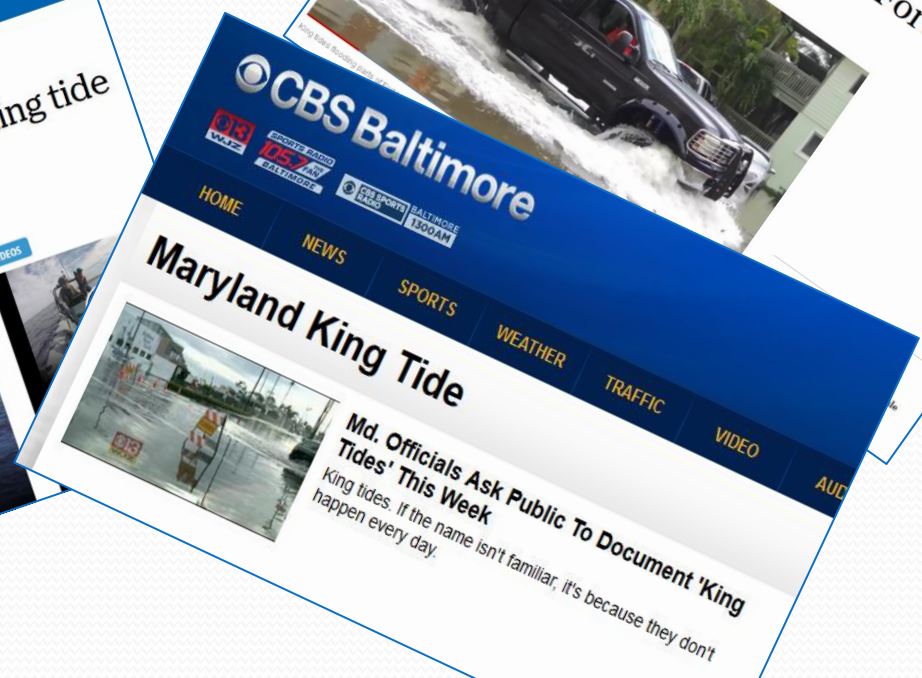
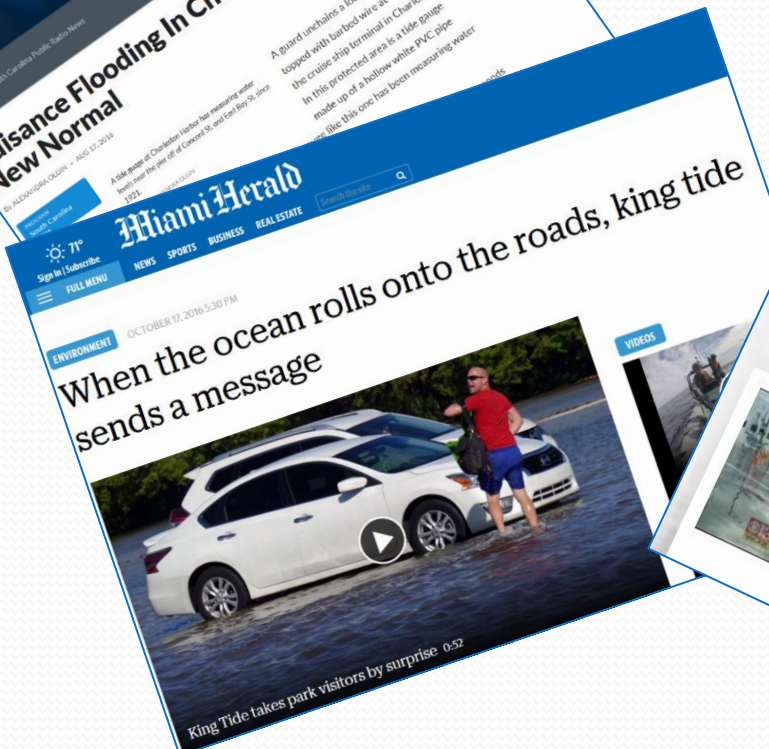
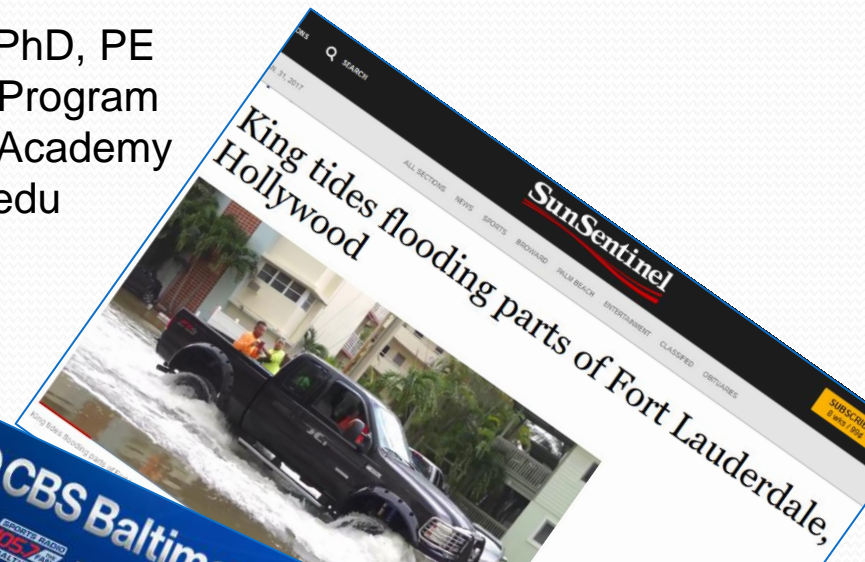


# Game of Inches: Nuisance Flooding and the King Tide Phenomenon

Prof. Dave Kriebel, PhD, PE  
Ocean Engineering Program  
United States Naval Academy  
kriebel@usna.edu



**Nuisance flooding** - flooding which causes public inconveniences such as frequent road closures, overwhelmed storm drains and compromised infrastructure (NOAA)

**King tide** - a colloquial term for an especially high tide, such as a perigean spring tide. "King tide" is not a scientific term, nor is it used in a scientific context. (Wikipedia)



## King Tides: What Explains High Water Threatening Global Coasts?

Periodic high tides are brought on by special alignment of heavenly bodies.

By **Marcus Woo**, for National Geographic

PUBLISHED JANUARY 30, 2014

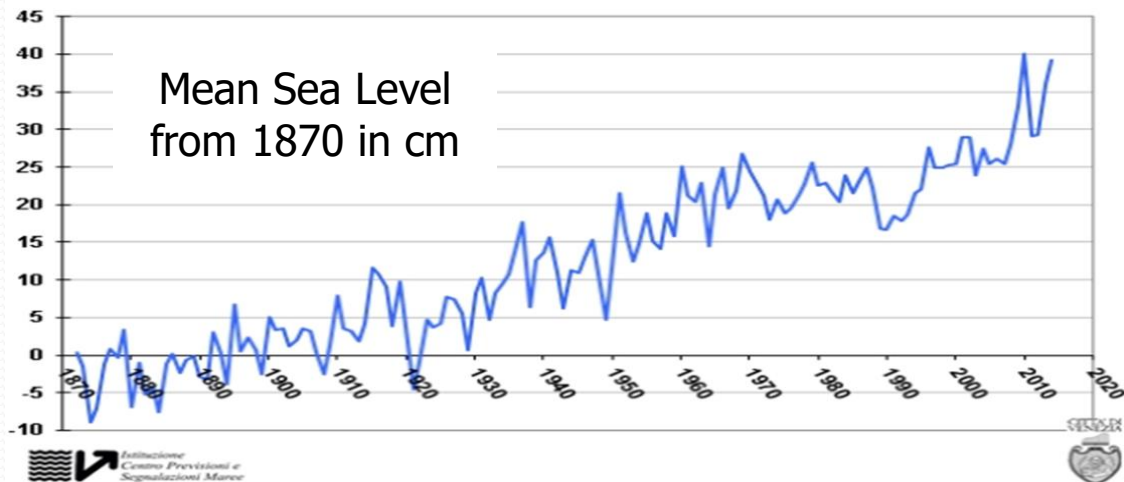
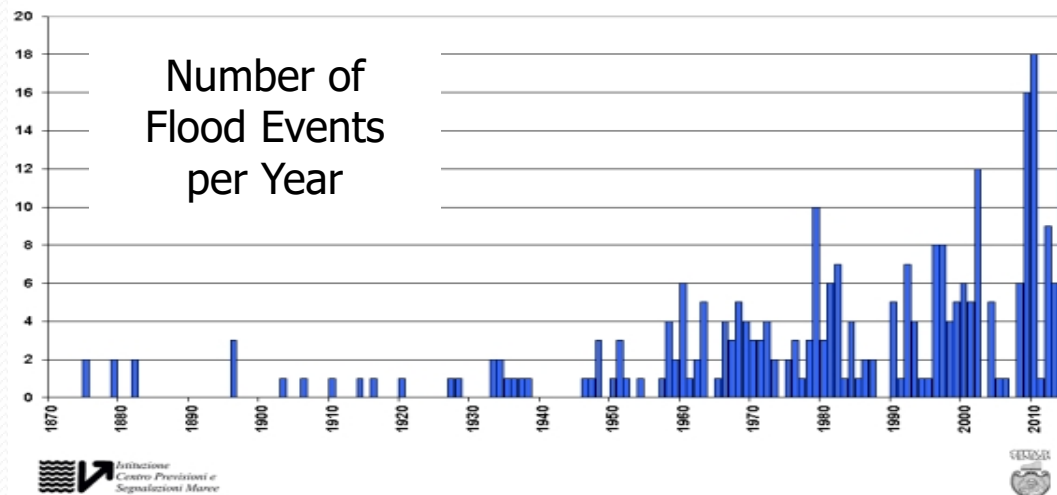


A king tide washes onto Newport Beach, California, on January 10, 2013.

PHOTOGRAPH BY MARK RIGHTMIRE, THE ORANGE COUNTY REGISTER/AP

# Venice Illustrates the Problem

- Venice, Italy “Acqua Alta” events flooding city center at an increasing rate
- Events increasing with increasing mean sea level
- Flood events caused by minor storm surge superimposed on high tides





Water at 103 cm

© SGP / FameFlynet.uk.com



Andrea Pattaro/AFP/Getty Images



<http://www.telegraph.co.uk>



<http://www.telegraph.co.uk>

## South Florida Illustrates the Problem



Las Olas Isles, Fort Lauderdale, Oct. 17, 2016.  
(Joe Cavaretta/Orlando Sentinel via AP)



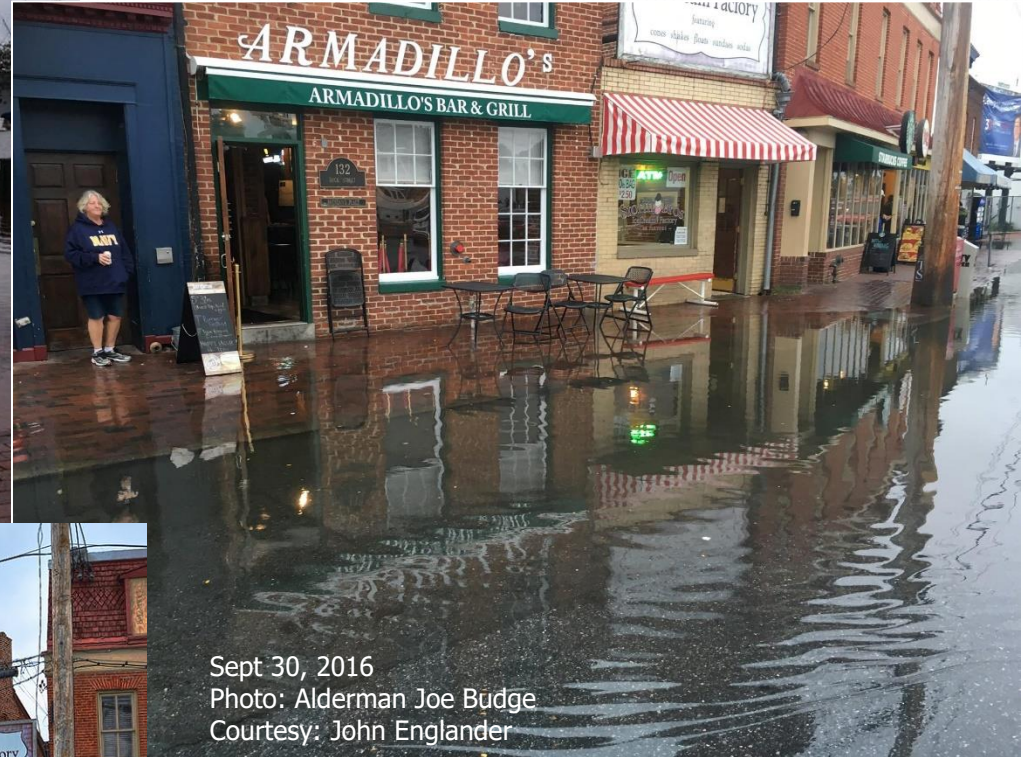
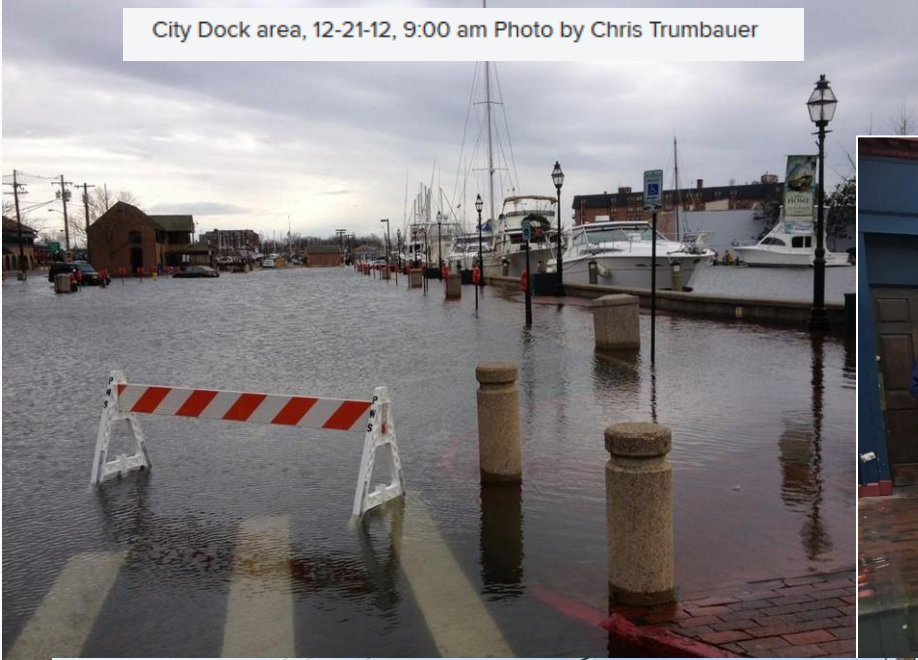
Flooded streets of Miami Beach, Collins Ave and 30th Street,  
during a King Tide on Sept. 28, 2015. (Miami Herald)



A flooded street in Miami Beach during  
the high tide on Sept. 29, 2015. (NOAA)

# Annapolis Illustrates the Problem

City Dock area, 12-21-12, 9:00 am Photo by Chris Trumbauer



Sept 30, 2016  
Photo: Alderman Joe Budge  
Courtesy: John Englander



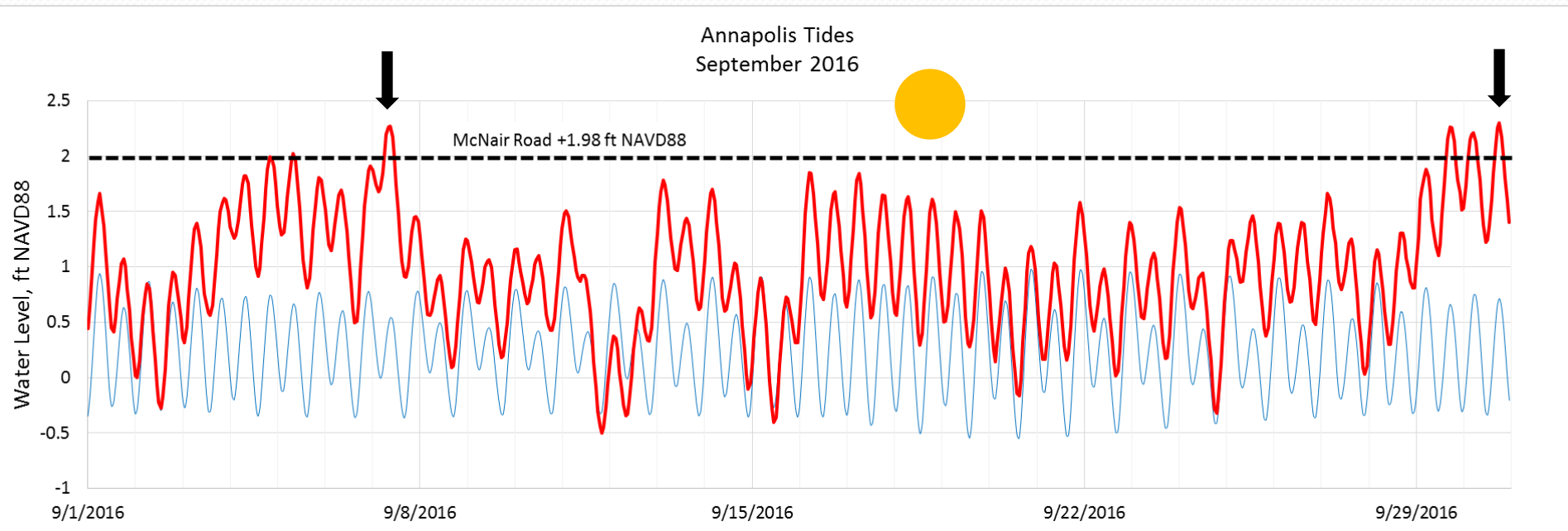
Dec 2012  
The Weather Channel

# The Naval Academy Illustrates the Problem

Nuisance Flooding  
US Naval Academy  
Sept 7, 2016  
Photos: D. Kriebel



# Annapolis Tide Data September 2016 Flooding of McNair Road, US Naval Academy

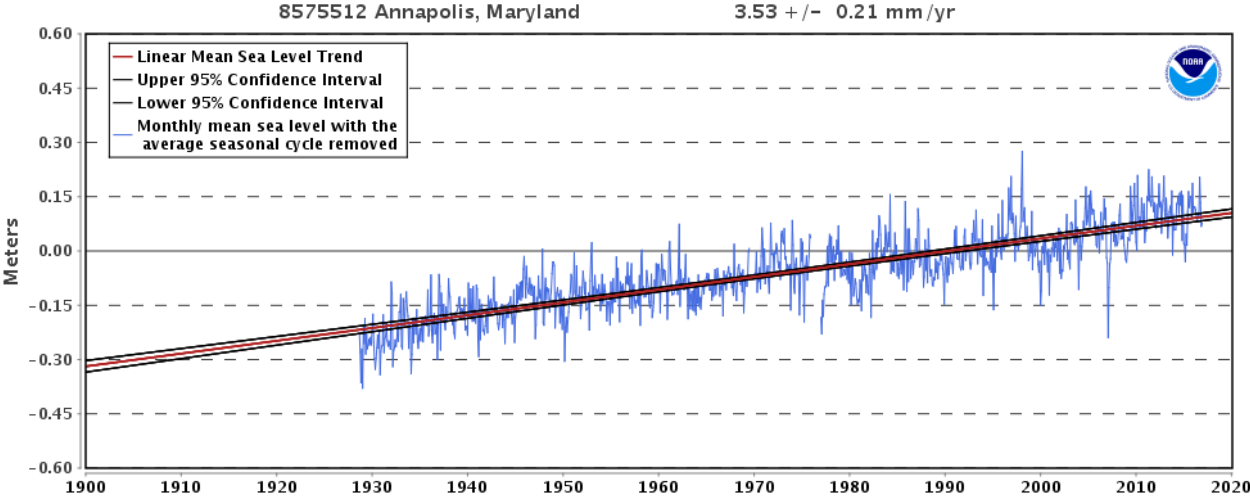


## What Are Causes?

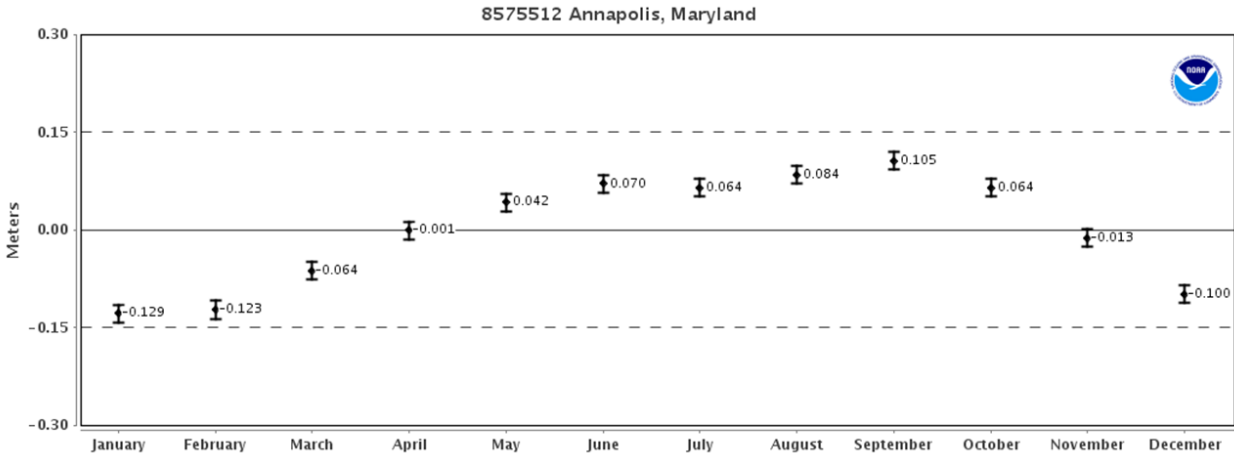
- Not strongly correlated to Perigean spring tide
- Strongly influenced by long term and seasonal mean sea level
- Strongly influenced by minor meteorological events



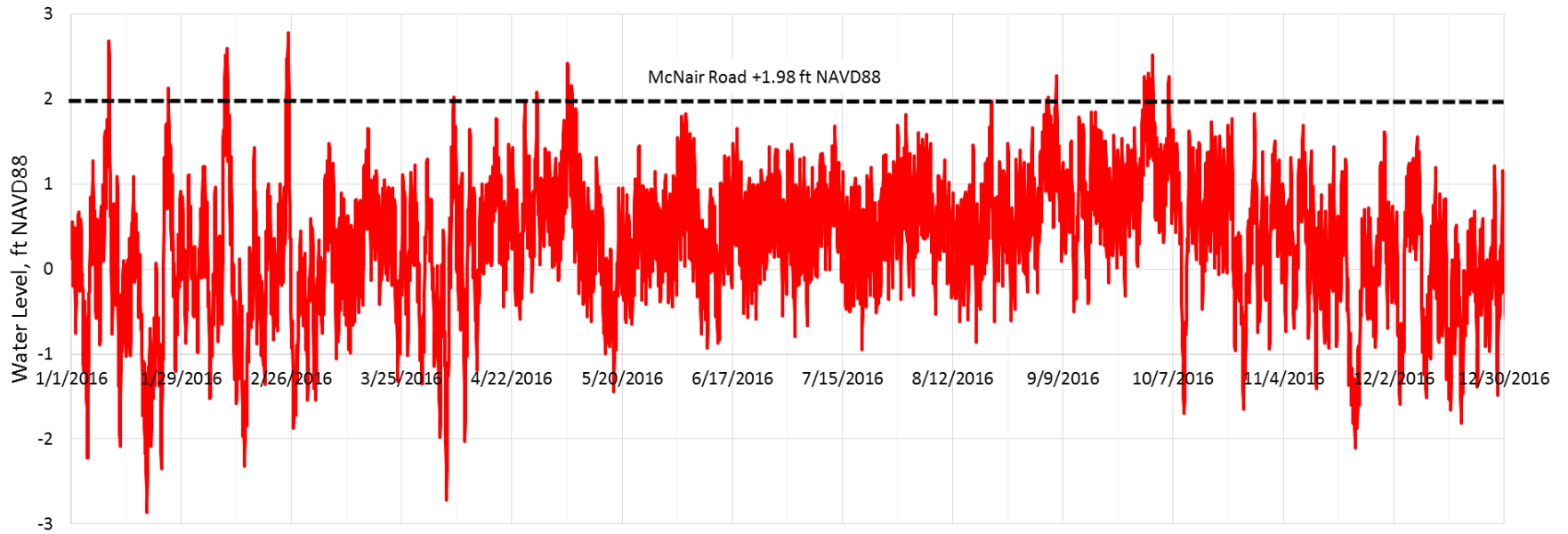
# Relative Sea Level Rise since 1992 (not accounted for in tide prediction)



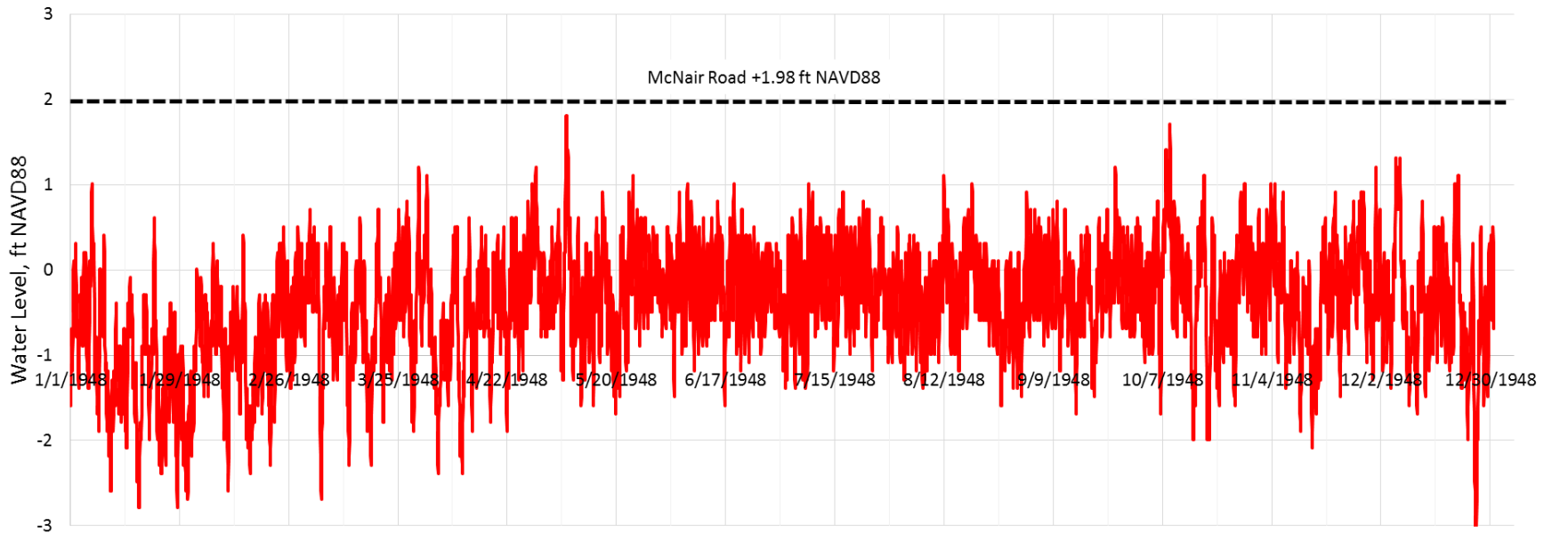
# Seasonal increase in mean sea level (not accounted for in tide prediction)



Annapolis Tides 2016



Annapolis Tides 1948

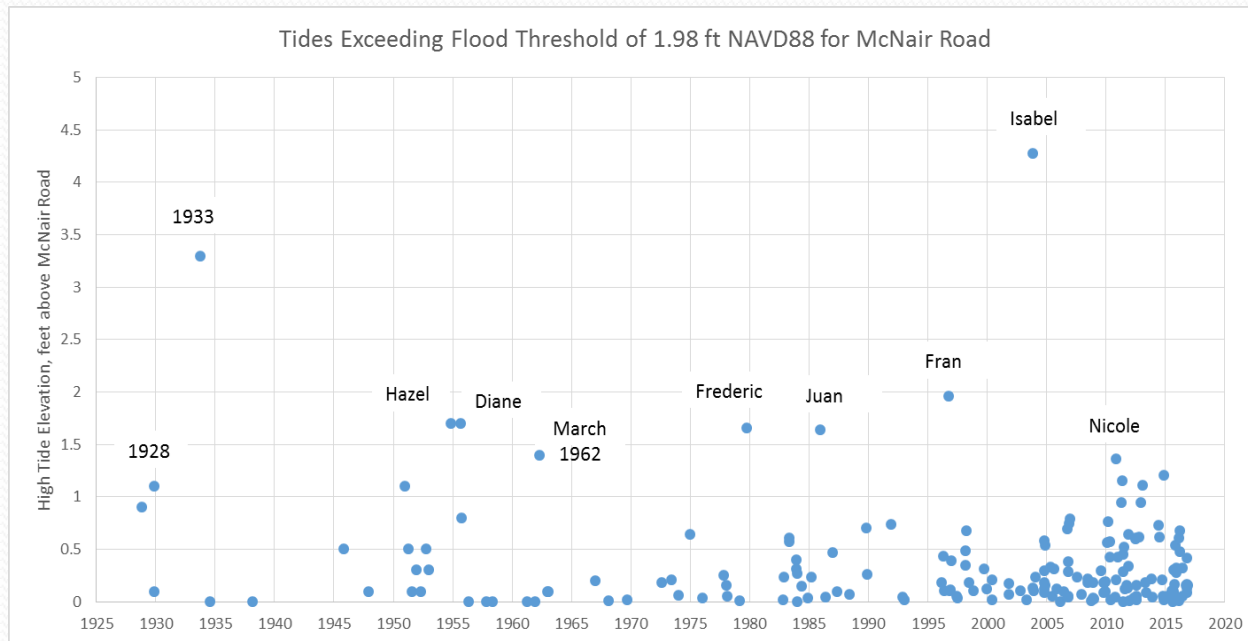
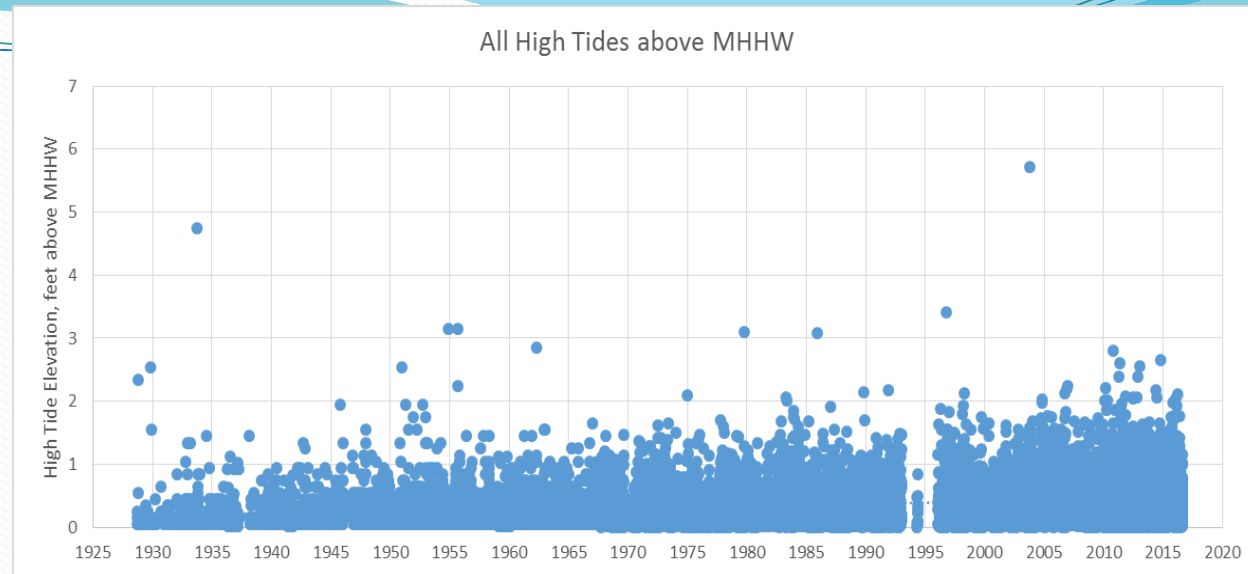


# Annapolis, MD

High Tide Peaks above thresholds:

- (1) MHHW=0.66 ft NAVD
- (2) McNair Rd=1.98 ft NAVD

Note:  
Data not detrended so  
sea level rise trend  
included



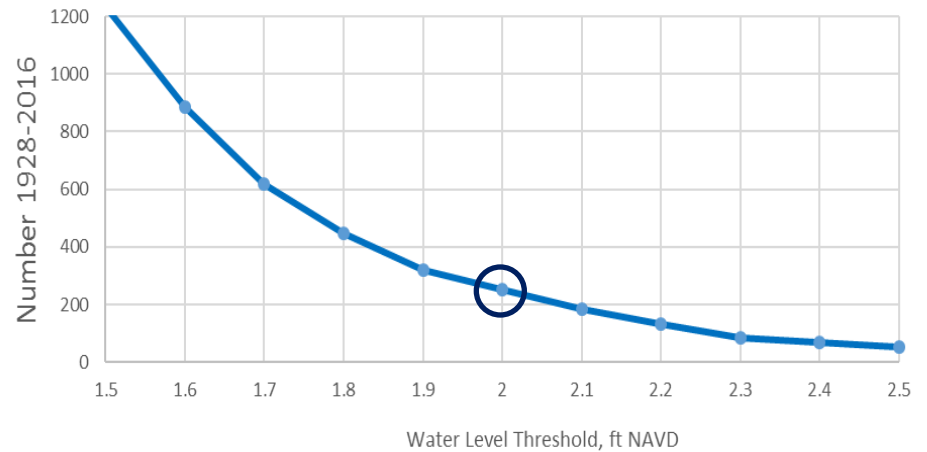
# Annapolis, MD

## Number of High Tide Flood Events as a Function of Threshold

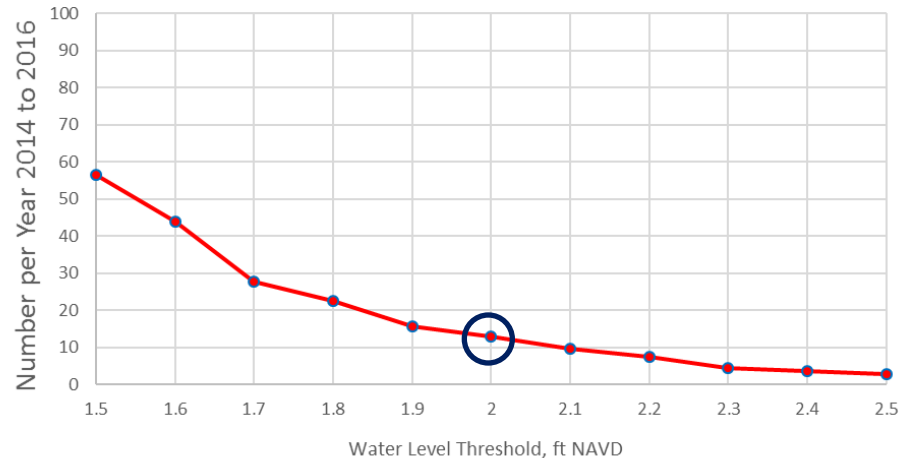
### Some Problematic Threshold elevations in Annapolis:

- (1) USNA McNair Rd 1.89 ft
- (2) Dock St Storm Drain 1.90 ft
- (3) City Dock Storm Drain 1.71 ft
- (4) Compromise St Storm Drain 1.67 ft
- (5) Newman Street Storm Drain 1.44 ft
- (6) Public Landing Storm Drain 2.09 ft

Total Number High Tides Above Threshold for Annapolis  
1928 to 2016



Average Annual High Tides Above Threshold for Annapolis  
2014-2016

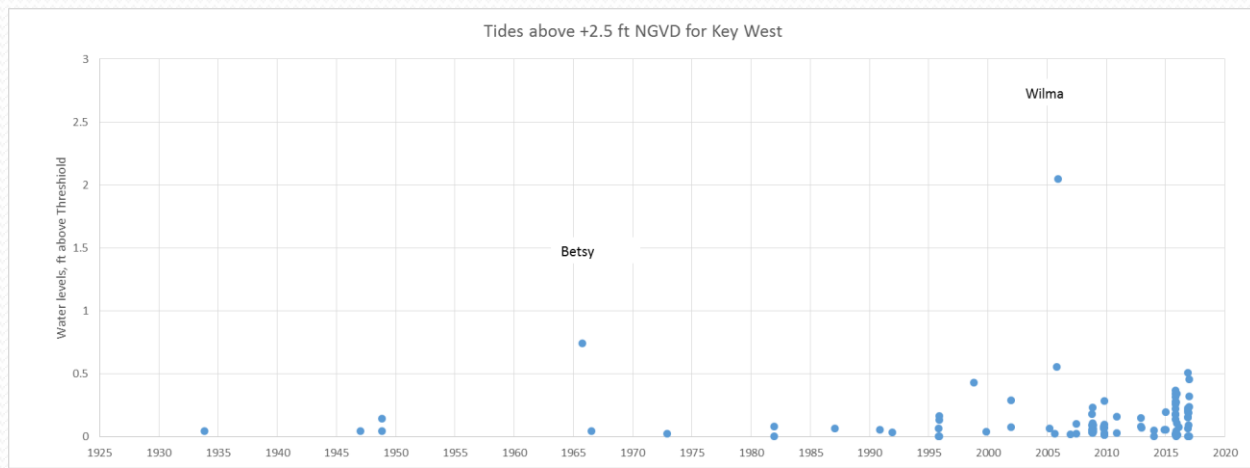
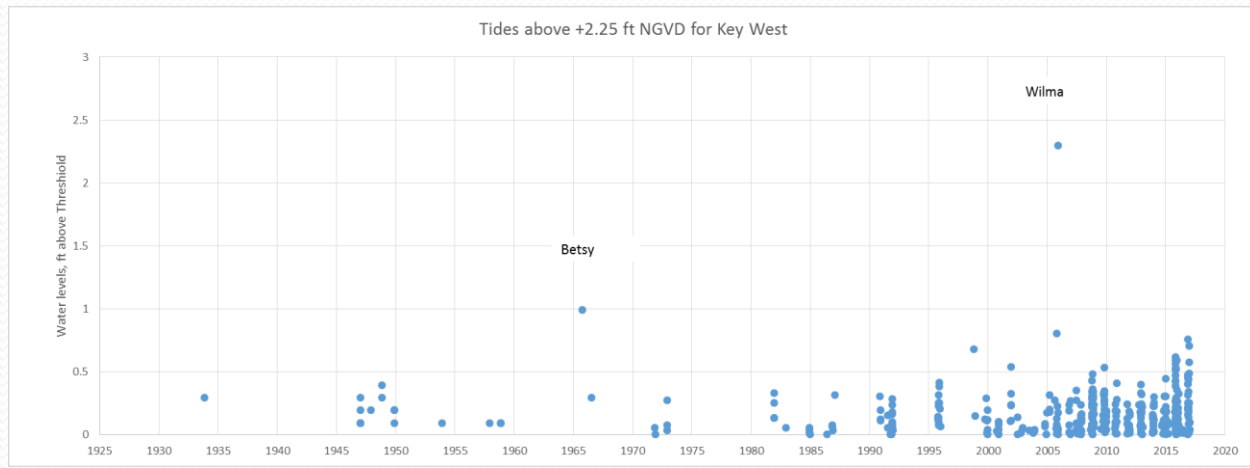
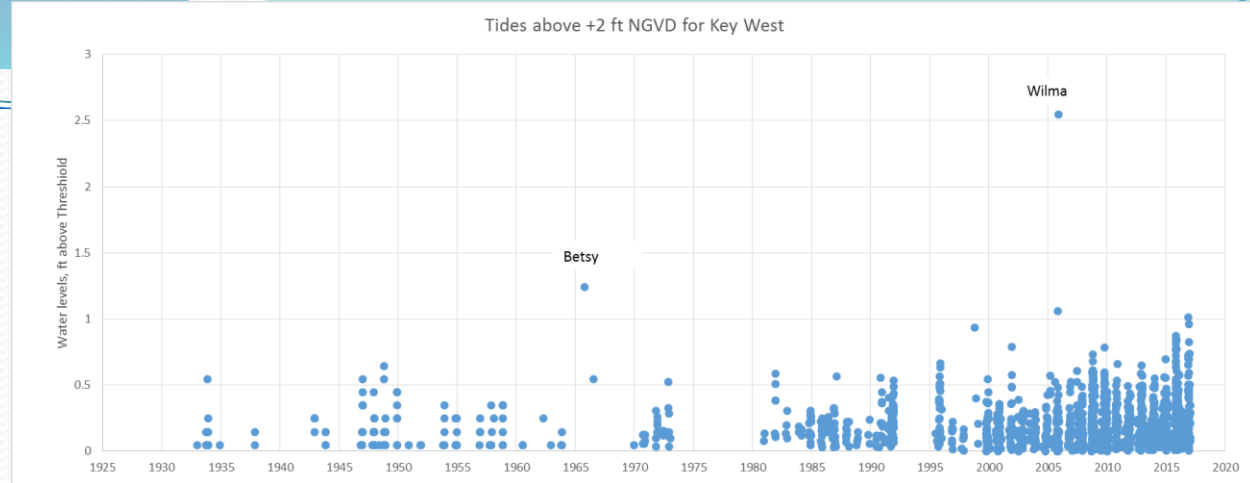




# Key West, FL

High Tide Peaks above thresholds:

- (1) +2.00 ft NGVD
- (2) +2.25 ft NGVD
- (3) +2.50 ft NGVD

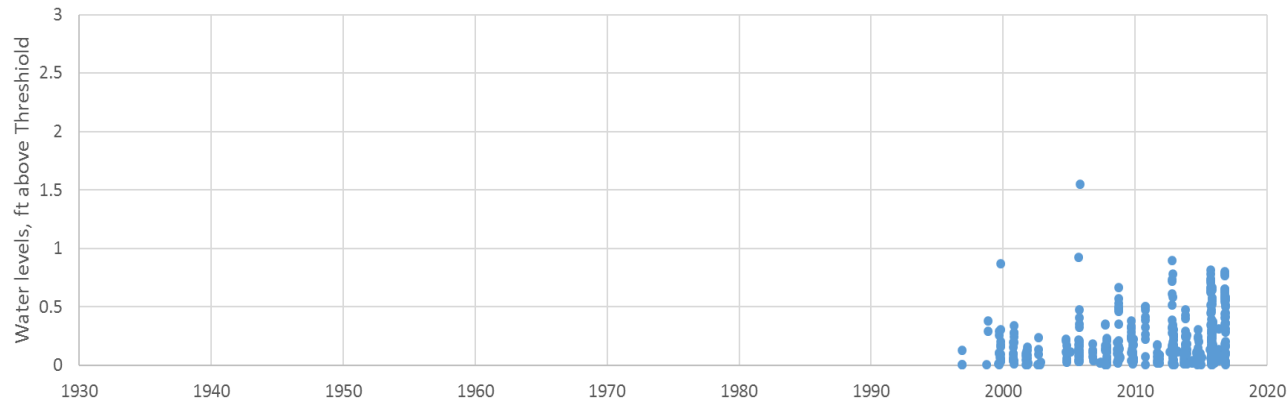


# Virginia Key, FL

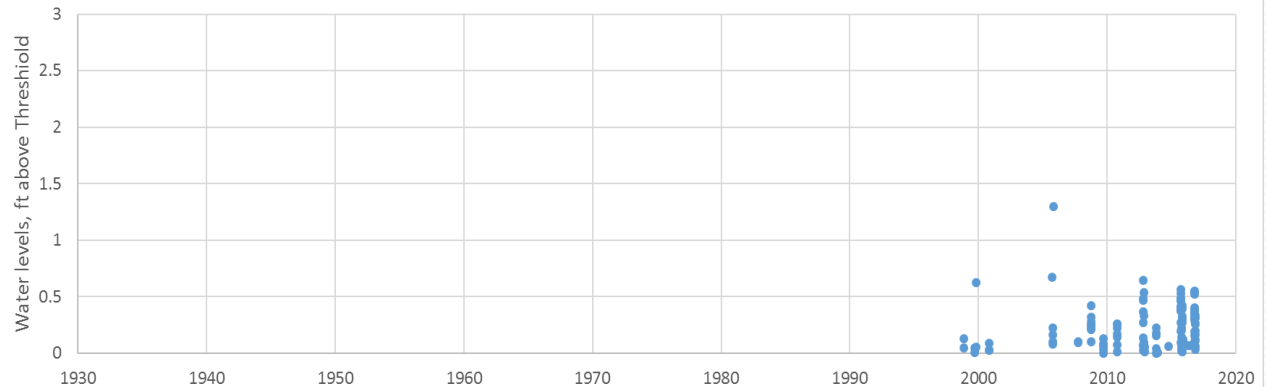
High Tide Peaks above thresholds:

- (1) +1.25 ft NAVD
- (2) +1.50 ft NAVD
- (3) +1.75 ft NAVD

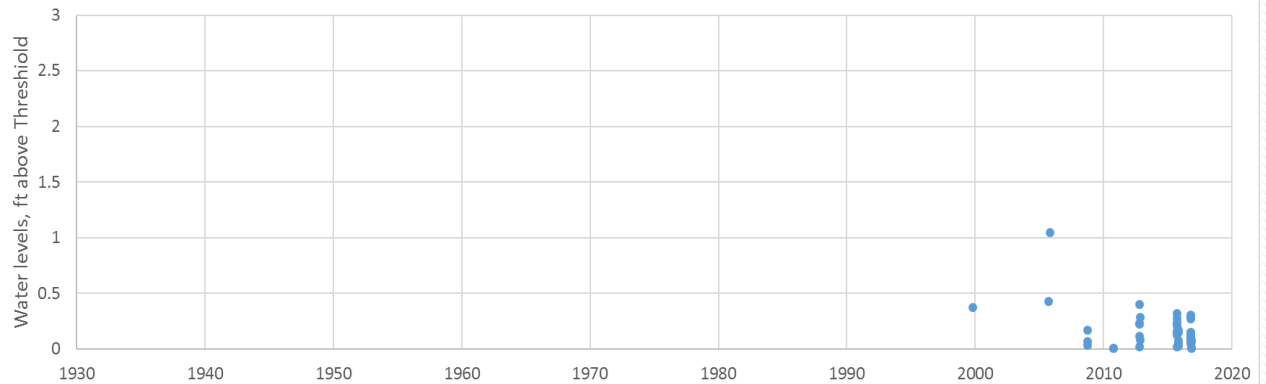
Tides above +1.25 ft NAVD for Virginia Key

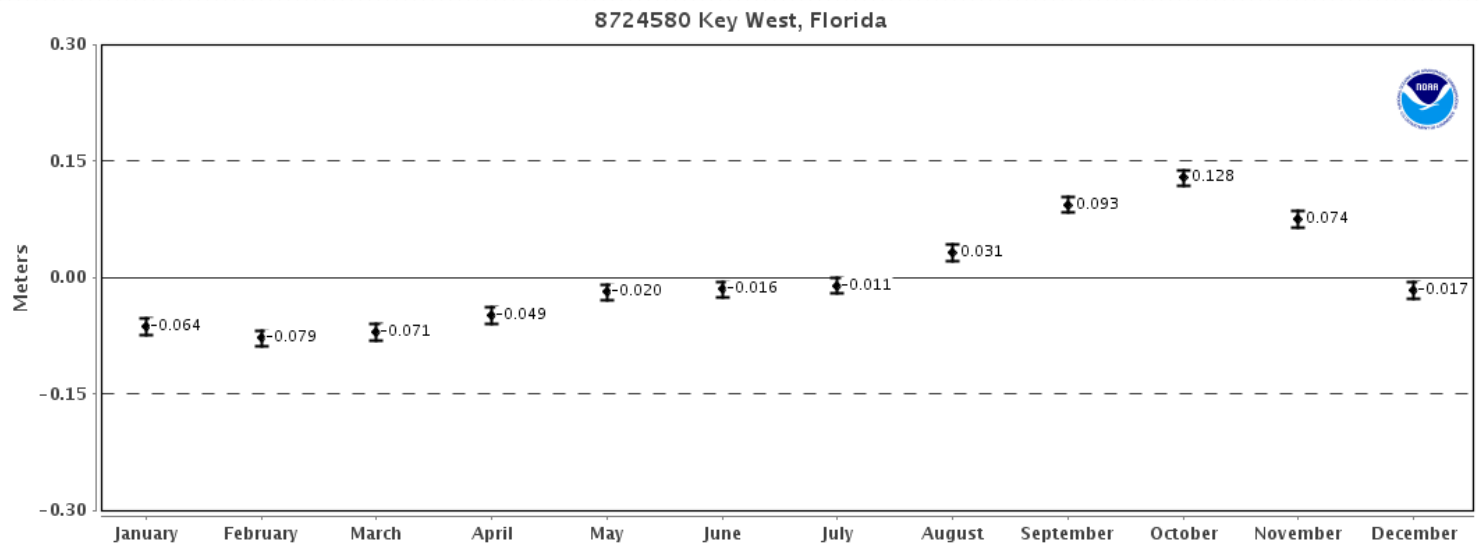
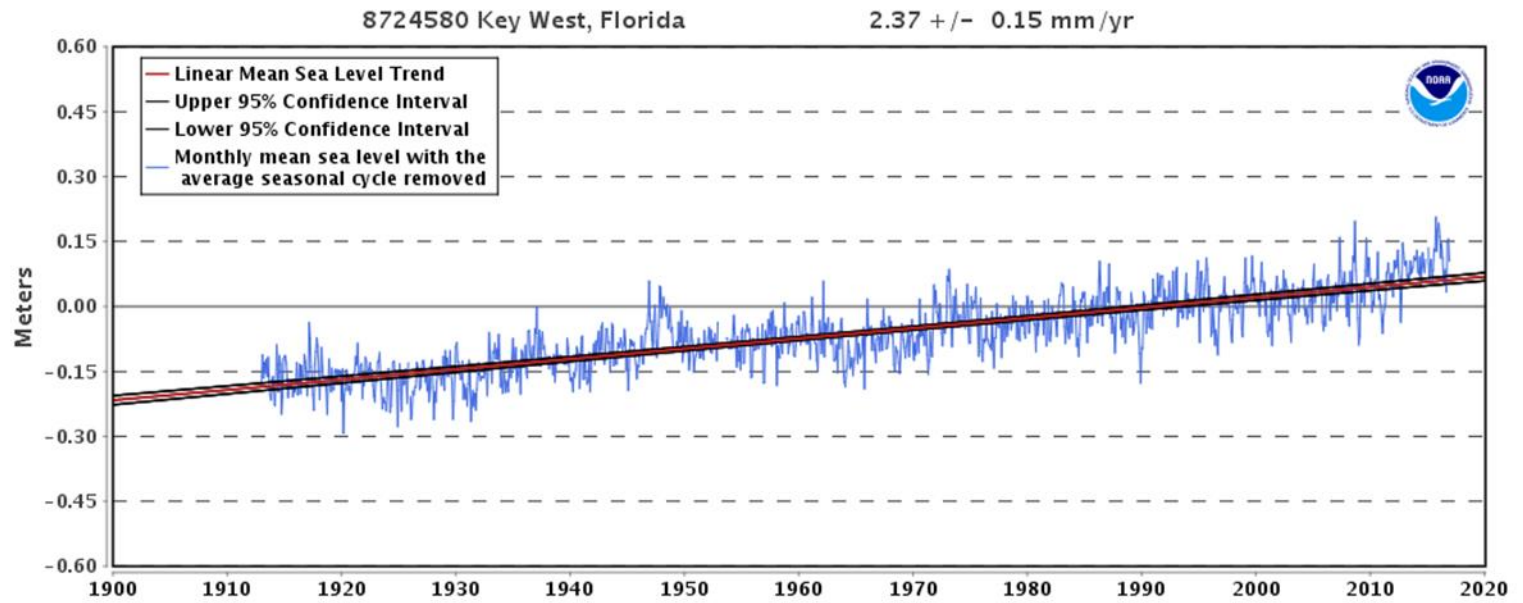


Tides above +1.5 ft NAVD for Virginia Key



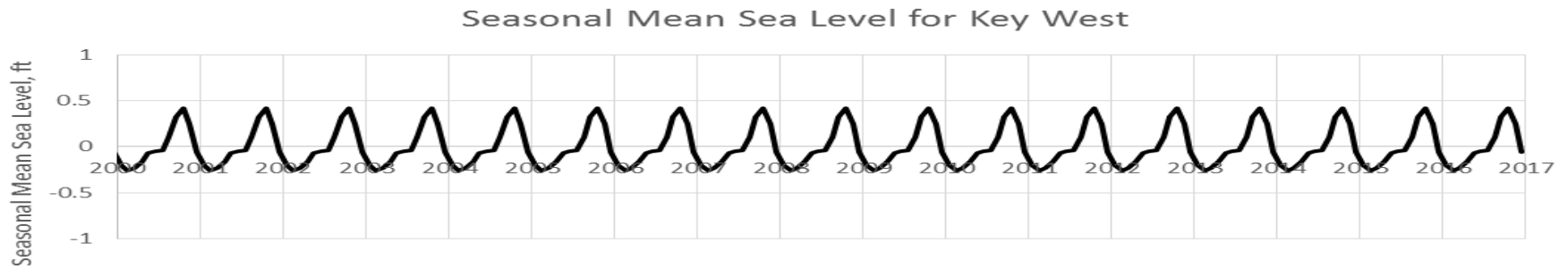
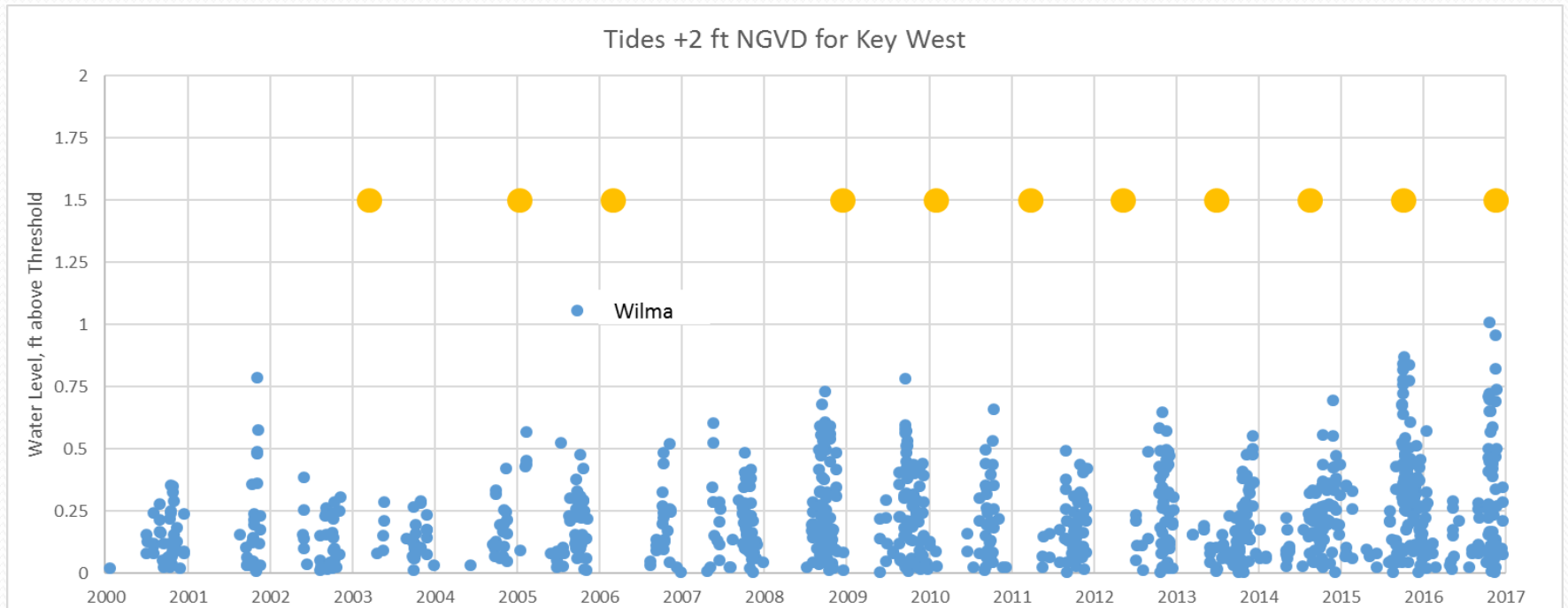
Tides above +1.75 ft NAVD for Virginia Key





# Key West, FL

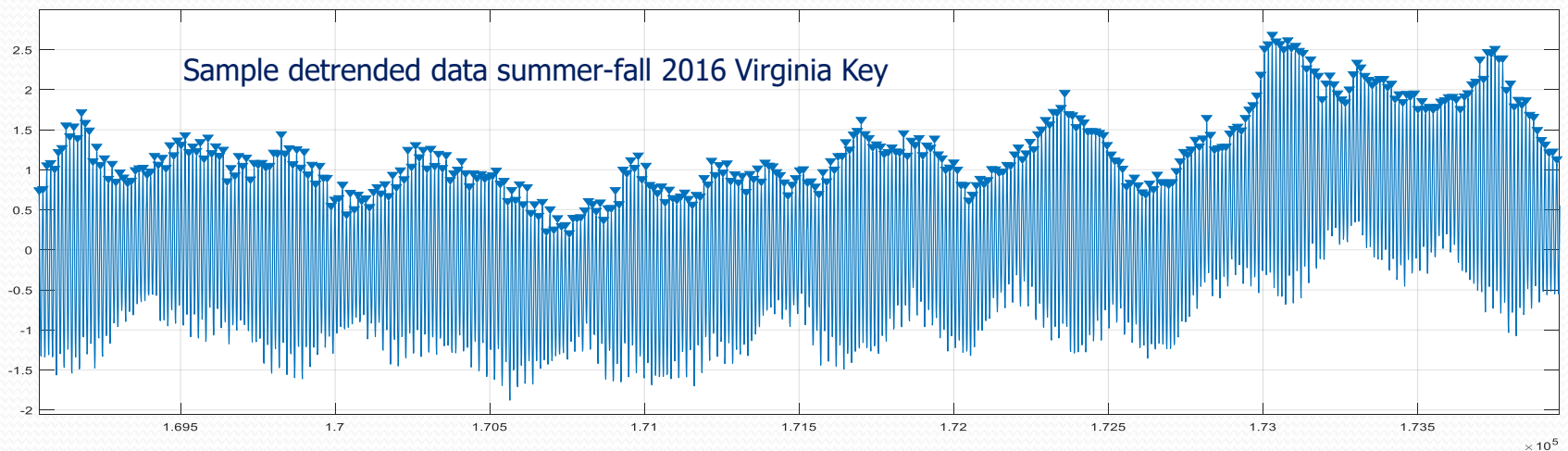
Little correlation to Proxigean Spring Tides  
Strong correlation to fall seasonal mean sea level





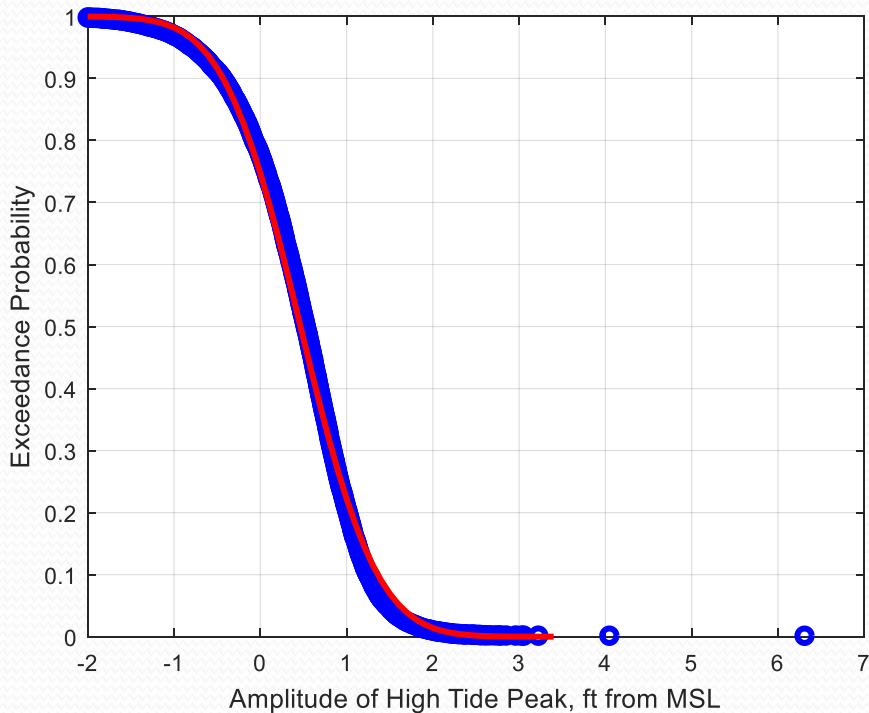
# Nuisance Flooding Projections with Future Sea Level Rise

- Hourly water levels from NOAA tide
  - Annapolis and Virginia Key 1996 to 2016
- Detrend to remove mean and long term linear sea level trend
  - Retain normal astronomical tides, meteorological events, seasonal mean sea level, and decadal sea level anomalies
- Identify high tide peaks – high tide amplitudes
  - Relative to “flat” mean sea level

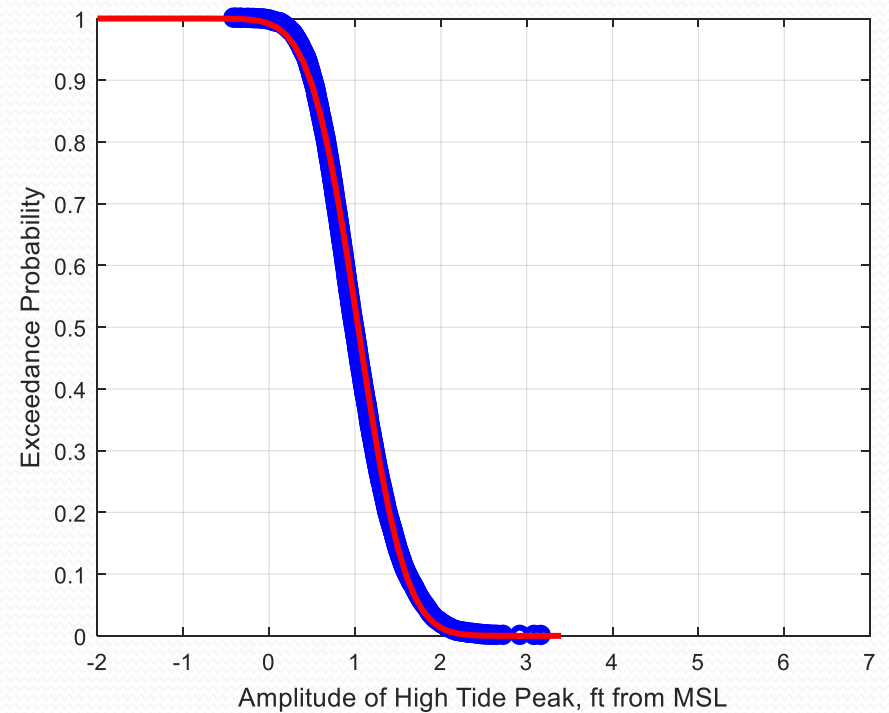


- Develop statistical curve for probability of peak high tide amplitudes
- Assume statistics are stationary
  - Relative to future point-in-time mean sea level

## Annapolis, MD

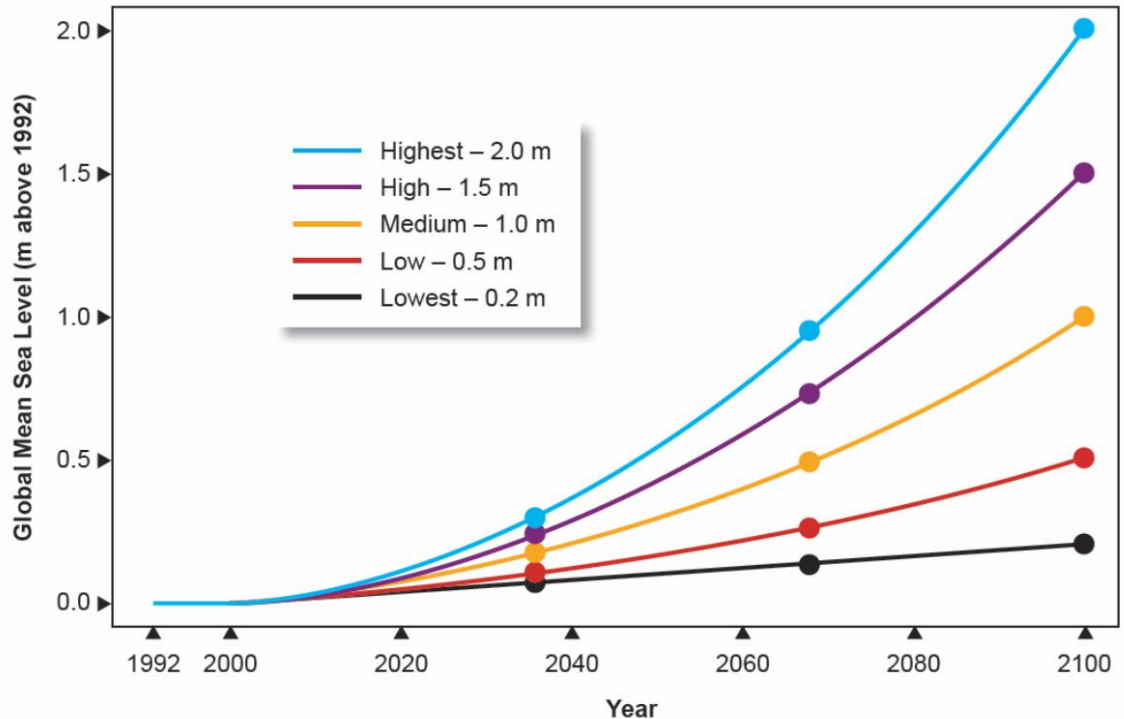
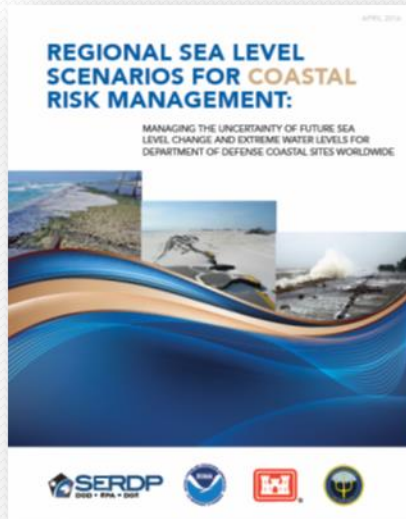


## Virginia Key, FL



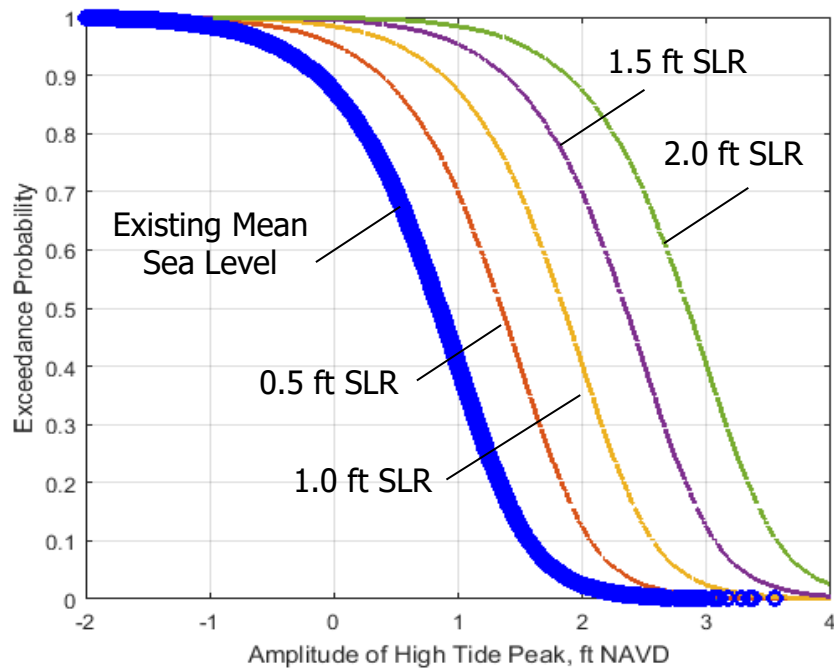
Both can be approximated by Normal or Gaussian Distribution

- Adopt future Global sea level rise scenario
- Add Vertical Land Movement
- Shift high tide probability curve by amount of future SLR
- Apply flood threshold
- Determine probability of flooding
  - Convert to number per year, etc

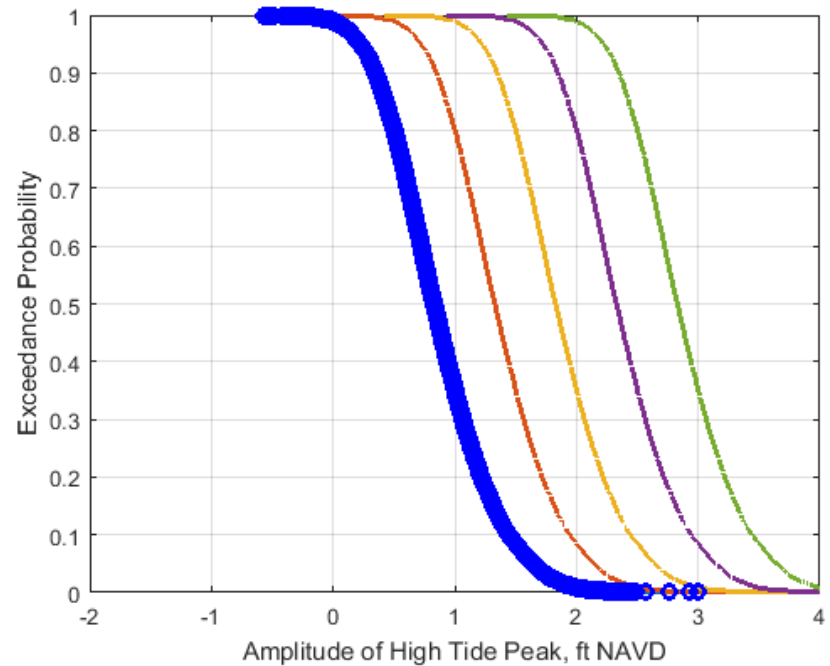


# Statistics of High Tide Amplitudes Shifted to NAVD88 Datum With 0.5, 1.0, 1.5, and 2.0 ft sea level rise

## Annapolis, MD

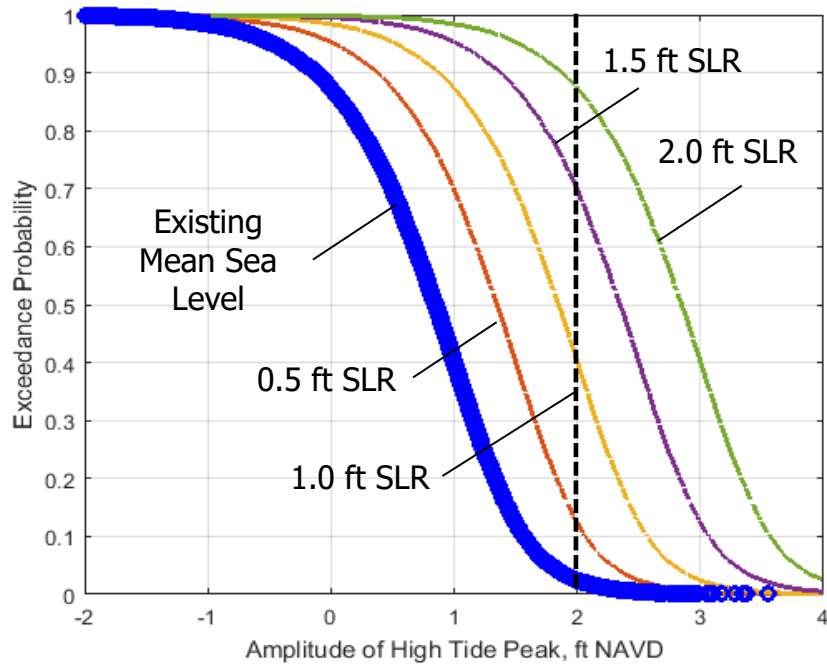


## Virginia Key, FL

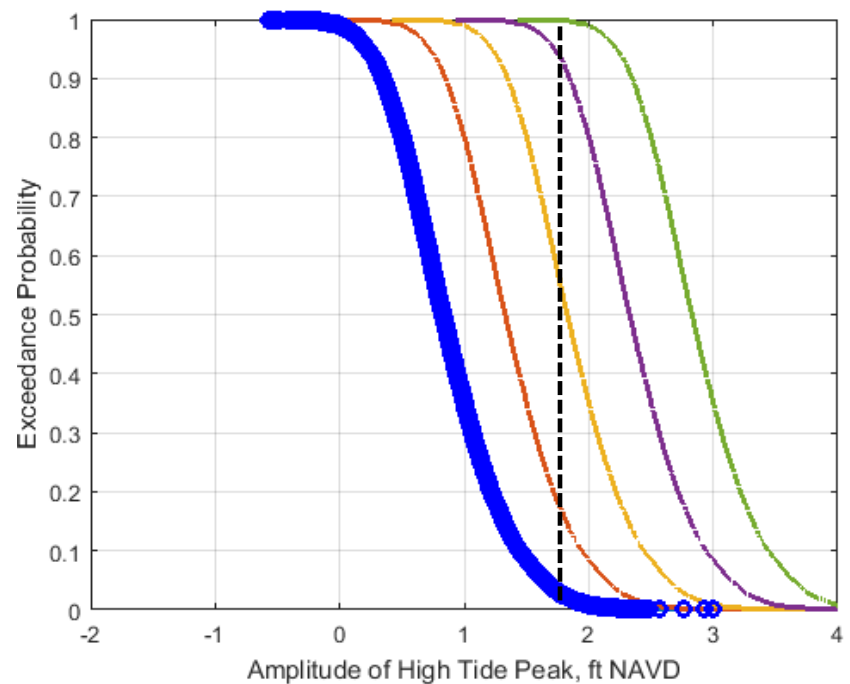


# Apply Threshold Elevations

Annapolis, MD  
Threshold=1.98 ft NAVD

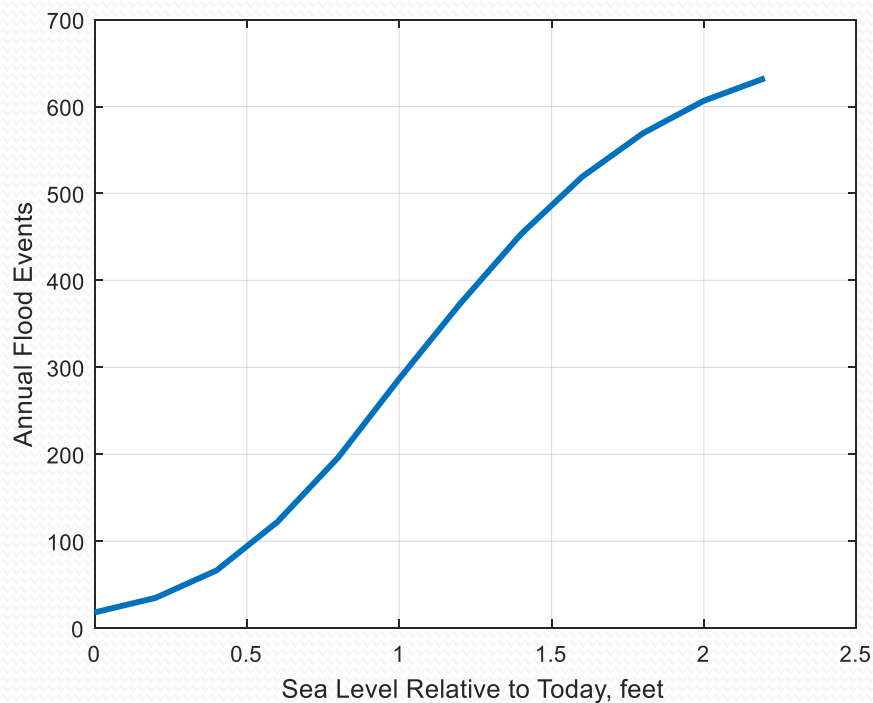


Virginia Key, FL  
Threshold = 1.75 ft NAVD

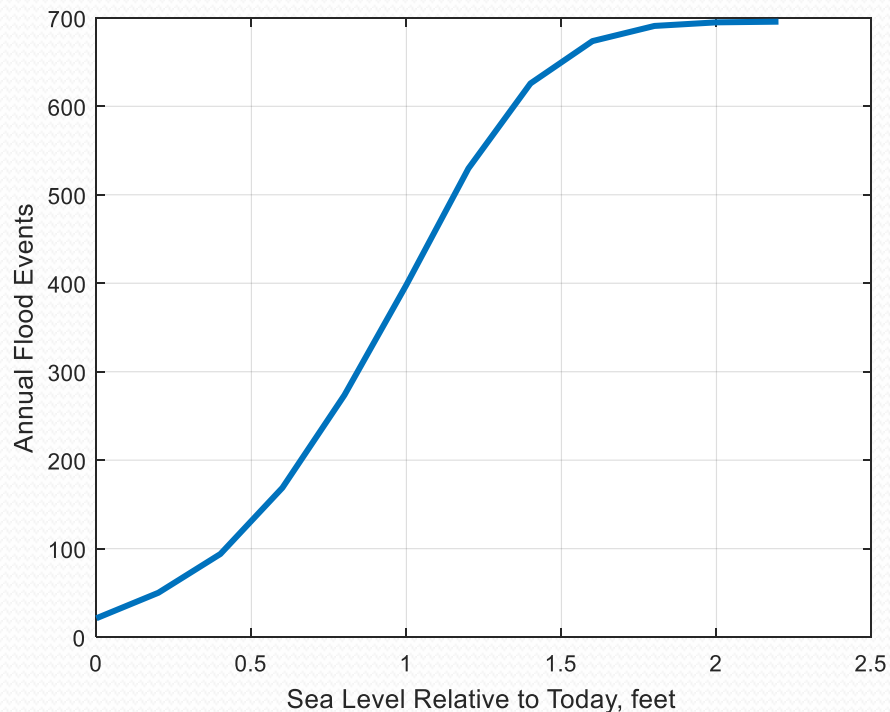


# Number of Flood Events with Future Sea Level Rise

**Annapolis, MD**  
Threshold=1.98 ft NAVD



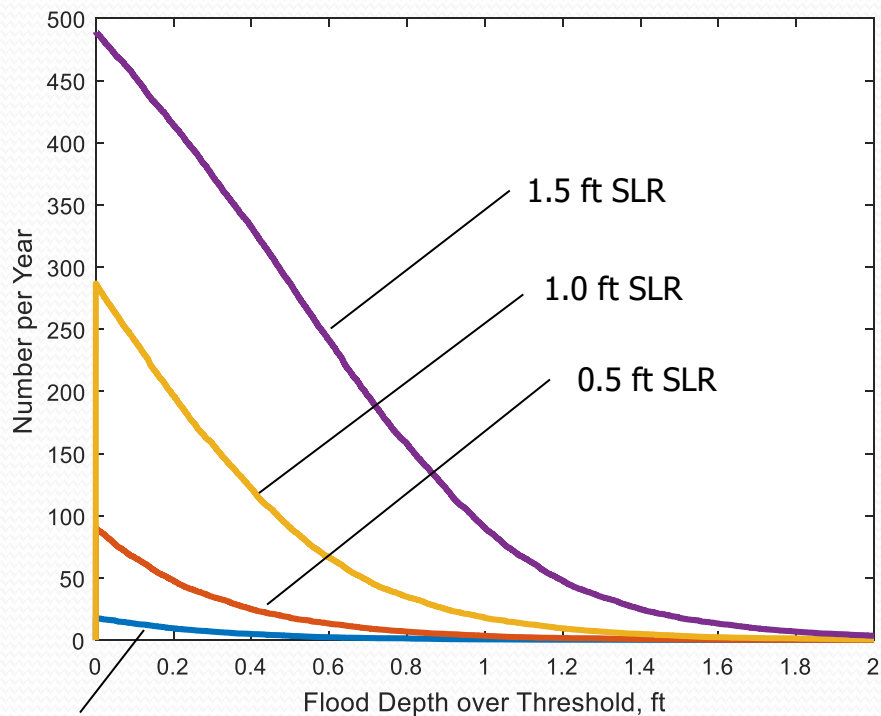
**Virginia Key, FL**  
Threshold = 1.75 ft NAVD



# Statistics of Flood Depth Over Threshold With 0, 0.5, 1.0, and 1.5 ft Sea Level Rise

## Annapolis, MD

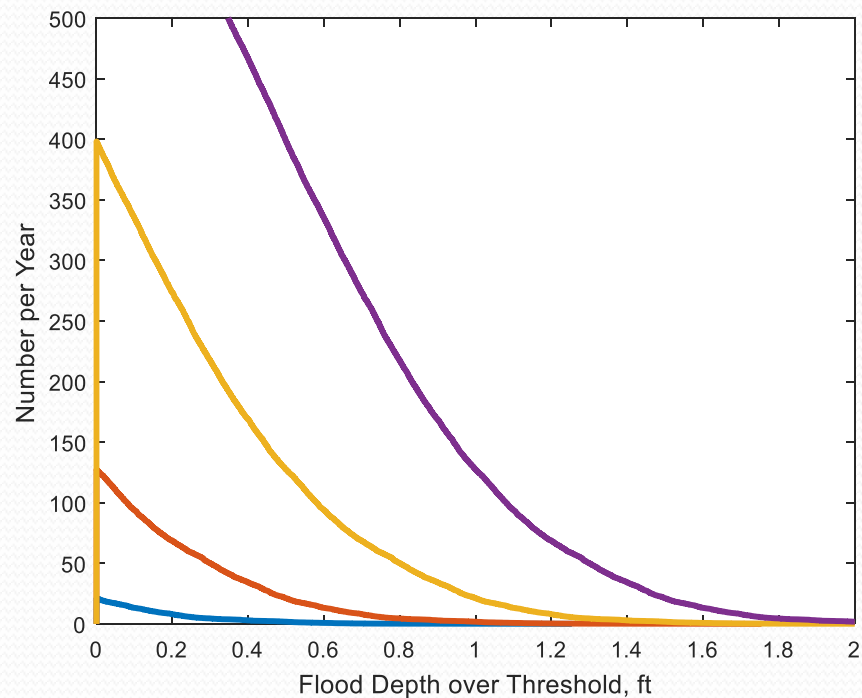
Threshold=1.98 ft NAVD



Existing  
Mean Sea  
Level

## Virginia Key, FL

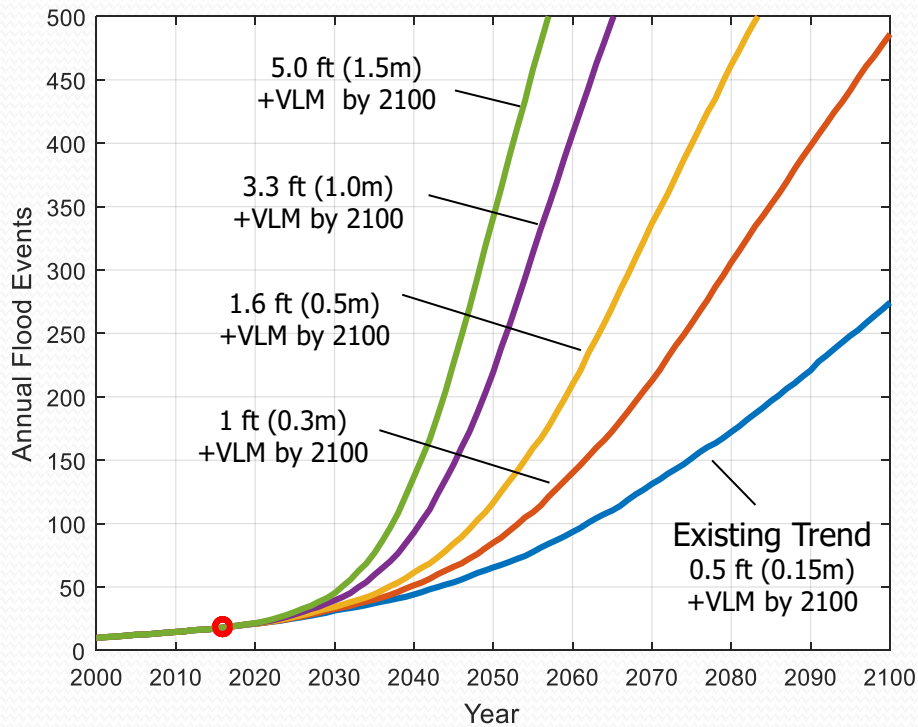
Threshold = 1.75 ft NAVD



# Number of Flood Events with Future Sea Level Rise Scenarios

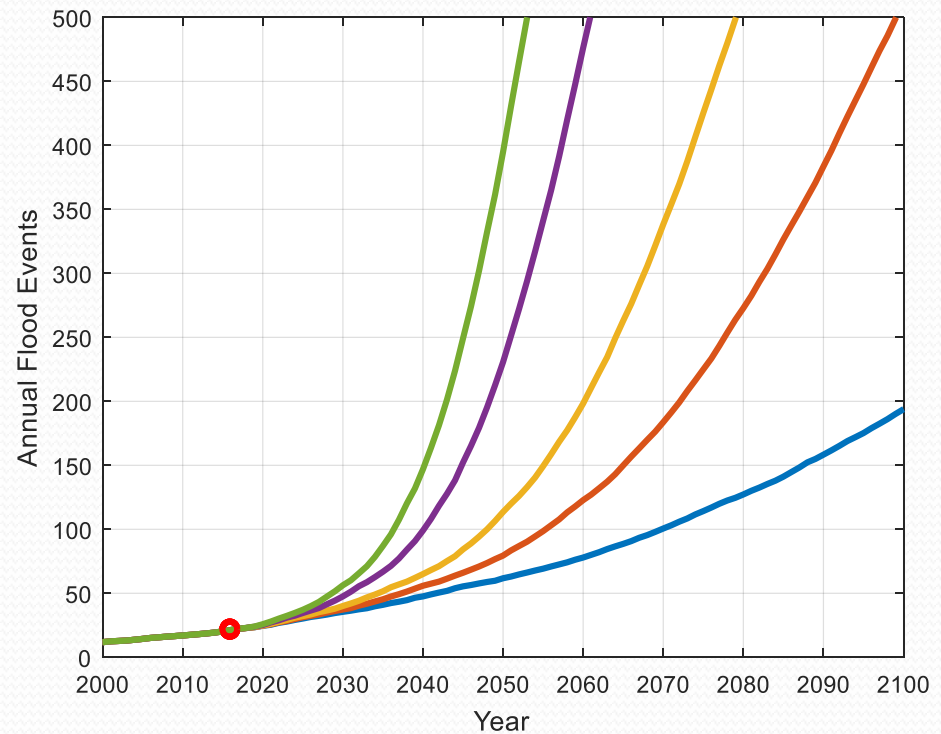
## Annapolis, MD

Threshold=1.98 ft NAVD



## Virginia Key, FL

Threshold = 1.75 ft NAVD



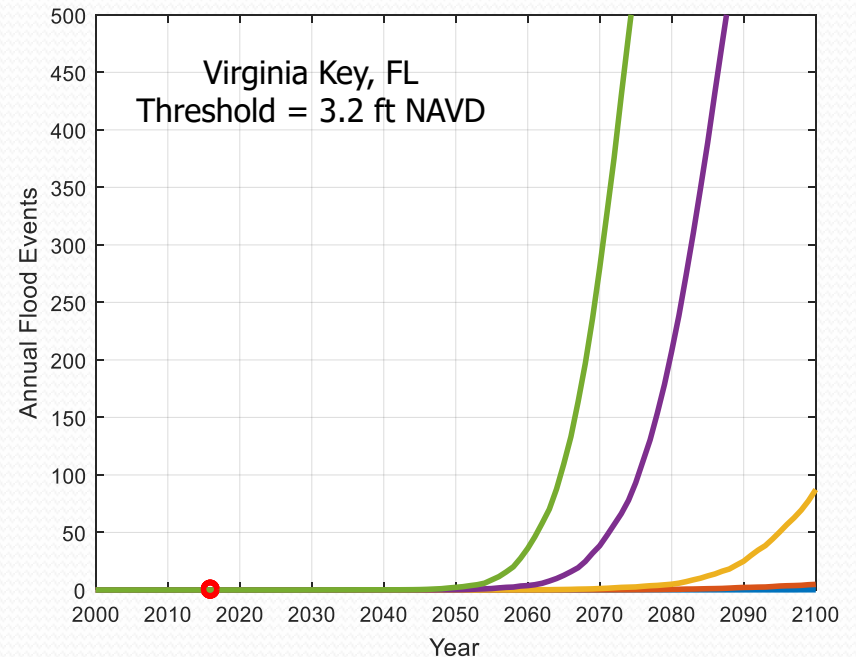
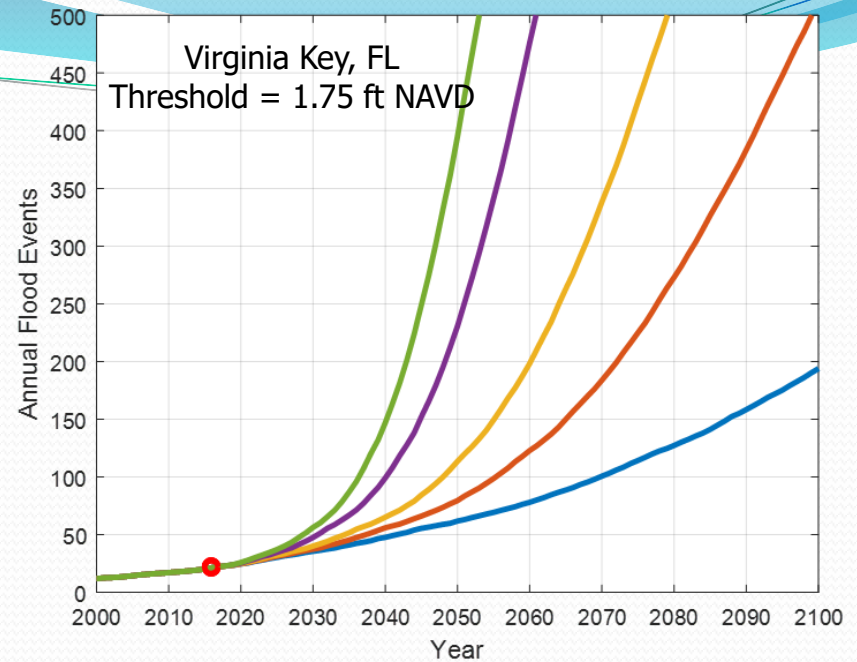


# Effect of Raising Streets in Miami Beach

Streets in Sunset Harbor area  
Old elevation 1.5 to 2.0 ft NAVD  
New elevation 3.2 ft NAVD



Photo of Miami Beach City Engineer Dr. Bruce Mowry in Sunset Harbor (Miami Herald)



# Conclusions

- **Nuisance Flooding and King Tides**
  - Need more precise definitions, but nuisance flood depths less than about 1 ft
  - Strong effect of long-term and seasonal (fall) increase in mean sea level
  - Strong effect of low-level meteorological events
  - Not uniquely related to perigean spring tides
- **Game of Inches**
  - Number of flood events changes dramatically as flood threshold, mean sea level, or both change by a few inches
- **Projections with Future Sea Level Rise**
  - Large increase in flood events expected even with current sea level trend
  - Dramatic increase under accelerated sea level scenarios
  - Can evaluate effect of adaptation actions