



# The link between the Gulf Stream and coastal sea level as seen in observations and models

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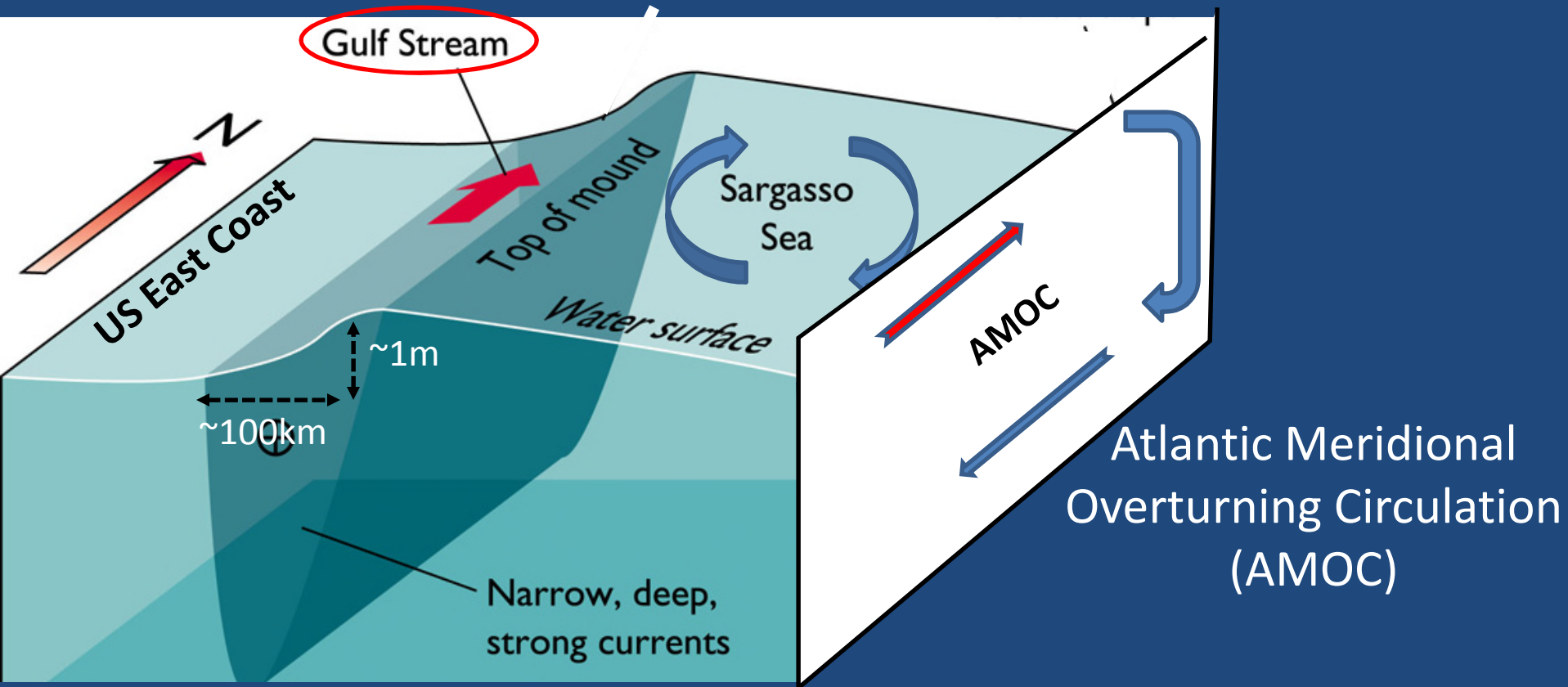
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# How can ocean dynamics affect coastal sea level?

Sea level is not level: ocean currents → sea level slope (Geostrophic balance)



- The Gulf Stream keeps sea level on the US East Coast ~1-1.5 m (3-5 feet) lower than water offshore → variations in GS strength or position will affect SL.
- In warmer climate the Atlantic Ocean circulation is expected to weaken  
If the Gulf Stream slows down → sea level on the US coast could rise!!!

- The idea that the Gulf Stream can induce coastal sea level variations along the US coast on a range of time scales is not new...

### Fluctuations in Monthly Sea Level on Eastern U.S. Coast as Related to Dynamics of Western North Atlantic Ocean

Montgomery, R.. *Journal of Marine Research* Volume: 1 Issue 2 (1938) ISSN: 0022-2409  
ISSN: 1543-9542

1938

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**Oceans**

JGR

### Fluctuations of monthly sea level as related to the intensity of the Gulf Stream from Key West to Norfolk

John P. Blaha [observations; monthly-seasonal scales]

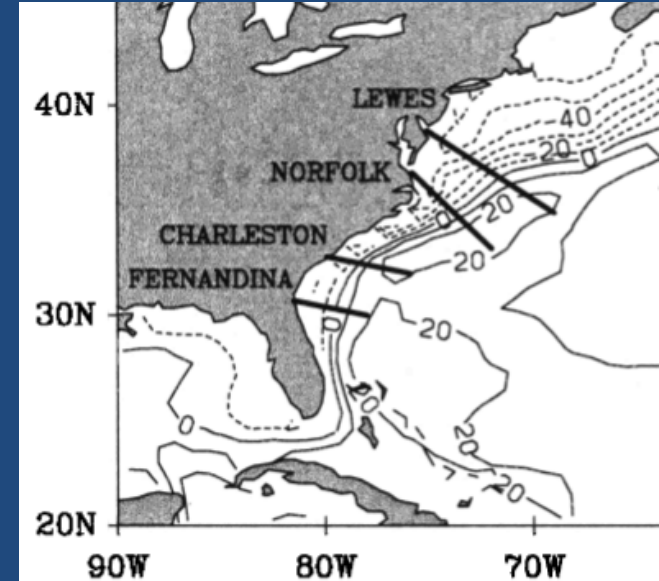
1984

### Geophysical Research Letters

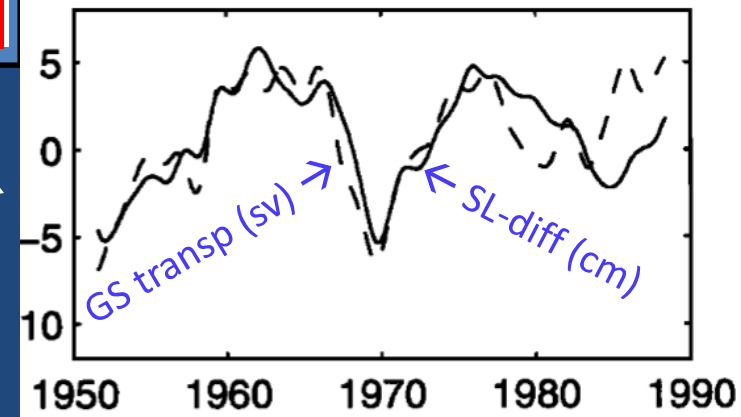
### Can long-term variability in the Gulf Stream Transport be inferred from sea level?

Tal Ezer [model; decadal time-scales]

2001



(b) Norfolk





Recent studies confirm the relation between variations in the Gulf Stream and coastal sea level, but the exact mechanism and time-scales involved need more research

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## Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast

Tal Ezer ✉, Larry P. Atkinson, William B. Corlett, Jose L. E. **2013**

### Earth's Future

Accelerated flooding along the U.S. East Coast:  
On the impact of sea-level rise, tides, storms,  
the Gulf Stream, and the North Atlantic  
Oscillations

Tal Ezer ✉, Larry P. Atkinson **2014**

## Accelerated sea level rise and Florida Current transport

J. Park<sup>1</sup> and W. Sweet<sup>2</sup>

Ocean  
Science

**2015**

### Global and Planetary Change

Detecting changes in the transport of the Gulf Stream and the  
Atlantic overturning circulation from coastal sea level data: The  
extreme decline in 2009–2010 and estimated variations for  
1935–2012

Tal Ezer ✉

**2015**

### Ocean Dynamics

Can the Gulf Stream induce coherent short-term fluctuations  
in sea level along the US East Coast? A modeling study

Tal Ezer<sup>1</sup>

**2016**

Gulf Stream

Also affected by :

Multidecadal  
and sea level  
rise

← AMO, AMOC, etc.

Seasonal,  
interannual  
and decadal

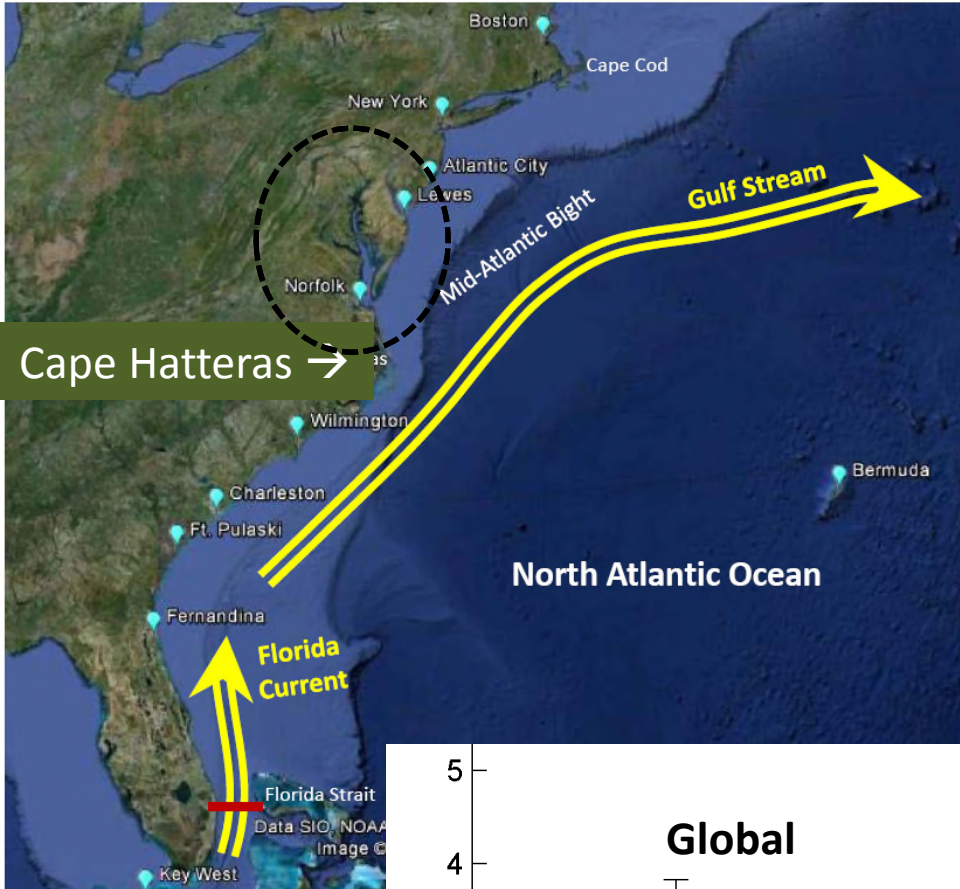
← NAO, ENSO,  
weather pattern,  
etc.

Daily, weakly,  
intraseasonal

← Tides, storm surges,  
etc.

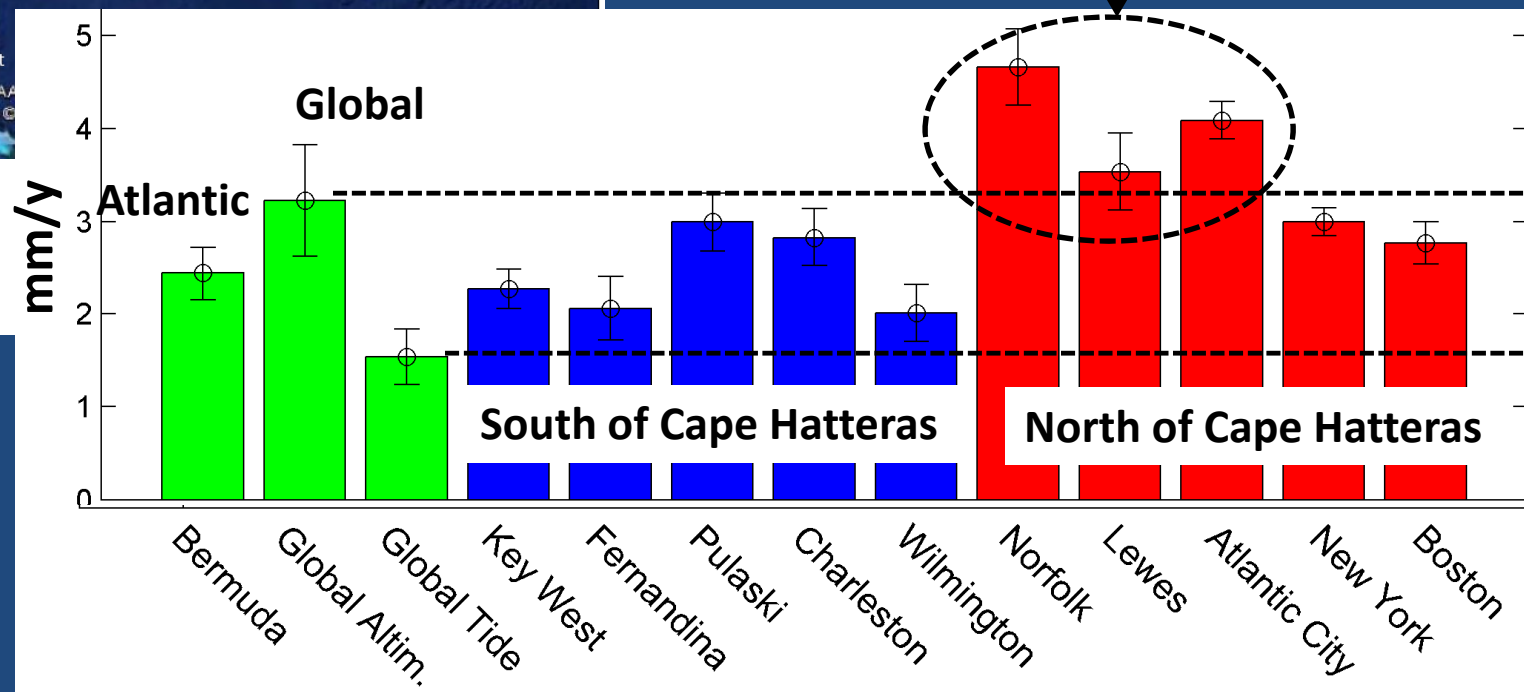
Coastal  
Sea-Level

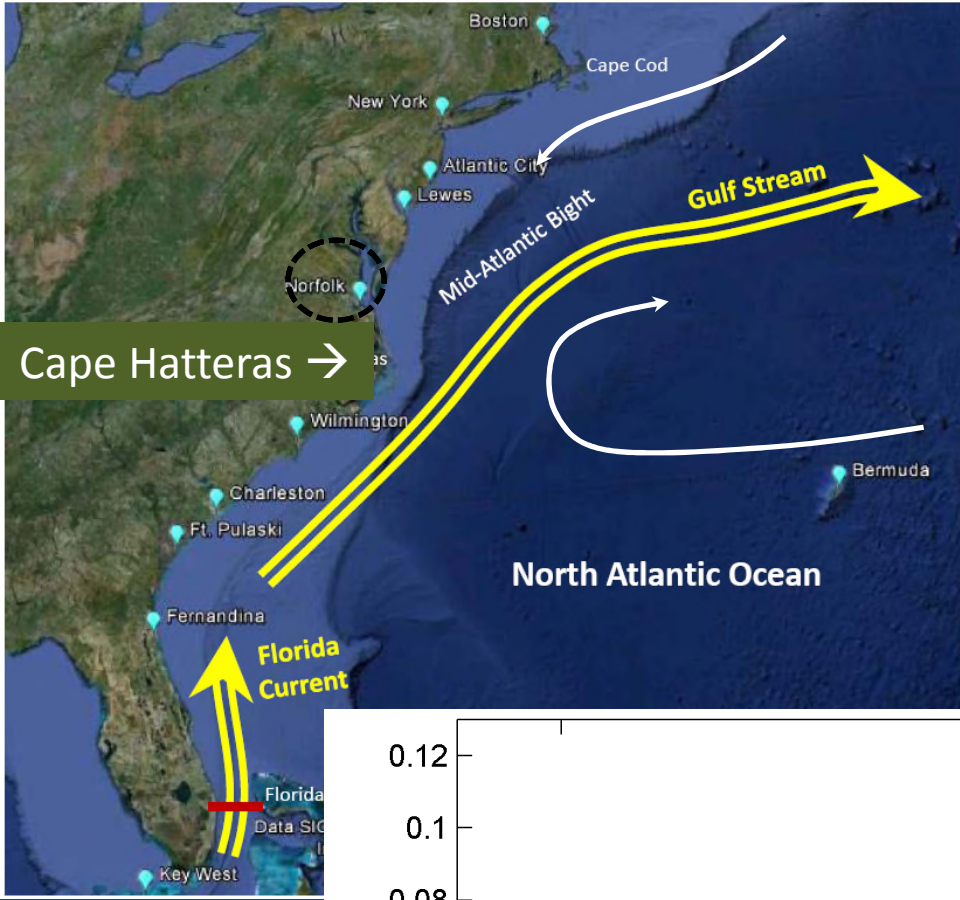
# Impact of the Gulf Stream on long-term sea level rise and decadal variability



# Mean Sea Level Rise Rates (from linear regression)

linear global SLR  
+  
postglacial land subsidence in  
the mid-Atlantic

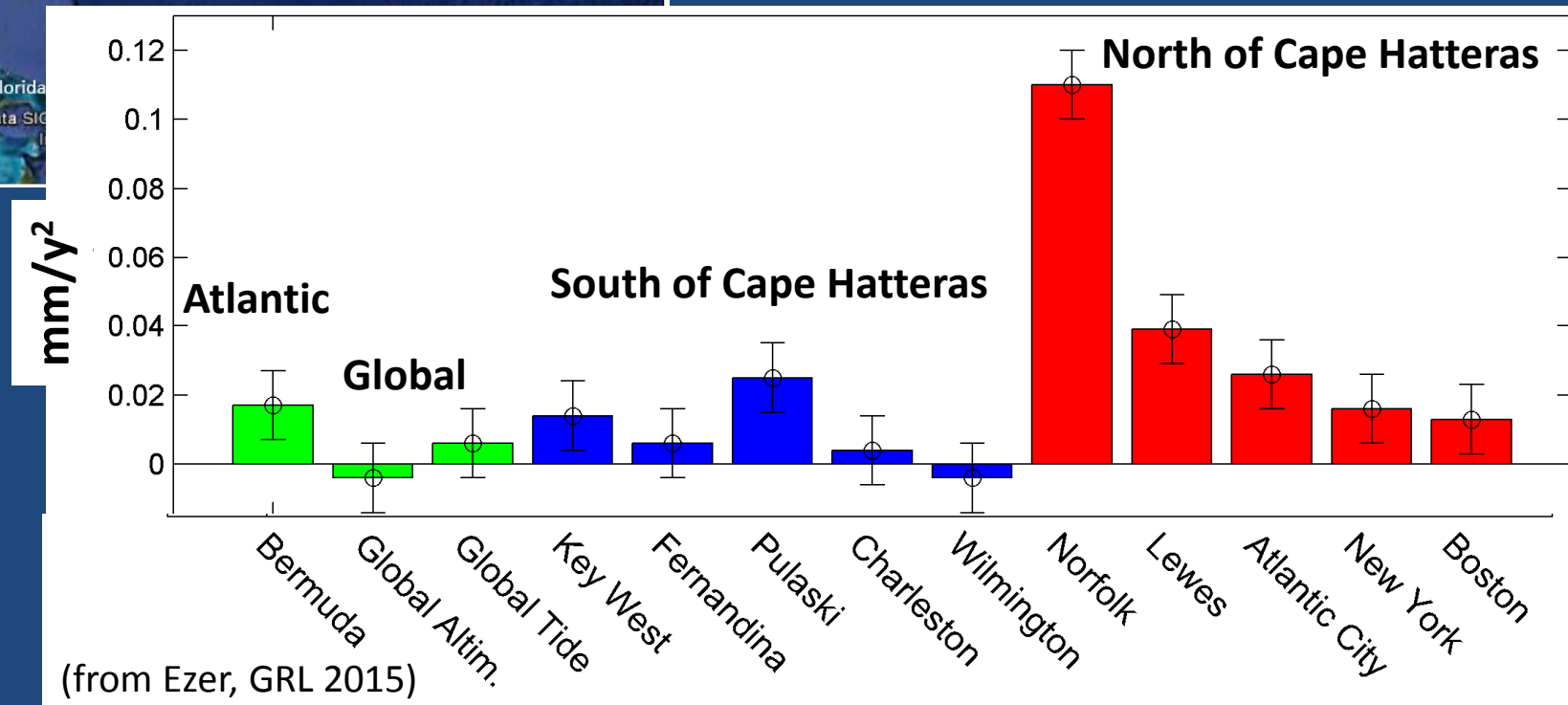




Pattern of sea level rise **acceleration** is affected by the Gulf Stream –

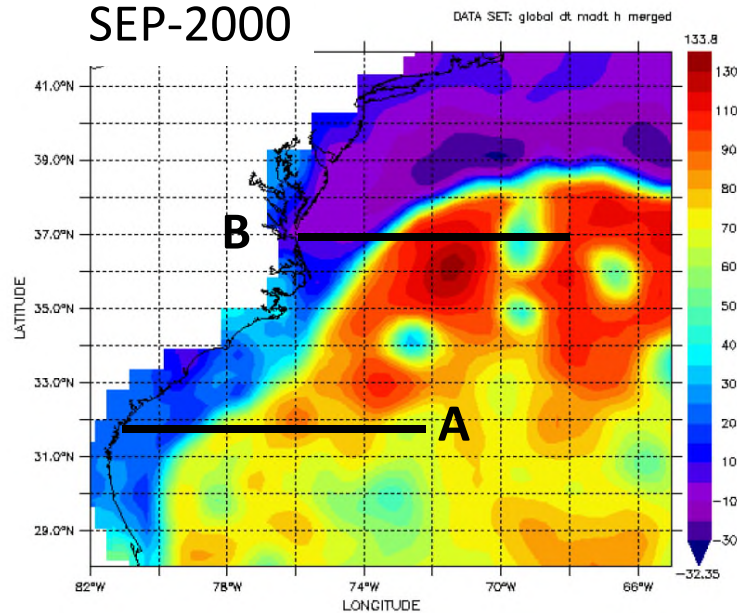
Especially north of the separation point of the GS

Why?



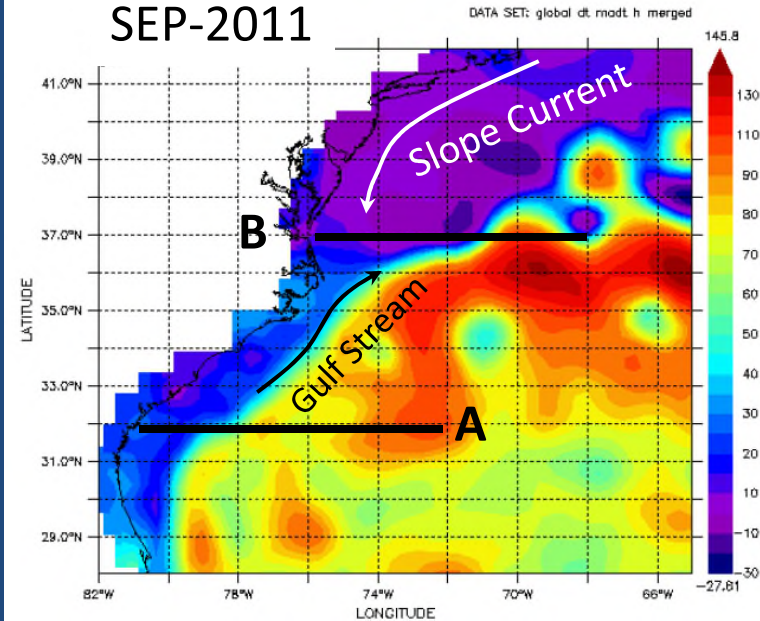


SEP-2000

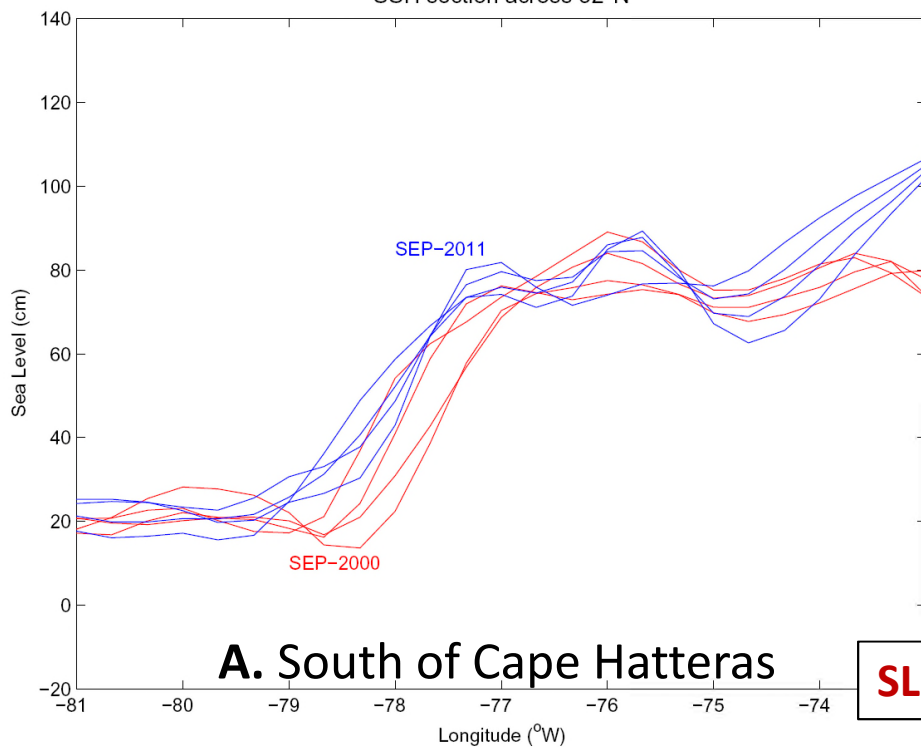


Sea Surface  
Height (SSH)  
from satellite  
altimeter data

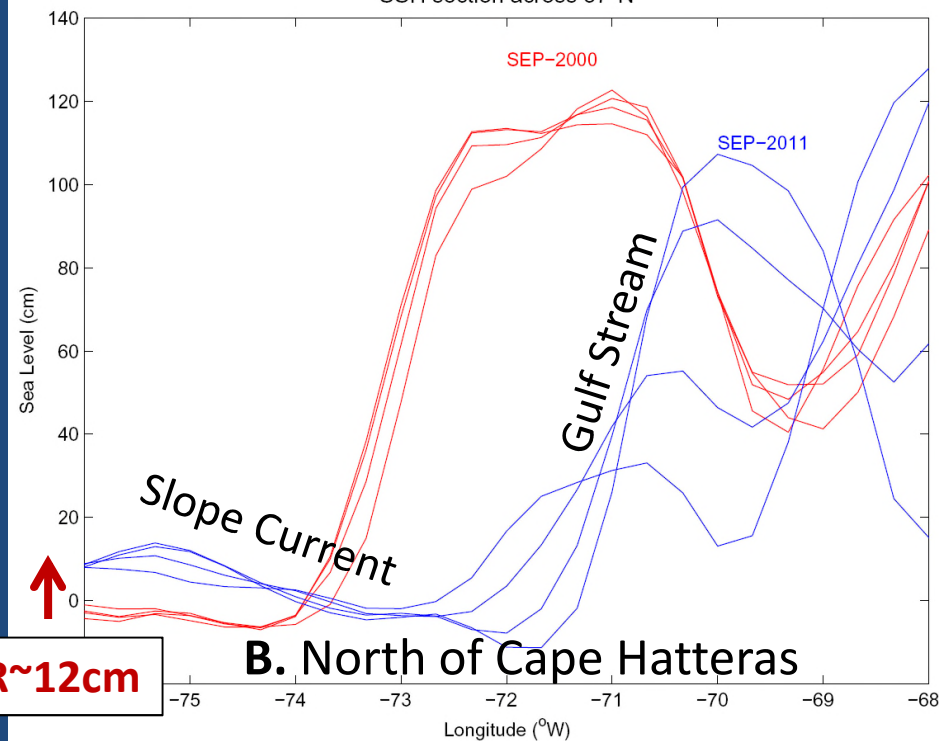
SEP-2011



SSH section across 32°N



SSH section across 37°N

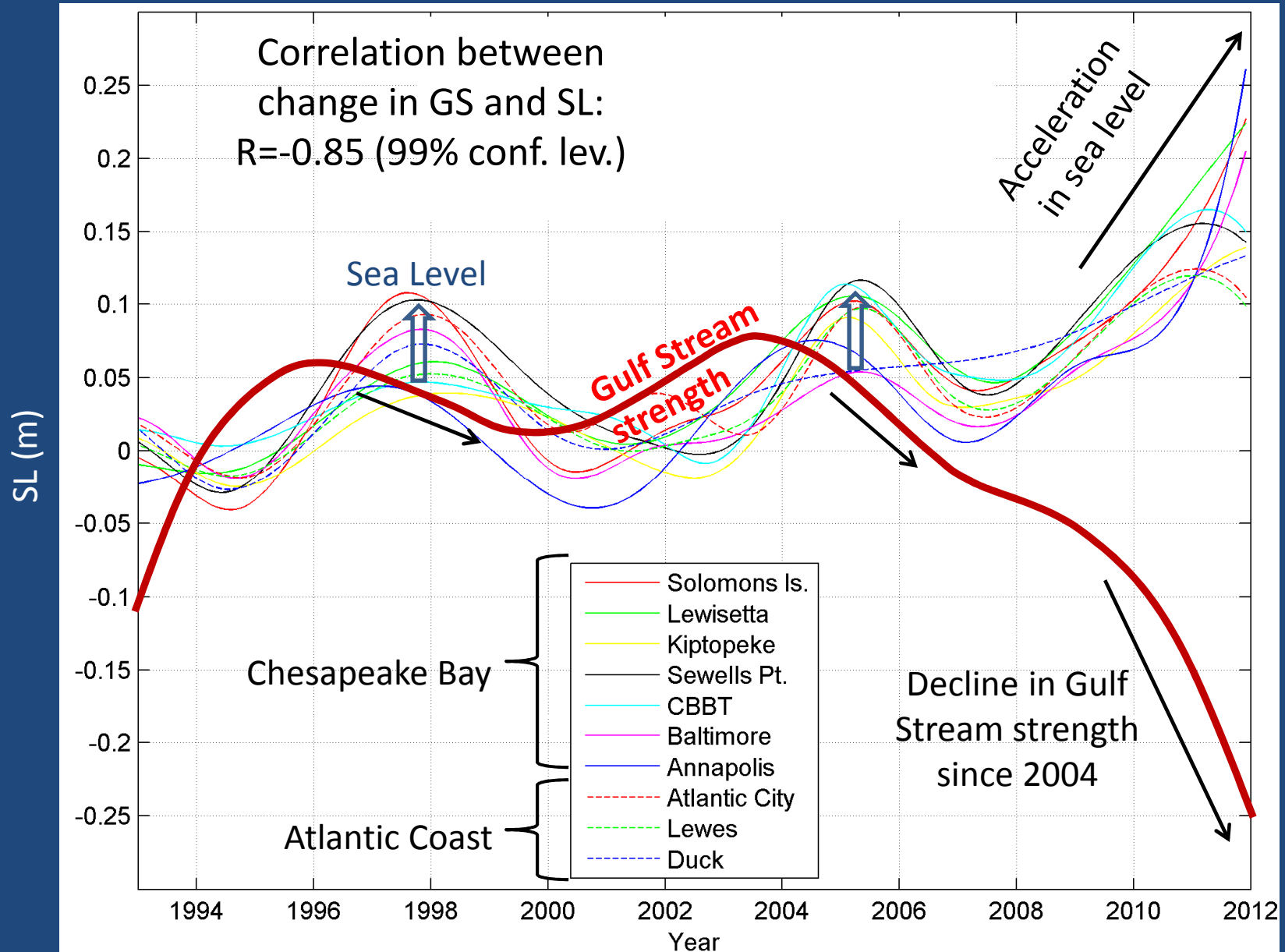


**SLR~12cm**



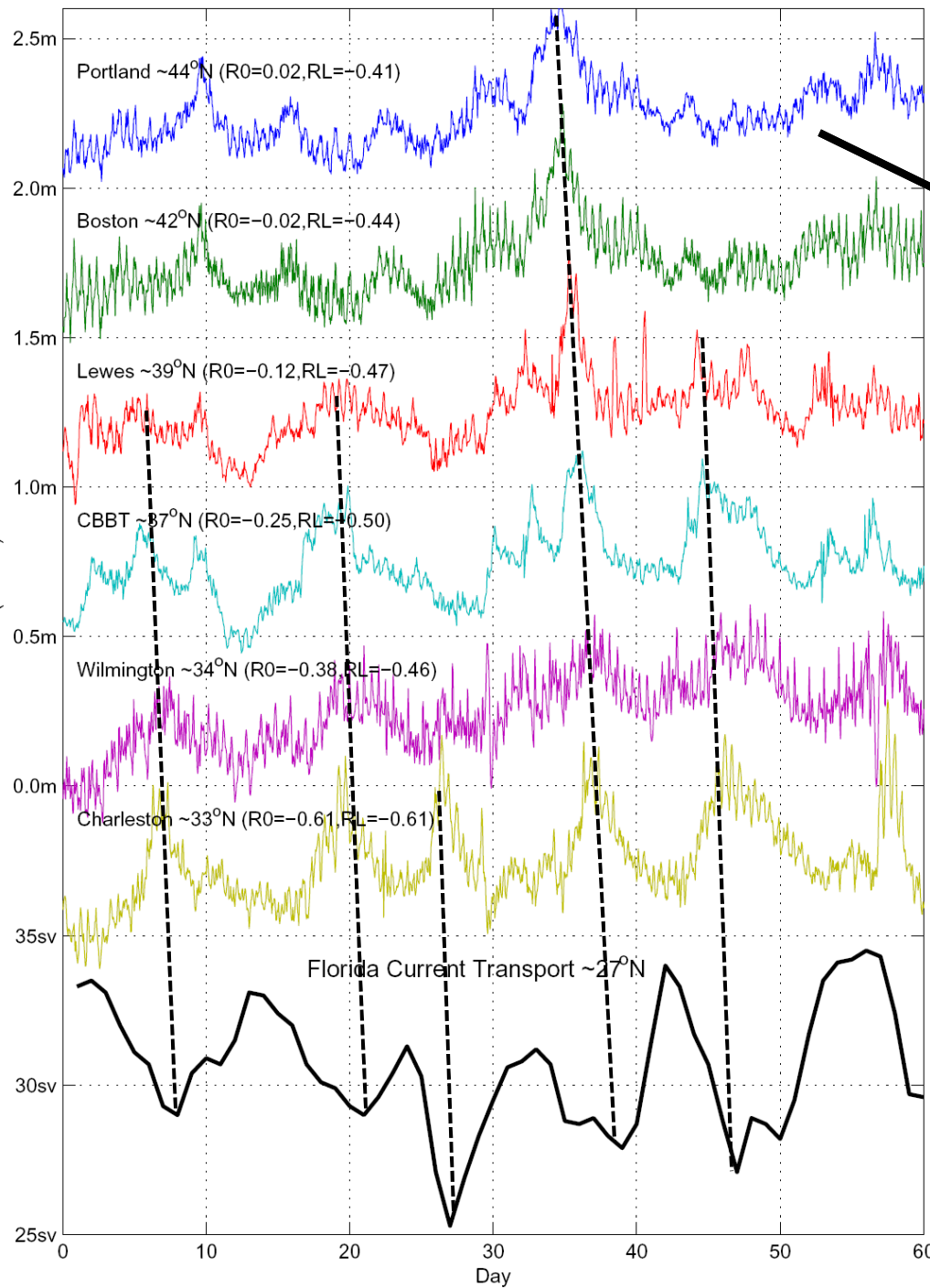
# Long-time scale variability (from Ezer et al., JGR, 2013)

Why do stations in different locations show the same pattern?



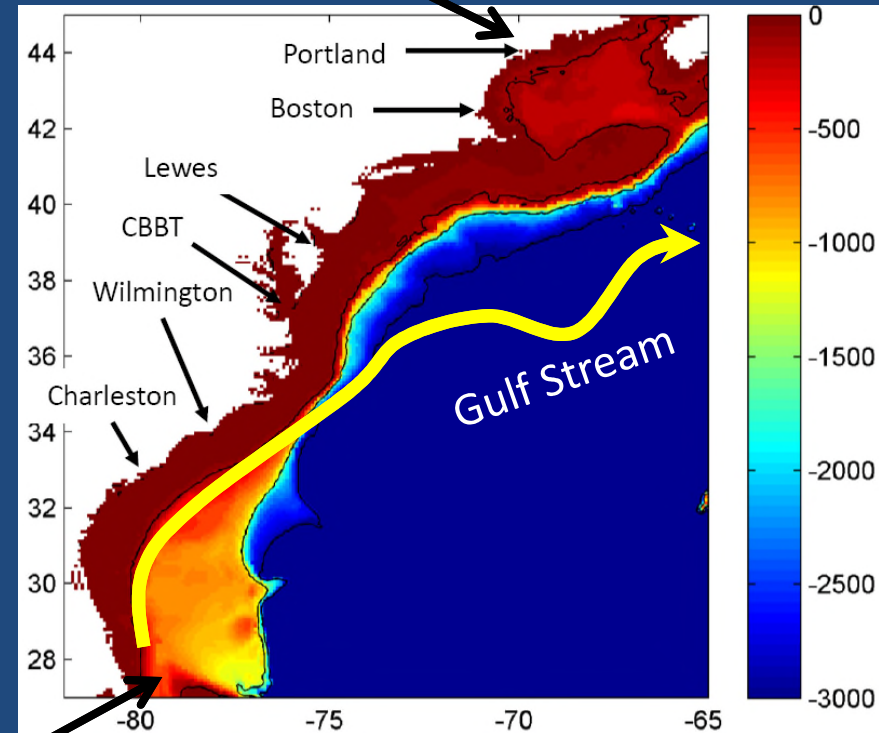
# Impact of the Gulf Stream on short-term variations of coastal sea level

Hourly Sea Level Residual (May-JUN, 2012)

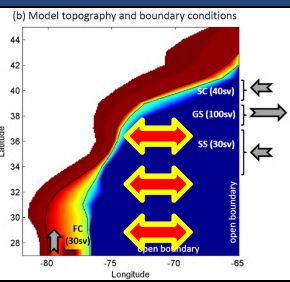


## Short-term fluctuations:

Coherent variations in coastal sL along the entire U.S. East Coast are **anti-correlated** with the transport of the Gulf Stream measured in the Florida Straits

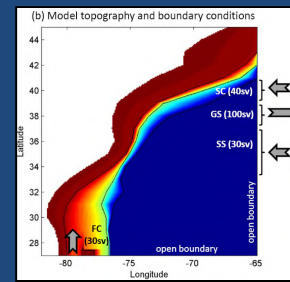


# Ocean circulation models can explain how the Gulf Stream can impact coastal sea level variations:

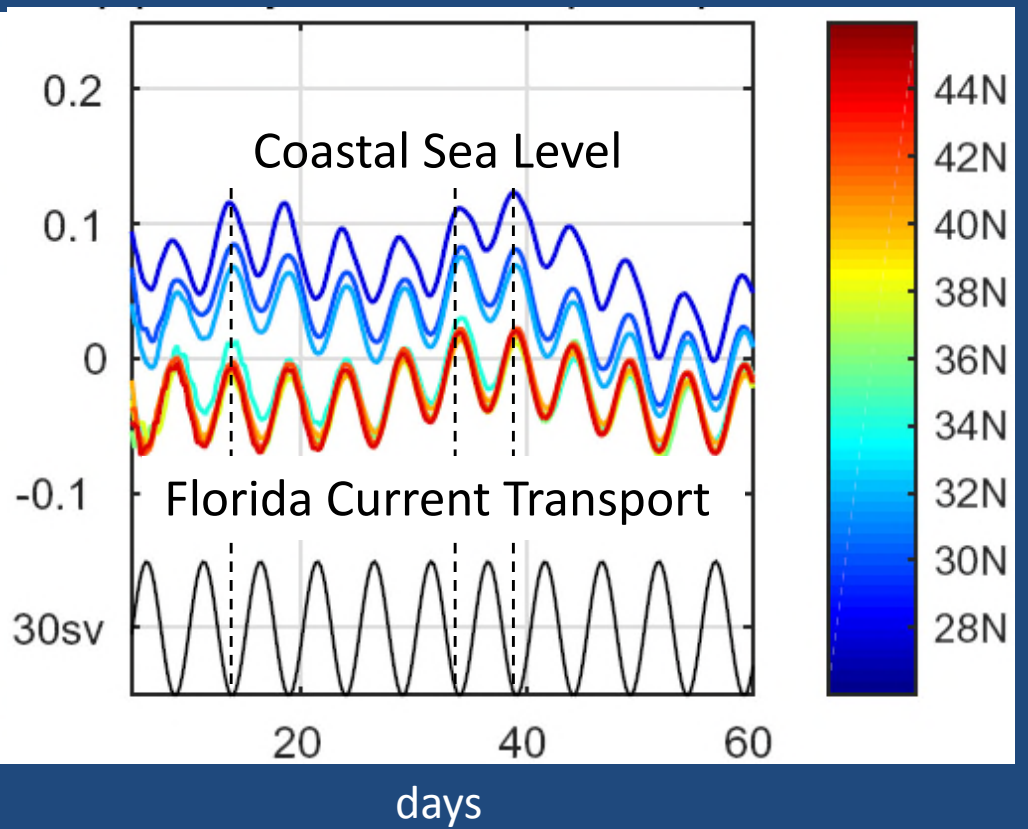
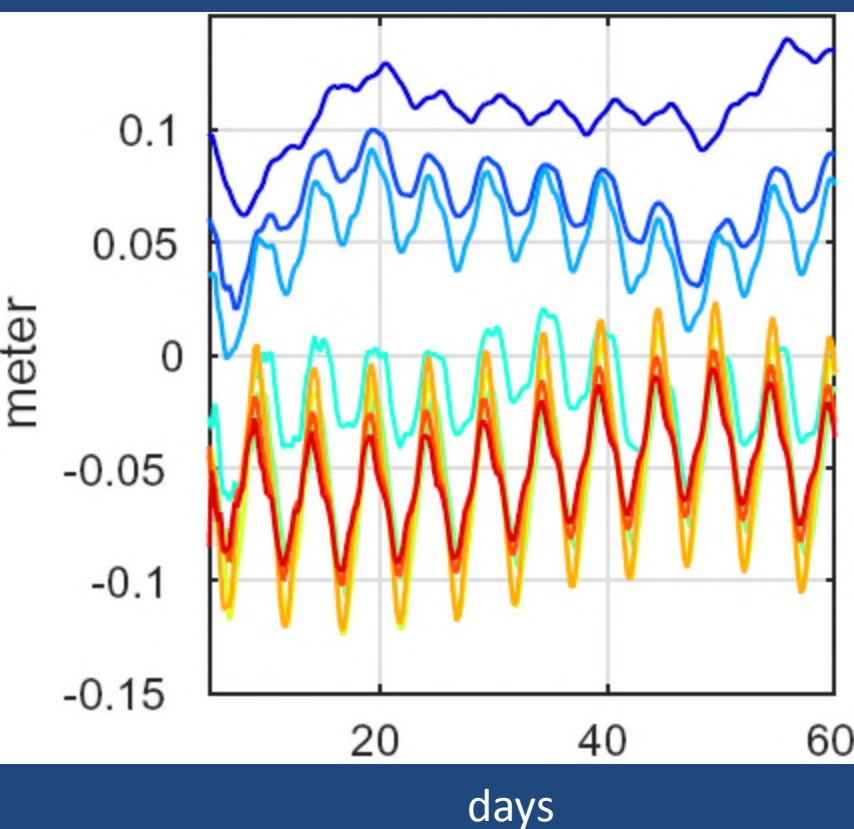


Wind-driven  
(zonal wind  $\pm 5$  m/s)  
[response depends on shelf width]

VS.



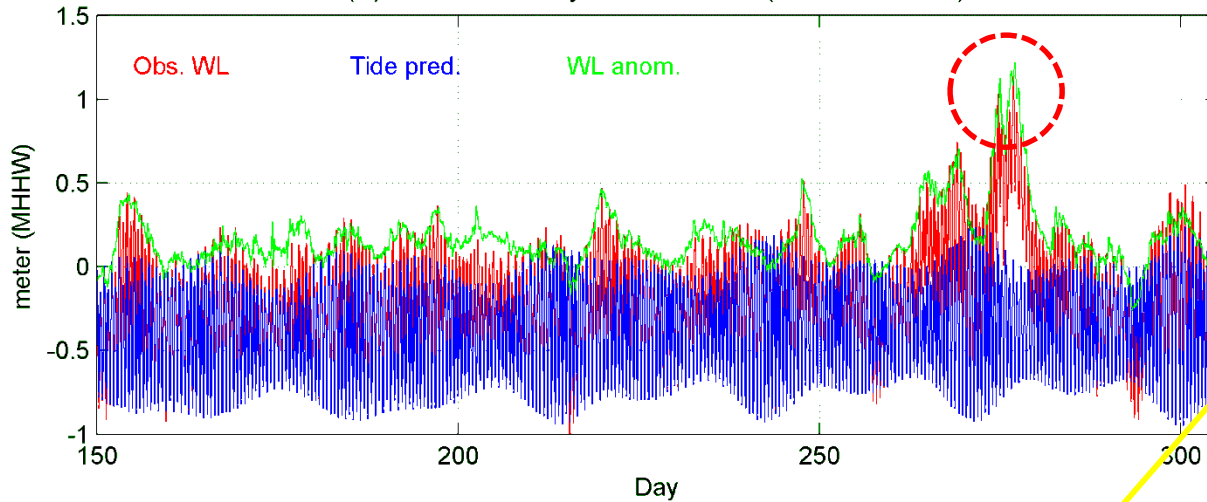
Gulf Stream-driven  
(transport  $\pm 10$  sv)  
[coherent response due to barotropic waves]





# Hurricane Joaquin (Sep-Oct 2015): severe flooding on the southeast US coast: a combination of the offshore Hurricane, Nor'easter and weakening Gulf Stream

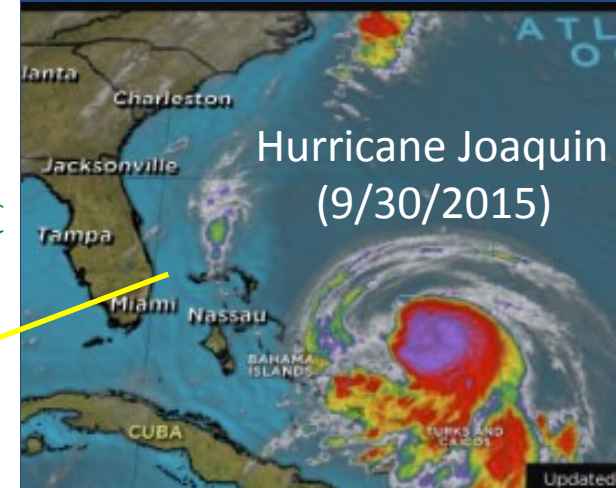
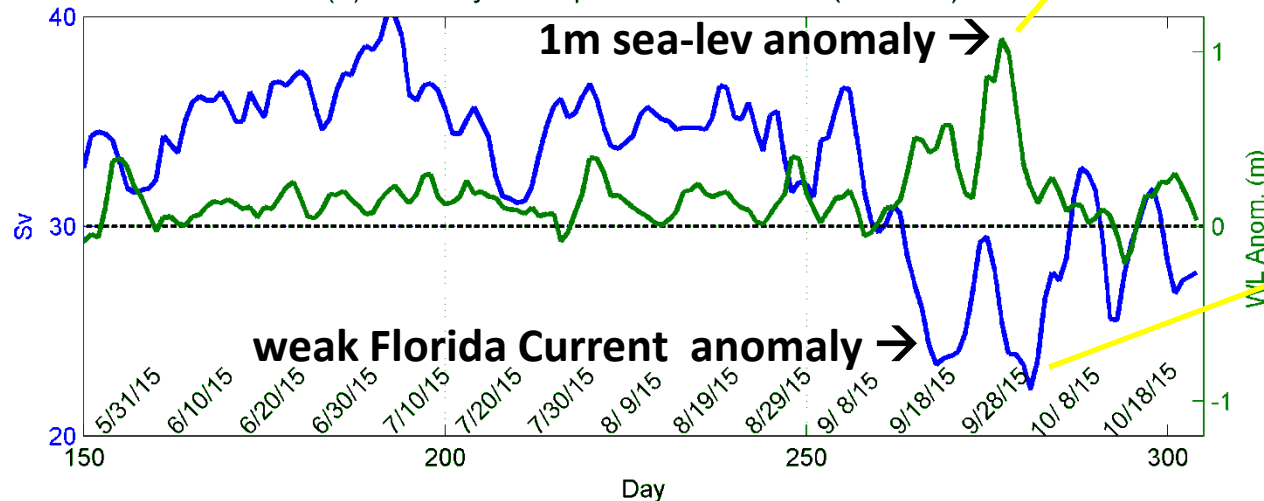
(a) Norfolk Hourly Water Level (Jun-Oct 2015)



Flooding in Norfolk, VA

Hurr. → GS → coastal SL

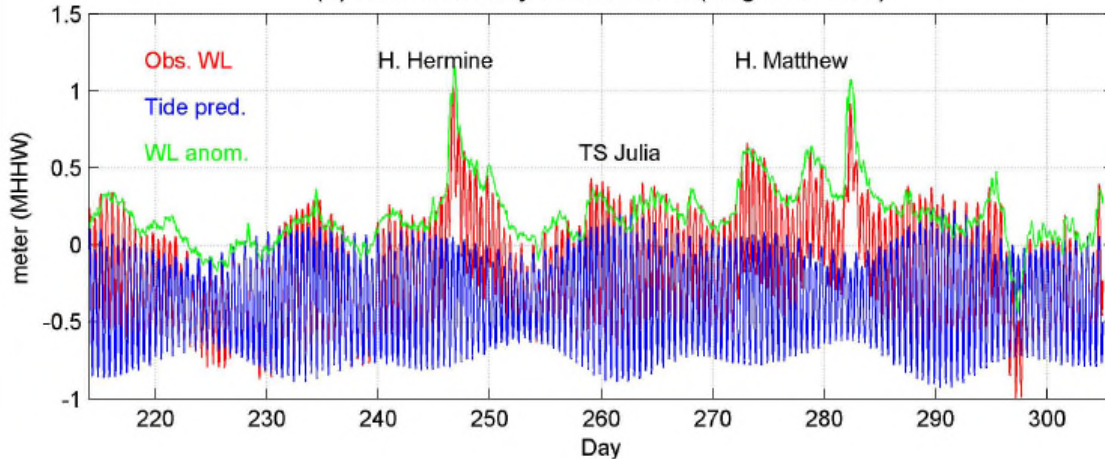
(b) FC Daily Transport vs. WL Anom. ( $R=-0.39$ )



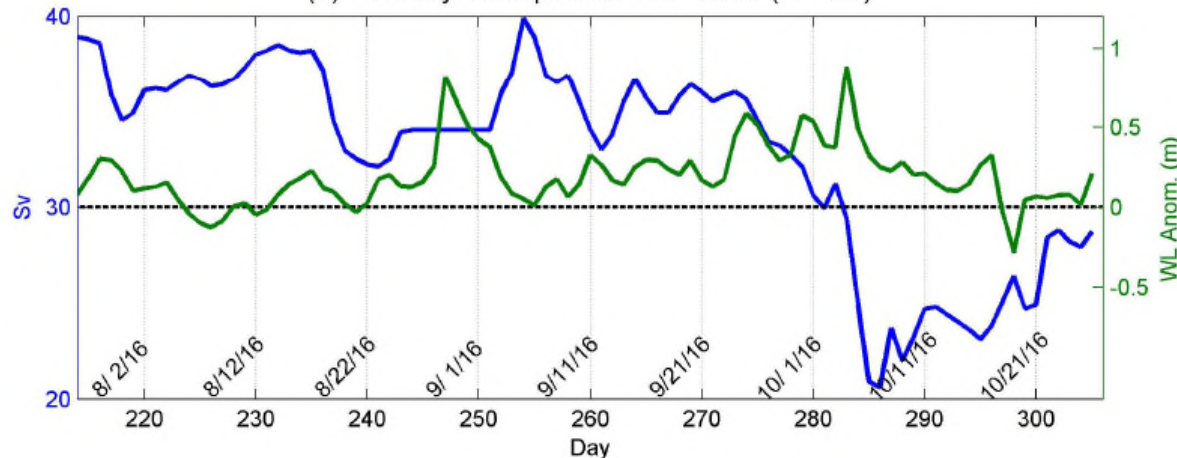
Hurricane Joaquin (9/30/2015)

**Hurricane Matthew** (Oct 2016): severe flooding in southeastern coasts (FL, GA, SC, NC), but also some flooding farther north (VA, DE) away from the storm-  
within few weeks Gulf Stream weakened from 40 Sv to 20 Sv!

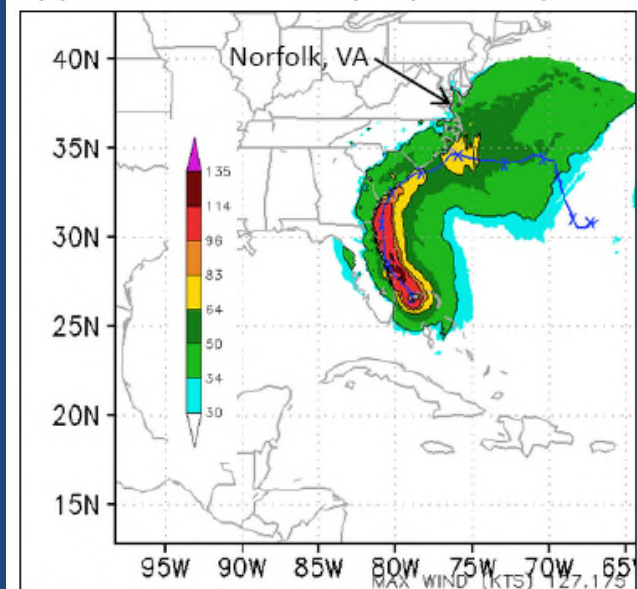
(a) Norfolk Hourly Water Level (Aug-Oct 2016)



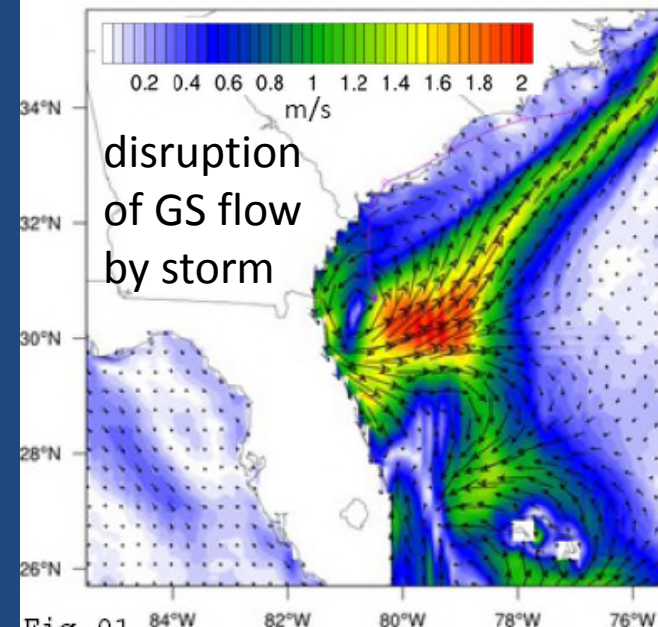
(b) FC Daily Transport vs. WL Anom. ( $R=-0.5$ )



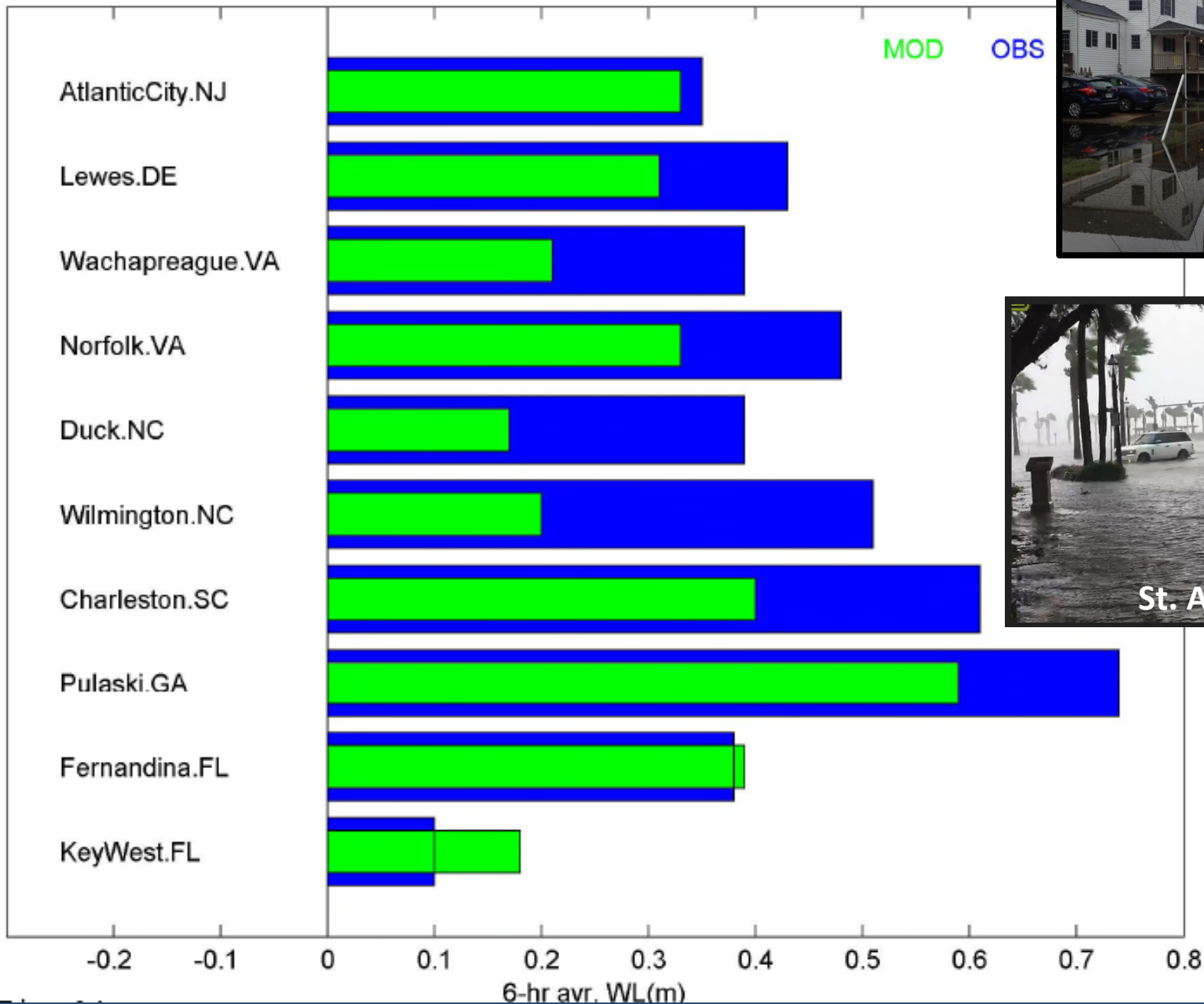
(a) HWRF 10m max wind (KNT) Oct. 7-12, 2016



(c) HWRF-POM forecast surf. vel. Oct. 8, 00hr



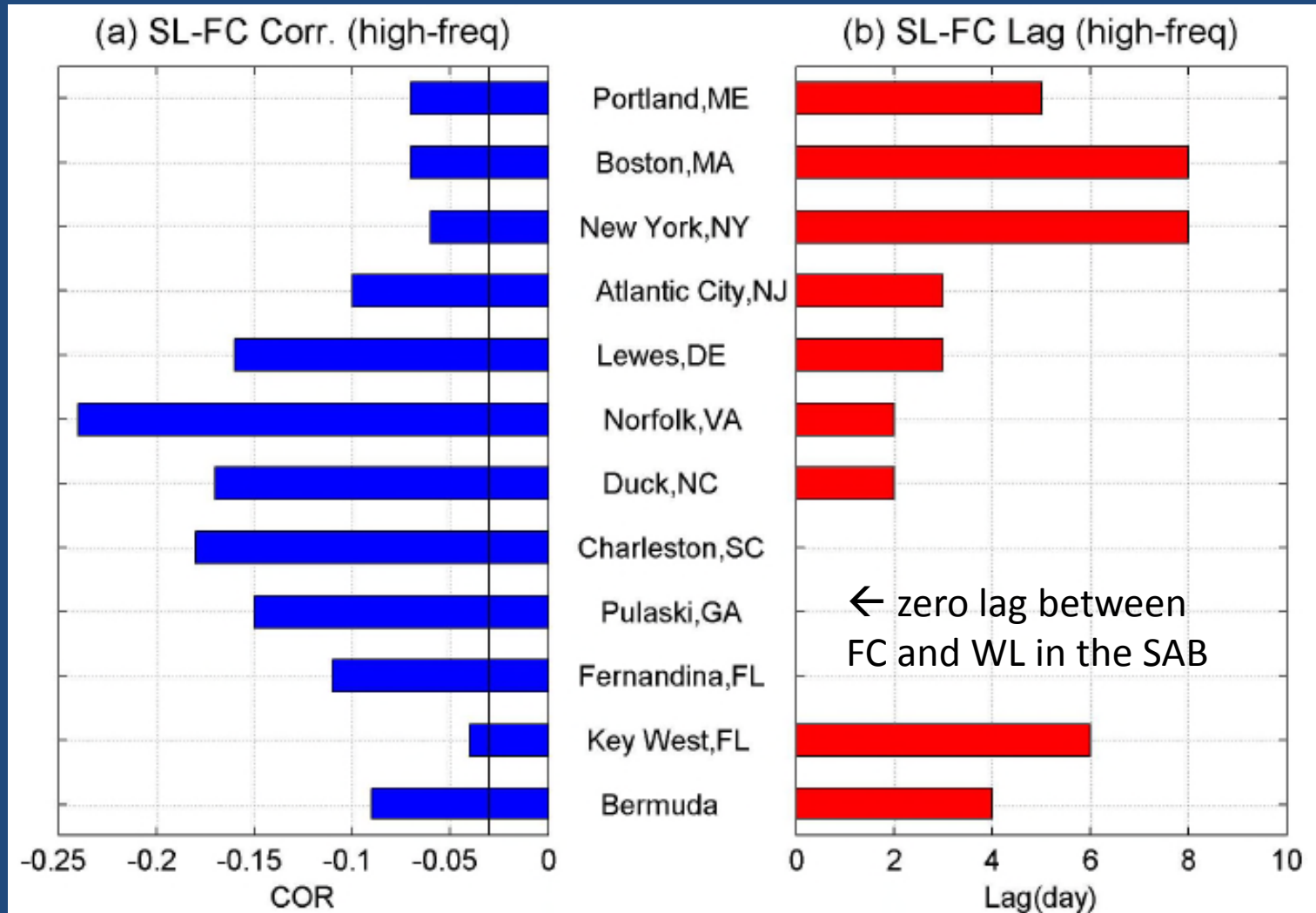
# Max WL rise during Hurricane Matthew (Oct7-12, 2016)





# Can we use the cable measurements of the Florida Current to predict high water level along the coast?

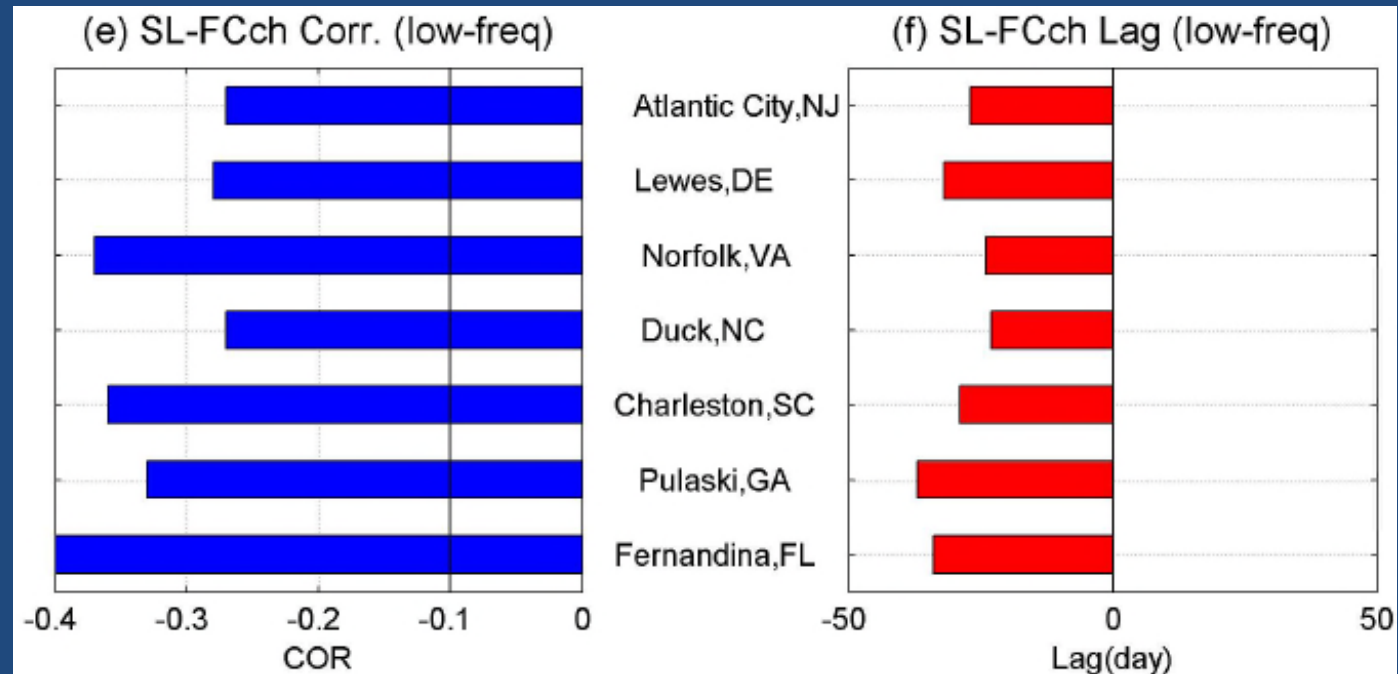
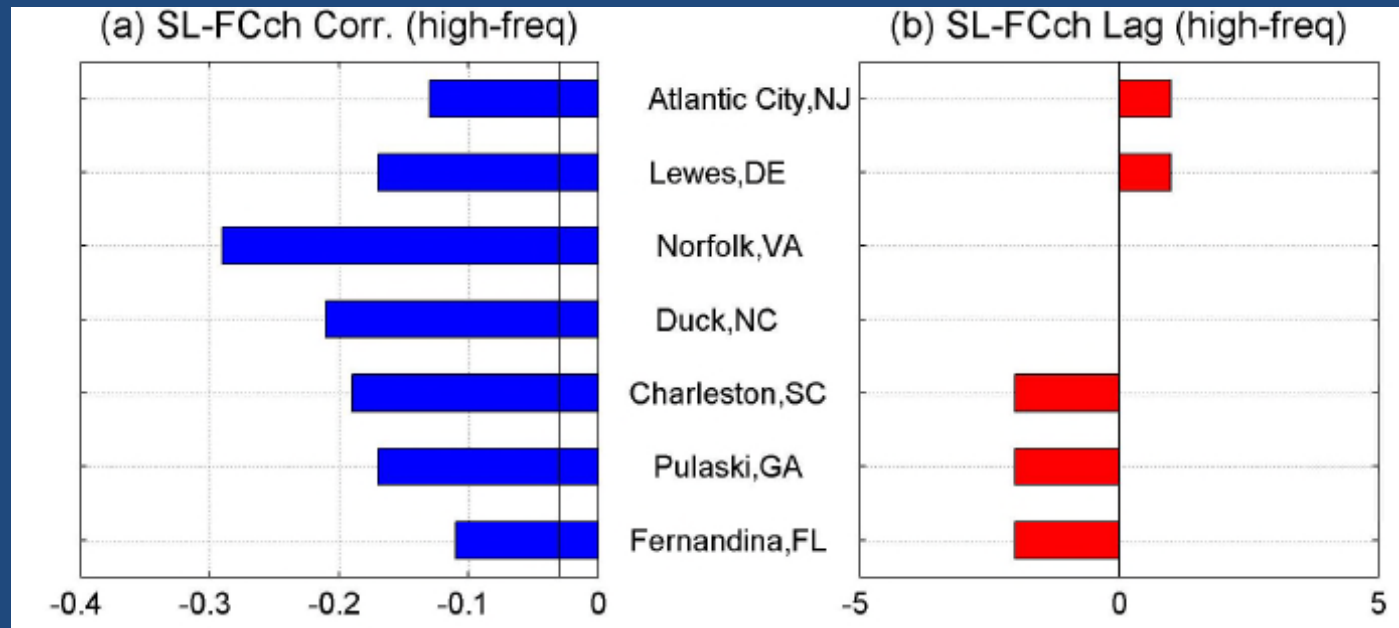
## Correlation between FC transport and high water level



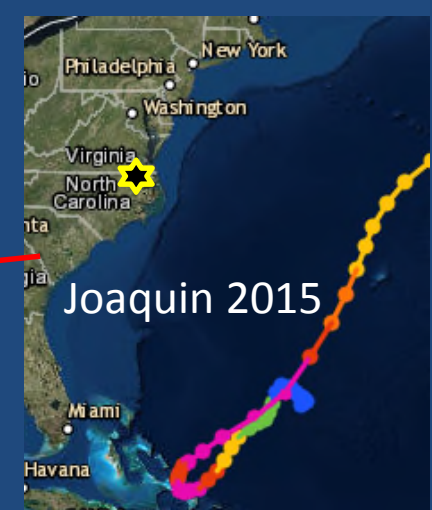
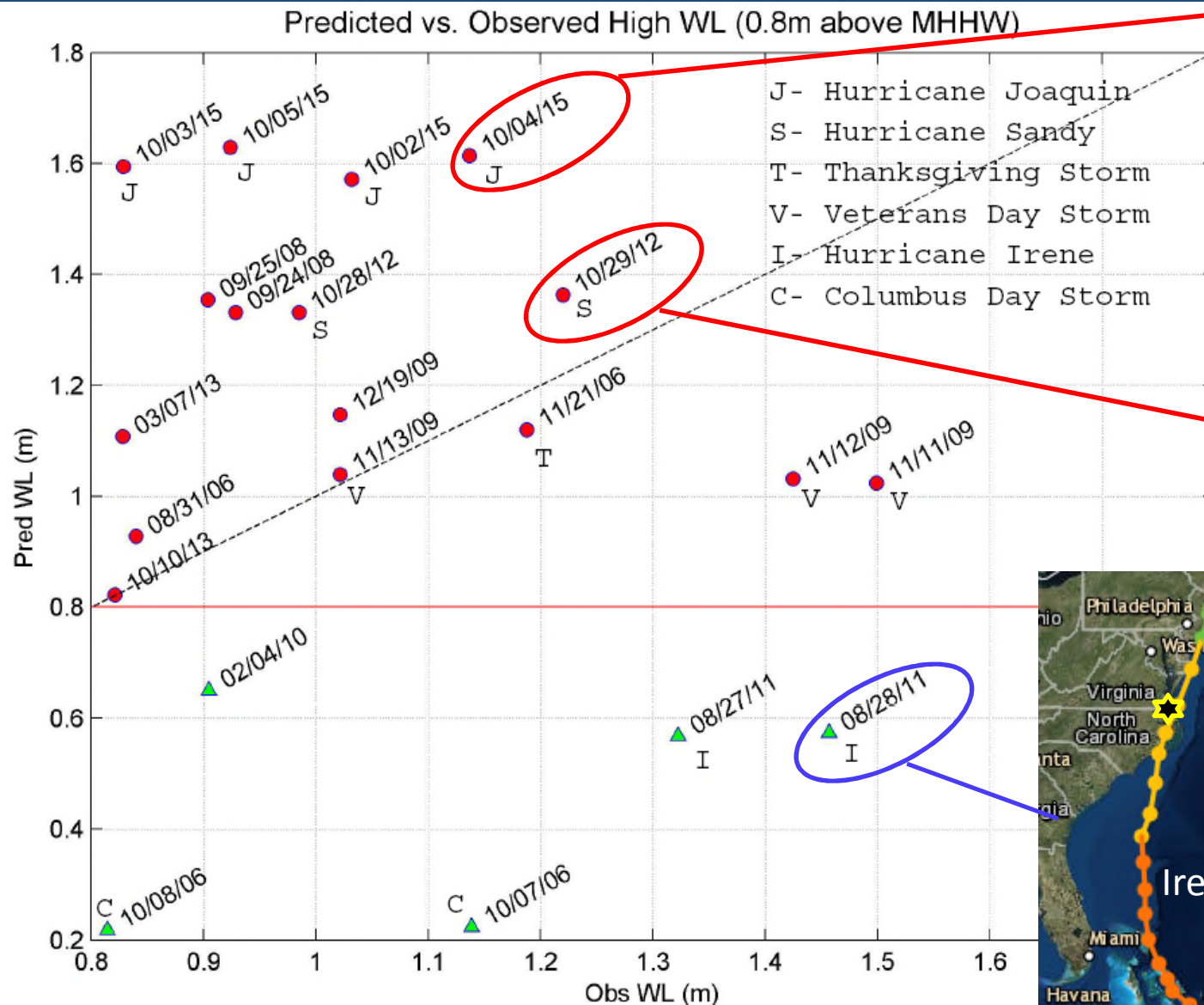


## Correlation between FC CHANGE and high water level

Negative correlation and negative lag means that when a **weakening FC is detected, high WL can be predicted over the next few days**

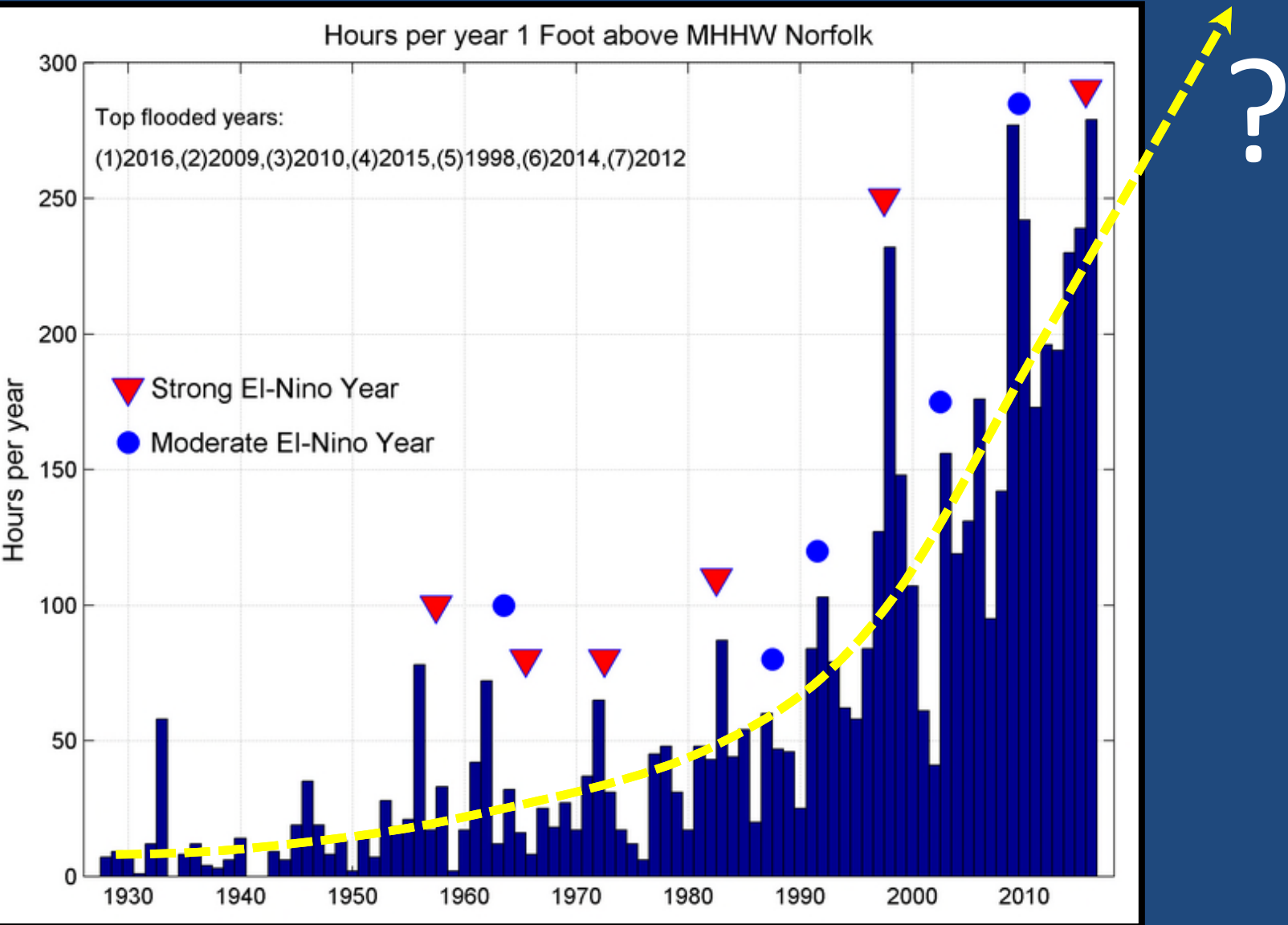


# Testing the regression to predict WL in Norfolk: past hurricanes and storms with WL>0.8 m (MHHW)



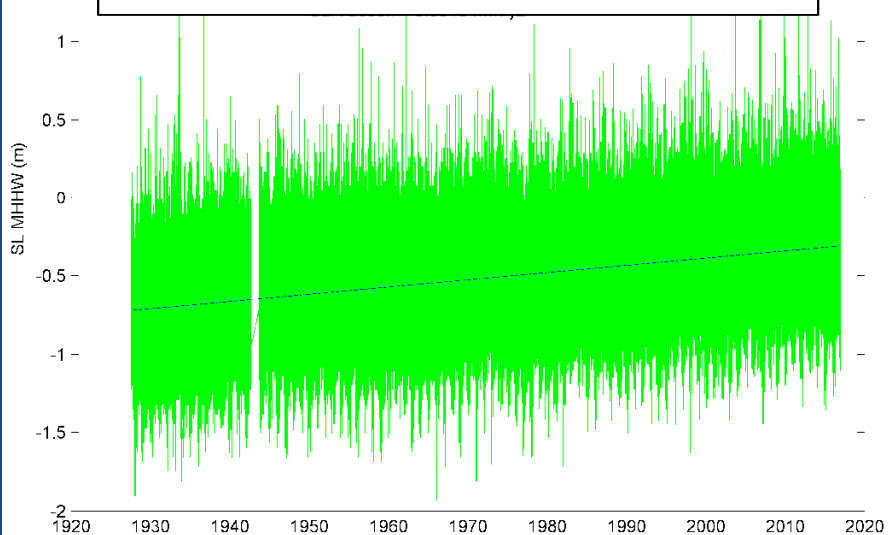
# Future projections of increased flooding

Acceleration in minor flooding is seen everywhere, but can we project future flooding?  
Future flooding depends on:  
(1) future sea level rise & (2) tidal range  
(3) storm frequency and intensity & (4) other influences (AMOC, ENSO, NAO, etc.)

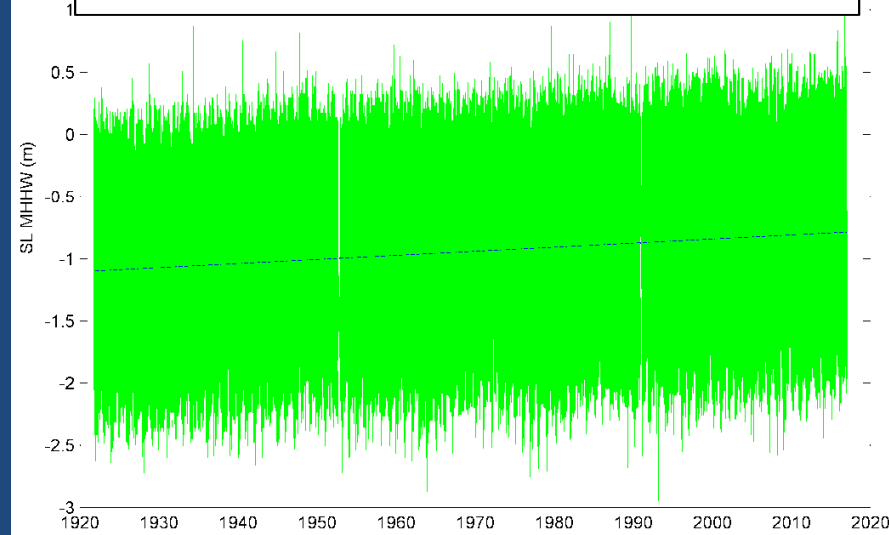




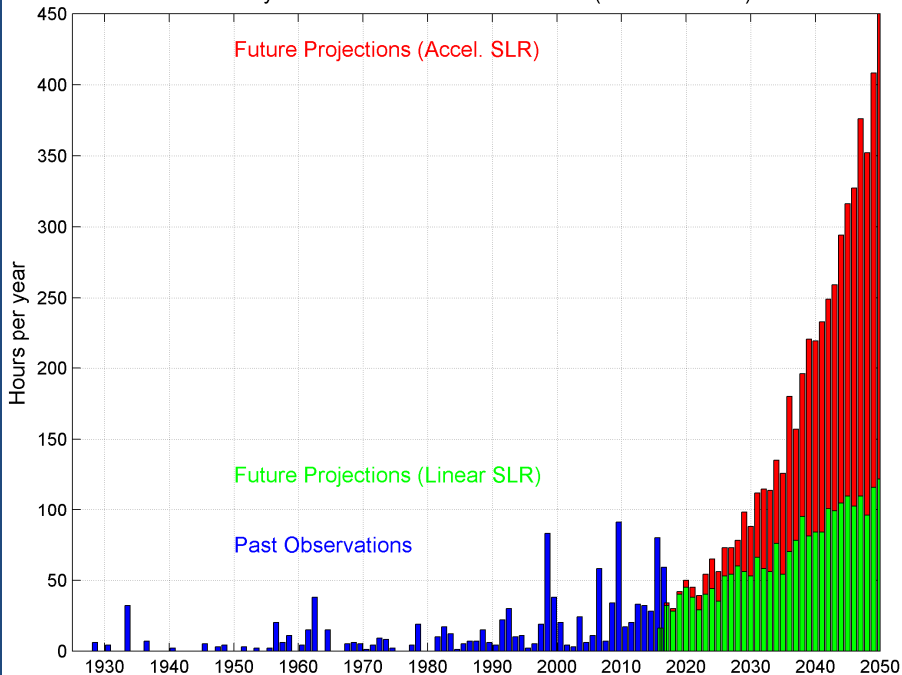
**Norfolk, VA:** mean SLR=4.6 mm/y  
Last 30y: 6.63, prev 30y: 4.1 mm/y  
Acceleration: 0.085 mm/y<sup>2</sup>



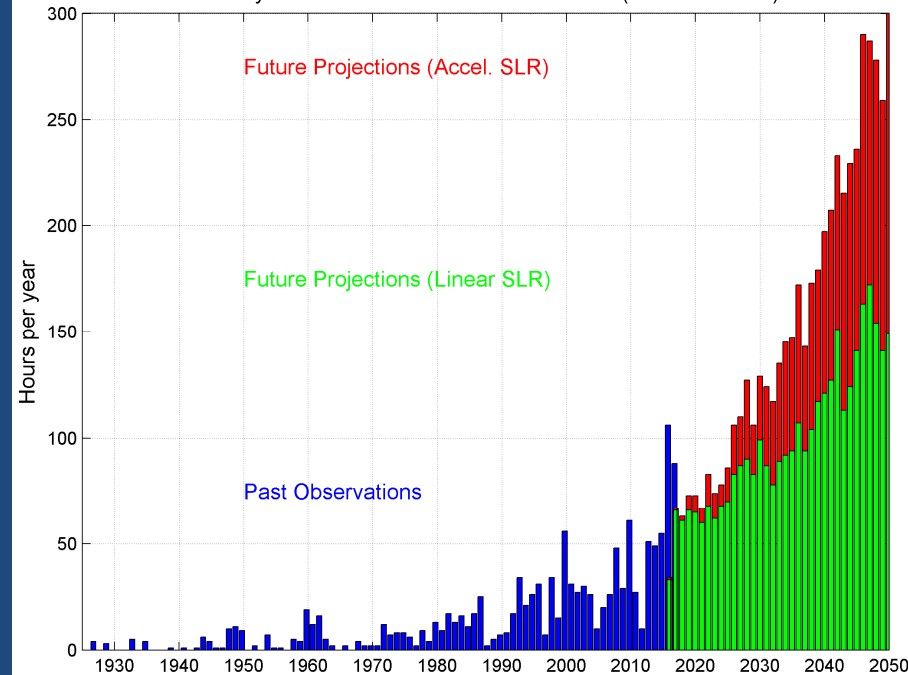
**Charleston, SC:** mean SLR=3.27 mm/y  
Last 30y: 4.37, prev 30y: 3.03 mm/y  
Acceleration: 0.045 mm/y<sup>2</sup>



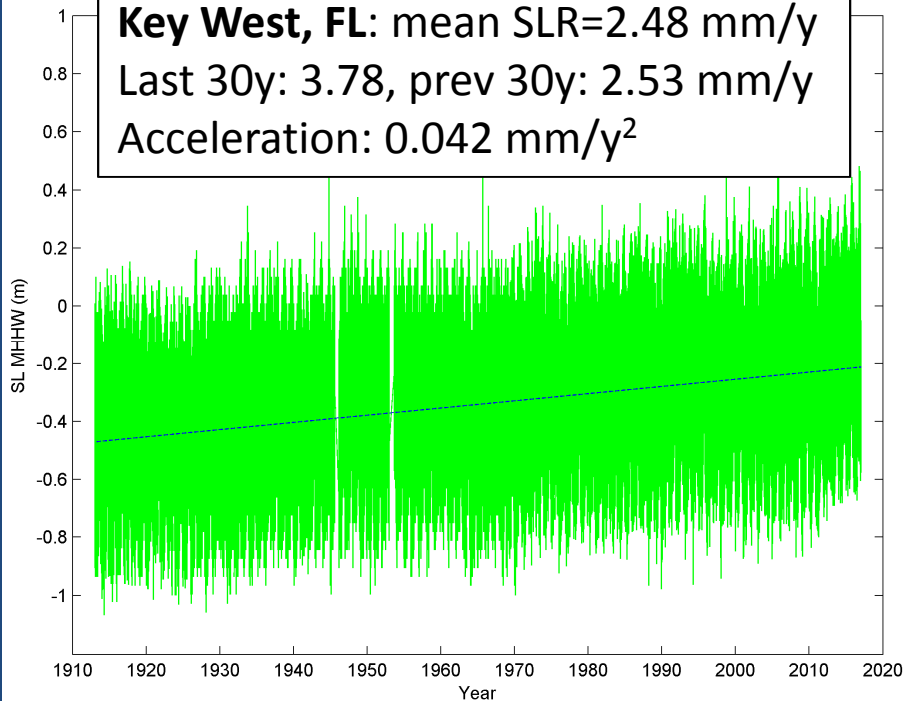
Hours/year of nuisance floods in Norfolk (MHHW+0.53m)



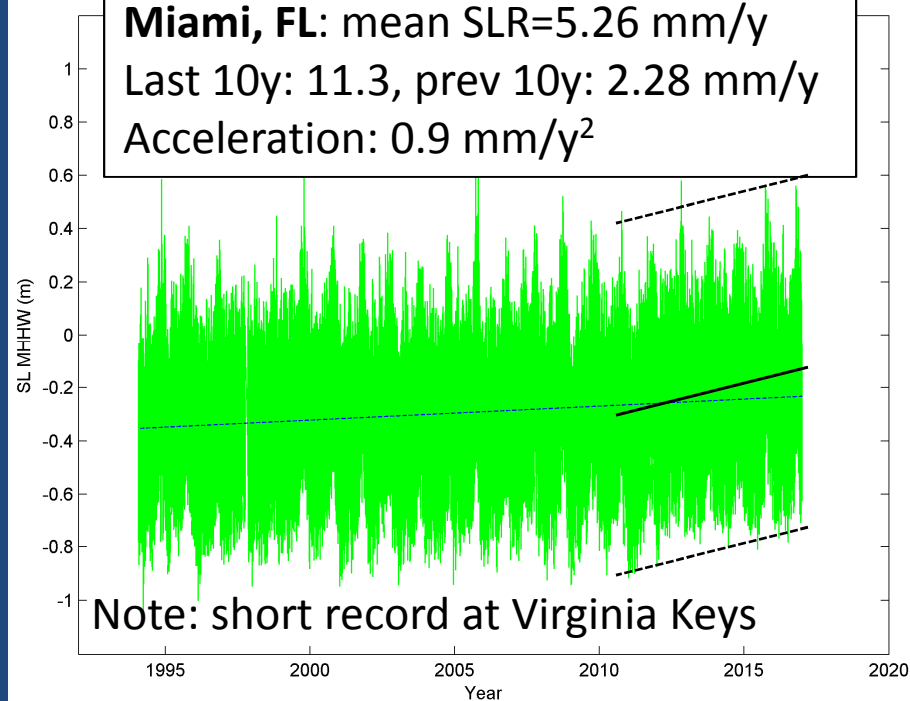
Hours/year of nuisance floods in Charleston (MHHW+0.38m)



**Key West, FL:** mean SLR=2.48 mm/y  
Last 30y: 3.78, prev 30y: 2.53 mm/y  
Acceleration: 0.042 mm/y<sup>2</sup>

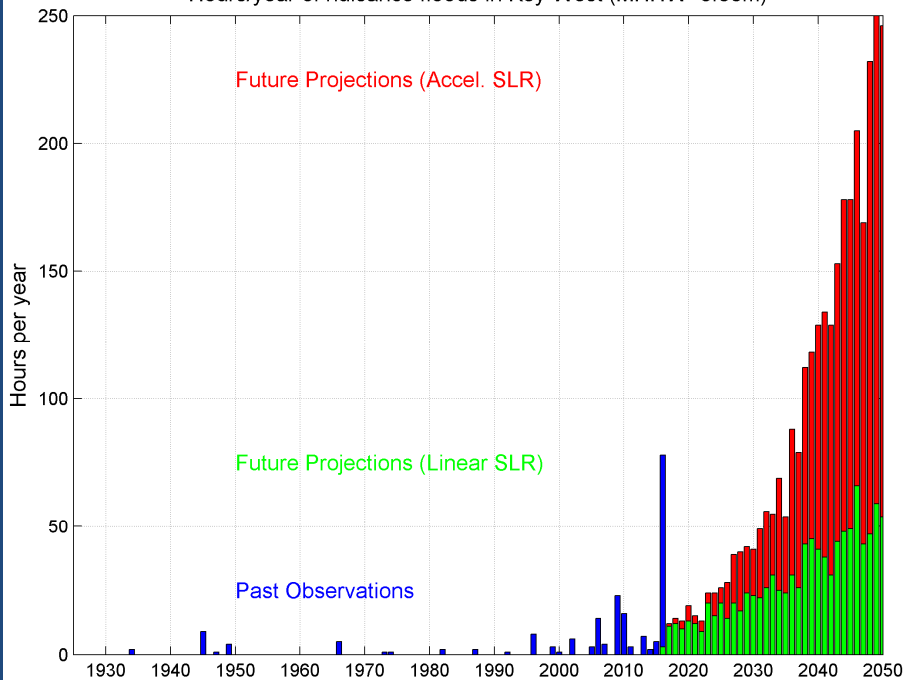


**Miami, FL:** mean SLR=5.26 mm/y  
Last 10y: 11.3, prev 10y: 2.28 mm/y  
Acceleration: 0.9 mm/y<sup>2</sup>

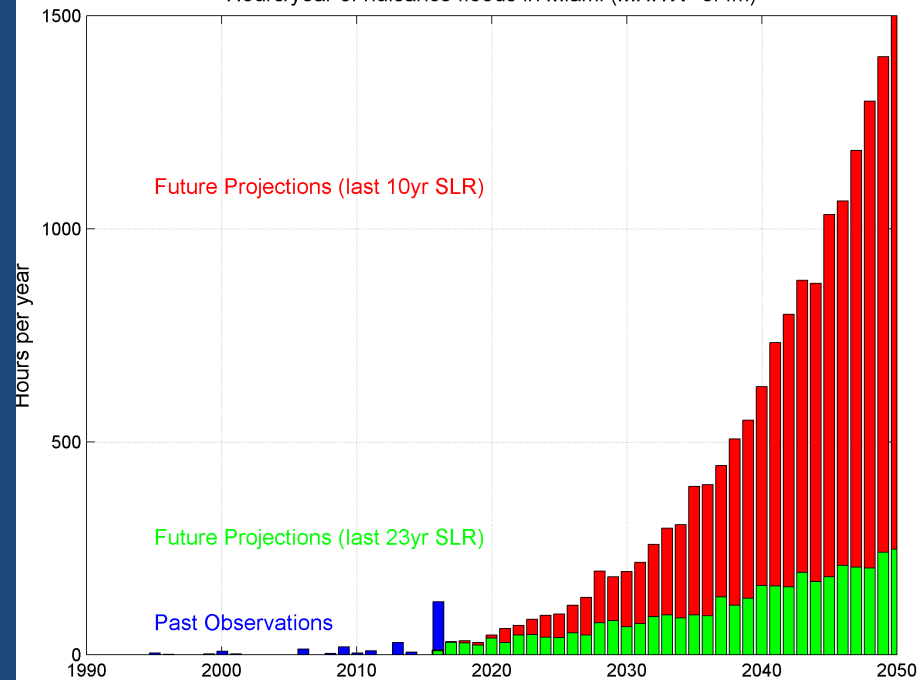


Note: short record at Virginia Keys

Hours/year of nuisance floods in Key West (MHHW+0.33m)



Hours/year of nuisance floods in Miami (MHHW+0.4m)



## Some recent ODU papers on the Gulf Stream- Sea Level connections (PDFs available on: <http://www.ccpo.odu.edu/~tezer/Pub.html>)

- Ezer, T. and L. P. Atkinson (2017), On the predictability of high water level along the U.S. East Coast: can the Florida Current measurement be an indicator for flooding caused by remote forcing?, *Ocean Dynamics*, doi:10.1007/s10236-017-1057-0
- Ezer, T. (2017), A modeling study of the role that bottom topography plays in Gulf Stream dynamics and in influencing the tilt of mean sea level along the U.S. East Coast, *Ocean Dynamics*, 67(5), 651-664, doi:10.1007/s10236-017-1052-5.
- Ezer, T. (2016), Can the Gulf Stream induce coherent short-term fluctuations in sea level along the U.S. East Coast?: A modeling study, *Ocean Dynamics*, 66(2), 207-220, doi:10.1007/s10236-016-0928-0.
- Ezer, T. (2015), Detecting changes in the transport of the Gulf Stream and the Atlantic overturning circulation from coastal sea level data: The extreme decline in 2009-2010 and estimated variations for 1935-2012, *Global and Planetary Change*, 129, 23-36, doi:10.1016/j.gloplacha.2015.03.002.
- Ezer, T. and L. P. Atkinson (2014), Accelerated flooding along the U. S. East Coast: On the impact of sea level rise, tides, storms, the Gulf Stream and the North Atlantic Oscillations. *Earth's Future*, 2(8), 362-382, doi:10.1002/2014EF000252.
- Ezer, T. (2013), Sea level rise, spatially uneven and temporally unsteady: why the U. S. east coast, the global tide gauge record and the global altimeter data show different trends, *Geophysical Research Letters*, 40(20), 5439-5444, doi:10.1002/2013GL057952.
- Ezer, T. L. P. Atkinson, W. B. Corlett and J. L. Blanco (2013), Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast, *Journal of Geophysical Research*, 118(2), 685-697, doi:10.1002/jgrc.20091.
- Ezer, T. and W. B. Corlett (2012), Is sea level rise accelerating in the Chesapeake Bay? A demonstration of a novel new approach for analyzing sea level data, *Geophysical Research Letters*, Vol. 39, L19605, doi:10.1029/2012GL053435.



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