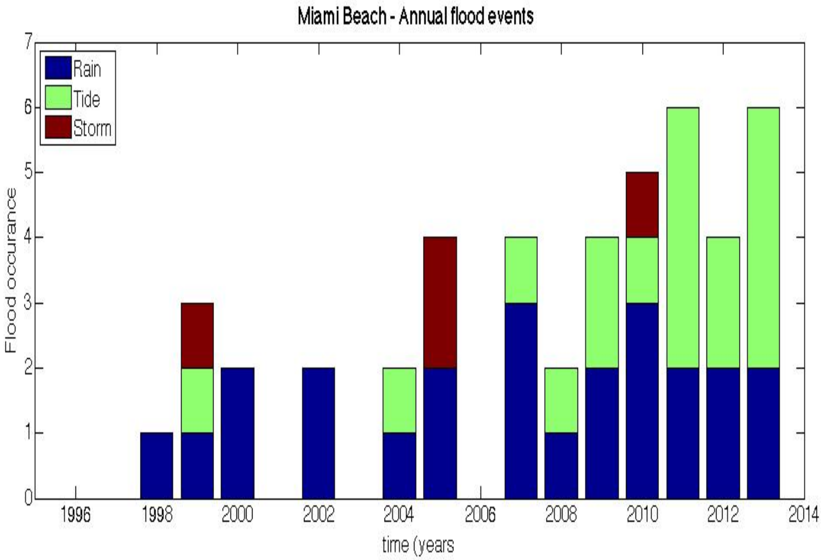
Increasing flooding frequency in Miami Beach as an indicator for accelerating rates of sea level rise along the US Atlantic shores

Shimon Wdowinski, Ronald Bray, Ben Kirtman

University of Miami



Venice – Acqua Alta

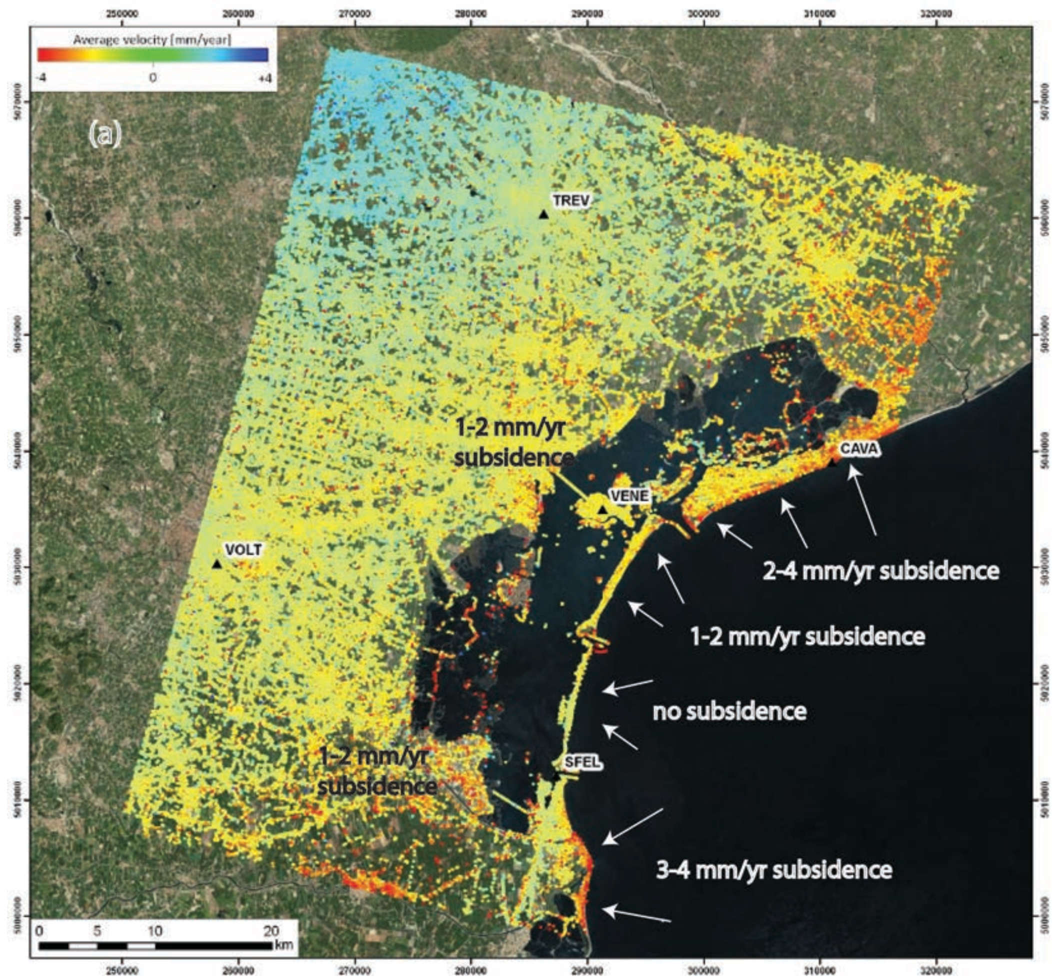
Venice - subsidence

Recent subsidence of the Venice Lagoon from continuous GPS and interferometric synthetic aperture radar

Bock et al. (2012)

Conclusion

Relative sea level rise in the city of Venice reflects both the effect of sea level rise and land subsidence.



October, 2015

Sea Level Rise (SLR) in Urban areas

How to quantify SLR?

<u>Common method:</u>
Vertical changes in Mean Sea Level

For example: In 2050, mean sea level in Miami Beach will be 50, 75, or 100 cm (2, 3, or 4 feet) higher than present.

<u>My suggestion:</u>
Changes in flooding frequency

For example: In 2050, Miami Beach will experience 30, 50, or 70 flooding events, compared with 2 events in 2008.

We can already use flooding frequency to quantify current effect of SLR in Miami Beach.

Recurrence Flooding Miami Beach

Flooding types/causes

- Rain
- Storm surge
- Tide
    - "Sunny Sky flooding"
    - "Lunar Flooding"

Recurrence Flooding in Miami Beach

Miami Herald Miami Beach

Select your community

Posted on 02.12.14

Miami Beach to spend up to $400 million to deal with flooding issues

Like 409

Moses Schwartz calls a tow truck to retrieve his SUV on the 800 block of Alton Road in Miami Beach in October 2013. WALTER MICHOT / MIAMI HERALD STAFF

Buy Photo

BY CHRISTINA VEIGA
CVEIGA@MIAMIHERALD.COM

Miami Beach, which sometimes floods from the bay even on a sunny day, is taking major steps to stay dry, with commissioners voting Wednesday to factor in higher tides and sea levels when planning for city projects.

The move is expected to double to $400 million the cost of keeping water out of Miami Beach's streets.

The city still isn't entirely sure how it will pay for the costly improvements, but hopes to tap into federal and state funds, grants and possibly borrow money against its utility accounts.

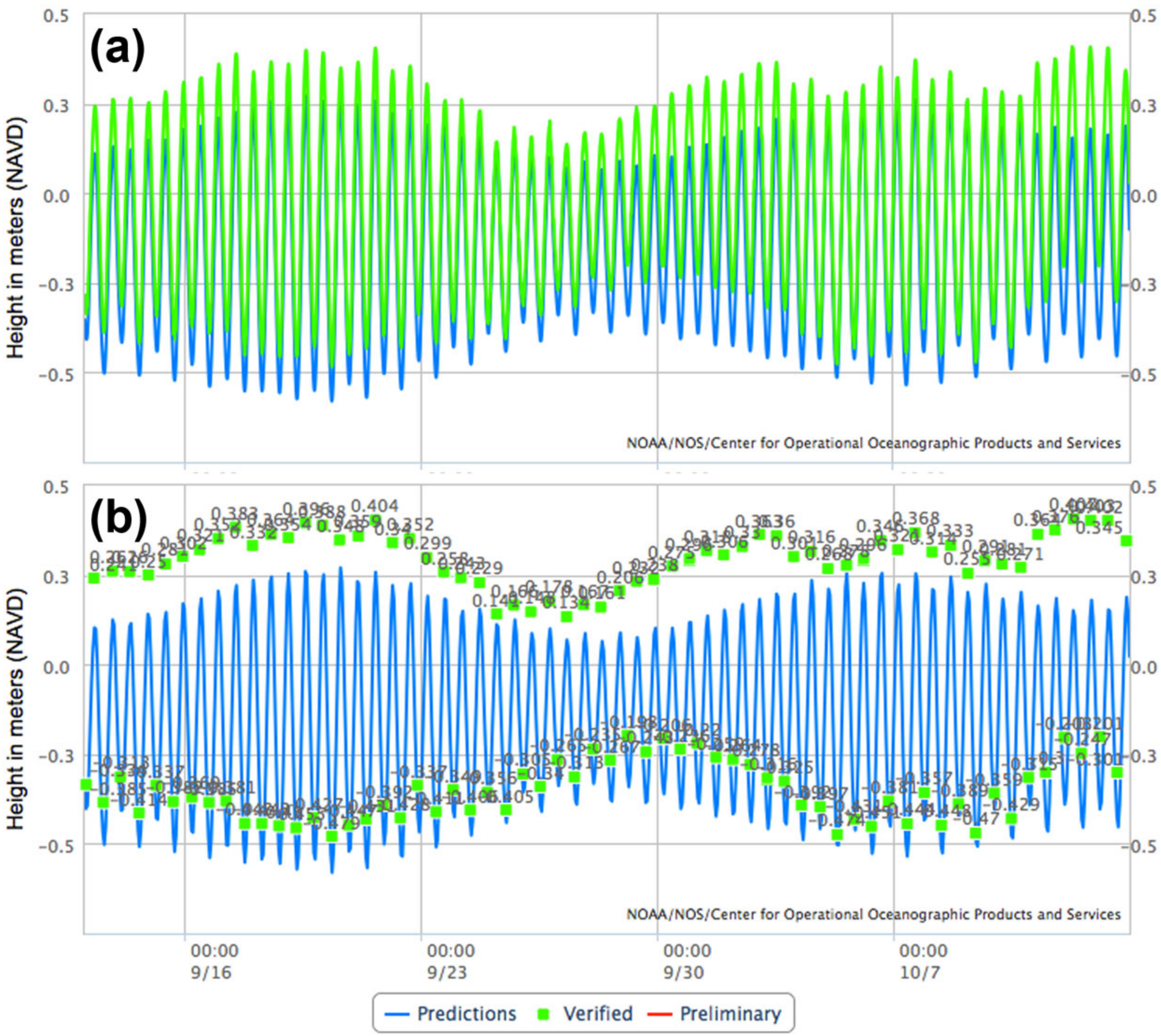
Presentation content

- Introduction
  - Recurrence flooding in Miami Beach
- Quantifying flooding frequency
  - Data - tide gauge, rain, insurance claim, media reports
  - Cross-reference analysis
  - Results - Increase in flooding frequency
- Tide gauge data analysis
  - Best-fit analysis
  - Ensemble Empirical Mode Decomposition (EEMD)
  - Results – Accelerating rates of Sea Level Rise
- Implications
  - Previous periods of accelerated rates
  - Possible causes
- Summary
- Acknowledgments

Data

- Tide gauge (Virginia Key)
- Rain gauge (RG)
- Media reports
- Insurance claims
- Miami Beach documentation

Virginia Key tide gauge record



Observed values:
Sampling rate
(6 minutes)

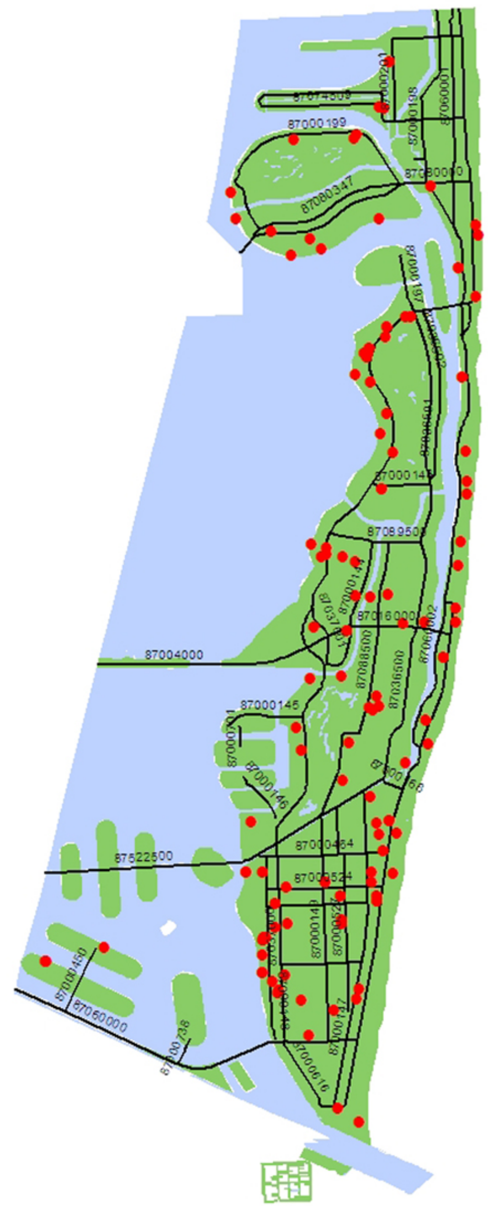
Datum: NAVD

Observed values:
HH – Daily highest
H – Daily other tide
LL - Daily lowest
L – Daily other tide

Observation period: 9/13/2013-10/13/2013

Insurance claim record

- Insurance companies are required to report FEMA on all flooding claims.
- FEMA shares the flooding claim dataset with counties.
- Miami-Dade County's Public Works and Waste Management office provided us a subset of the dataset containing locations and times of claims. (Other claim details are considered private information.)



Media reports

Lunar Flooding on Miami Beach is Loony

by TONY GARCIA on SEPTEMBER 17, 2009 · 6 COMMENTS

Why Belle Isle and South Beach flood without rain

Posted on October 9, 2010 | 6 Comments

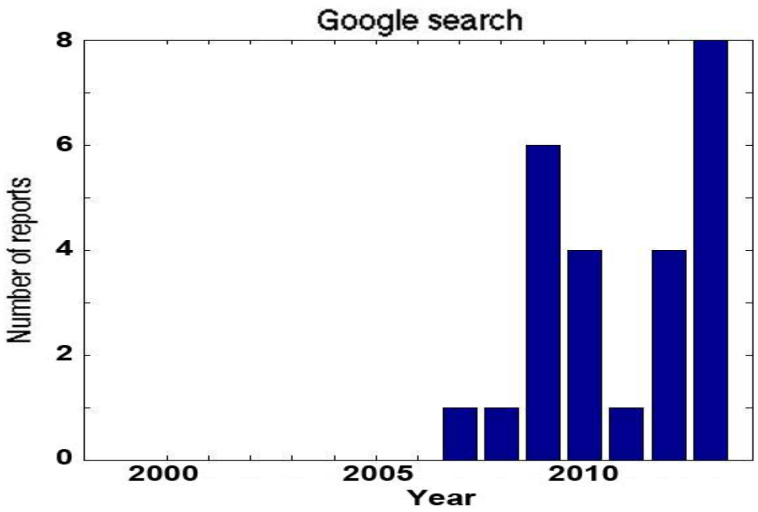
Miami Flooding Getting Worse With Sea-Level Rise

Sun Sentinel | By KEN KAYE
Posted: 10/17/2013 8:00 am EDT | Updated: 10/18/2013 8:04 am EDT

High Tide Causes Street Flooding in Portions of Miami Beach, Broward

Flooding affected Alton Road and West Avenue on South Beach and Cordova Road in Broward.

By Laura Rodriguez, Alexandra Leon and Adam Berg | Friday, Oct 18, 2013 | Updated 1:15 AM EST



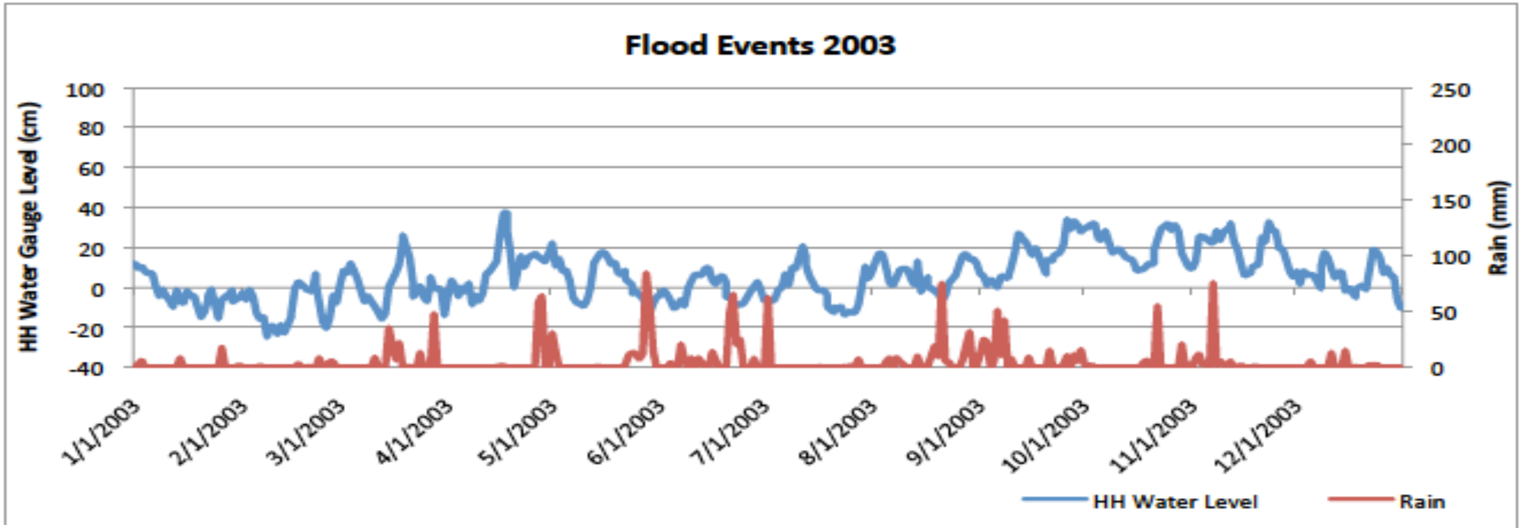
Other data

- Rain gauge – time series
- Miami Beach documentation
  - Pictures with time and location of flooding events

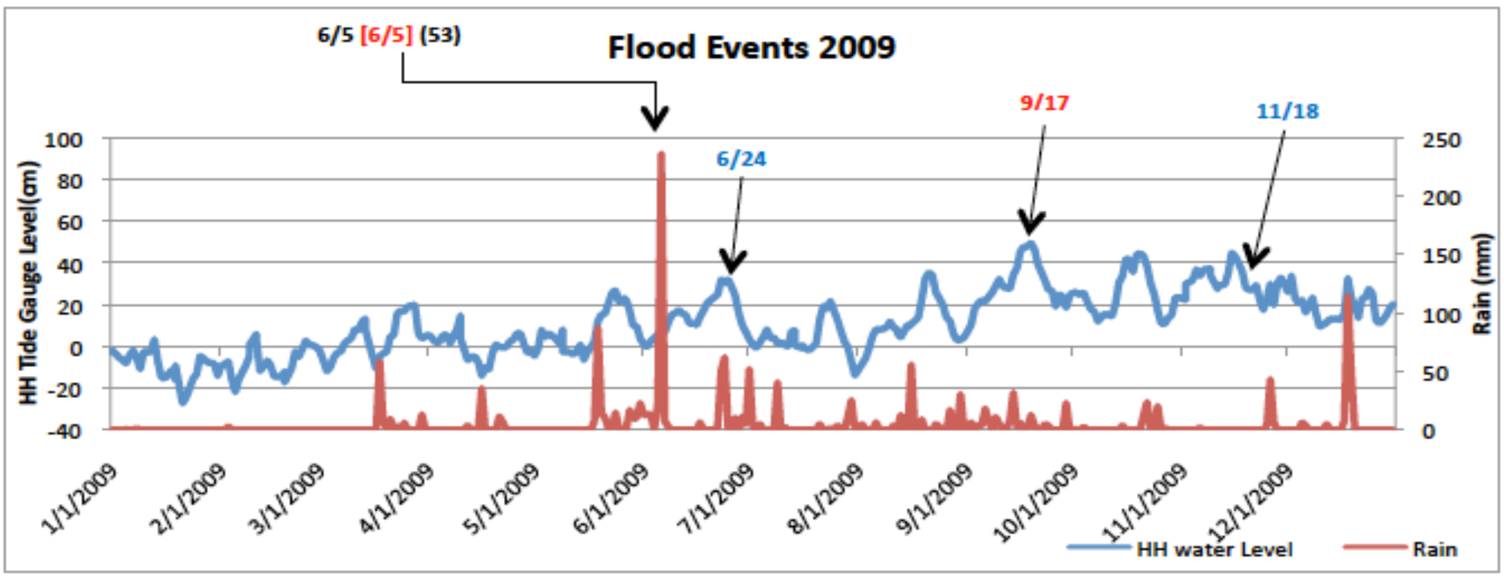
10-11-11 High Tide (Alton & 5)

9-26-11 Rainfall (Alton & 9)

Cross-reference analysis



No flooding events



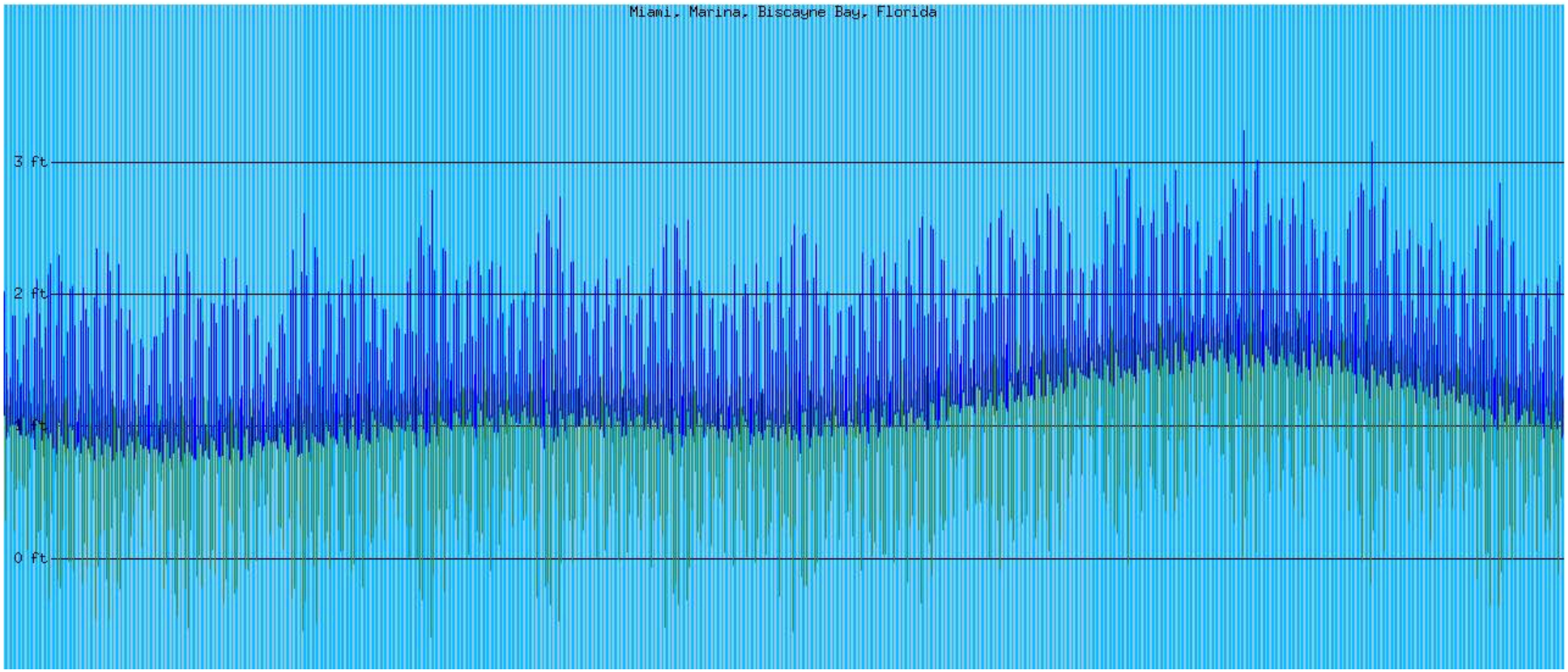
Four flooding events:
6/5 – Rain
6/24 - Rain
9/17 - Tide
11/18 - Tide

Black text – Insurance claims Red text – Media reports Blue text – Miami Beach documentation

Predicted astronomical tides

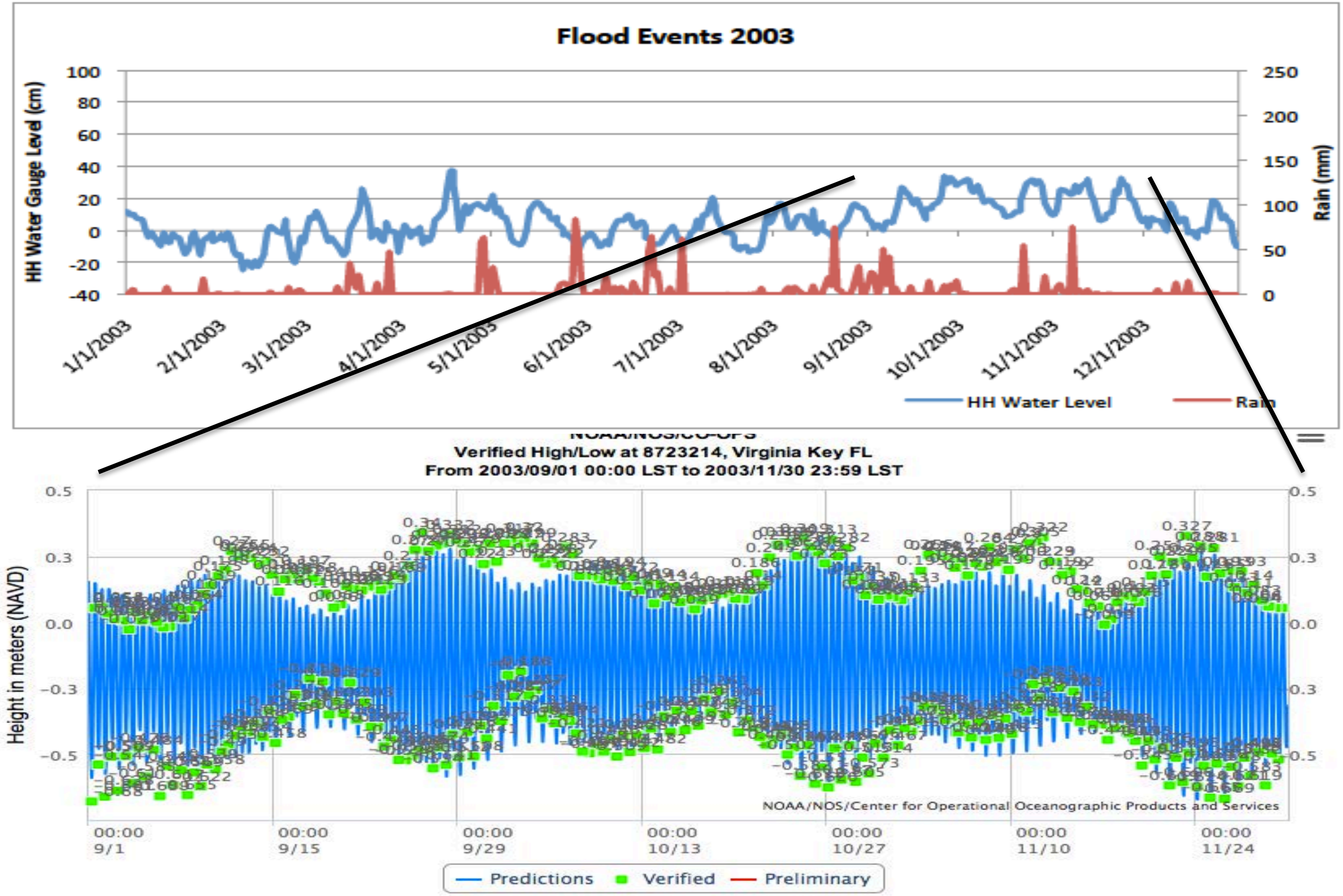
Miami, Marina, Biscayne Bay, Florida

13 January 2012 - 1 January 2013



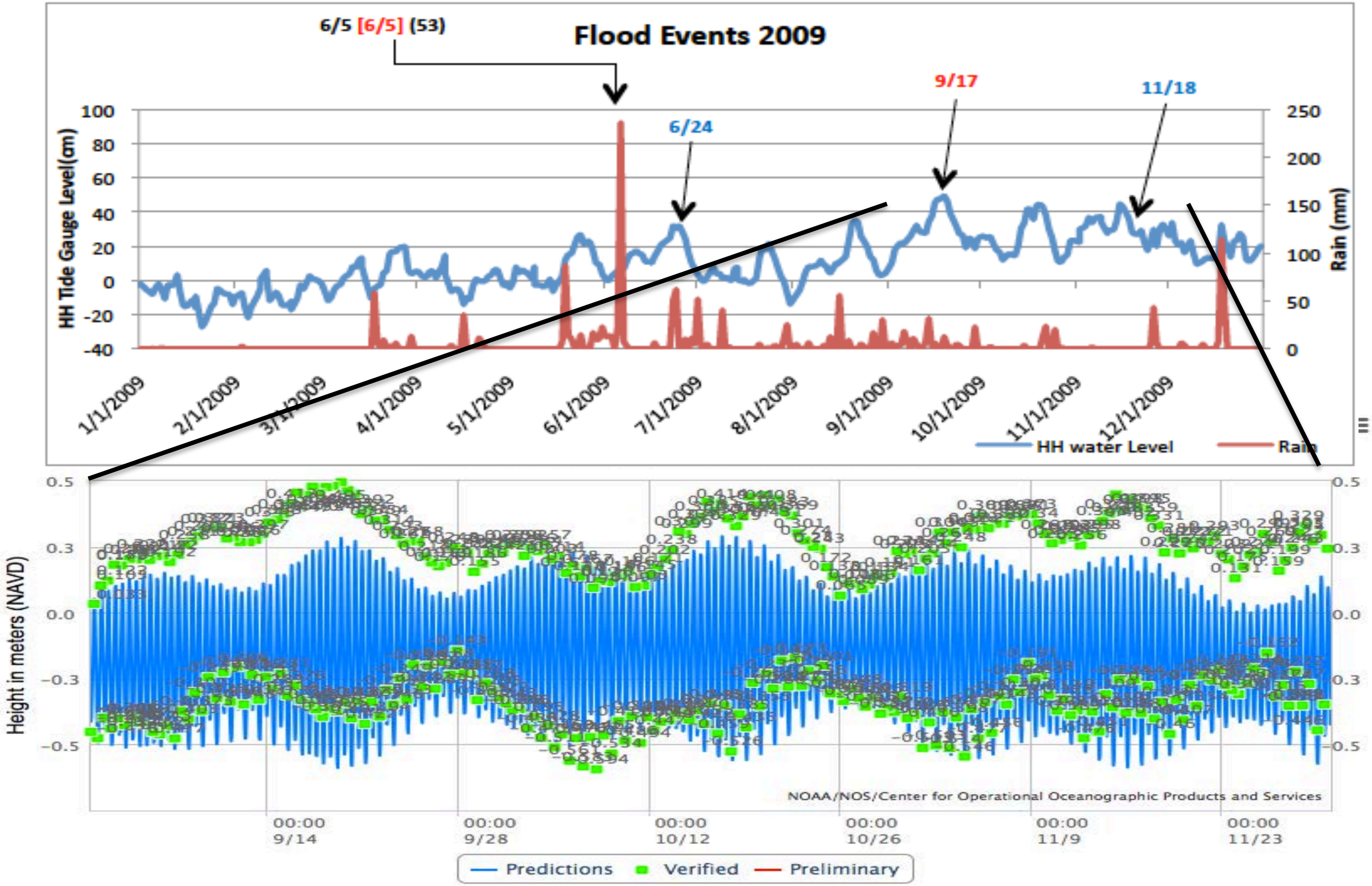
- High tide level around the fall equinox (September-October)
- Secondary high tide level around the spring equinox (March)

Virginia Key tide record -2003



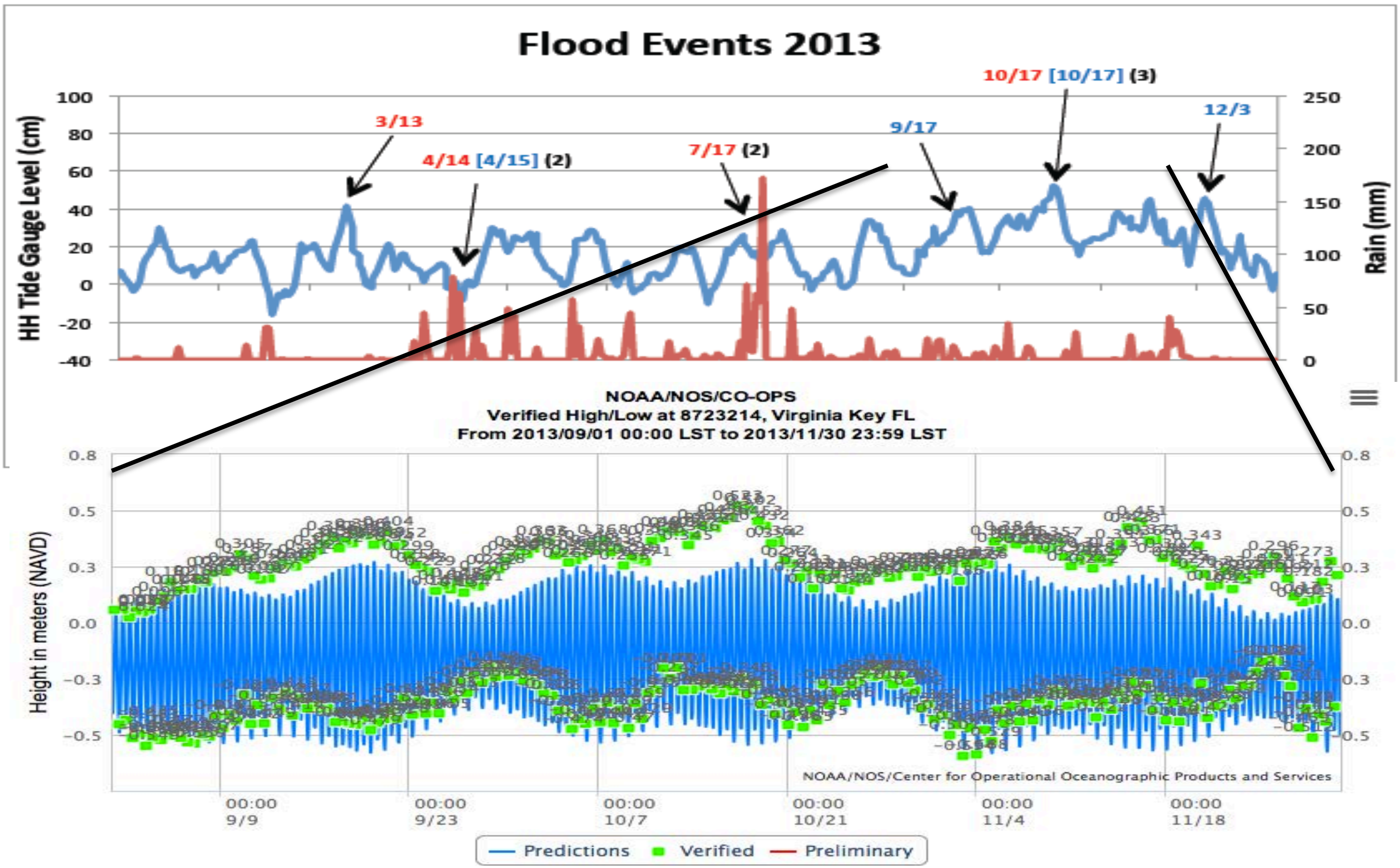
- Observed levels are similar to the predicted levels for the months of September - November

Virginia Key tide record -2009



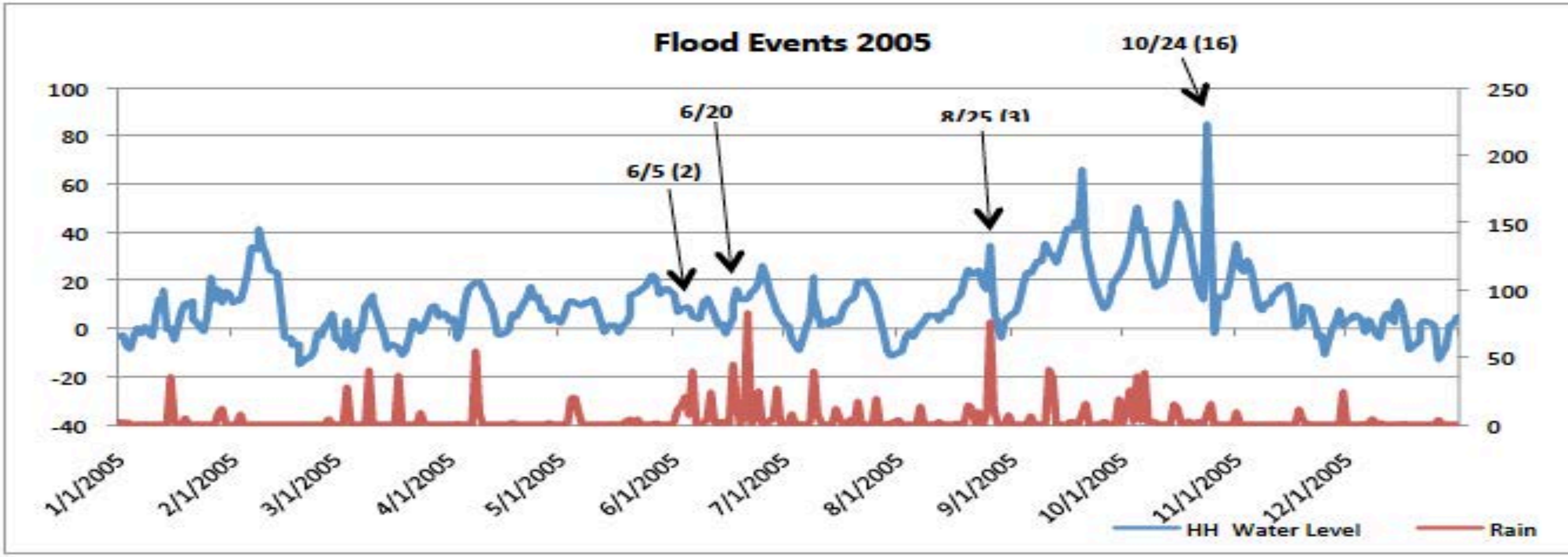
- Observed levels are systematically higher than predicted levels for the months of September - November

Virginia Key tide record -2013



- Observed levels are systematically higher than predicted levels for the months of September - November

Virginia Key tide record -2005



Hurricane (surge) induced flood events - multiple claim records

- Katrina – 8/25
- Wilma – 10/24

Miami Beach flooding

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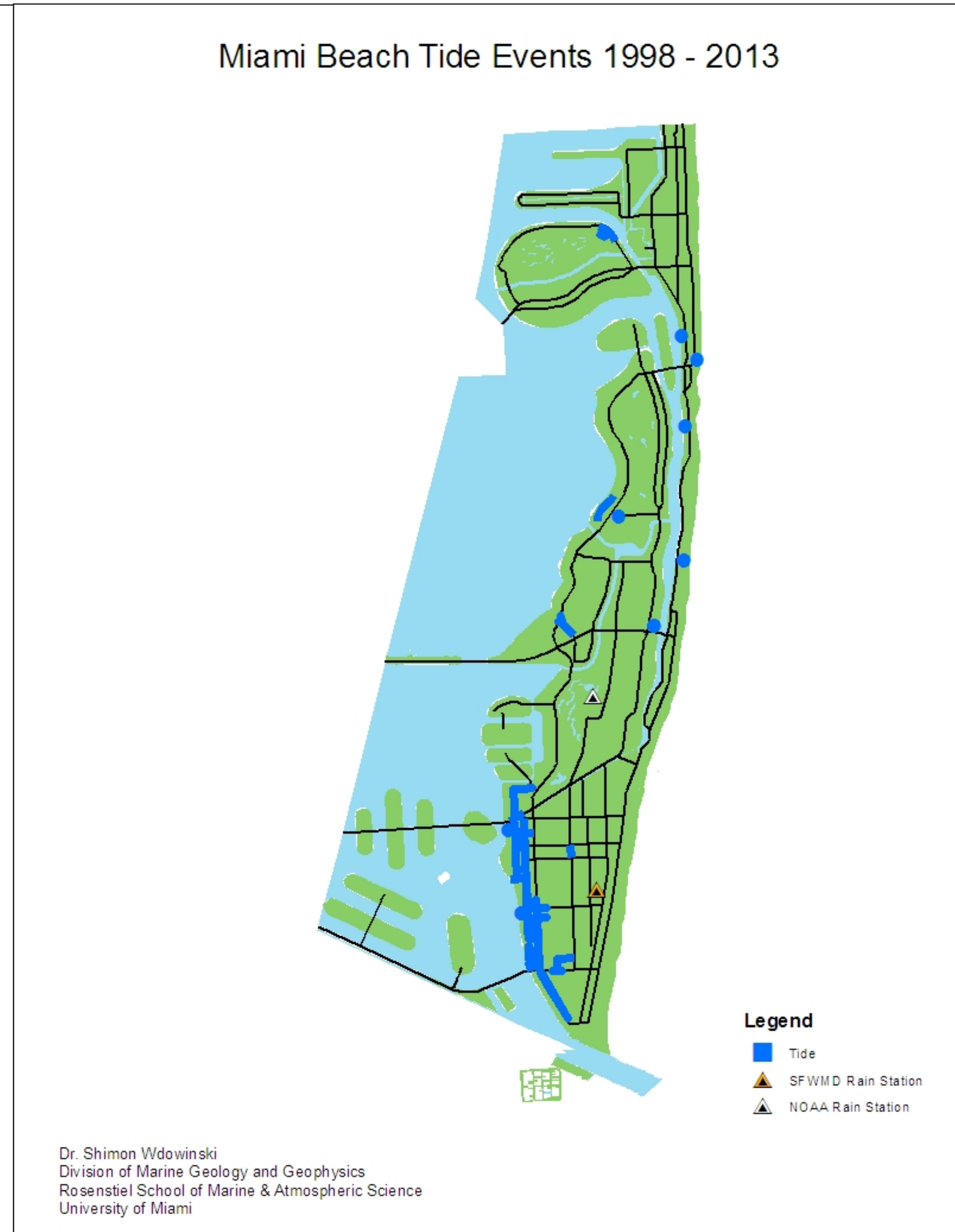
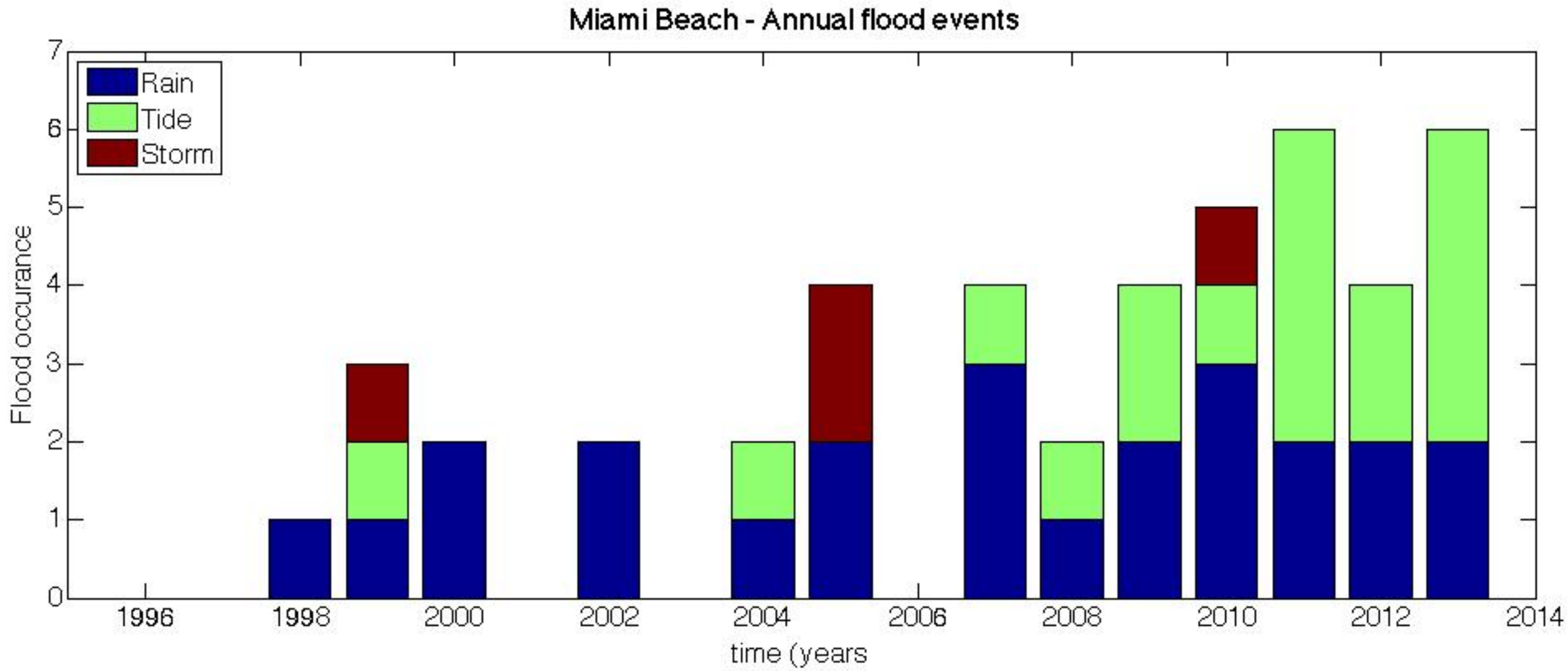
Miami Beach flooding



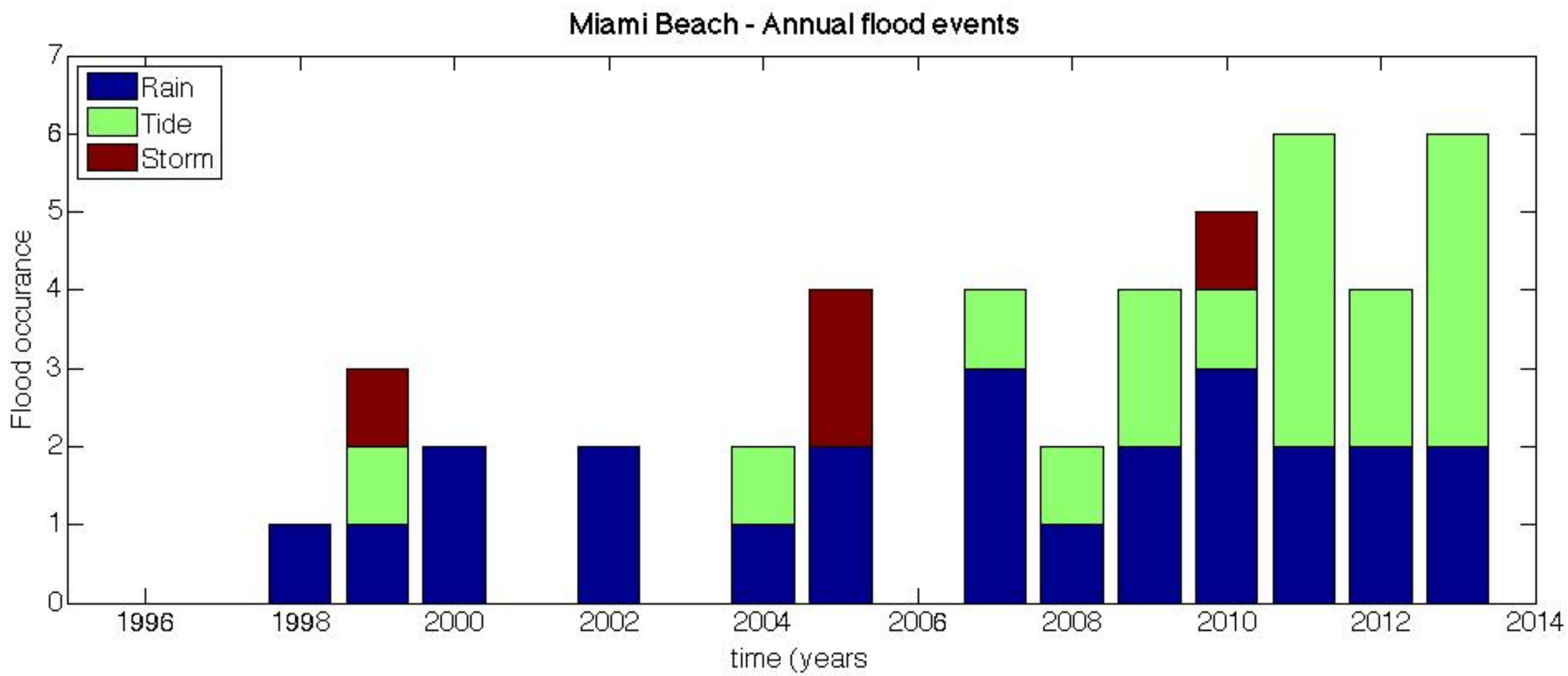
Miami Beach flooding frequency



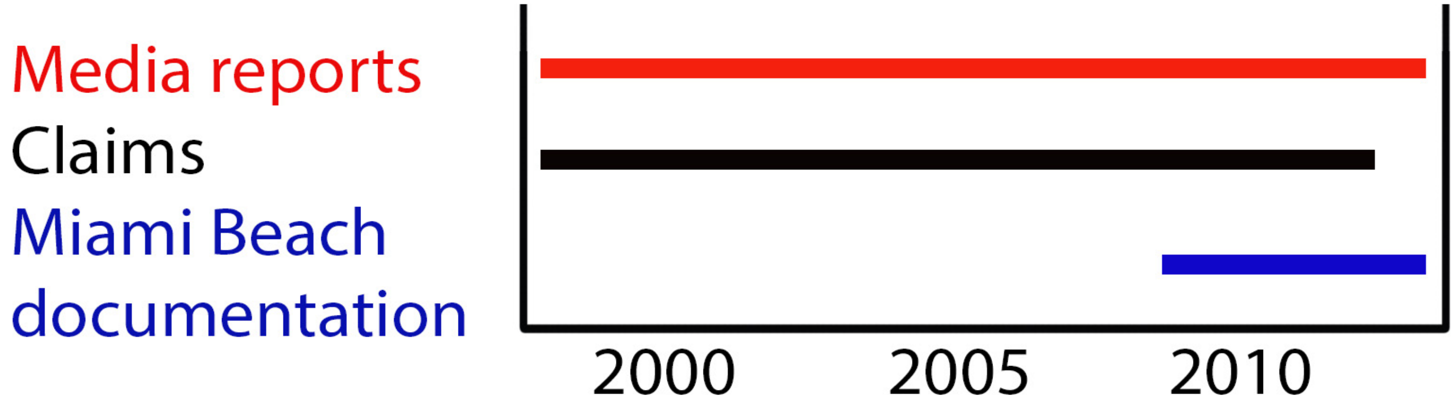
Flooding frequency

- **Rain induced events**
  - 1998-2006 – Average of 1 event per year (9 events in 9 years)
  - 2007-2013 – Average of 2 events per year (15 events in 7 years)
- **Tide induced events**
  - 1998-2006 – Average of 0.2 events per year (2 events in 9 years)
  - 2007-2013 – Average of 2 events per year (15 events in 7 years)

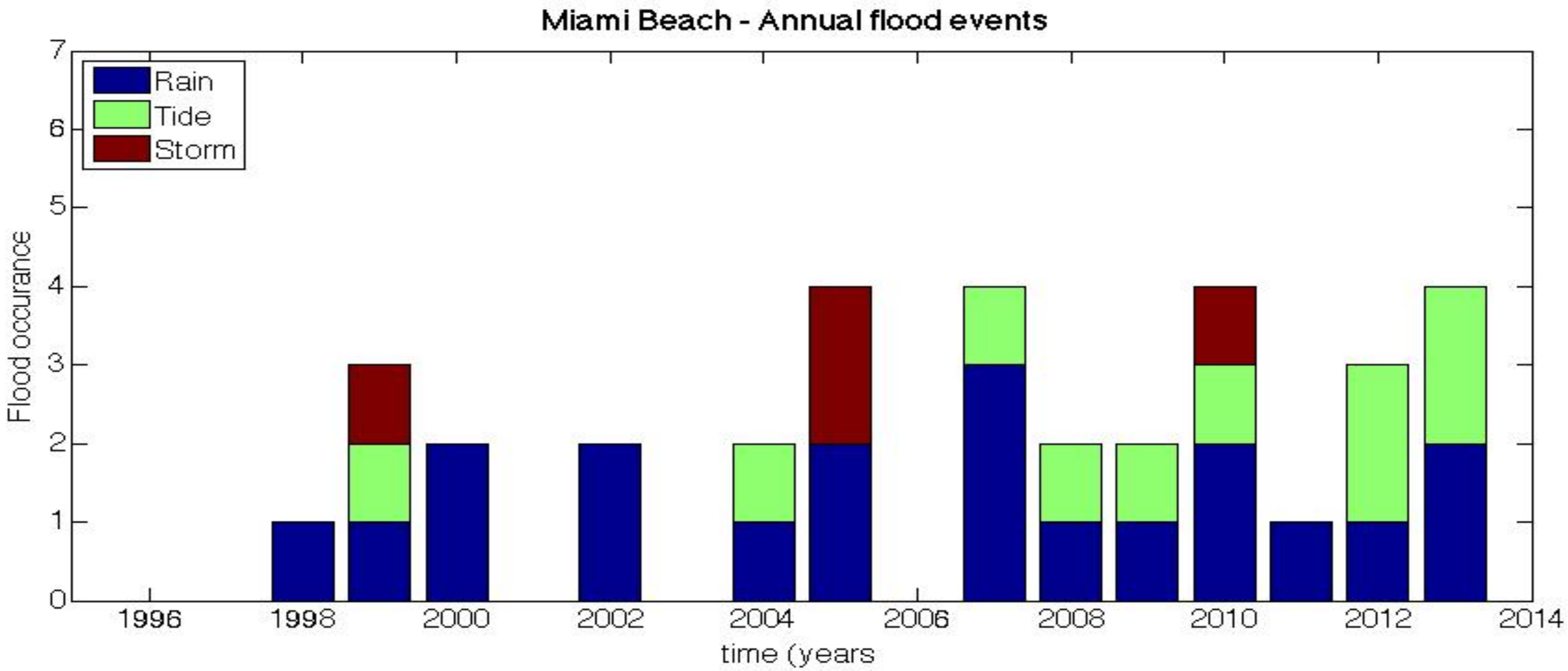
Miami Beach flooding frequency



Possible bias by incomplete data sources



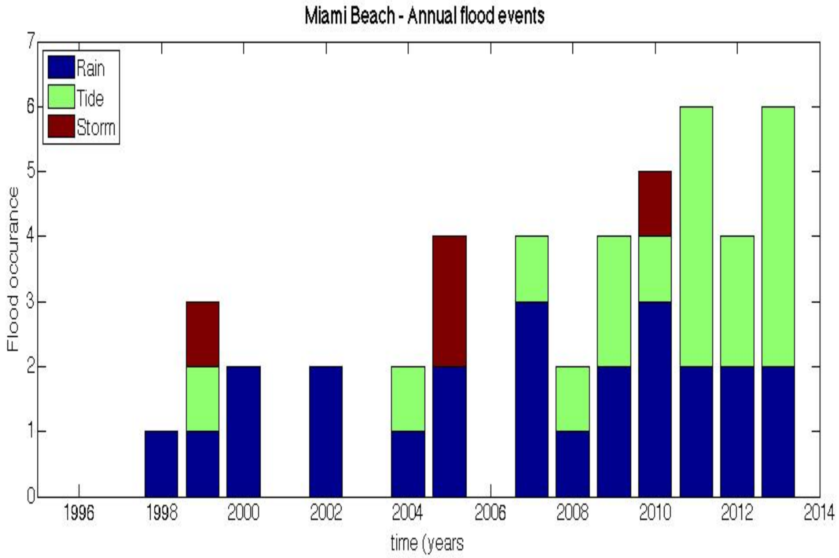
Miami Beach flooding frequency

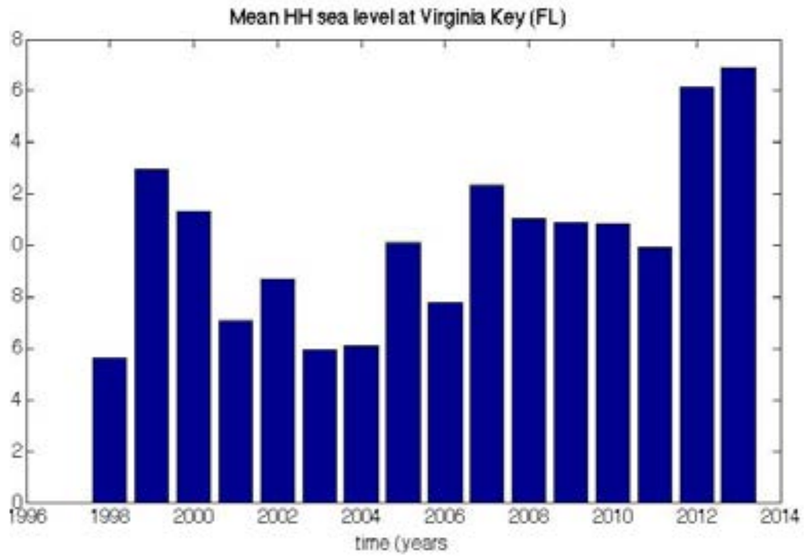


Flooding frequency – **without Miami Beach documentation**

- **Rain induced events**
  - 1998-2006 – Average of 1 event per year (9 events in 9 years)
  - 2007-2013 – Average of 1.5 events per year (11 events in 7 years)
- **Tide induced events**
  - 1998-2006 – Average of 0.2 event per year (2 events in 9 years)
  - 2007-2013 – Average of 1 event per year (8 events in 7 years)

Flooding frequency vs. mean HH level at VK



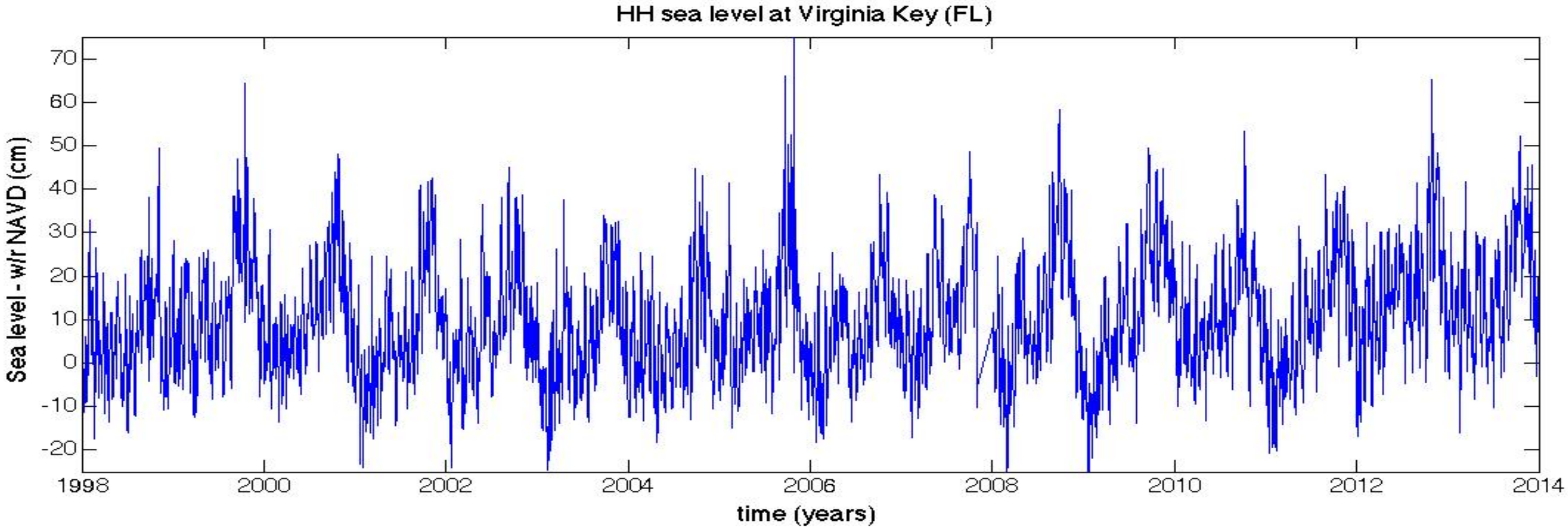


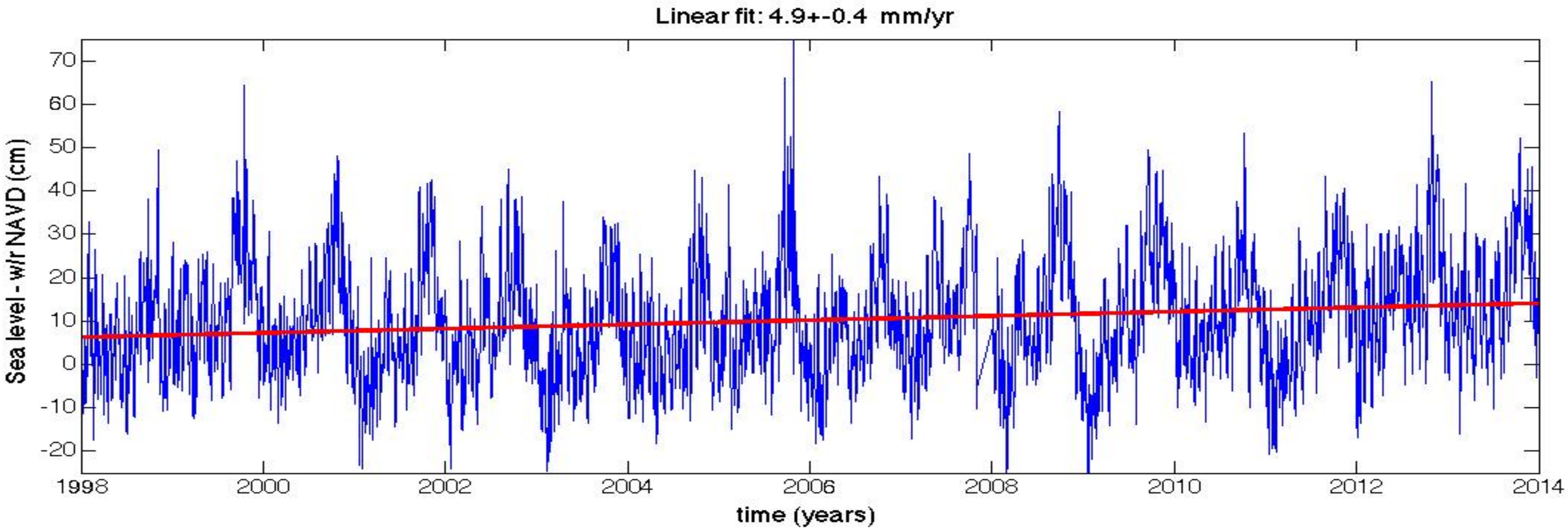
Flooding frequency – significant increase since 2007

- Rain – Increase from 1 event per year (prior to 2007) to 1.5-2 events per year after 2007
- Tide – Increase from 0.2 event per year (prior to 2007) to 1-2 events per year after 2007

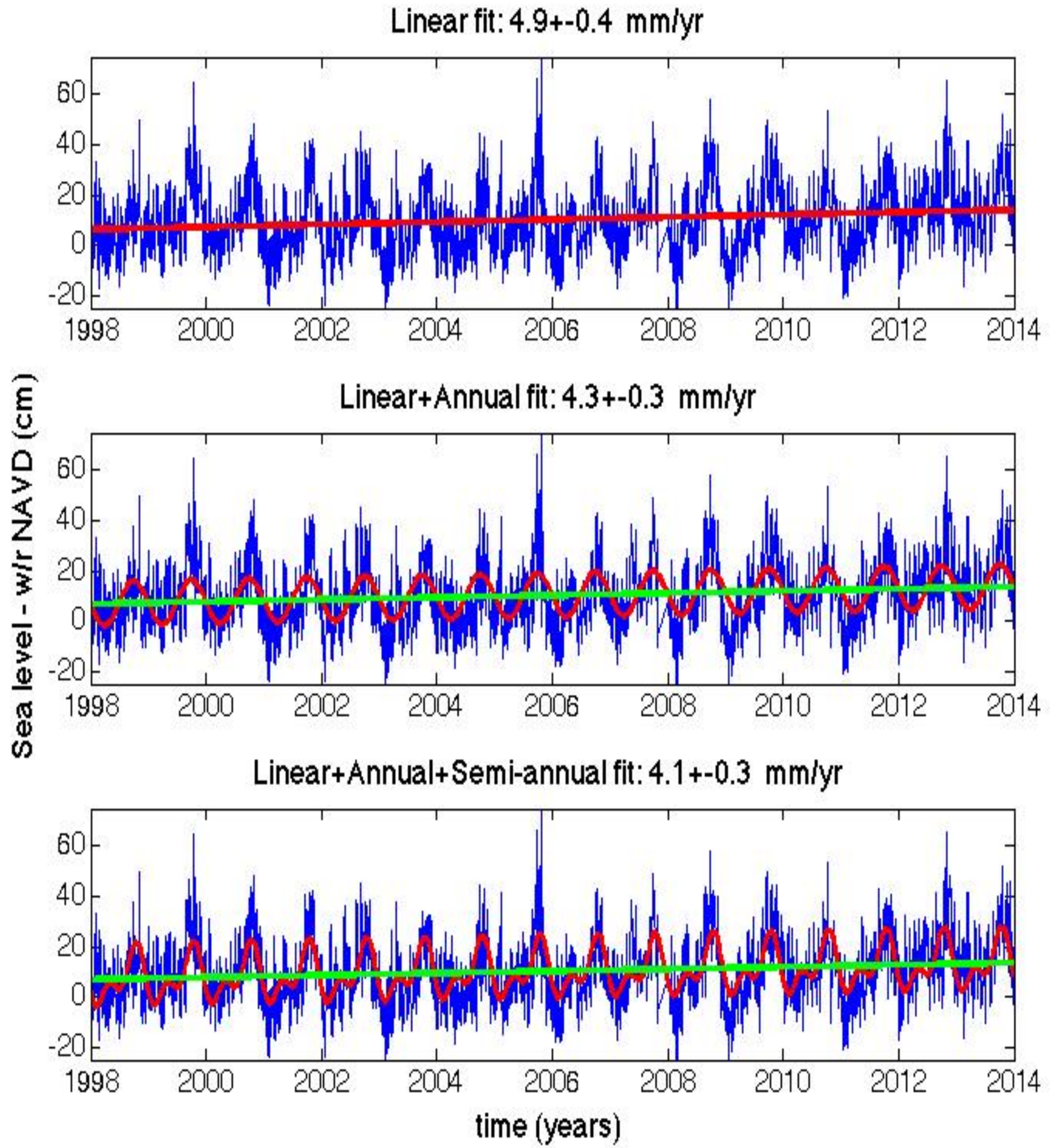
- Increased flooding frequency correlates with higher annual mean HH level at VK

Virginia Key – daily HH level



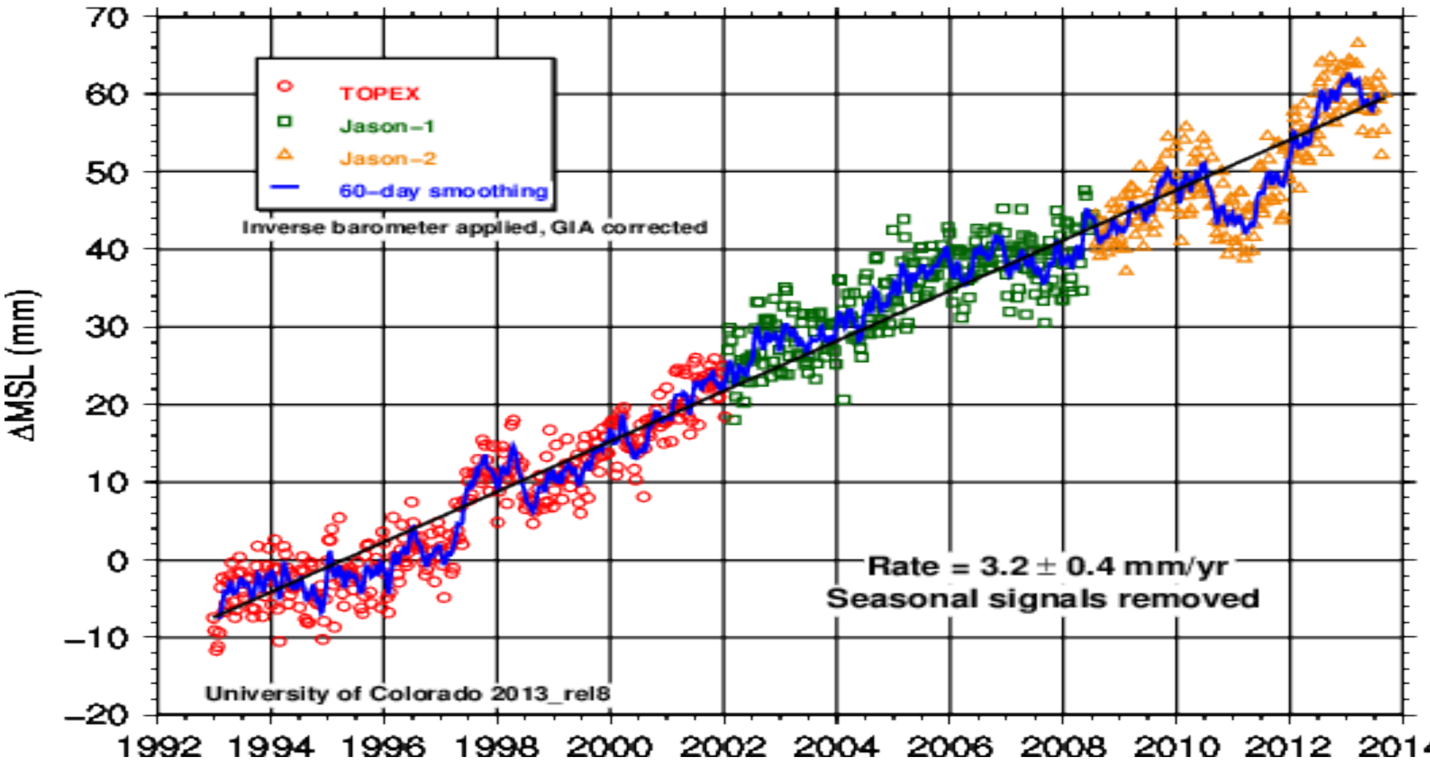


Rate of SLR depends on the fi
It reduces when annual and semi-annual terms are included.



Globally averaged rate of SLR

Calculated from satellite observations (Radar altimetry)



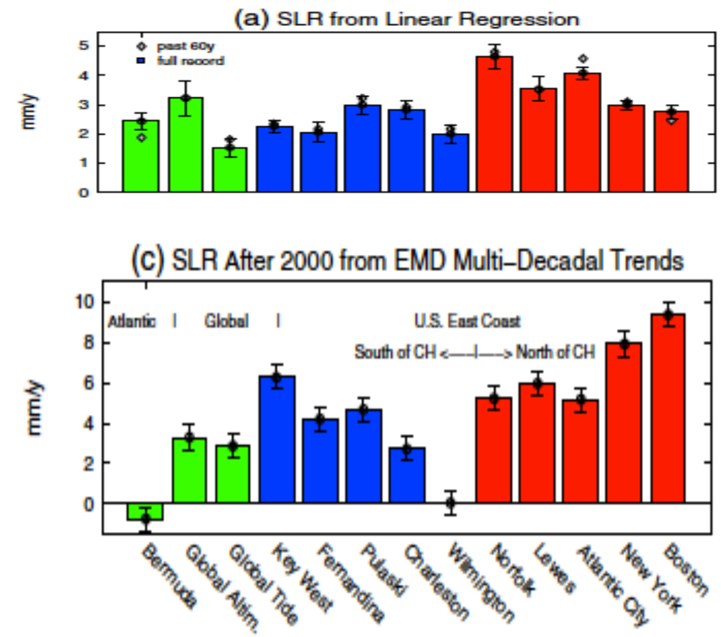
Nerem (2013)

The the rate of SLR at VK 4.1±0.3 to 4.9±0.4 mm/yr
is higher than the global average rate of 3.2±0.3 mm/yr.

Accelerating rates of SLR

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

Station	Latitude	Longitude	Period	A mean SLR (mm/y)	B SLR after 2000 (mm/y)
Boston, MA	42.35°N	71.05°W	1921-2012	2.77±0.23	9.36±0.6
New York, NY	40.70°N	74.01°W	1893-2012	3.00±0.15	7.91±0.6
Atlantic City, NJ	39.36°N	74.42°W	1911-2012	4.09±0.20	5.17±0.6
Lewes, DE	38.78°N	75.12°W	1947-2012	3.54±0.41	5.97±0.6
Norfolk, VA	36.95°N	76.33°W	1948-2012	4.66±0.41	5.22±0.6
Wilmington, NC	34.23°N	77.95°W	1935-2012	2.01±0.31	0.04±0.6
Charleston, SC	32.78°N	79.93°W	1935-2012	2.83±0.31	2.72±0.6
Ft. Pulaski, GA	32.03°N	80.90°W	1935-2012	3.00±0.31	4.67±0.6
Fernandina, FL	30.67°N	81.47°W	1939-2012	2.06±0.34	4.19±0.6
Key West, FL	24.56°N	81.81°W	1913-2012	2.27±0.21	6.26±0.6

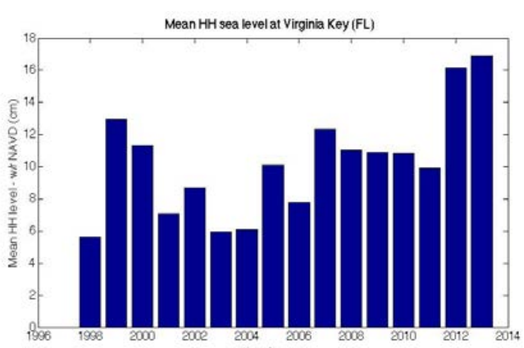


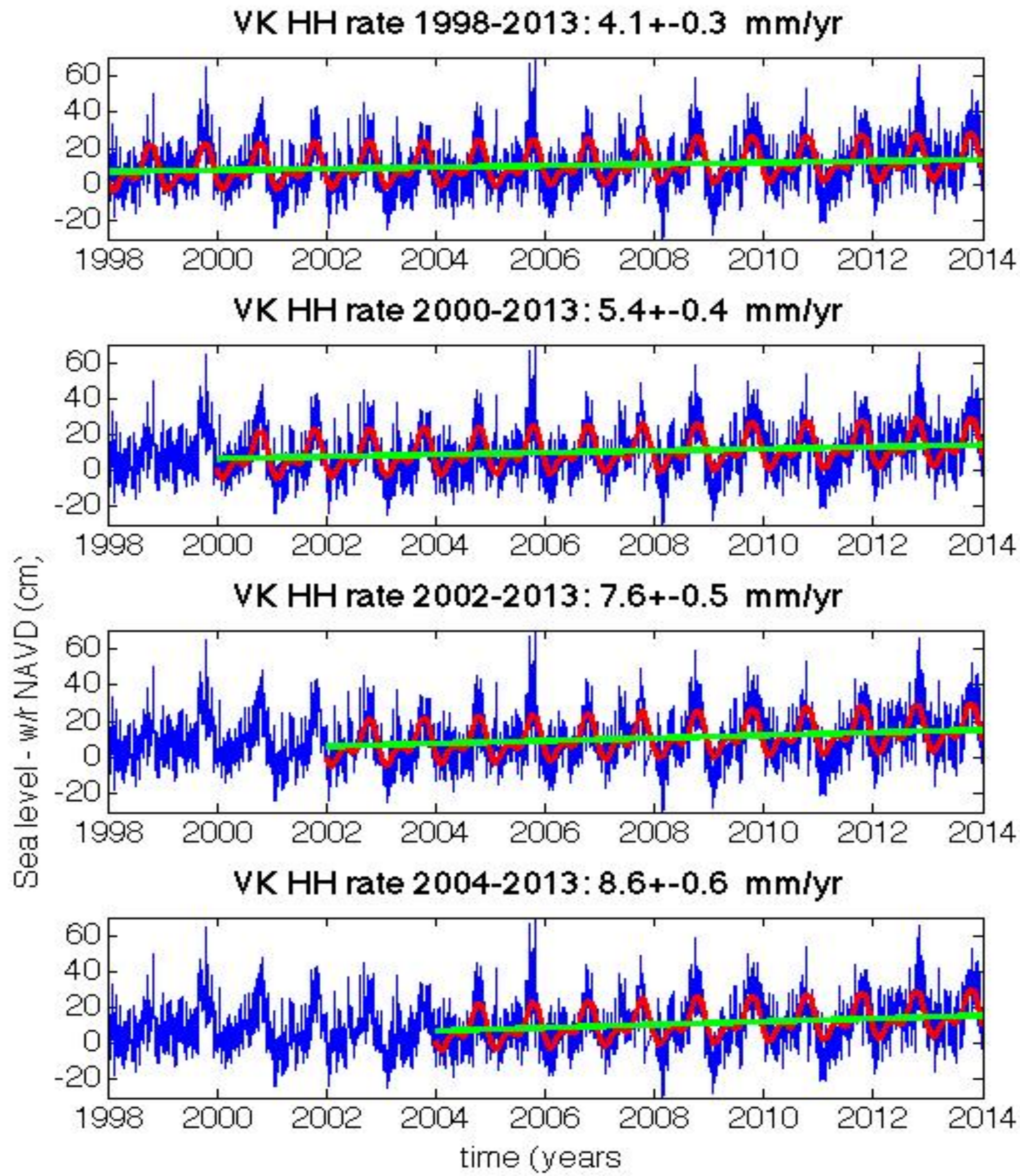
Ezer (2013)

Ezer (2013) suggested that the acceleration of SLR began in 2000.

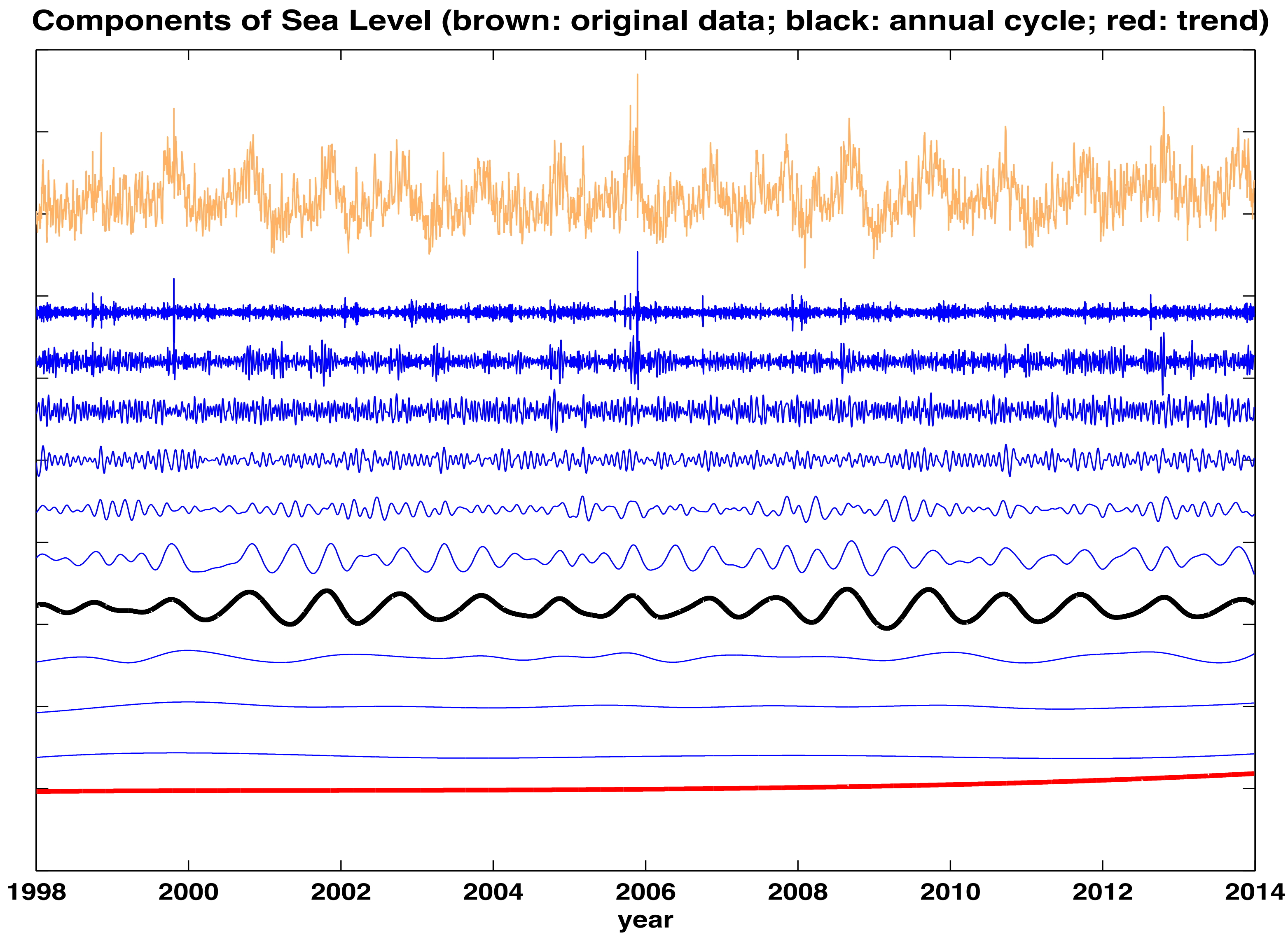
Changing the extent of the time series shows that the rate of SLR increases as the series shortens.

The observed pattern suggests that the SLR acceleration in VK began after 2004, which is supported by calculating annual mean HH levels (see histogram).





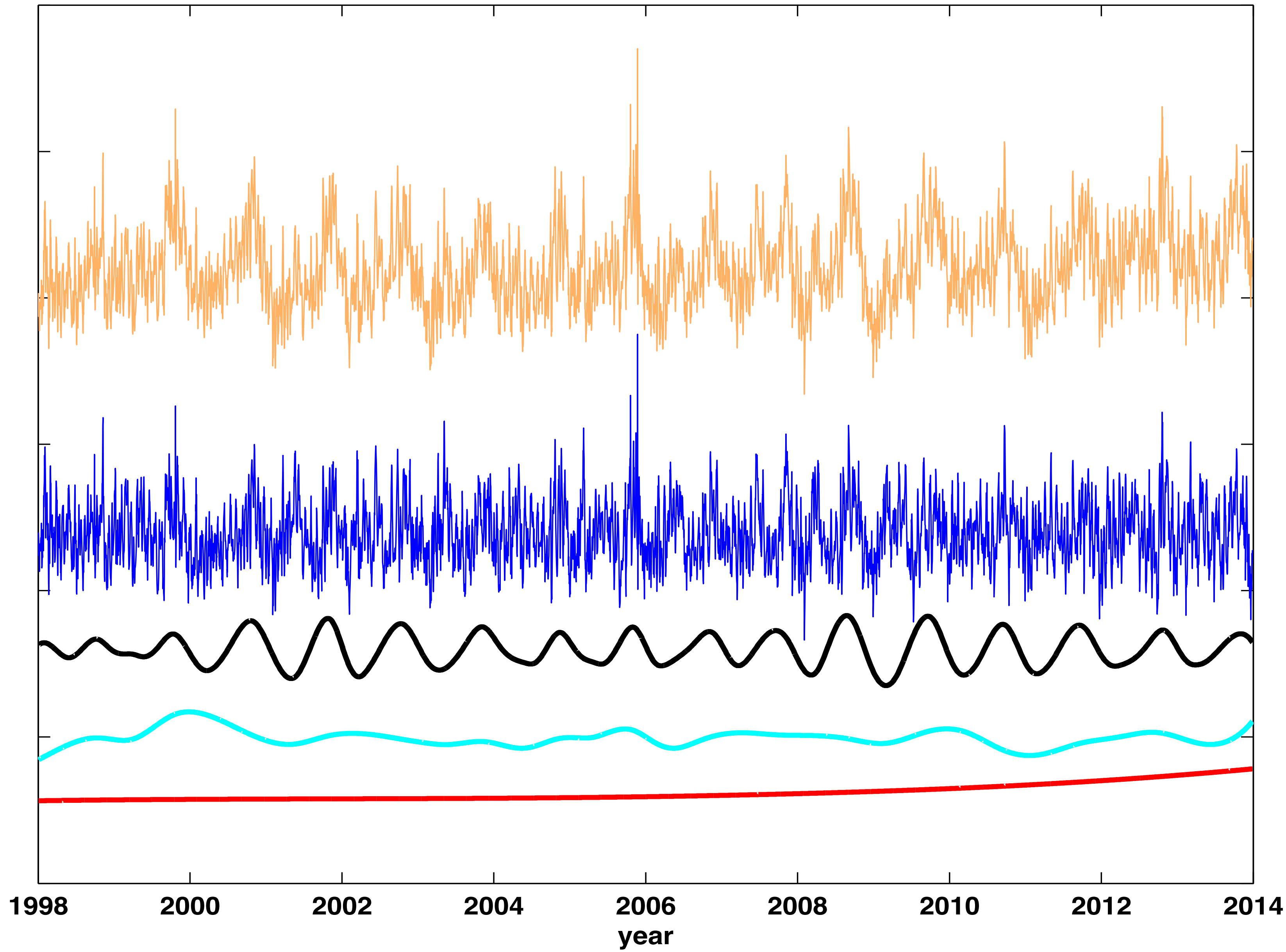
Ensemble Empirical Mode Decomposition - EEMD



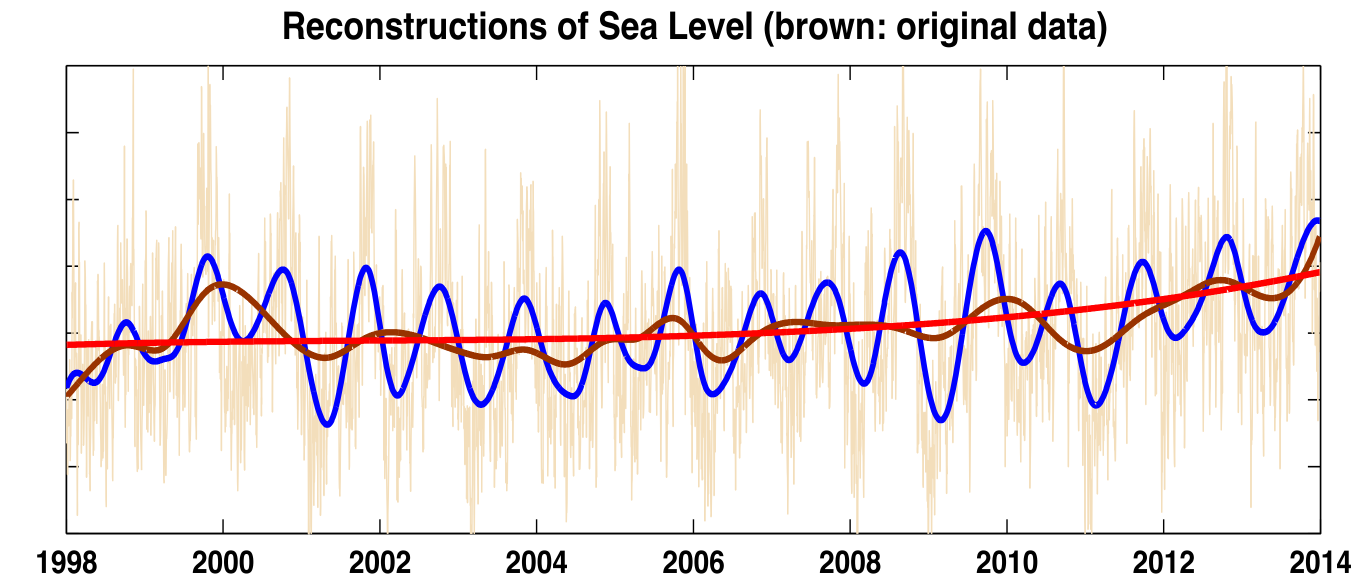
Calculated by: Zhaohua Wu (FSU)

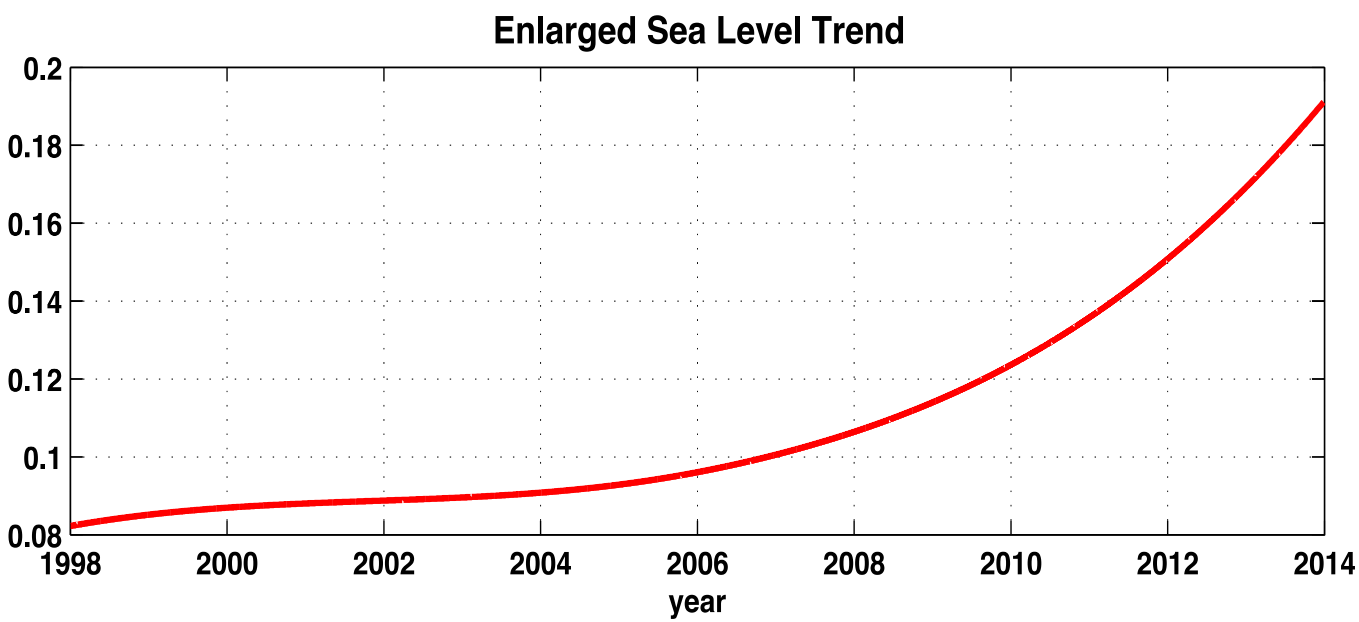
Ensemble Empirical Mode Decomposition - EEMD

EEMD as a Filter (brown: original data; blue: high fre.; black: MAC; cyan: interannual; red: trend)



EEMD – Virginia Key

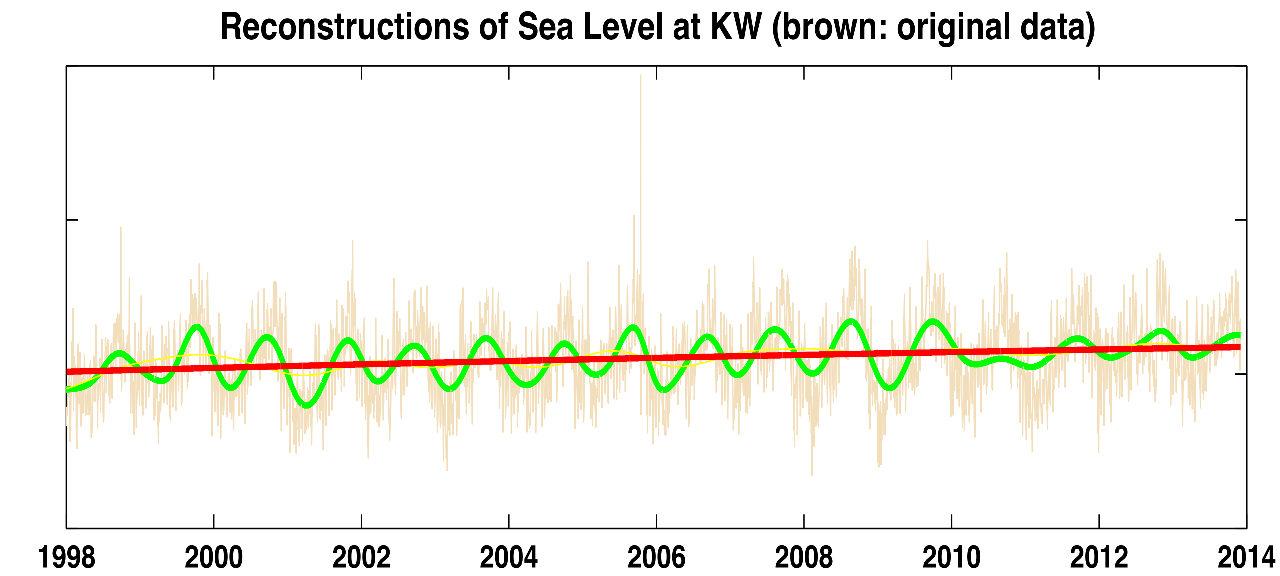


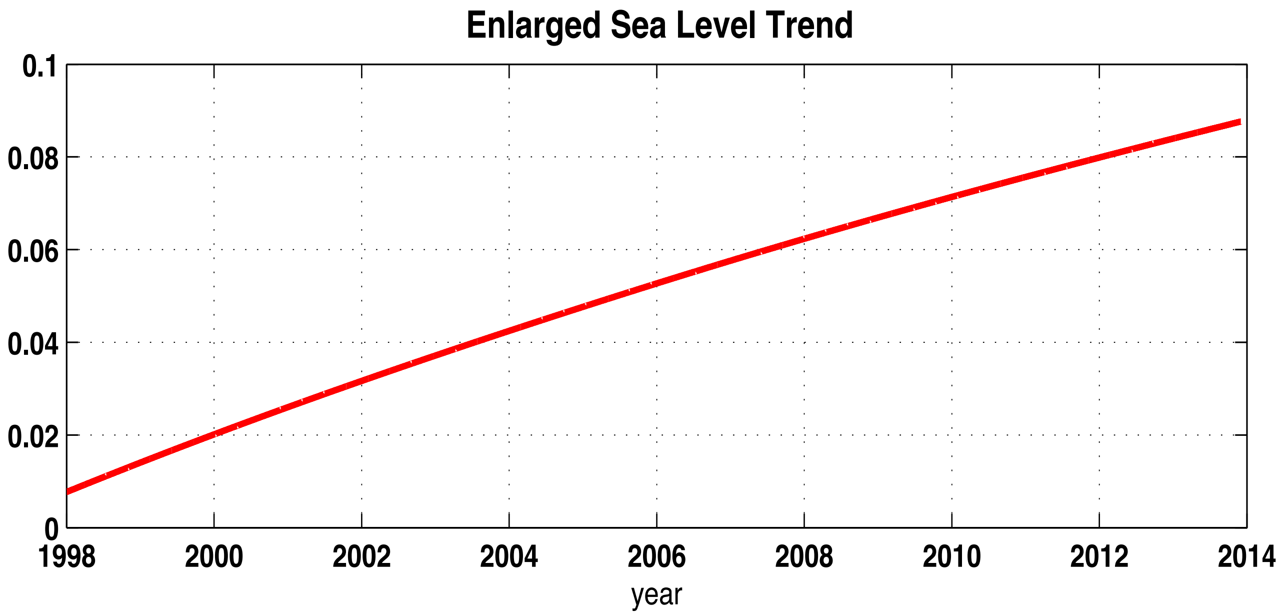


Acceleration of SLR since 2006

Total trend increase since 2006 – 10 cm

EEMD – Key West





High SLR rate since 1998

Results agree with the analysis of Ezer (2013)

Total trend increase since 1998 – 8 cm

Accelerating rates of SLR

Since 2006, the rate of SLR is even higher.

Station	1998-2013	2004- 2013
Cape Canaveral	3.1±0.6	6.3±1.0
Virginia Key	4.1±0.3	8.6±0.6
Key West	4.7±0.3	5.3±0.6
Naples	5.0±0.4	6.7±0.7

Delayed acceleration in Virginia Key and Cape Canaveral

Accelerating rates of SLR

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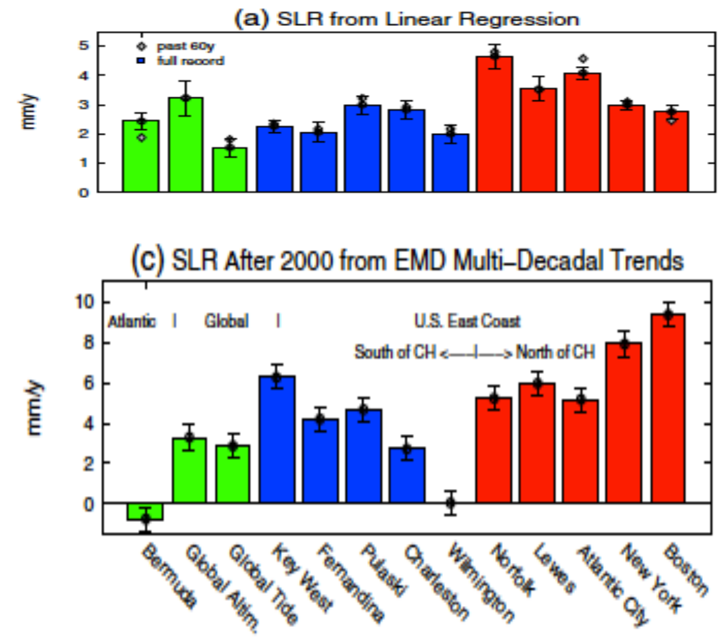
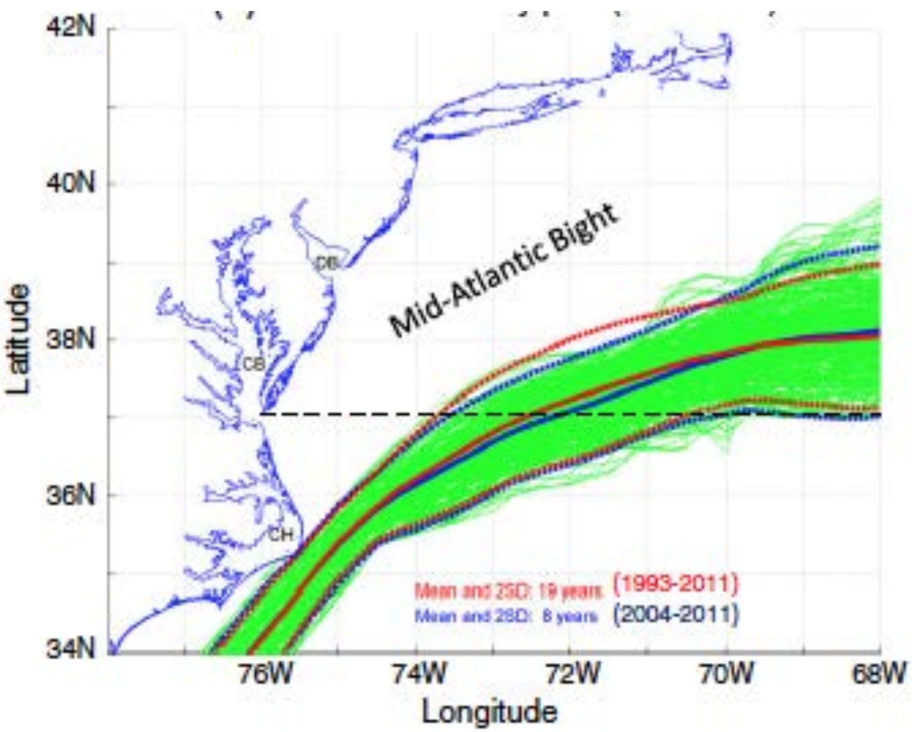


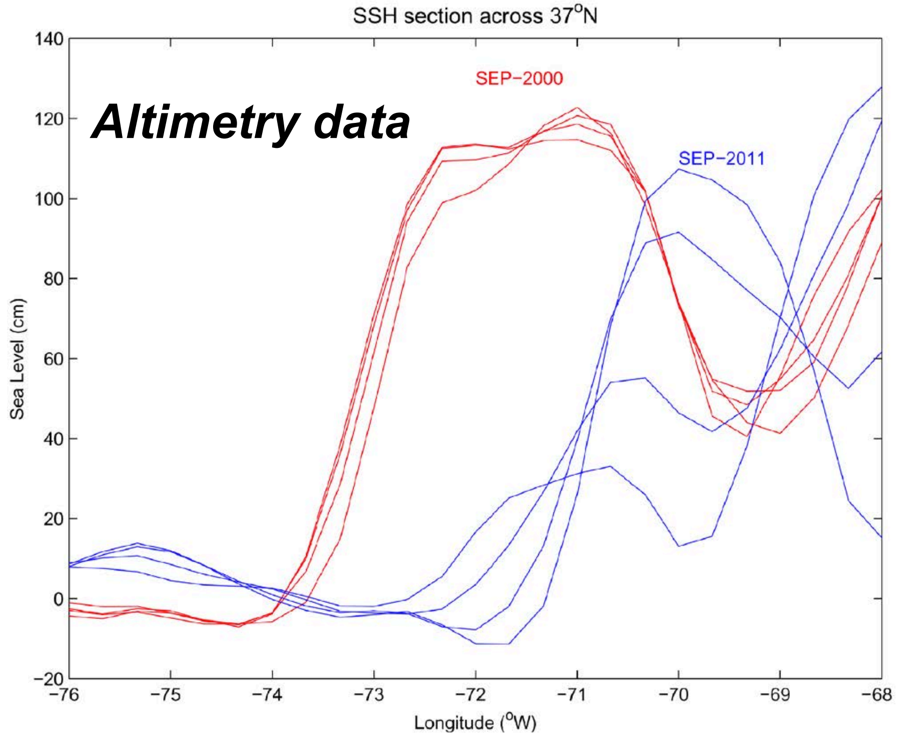
Ezer (2013)

Accelerating rates of SLR

Location of GS front (altimetry data)



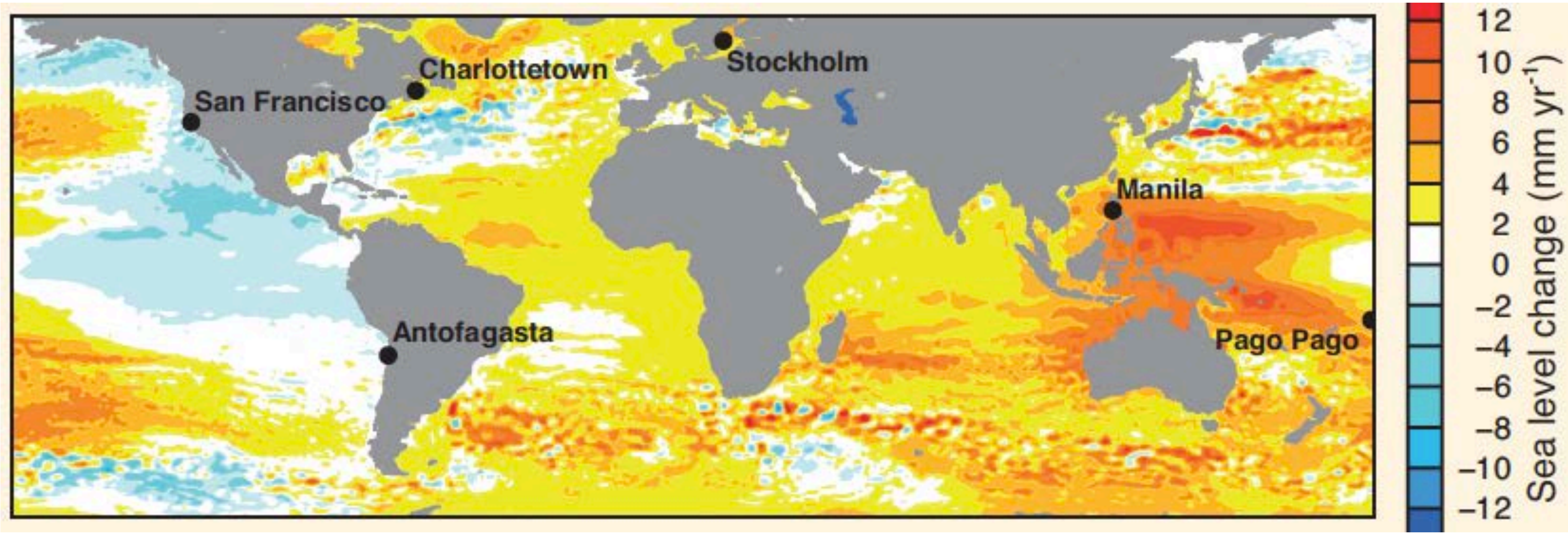
Sea level (cm)



- The Gulf Stream (GS) creates dynamic sea level topography, which is proportional to GS velocity.
- Weakening of the GS leads to the relaxation of the dynamic sea level topography and increase of near shore sea level.

Ezer et al. (2013)

Weakening of the Gulf Stream



Altimetry measurements of sea level changes (1992-2012) indicate sea level subsidence along the Gulf Stream.

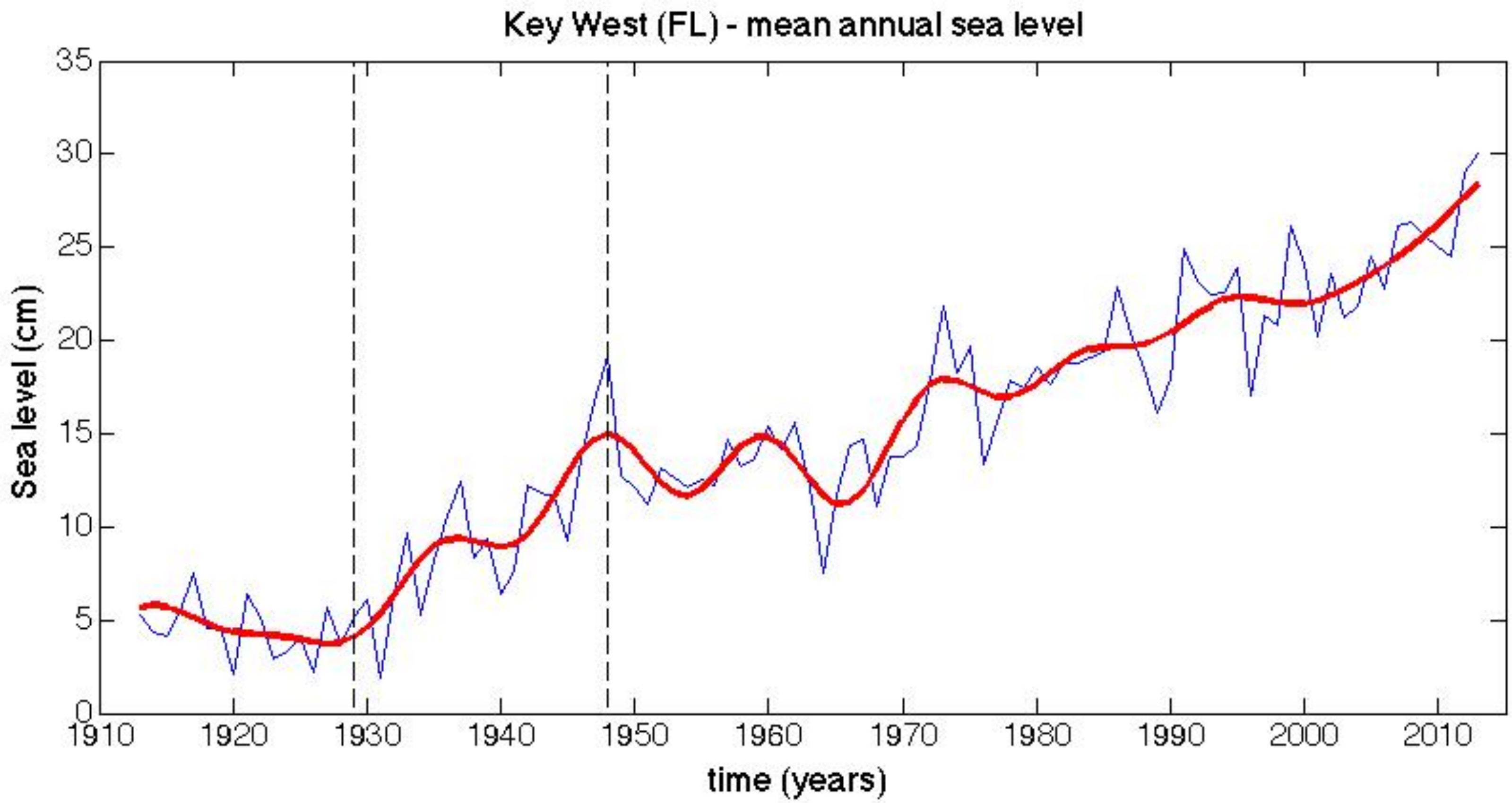
IPCC report (2013)

Accelerating rates of SLR

Ezer et al. (2013)

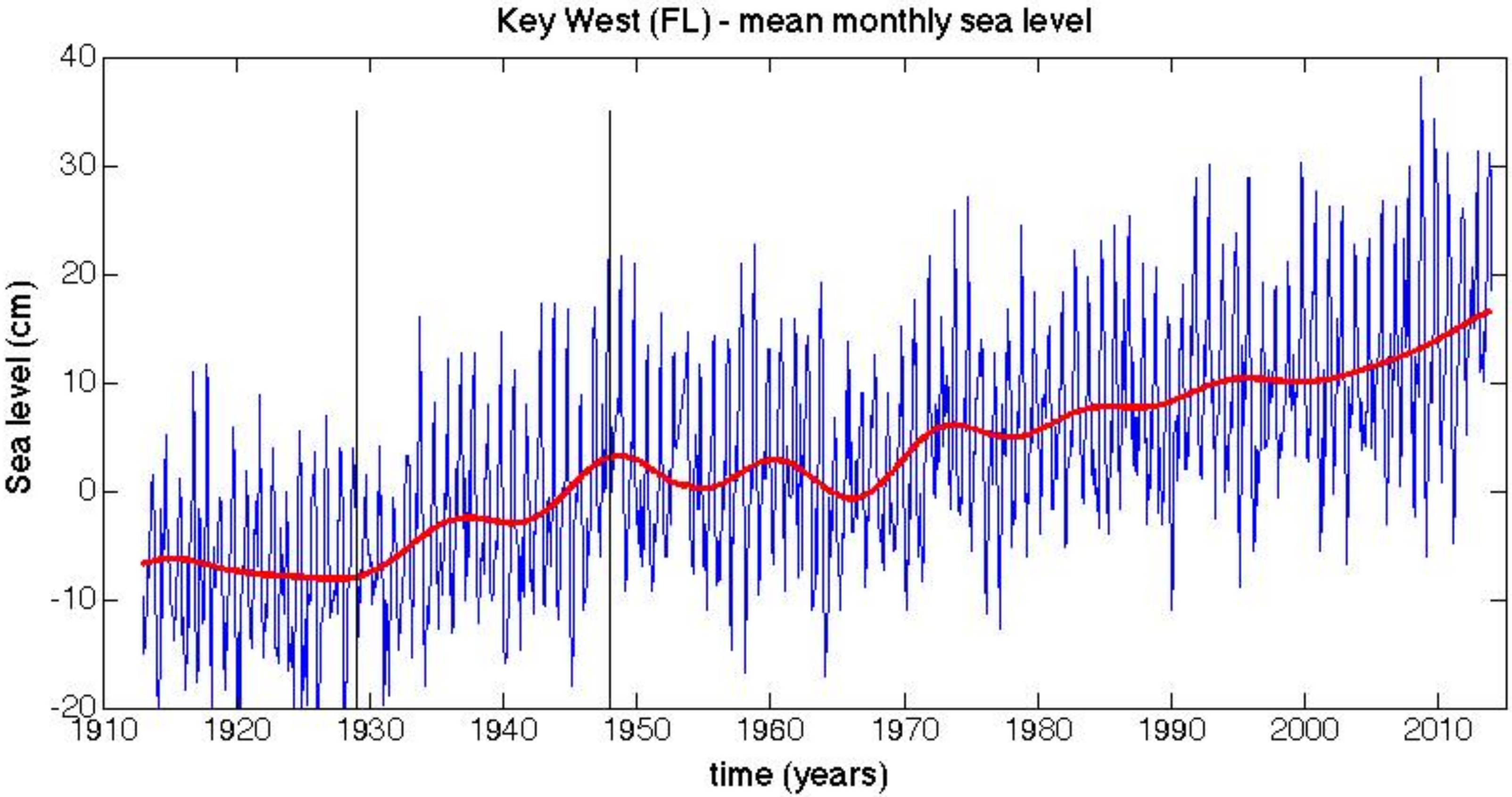
- SLR in Miami Beach and Cape Canaveral are affected by the Florida current, which flows through the Florida Straits.
- In both locations, the SLR acceleration began in 2006, several years after the acceleration started along the Gulf Stream and within the Gulf of Mexico (around 2000).
- Why?

Past SLR acceleration



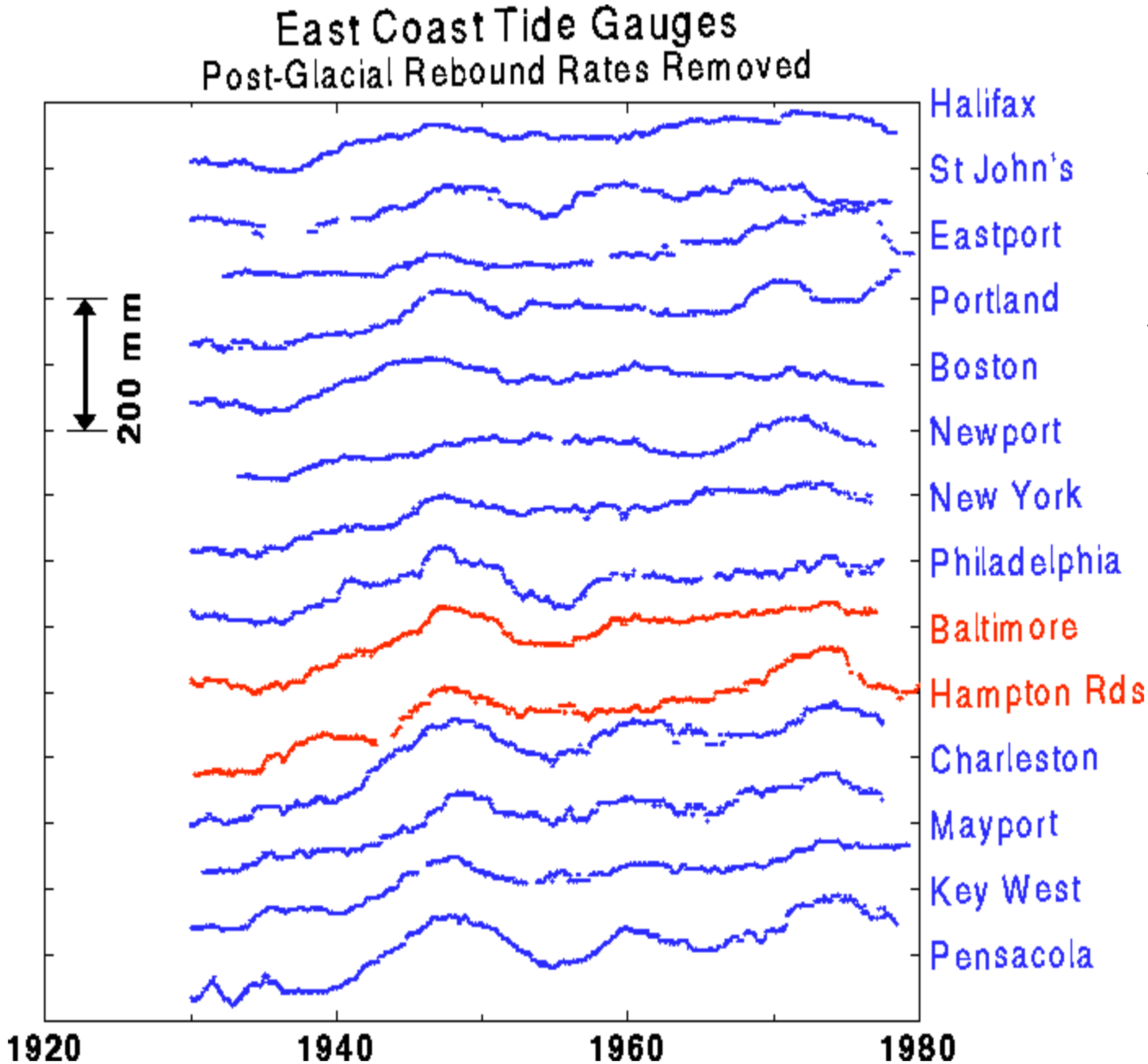
Accelerated rate of SLR along the US Atlantic coast between 1929-1948

Past SLR acceleration



Accelerated rate of SLR along the US Atlantic coast between 1929-1948

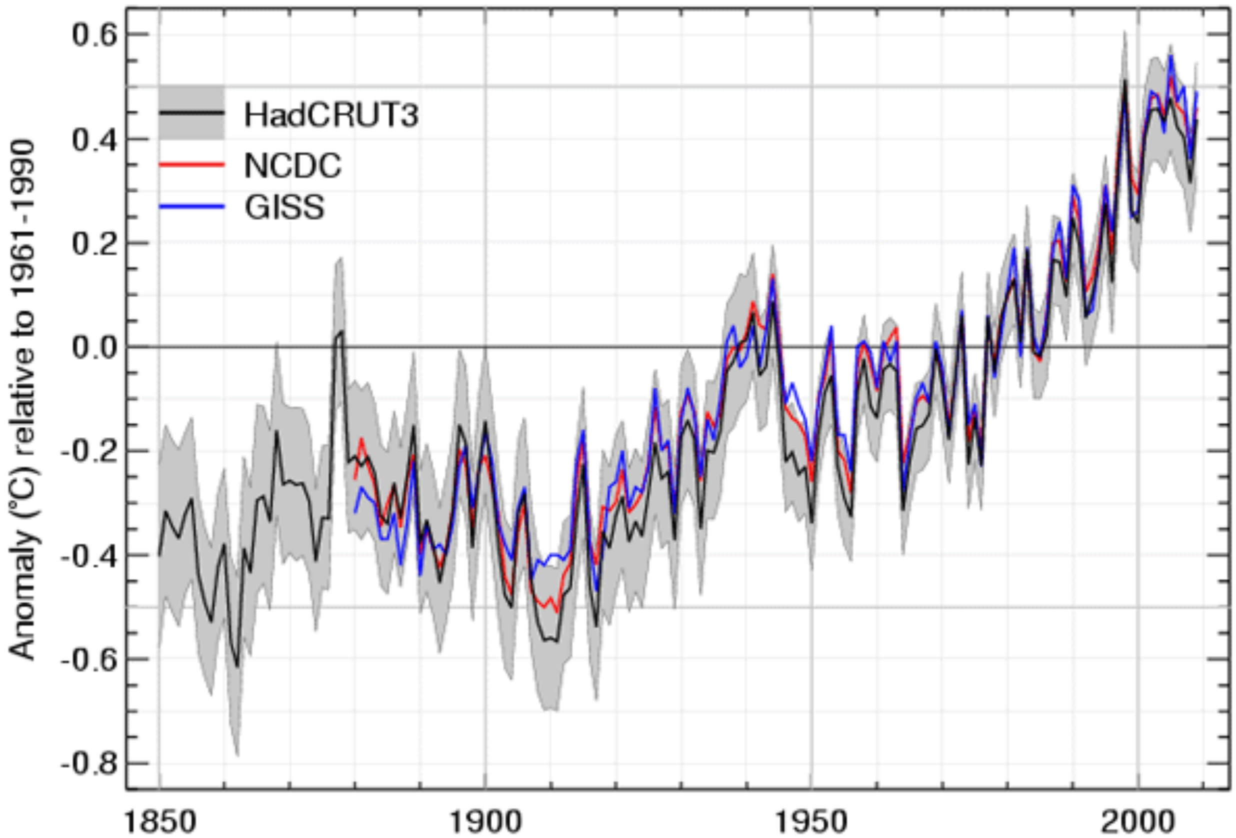
Past SLR acceleration



Accelerated rates of SLR along the US Atlantic coast between 1930-1950

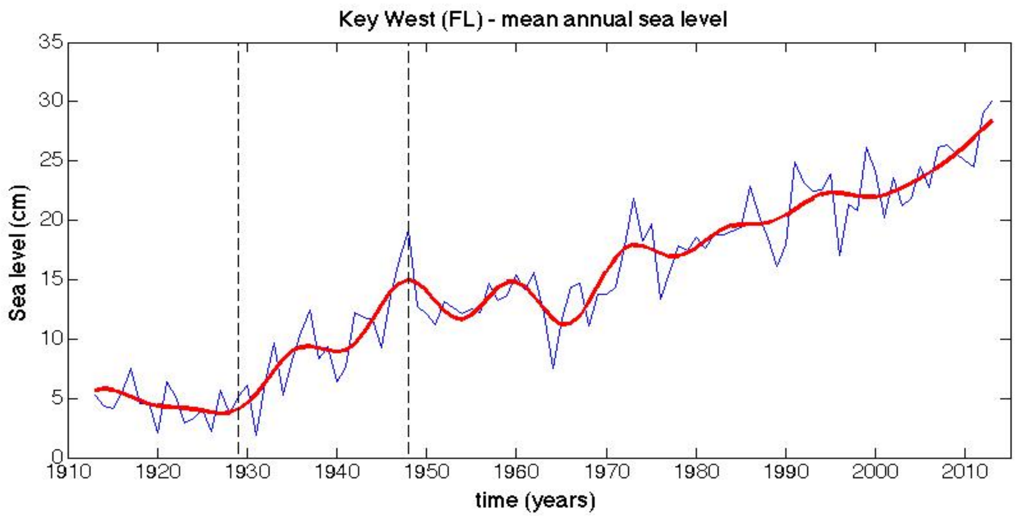
Source: NOAA page of Sea Level
https://www.ngs.noaa.gov/GRD/GPS/Projects/CB/SEALEVEL/sealevel.html

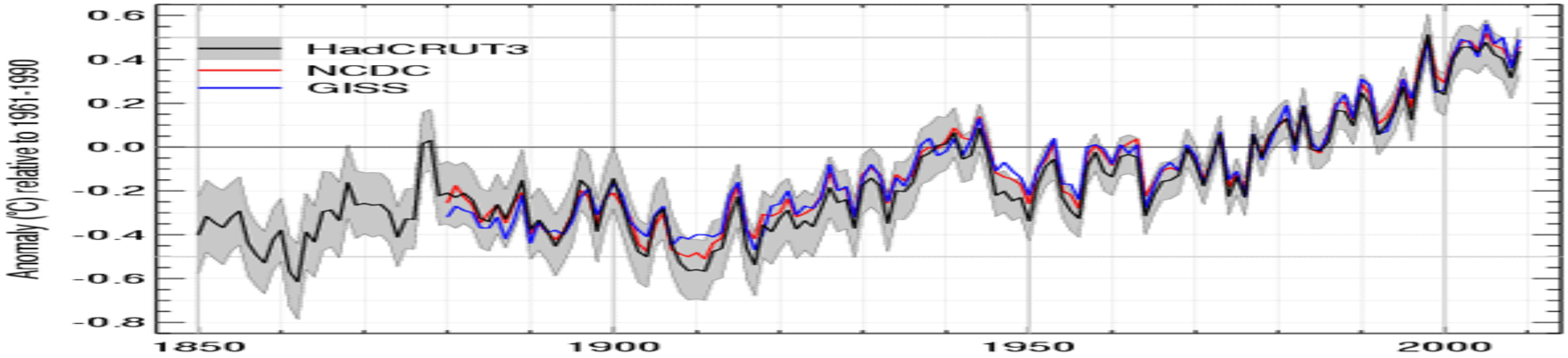
Past SLR acceleration



Global temperature 1850-2008 Average annual surface temperature, as reported independently by NOAA (*NCDC), NASA (GISS) and the Hadley Centre and Climate Research Unit of the University of East Anglia in the UK (HadCRUT3).*

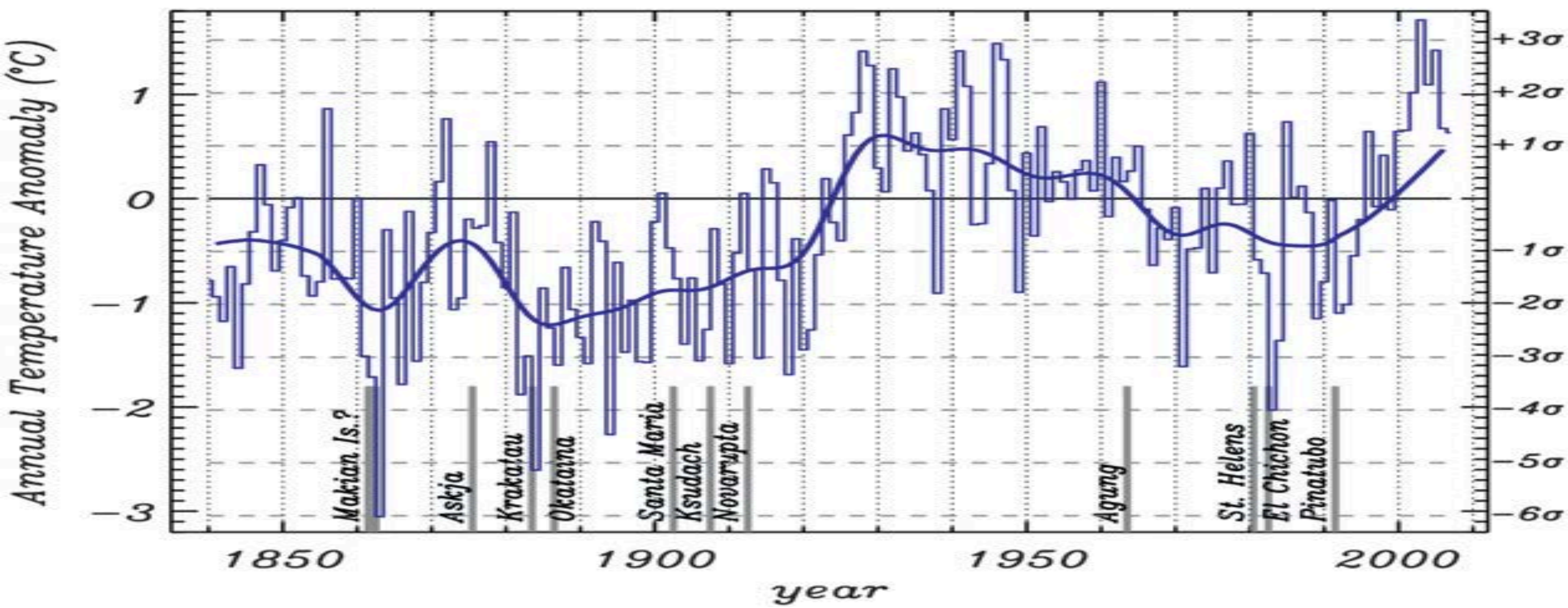
Past SLR acceleration





The high rate of SLR along the US Atlantic cost occurred between 1930-1950. It is only partly correlates with a global warming trend that occurred between1910-1940.

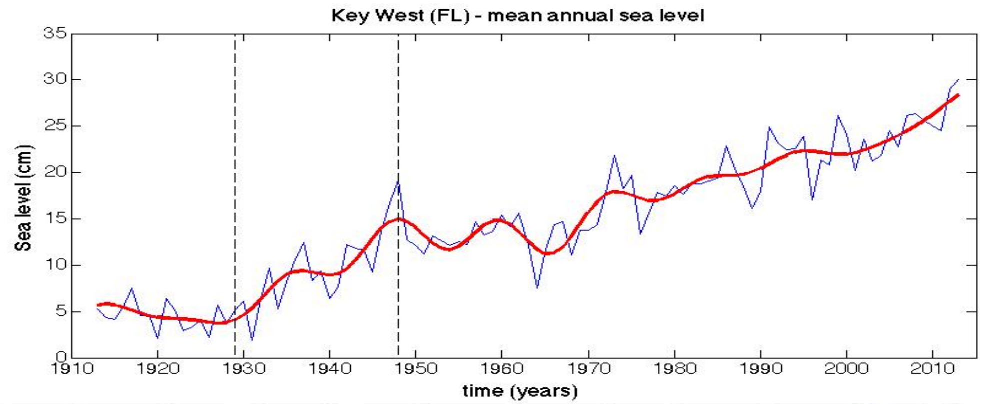
Past SLR acceleration

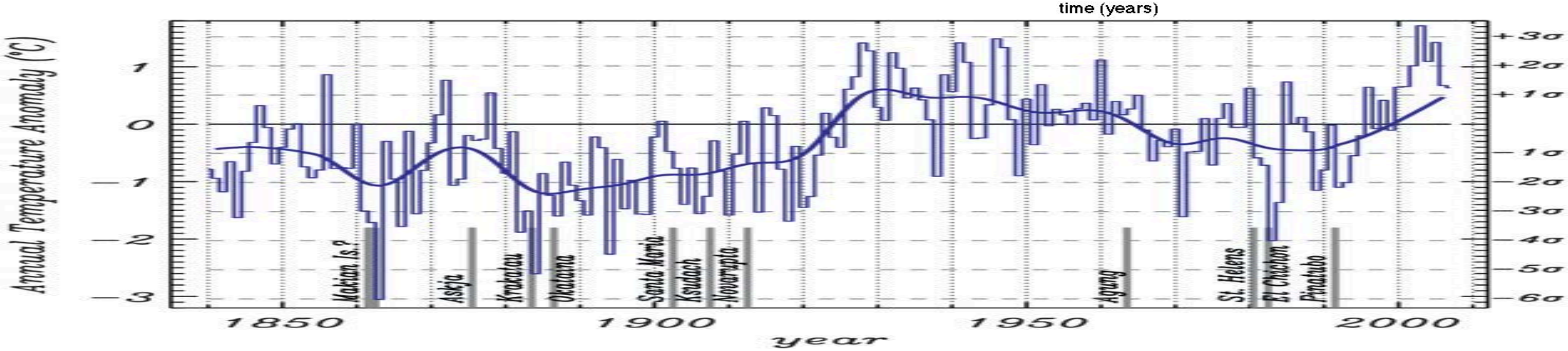


Box and Yang (2009)

During1925-1948 air surface temperatures in Greenland was anomalously high (similar to present-day temperature levels).

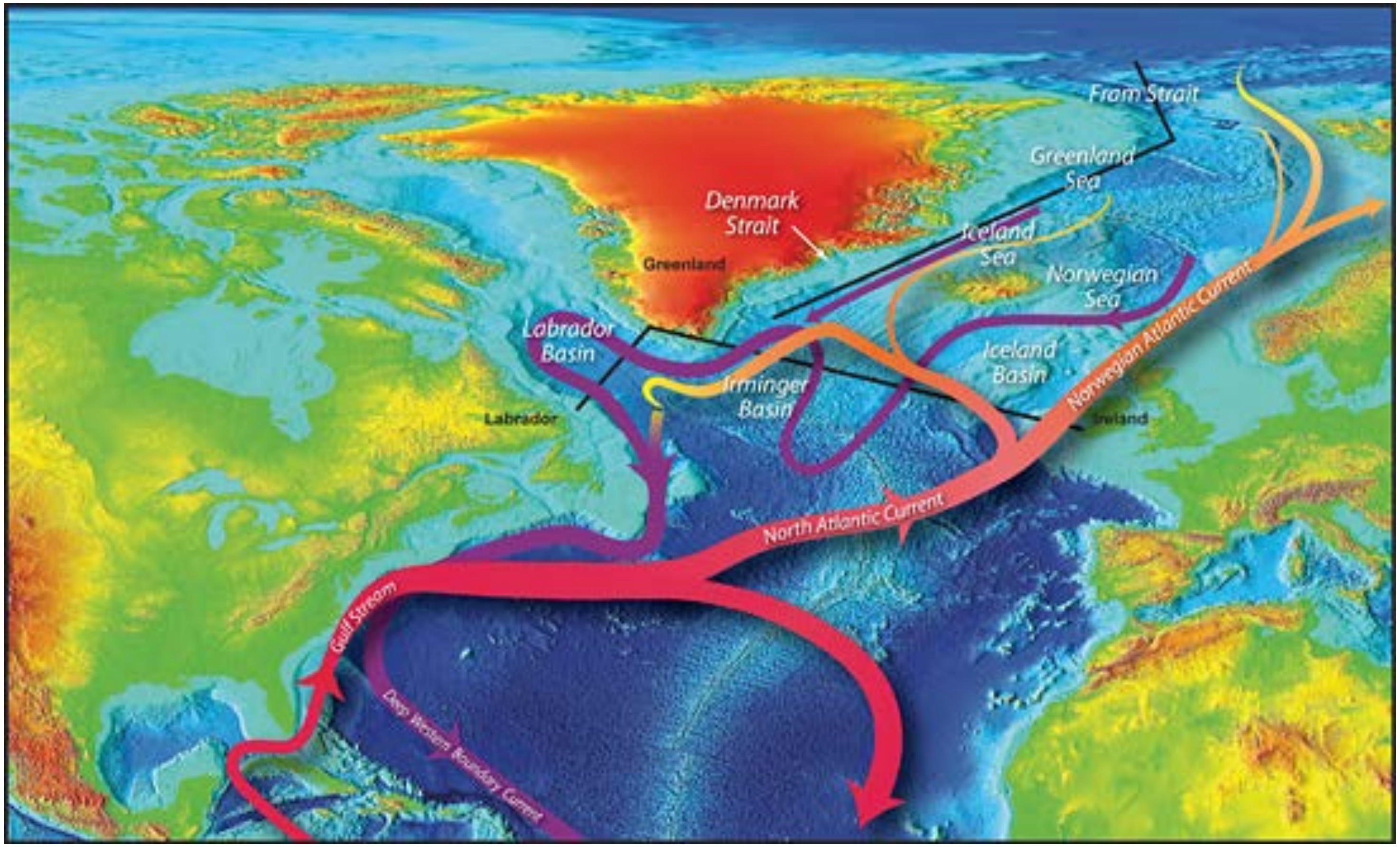
Past SLR acceleration





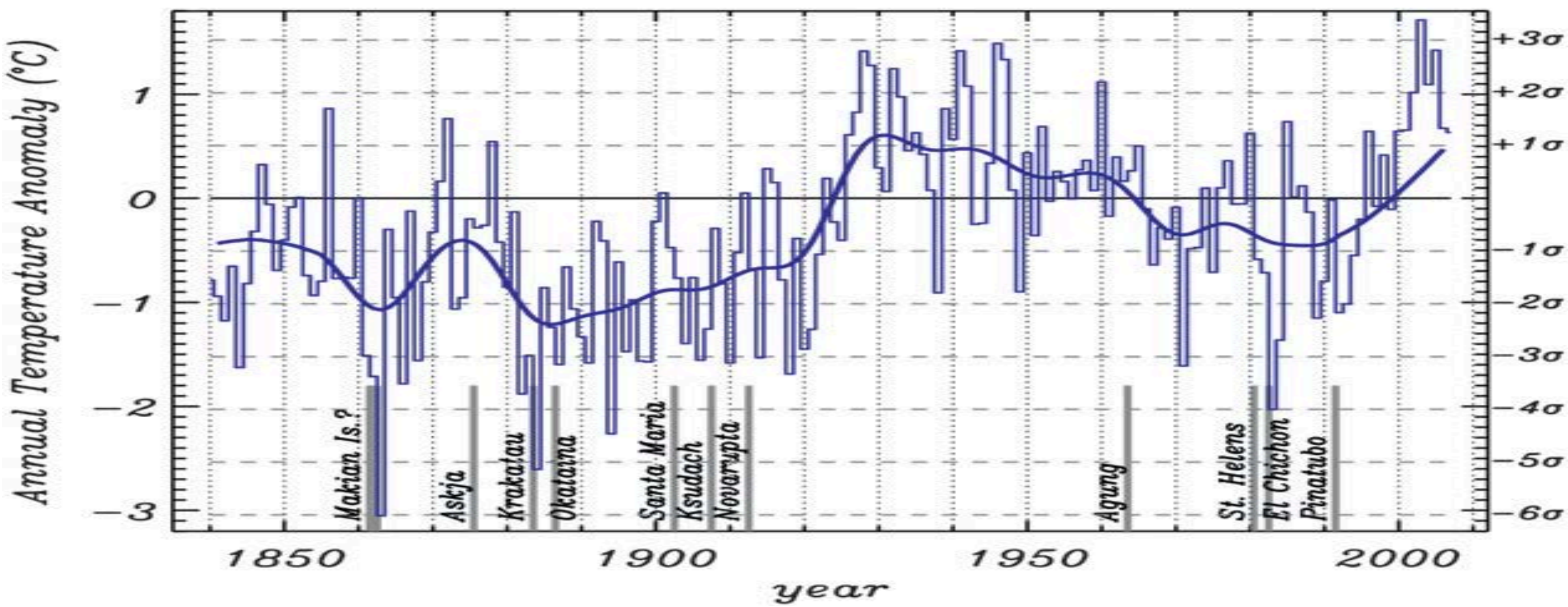
- The correlation between high air surface temperatures in Greenland and accelerated rate of SLR during 1930-1950 suggests a strong ties between rapid ice melt in Greenland, weakening of the GS, and high rates of SLR.
- There is a delay (5-8 years) between beginning of warming phase in Greenland and the acceleration of SLR along the Atlantic shores.

Atlantic Meridional Overturning Circulation (AMOC)



[Woods Hole's image of the day]

Current phase of ice melt in Greenland



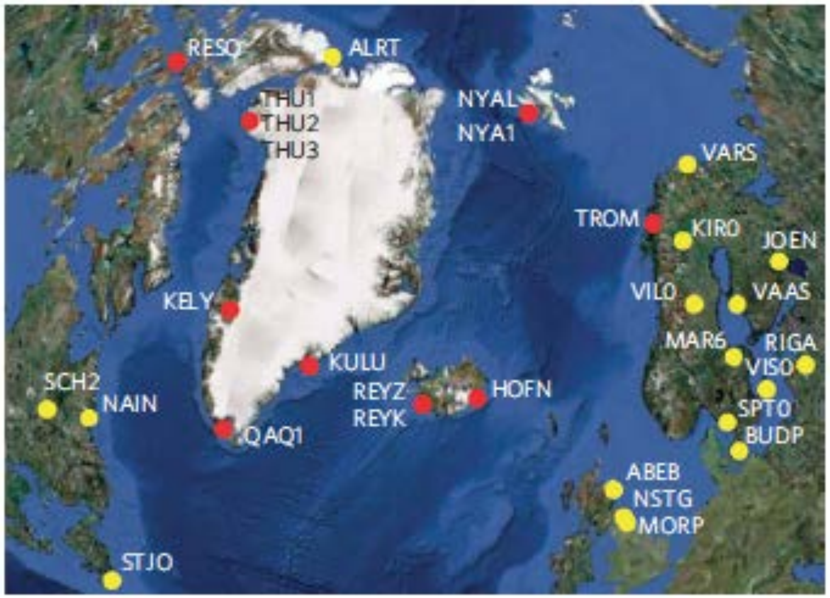
Box and Yang (2009)

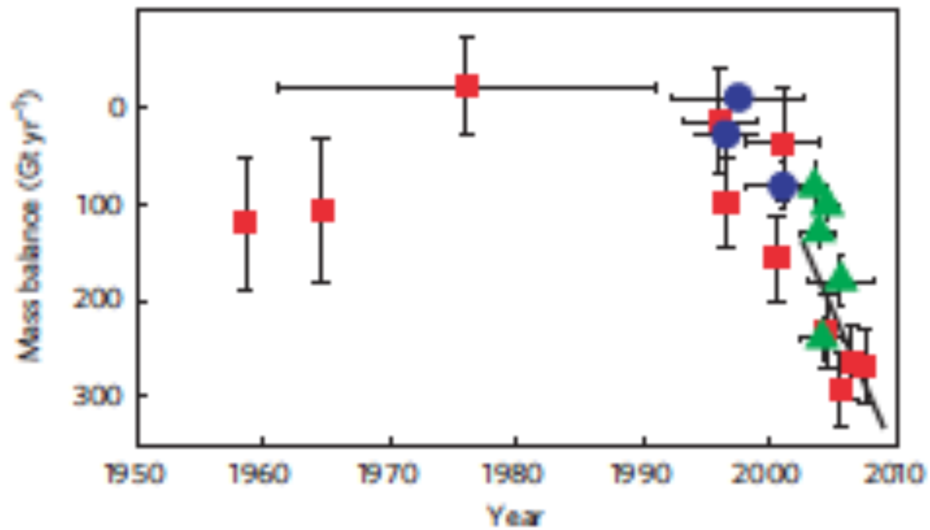
- High surface temperature in Greenland start occurring in the mid-1990's.
- Possibly ~5 year delay between ice melt in Greenland and accelerated rate of SLR along the Atlantic shores.

Current phase of ice melt in Greenland

Accelerating uplift in the North Atlantic region as an indicator of ice loss

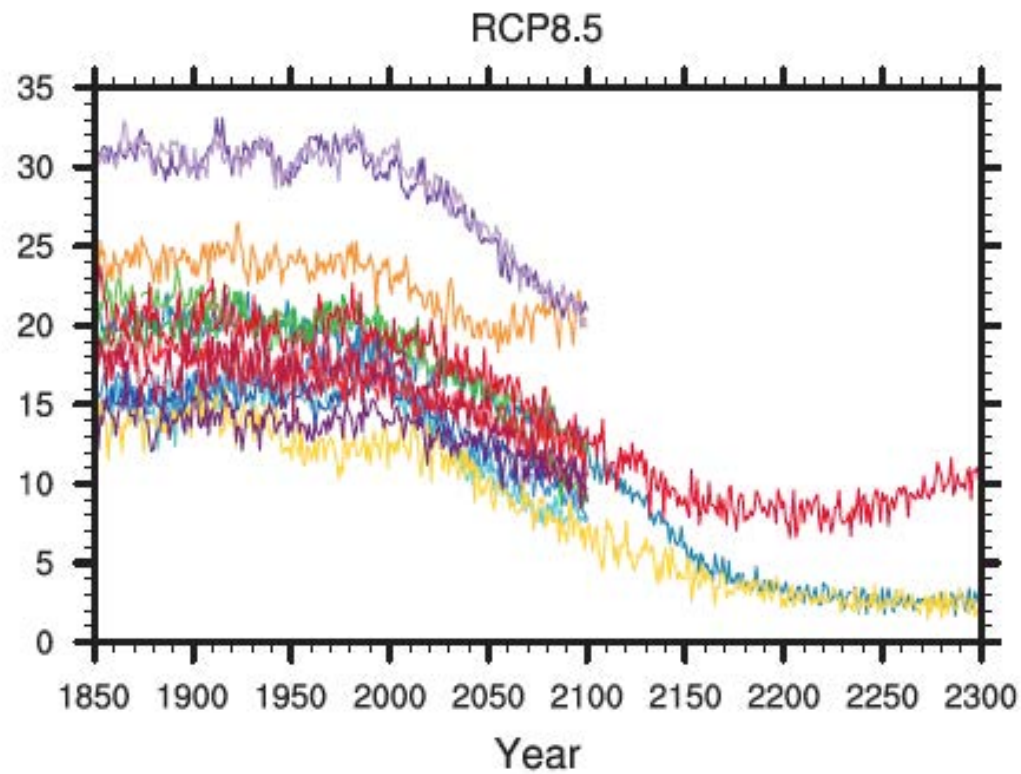
Jiang et al. (2010)





- Based on accelerated rate of crustal uplift, as measured by GPS stations, Jiang et al. (2010) suggested that the current phase of Greenland ice melt began in mid-1990’s.

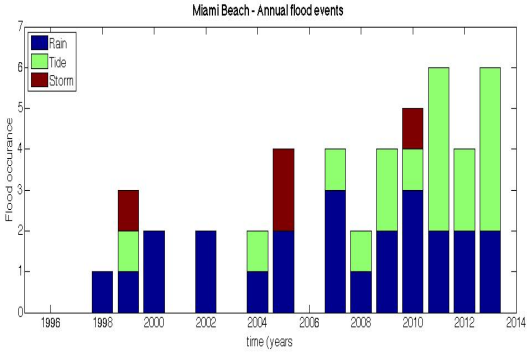
AMOC forecasting

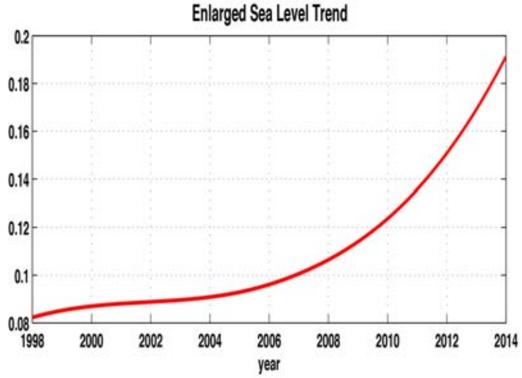


AMOC forecast according to IPCC report (2013):
Continue weakening of AMOC
⇒ Further weakening of the Gulf Stream
⇒ High rates of SLR along the US Atlantic shores
(higher than average global rates)

Summary - I

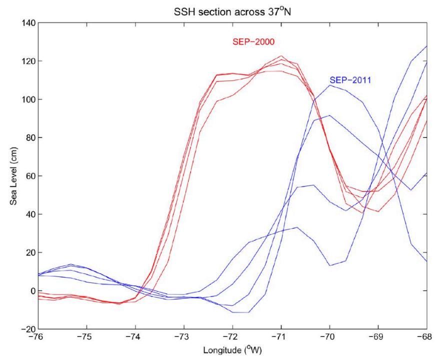
- Flooding frequency in Miami Beach increased since 2006
- The local rate of SLR in Miami since 2006 is > 8 mm/yr, almost three times higher than the average global rate.
- Since 2006 local sea level in Miami rose by ~ 10 cm, causing more frequent rain and tide ("sunny sky") flooding events.
- The Miami-Beach $400 million engineering project may work during rain-induced flood events, but will be less efficient in tide-induced events.



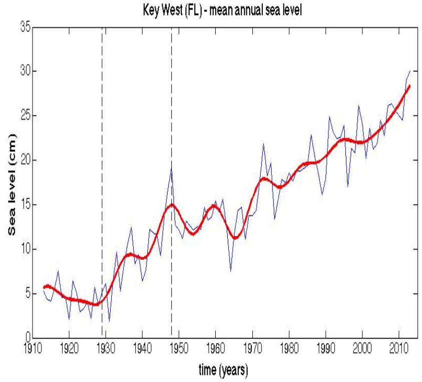


Summary - II

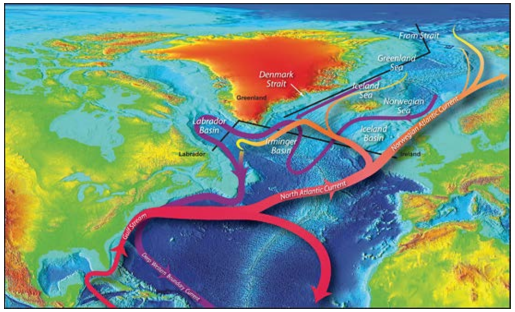
- The accelerating rate of SLR in Miami is consistent with similar rates found along the US Atlantic coast, and are caused by the weakening of the Gulf Stream.



- A similar period of accelerating rates of SLR occurred along the US Atlantic coast between 1930-1950. It is correlated with a period of anomalously high surface air temperature in Greenland.



- We suggest that the increasing rate of ice melt in Greenland affects the AMOC, weakens the Gulf Stream, increases the rate of SLR along the US Atlantic shores, and consequently increases flooding frequency in Miami Beach.



Acknowledgements

- **Tide gauge data** - NOAA
- **Flood Claim record**
  Marcia Steelman, Miami-Dade County Public Works
- **Additional flood documentation - Pictures Miami Beach**
  Elizabeth Wheaton and Margarita Wells – City of Miami Beach, Public Works Department

  Christine Borski - City of Miami Beach, Office of the City Manager
- **EEMD calculations** - Zhaohua Wu (FSU)