

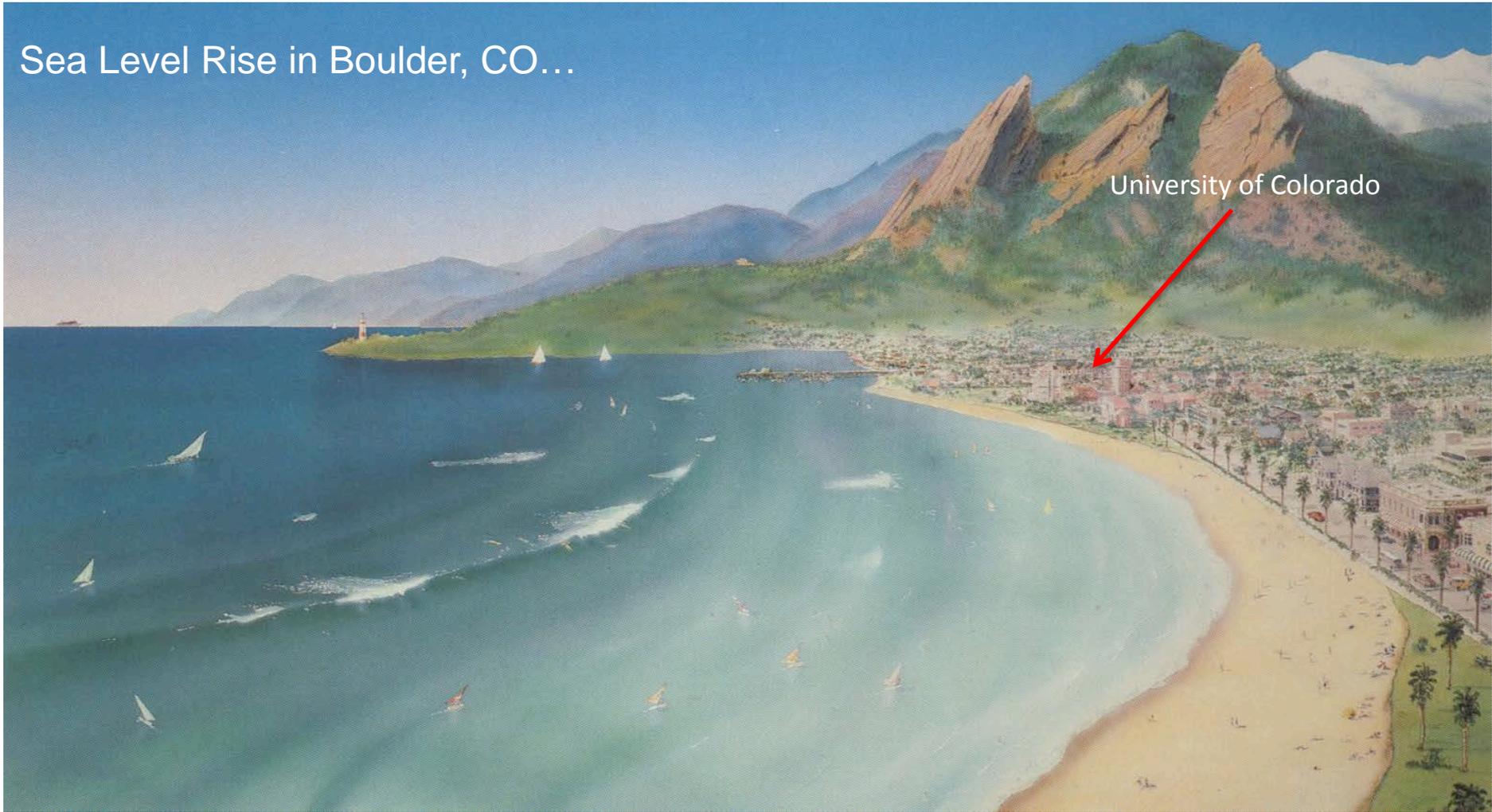
Understanding Sea Level Change on Global and Local Scales

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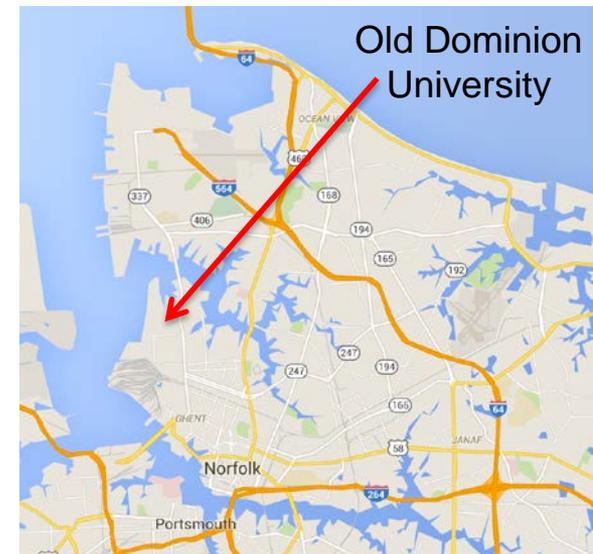
Sea Level Rise in Boulder, CO...



University of Colorado



Sea Level Rise in Norfolk, VA...



Sea Level Rise in Norfolk, VA... Tropical Storm Julia, 2016



(Photo Credit: Accuweather.com)



Sea Level Rise in Norfolk, VA... 2016 Hurricane Matthew



(Photo Credit: Bill Tiernan/The Virginian-Pilot via AP)



Sea Level Rise in Norfolk, VA... 2016 Hurricane Matthew

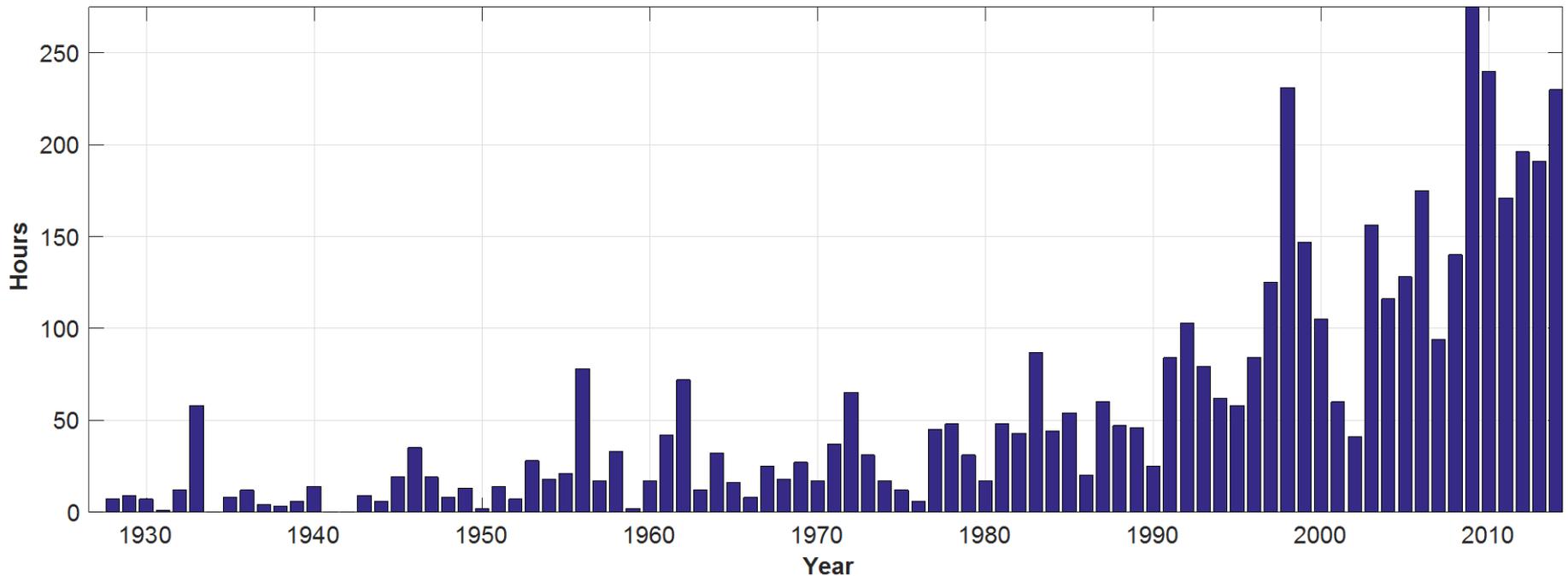


(Photo Credit: Bill Tiernan/The Virginian-Pilot via AP)



Hours spent 1-ft above MHHW in Norfolk, VA

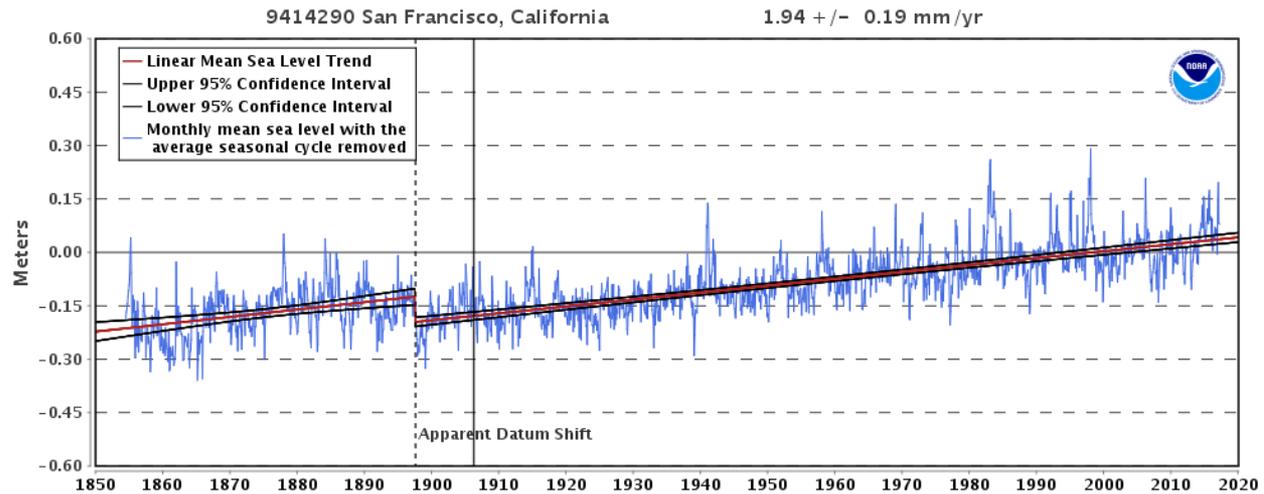
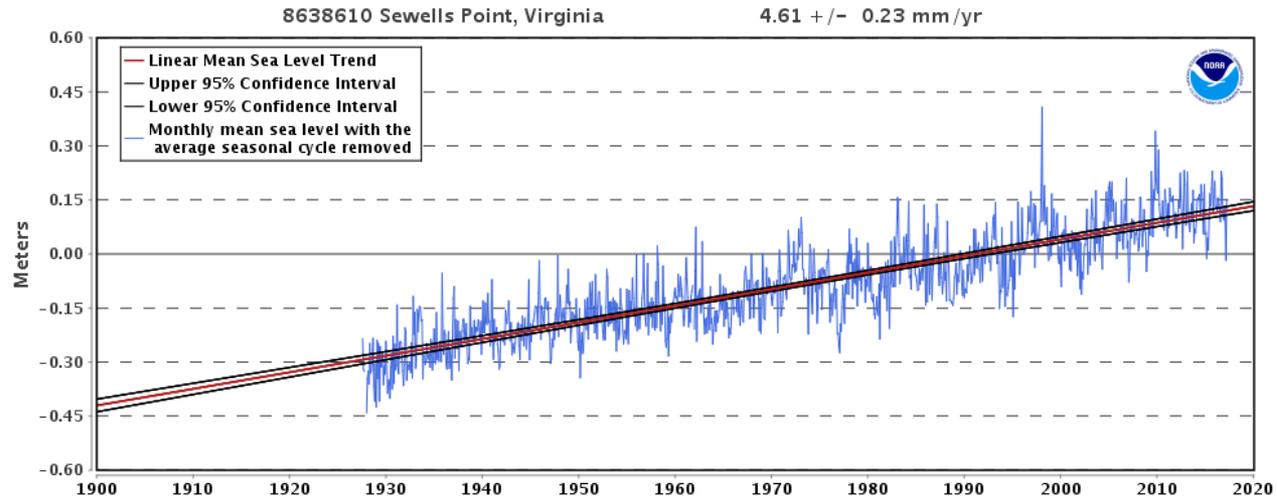
Extreme events are not required for coastal flooding to occur.



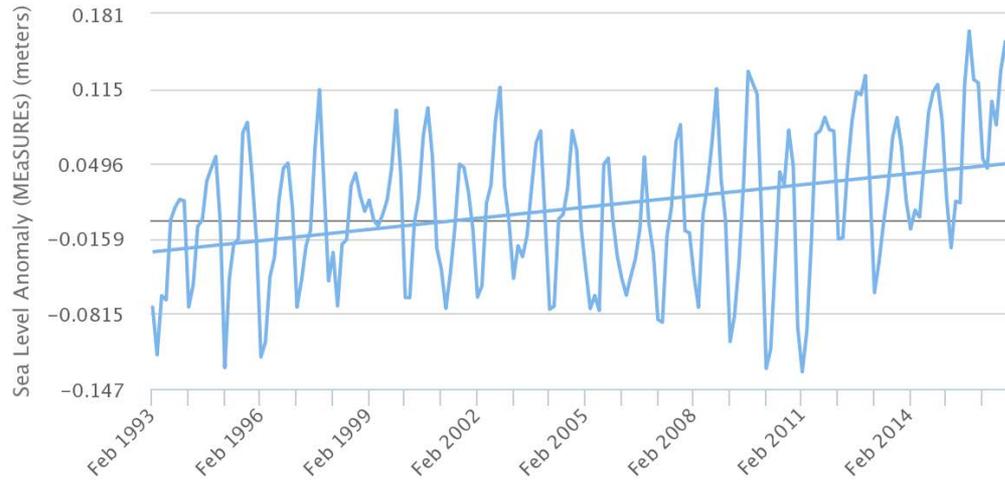
Why is coastal flooding such a problem in Norfolk/SE Virginia?



Long-term Sea Level Change

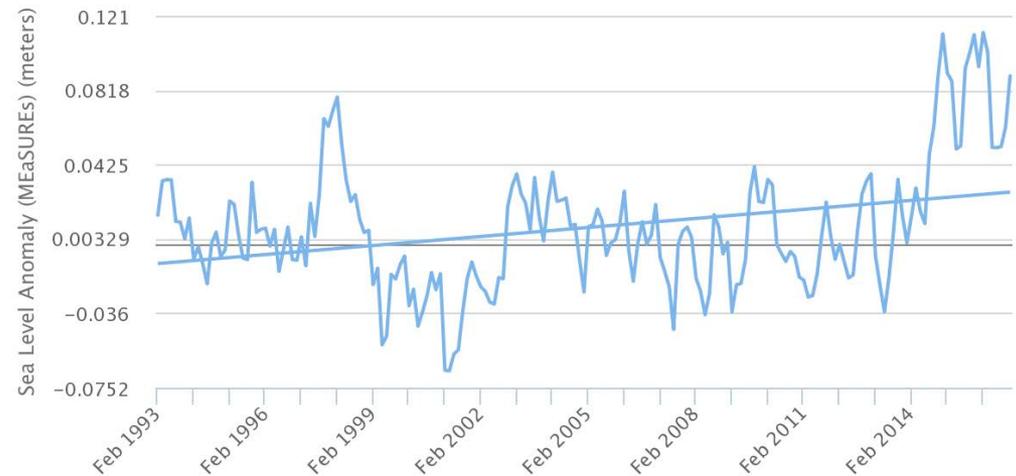


More Recent Sea Level Change



East coast sea level trend 1993 to 2016:
3.3 mm/yr.

West coast sea level trend 1993-2016:
1.95 mm/yr.



(sealevel.nasa.gov)



Global vs. Regional Sea Level

- For decision-making purposes, global sea level estimates and projections are of little use.
- More relevant question: how has sea level changed at a particular location and how will it change at that location in the future?
- There are a three fundamental ways global sea level can be changed:
 1. Changing volume of existing ocean water (thermal expansion).
 2. Adding water mass (melting land ice, land water storage).
 3. Changing the depth of the ocean basins by movement of Earth's crust (Glacial Isostatic Adjustment ~ 0.3 mm/yr).
- Regional variations from the global mean occur due to climate variability, ocean dynamics, and self-attraction/loading patterns of ice melt.
 - At the coast, land subsidence also results in relative sea level rise.



Equation for Relative Regional Sea Level Change

Separating the individual components, Relative Regional Sea Level (RRSL) can be described by the following equation:

$$\Delta RSL = \Delta CV + \Delta OD + \Delta GIS + \Delta AIS + \Delta MGIC - \Delta VL$$

CV - Climate Variability (ENSO, PDO, etc.)

OD – Ocean Dynamics (thermosteric + halosteric + ocean circulation)

GIS – Greenland Ice Sheet

AIS – Antarctic Ice Sheet

MGIC –Mountain Glacier Ice Contribution

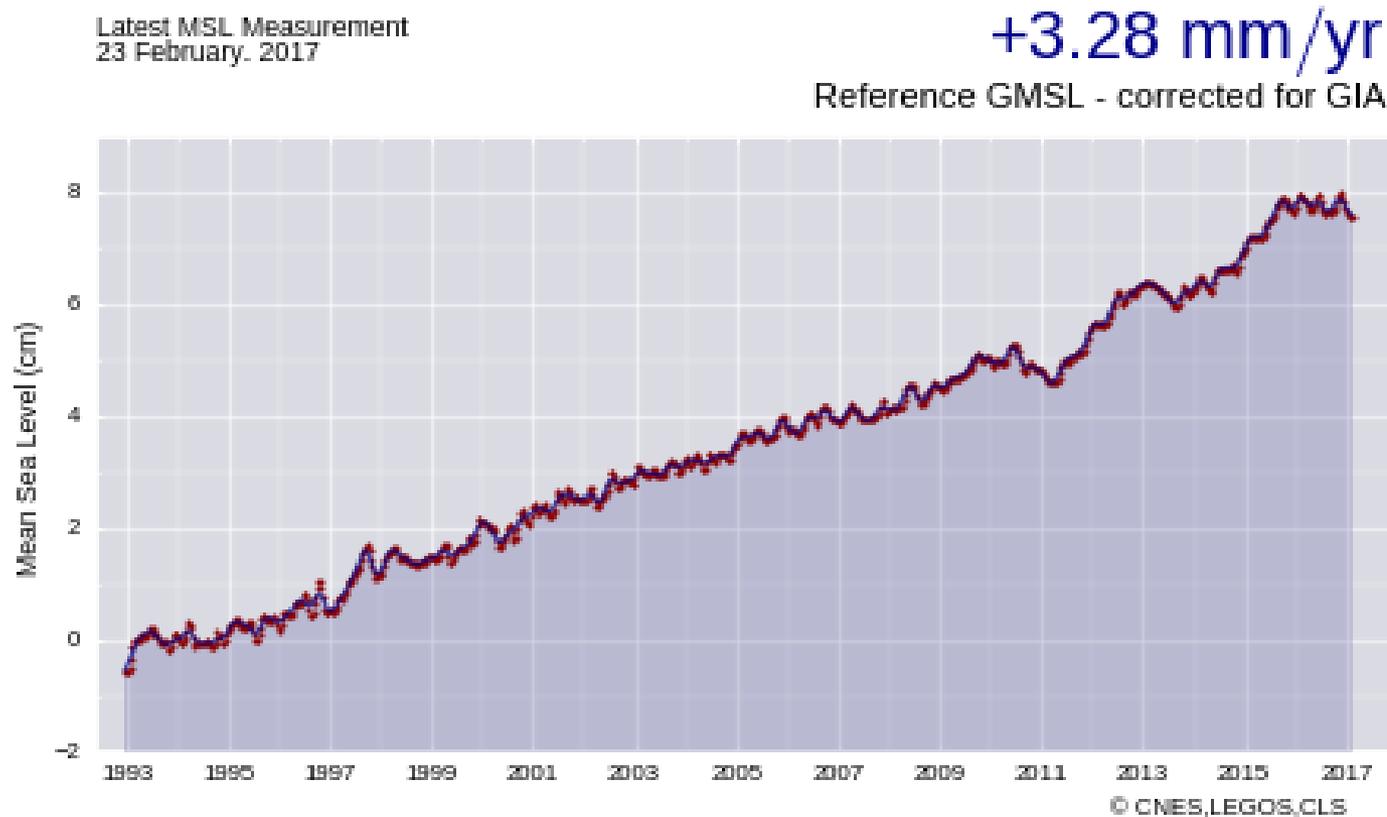
VL – Vertical Land Motion

Each of these factors contribute differently across a range of timescales → must understand each component to accurately project future sea level rise.



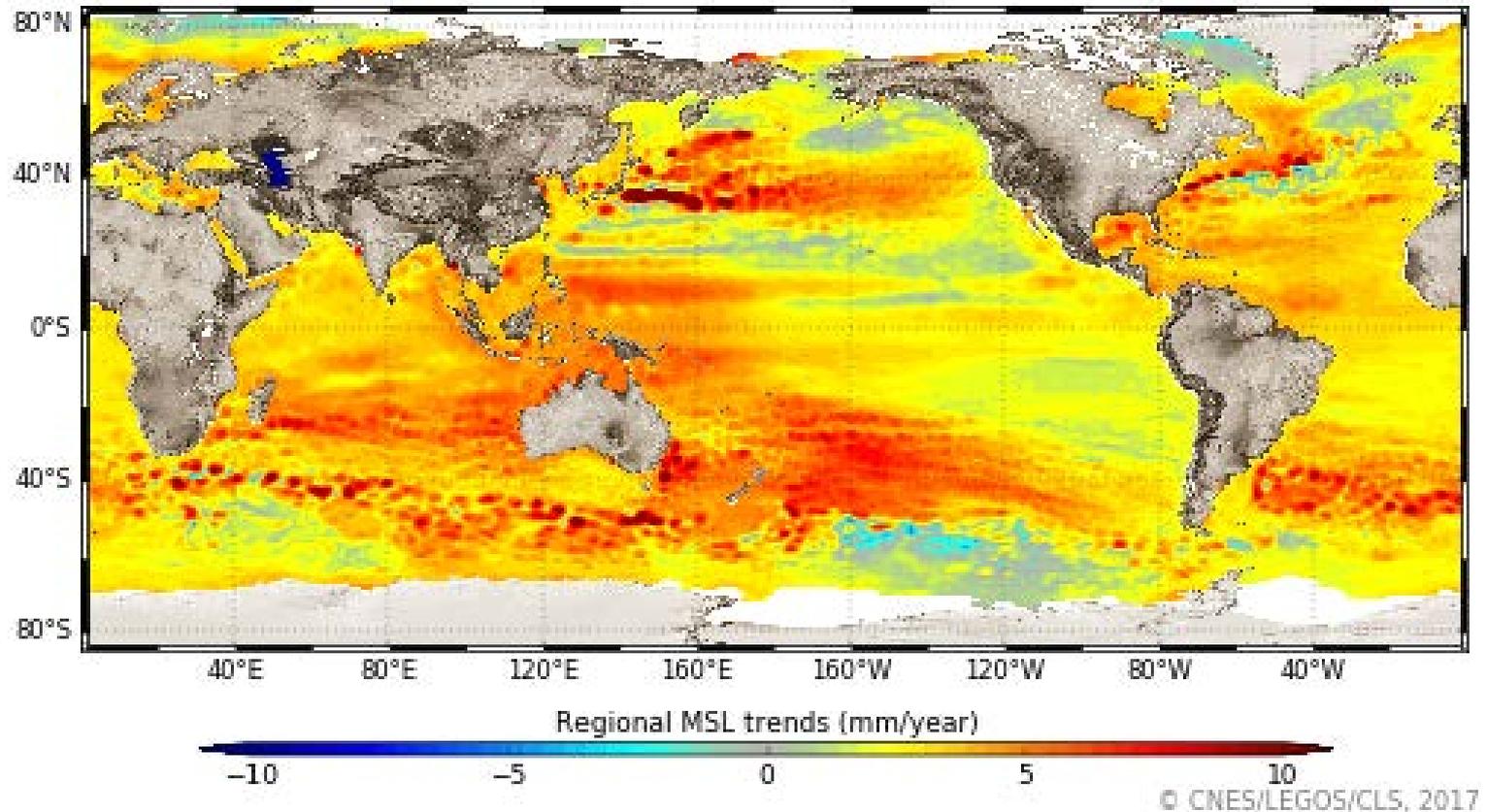
Sea level 1993 - Present

- With satellite altimetry, we have near-global and continuous measurements of sea level since 1993.
- Rate of global mean sea level (GMSL) rise since 1993 ~ 3.3 mm/yr.



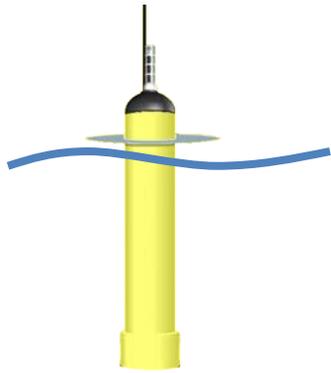
Sea level 1993 - Present

- Regional trends can be up to 4x the trend in GMSL.



Closing the Sea Level Budget

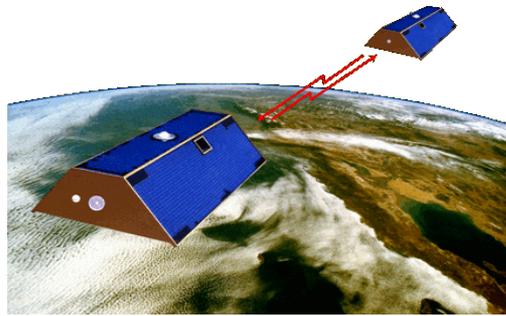
Addition of Heat



Argo

+

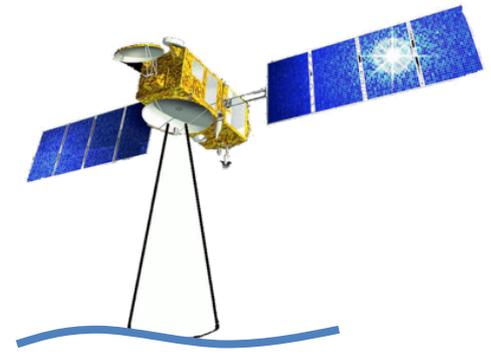
Addition of Freshwater



GRACE

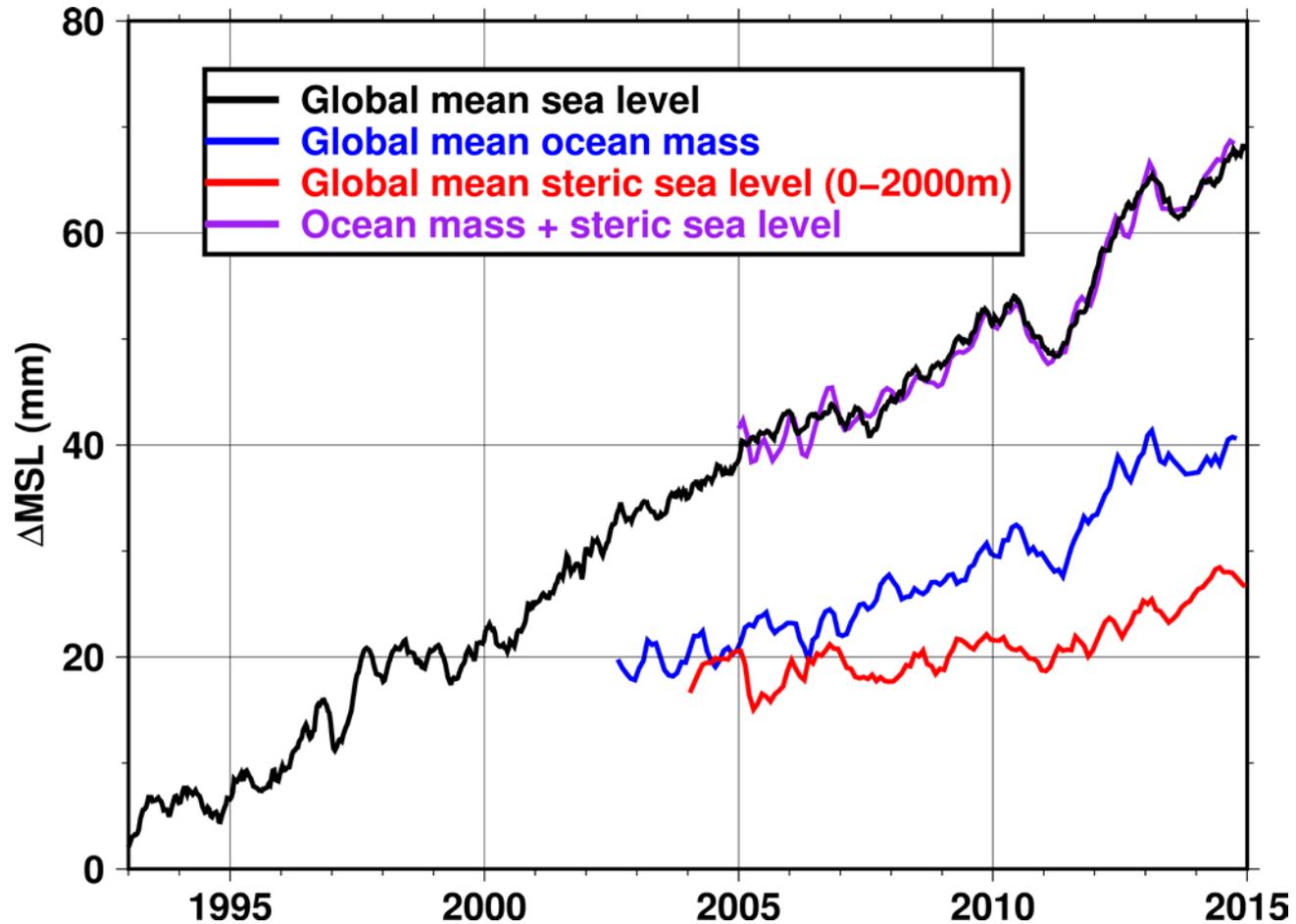
=
(roughly)

Total Sea Level Rise



Satellite Altimetry

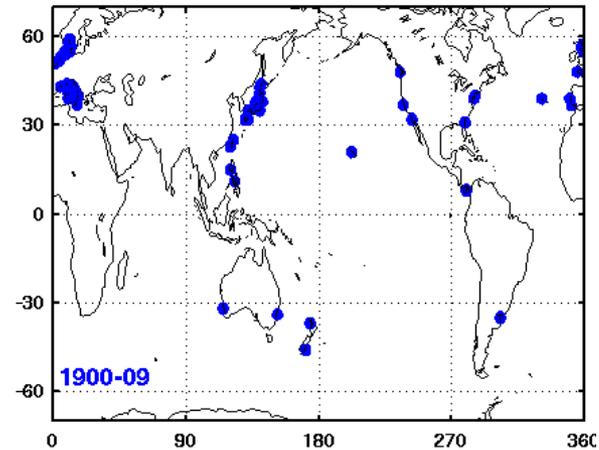
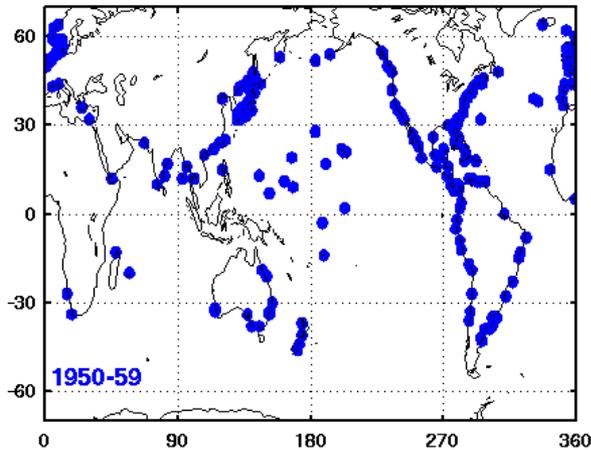
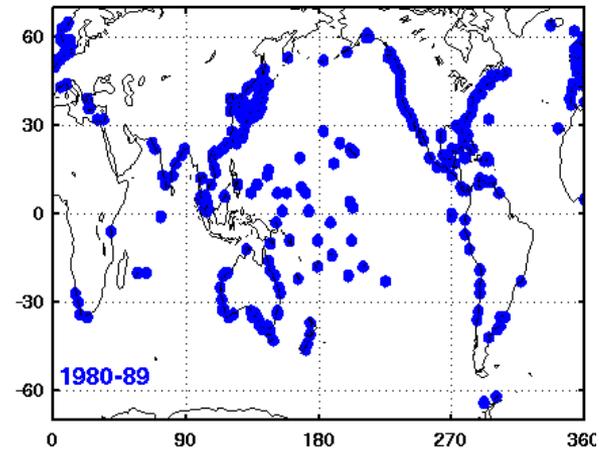
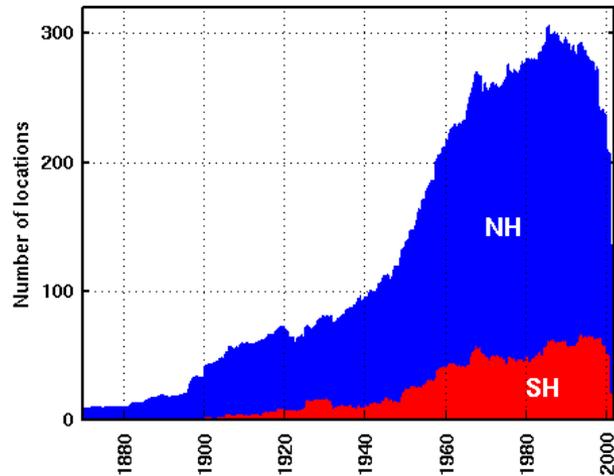
Closing the Sea Level Budget



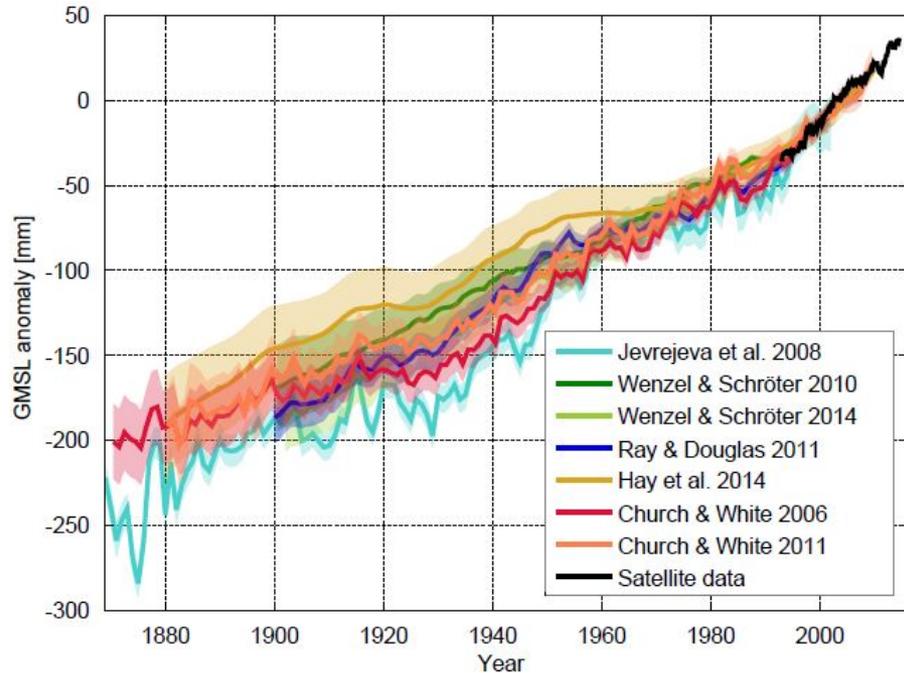
(Leuliette, 2016)



Sea Level Prior to Satellite Altimetry

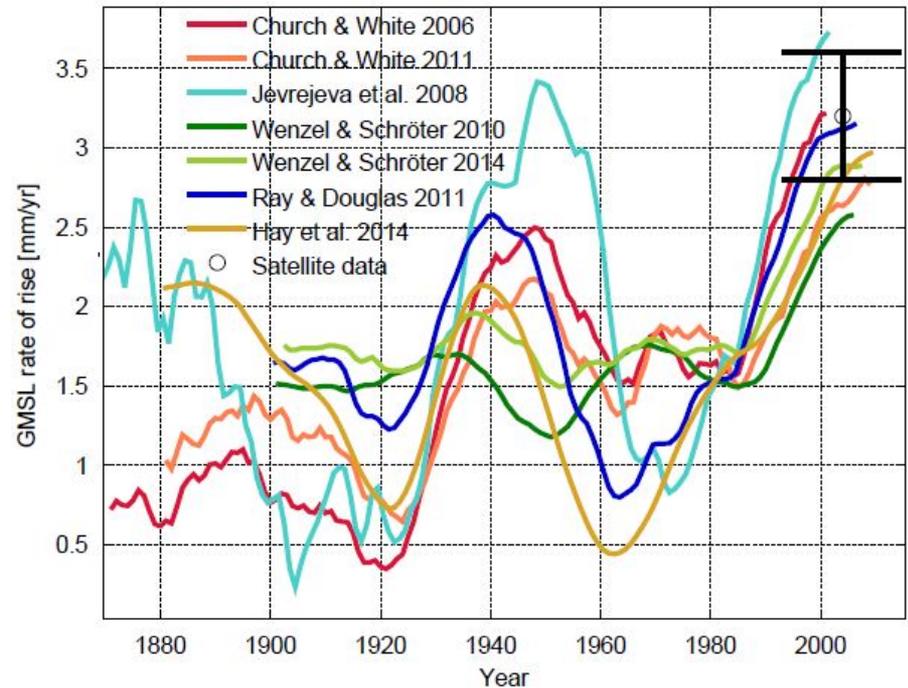


Sea Level Prior to Satellite Altimetry



The “zoo of sea level curves”

– Stefan Rahmstorf, *RealClimate.org*



GMSL Trends 1900-1990

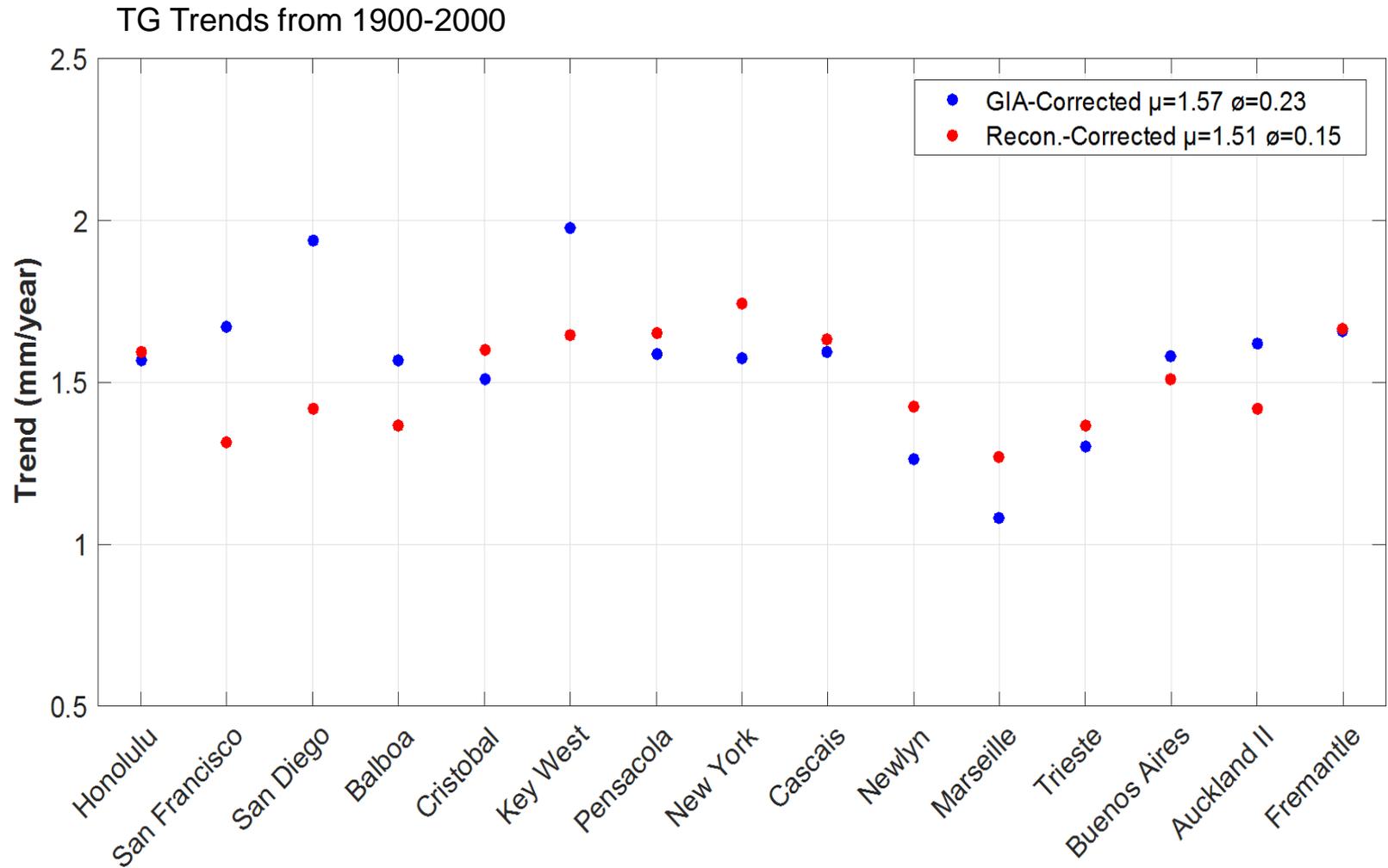
Jevrejeva et al. [2008]	1.9 mm/year
Church and White et al. [2011]	1.5 mm/year
Ray and Douglas [2011]	1.7 mm/year
Hay et al. [2015]	1.2 mm/year



Sea Level Prior to Satellite Altimetry

The image is a screenshot of a USA Today news article. At the top, the USA Today logo is on the left, and a search bar is on the right. Below the logo is a navigation menu with categories: NEWS, SPORTS, LIFE, MONEY, TECH (highlighted in orange), TRAVEL, OPINION, 68°, CROSSWORDS, WASHINGTON, VIDEO, STOCKS, APPS, and MORE. The article title is "Sea level rise accelerating nearly 3x faster than during 20th century". The author is "Doyle Rice, USA TODAY" and the date is "4:38 p.m. ET May 23, 2017". The main image shows a large glacier with a "60" logo in the top left corner. Below the image is a quote: "It's no secret sea waters are rising. Angeli Kakade (@angelikakade) has the story. Buzz60". To the right of the article is an advertisement for Kenmore appliances, featuring the text "Kenmore. Be Amazing. — EXCLUSIVELY AT — sears" and "manage your home from anywhere." with a "connect now" button and an image of a hand holding a smartphone. On the left side of the article, there are social media sharing icons for Facebook (3487), Twitter, LinkedIn (31), Email, and a comment icon (147). At the bottom of the article, there are icons for "CONNECT", "TWEET", "LINKEDIN", "COMMENT", "EMAIL", and "MORE".

Sea Level Prior to Satellite Altimetry



Understanding Sea Level Change: Challenges

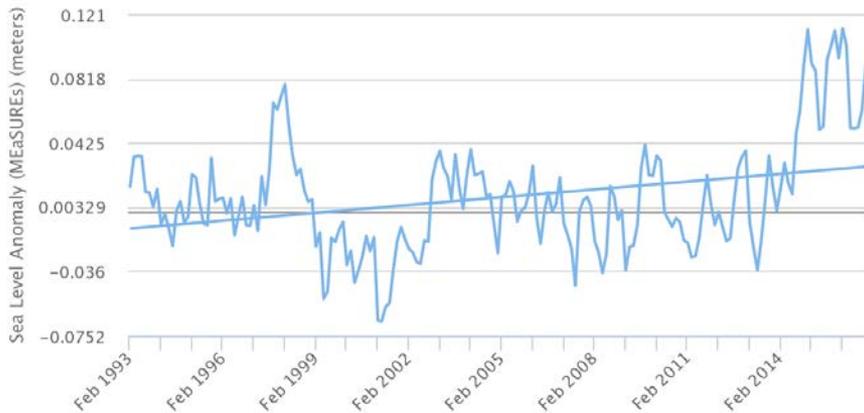
- Satellites
 - Near-global coverage, continuous and consistent measurements.
 - Short records – heavily influenced by internal climate variability → difficult to separate long-term, anthropogenic sea level rise.



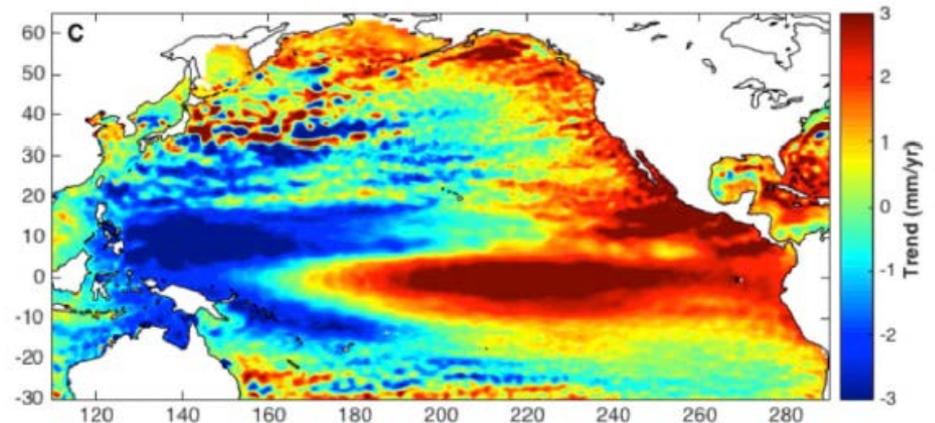
Understanding Sea Level Change: Challenges

- Satellites

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West-coast sea level 1993-2016

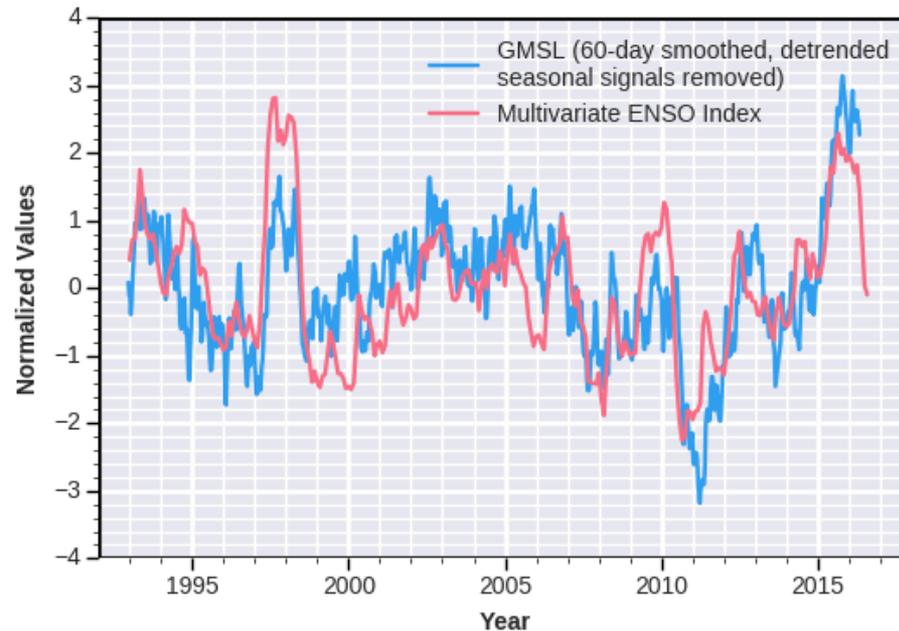


Change in sea level from 2011-2016

Understanding Sea Level Change: Challenges

- Satellites

- Near-global coverage, continuous and consistent measurements.
- Short records – heavily influenced by internal climate variability → difficult to separate long-term, anthropogenic sea level rise.



Understanding Sea Level Change: Challenges

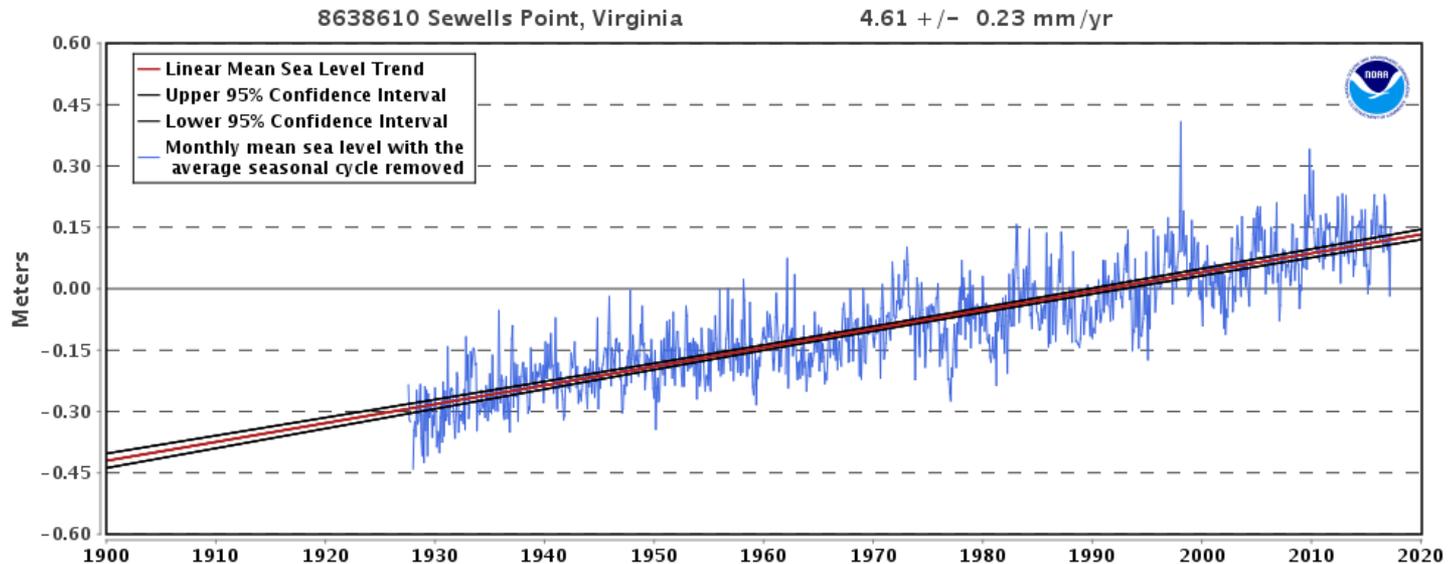
- Satellites
 - Near-global coverage, continuous and consistent measurements.
 - Short records – heavily influenced by internal climate variability → difficult to separate long-term, anthropogenic sea level rise.
- Tide gauges
 - Long records extending back into the 19th century.
 - Poor spatial coverage → there is still regional variability on these long timescales.
 - Difficult to separate land vs. ocean.



SE Virginia Sea Level Rise

- Causes

- Long-term anthropogenic sea level rise – combination of melting ice and thermal expansion.
- Ocean dynamics – e.g. slowing Gulf Stream leads to increased sea level along the coast.
- Land subsidence – combination of GIA, Chesapeake Bay Impact Crater, and groundwater pumping.
- **What is the relative contribution of each cause?**



Informational/Observational Needs

- By no means an exhaustive list, and largely formed by my experiences in SE Virginia:
 - Continuity of satellite records – GRACE, satellite altimetry
 - Near-coast sea level measurements
 - High-resolution estimates of land subsidence
 - Accessible (and understandable) information on the drivers of sea level change
 - Regional/local projections of sea level (across a range of timescales with associated uncertainties).
 - Planning for future sea level rise is already underway.
 - What can be done now, given the current state of sea level science, to provide coastal communities with information upon which planning efforts can be based?



Summary

- Global mean sea level change:
 - Long timescales: thermal expansion and addition of freshwater
 - Short timescales: climate variability.
- Regional sea level change:
 - Long timescales: Self-attraction/loading patterns of ice melt, thermal expansion, ocean dynamics, climate variability.
 - Short timescales: climate variability, ocean dynamics.
- The contributors to sea level rise are well observed in the past two decades leading to an improved understanding of sea level change.
- Historic observations of sea level are limited, leading to poorly constrained global and regional sea level estimates.
 - Unclear context for modern observations.
- Accurate projections of regional sea level rise are needed for planning purposes.
 - Requires understanding of all the contributors to regional sea level rise across a range of timescales.

