The Ocean in Motion: Sea Level Rise and Tides

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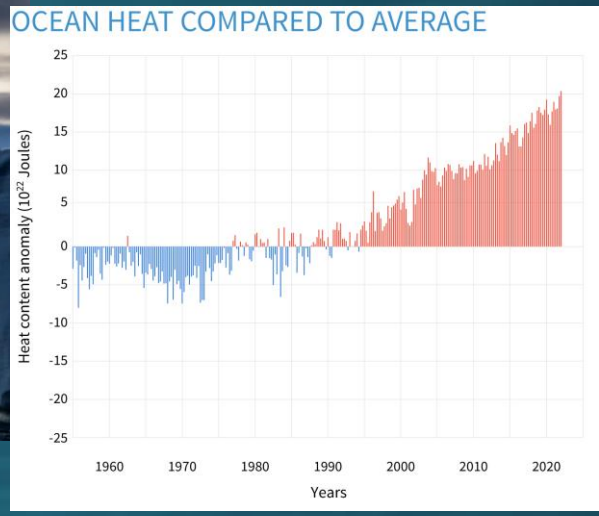
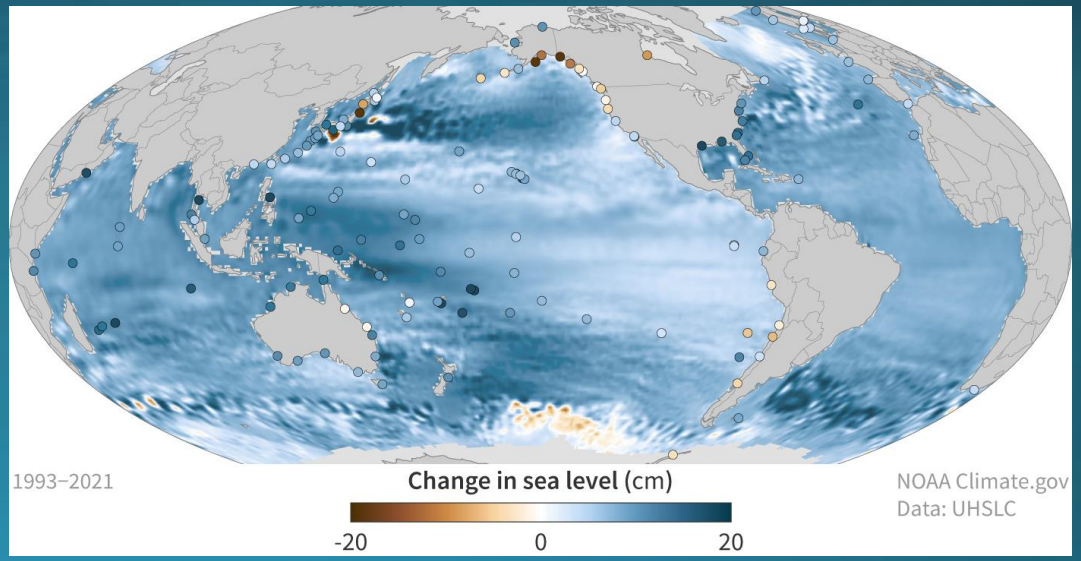
What is Sea Level Rise?

- An average increase in the global ocean height
- Almost entirely driven by just two factors:
  - Ice melt (2/3)
  - Thermal expansion (1/3)

- Global average rate over past 30 years is ~ 0.14 inches/year (3.4 mm/yr), but not uniform everywhere

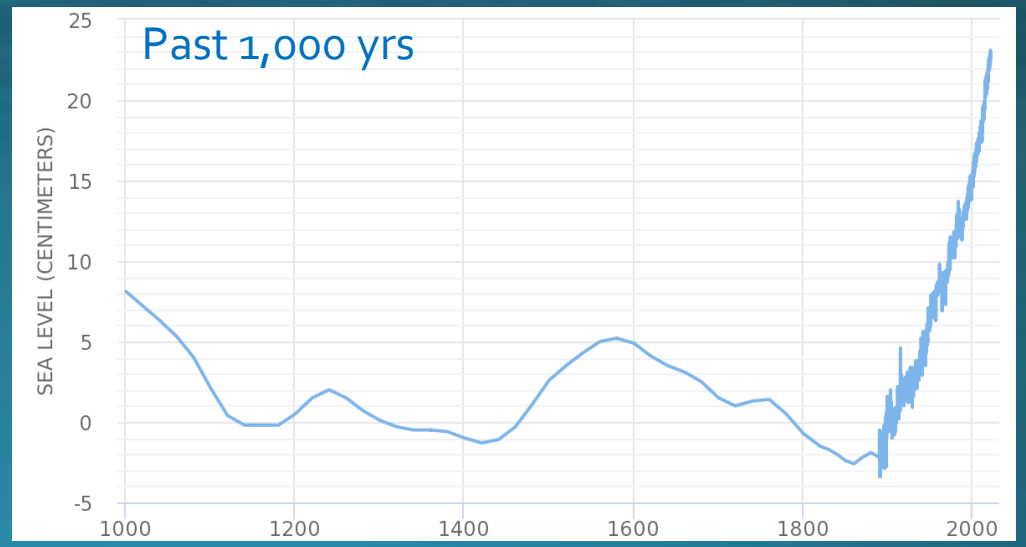




Historical Perspective

- Global sea level has naturally fluctuated by enormous amounts as Ice Ages come and go
- What we think of as a static "coastline" is actually moving and evolving
- Sea level today is about 400 feet higher than it was 20,000 years ago, and about 100 feet lower than it was 2,000,000 years ago
- But the current rate of SLR is greater than it has been for at least 6,000 years
- There is no dispute that man-made climate change has triggered rapid sea level rise in the past 150 years

Historical Perspective



Charts generated from sealevels.org

Historical Perspective

- Earth naturally warms and cools over 10s and 100s of thousands of years, causing the amount of ice stored in the polar ice caps to fluctuate… sometimes the ice caps cover significant portions of the continents (*glacial*) and sometimes the ice caps are almost gone (*interglacial*).
- These cycles are called "Milanković Cycles" and are a result of small overlapping periodic changes in the Earth's orbital properties
  - Discovered by Milutin Milanković in the 1920s
  - Linked to climate change and Ice Ages by Hays et al. in 1970s
  - **Eccentricity** of orbit, ~95,000 years
  - **Obliquity** of axial tilt, ~41,000 years
  - **Precession** of axial tilt, ~26,000 years

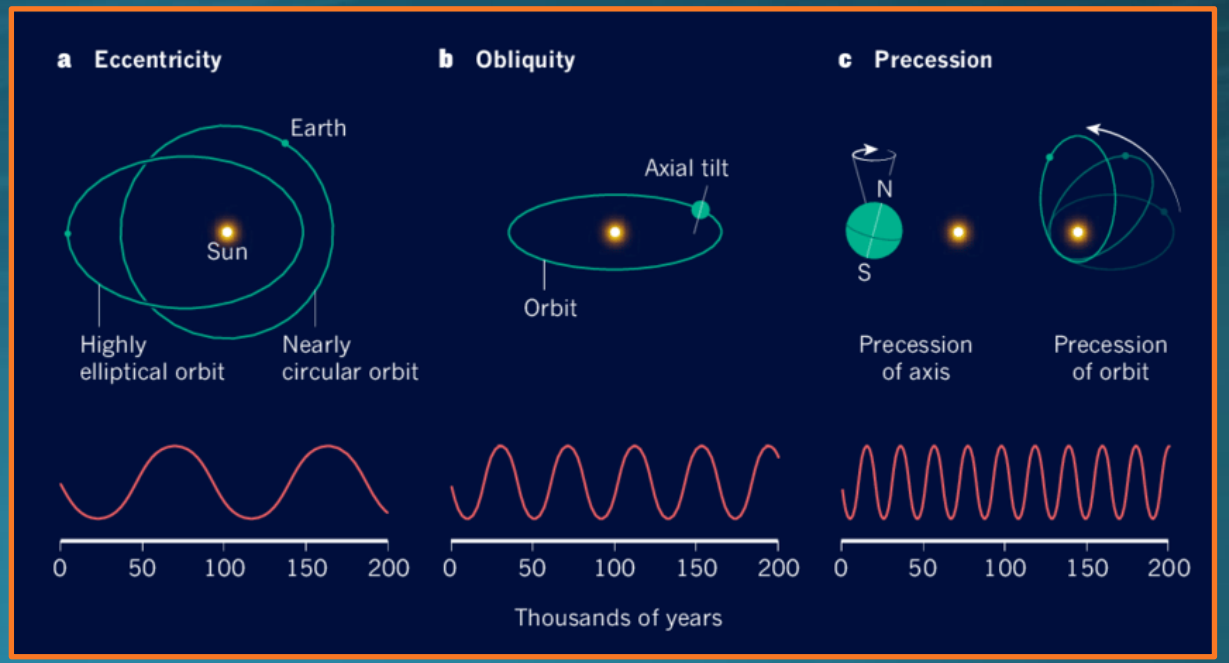
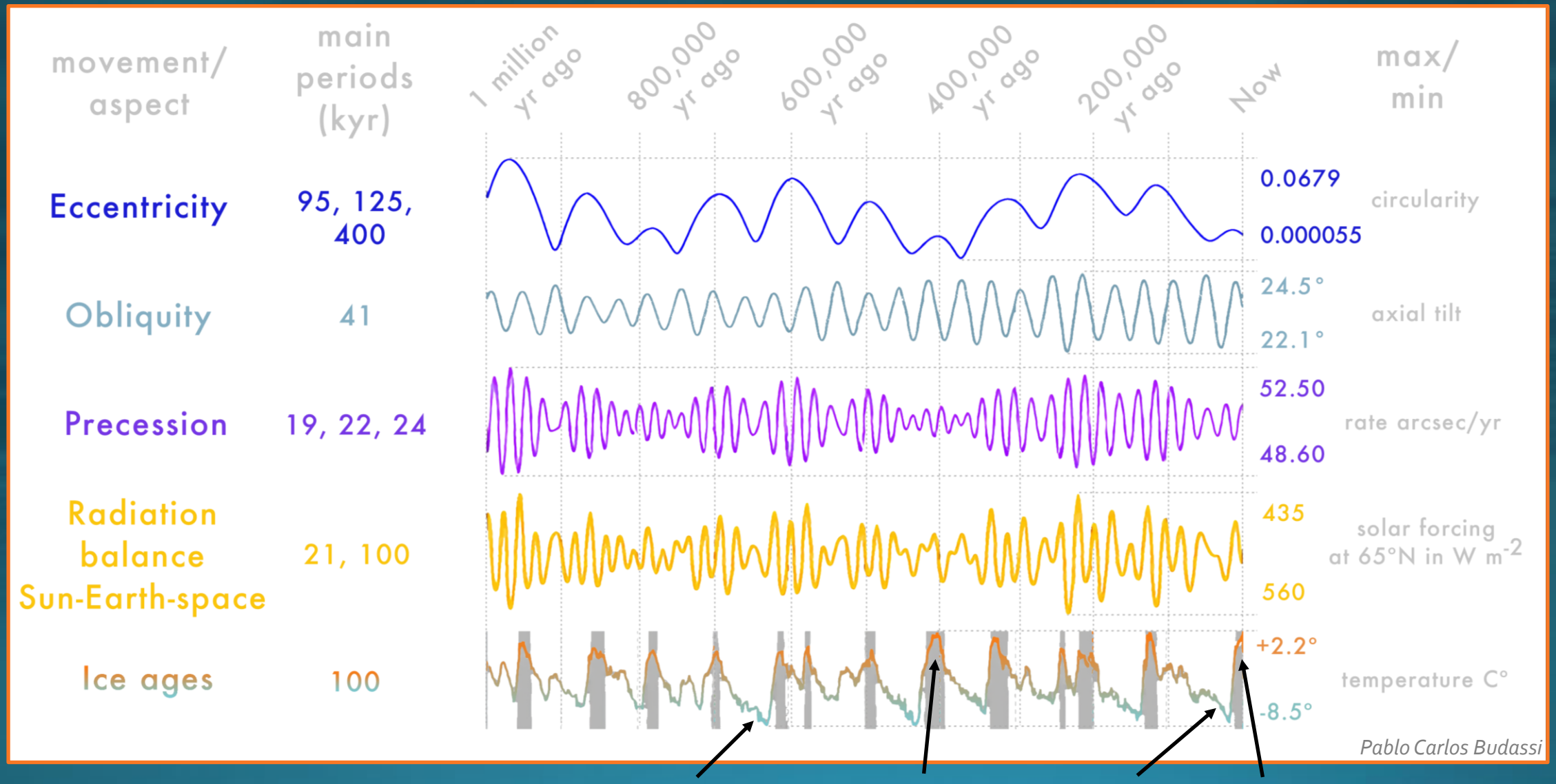


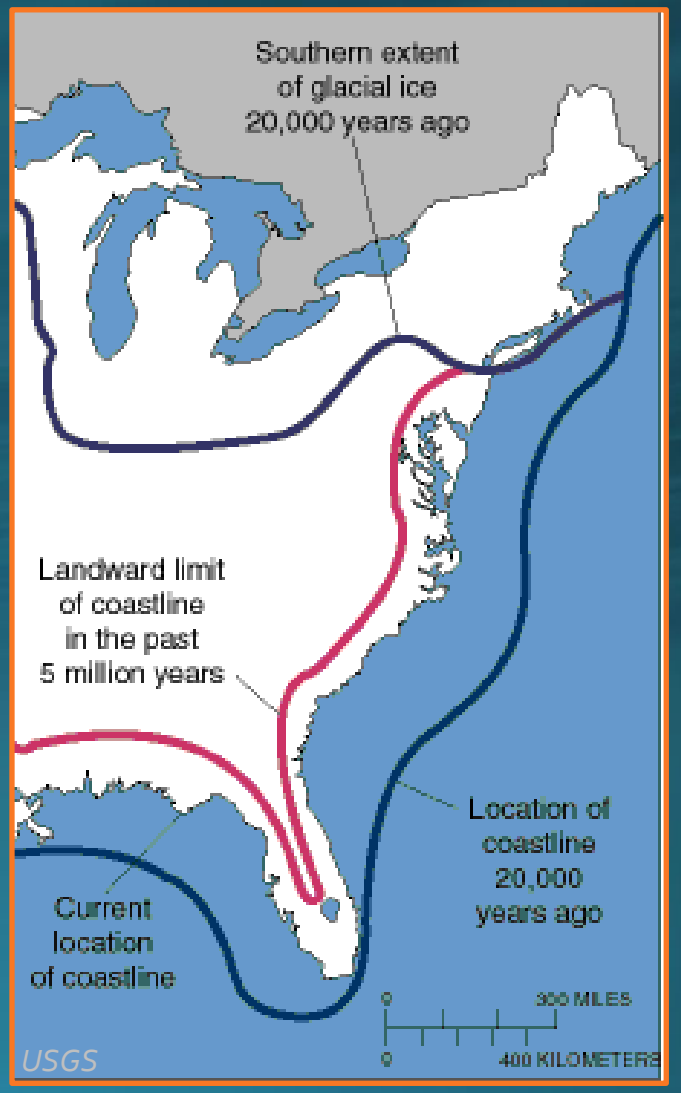
Figure 1 of Maslin, 2016 (Nature)

Historical Perspective



So What's the Big Deal?

- Sea level and the coastline have changed drastically, driven by astronomical factors… why are we now so concerned about just a few feet of sea level rise?
  1. The current rate of SLR is dramatic even by historical standards
  2. It is not being driven by natural causes (such as periods of extreme SLR during "meltwater pulses" at the end of an Ige Age)
  3. All coastal cities and ports in the world were built when the coastline was steady… that is now changing and threatening billions of people. The last time sea level was higher than it is now was ~400,000 years ago!



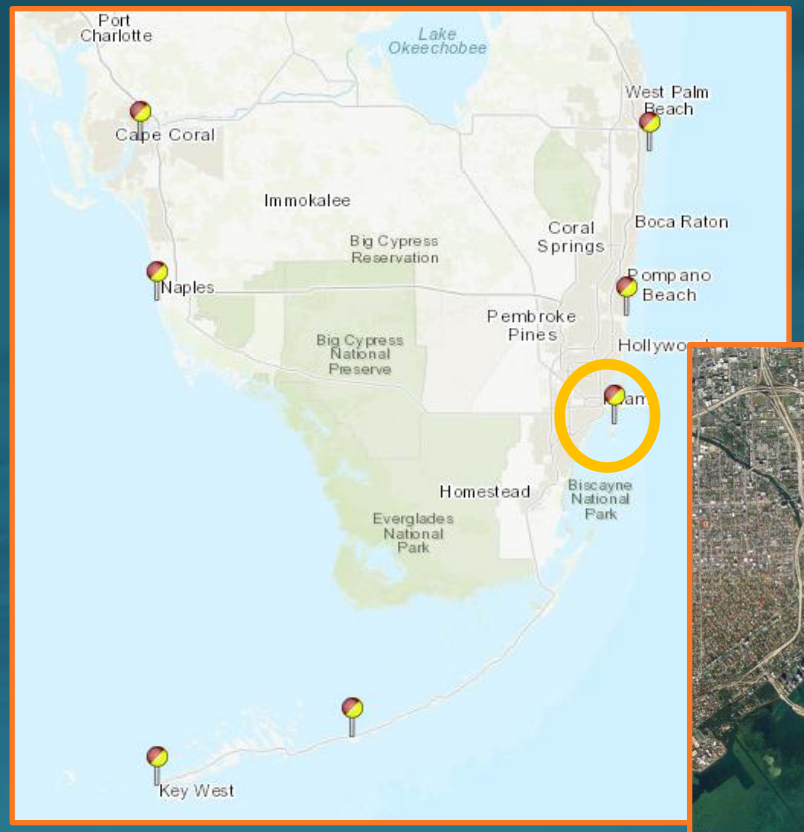
Observe & Monitor Sea Level Rise

- We can measure the current rate of sea level rise at a local level and within our lifetimes
- Tide gauges with long records are critical in determining the rate and variability of SLR around the world
- But, we have to understand the tide gauge data before drawing conclusions from them

Virginia Key NOAA acoustic tide gauge photo by Brian McNoldy

Miami-area Station History & Location

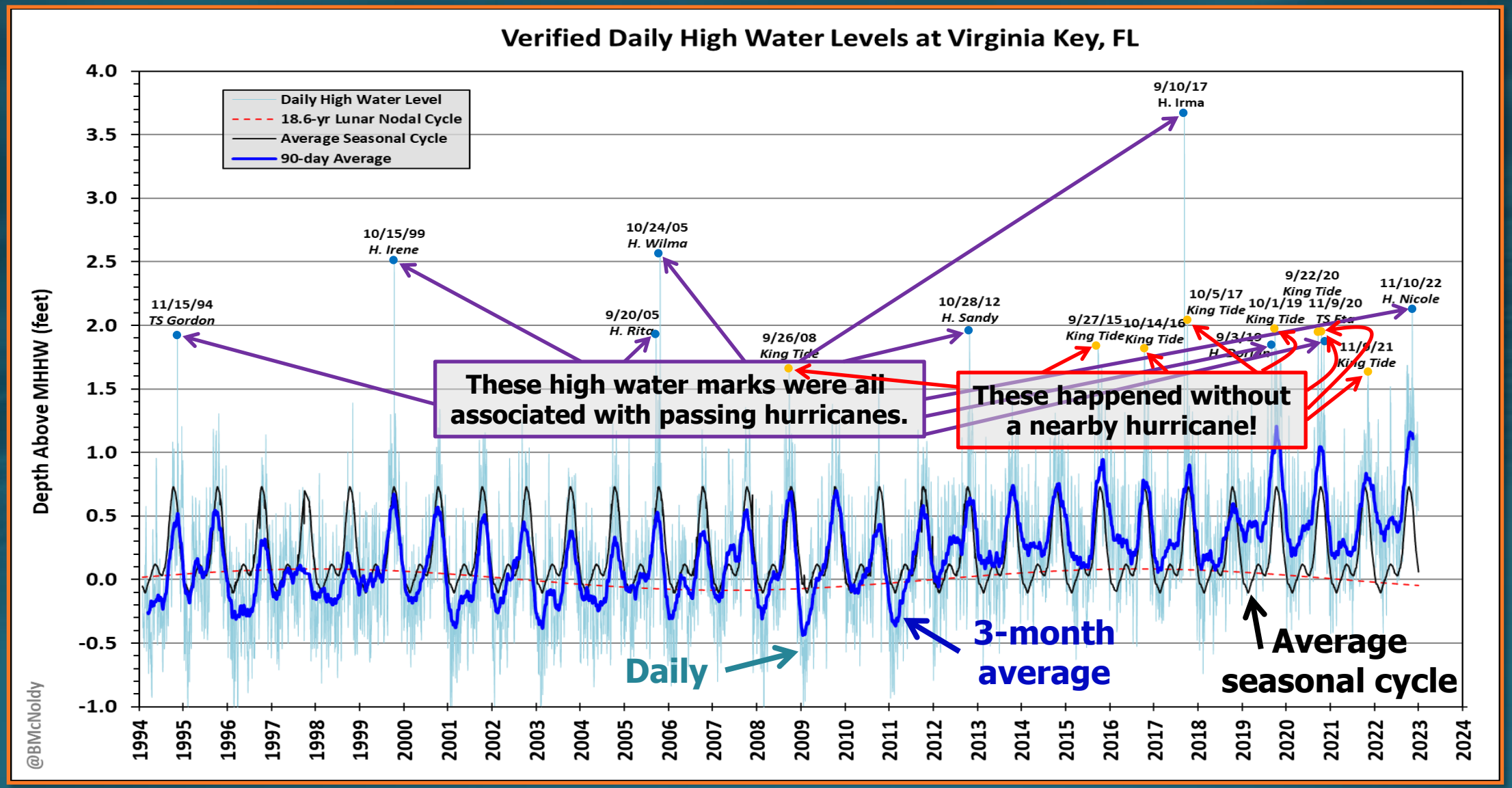
- NOAA CO-OPS installed a tide gauge on Virginia Key in 1994
- Station is located at the Univ. of Miami's Rosenstiel School of Marine, Atmospheric, and Earth Science campus
- Data are collected and reported in real-time every 6 minutes… then quality-controlled and verified every month



NOAA CO-OPS tide gauges in south Florida

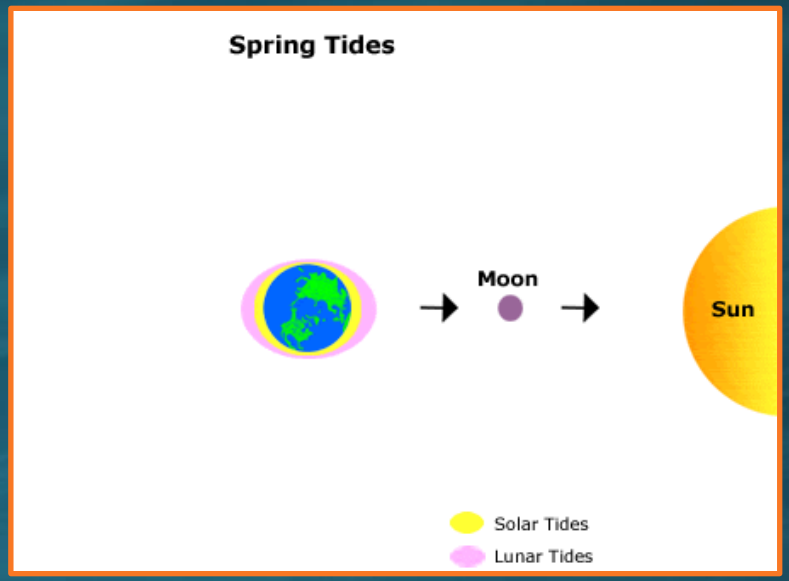
Virginia Key area

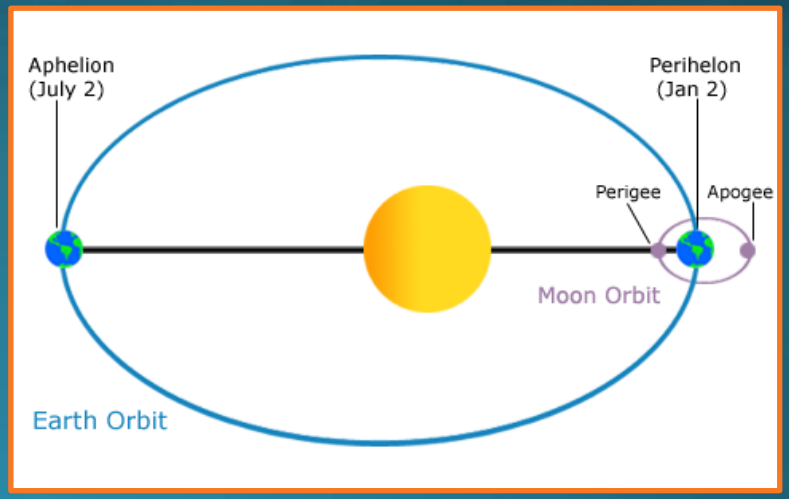
Daily Data & High Water Marks



What Factors Influence Tides?

- Phase of the moon
  - Full and new moons exert greater tidal pull on oceans
- Earth's proximity to the moon
  - Moon's elliptical orbit means once/month it's closer to Earth, producing greater tidal forces
  - "perigee" vs "apogee"
- Earth's proximity to the sun
  - Earth's elliptical orbit means once/year (January) it's closer to the sun, producing greater tidal forces
  - "perihelion" vs "aphelion"
- Lunar Nodal Cycle
  - Precession in the moon's orbital plane causes an 18.6-year cycle in mean sea level. This can be significant enough to not ignore… more on this later



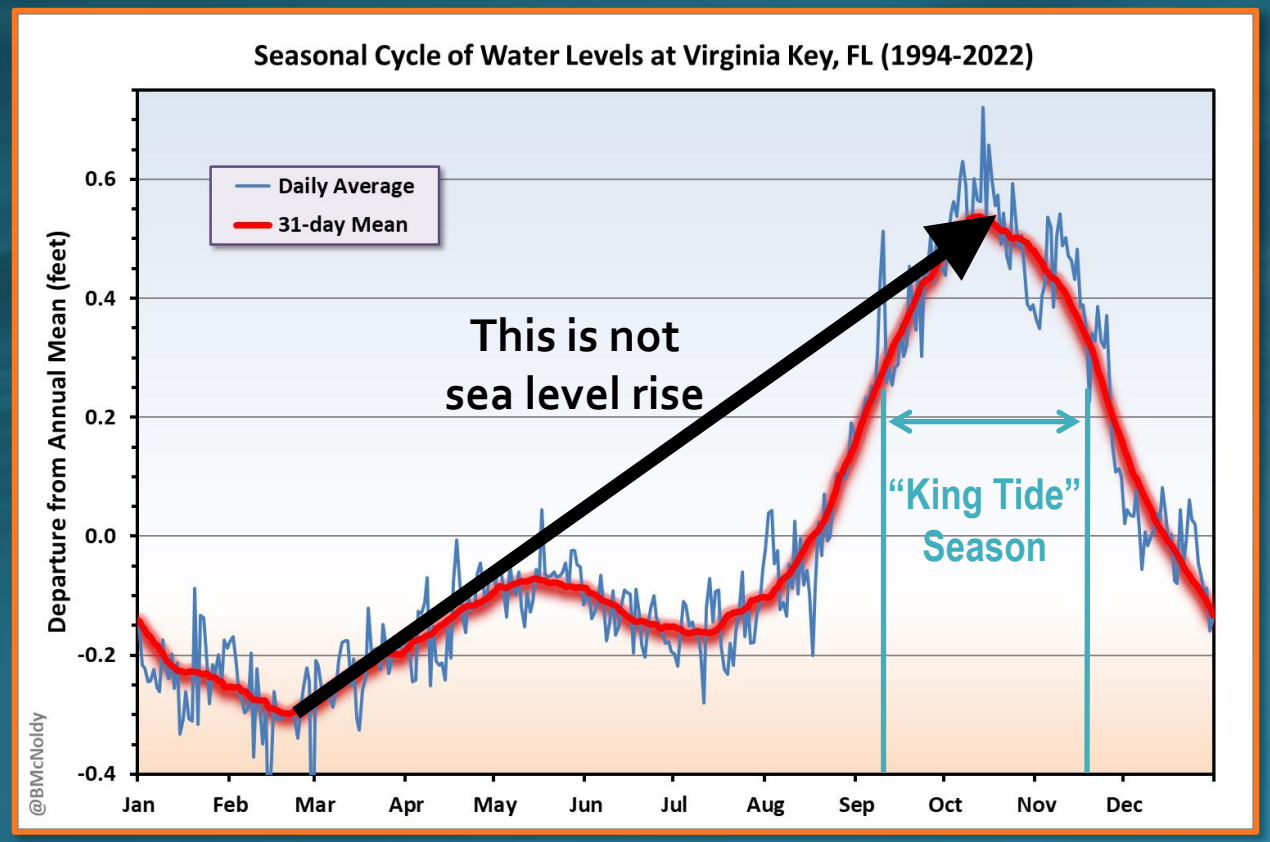


What Factors Influence Tides?

- Wind speed and direction
- Ocean temperature
- Atmospheric pressure
- Ocean currents
- All of these have an average/climatological local influence which is included in tide predictions… but *specific events and current conditions are not*

Average Seasonal Cycle of Sea Level in Southeast Florida

- For the reasons just outlined, water levels are naturally lowest in Jan-Feb-Mar and highest in Sep-Oct-Nov in the area

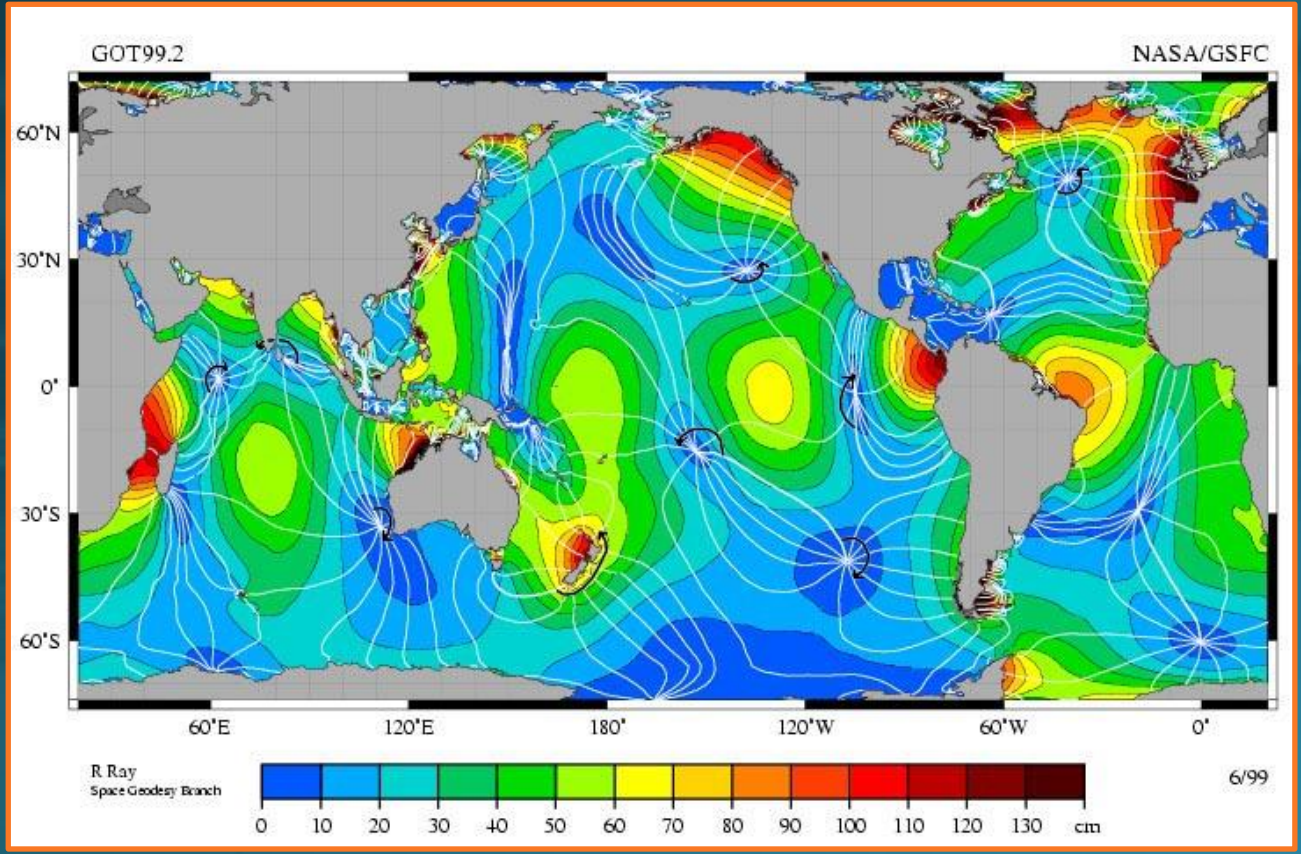


~10 in (25 cm)

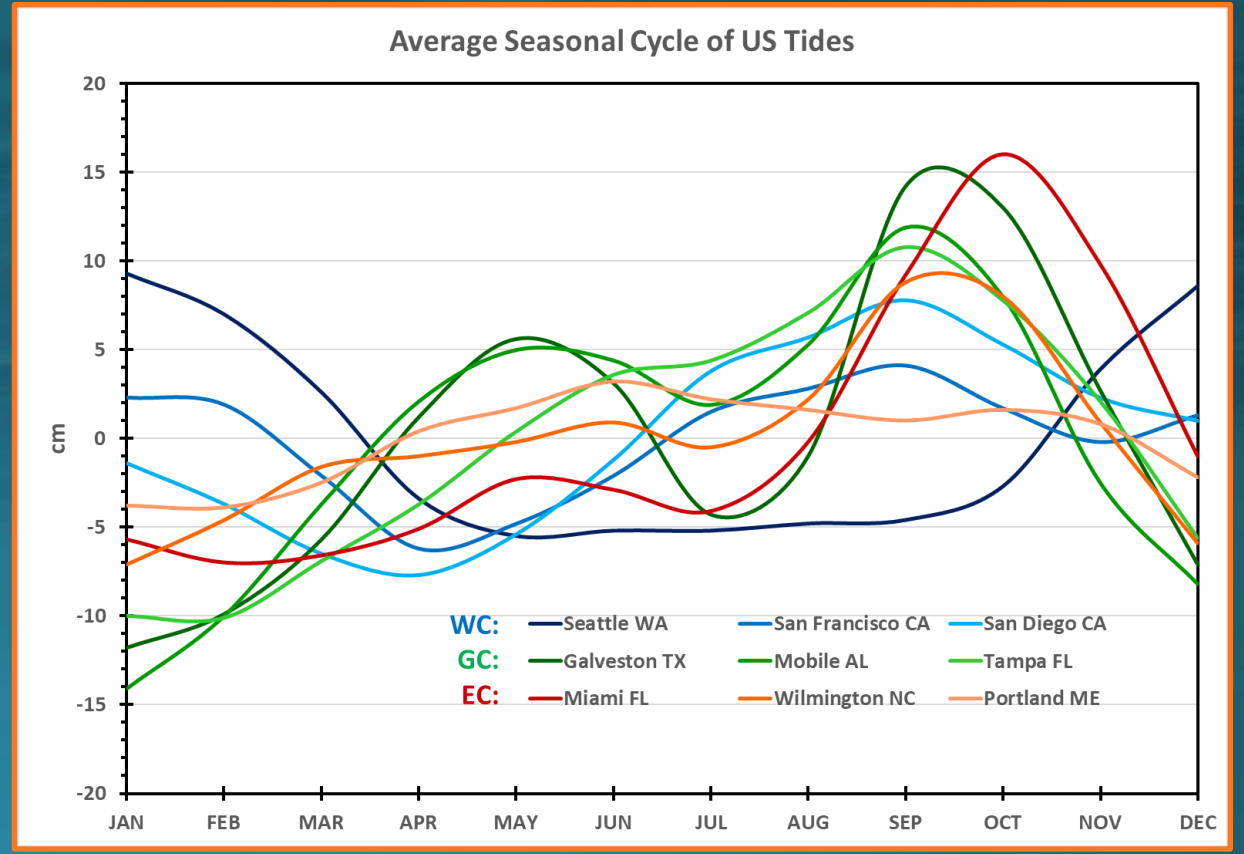
But, Not the Same Everywhere!

- Tidal ranges have distinct daily and annual variations

DIURNAL

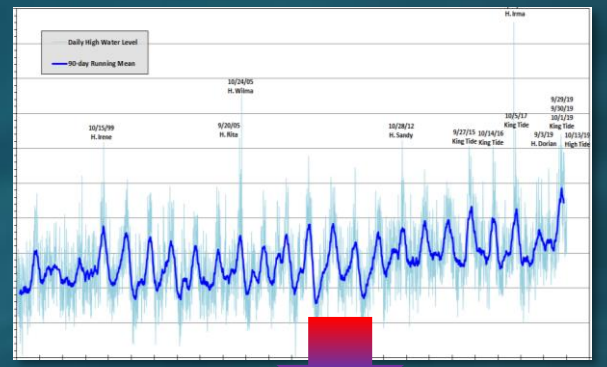


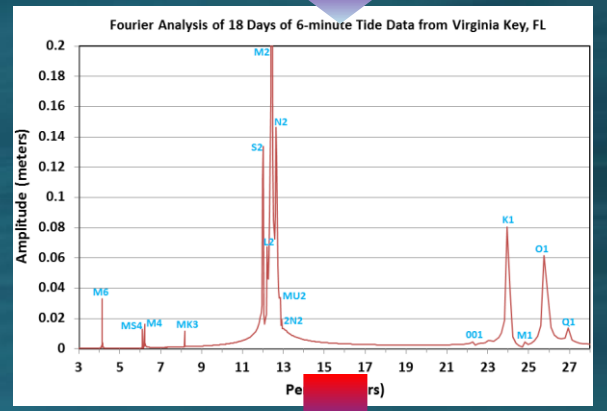
ANNUAL

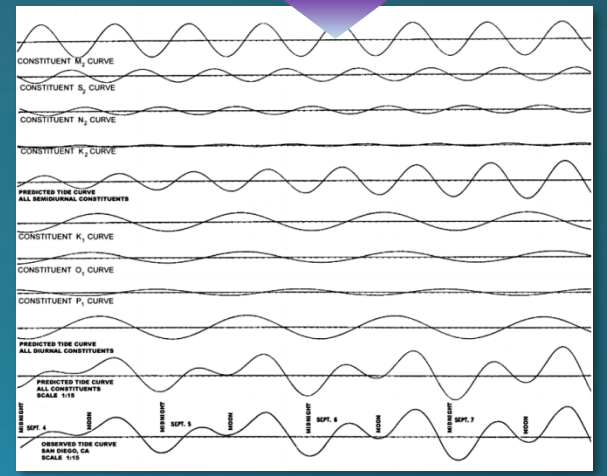


What Tide Predictions Are… and Are Not

- Tide predictions rely on a long time series of actual tide observations at a location.
  - A Fourier decomposition is performed to produce a list of sinusoidal components ("harmonic constituents"), each with a phase, frequency, and amplitude
  - These components are added together to arrive at a reconstructed total water level relative to a vertical datum of choice
- *NOAA's tide predictions are not like weather forecasts*… they are essentially astronomy + climatology.

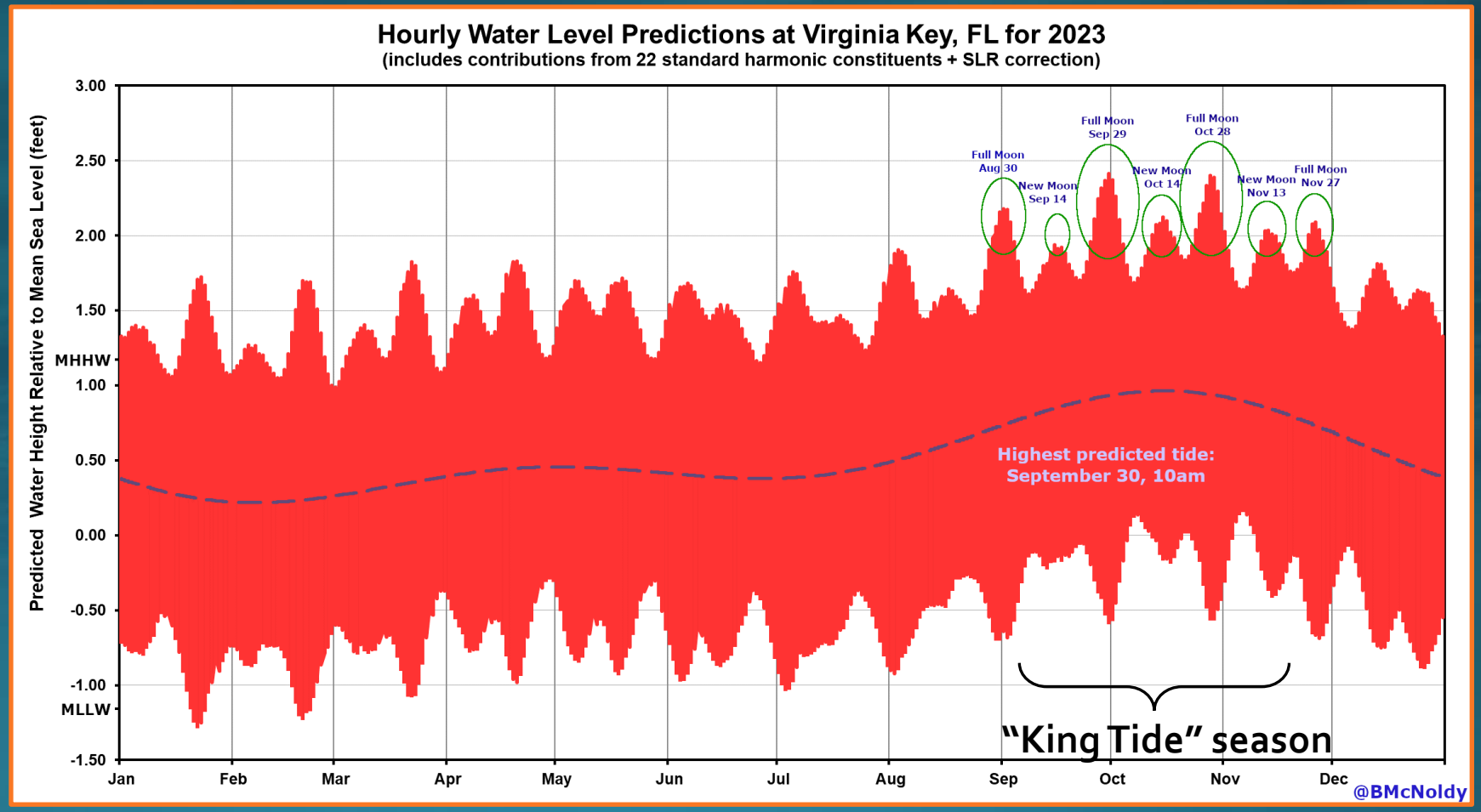






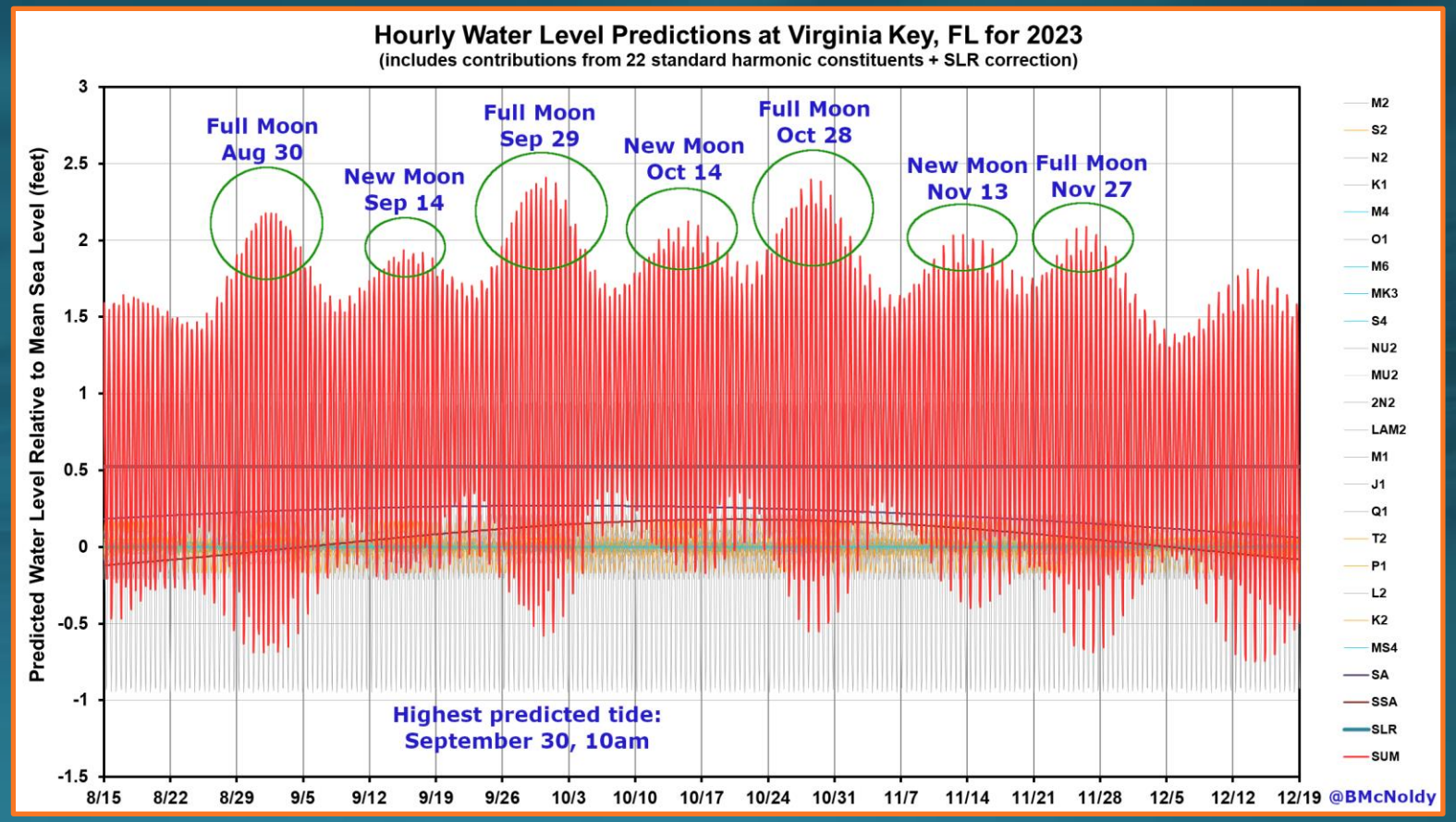
2023 Tide Predictions for Southeast Florida

- Water level shown relative to the 1983-2001 epoch mean sea level (MSL) at this location
- I add 6.3 in (16 cm) to that to adjust to 2020-2022 MSL
- Mean seasonal cycle peaks ~Oct 15… highest predicted tide of the year will *typically* occur near the full or new moon closest to that date



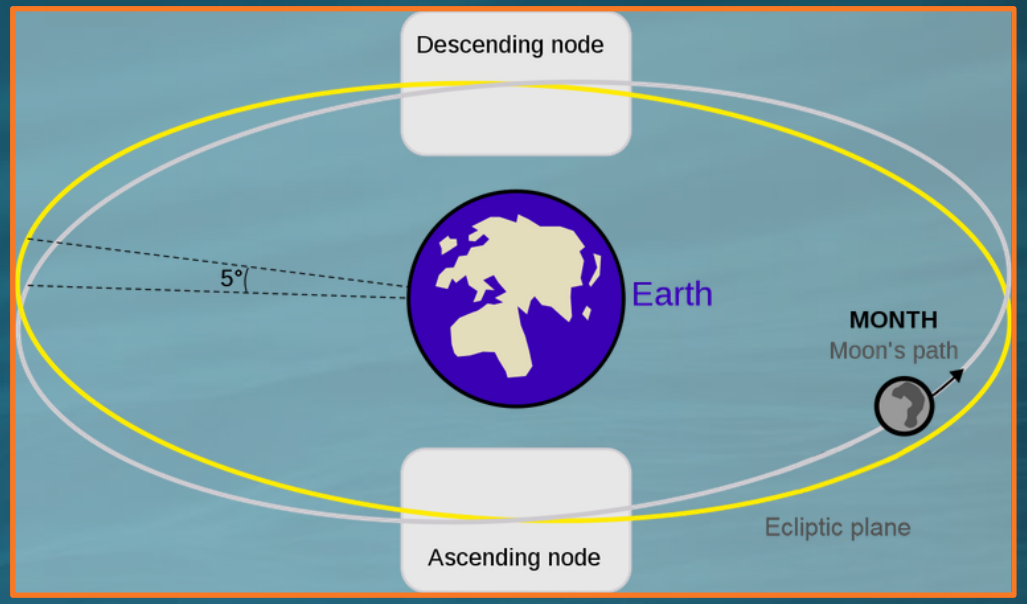
Zooming In

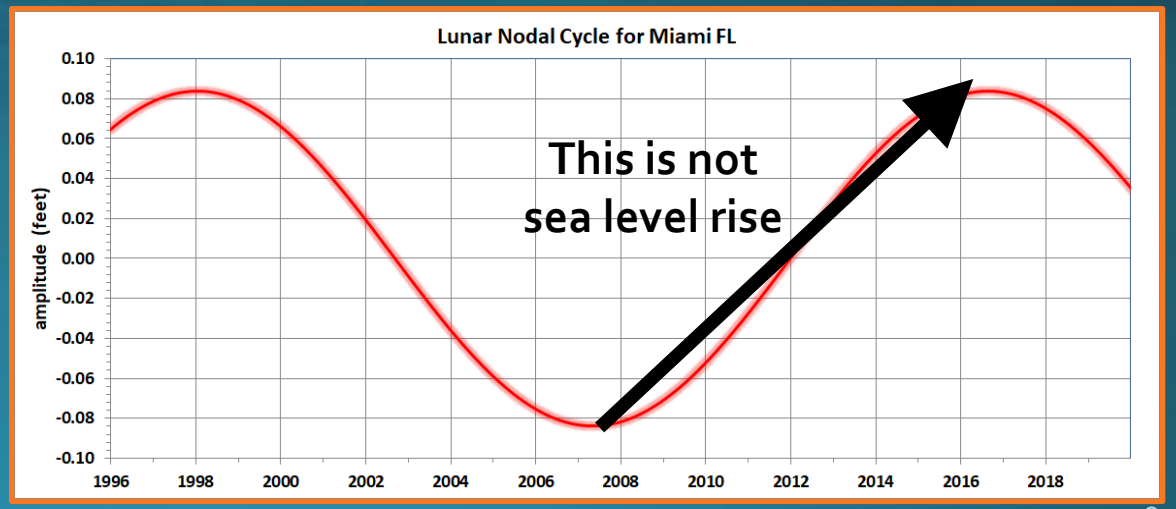
- This chart shows just 4 months from the previous chart, with the various harmonic constituents plotted separately, plus a 6.3-inch (16 cm) offset for sea level rise.



18.6-year Lunar Nodal Cycle

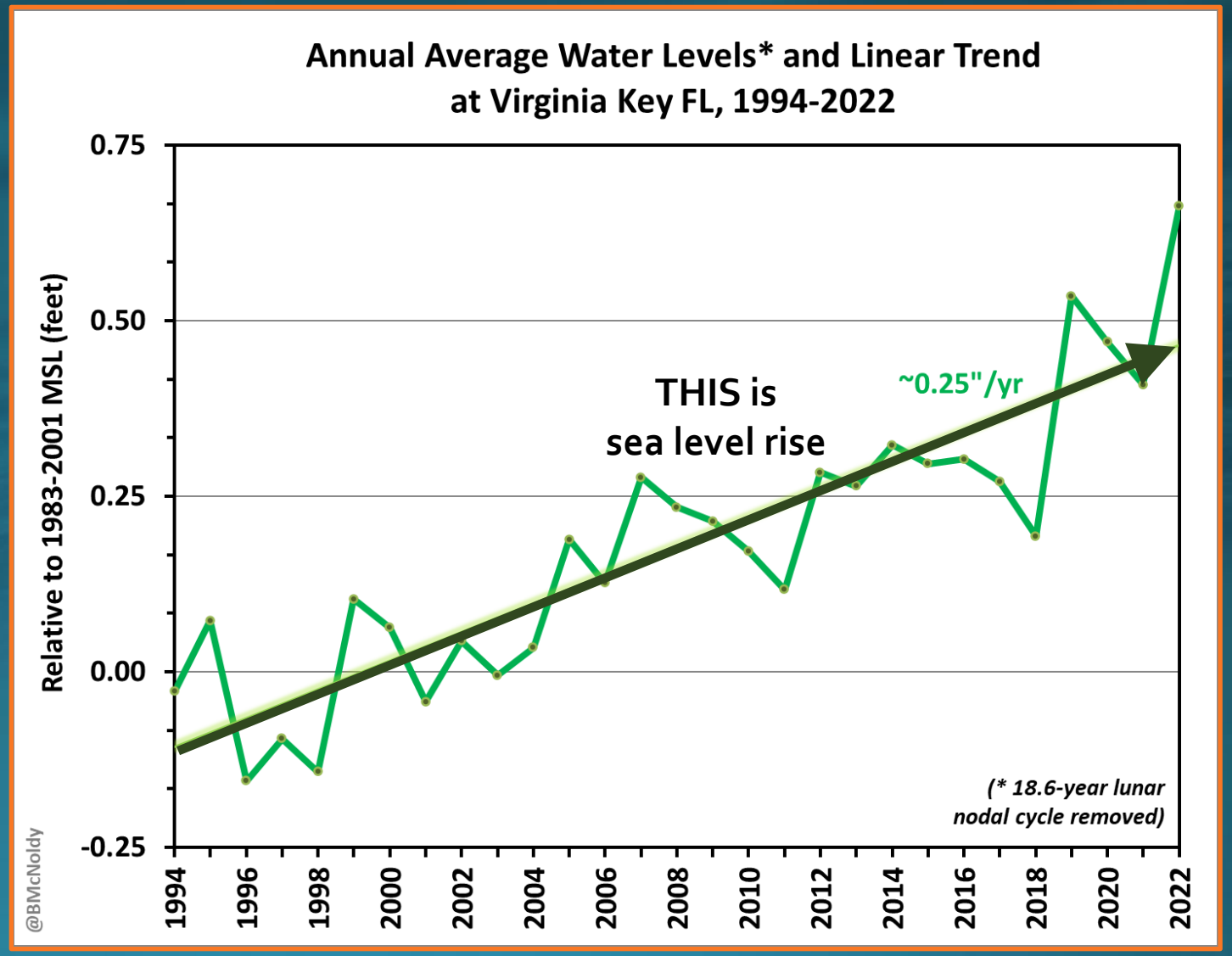
- Moon's orbital plane is tilted relative to Earth's, tilt varies +/- 5°
- The planes intersect at "nodes"
- Moon's orbital plane precesses over a period of ~18.6 years.
- Discovered 5000+ years ago, published nearly 300 years ago
- The [mis]alignment has an impact on global sea levels, though not the same everywhere
  - In Miami area, it's +/- 1 inch (2.5 cm)
- https://theconversation.com/this-supermoon-has-a-twist-expect-flooding-but-a-lunar-cycle-is-masking-effects-of-sea-level-rise-158412





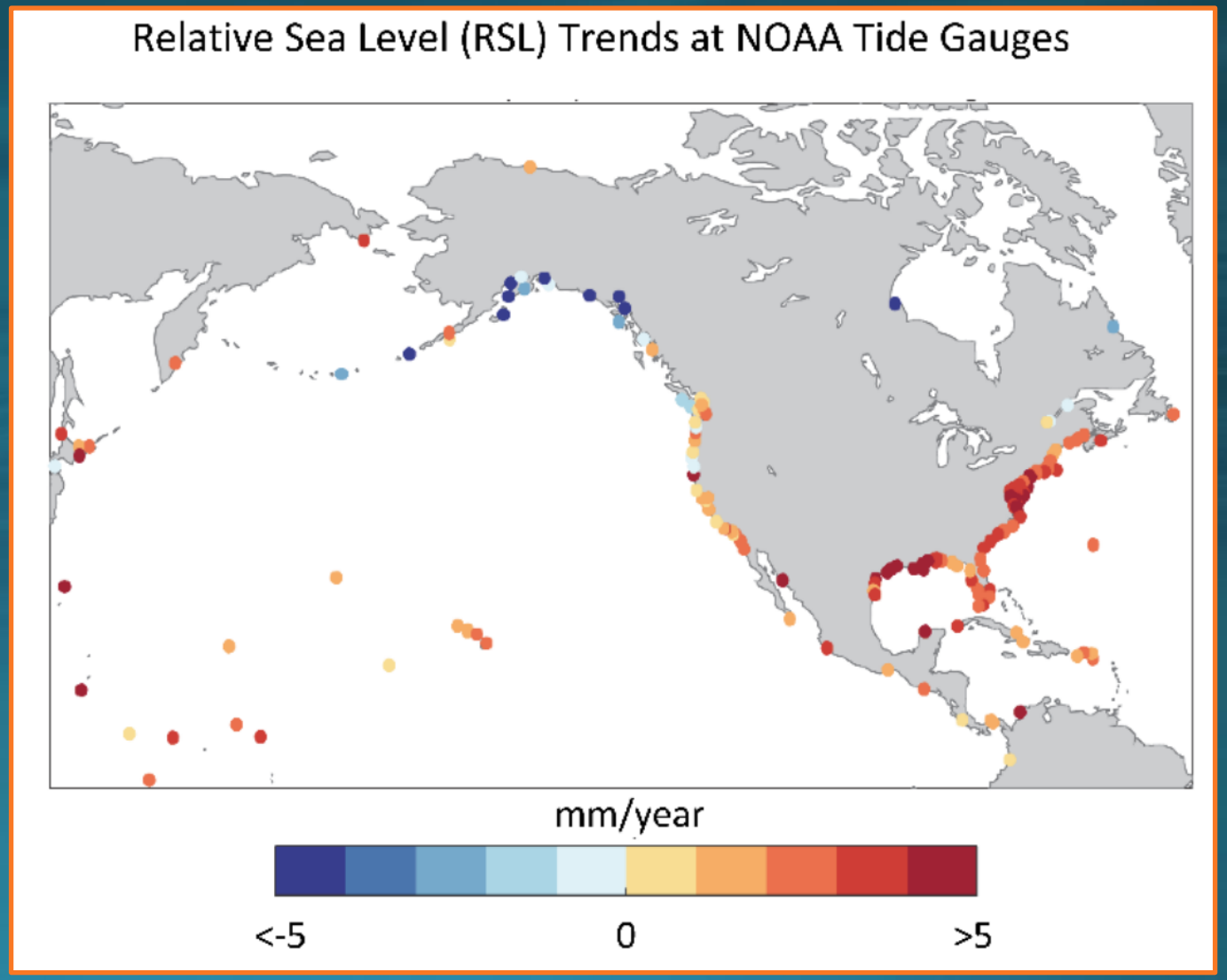
Tides ≠ Sea Level Rise

- Now that we understand some of the natural variations, we can remove the major cycles and look at the remaining trend (linear for simplicity)
- There are ups & downs in annual averages, but the overall trend is definitely upward
  - *~0.25 in/yr* (0.64 cm/yr) in southeast Florida



SLR Trend Varies by Location

- There is significant variability in the rate of sea level rise
- The global average trend is +0.14 in/yr (3.6 mm/yr), but U.S. Gulf coast and east coast are more rapid
- High latitudes can be negative because of postglacial rebound



NOAA (Sweet et al., February 2018)

"Relative" Sea Level Rise

- Another important factor that can alter the local rate of observed sea level rise is **vertical land motion (VLM)**
  - *Subsidence*: the land is sinking, amplifying the effect of sea level rise
  - *Uplift*: the land is rising, suppressing or even reversing the effect of sea level rise
- VLM results from *postglacial rebound* (Earth's crust rises following significant ice loss), *aquifer depletion* (Earth's crust depresses when material removed from under it), *plate techtonics*, *sediment transport*, etc

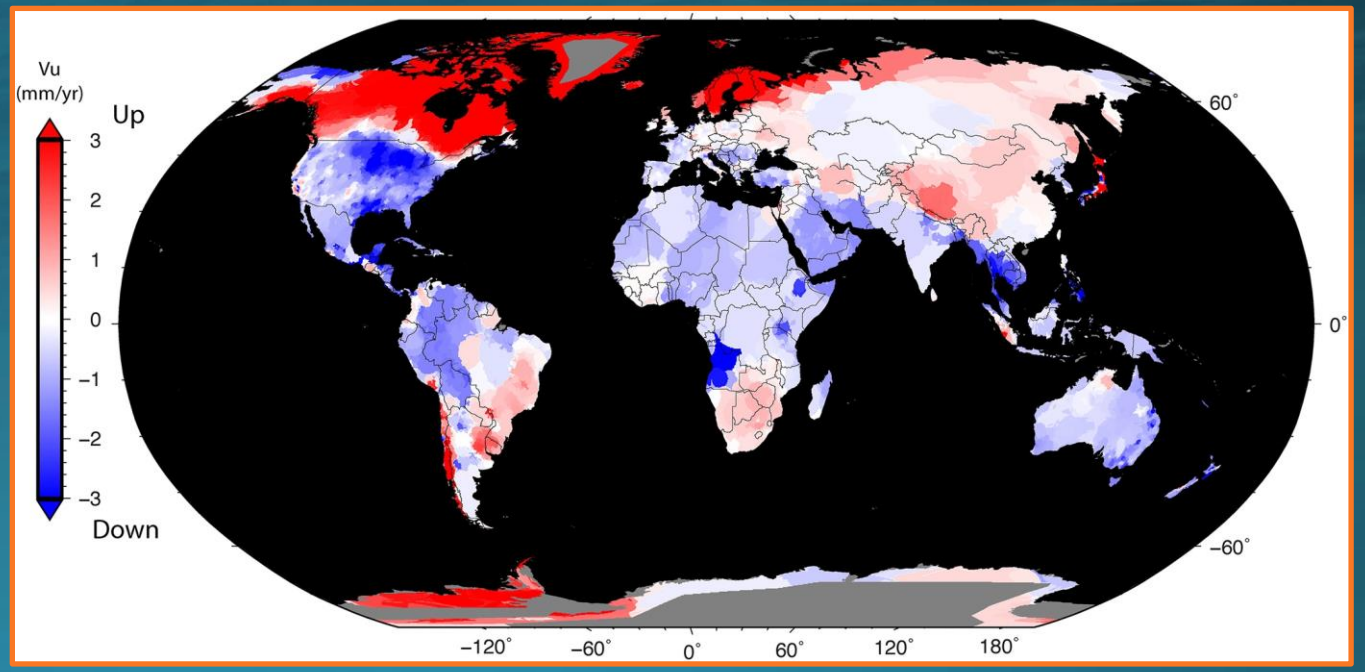
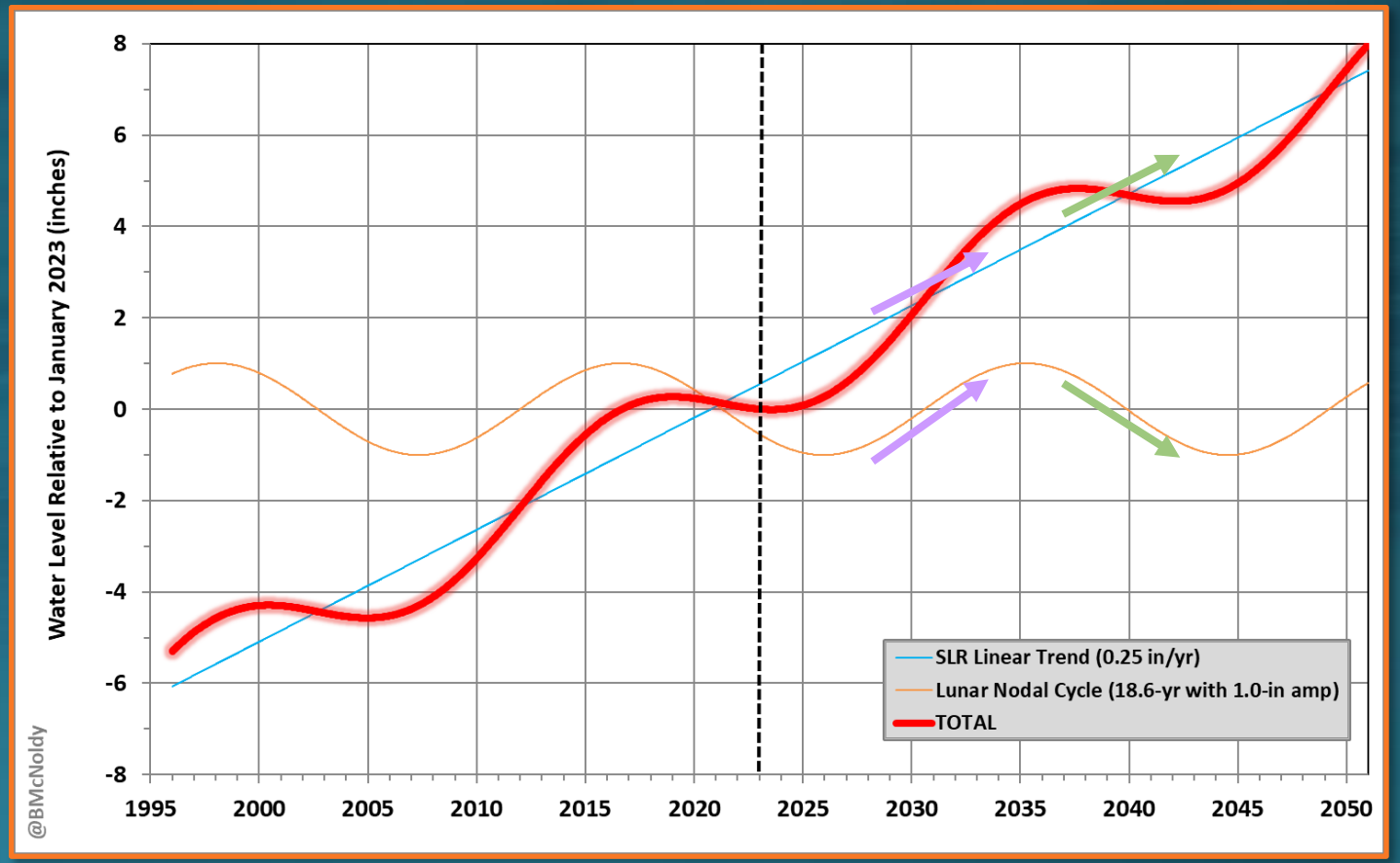


Figure 9 of Hammond et al., 2021 (JGR)

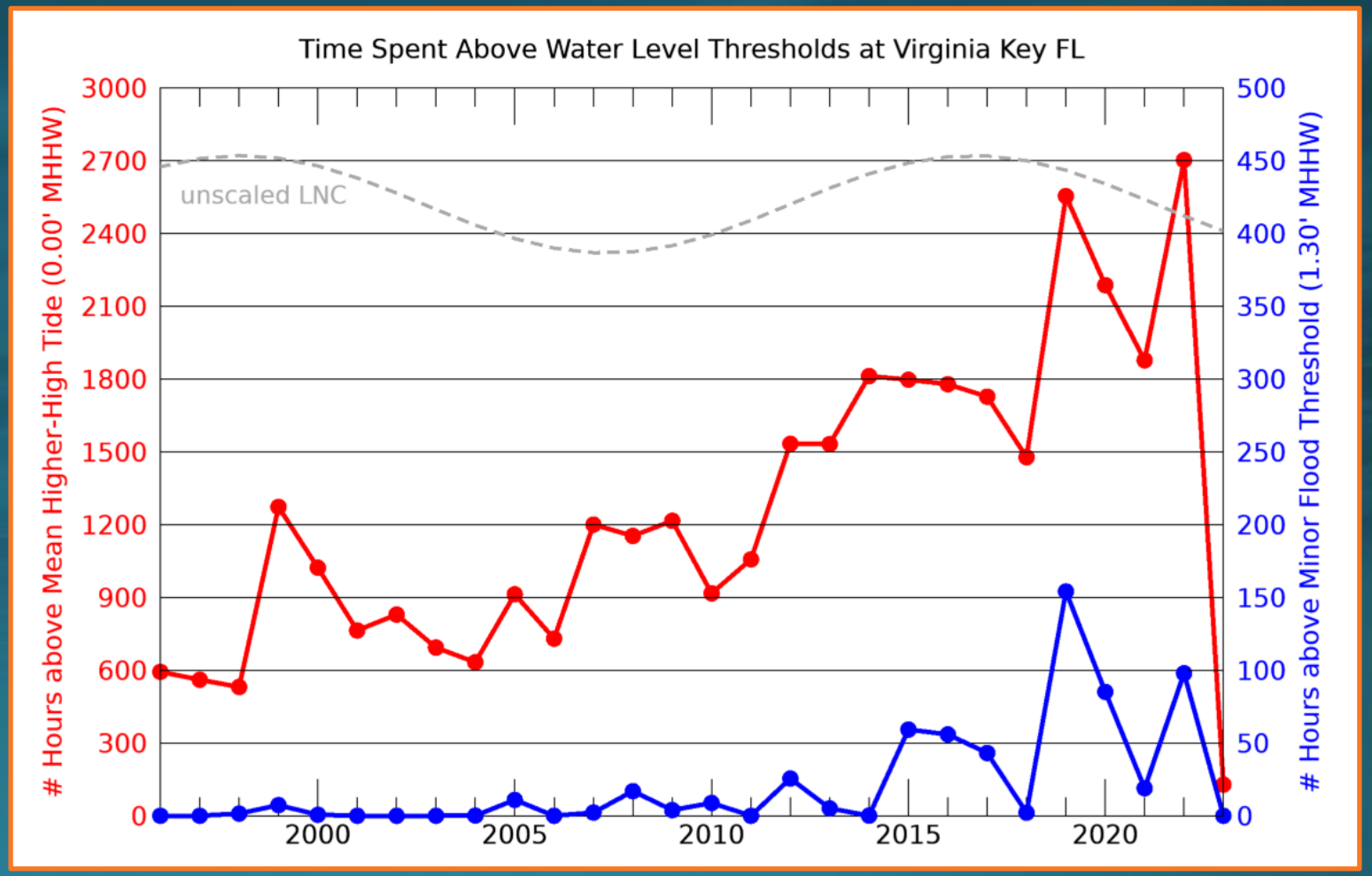
"Apparent" Sea Level Rise

- Recall the 18.6-year *lunar nodal cycle*…
  - Here, the peak slope of the oscillation roughly matches the simple linear rate of sea level rise!
  - During upward phase, it ~ doubles SLR
  - During downward phase, it ~ negates SLR
  - Their sum is a very crude representation of the observed water level (ignoring the certain future acceleration of SLR)



High Tide Flooding

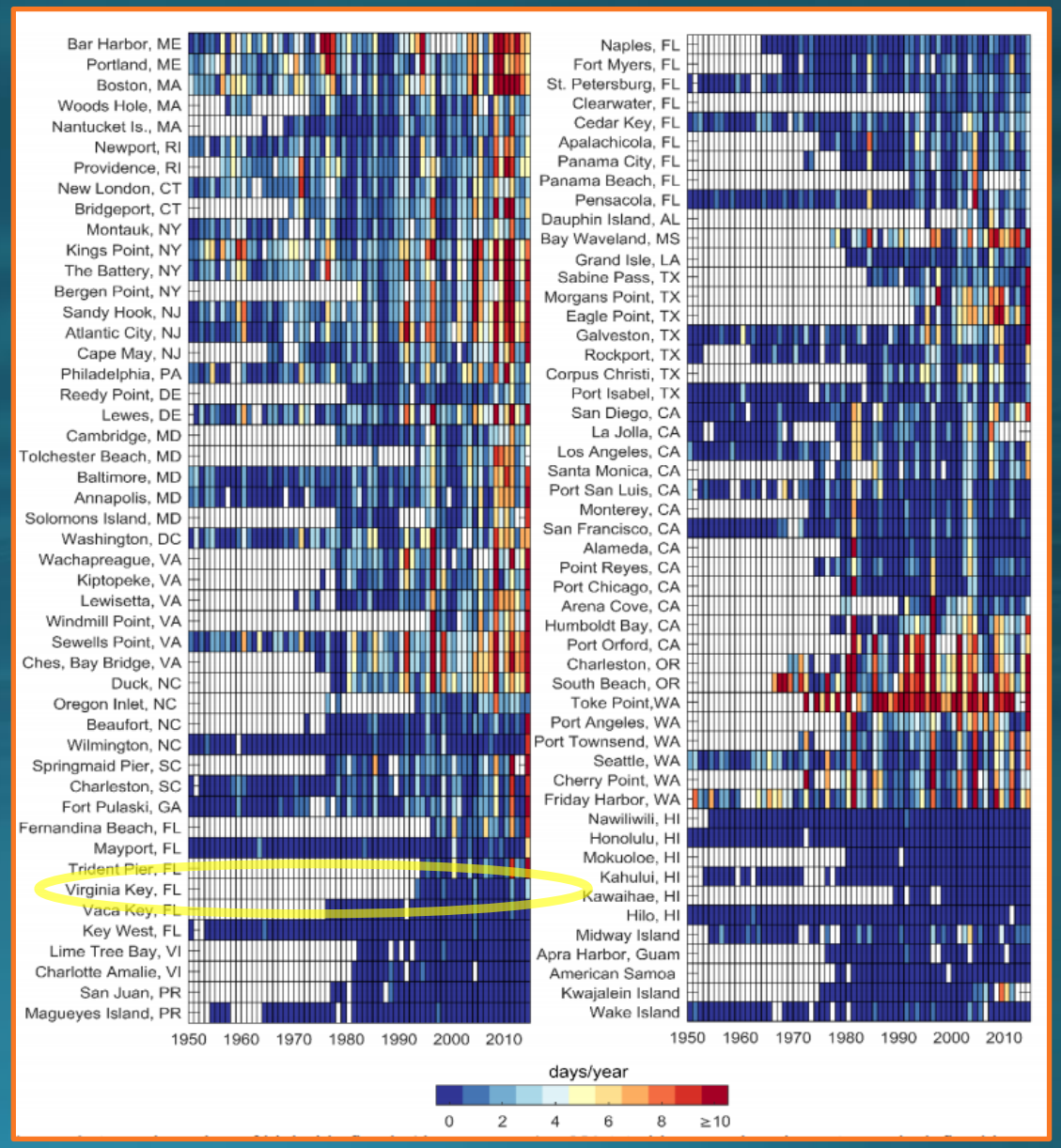
- "sunny-day flooding"
- "nuisance flooding"
- When low-lying areas experience tidal inundation… no rainfall needed
- From the tide gauge measurements, we can add up the number of hours the water level spends above certain thresholds each year
- Miami: Almost never above the "minor flood threshold" two decades ago, but 160 hours in 2019!



https://bmcnoldy.earth.miami.edu/vk/

Not Just Florida…

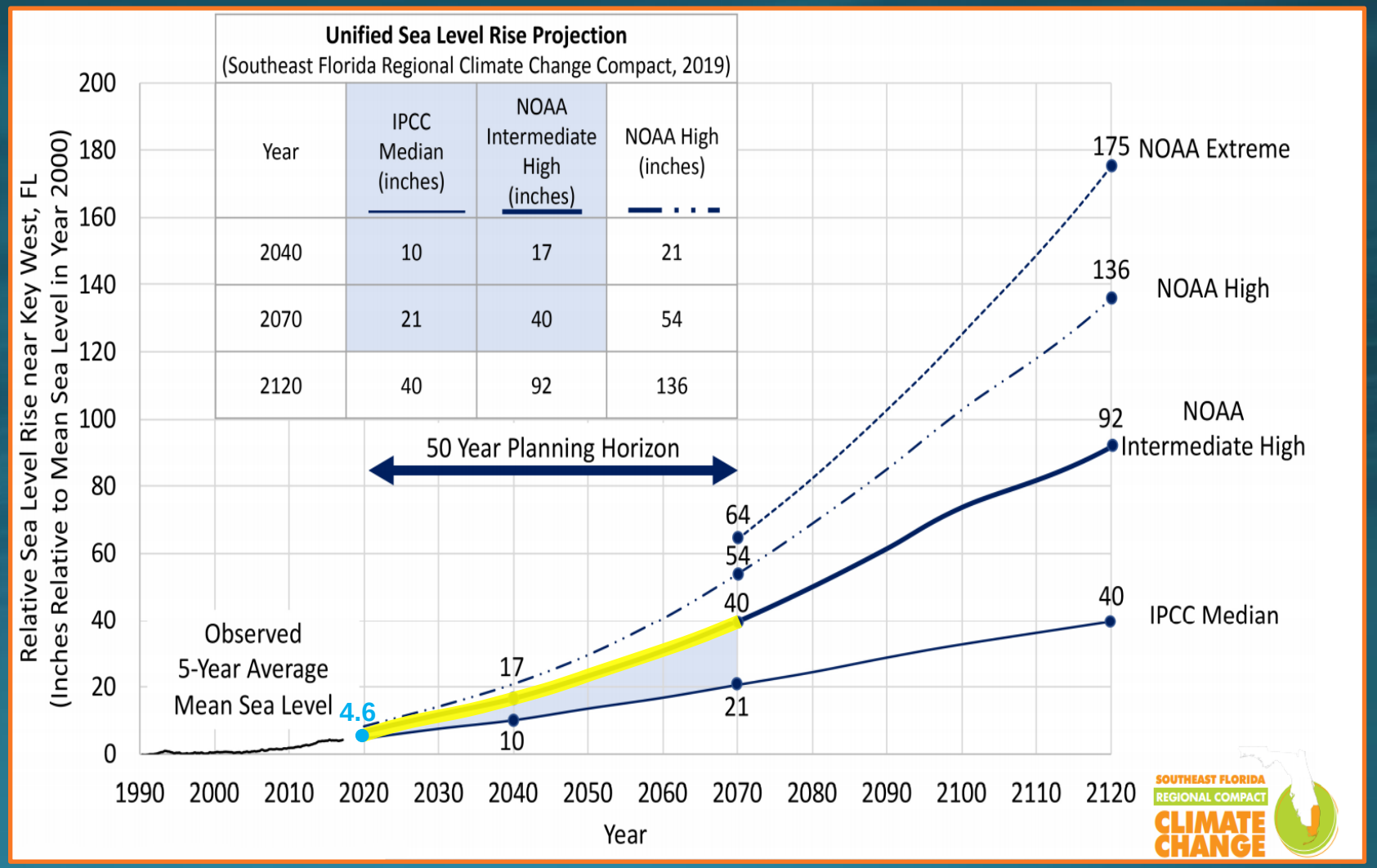
- This chart shows the number of days per year with high tide flooding (HTF) at all U.S. tide gauge locations from 1950-2017.
- What was once observed occasionally in a few locations is now observed everywhere and at greater frequency



NOAA (Sweet et al., February 2018)

Sea Level Rise Projections

- Using NOAA's "*Intermediate High*" SLR curve adjusted to south Florida, we could see:
  - *~1 ft (31 cm) in 20 yrs*
  - *~3 ft (91 cm) in 50 yrs*
  - *~7 ft (215 cm) in 100 yrs*
- *None of south Florida will look or function the way it does now in 50+ years… big changes are coming whether we are prepared for them or not!*



Summary

- Understanding sea level rise and tides involves oceanography, geology, astronomy, and meteorology!
- Earth's mean sea level rises and falls by hundreds of feet on glacial timescales driven by orbital fluctuations
- On "human" timescales, natural cycles and motions influence *apparent sea level rise locally*, but *actual* sea level rise on a global scale is dominated by ice melt and thermal expansion of the ocean
- In the past 150 years, SLR has accelerated at an alarming rate due to man-made global warming, endangering coastal cities and billions of people (not limited to just coastal residents, but also anyone who relies on ports and coastal infrastructure for goods)
- There are numerous factors and cycles that complicate the interpretation of tide gauge data to arrive at SLR rates
- Sea level has risen ~6.3 inches (~16 cm) in the past 29 years in southeast Florida… or an *average rate of 0.25 in/yr* (6.4 mm/yr) – roughly *twice* the global average. An additional 3 feet of SLR is likely in the coming 50 years.
- Sea level rise is a ***slow-motion crisis*** on a global scale