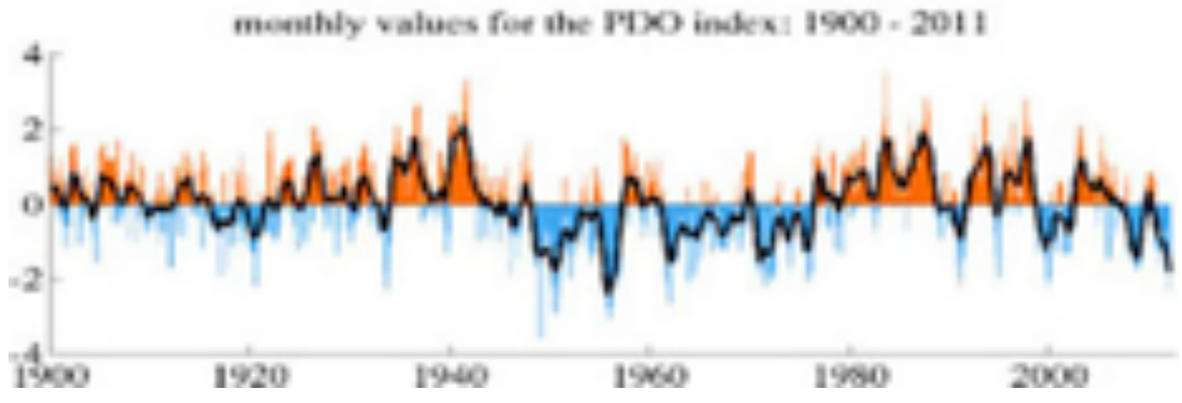
Regional linear sea level anomaly rates along U.S. coast (blue; dashed/dotted = 67%/95% confidence intervals), compared to ICE-5G projections of GIA rates (red) [Peltier, 2004] and geological estimates of late Holocene SLR [Engelhart et al., 2009] (green; lines = 1[?]).

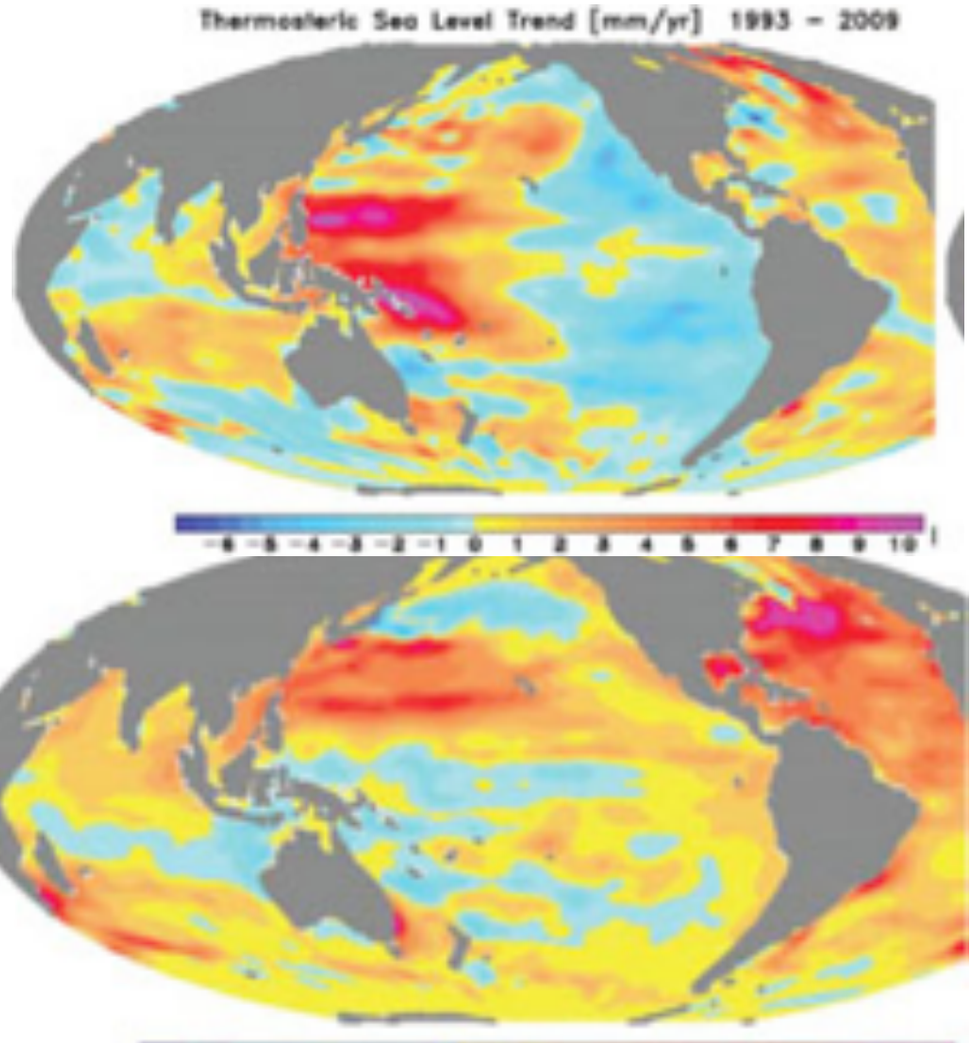
The mid-Atlantic coast has experienced almost double the rate of sea level rise over the past few decades - related to NAO and GIA

Recurring coupled ocean-atmosphere patterns and effects on sea level

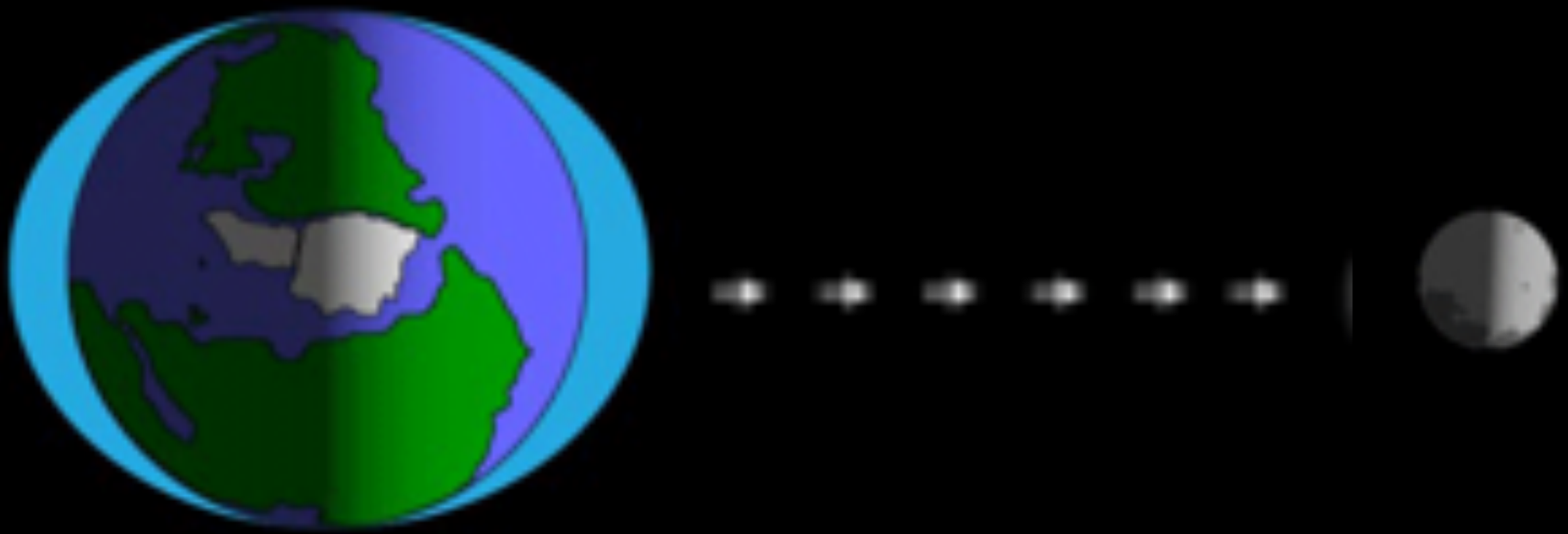


The Pacific Decadal Oscillation (PDO) is a longer-time scale pattern of ocean variability that spans more of the Pacific Ocean than ENSO. Because of the long-lived nature of these oscillations, they can have significant influence on trends calculated over short periods



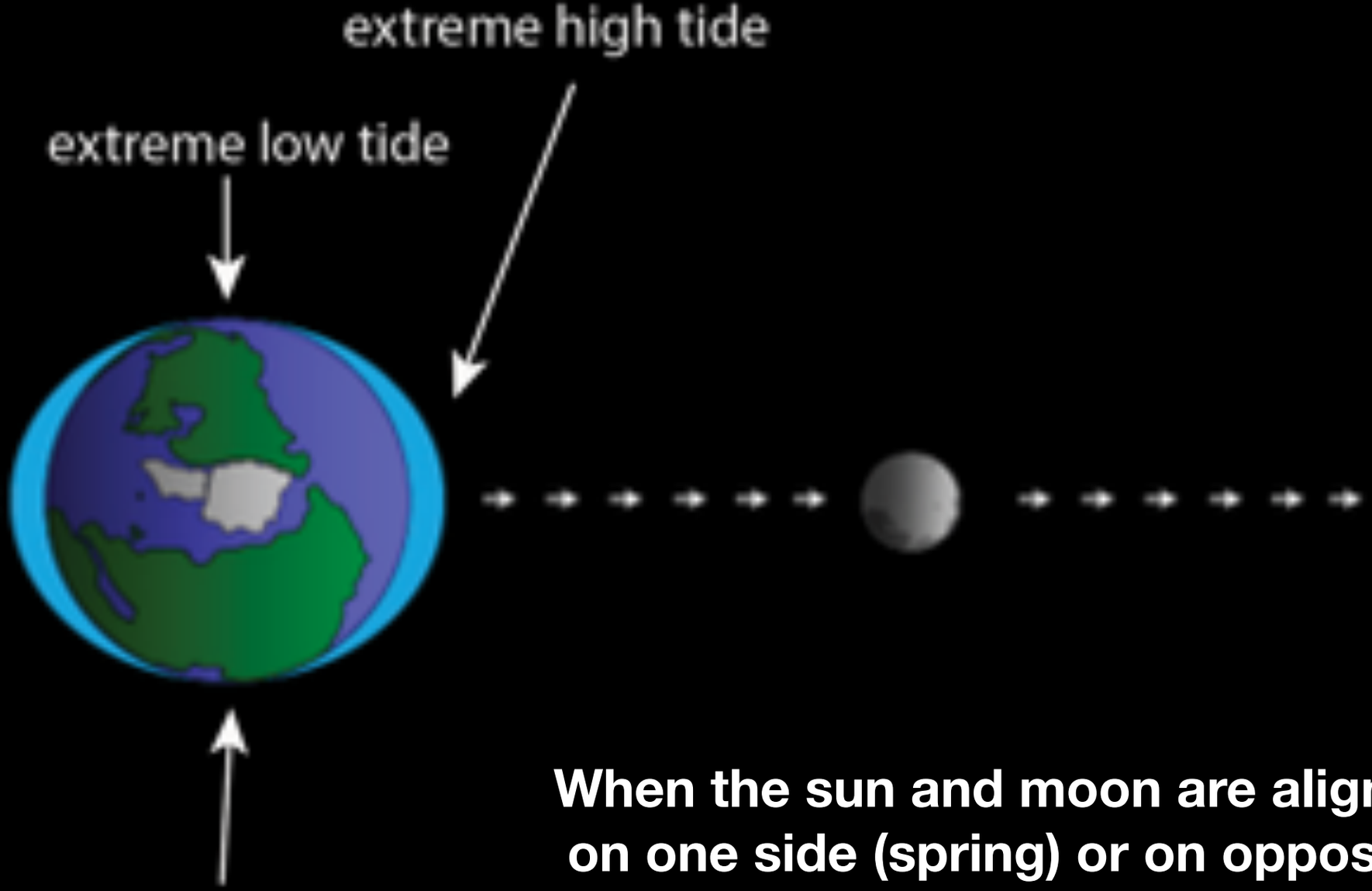


Tides



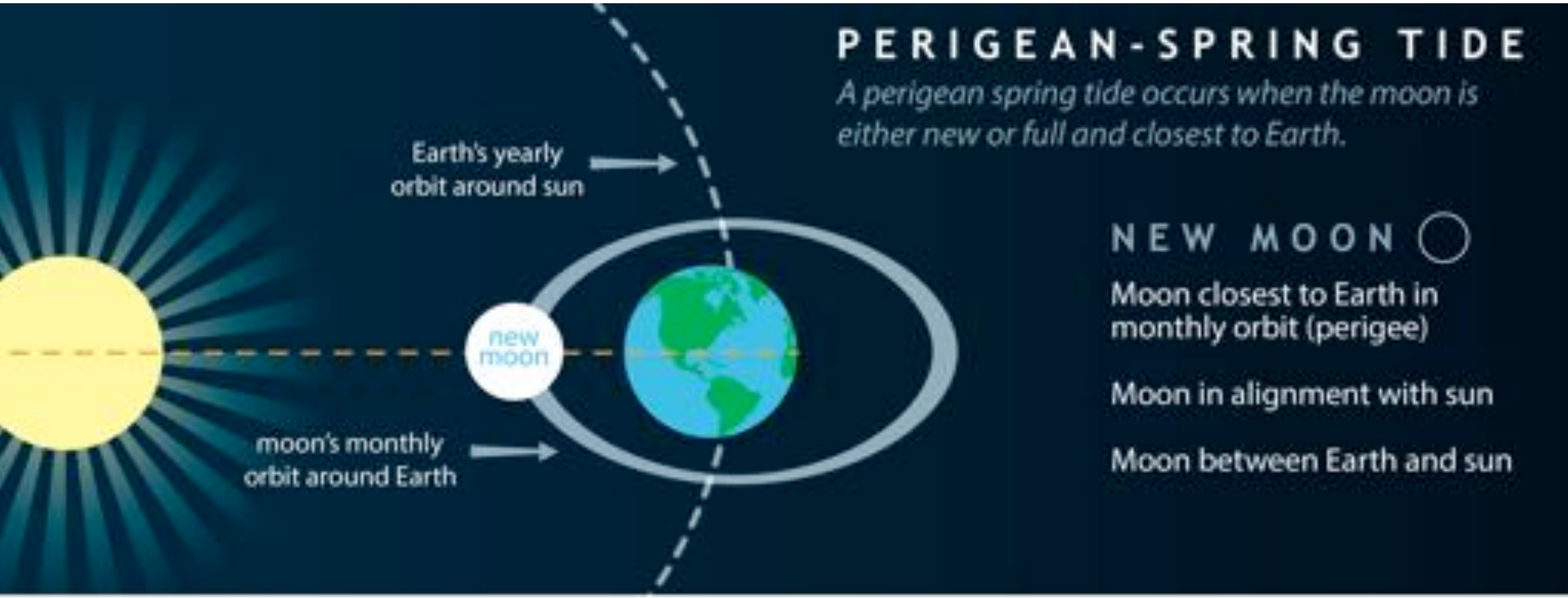
There is a tidal bulge on both sides of the earth because the gravitational pull also effects the Earth's solid shape and so squashes the far side of the Earth, producing a second tide. However, water can't flow easily everywhere because of continents, so some places have only one high tides per day)

Tides



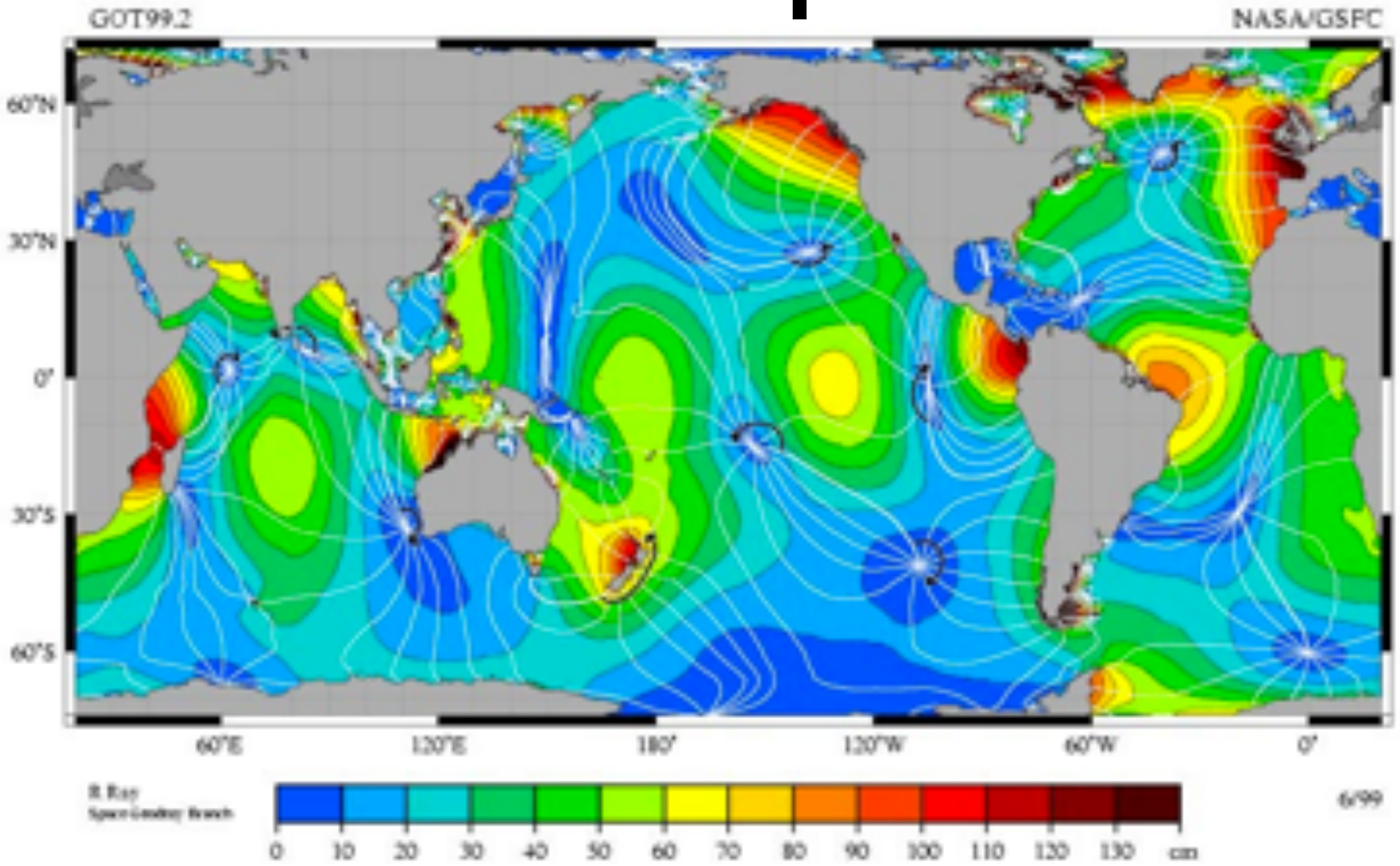
When the sun and moon are aligned on one side (spring) or on opposite sides (neap), the addition of both of their gravitational pulls causes extreme tides

Perigean-spring (King) Tides



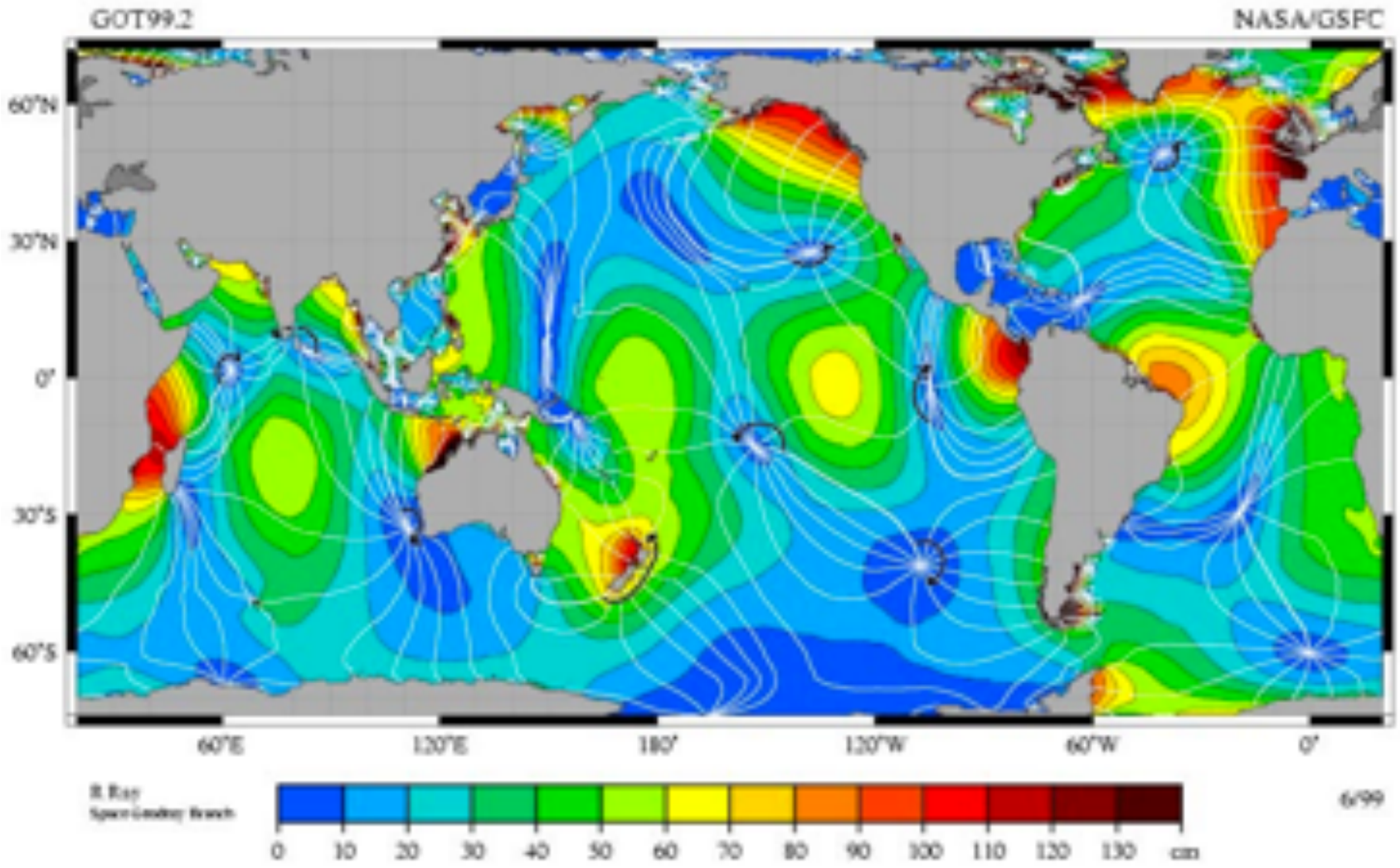
When the sun-moon-earth alignment coincides with the moon's perigee (when it is closest to earth in its elliptical orbit) – this produces a particularly extreme tide known as a perigean spring tide (or commonly, king tide) – a few times a year (though typically one will be the most extreme)

Tidal amplitude



Map of the M2 tidal amplitude - “principal lunar semi-diurnal tide” or the twice daily tide that is the largest tide in most of the world

Tidal amplitude

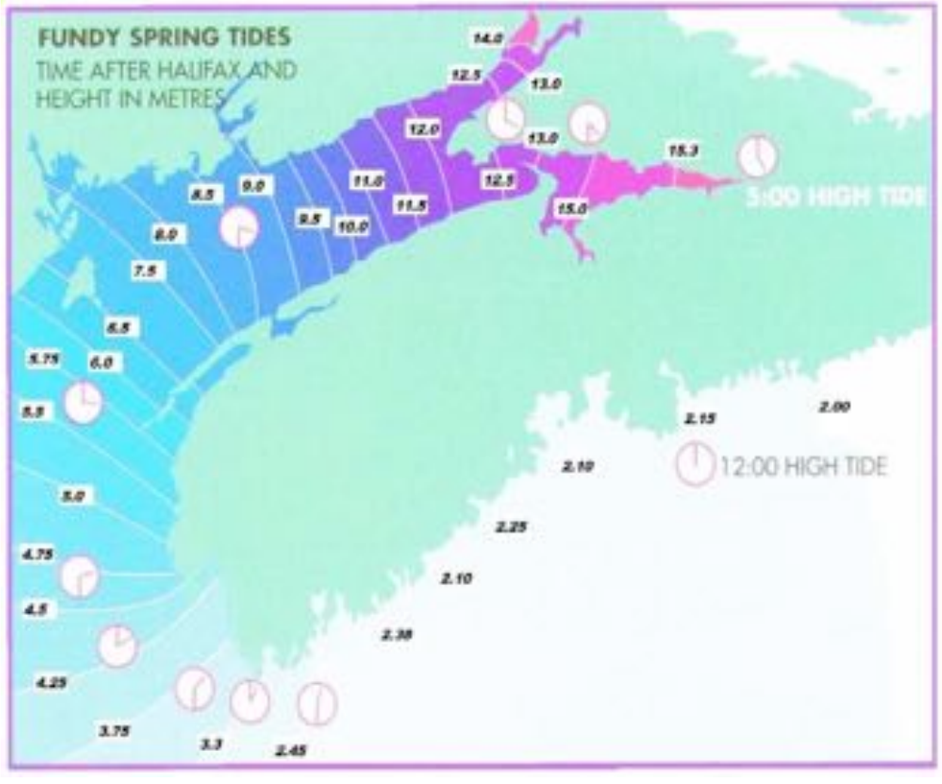


The tidal “bulge” due to gravity will push water in one direction in an ocean basin until it reaches a coast and “piles up” on shore. Thus tides tend to be higher:

1. **At the coast**
2. **In larger ocean basins**
3. **In bays that “funnel” tides**

Tidal amplitude

Tidal amplitude at the Bay of Fundy in Nova Scotia reach 15+ meters

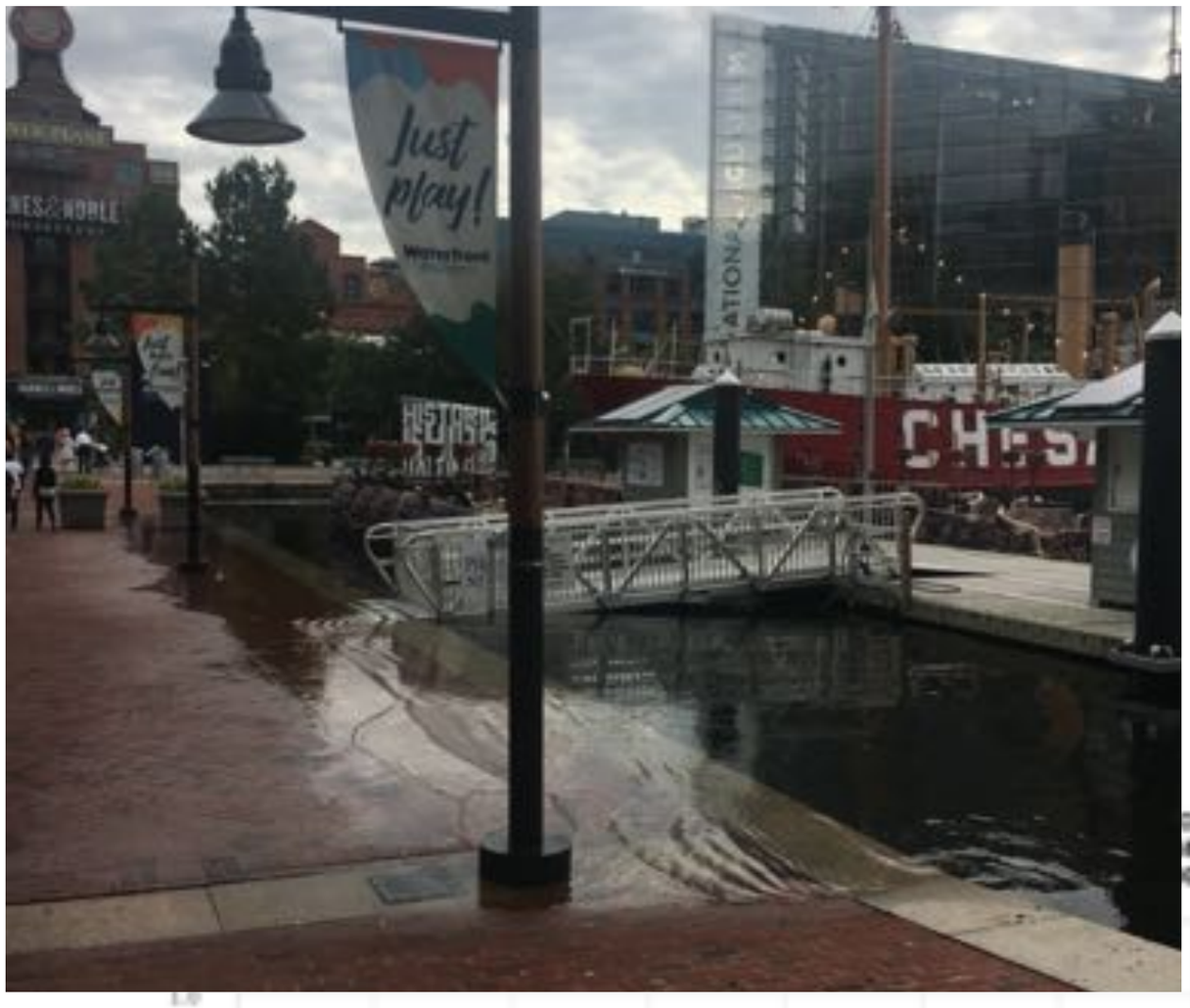


“Sunny-day” flooding

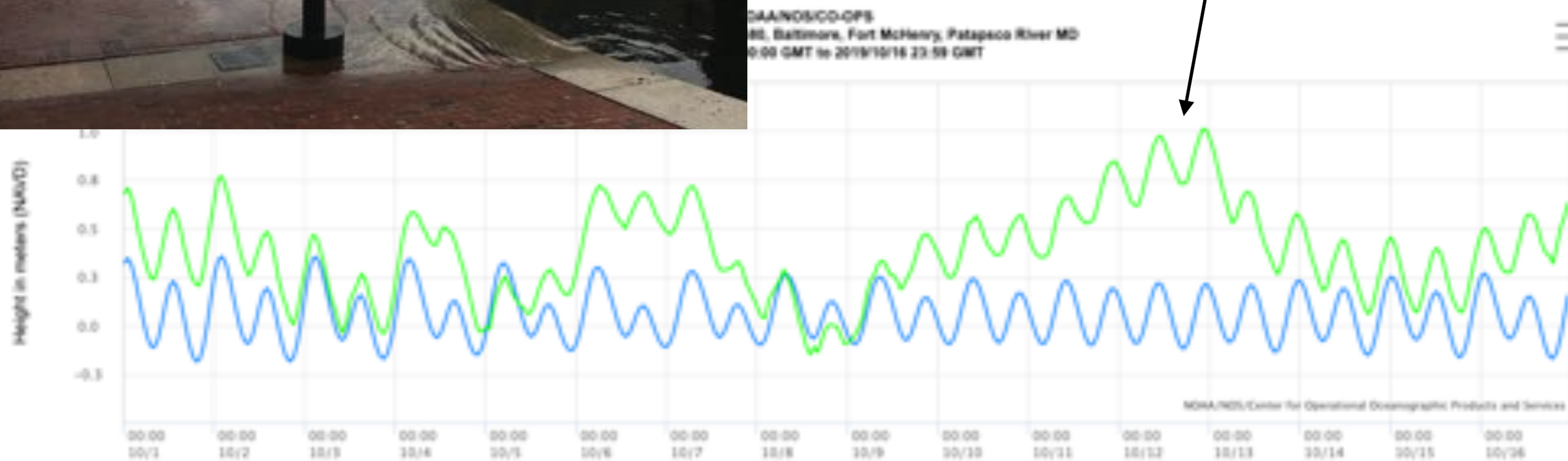
Downtown Miami on a sunny day

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

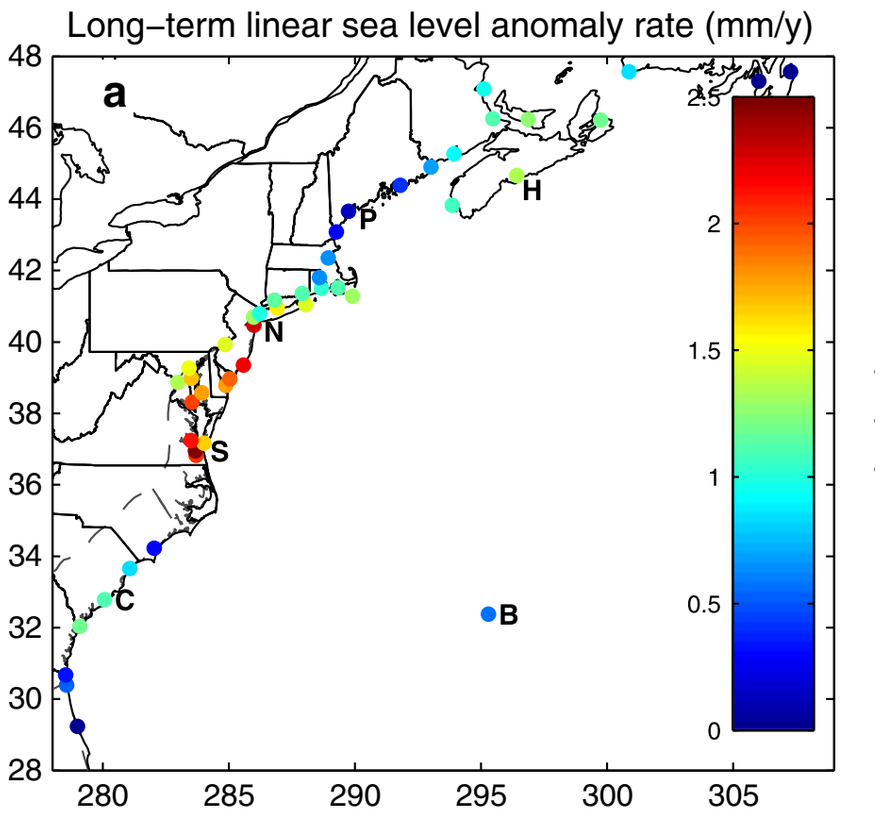
“Sunny-day” flooding



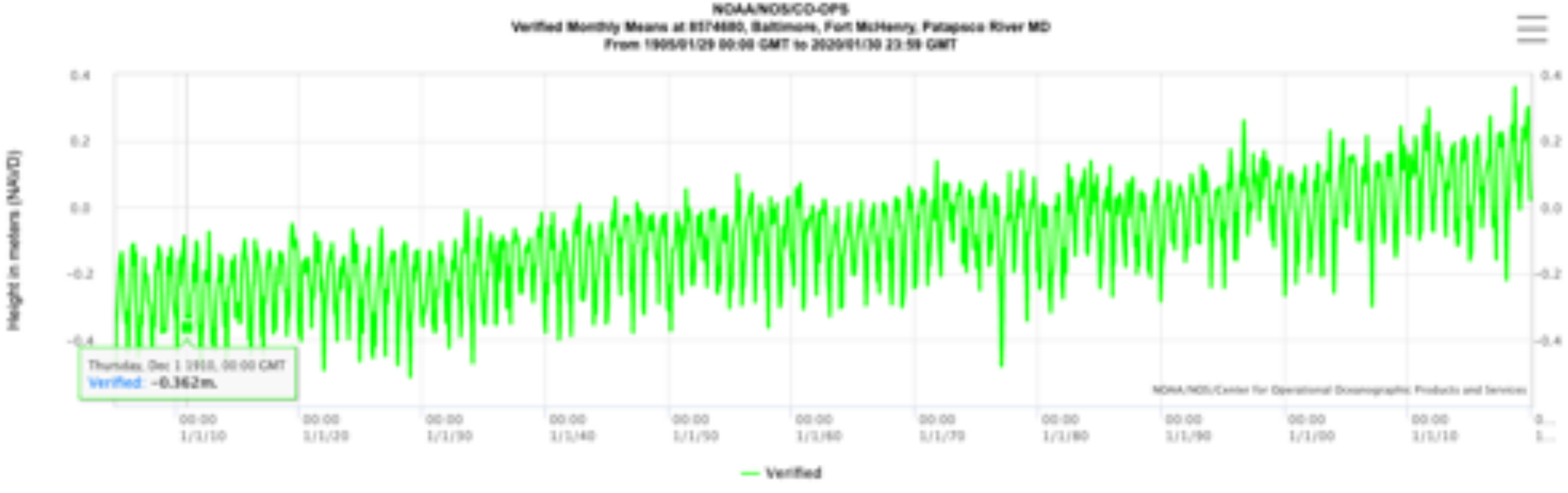
My not very good picture from Baltimore Harbor in October 2019 - not even high tide



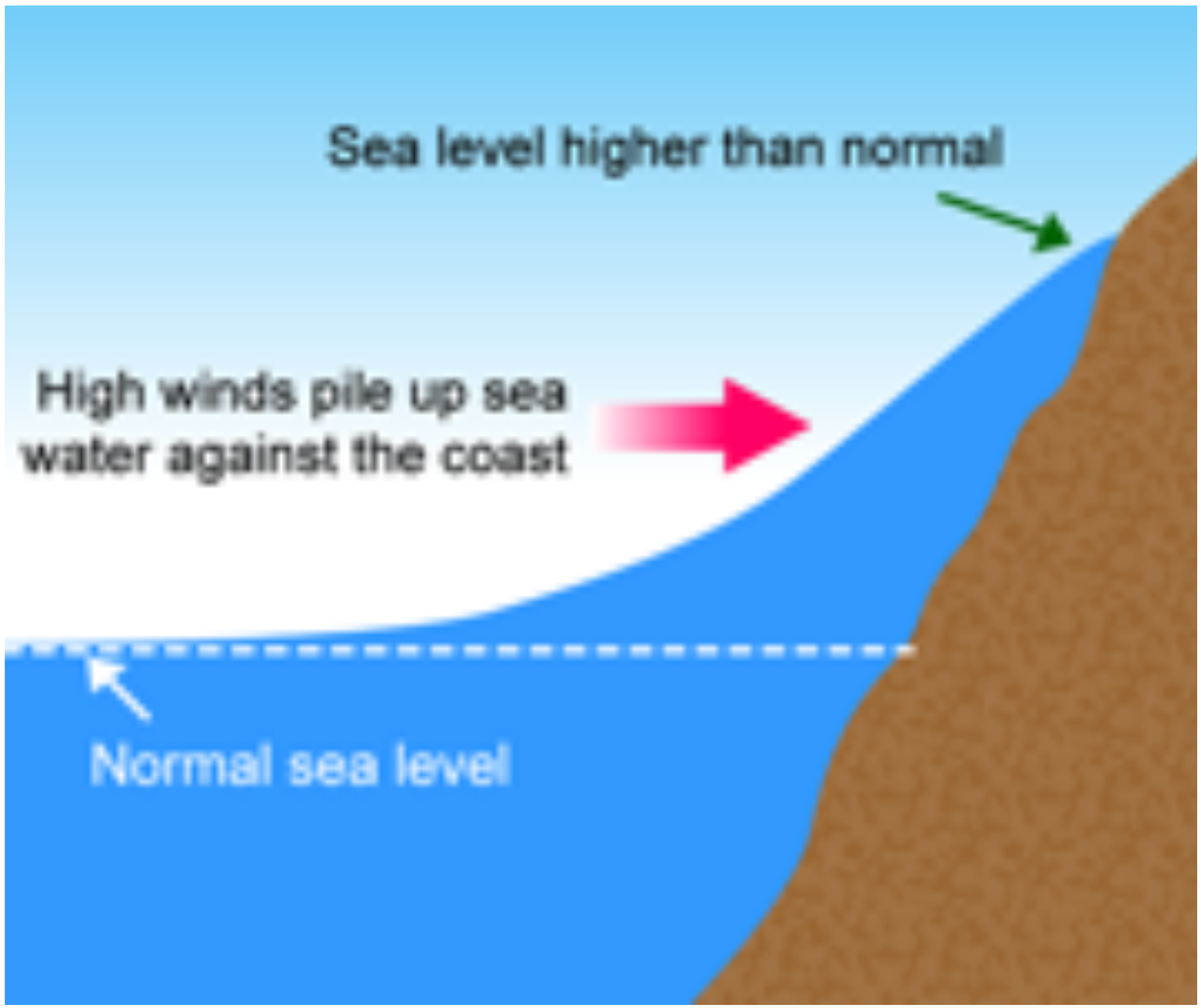
“Sunny-day” flooding



Baltimore Tide Gauge (running since almost 1900!)



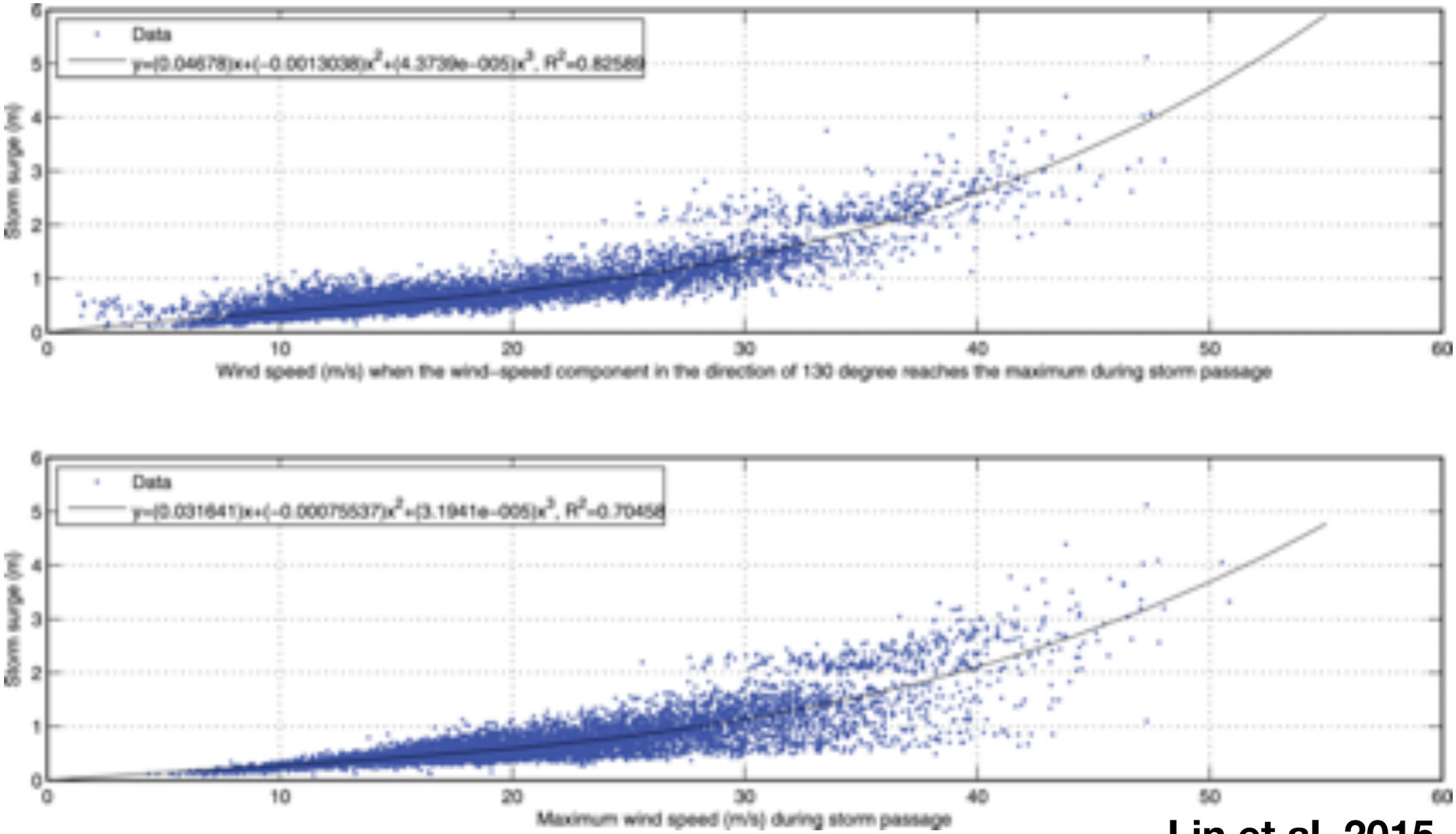
Storm (or high wind) surge events



Winds from a tropical storm making landfall or simply a day with high onshore winds pile up water against the coast and produce flooding - in low lying coastal areas are often the most damaging part of storms (inverse barometer plays a much smaller role)

Factors influencing storm surge height

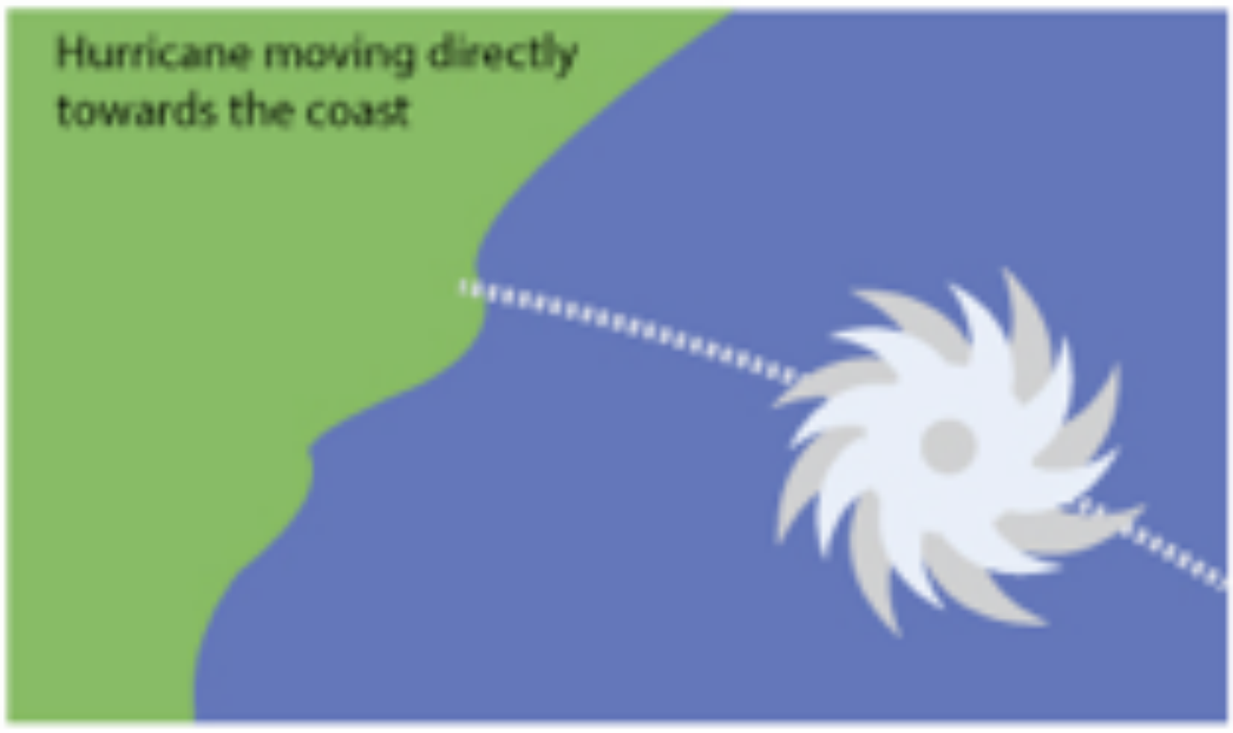
1. Wind speed and speed relative to coast



Lin et al. 2015

Factors influencing storm surge height

2. Coastline geography/shape: angle and speed of storm relative to coastline

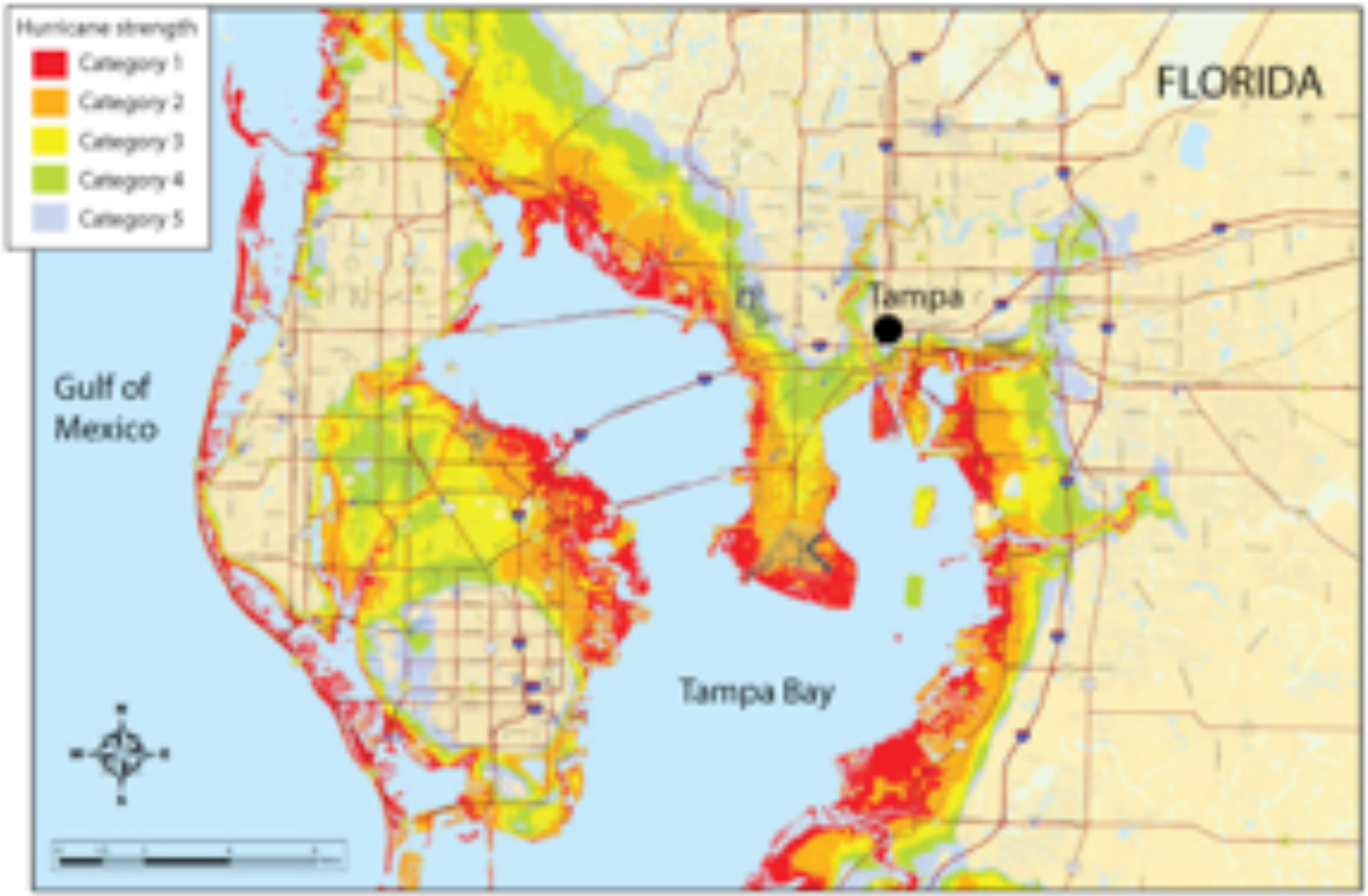


When a hurricane approaches the coast directly it is likely to cause a larger storm surge (left) than a hurricane that approaches at an oblique angle (right). But…fast storms produce higher storm surge on straight coastlines, but slow storms produce higher surge in bays

Credit: UCAR/L.S. Gardiner

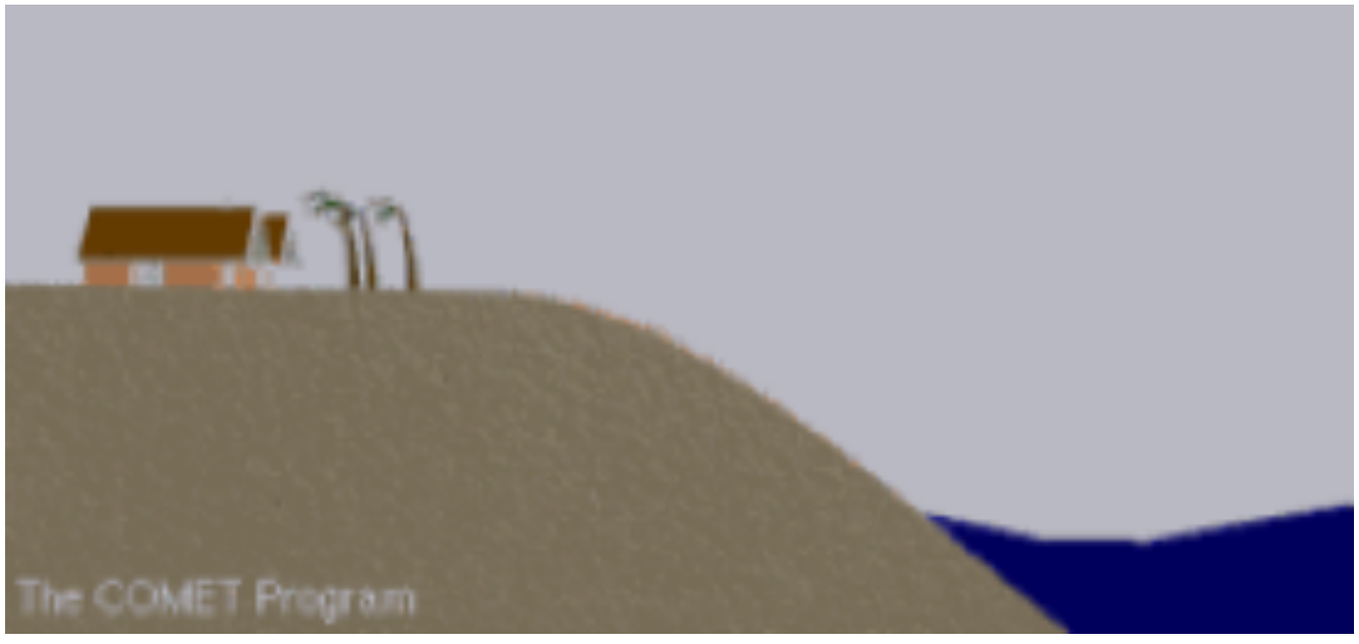
Factors influencing storm surge height

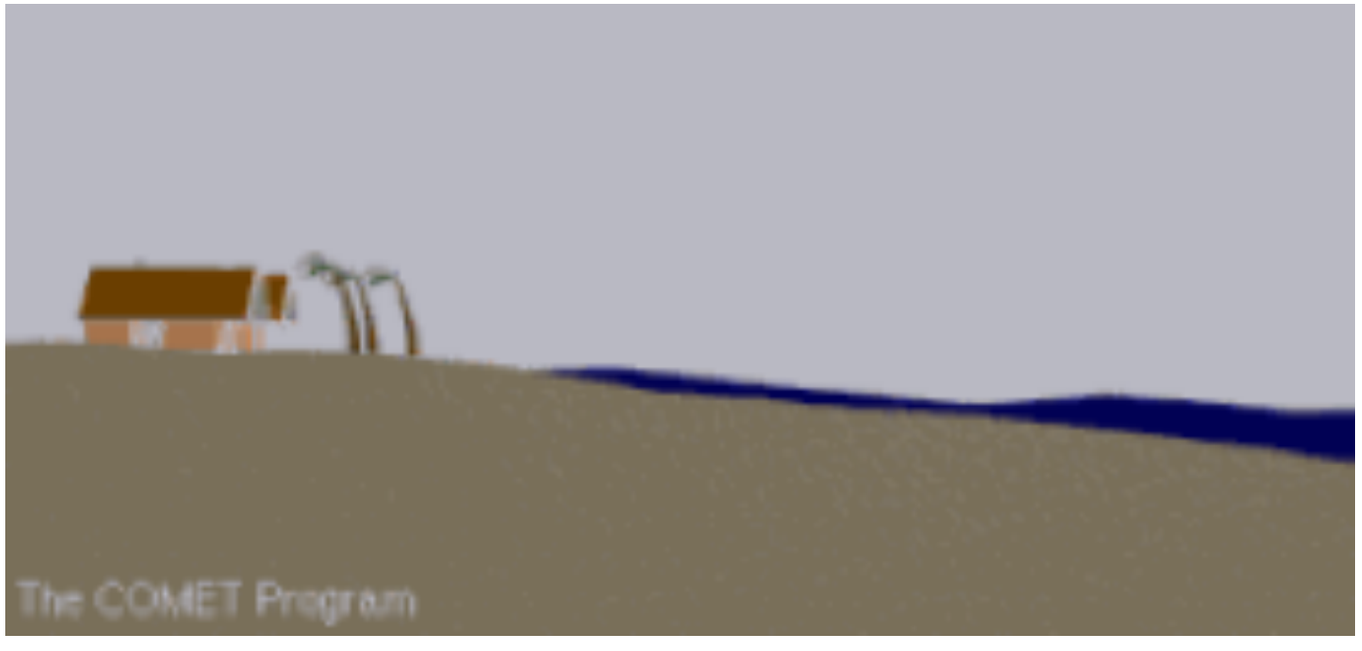
2. Coastline geography/shape: angle and speed of storm relative to coastline



Factors influencing storm surge height

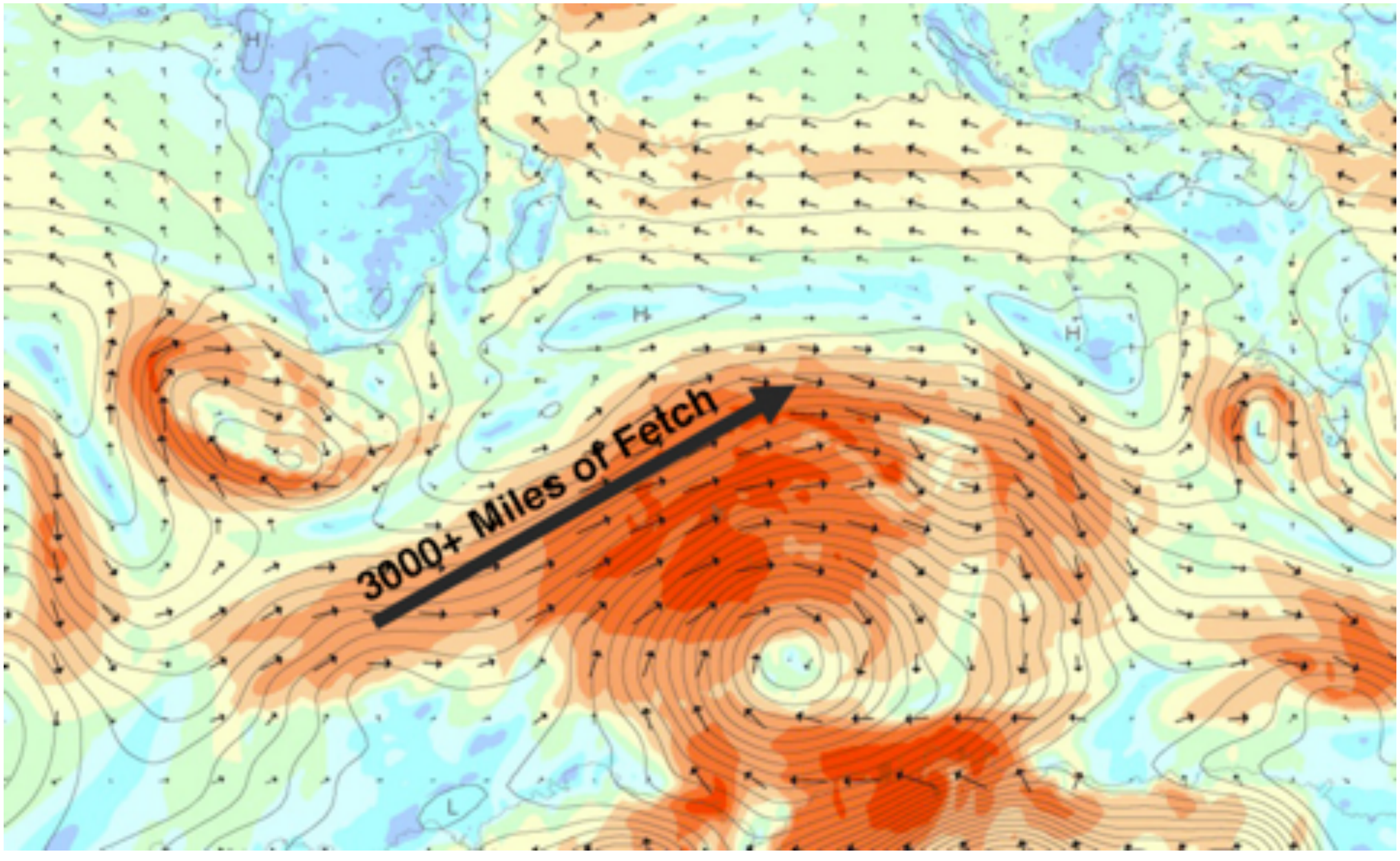
3. Near-shore slope





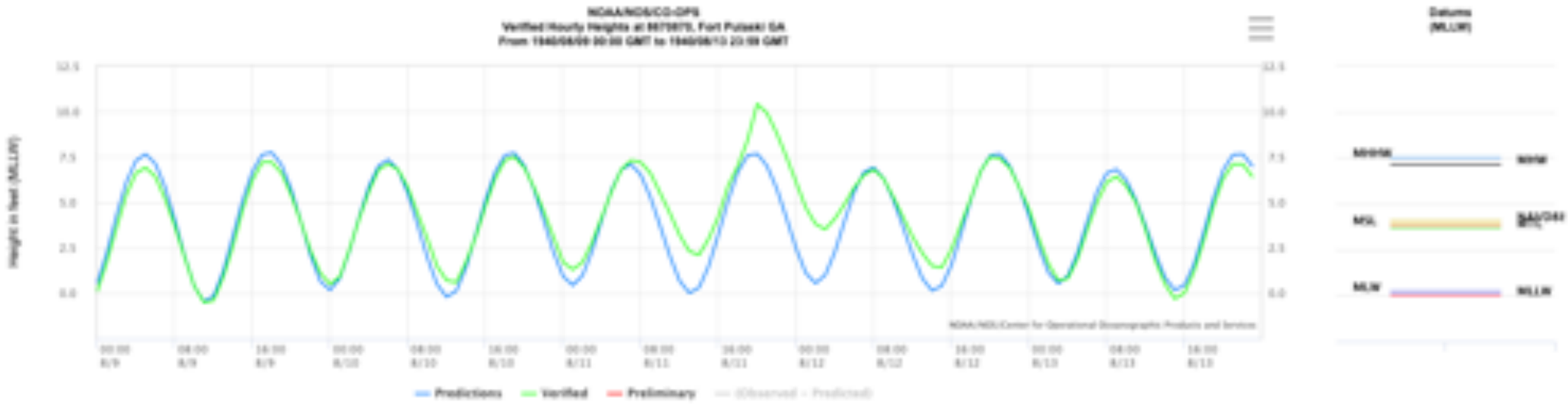
Factors influencing storm surge height

4. Storm size and “fetch” of high winds



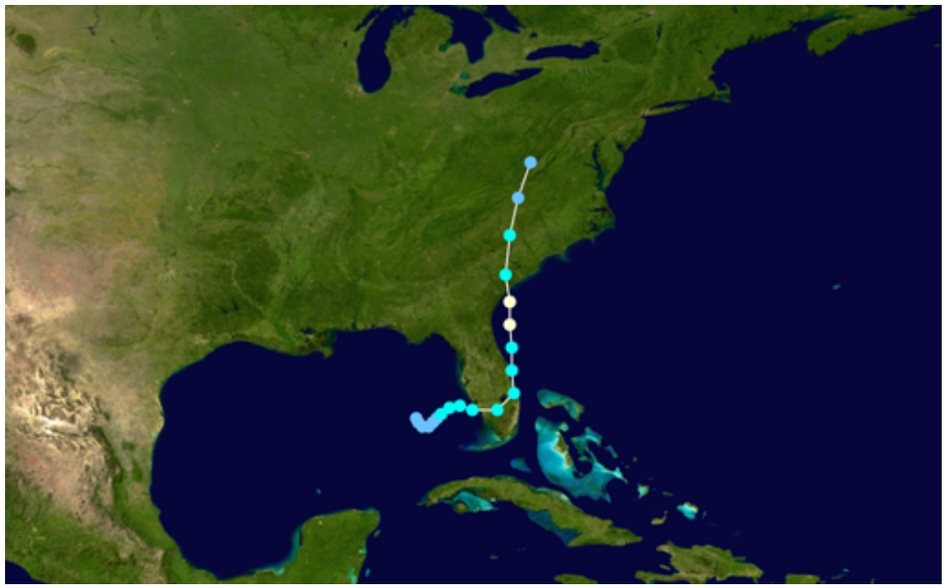
1940 South Carolina (and GA) Hurricane

75 mph wind at landfall - 50+ killed

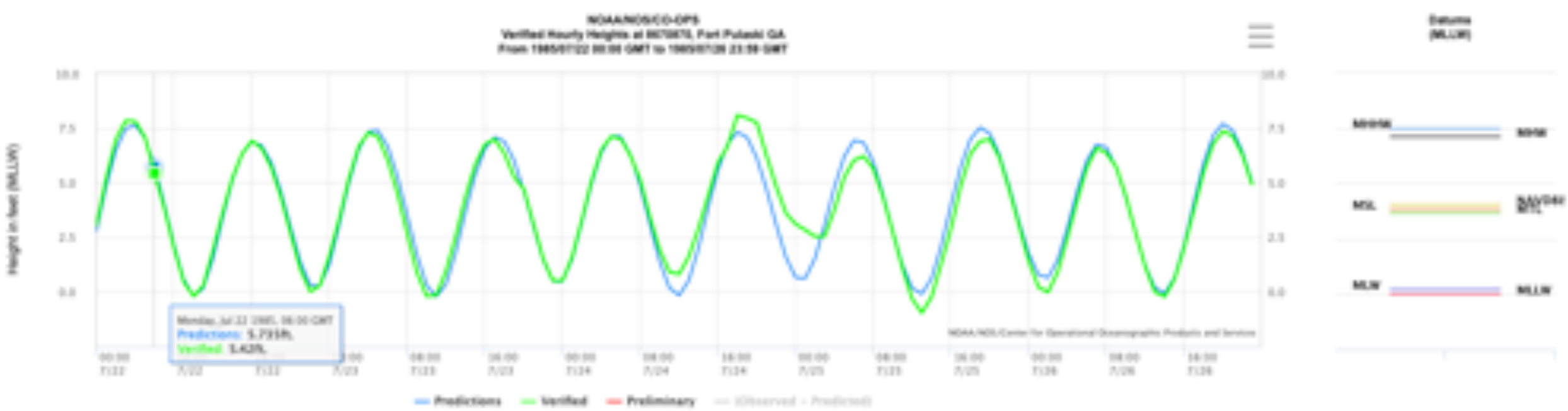


1985 Hurricane Bob

75 mph wind at landfall - 5 deaths



Most of the damage elsewhere due to wind damage - not coastal flooding



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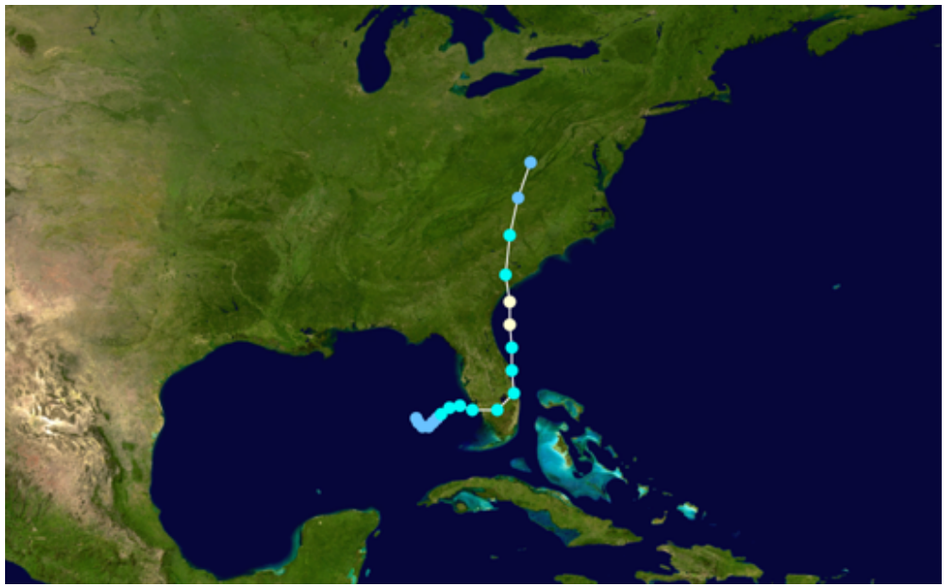

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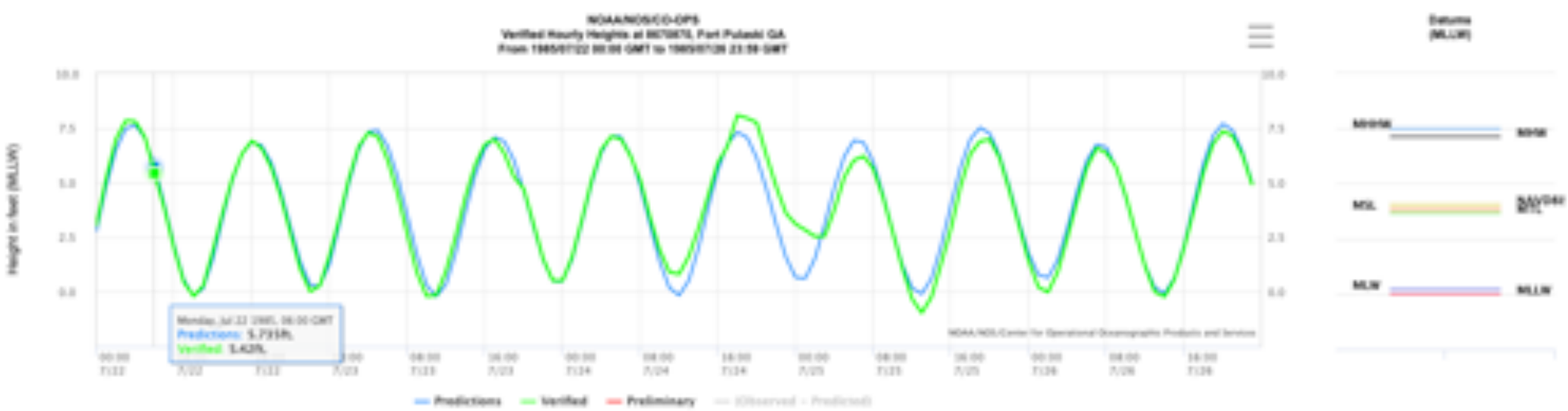
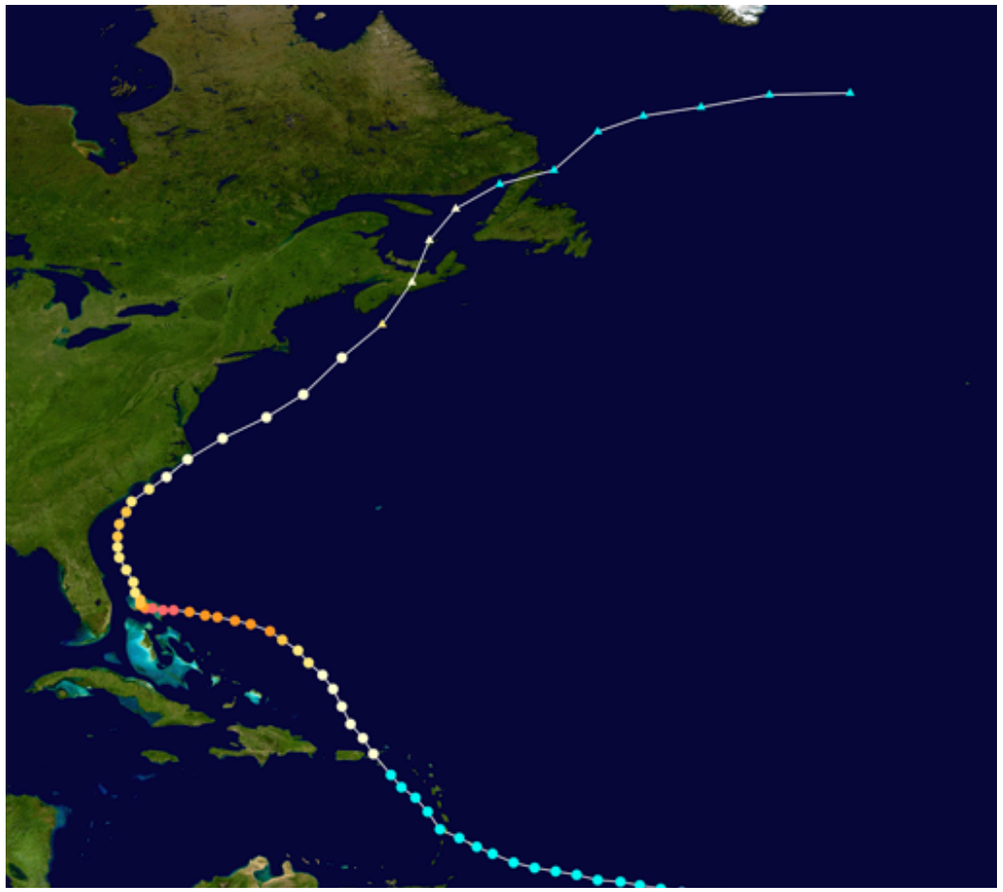
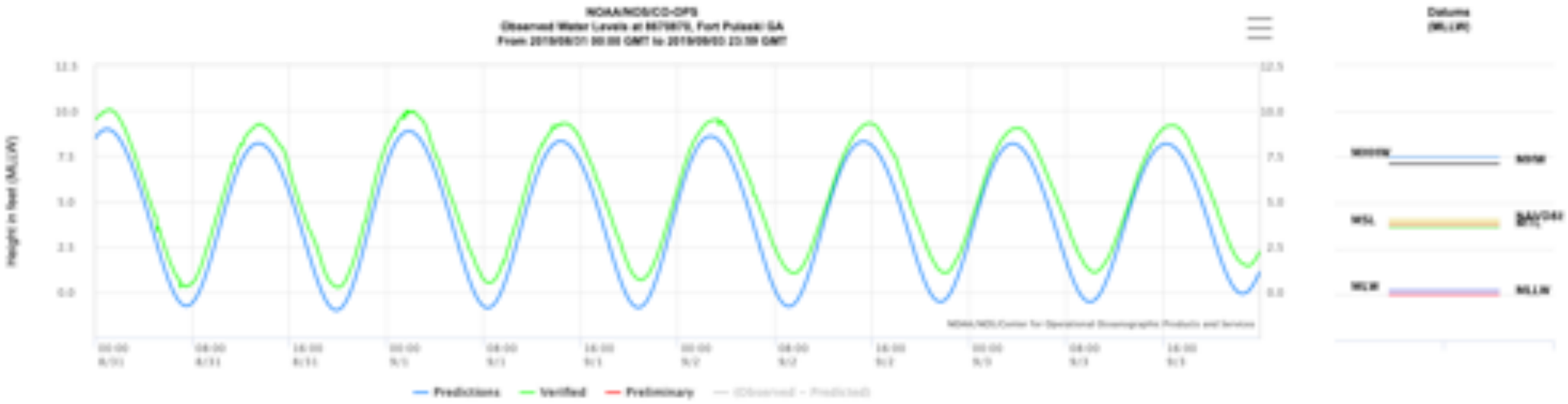


2019 Hurricane Dorian

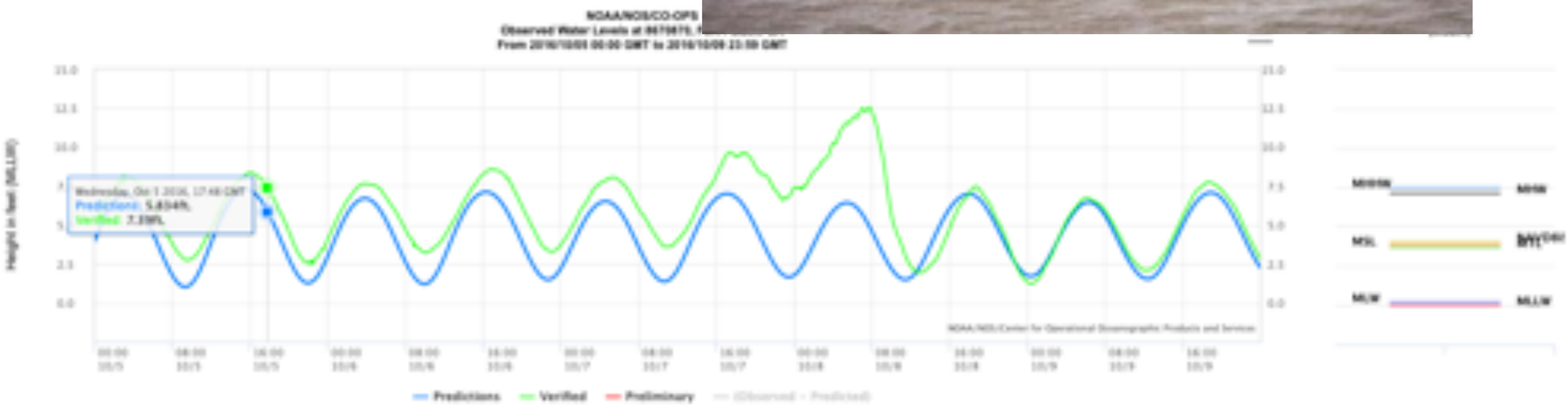


One of the most intense Atlantic hurricanes in history



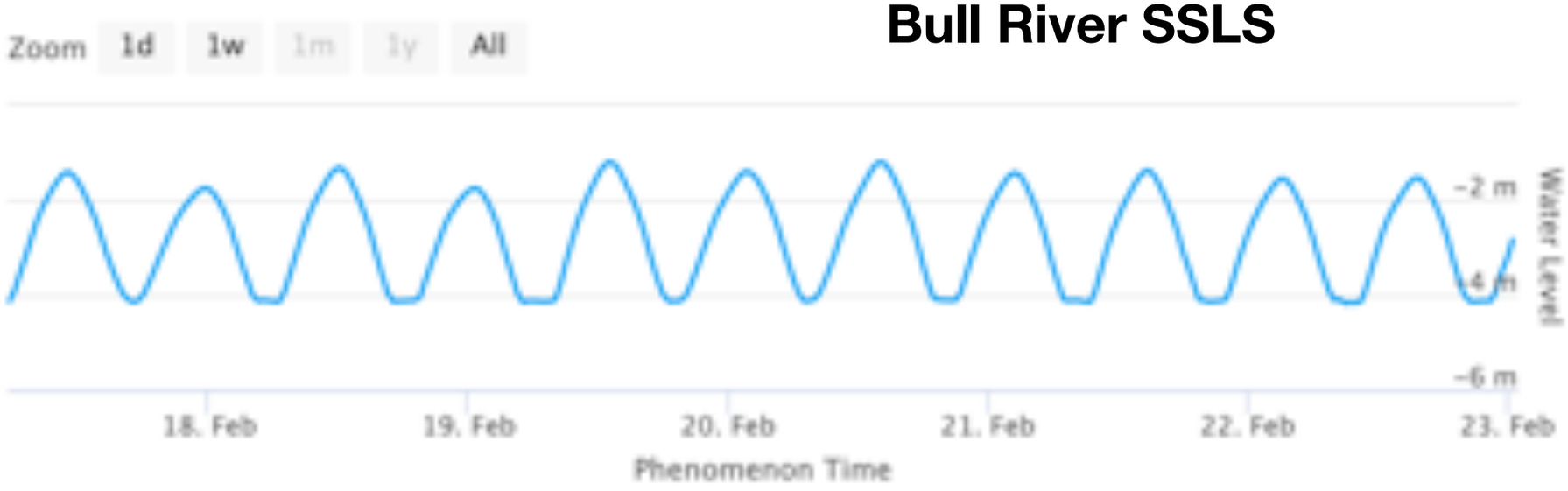
2016 Hurricane Matthew

Never “officially” made landfall in GA -
>40 US deaths, $5+ billion damages in US



Feb 2019 High Wind/Tide Event

Bull River SSLS



Stat	Value
Last	-3.188 m
Min	-4.257 m
Max	-1.186 m
Average	-2.9118 m

“Typical week” Bull River SSLS

Stat	Value
Last	-4.226 m
Min	-4.226 m
Max	-1.574 m
Average	-2.8892 m

Coffee Bluff SSLS

Stat	Value
Last	-2.181 m
Min	-4.296 m
Max	-1.109 m
Average	-2.4505 m

Feb 2019 High Wind/Tide Event

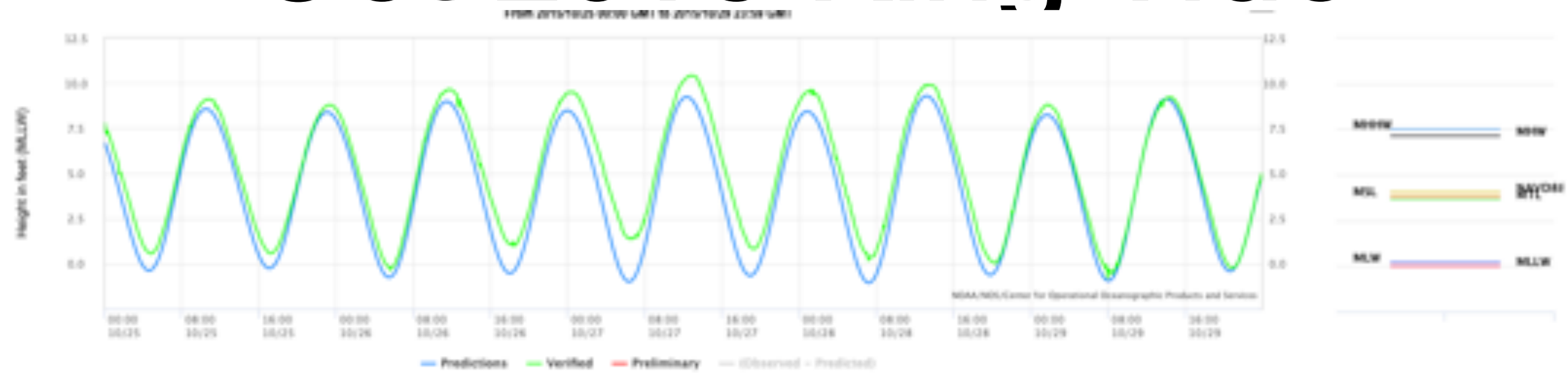
TRAFFIC

All of Hwy 80 back open following coastal flooding

High tide Wednesday morning along Hwy 80 near Fort Pulaski.

By Jennifer Lifsey | February 19, 2019 at 1:02 PM EST - Updated February 20 at 10:21 AM

Oct 2015 King Tide

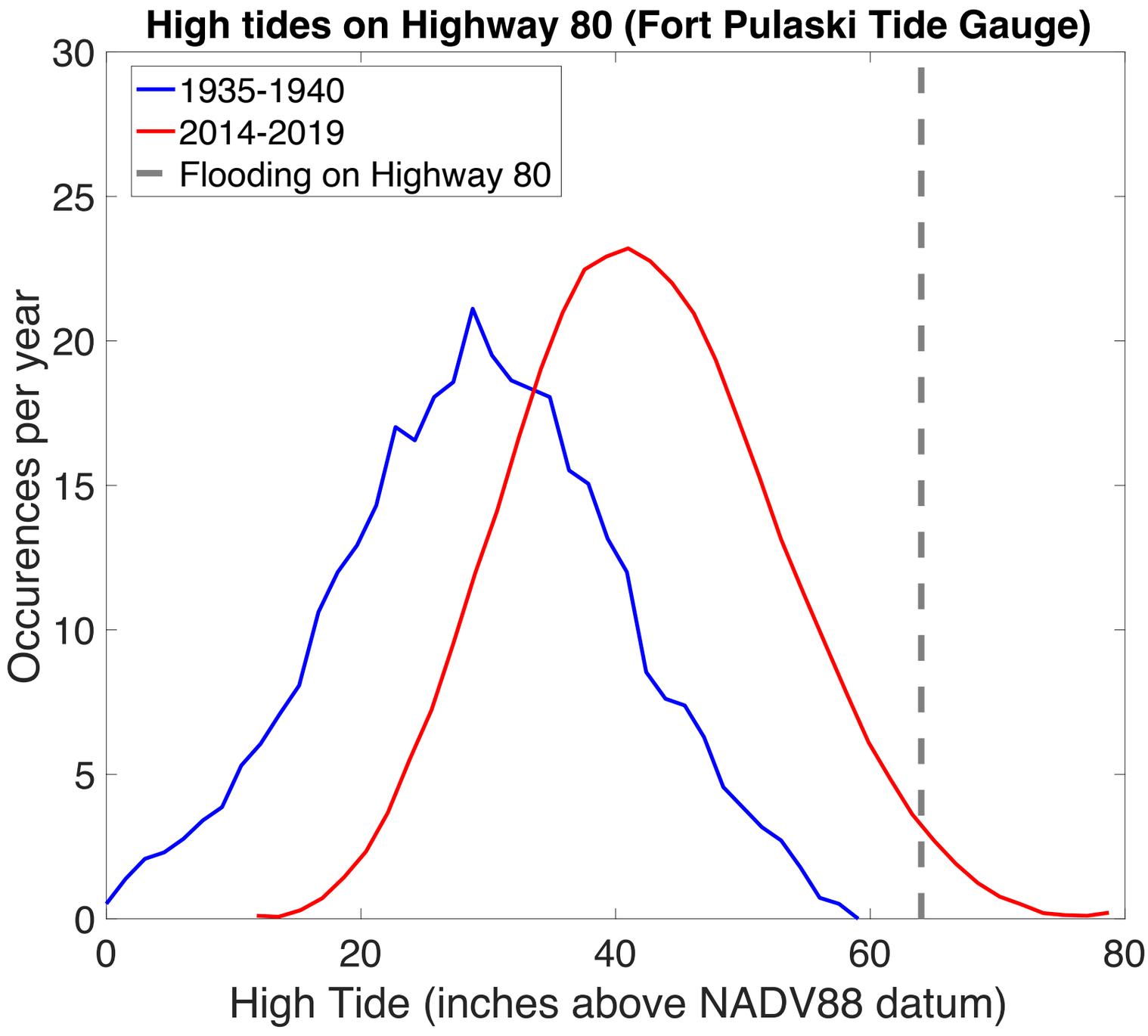


Highway 80 floods on Oct. 27, 2015 during a King Tide event cutting off all road access from Tybee Island to emergency services (9.6’ floods H80)

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