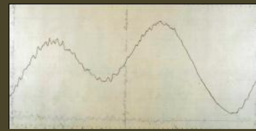
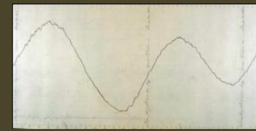
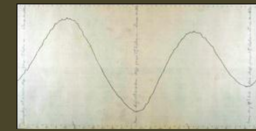
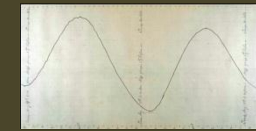






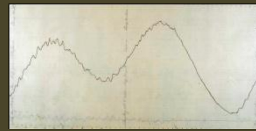
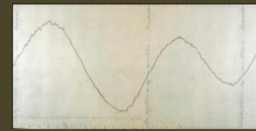
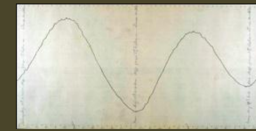
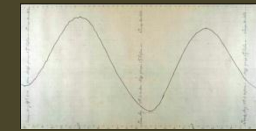
Hurricane Sandy and Increasing Storm Risk in New York Harbor, 1844-2013: A Perspective from NOAA Historical Data

David Jay and Stefan Talke

Portland State University

Philip Orton

Stevens Institute of technology

Roadmap –

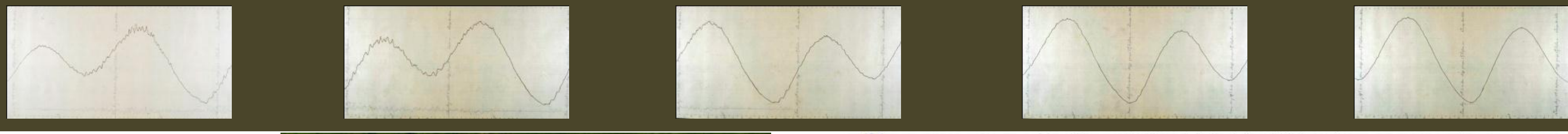
- Brief review of Hurricane Sandy
- What can NOAA historical data tell us about the risk of such storms?
- Using NOAA data to understand how a storm surge behaves in New York Harbor, and how this has changed

Hurricane Sandy – A Brief Review

For additional details, see:

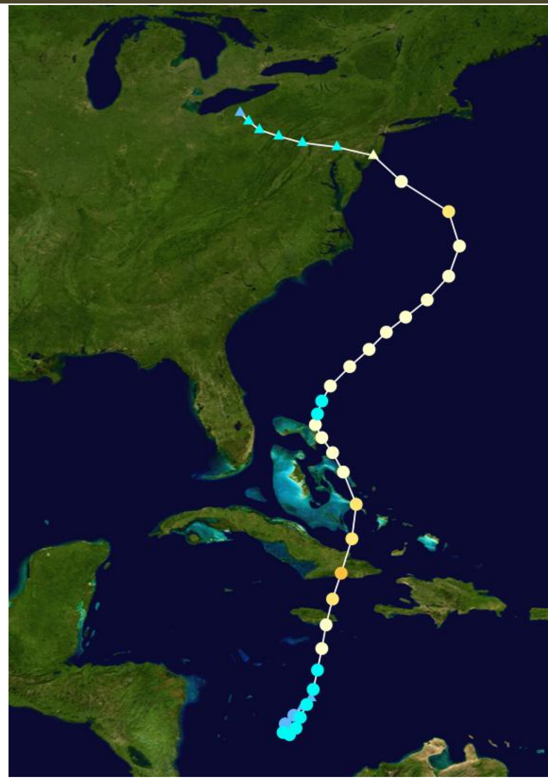
Service Assessment Hurricane/Post Tropical Cyclone Sandy, October 22-29, 2012

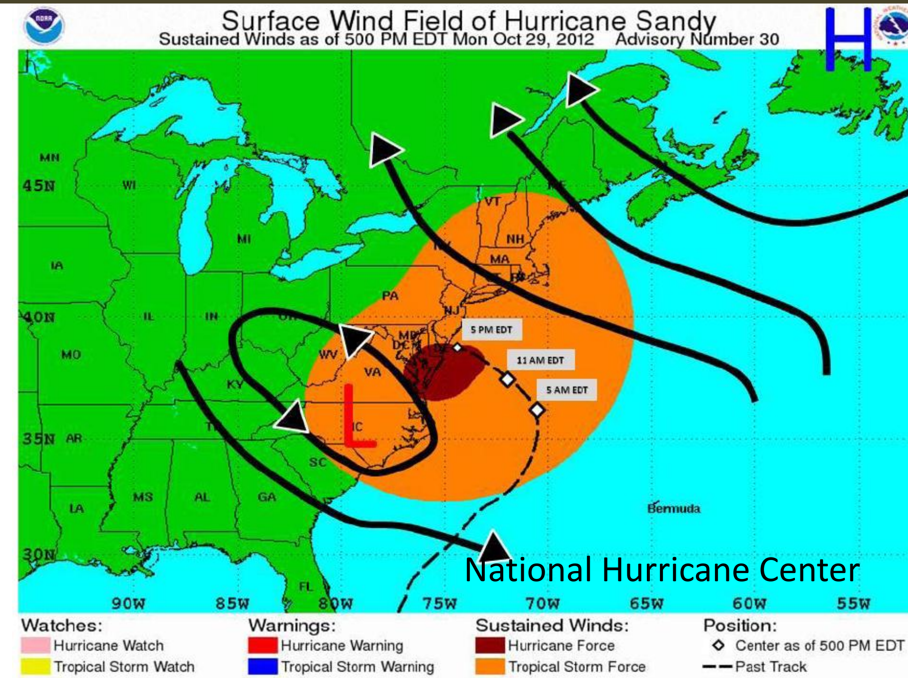
NOAA National Weather Service



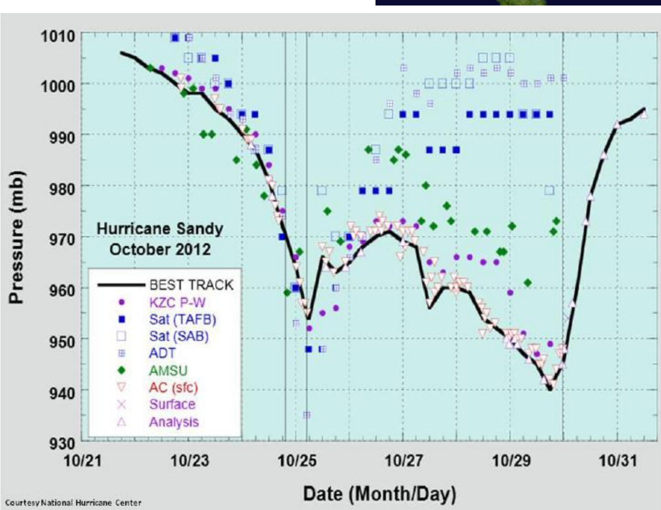
Storm Track –

Wikipedia; background image NOAA





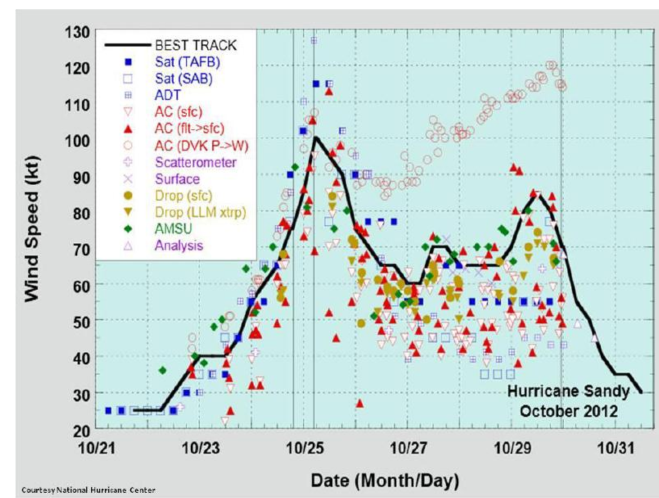
An enormous storm; the rare "left turn" was caused by high SLP over Greenland



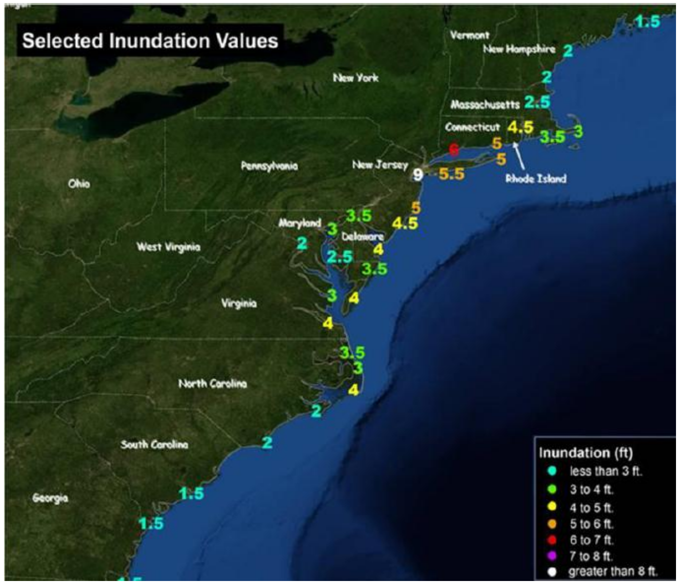
Sea level Pressure

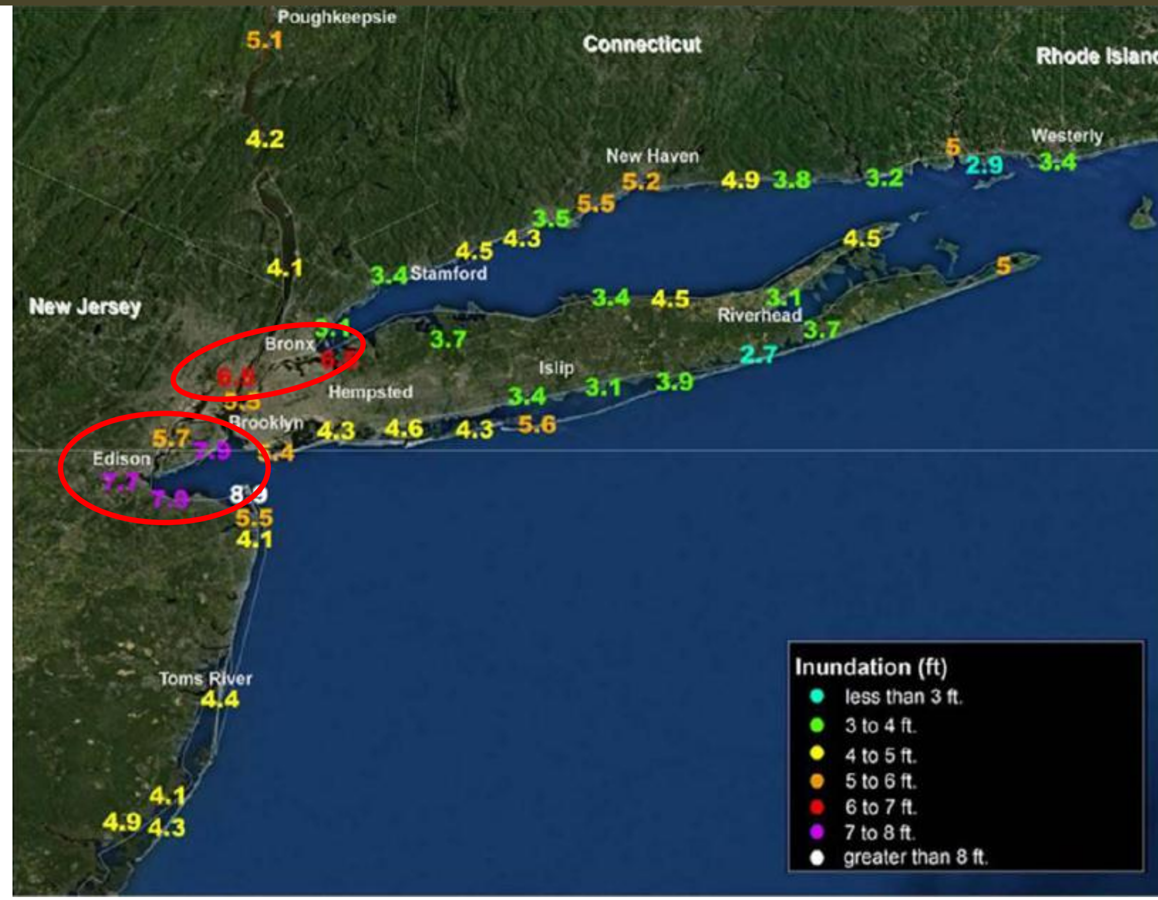
Wind Speeds

National Hurricane Center



Inundation–



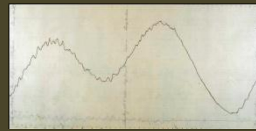
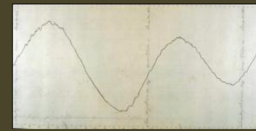
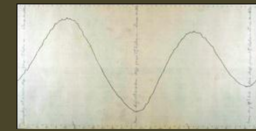
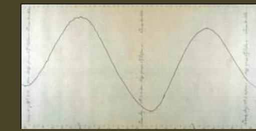


Inundation (ft) above ground level (AGL), from NOS gauges:

The greatest inundation was on the r.h side of the storm, aided by strong winds from the northeast

Raritan Bay is funnel shaped, facing into the wind

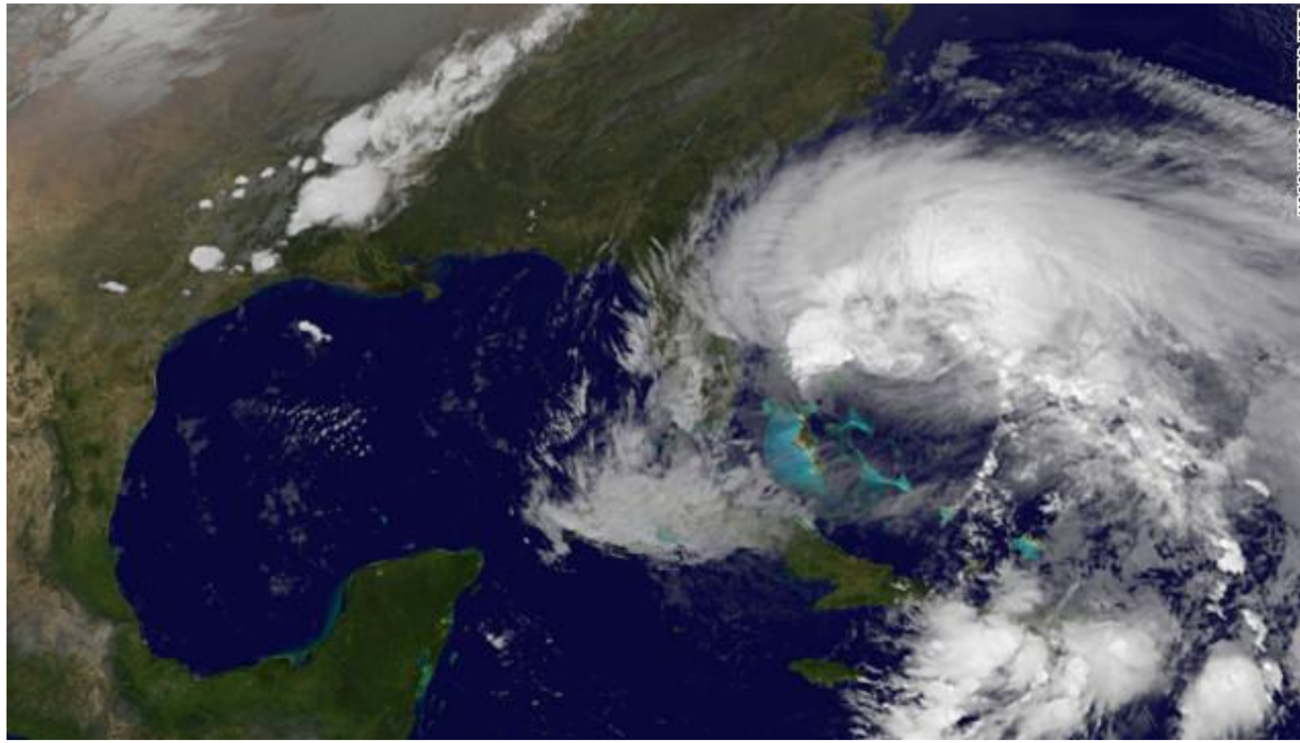
But what happened in the East River Tidal Strait? (I'll get to that!)



Learning from Historical NOAA Data –

Superstorm Sandy: The worst storm surge in NYH since….?

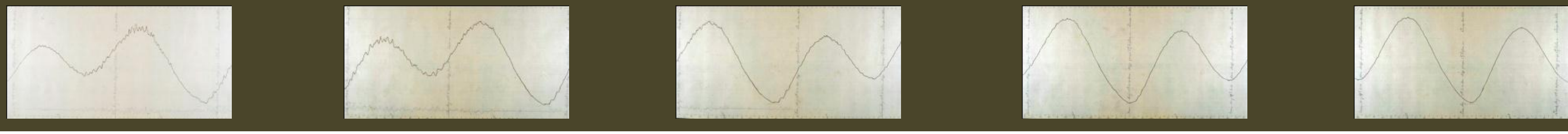
Hurricanes in 1788, 1821, & 1893 predate modern data but are important to risk

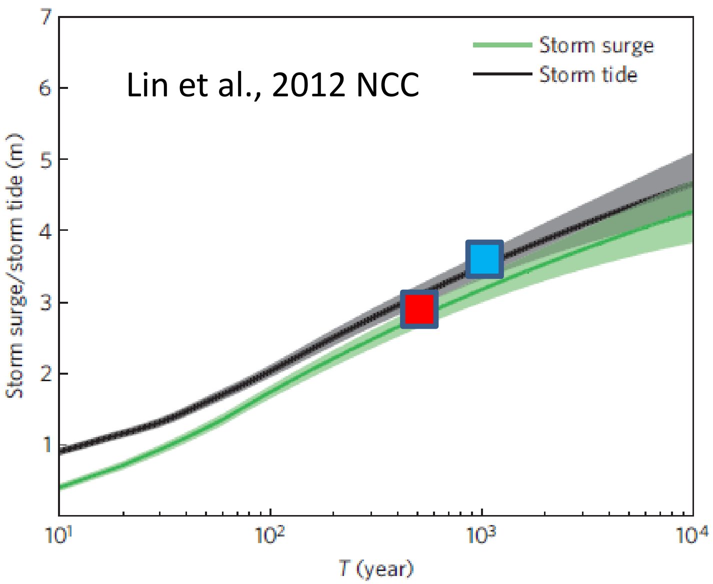


Lack of data is a general problem in analyzing rare, extreme events… What to do? Recovering historical data is an important tool.

Summarized from:

S.A. Talke, P. Orton, and D.A. Jay, [2014], Increasing storm tides in New York Harbor, 1844-2013, Submitted to *Geophysical Research Letters,* and other papers in preparation



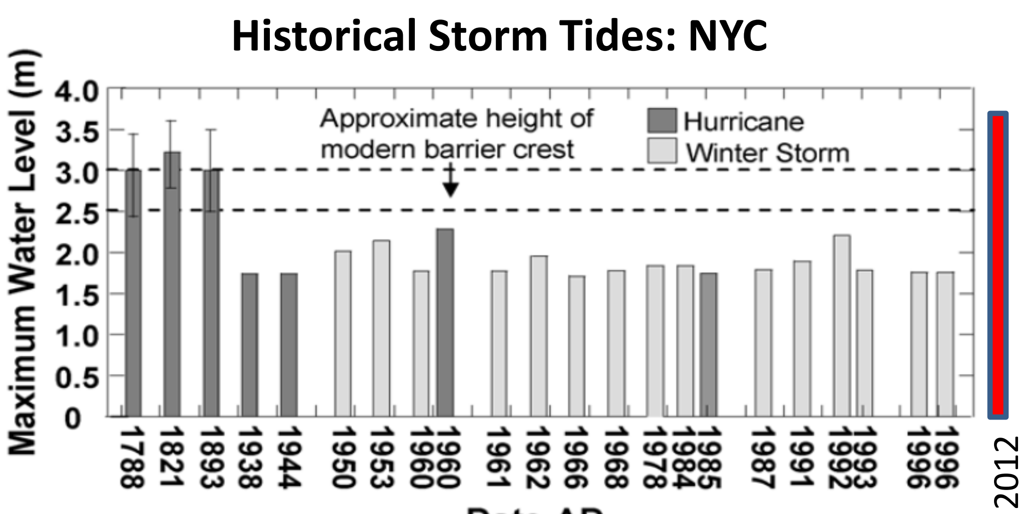


<u>Approach 1</u>: Numerical simulation + Generalized Pareto Distribution to assess storm surge and return period

- Storm-surge: ~ 500 year Sandy return period
- Storm tide: surge + astronomical tide: ~1000 years return

<u>Approach 2</u>: Analyze available annual extremes: 1570 year return storm tide (Sweet et al., 2013)

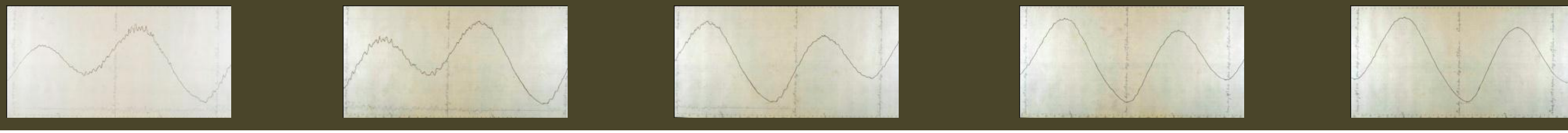
Previous Analyses of NYH storm-tide risk



Scileppi & Donnelly, 2007 G3

<u>Approach 3</u>: Proxy-based historical reconstruction.
→ Suggests 3 historical storm-tides since 1788 approached the level of hurricane Sandy.

Question: Is New York more vulnerable to extreme events than modeling suggests? Or are historical estimates in error?



Our Approach –

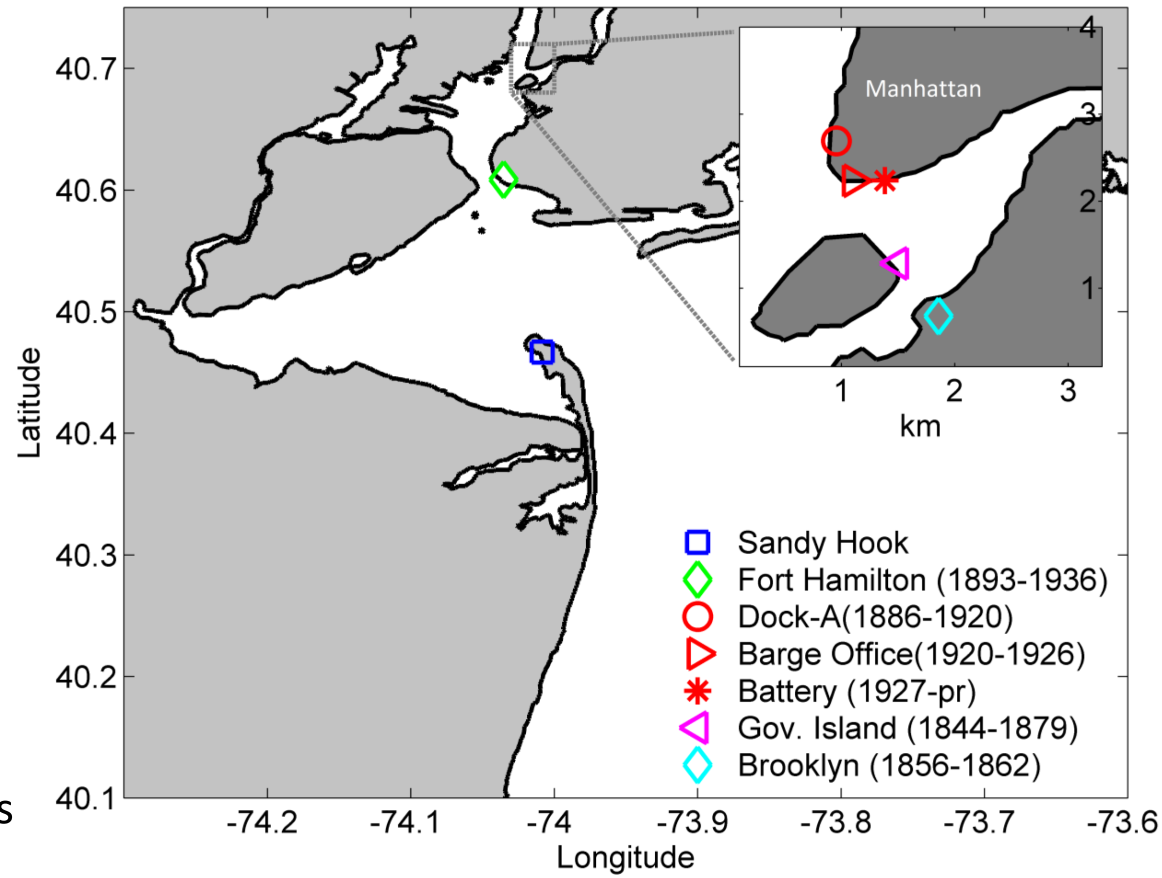
Use historic NOAA tide data from 1844-2012 to provide:

> Insights into the ***probability of extreme*** storm surge in NYH

> Clues about the ***long-term changes*** and their causes

> Add 1821 as another large event

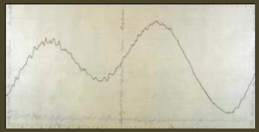
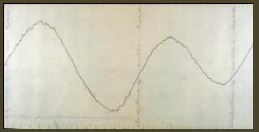
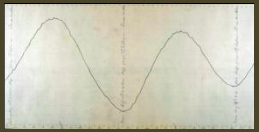
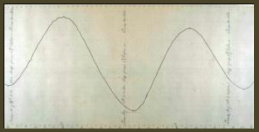
Use contemporary tide data and models to understand mechanisms



For the future, are there possible ***mitigation strategies*** at the local level?

Above: Tide Data has been measured nearly continuously in New York area since 1844.

These data are in the National Archives

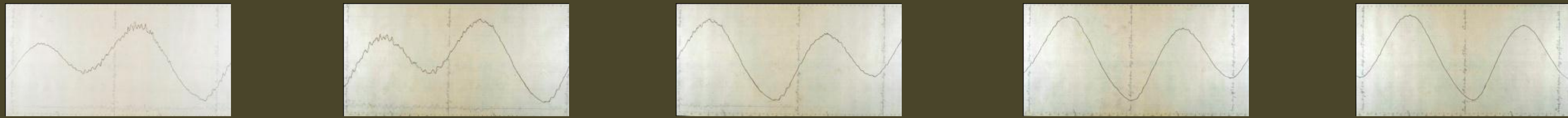
Data Recovery and Digitization

1. Pictures of data taken in archives
2. Students digitize the data
3. Quality Assurance, including:
   (a) Redundancy
   (b) Differencing to identify spikes
   (c) Harmonic analysis
   (d) New York Times archives, 1851-present

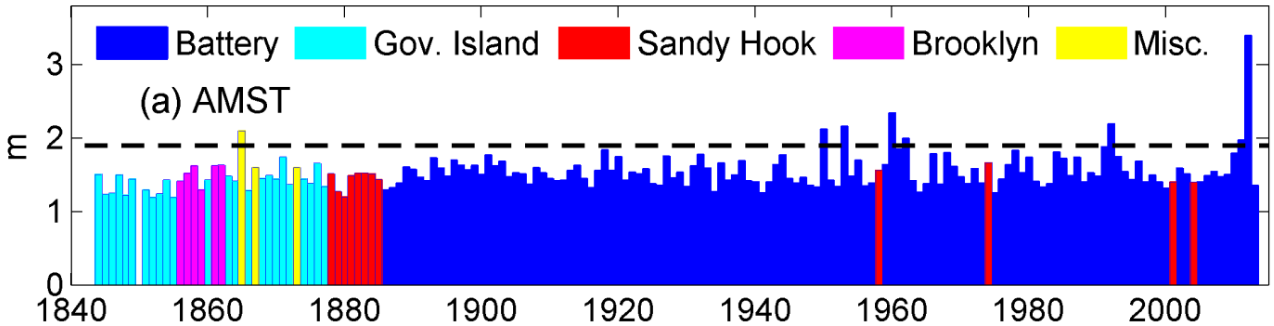
Analysis Methods

1. Tidal analysis to separate storm surge from astronomical tide
2. Extreme value statistical analysis on:
   --Annual extremes (1844- 2012)
   --Hurricane Storm Tides (1844- 2012)
   --Hurricane Storm surge (1860- 2012)

   The GPD and GEV probability curves are fit to data to estimate return periods



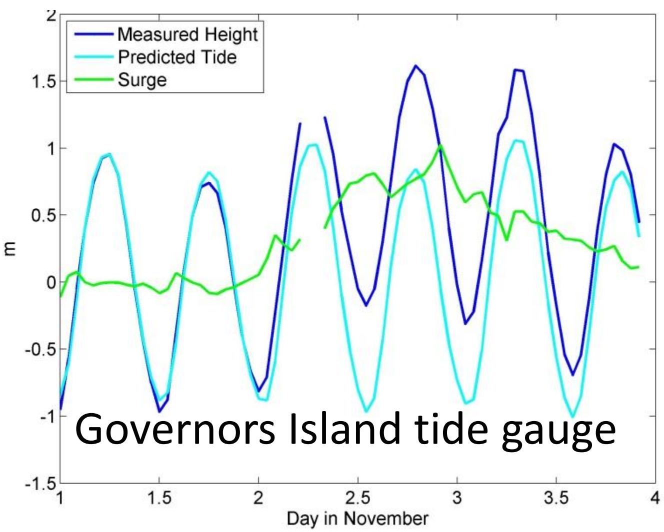
Results



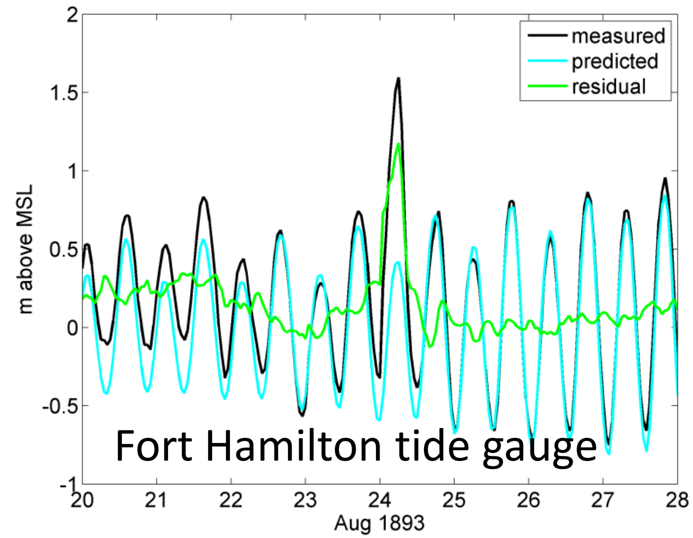
AMST: The annual extreme storm tide (highest measured water level - annual mean sea level)

Before 1950, only 1 event exceeded 1.9m; after 1950, seven have.

1861: "Expedition" Hurricane

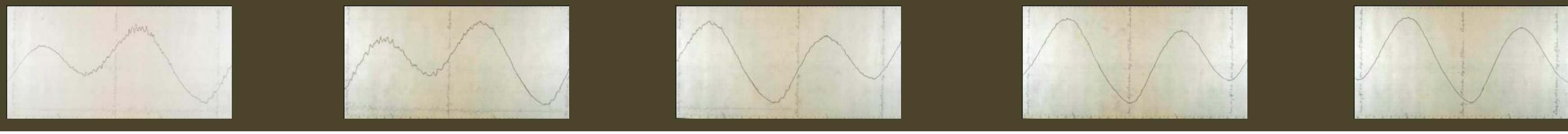


1893: New York Hurricane

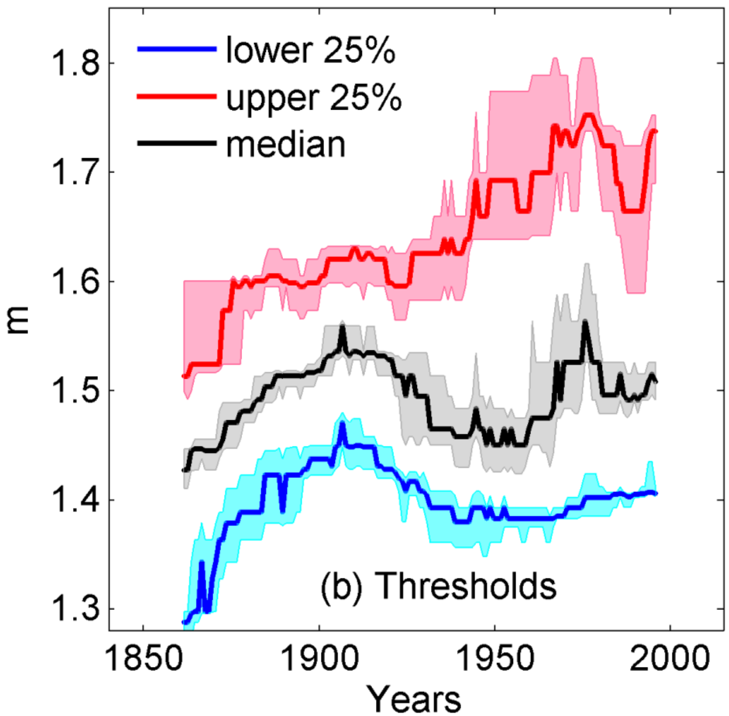


Some historical hurricanes of interest….

Note: The 1893 hurricane was only 1.6m; not even largest event of the year



Results



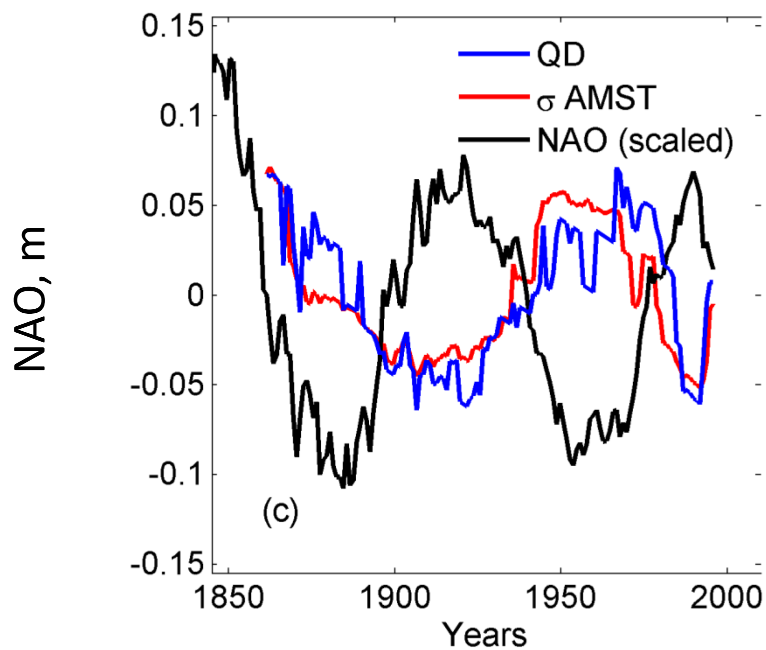
Left: The annual storm-tide is increasing, based on a 36 yr. running median.

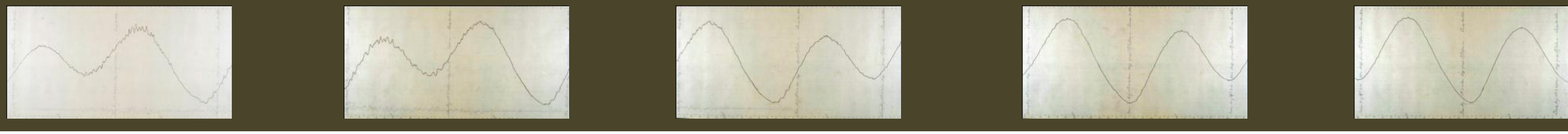
In particular, the upper quartile threshold—the 75% level– has increased by ~20cm.

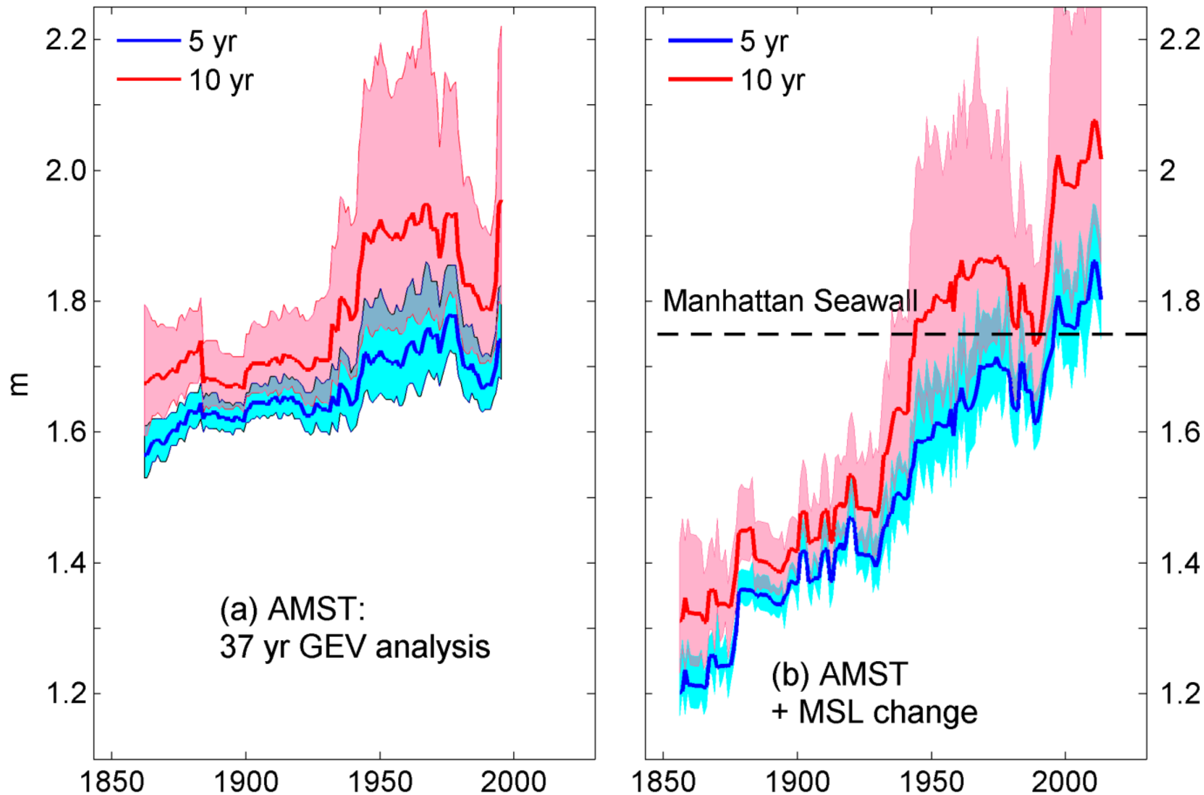
Significant natural variability. North Atlantic Oscillation (NAO)?

Yes: The detrended difference between upper and lower quartile is *anti-correlated* with a 36 yr median NAO index. $R^2 = 0.92$, p-value < 0.1

Hence, there is an increased 'spread' in statistics during negative NAO years





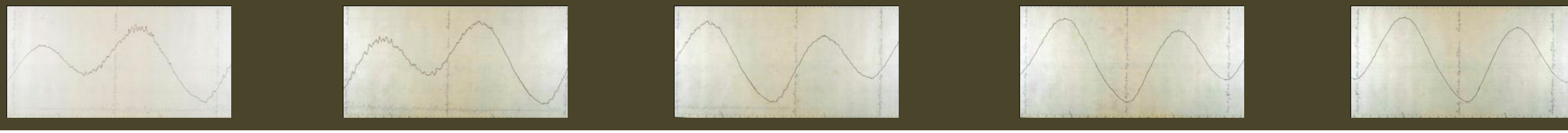


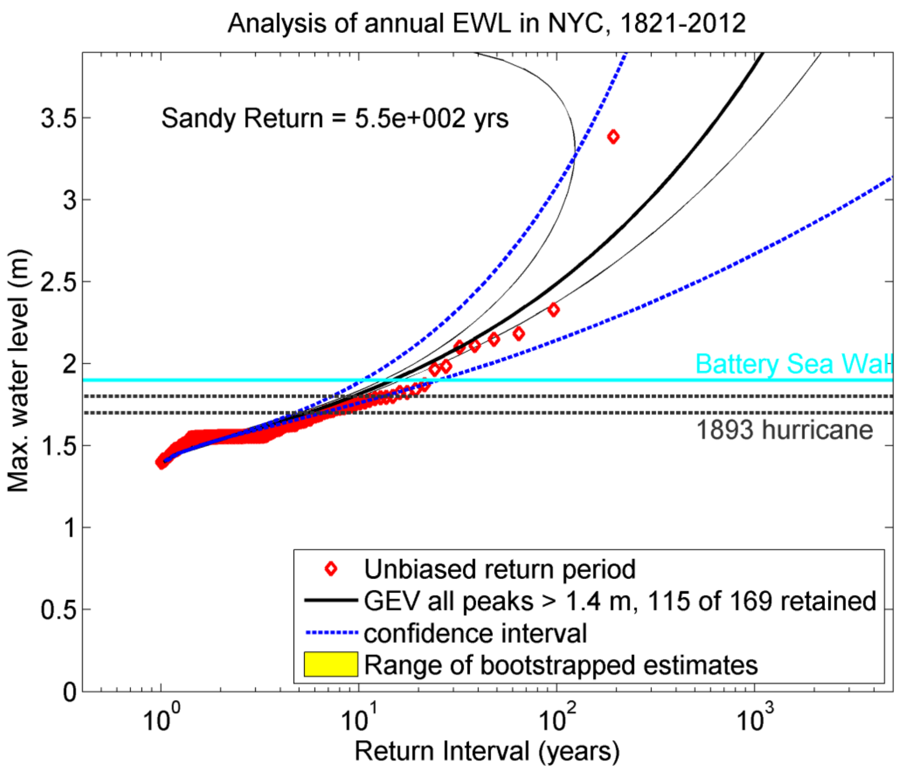
If 45 cm relative sea-level rise is included, we find that the combined change is 75 cm

The 10 yr storm-tide now exceeds the Battery sea-wall.

Above: Generalized extreme value (GEV) analysis finds a nearly 30 cm increase in the 10 yr storm-tide level since mid-1800s

What is the Sandy Level return period?

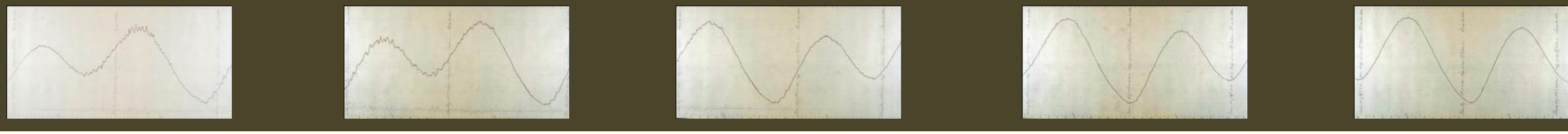




What is the Sandy Level return period?

If the AMST from 1844-2013 are used, the estimate is > 5000 years.

Can this possibly be correct, considering the 1821 hurricane was reported to be nearly as high as Sandy?



To obtain an adequate ***extreme*** risk assessment, we next include the 1821 Hurricane

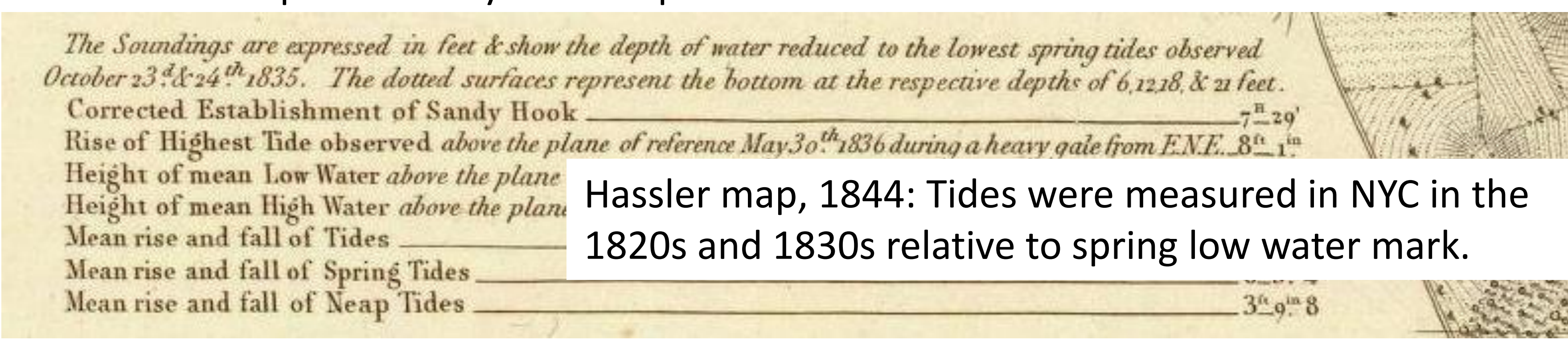
"THE GAZETTE AND GENERAL ADVERTISER" - September 7, 1821

Singular fact - In one hour during the tornado of Monday evening, the water was forced into the East River 13 feet and 4 inches above low water mark. On the sudden shifting of the wind, the water went off in half the time that it came in. The regularity of the tides had no effect upon the water, which yielded entirely to the force of the wind.

Reprinted from Gofsayef, 1957

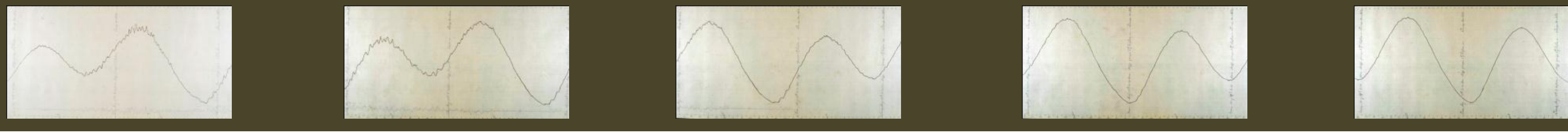
Contemporary account from 1821: "water was forced into the East River ***13 feet and 4 inches*** above ***low water mark***"

From contemporary practices in England, there was a staff gauge and probably primitive tide predictions were published by an entrepreneur

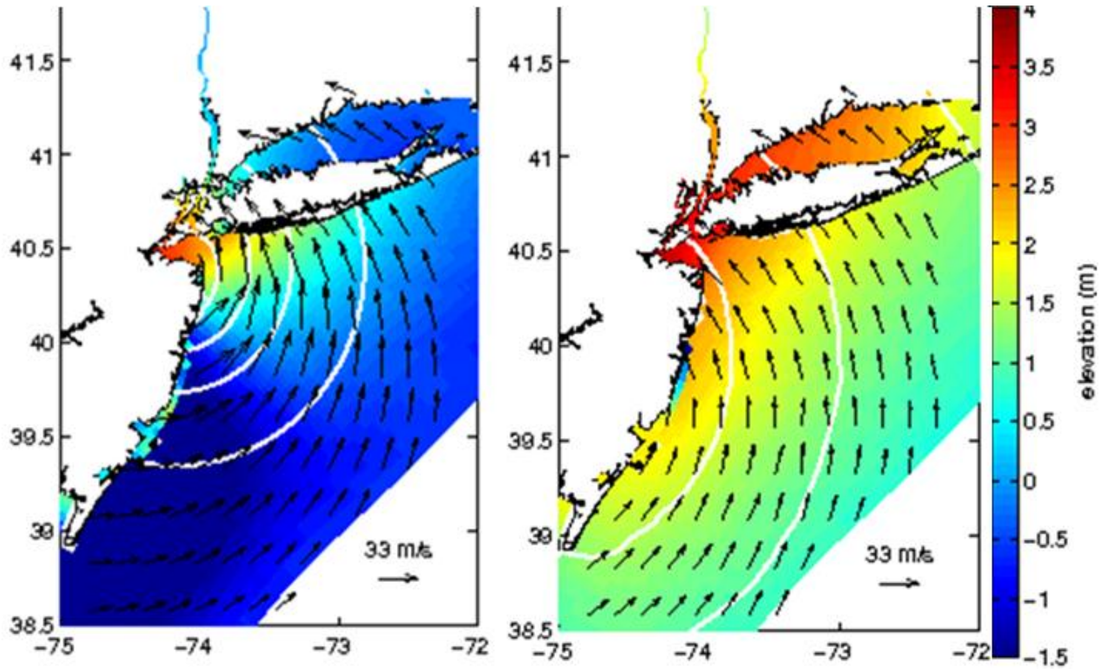


Hassler map, 1844: Tides were measured in NYC in the 1820s and 1830s relative to spring low water mark.

The'low water mark' was probably an **extreme low water datum.** Hence the storm surge probably reached ~**3.5m** (larger than Sandy). The storm tide was probably ~**3m**, 0.5m less than the Scileppi & Donnelly estimate but similar to Gofsayef, 1957 (2.7-3m).



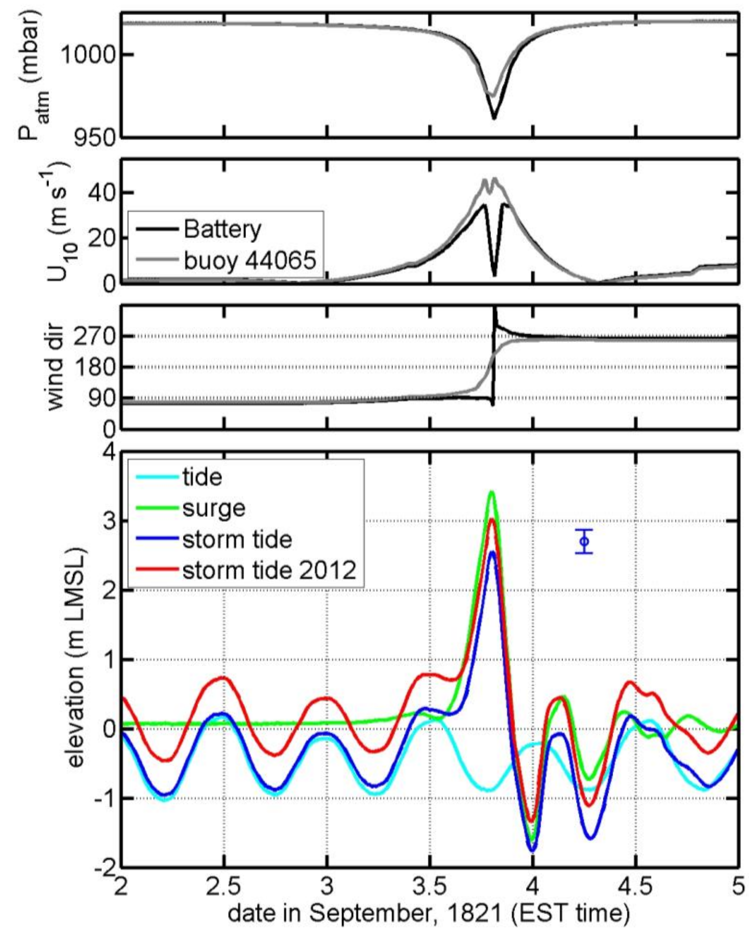
The 1821 Hurricane model using Steven's Institute ECOM
(Modern bathymetry/topography)



1821 (based on Boose et al., 2001 Climatology)

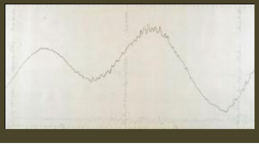
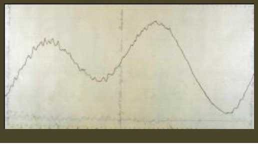
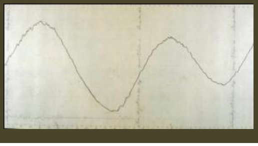
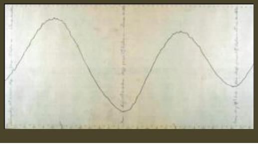
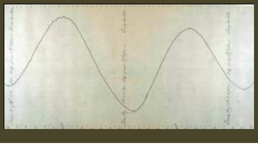
2012--Sandy

images: P. Orton, SIT

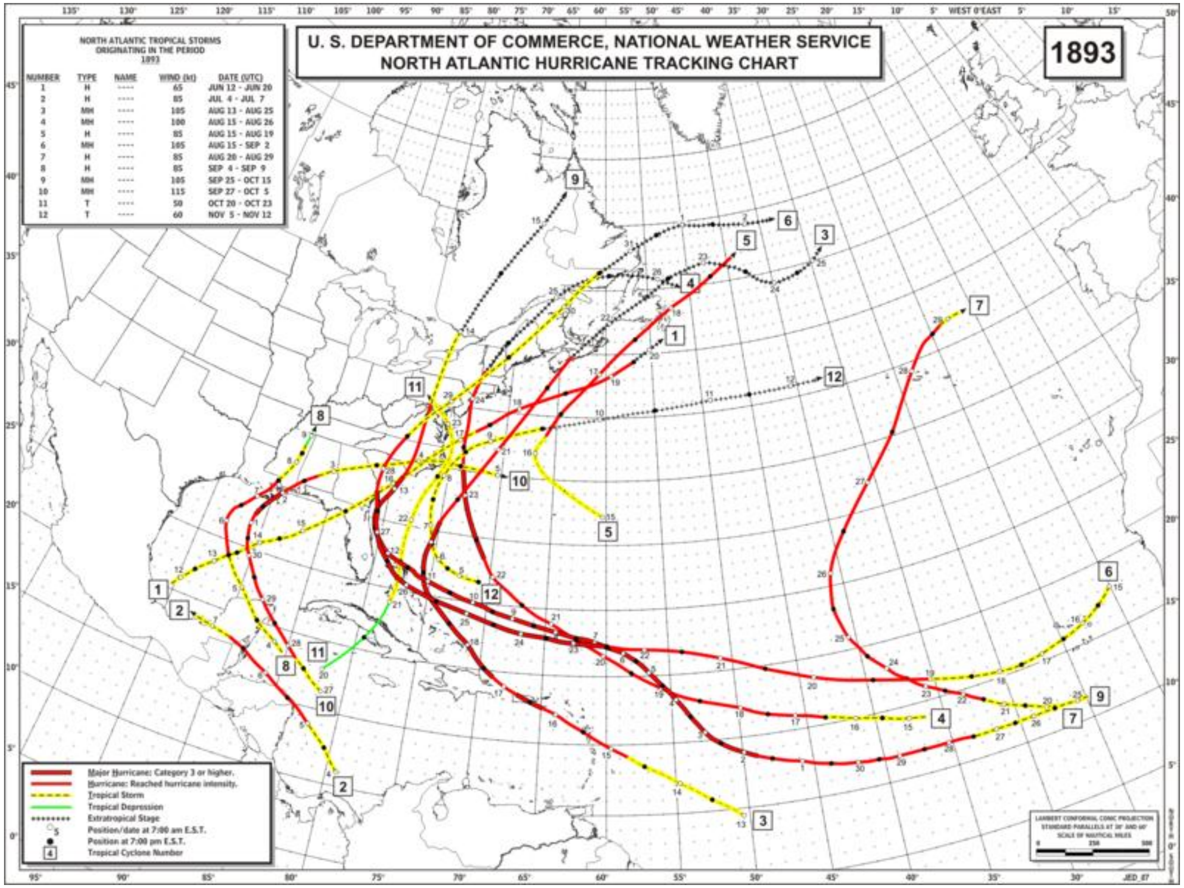


The 1821 Hurricane model

→ Storm tide = **3+/-0.2m** **(red line)**

Next Step: Separate tropical storms from Extra tropical storms

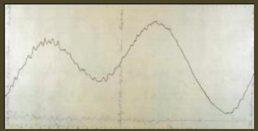
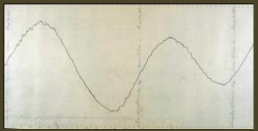
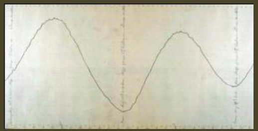
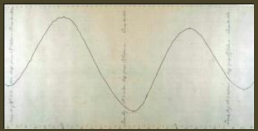


http://en.wikipedia.org/wiki/File:1893_Atlantic_hurricane_season_map.png

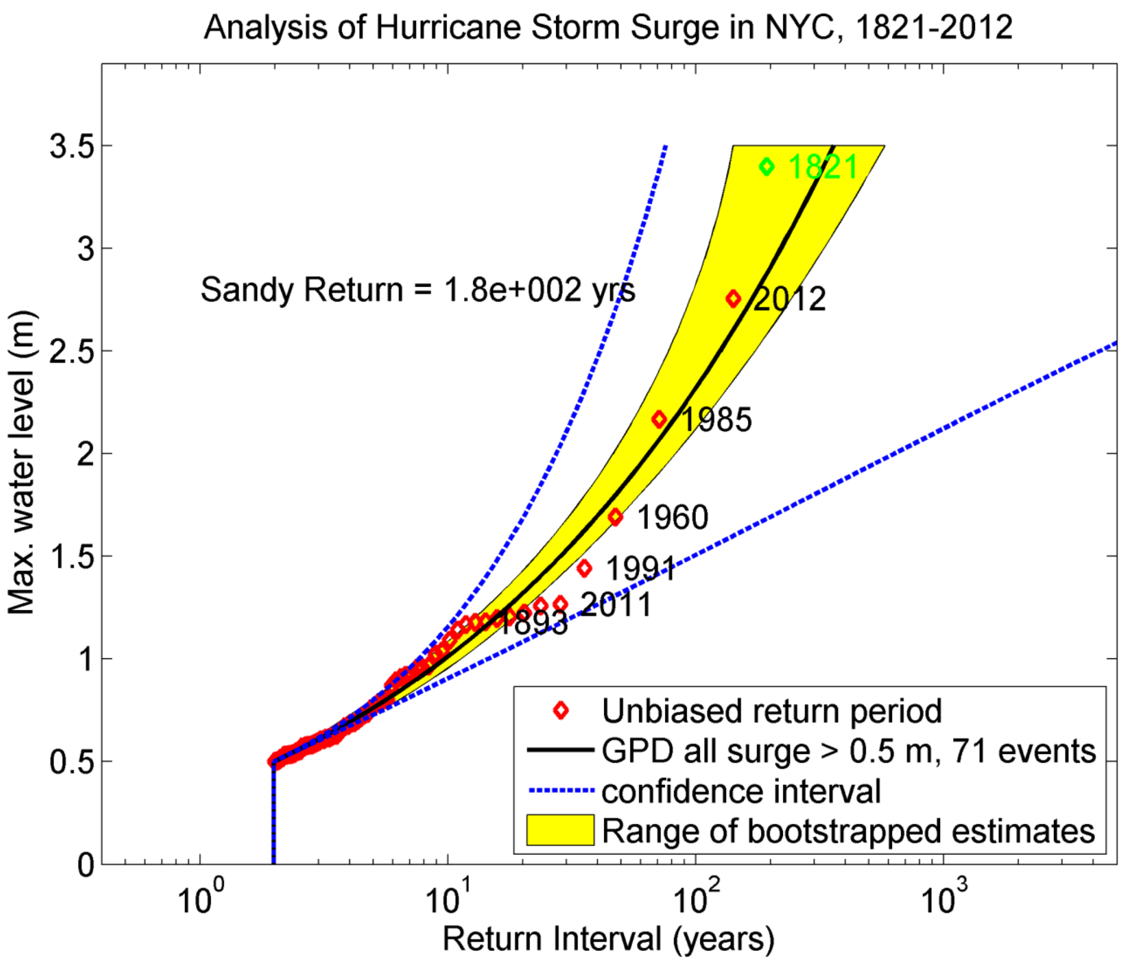
Storm tracks for all hurricanes from 1851-present are listed on Wikipedia

Strategy: compile list of storm tracks near NY, look for signal in water level

http://en.wikipedia.org/wiki/List_of_New_York_hurricanes

Storm Surge Return Period Estimate (GPD analysis), with 1821

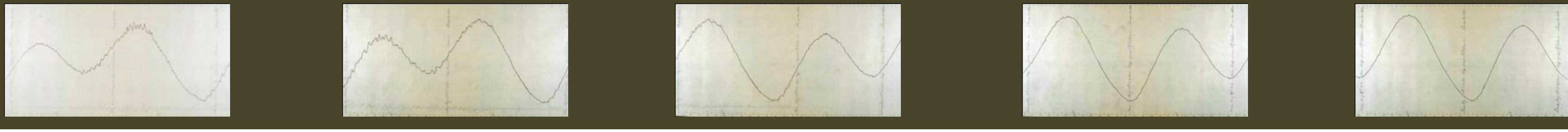


Sandy Surge Return period: About once in 200 years.

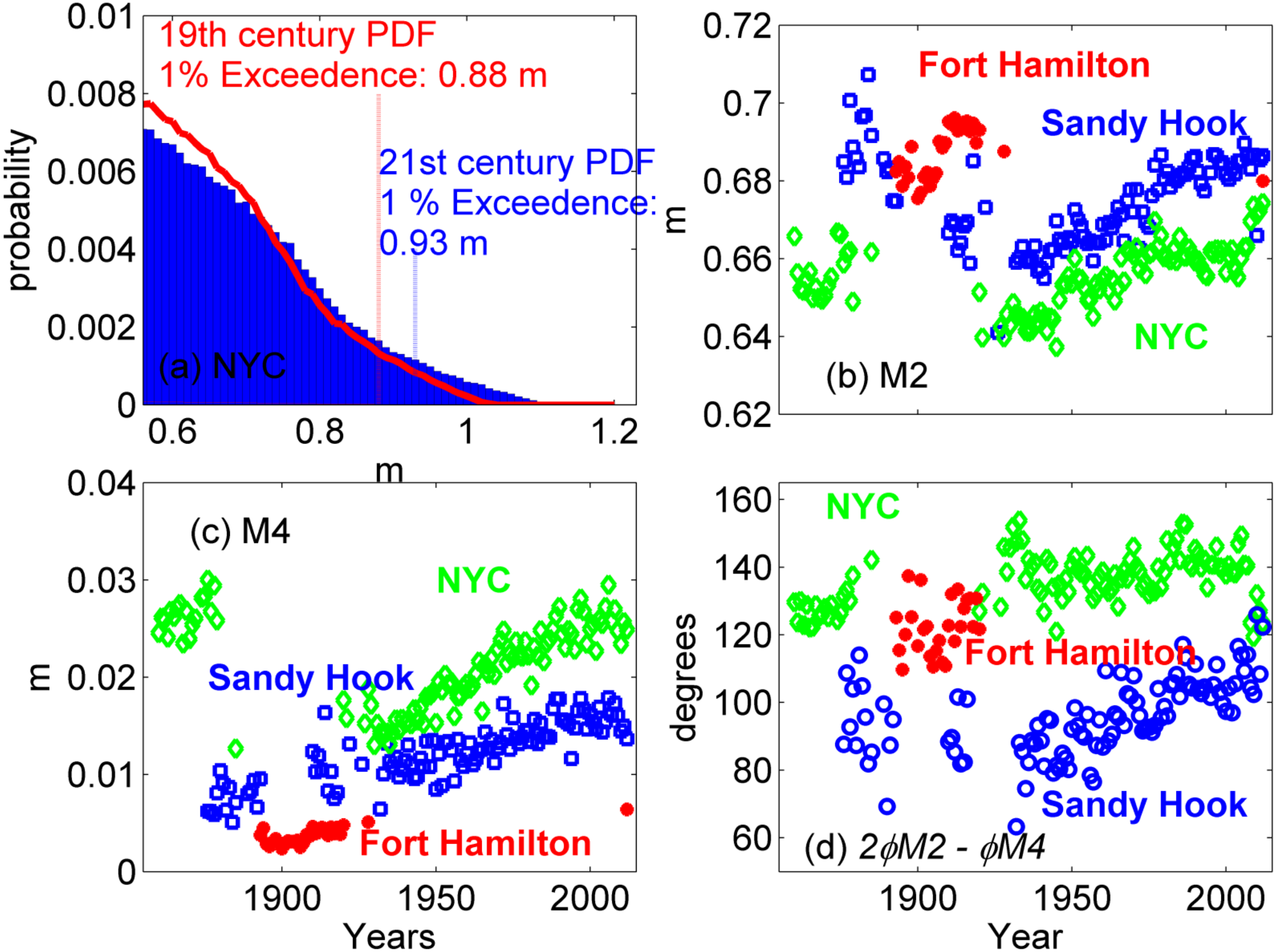
Note that 4 of 6 largest events have occurred since 1980;

1821 event still the largest!

Still to do: Non-stationary analysis



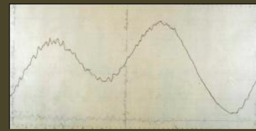
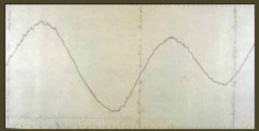
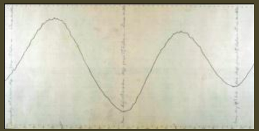
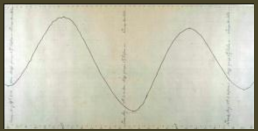
Remaining Question: Is there a local component to the long term trend – or is it all climate change/variability?



Shift in tide properties may account for some of the change

With our data, we can changes in harbor dynamics – looks like friction has changed.

NYC = The Battery

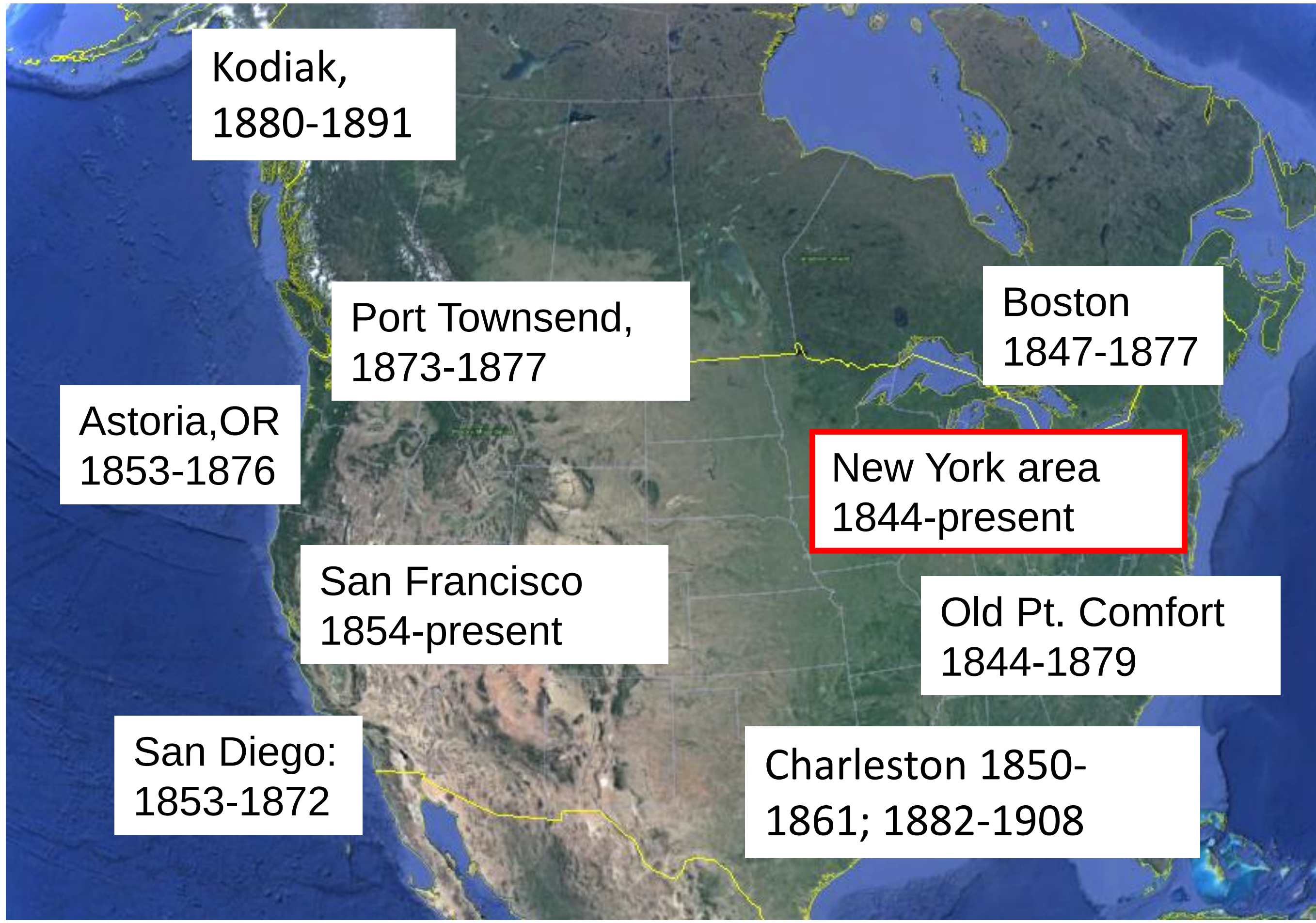
Wouldn't it be nice if more historical tide measurements existed ?

They do!

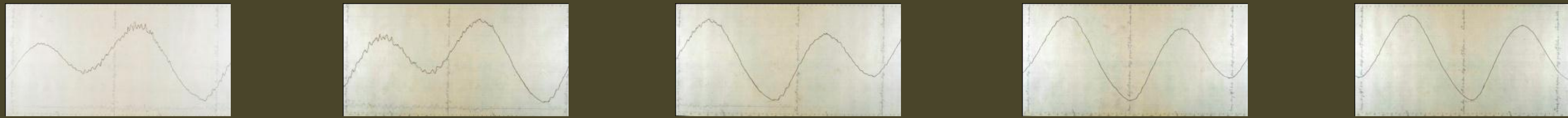
There are records of US tides back to the 1830s in US National archives

More than 500 station-years of unprocessed data still exist in the National Archives

Data as marigrams or hourly and high/low tabulations



See *Talke & Jay, 2013 Journal of Coastal Research*



Conclusions from Historical Analyses –

1. Old data exist to ground-truth proxy estimates of surge risk

2. When more data are used, storm surge risk in New York appears to be higher than found in other estimates. Non-stationary nature of risk makes it difficult to determine the present and future risk

3. Storm tide amplitudes have shifted independent of sea-level rise.

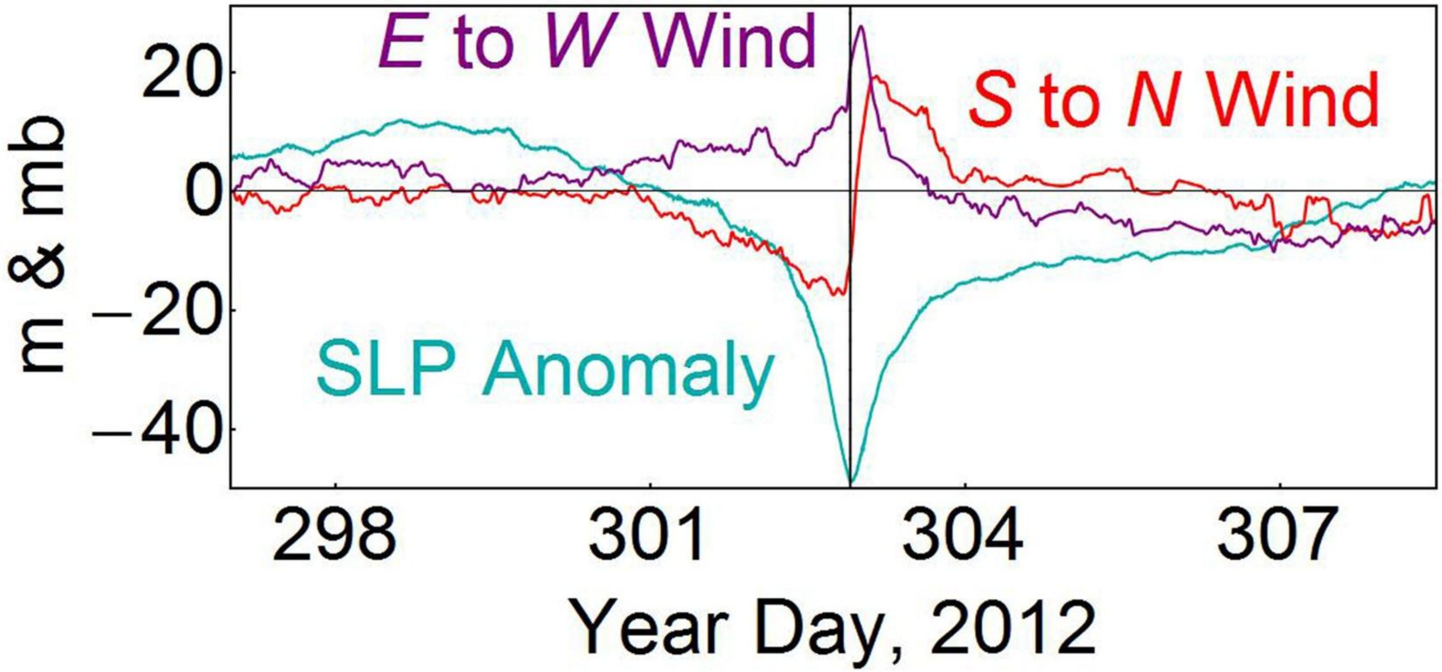
4. Tides show evidence of secular shifts. Hence, some of the increased storm risk is likely due to changes in harbor dynamics

5. More work is justified to distinguish the local anthropogenic influence from larger scale (NAO-relate) aspects

A Quick Look at the NYH Response to Surge –

In the time and frequency domains

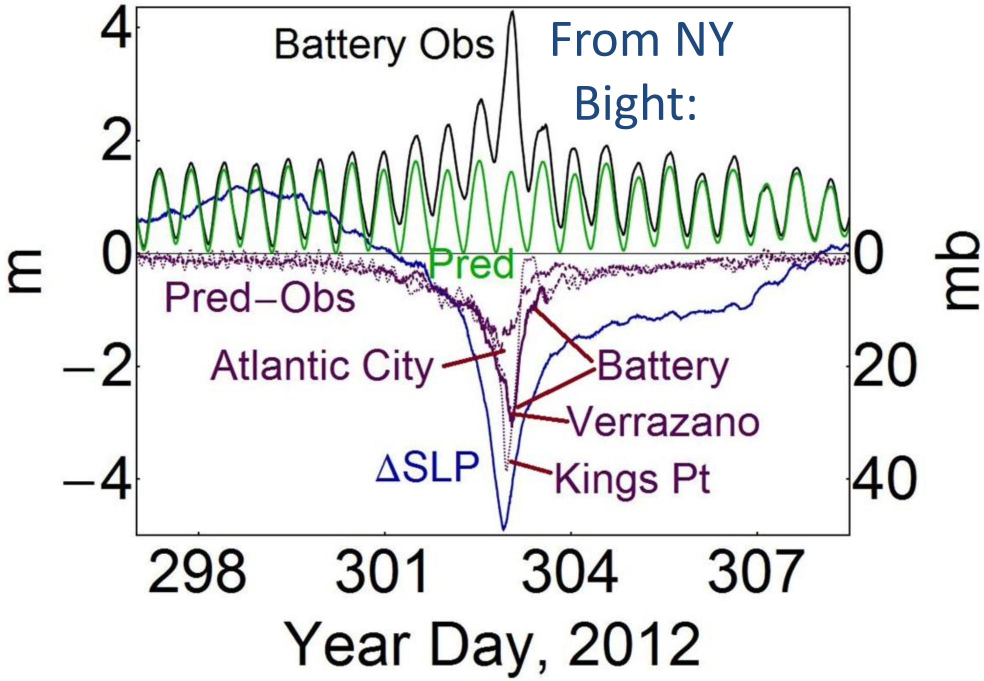
Sandy Atmospheric Forcing in NY Area –

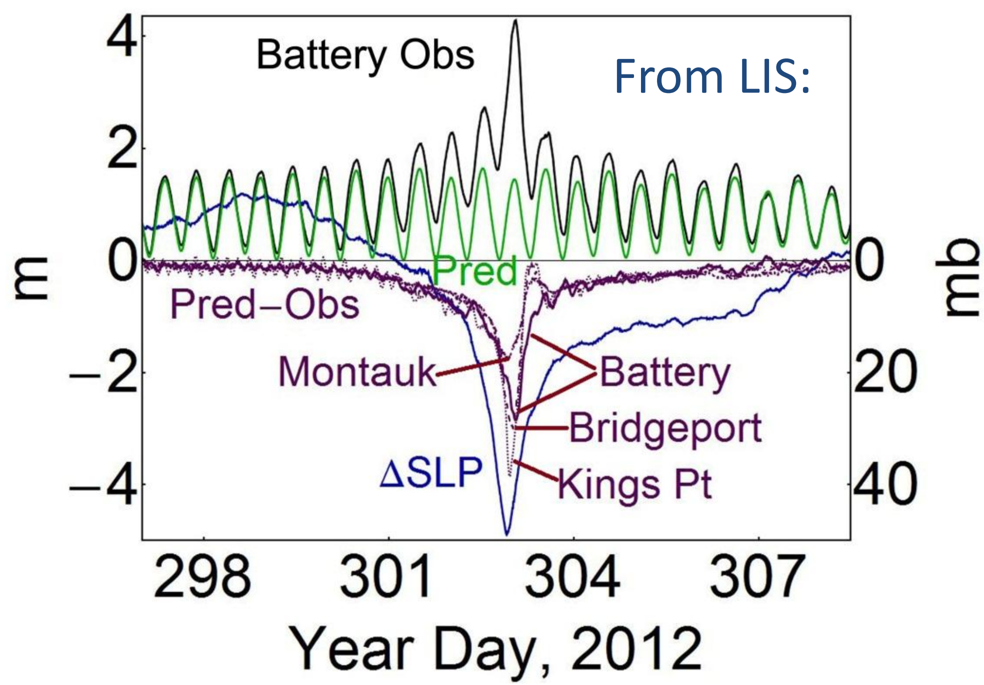


- Wind direction switches from NE to SE just before lowest SLP
- E to W wind speed peaks shortly thereafter
- Both pressure and wind will drive a storm surge

Water Level Response (time domain) –

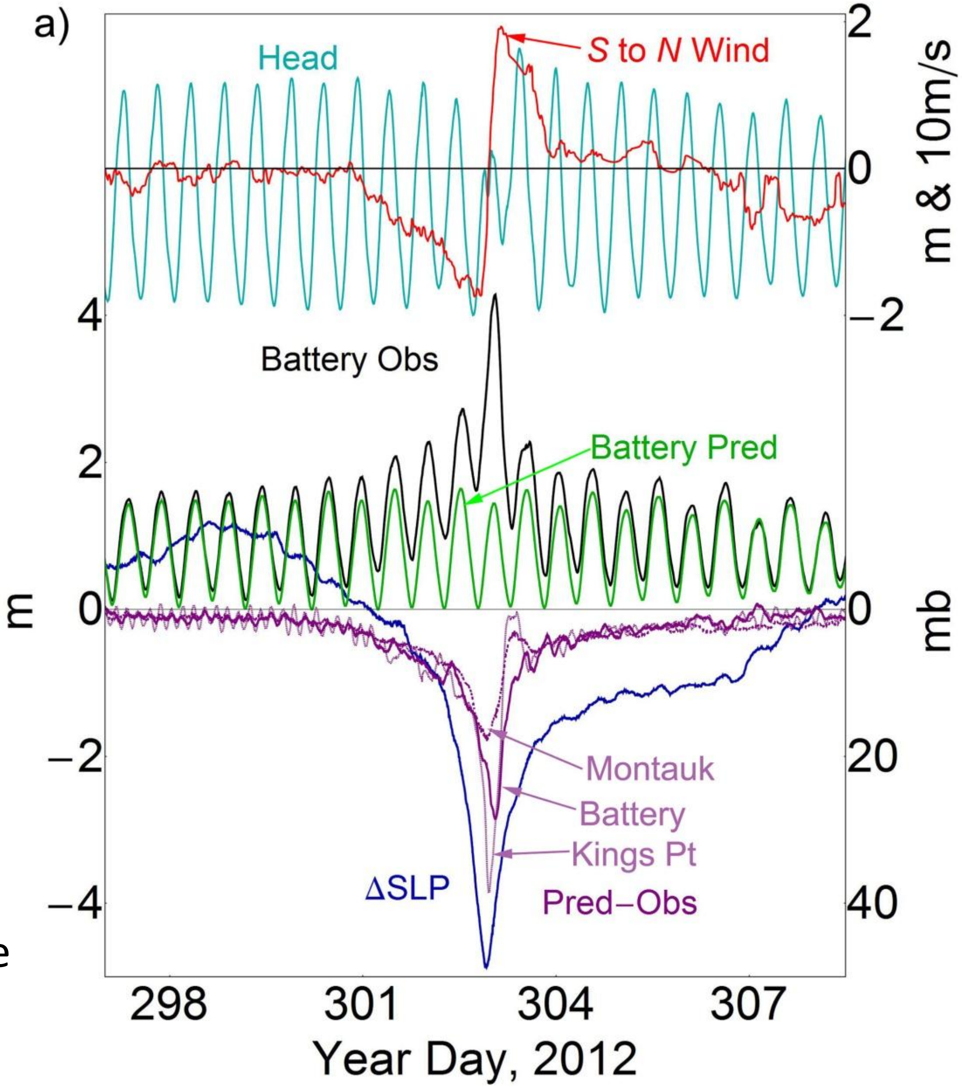
- Surge enters NYH from two directions:
  - Long Island Sound (LIS) via East River tidal strait, and
  - Lower New York Bay and NY Bight
- Look at time histories from both directions





Water Levels and Winds –

- Less surge at The Battery that at Kings Pt
- The East River is key to flooding in Manhattan:
  - Currents in the East River are hydraulic – water runs downhill
  - Currents in East River were weak for ~12 hrs
  - Wind reversal may have prevented worse flooding in Lower Manhattan
  - But it also prolonged the surge there



NYH is much more connected to LIS than it was before blasting of rocks at Hell Gate, starting 1851

This may be connected to the local part of the increasing surge risk

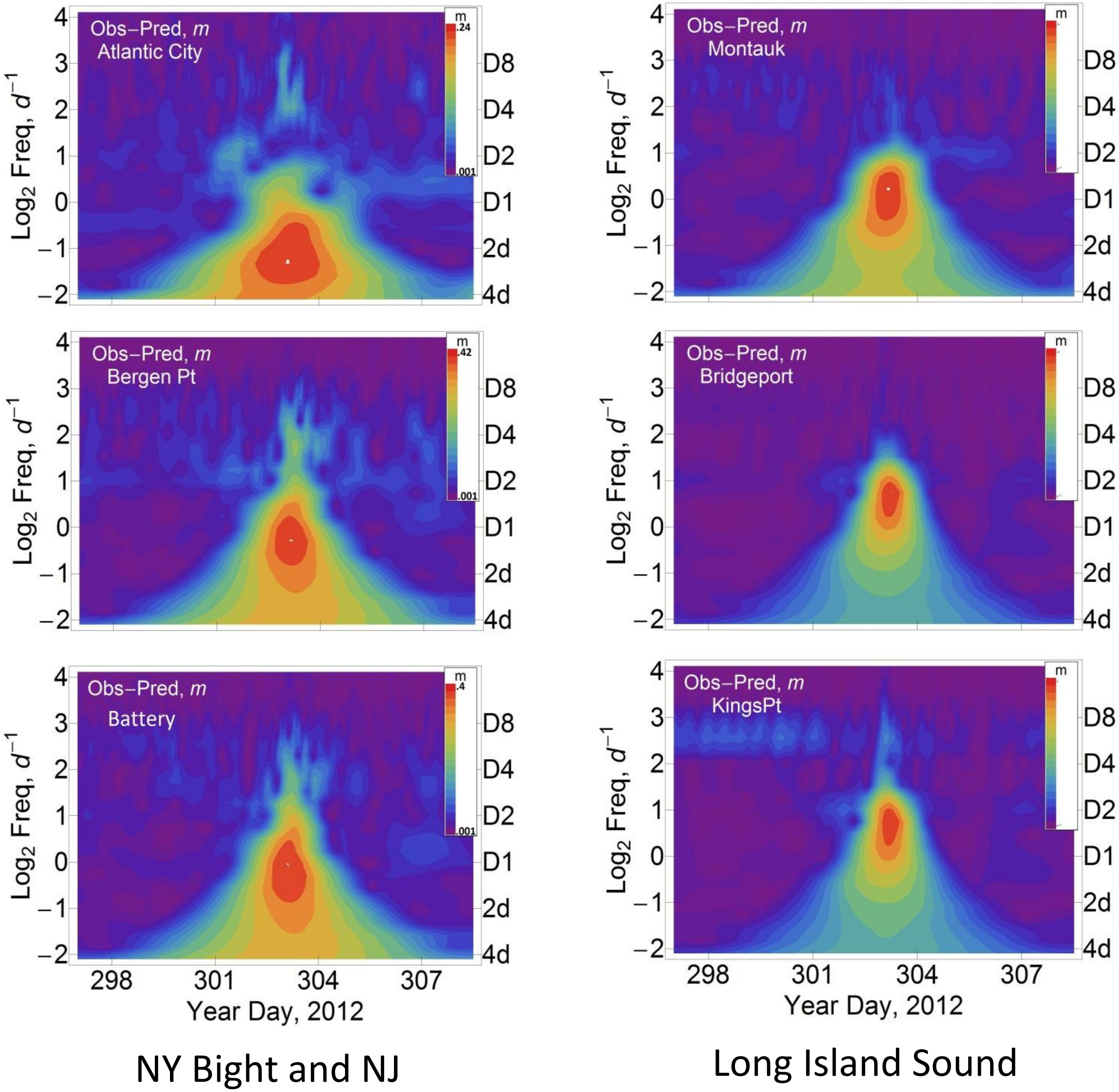
A Frequency Domain view of the Surge –

CWT scaleograms show:

Long Island Sound is resonant at semidiurnal frequencies (D2).

Atlantic City matches SLP forcing (more or less)

NYH is more diurnal (D1) and “rings” at overtide frequencies well after the surge subsides



- We use a continuous wavelet transform (CWT) to analyze time-variable frequency content. This is especially useful for events

Insights from the Frequency Domain –

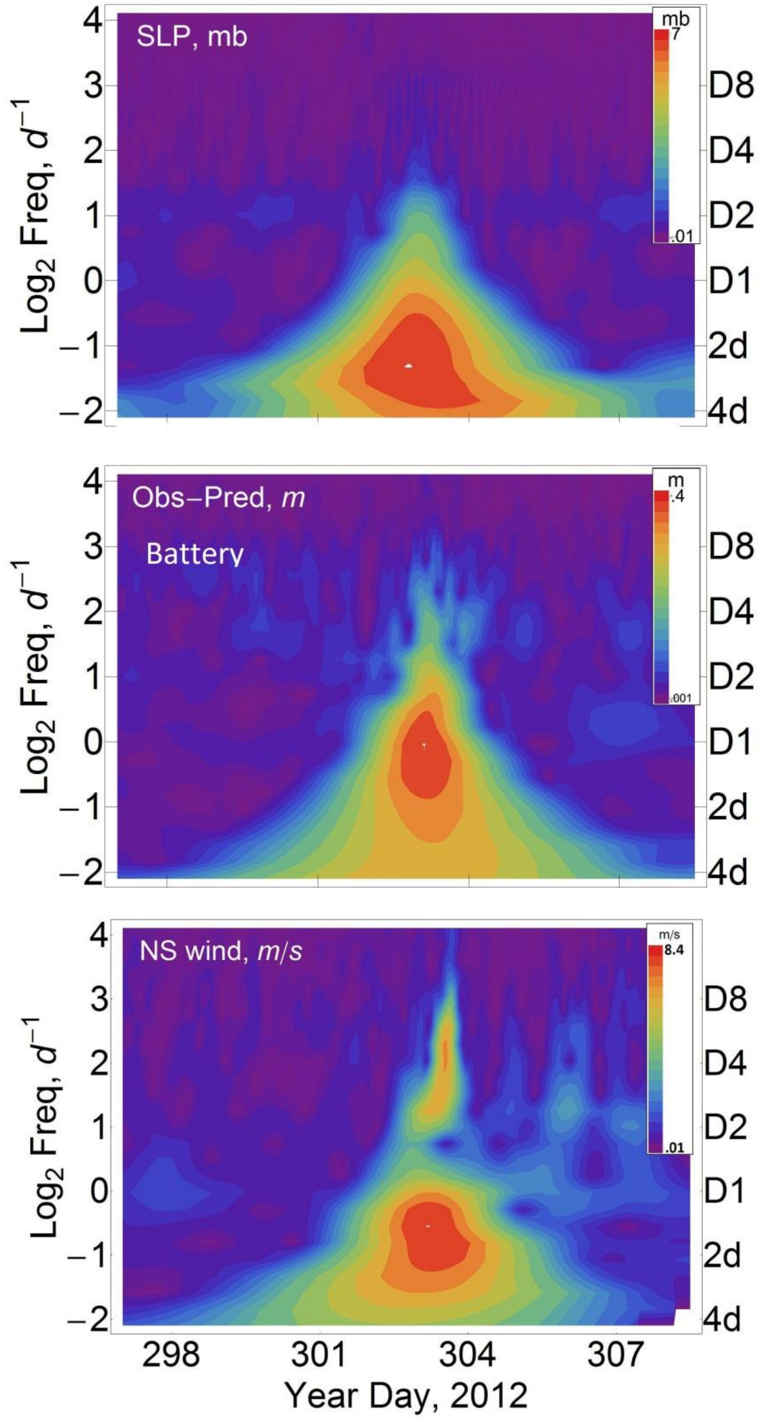
Compare surge at The Battery to forcing (wind & SLP) using CWT

(like trying to match fingerprints)

> There is not a close match of the surge with either the N-S wind or SLP
  - Frequencies don't match
  - Surge at The Battery outlasts the forcing

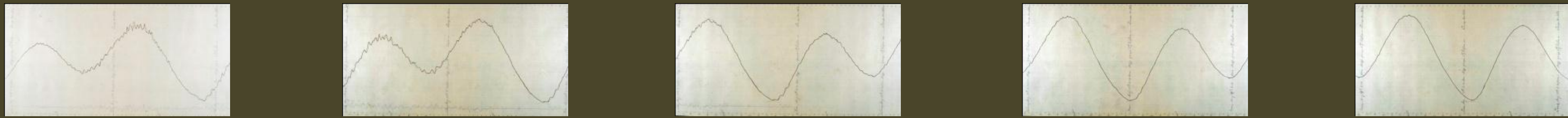
> N-S wind does have some high-frequency energy, because of the sharp reversal during the peak of the storm

>Conclusion: internal dynamics are important and non-linear

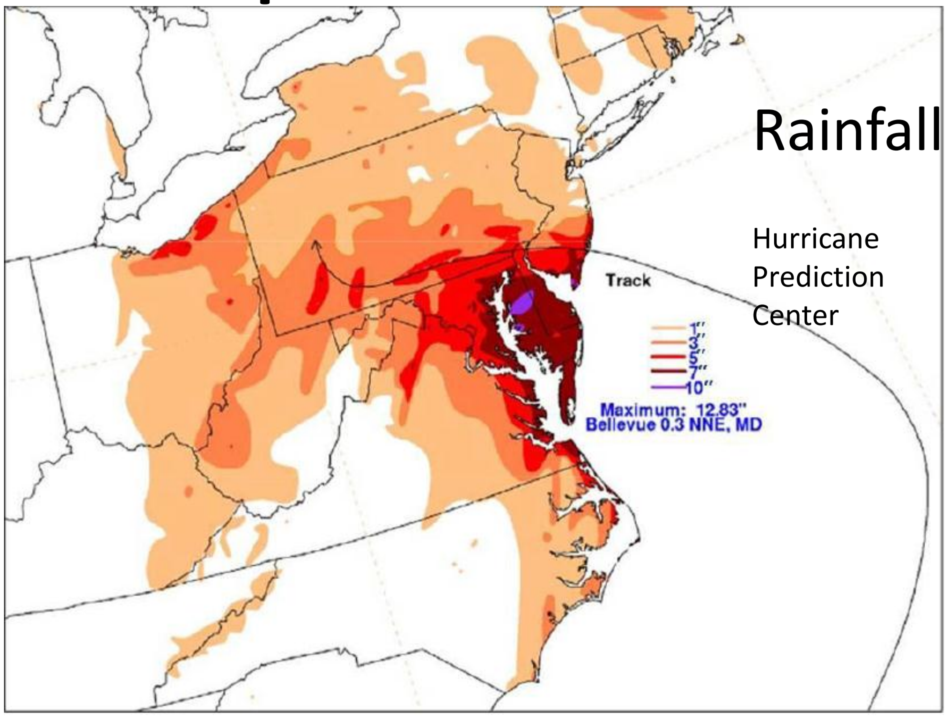


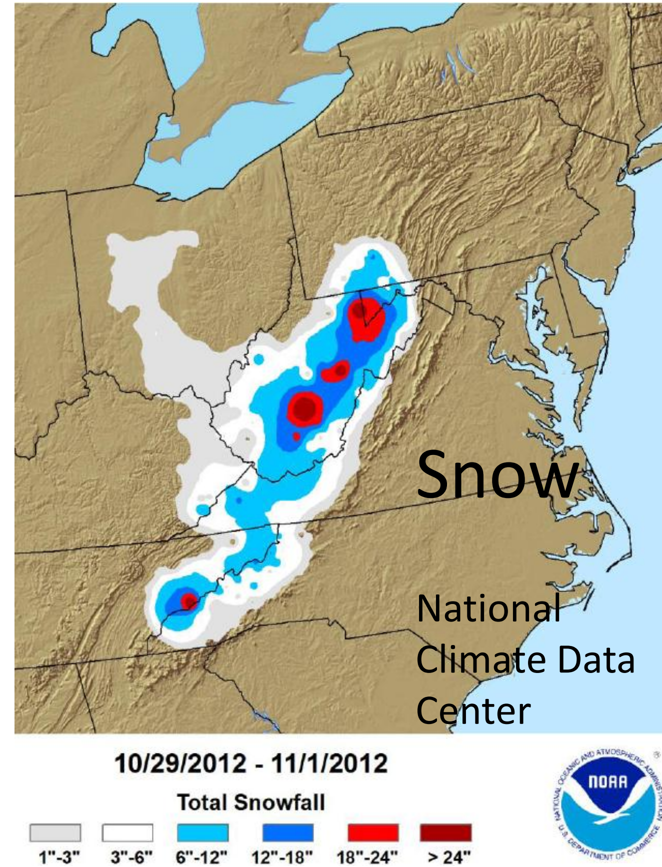
Conclusions –

- NY Harbor is topographically complex and responds in a complicated way to surges
- Water comes into NY Bay from both the NY Bight and Long Island Sound:
  - LIS is resonant at ~12.4hrs, the frequency of the M_2 tide
  - NY Harbor responds at lower and higher frequencies
- The East River was critical to inundation in Manhattan during Sandy
  - Not clear if this is always true
- The East River has been heavily altered, and this alteration may (or may not) be significant in the increasing storm tide risk found in the 1844-2013 data

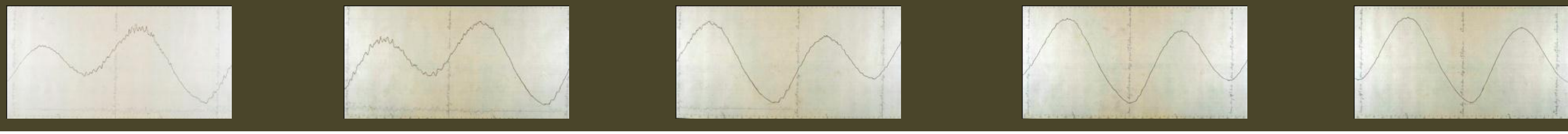


Precipitation –

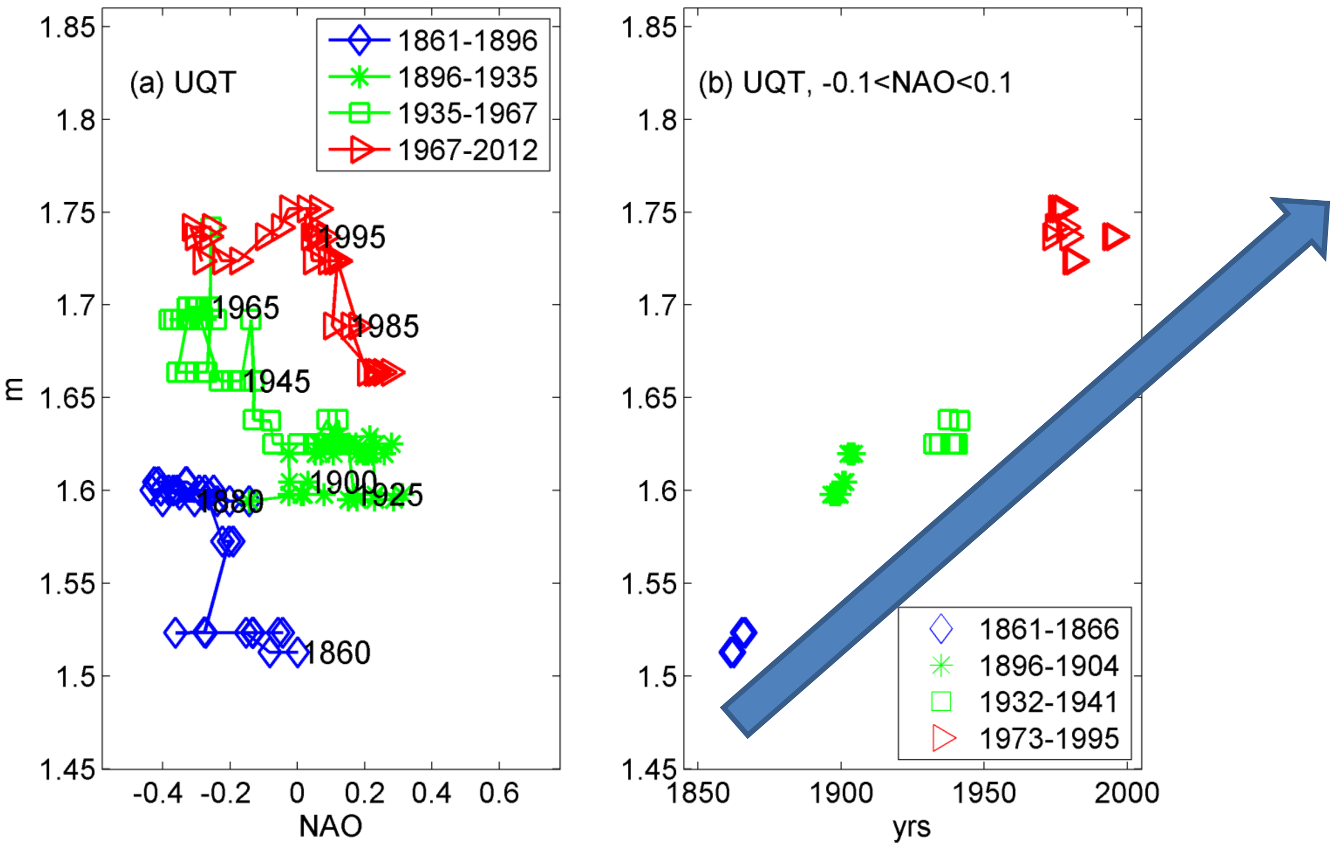




Heavy rainfall was <u>not</u> a NYH problem

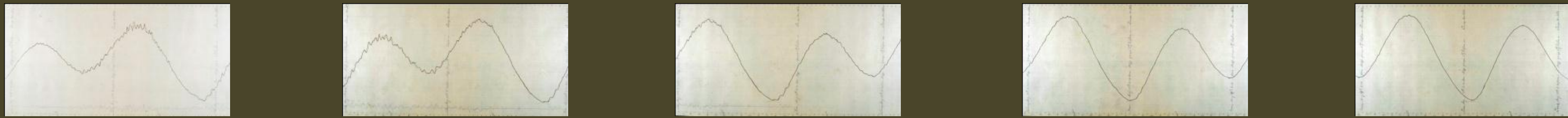


Below: An approximately linear relationship is found between NAO index and upper quartile threshold (UQT). Storm risk is ***largest*** for ***negative NAO***



For constant NAO index, a 20cm increase in the upper quartile (once in 4 year) storm tide level!

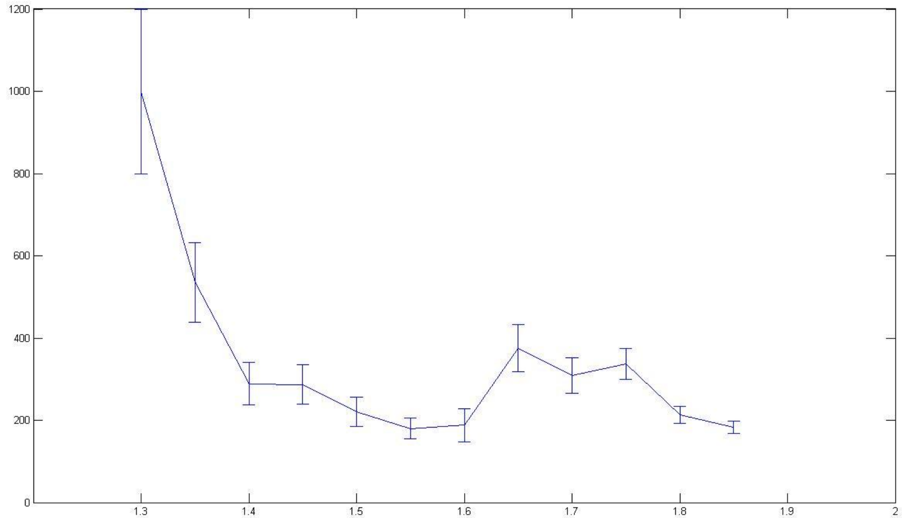
(Note this is not sea-level induced signal; sea level trend removed)



Preliminary Storm Tide Return Period Estimate (GPD analysis)

A bootstrapping technique is used to ‘infill’ unknown data between 1821 and 1843

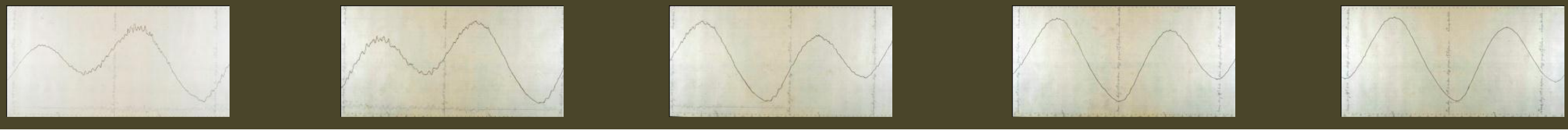
Return period



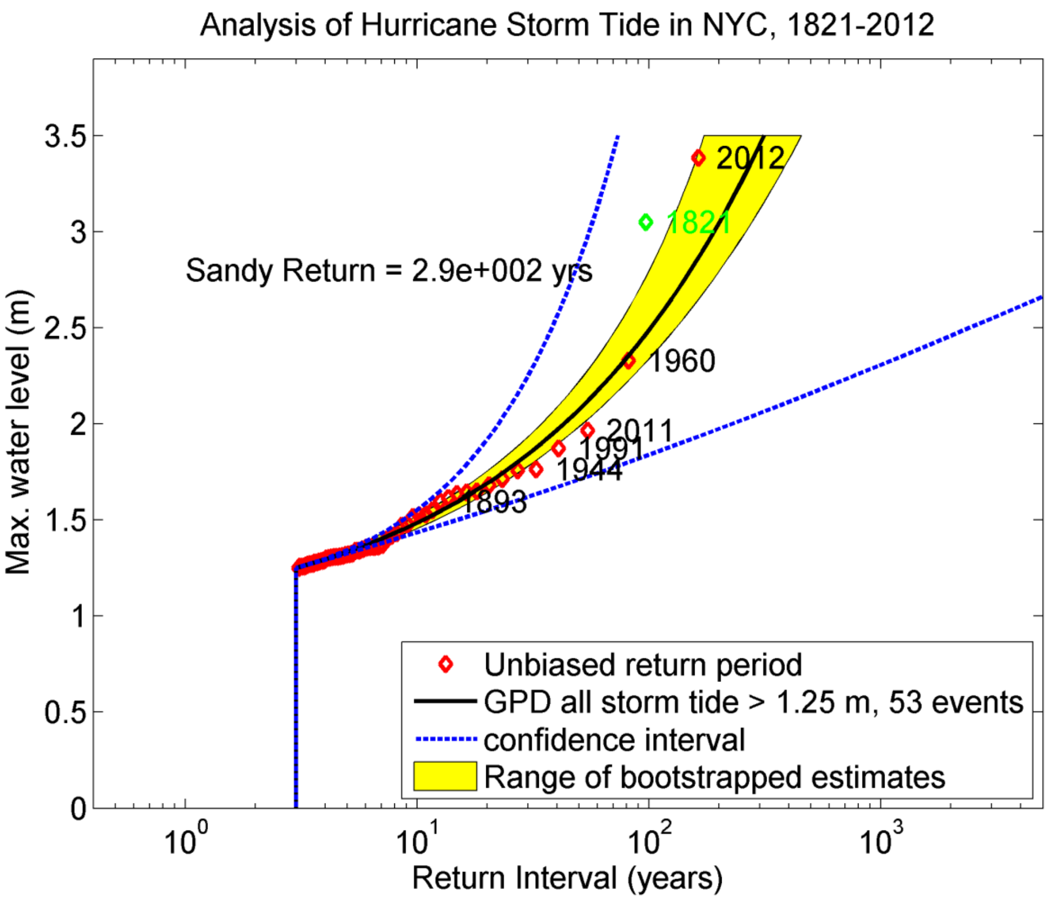
Threshold

Results converge above a threshold of about 1.4m

These results show the importance of including all known events in a statistical analysis.



Preliminary Storm Tide Return Period Estimate (GPD analysis)

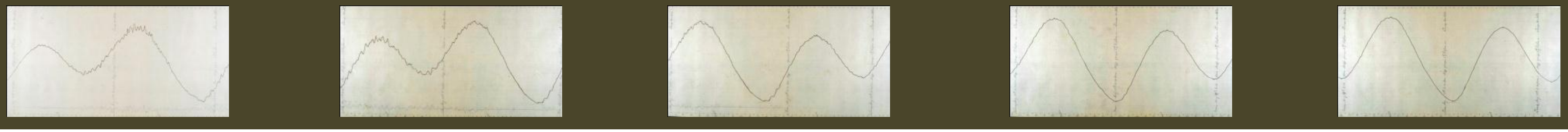


A bootstrapping technique is used to ‘infill’ unknown data between 1821 and 1843

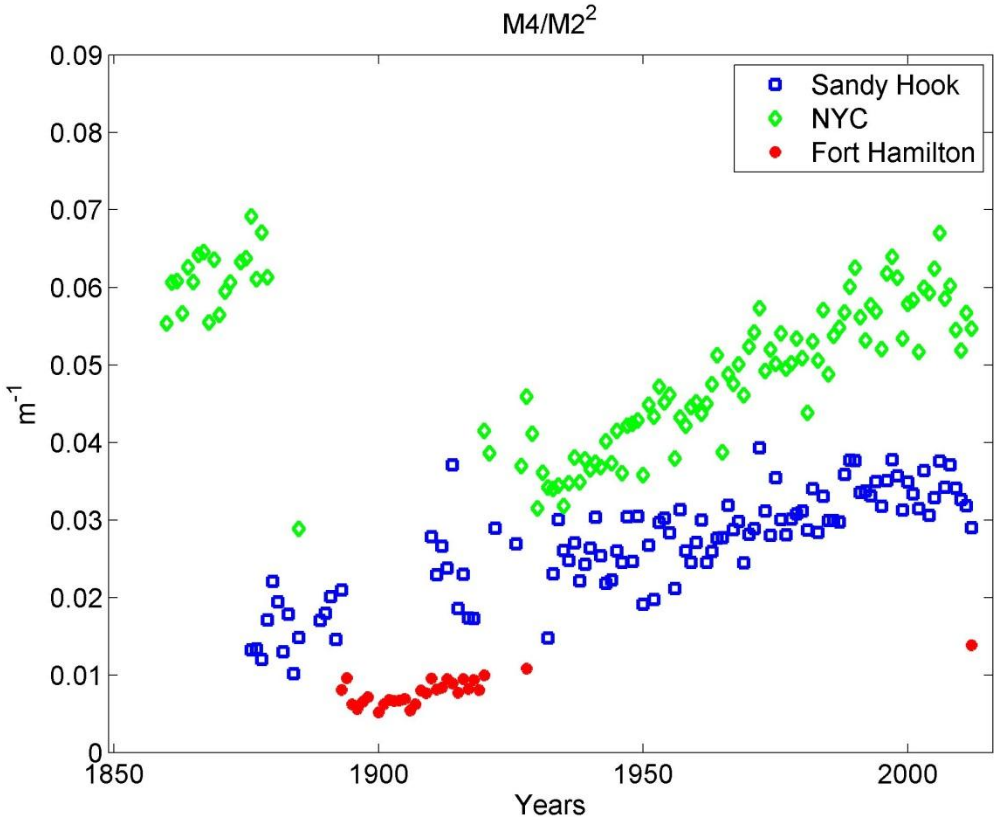
Storm Tide Return (Sandy level):

~300 years (range 200-400yrs depending on cutoff)

These results show the importance of including all known events in a statistical analysis.



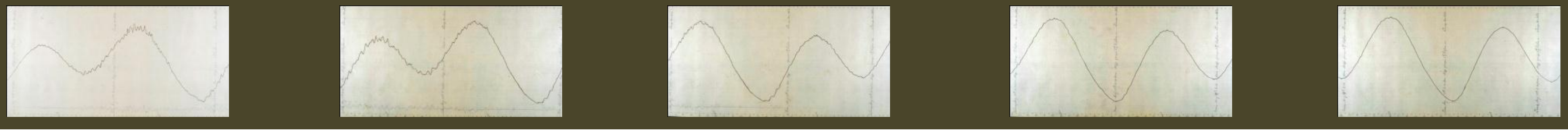
Remaining Question: Why is there a long term trend?



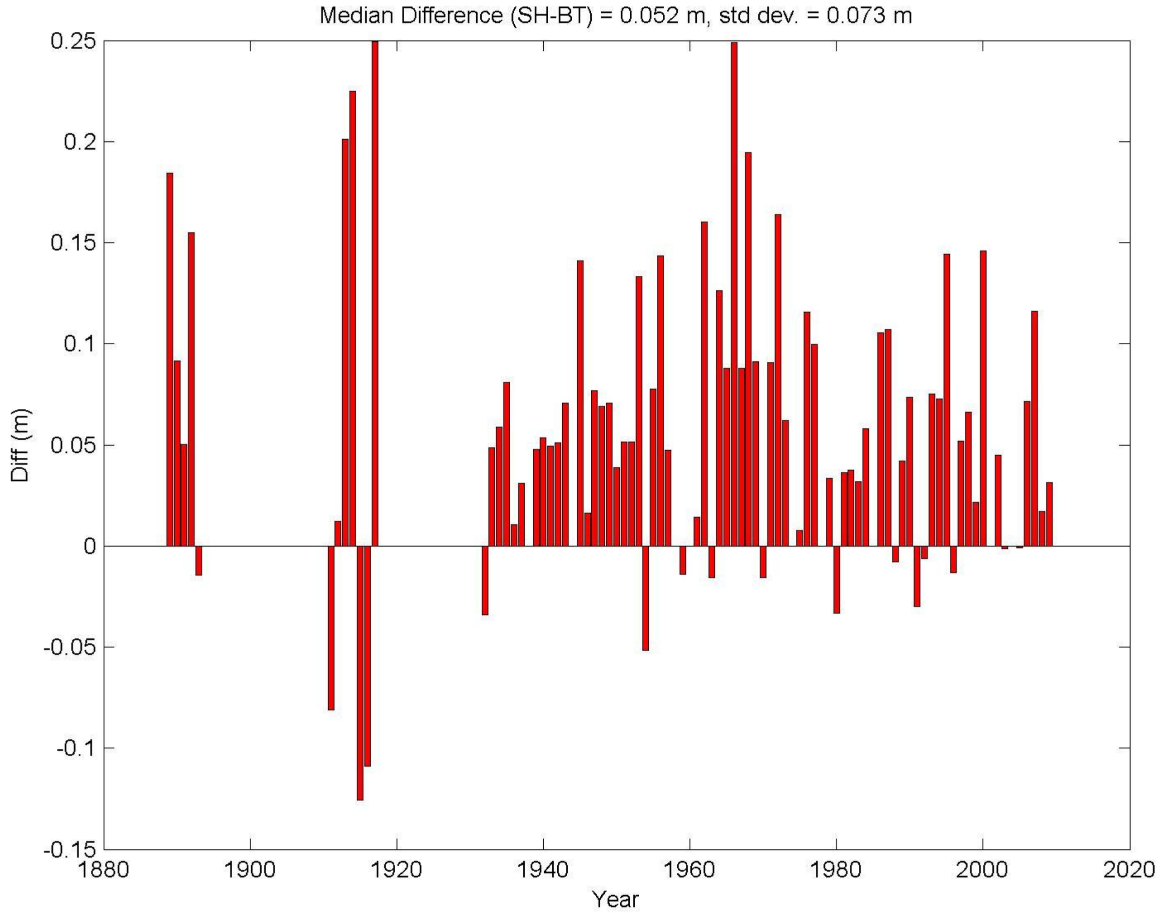
With our data, we can begin to investigate local changes.

The M2 tide and the M4 overtide (frictionally produced) have shifted over time in NYC.

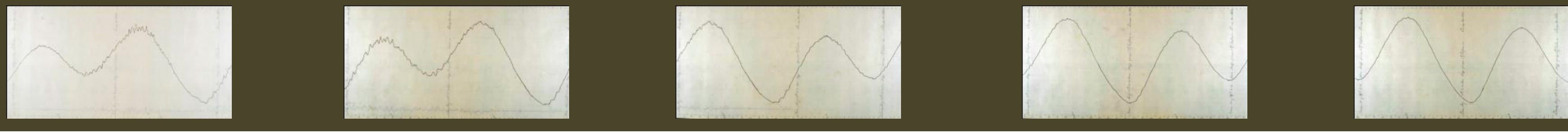
This is evidence of local perturbations in the estuary and shallow coastal region



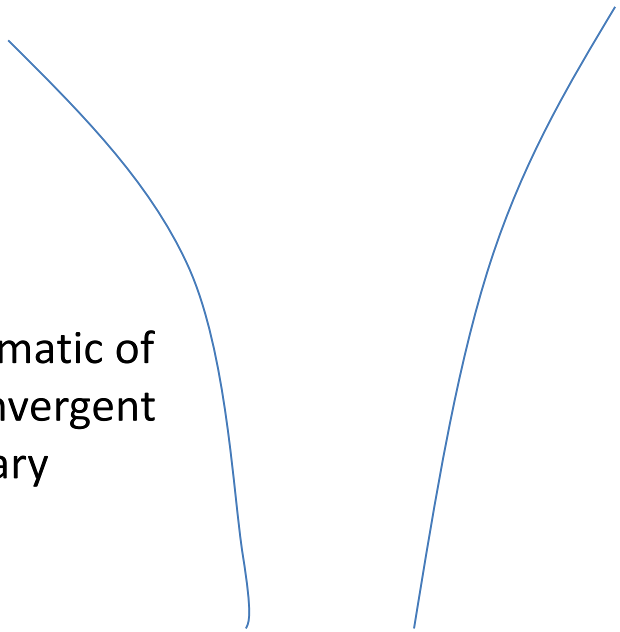
Has the spatial attenuation between Sandy Hook and the Battery changed?



Maybe; However, more coincident historical data needs to be found/considered to establish statistical significance



What might be happening? Friction and Depth Changes



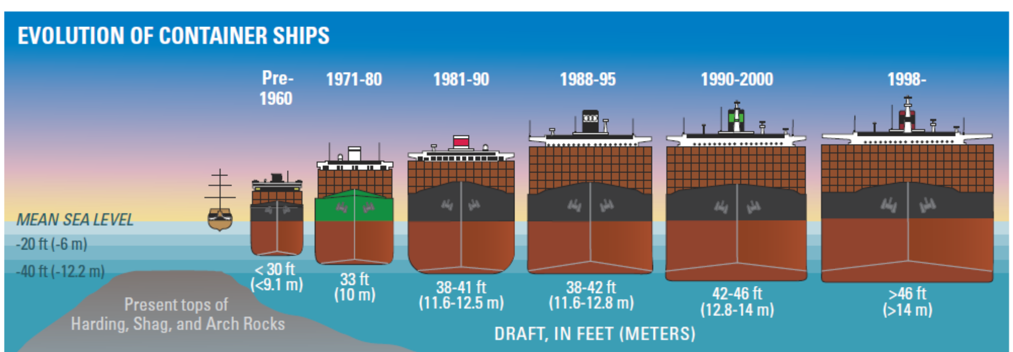
Schematic of a convergent estuary

Observation: Tides in an estuary are a balance between convergence (amplifies height) and friction (reduces height) (Friedrichs & Aubrey, 1994):

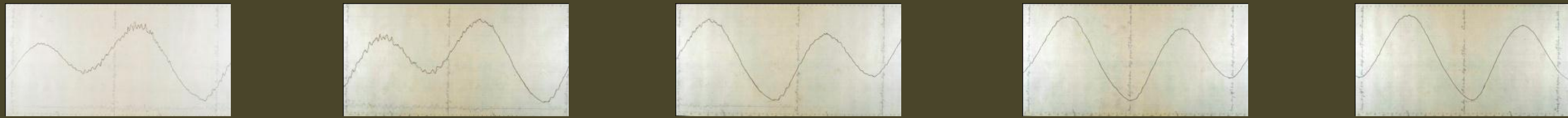
$$0 = -g\frac{\partial \zeta}{\partial x} - F .$$

$$F = \frac{8}{3\pi}\frac{c_d U}{\bar{h}} u = r u$$

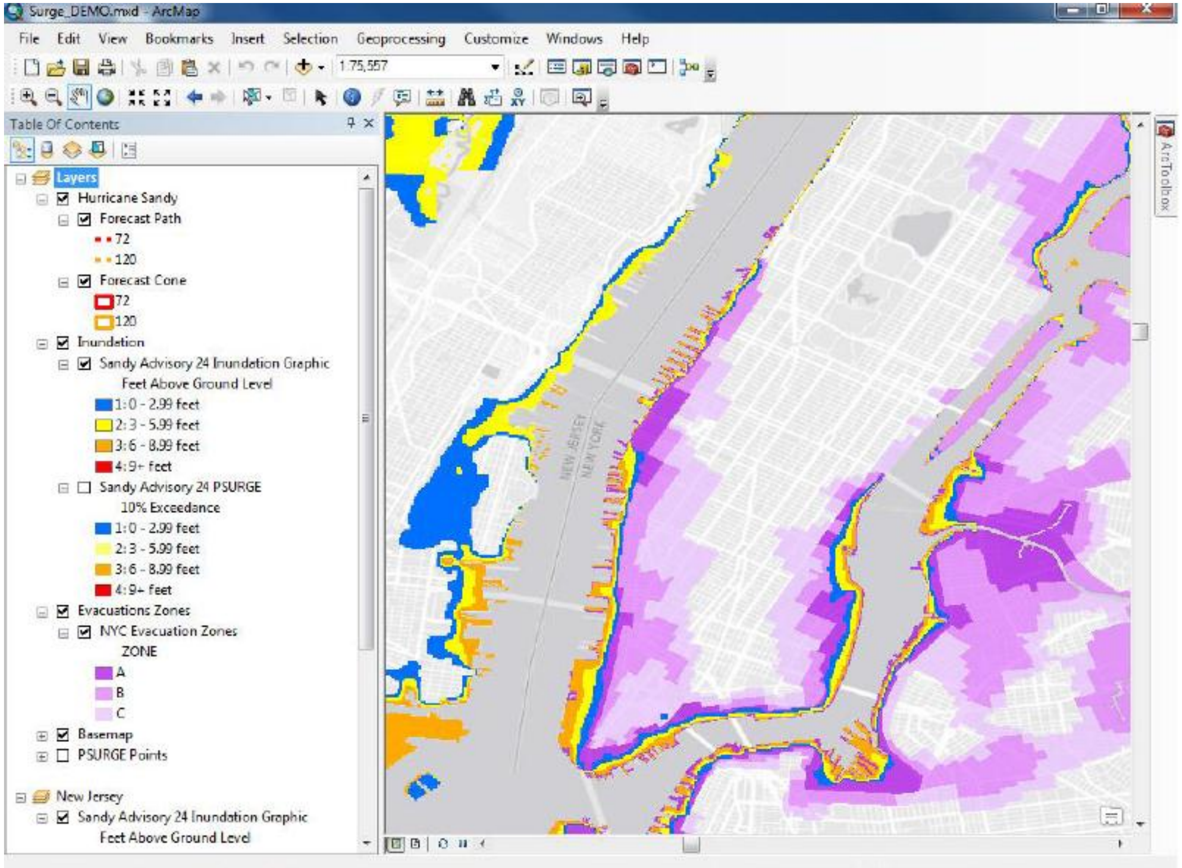
Hence: Reducing Friction and increasing channel depth tend to increase tidal amplitudes



Conclusion: Modern tidal characteristics, storm surge, and storm-tide interaction have changed since 1800s due to altered bathymetry.

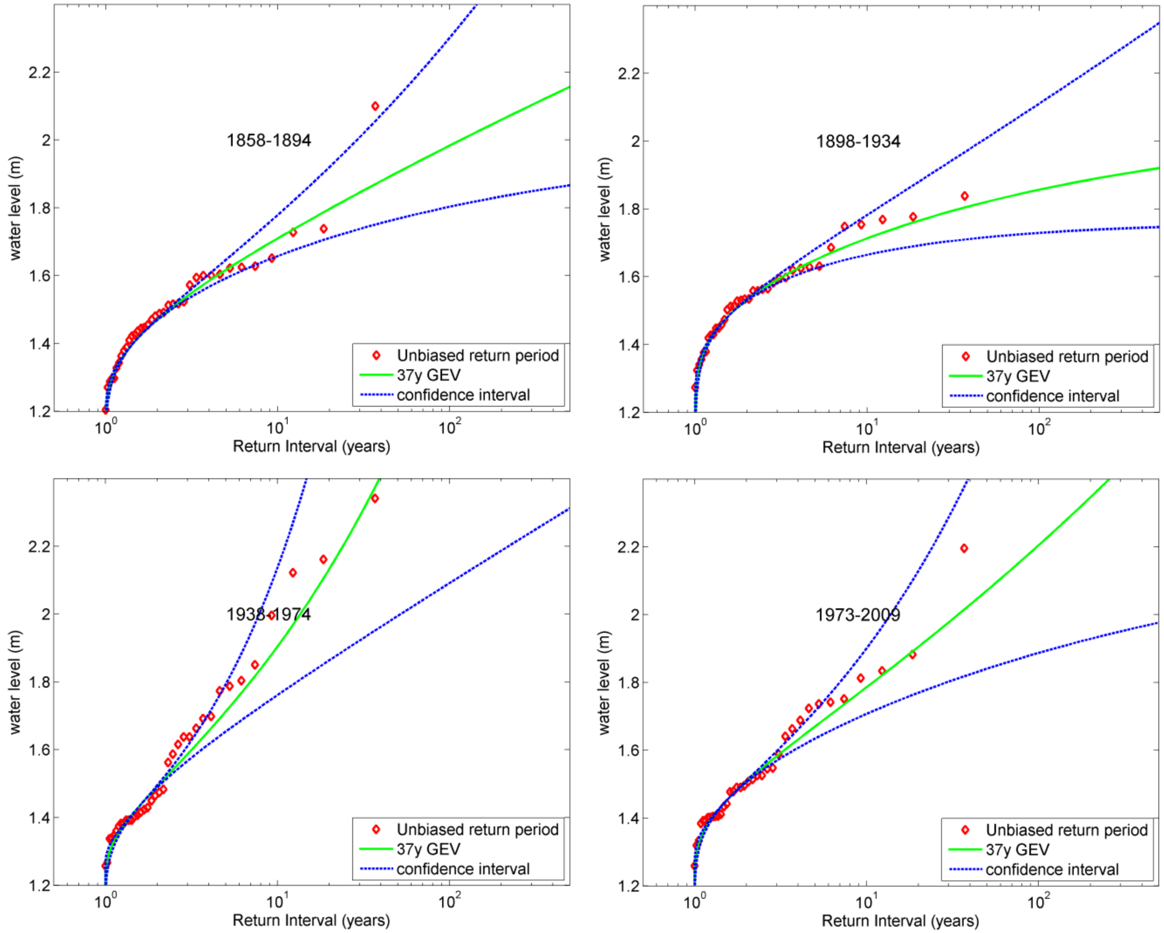


NYC Evacuation Zones (Example) –

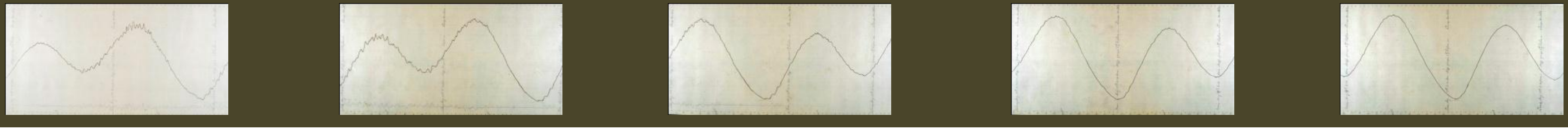


Detail of extensive evacuation zones in NYC and New Jersey
National Hurricane Center

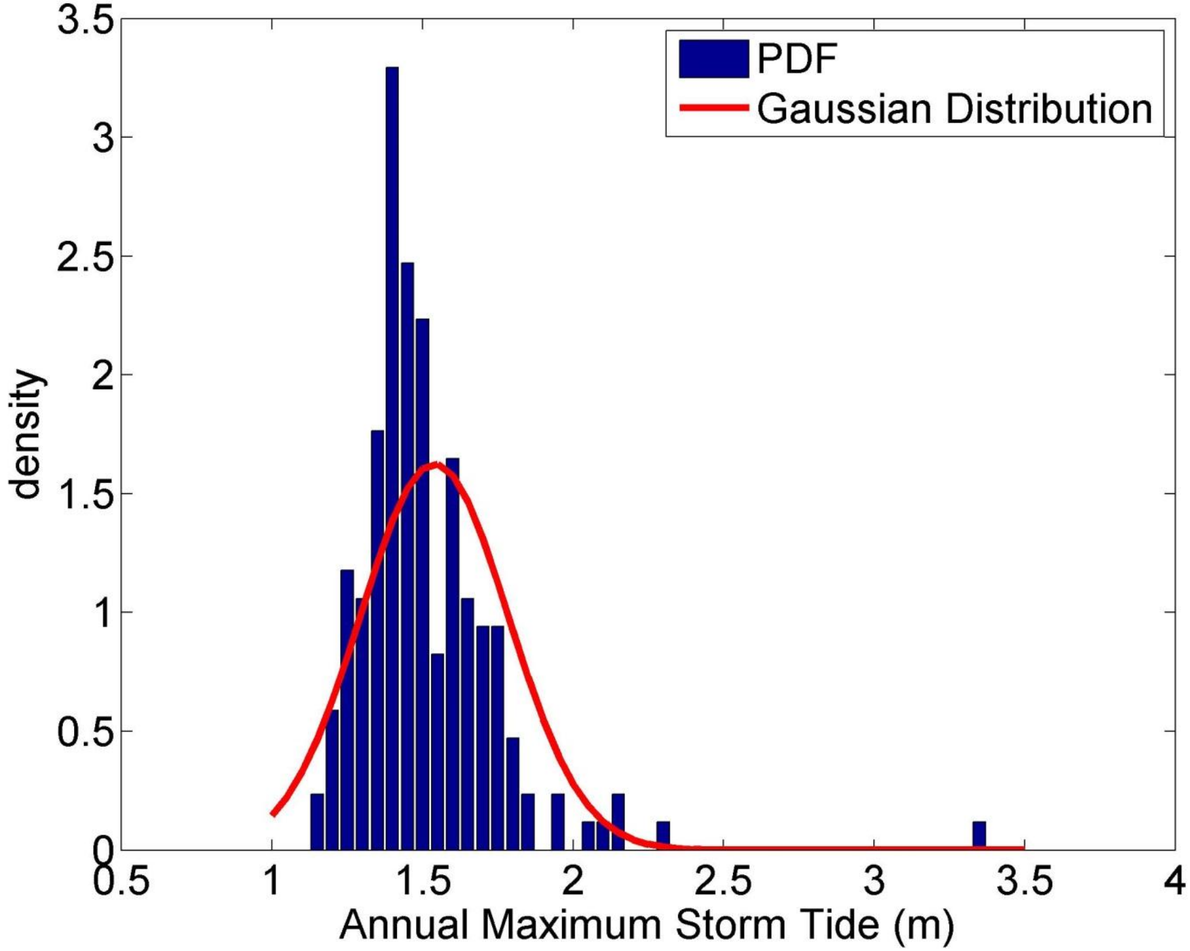
GEV Analysis



A GEV analysis on 37 year blocks of sequentially incremented data is performed. Risk is non-stationary



The dilemma of modeling the tail of the AMST— GEV Analysis



Data—1844-2013

AMST = Annual Maximum Storm Tide