East Coast Sea Level Rise:
Recent Findings and Understanding

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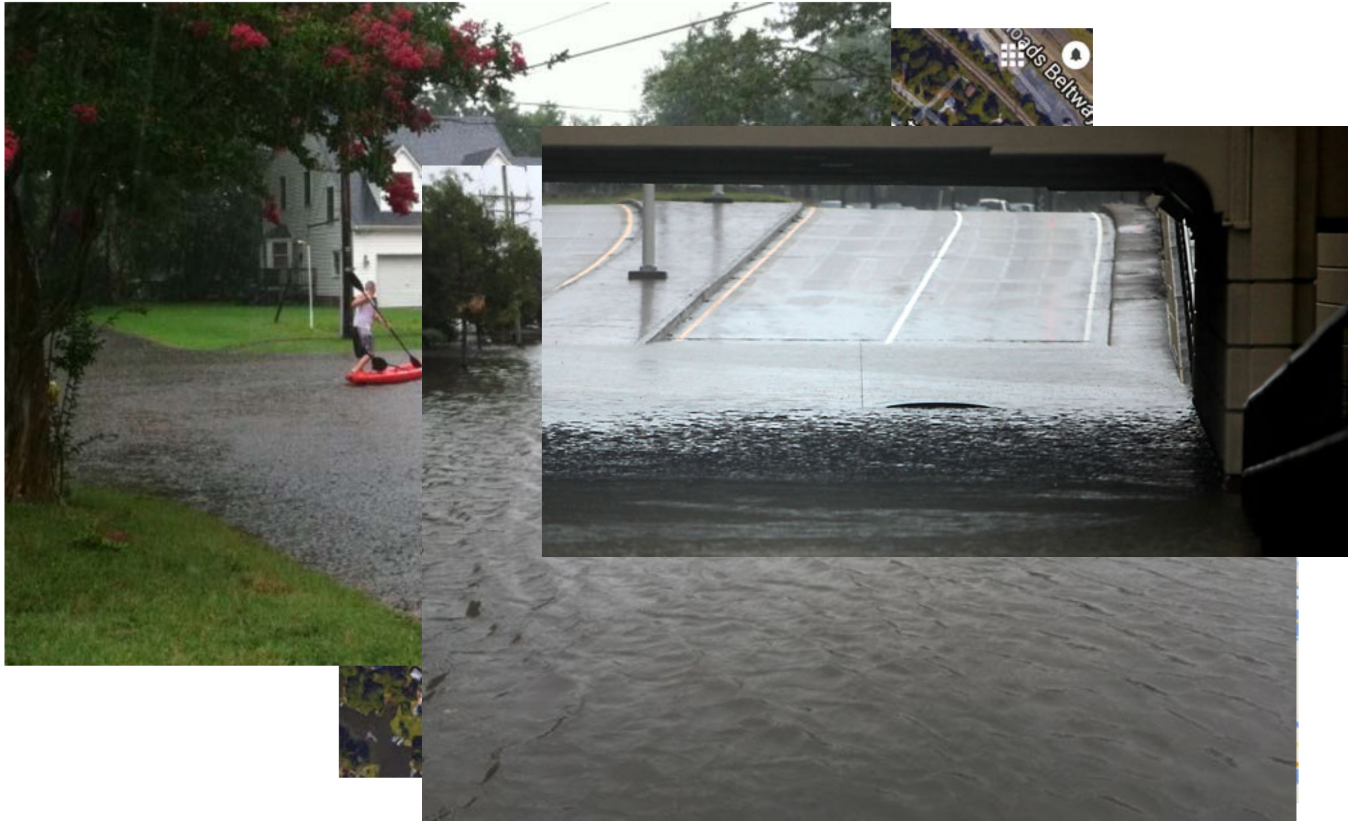
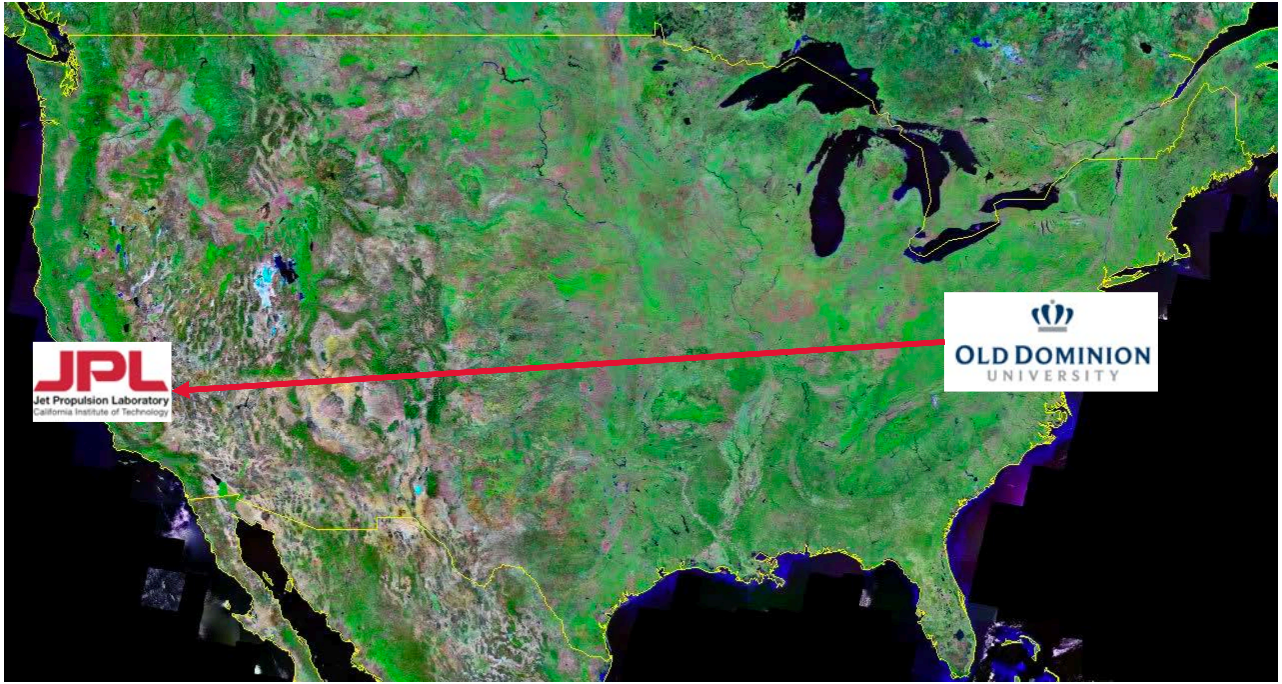


East Coast to West Coast



Lessons Learned

1. Sea level rise is a problem now.
2. Planning efforts are underway and money is being spent.
3. There is a diverse set of stakeholders undertaking these efforts.
4. Their needs, in terms of sea level information, are equally diverse → driven by the range of timescales upon which sea level varies.

Naval Facilities in Hampton Roads

Drivers of East Coast Sea Level Variability

Physical processes drive sea level change on a range of timescales and can have large associated magnitudes.

Physical Process	Temporal Scale	Potential Magnitude (yearly)
Wind Waves (e.g. dynamical effects, runup)	seconds to minutes	< 10 meters
Storm Surge	minutes to days	< 15 meters
Tides	hours	< 15 meters
Seasonal Cycles	months	< 0.5 meters
Ocean/Atmospheric Variability (e.g. ENSO)	months to years	< 0.5 meters
Ocean Eddies and Planetary Waves	months to years	< 0.5 meters
Ocean Gyre and Over-turning Variability	years to decades	< 0.5 meters
Land Ice Melt/Discharge	years to centuries	millimeters to centimeters
Thermal Expansion	years to centuries	millimeters to centimeters
Vertical Land Motion	minutes to centuries	millimeters to meters

(Sweet et al. NOAA, 2019)

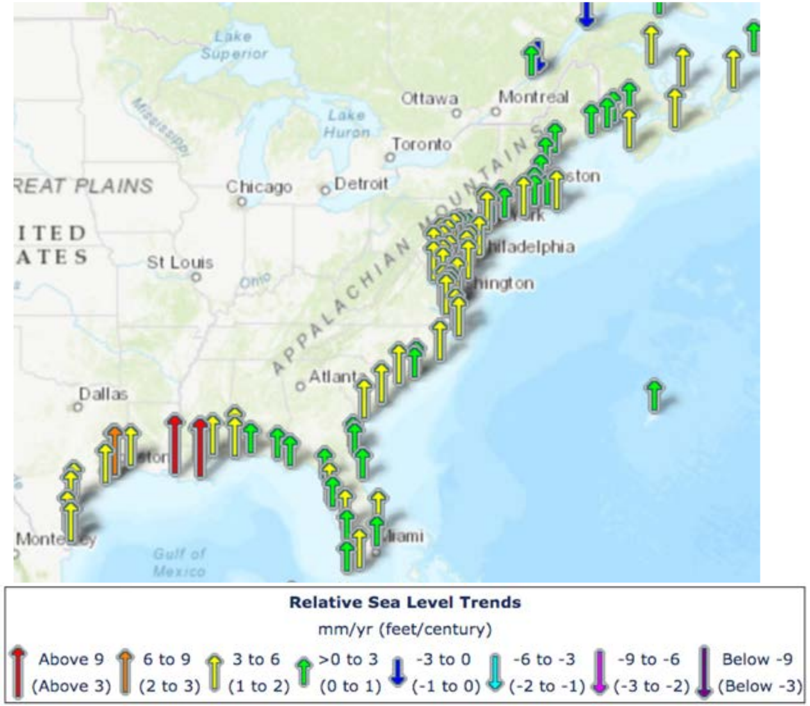
Separating Timescales of Variability

$$RSLR(r,t) = HF(r,t) + IC(r,t) + LT(r,t) + LM(r,t)$$

- **High frequency (HF)** – tides, storm surge, wind-driven events
- **Internal/Climate Variability (IC)** – Seasonal to decadal variability, NAO, ENSO, etc.
- **Long-Term (LT)** – trend associated with ice melt , thermal expansion, long-term changes in ocean dynamics
- **Land motion (LM)** – both long and short timescale vertical land motion

LT: Relative Sea Level Trends

Relative Sea Level Trends Along U.S. East Coast Over Length of Record

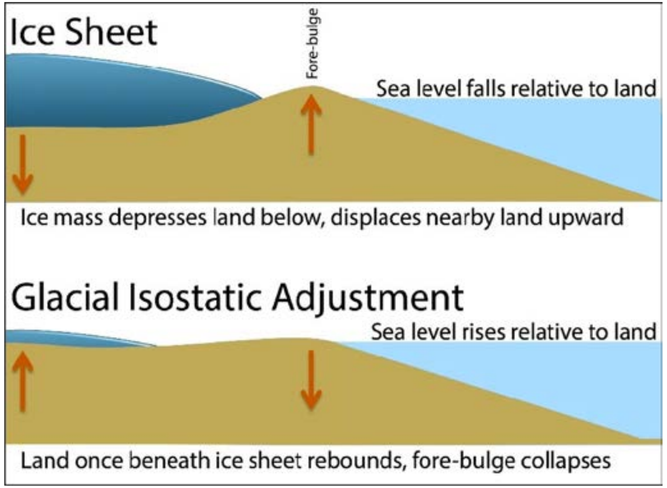


https://tidesandcurrents.noaa.gov/sltrends/

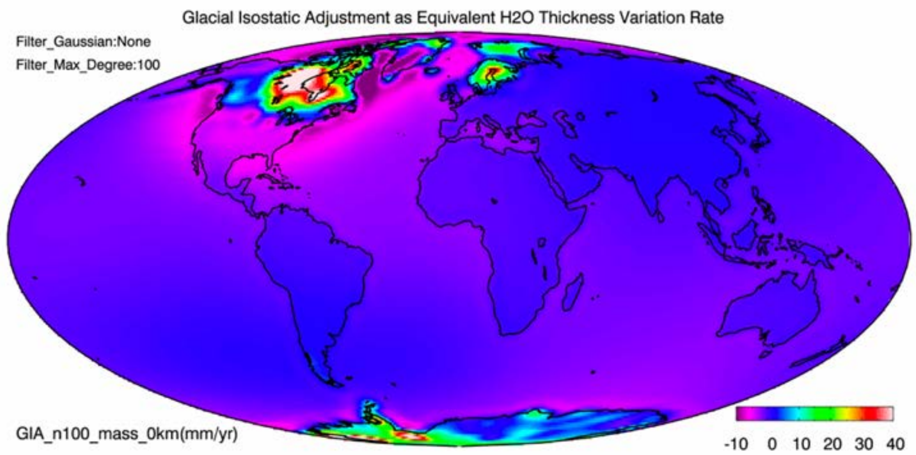
- Every gauge along U.S. East Coast has positive relative sea level trend (minimum 30-year record length).
- There is spatial trend variability between gauges over this longer time period → can we explain this spatial variability and understand what is driving these trends?
- Two dominant drivers on long timescales – glacial isostatic adjustment and mass redistribution associated with ice melt.

LT: Spatial Variability in Trends Along East Coast

The role of glacial isostatic adjustment



Mitchell et al. (2018)



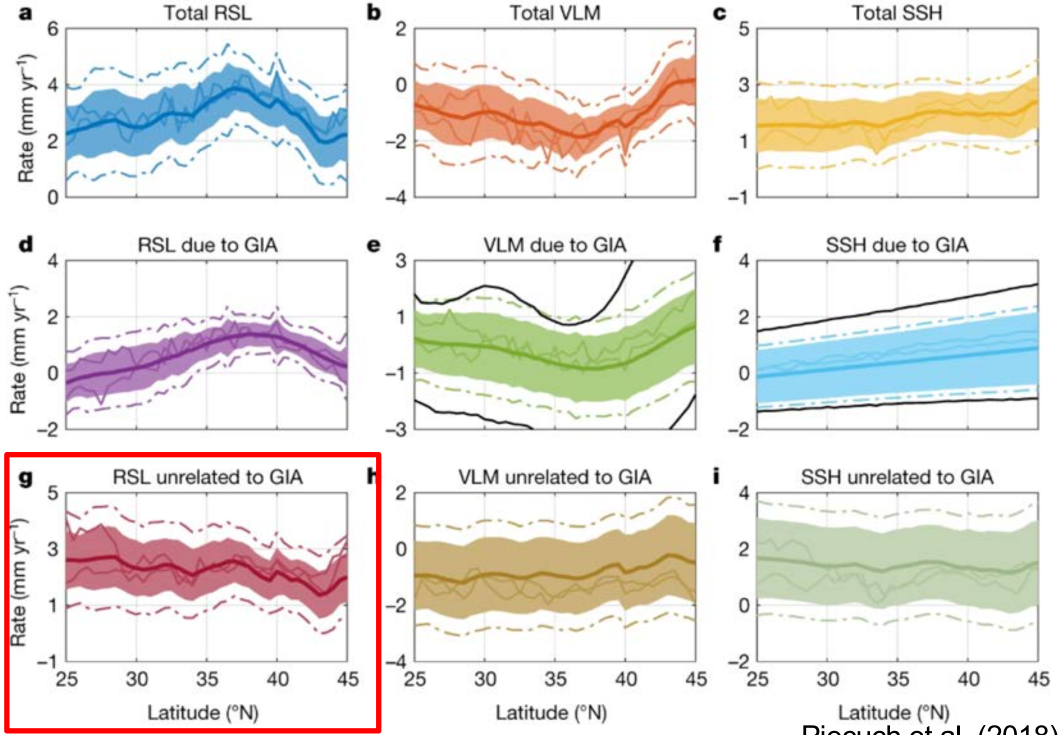
Sealevel.nasa.gov

- The ongoing movement of land in response to the unloading of ice from the last glacial maximum is call glacial isostatic adjustment (GIA).
- While land under and around ice is rising, the U.S. East Coast is located on the forebulge which is subsiding.

LT: Spatial Variability in Trends Along East Coast

The role of glacial isostatic adjustment

- Piecuch et al. (2018) found that GIA is the dominant control on regional spatial differences in relative sea-level trends along the US East Coast from 1900–2017, explaining most of the large-scale spatial variance.

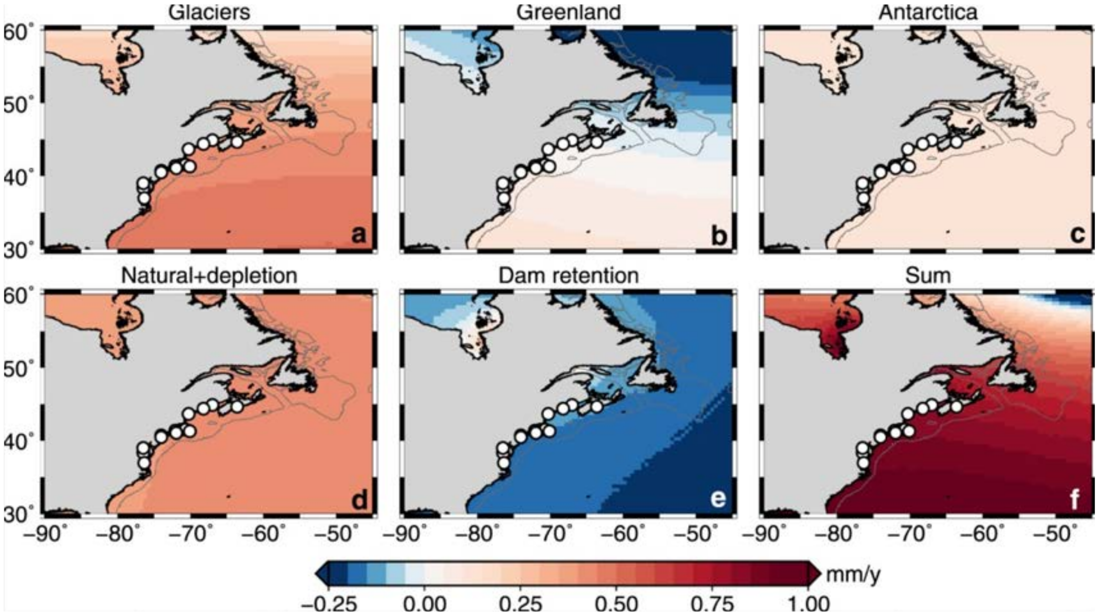


Piecuch et al. (2018)

LT: Closing the Regional Trend Budget

- Frederikse et al. (2017) assessed the trend budget of relative sea level rise along the NE U.S. coast from 1965-2014.

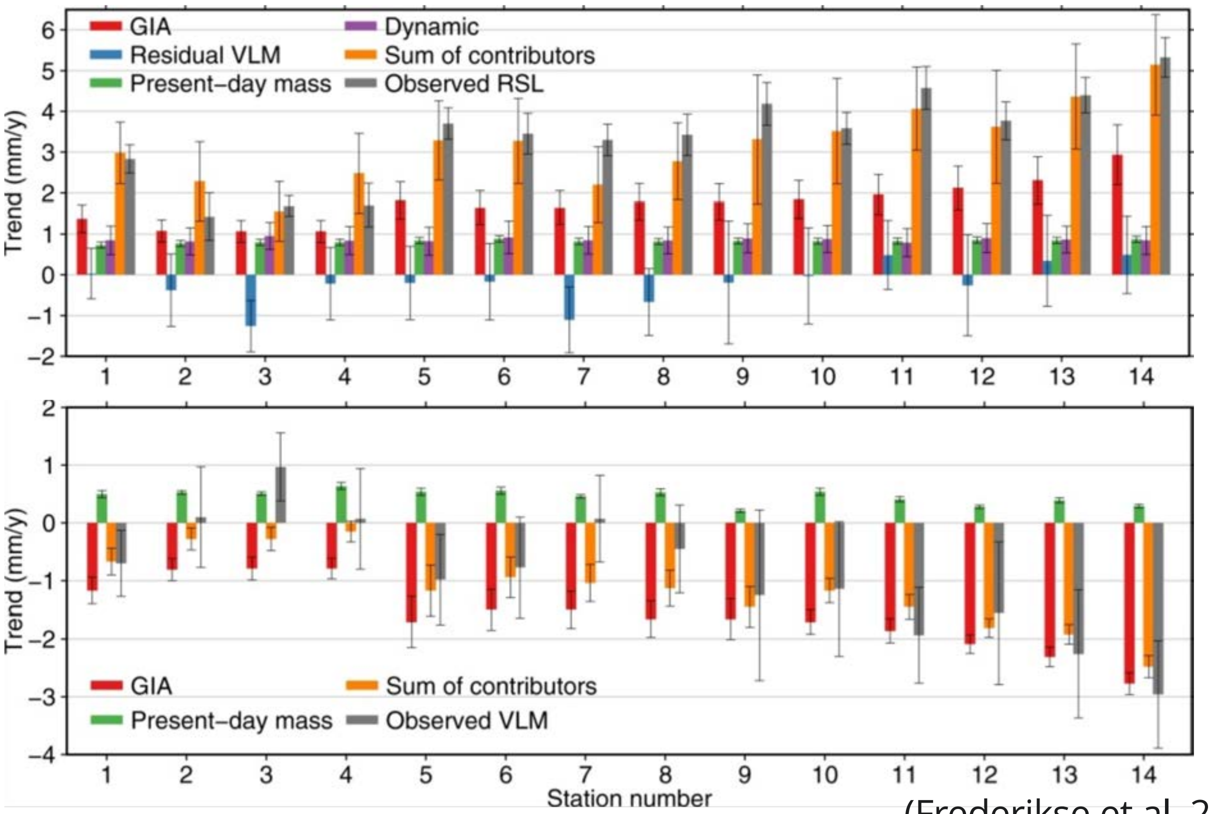
- Computed trends associated with GIA, non-GIA VLM, sterodynamic variability, and mass redistribution → compared sum of individual contributors to trend measured at tide gauges.



Linear trends in the resulting relative sea-level changes caused by (a–e) each individual present-day mass redistribution process and (f) the sum of these processes (Frederikse et al. 2017).

LT: Closing the Regional Trend Budget

- Trend budget closed within uncertainty for 12 of 14 gauges over study time period (1965-2014).
- Dominant drivers of trend were found to be GIA, mass-redistribution and sterodynamic.



(Frederikse et al. 2017

LT: Key Takeaways

- Long-term relative sea level trends along the U.S. East Coast are well understood and associated with drivers that should be expected to continue into the future (GIA and mass redistribution associated with ice melt).

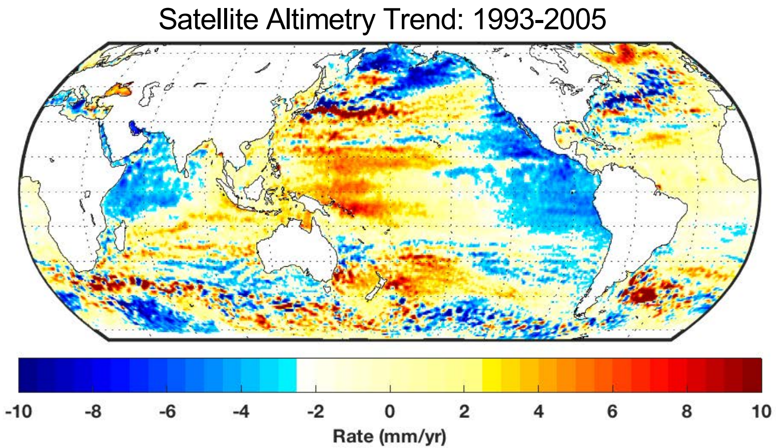
- These drivers also result in spatial variations in the long-term trends along the coast, with GIA playing a dominant role.

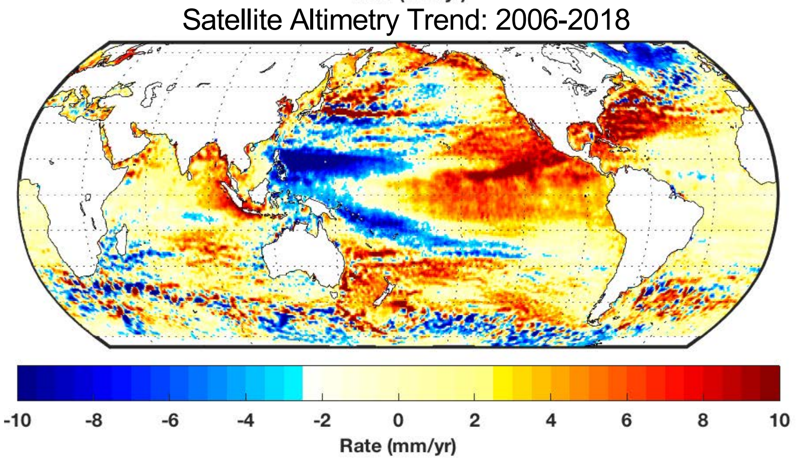
- As shown in Frederikse et al. (2017), phasing of internal decadal variability also impacts the trend as the record length gets shorter → suggest significant sea level contribution from variability on shorter timescales.

IC: East Coast Variability on Shorter Timescales

- Sea level variability over the past decade along the U.S. East Coast has been heavily studied in recent years.

- Likely due in part to complexity of the problem and also in part to a large recent shift in observed short-term sea level trends along the coast.





IC: Contribution to East Coast Sea Level

- **A range of drivers impact East Coast Sea Level on seasonal to decadal timescales:**

- **Atlantic Meridional Overturning Circulation (AMOC) Variability**: Bingham & Hughes, 2009; Ezer, 2013; 2016; Goddard et al., 2015; Hu & Bates, 2018; Kopp, 2013; Landerer et al., 2007; Little et al., 2017; Piecuch et al., 2019; Yin et al., 2009.
- **Variations in Florida Current:** Baringer et al. 2017**;** Domingues et al., 2018; Sweet et al., 2016
- **North Atlantic Oscillation (NAO):** Kenigson et al., 2018; Piecuch and Ponte, 2015; Piecuch et al. 2019; Valle-Levinson et al. 2017
- **El Nino-Southern Oscillation (ENSO**): Domingues et al. 2018; Thompson et al., 2014; Valle-Levinson et al. 2017
- **River Discharge:** Piecuch et al., 2018
- **Seasonal Amplitude Modulation:** Calafat et al. 2018

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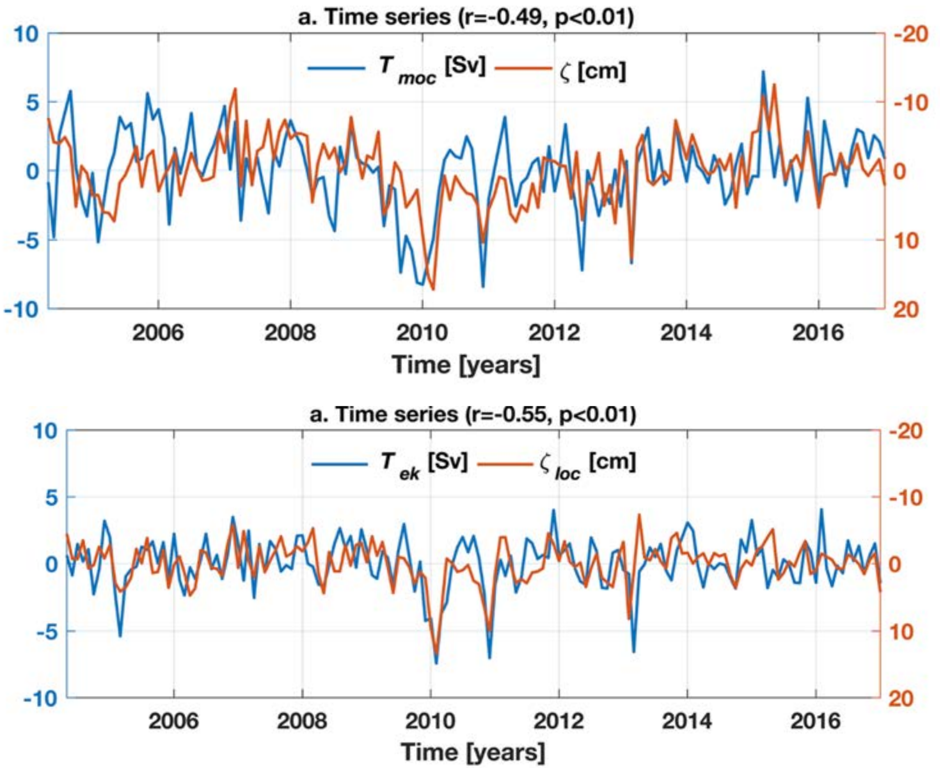
IC: Northeast Coast – Piecuch et al. 2019

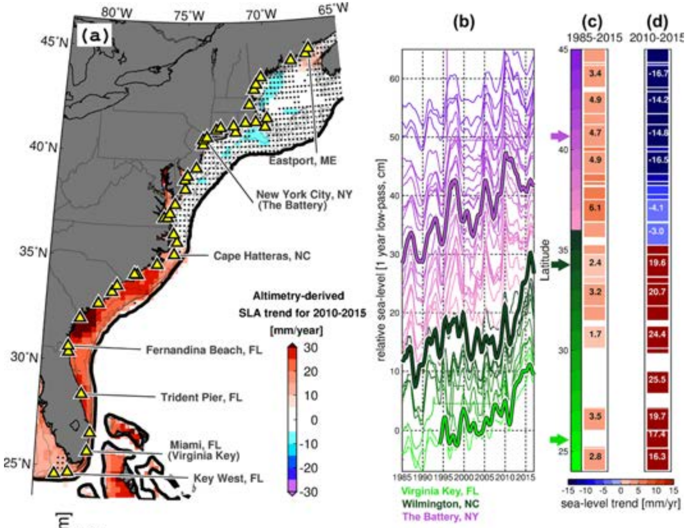
- Re-examined link between AMOC and NE sea level.
- Confirmed that AMOC intensity and NE sea level were anti-correlated, but found both controlled simultaneously by the NAO.
- With high NAO, the trade winds are stronger than normal, which in turn strengthens AMOC.
- At the same time, the westerly winds over New England are also stronger than usual.
- Together with unusually high air pressure on the northeast coast, this lowers the average sea level.

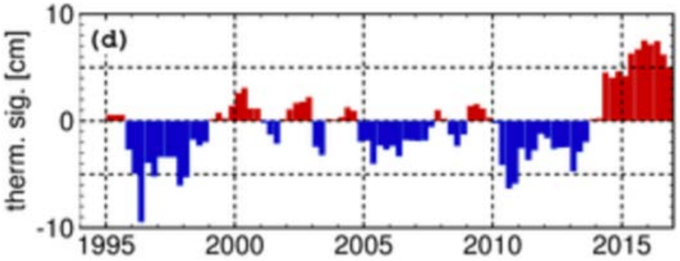


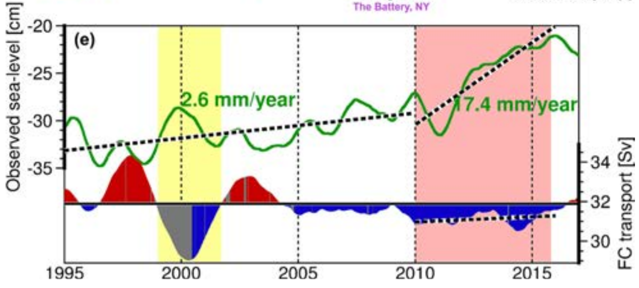
(Piecuch et al, 2019).

IC: Southeast Coast – Domingues et al. 2018

- Studied the high rates of sea level rise (~2 cm/year) along SE coast from 2010-2015
- Showed that sea level rise recorded between Key West and Cape Hatteras was mostly caused by the warming of waters carried by the Florida Current during 2010–2015.





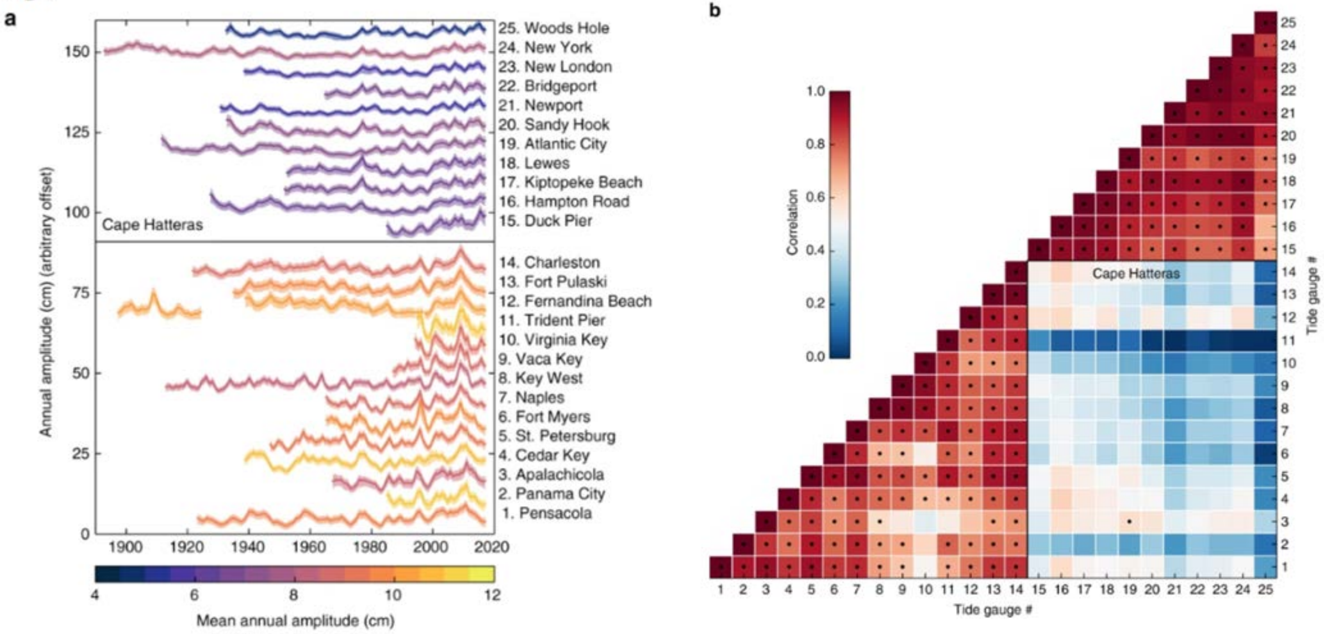


(Domingues et al, 2019).

IC: Seasonal Amplitude Modulation: Calafat et al. 2018

- Found significant decadal fluctuations in amplitude of seasonal cycle from year-to-year.
- Primary driver of these fluctuations involves incident Rossby waves that generate fast western-boundary waves.
- Consistent modulation was found north and south of Cape Hatteras.

Fig. 1



IC: Key Takeaways

- Wide range of drivers impacting US East Coast sea level on seasonal to decadal timescales.
- As a result of this diversity of contributors to sea level change, it is challenging to separate relevant processes and allow for attribution.
- Many of the referenced studies are specific to a particular time period of study → difficult to examine in more depth with available observations.
- Understanding of seasonal to decadal variability along East Coast is still evolving and further study is required.

Summary

- Long-term trends and dominant drivers of sea level change along US East Coast are relatively well understood.
  - Driven by processes that are likely to continue or accelerate in the future.
- Shorter-term variability is more complex although substantial recent progress has been made.
- From a planning perspective, it is critical to understand how these timescales of variability combine with high-frequency signals to change sea levels and impact coastal flooding.
  - With the relative sea level rise that has taken place over the last century, the gap between the average high-tide and flooding conditions can be overcome by a wide range of sea level variability.

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