ODU Climate Change and Sea Level Rise Initiative

STAC Workshop
Annapolis, MD
Mar 7, 2016

Sea level rise in the Chesapeake Bay area: causes, trends and future projections

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Old Dominion University, **Norfolk*, VA**, USA

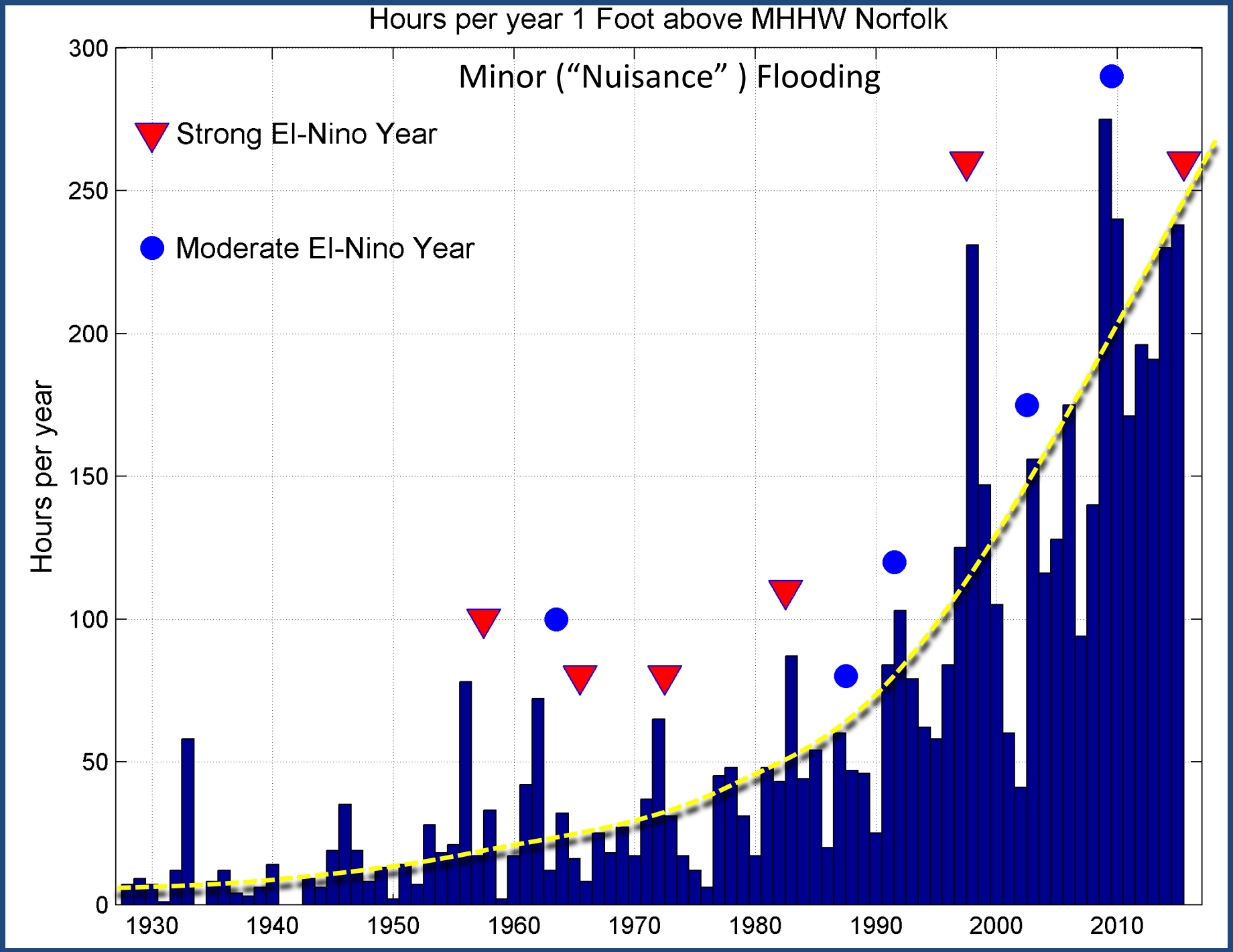
* "Norfolk has been ranked second only to New Orleans among U.S. coastal cities threatened by flooding"

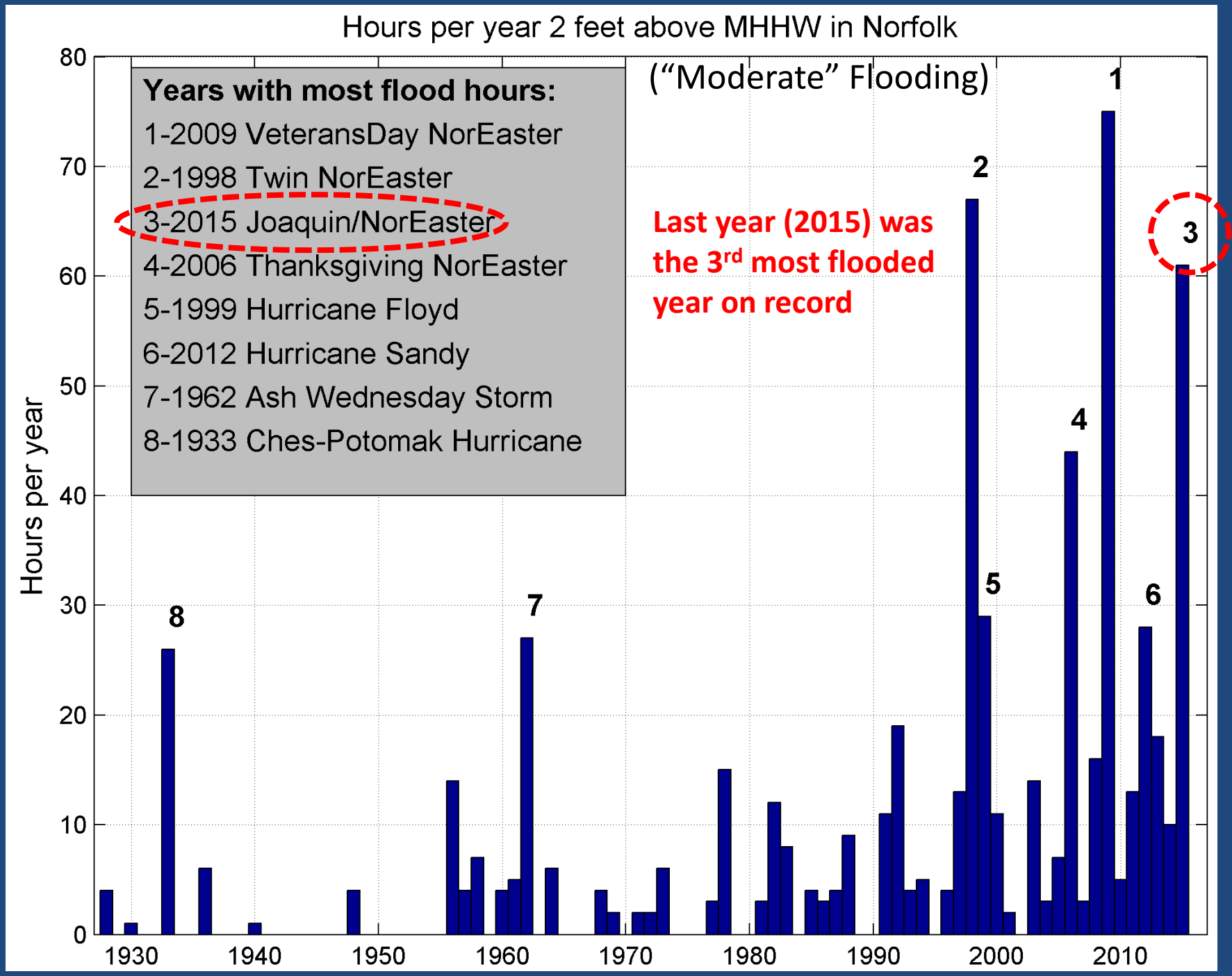
What sea level rise looks like today: Historic Hague neighborhood of Norfolk, VA

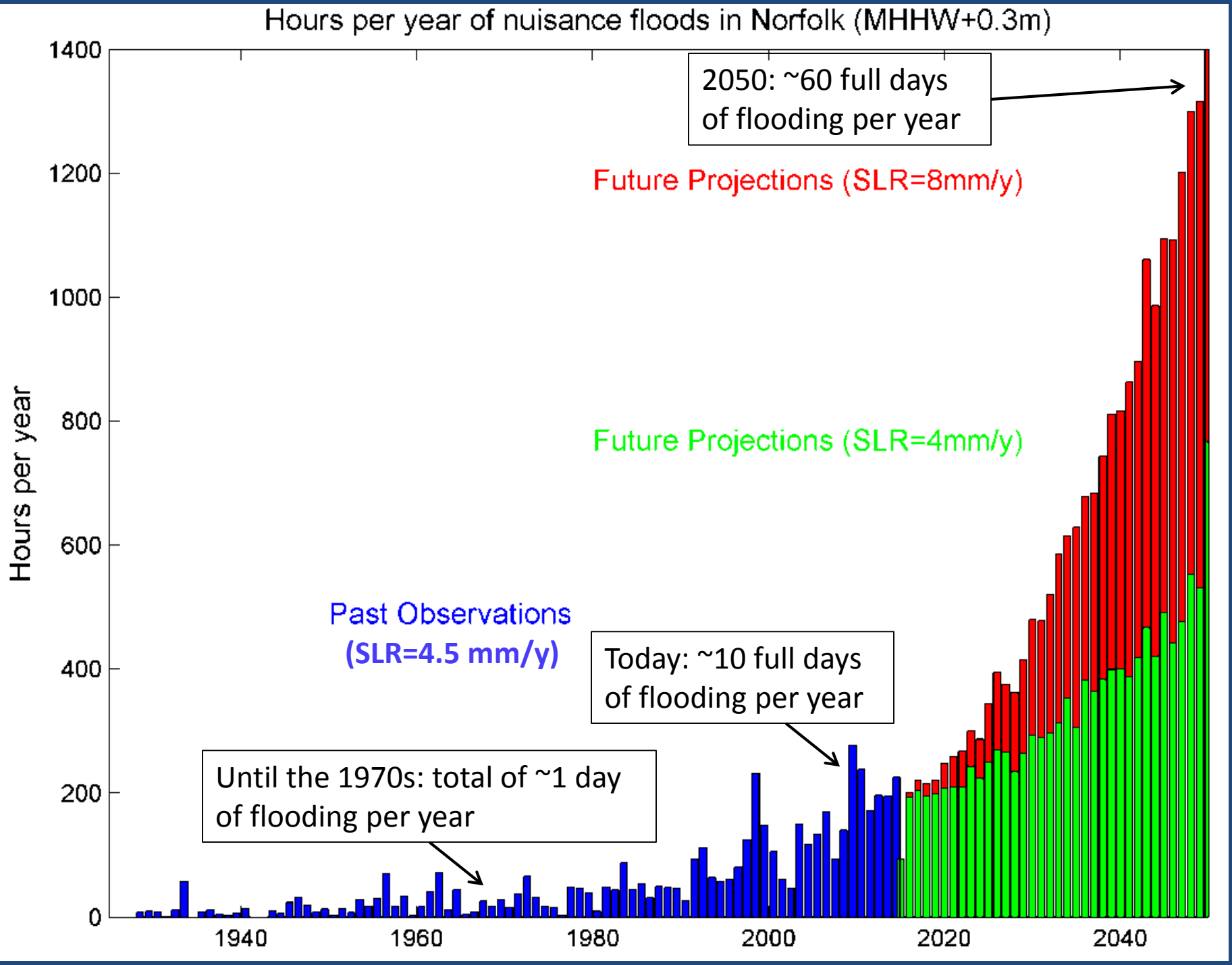
Raising houses in flood-prone streets of Norfolk

Cost: ~$100,000 per house

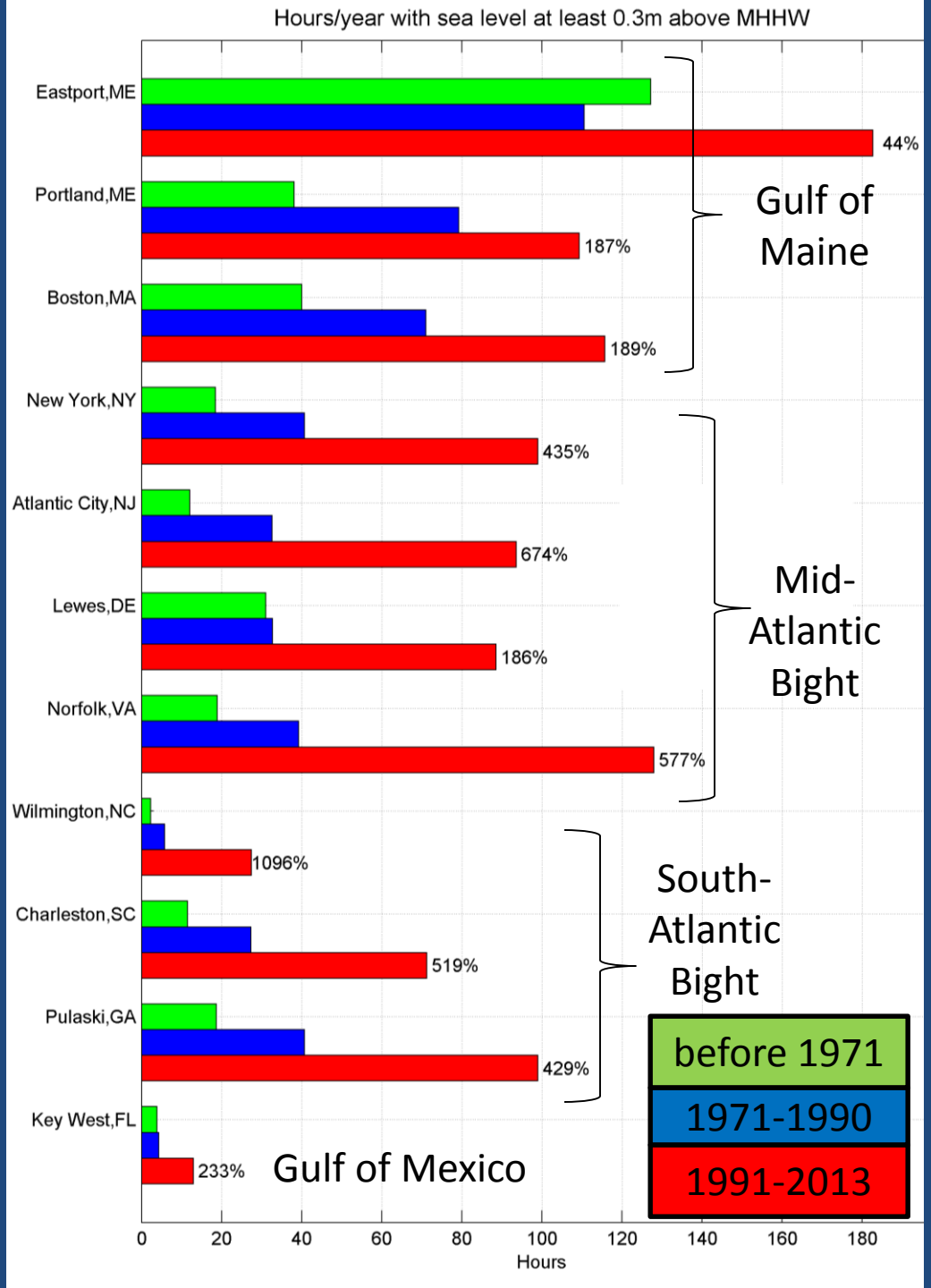
Repetitive flood damage claims in Norfolk:
(source: Norfolk City Planning Dept.)
2009- ~200 claims
2011- ~750 claims
2012- ~900 claims


Hours per year 1 Foot above MHHW Norfolk
Minor (“Nuisance”) Flooding
Strong El-Nino Year
Moderate El-Nino Year
Hours per year
300
250
200
150
100
50
0
1930
1940
1950
1960
1970
1980
1990
2000
2010


Hours per year 2 feet above MHHW in Norfolk
("Moderate" Flooding)
Years with most flood hours:
1-2009 VeteransDay NorEaster
2-1998 Twin NorEaster
3-2015 Joaquin/NorEaster
4-2006 Thanksgiving NorEaster
5-1999 Hurricane Floyd
6-2012 Hurricane Sandy
7-1962 Ash Wednesday Storm
8-1933 Ches-Potomak Hurricane
Last year (2015) was the 3rd most flooded year on record
Hours per year
0
10
20
30
40
50
60
70
80
1930
1940
1950
1960
1970
1980
1990
2000
2010
1
2
3
4
5
6
7
8

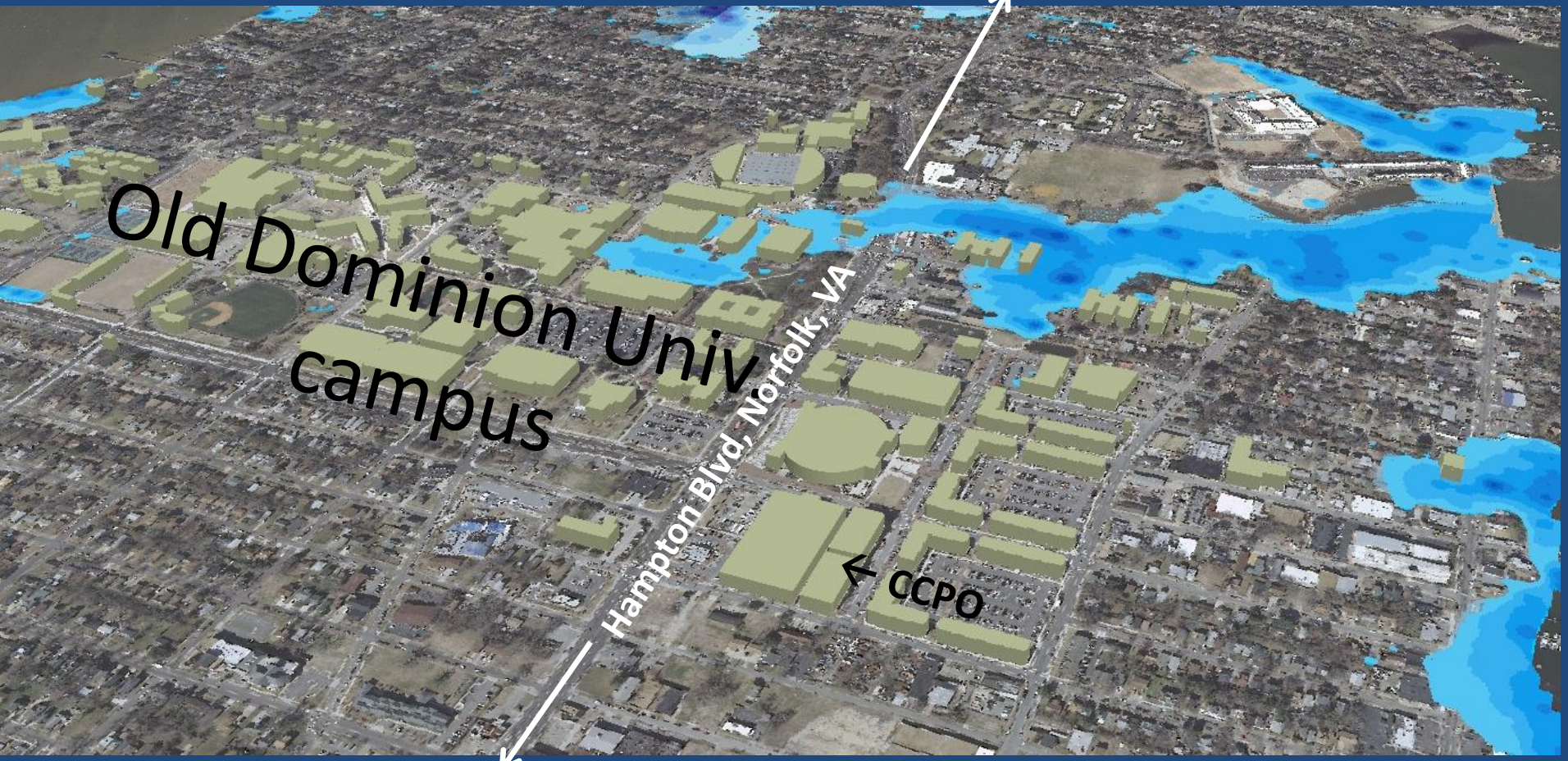

Hours per year of nuisance floods in Norfolk (MHHW+0.3m)
Hours per year
1400
1200
1000
800
600
400
200
0
1940
1960
1980
2000
2020
2040
2050: ~60 full days of flooding per year
Future Projections (SLR=8mm/y)
Future Projections (SLR=4mm/y)
Past Observations (SLR=4.5 mm/y)
Today: ~10 full days of flooding per year
Until the 1970s: total of ~1 day of flooding per year

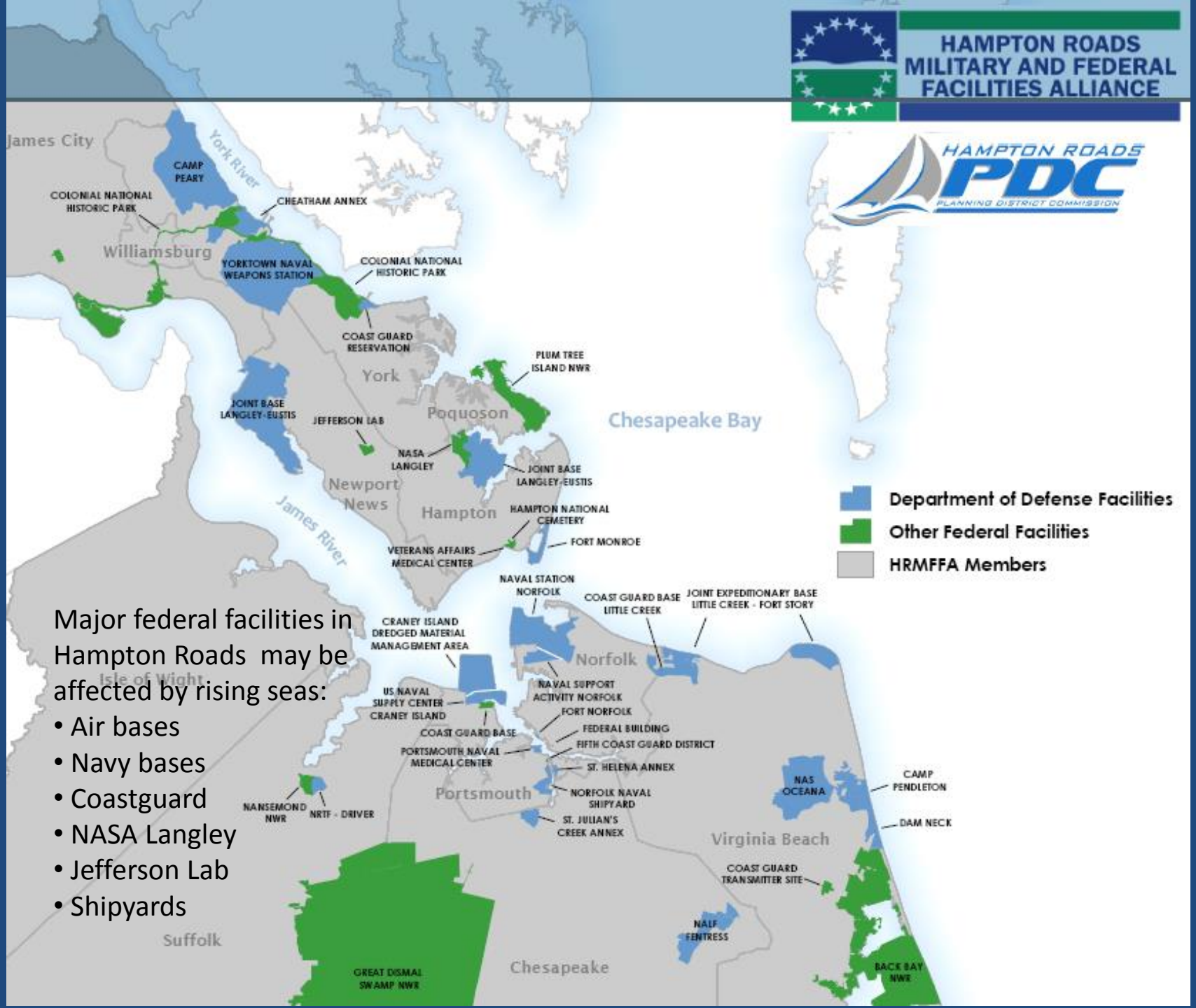
Acceleration in minor flooding is clear along the entire US East Coast



(from: Ezer & Atkinson , Accelerated flooding along US coasts, Earth's Future, 2014)

Flooding affects universities, navy, commerce, medical facilities, etc.





Major federal facilities in Hampton Roads may be affected by rising seas:

- Air bases
- Navy bases
- Coastguard
- NASA Langley
- Jefferson Lab
- Shipyards

ODU's research and education activities to address sea level rise:

- since 2010
- since 2014
- 2014-2016

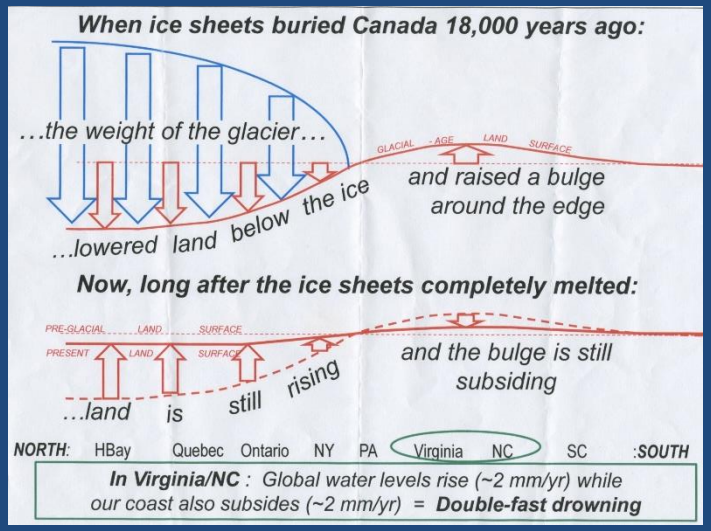
Local sea level rise (SLR) is the result of several processes:

- Global Sea Rise

thermal expansion
melting ice sheets & glaciers
volume change

- Land Motion

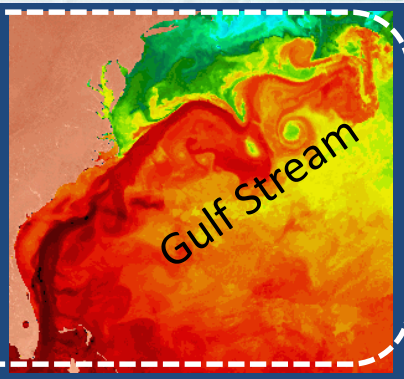
Glacial Isostatic Adjustment (GIA), Groundwater extraction, hydrology, geology, etc.



contribute to regional variations in SLR

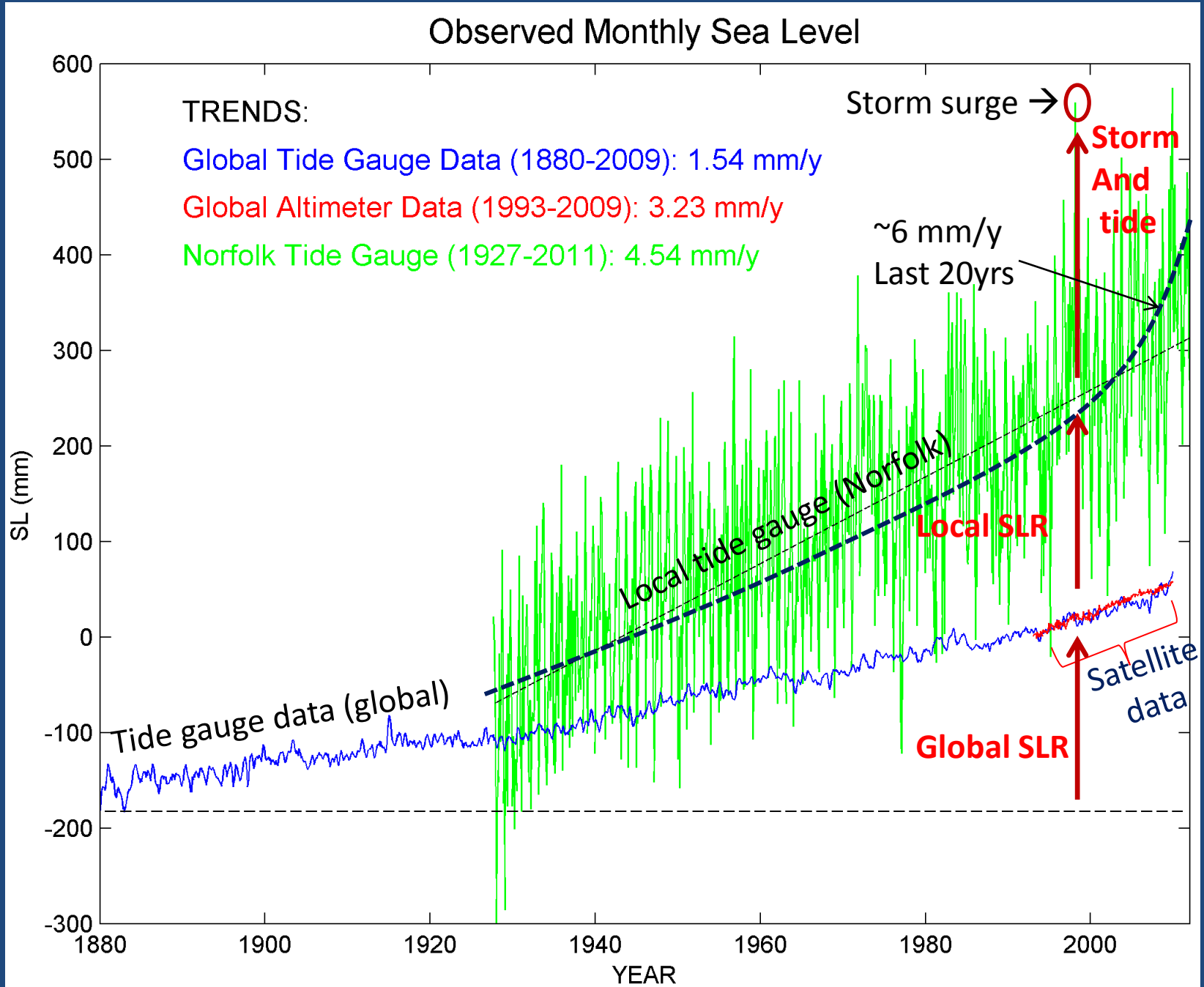
- Oceanic & Atmospheric Dynamics

Gulf Stream, Atlantic Meridional Overturning Circulation (AMOC), North Atlantic Oscillations (NAO), ENSO, etc.



least understood

Local Sea Level Rise (SLR) – a combination of several factors

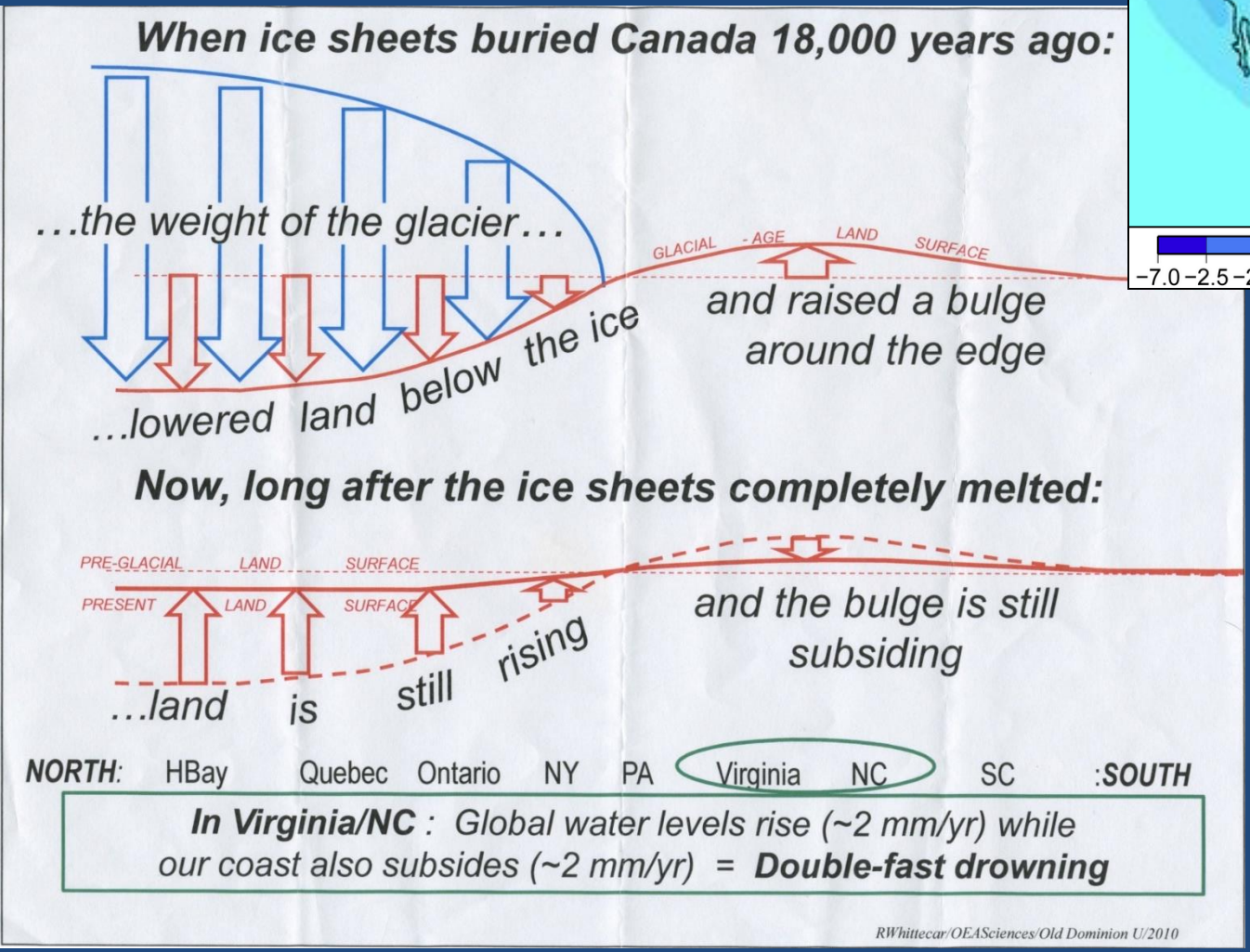


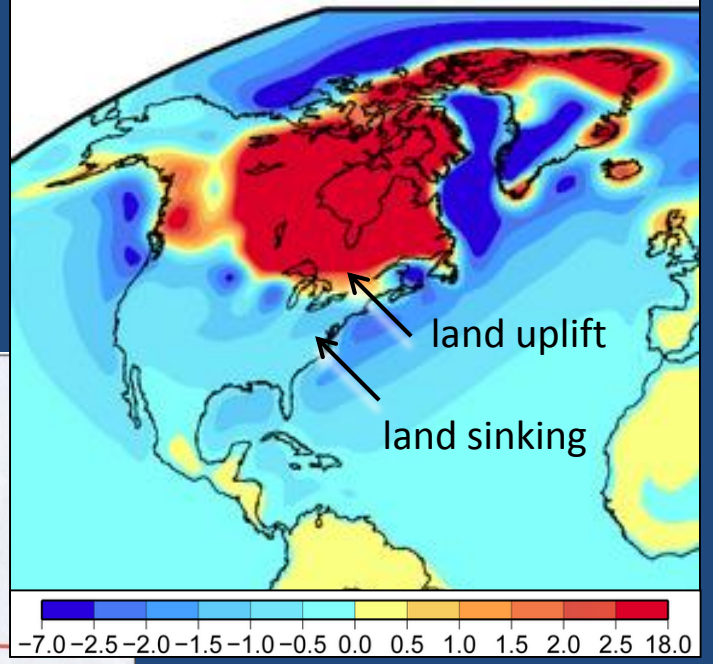
Impact from changes in ocean currents

land Subsidence (we are sinking…)

Land **Subsidence:**

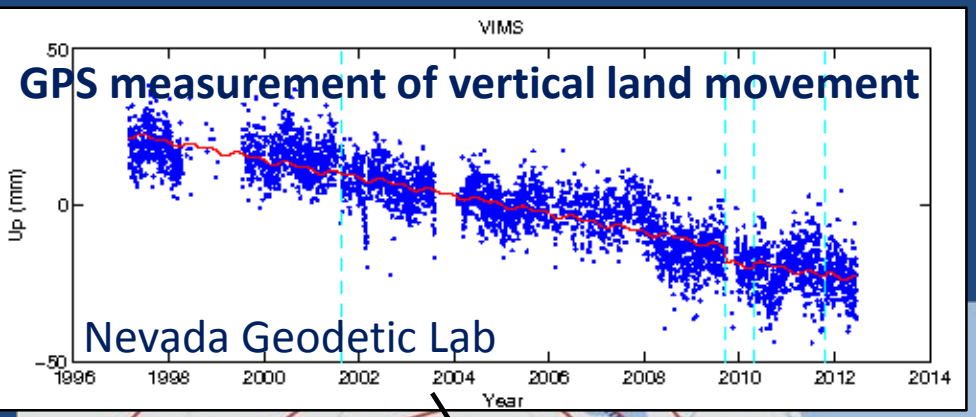
Glacial Isostatic Adjustment (GIA): due to post glacial rebound the land is sinking (especially in VA, NC, MD)



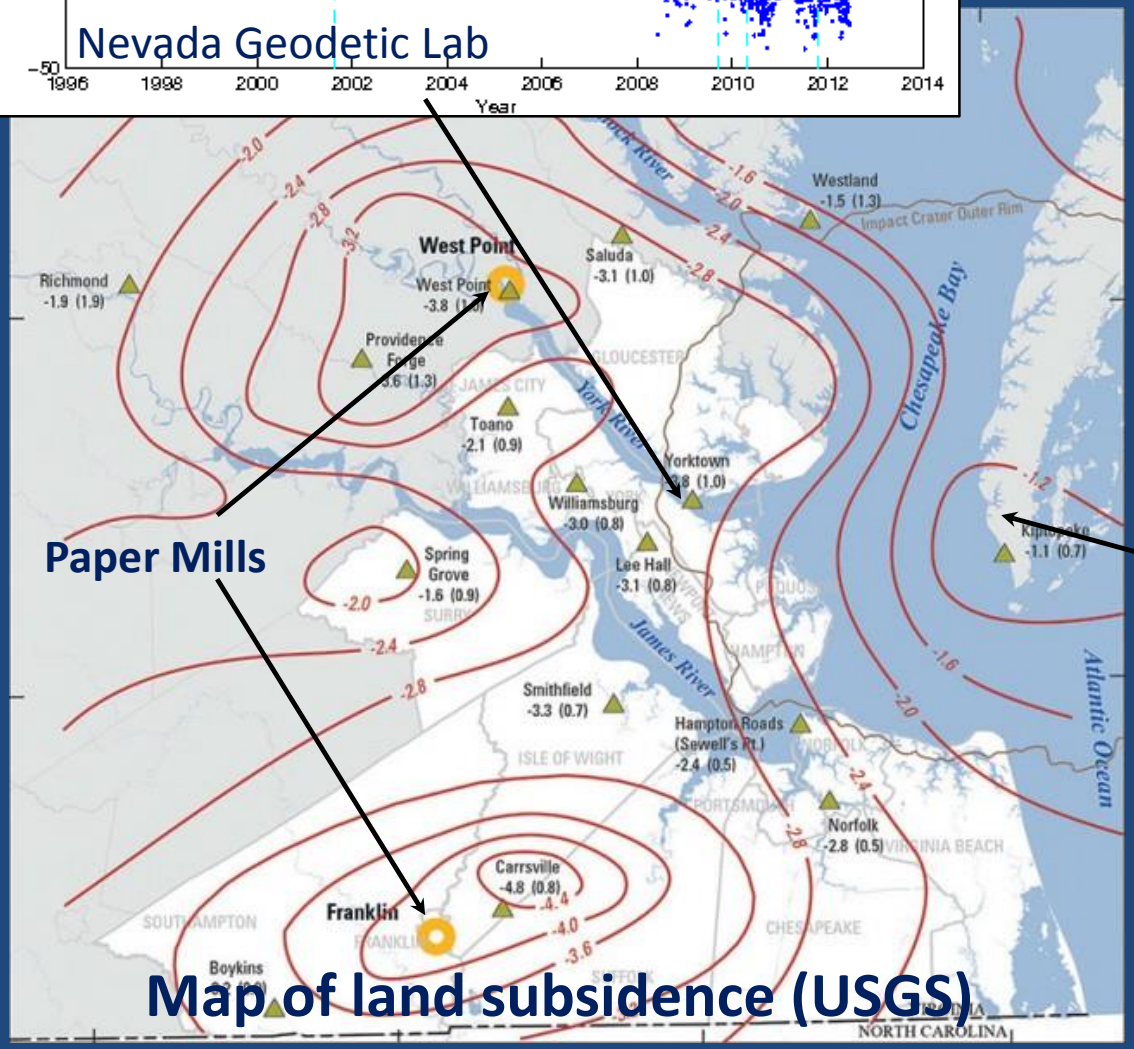


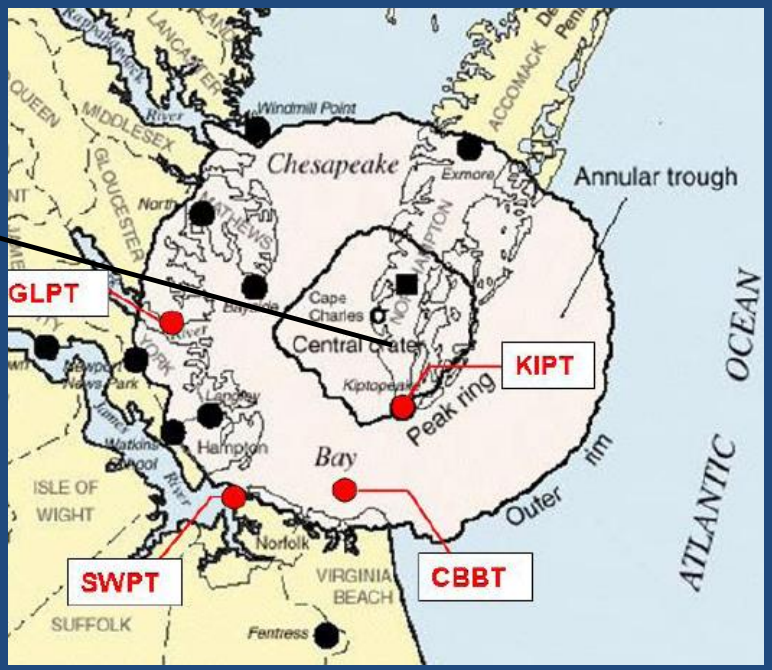
Other contributions to subsidence: sediment compactions, groundwater removal, etc. (Boon et al., 2010)

While global sea level is rising, land is sinking (~1.5-3 mm/yr in VA)



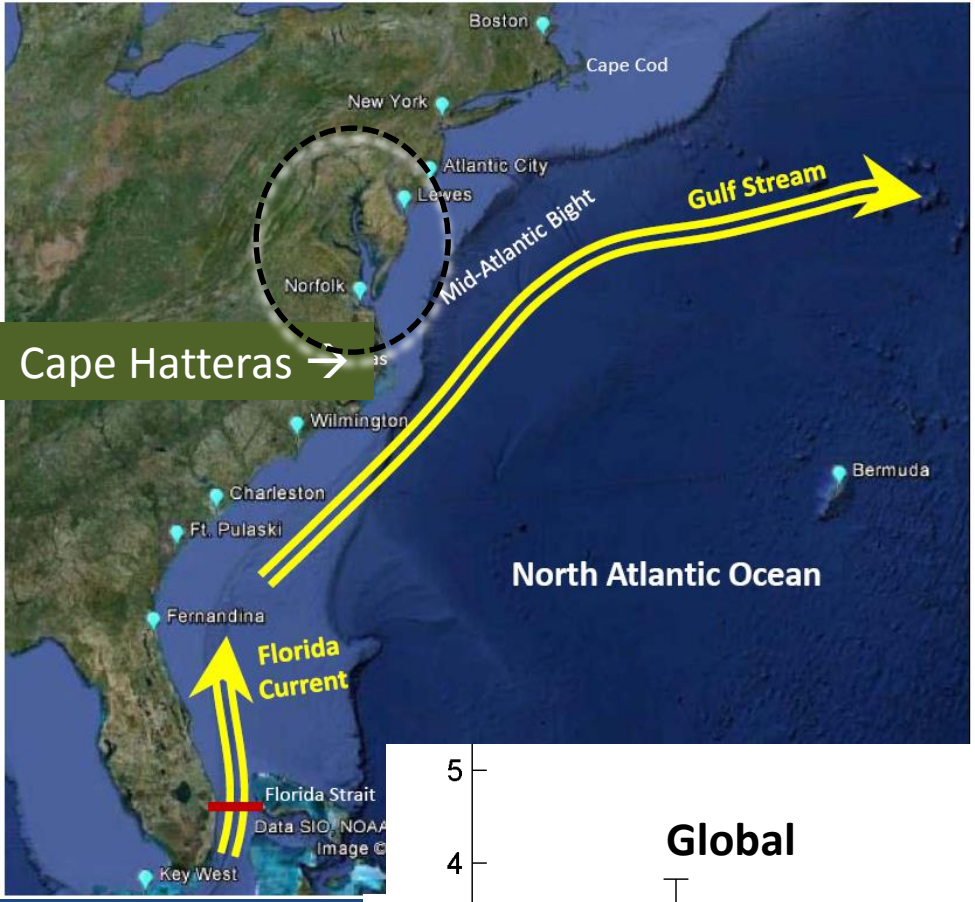
- Post glacial rebound
- Underground water extraction (West Point & Franklin paper mills)
- Other geological reasons (Chesapeake Impact Crater?)

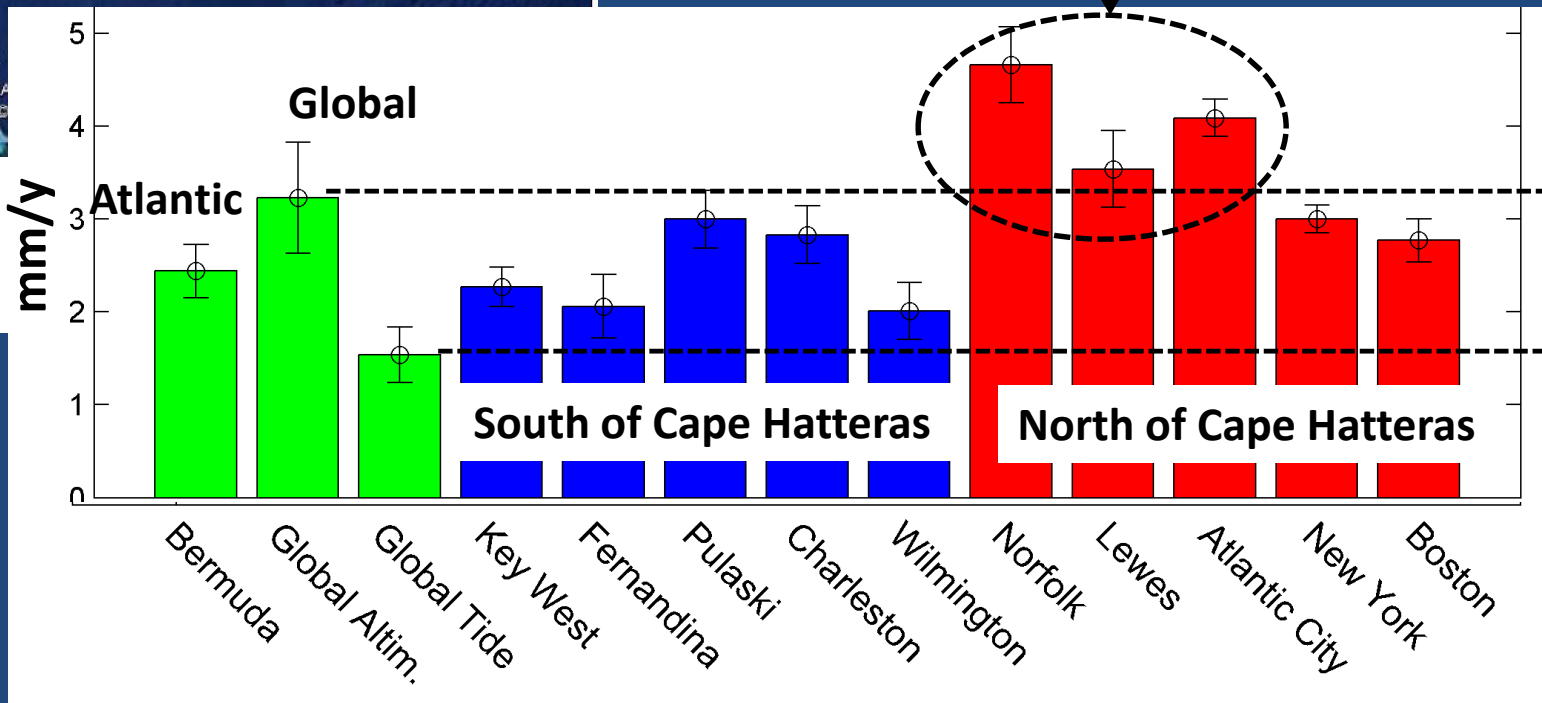




Mean Sea Level Rise Rates
(from linear regression)

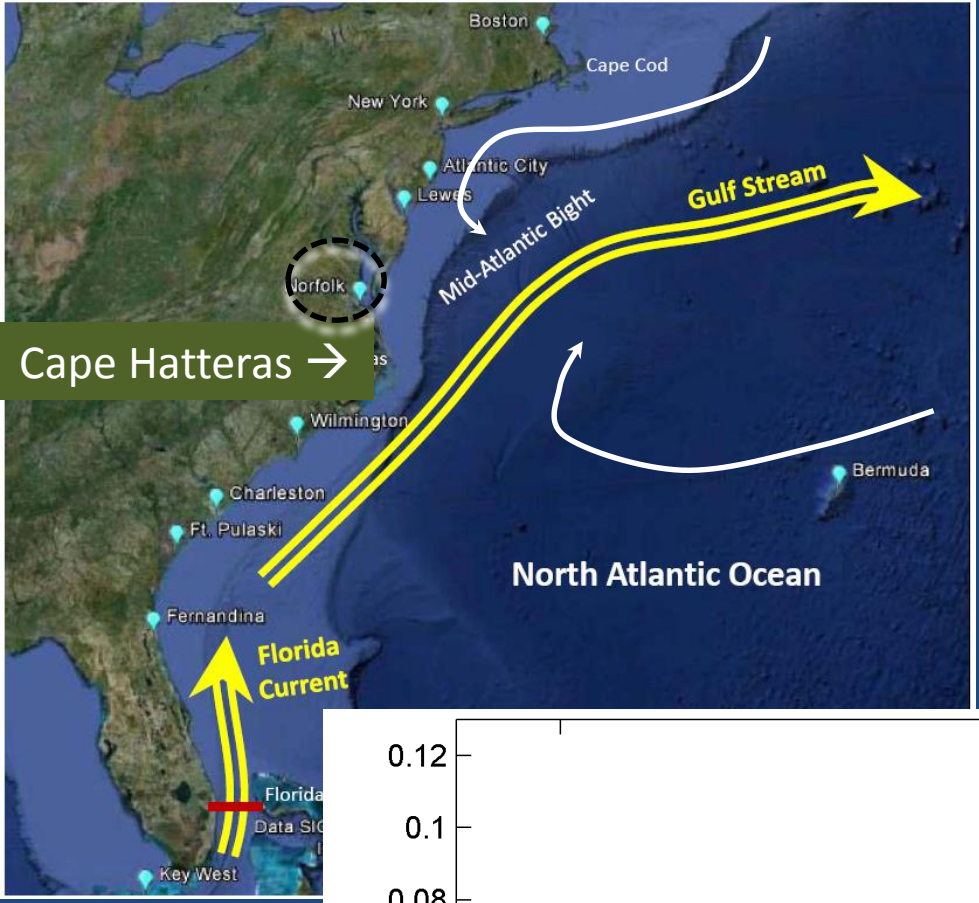
linear global SLR
+
postglacial land subsidence in the mid-Atlantic

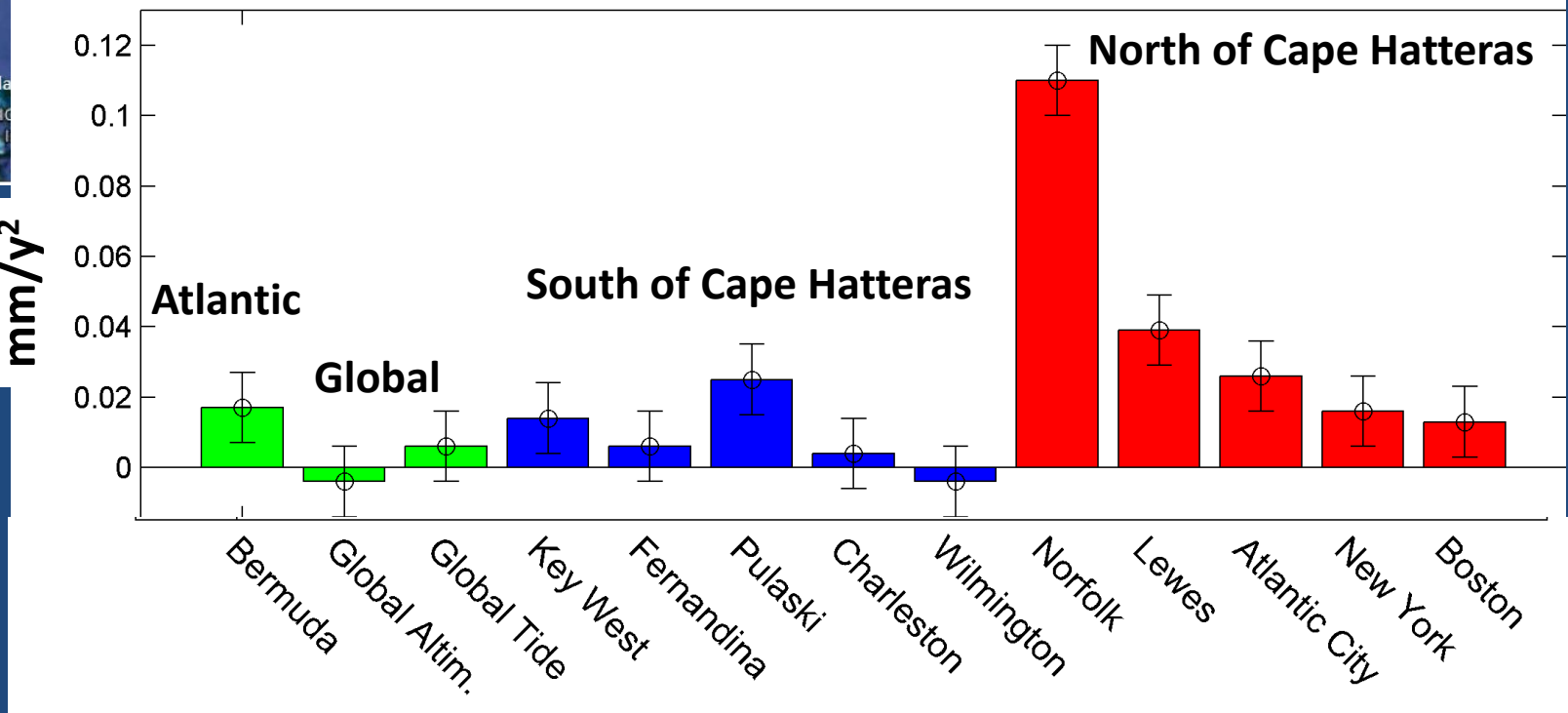




Sea Level Rise Acceleration

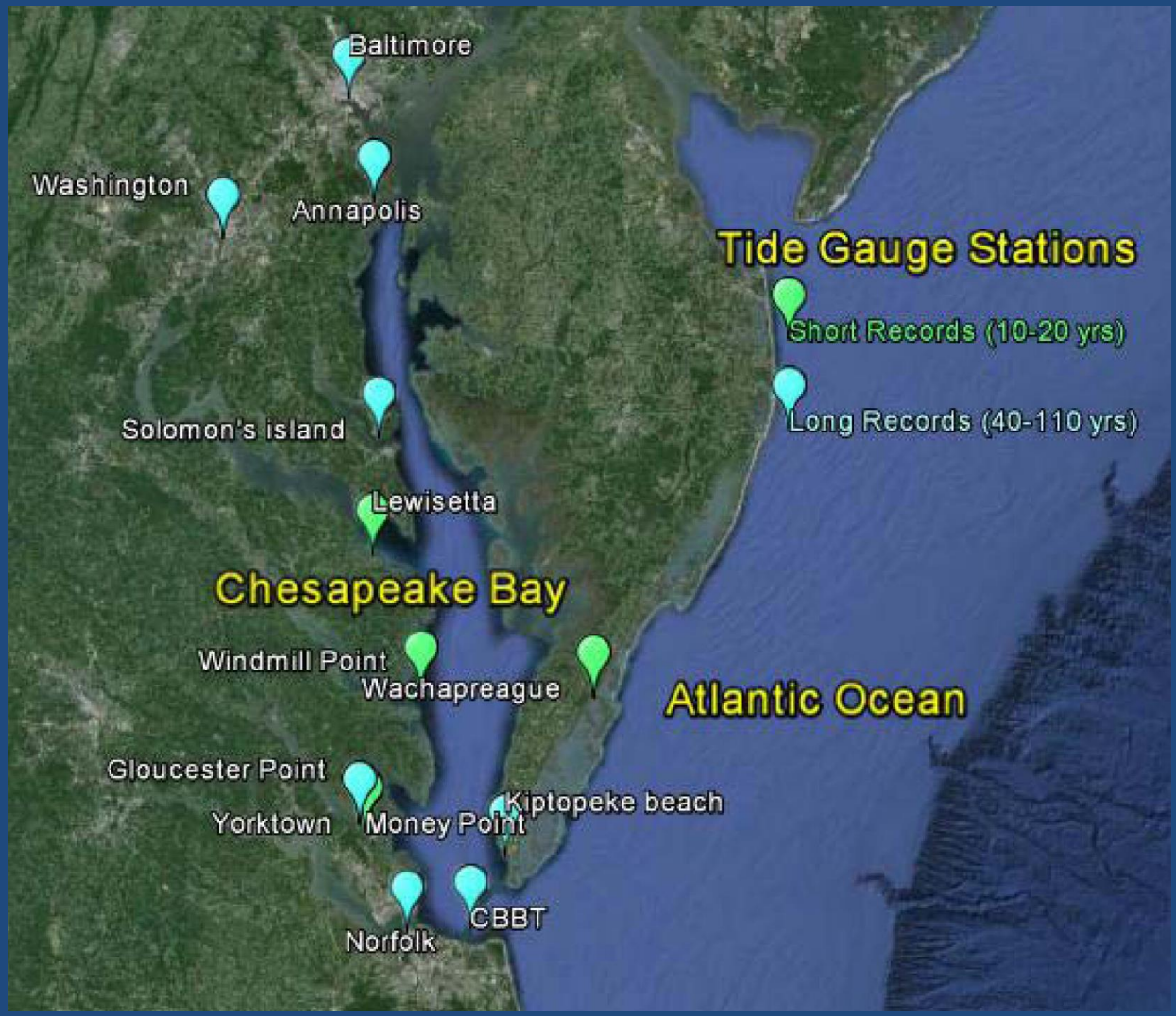
- Driven mostly by ocean dynamics
  - Distinctly larger acceleration north of Cape Hatteras

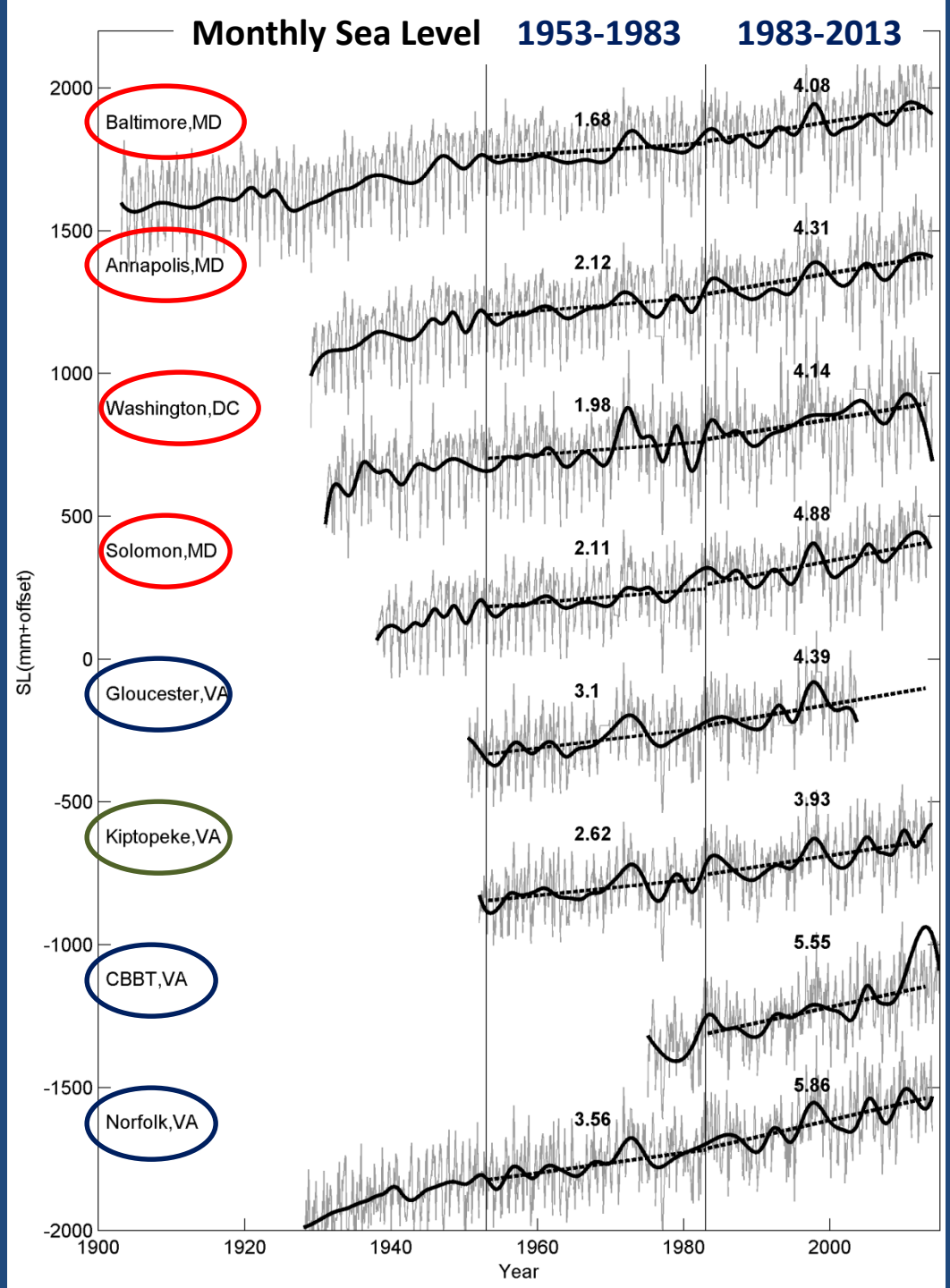




Rates of sea level rise (SLR) around the Chesapeake Bay

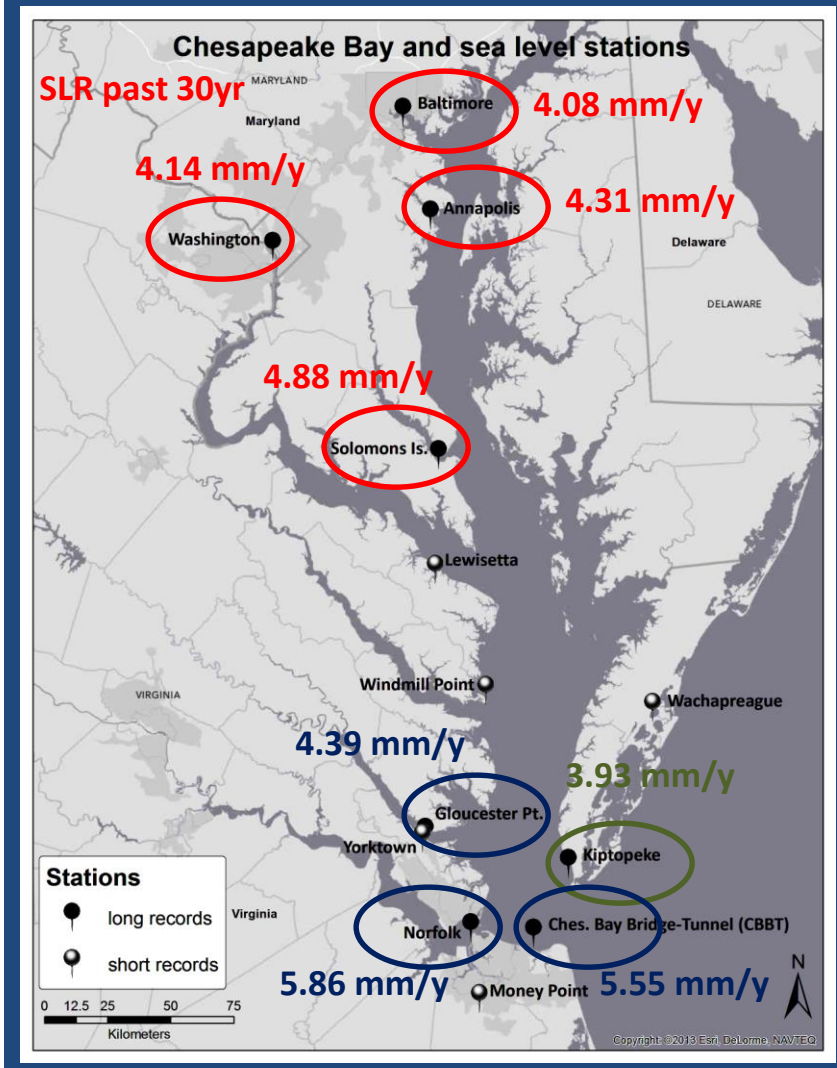
- What are the past trends?
- Are they constant or changing?
- What can they tell us about future SLR?

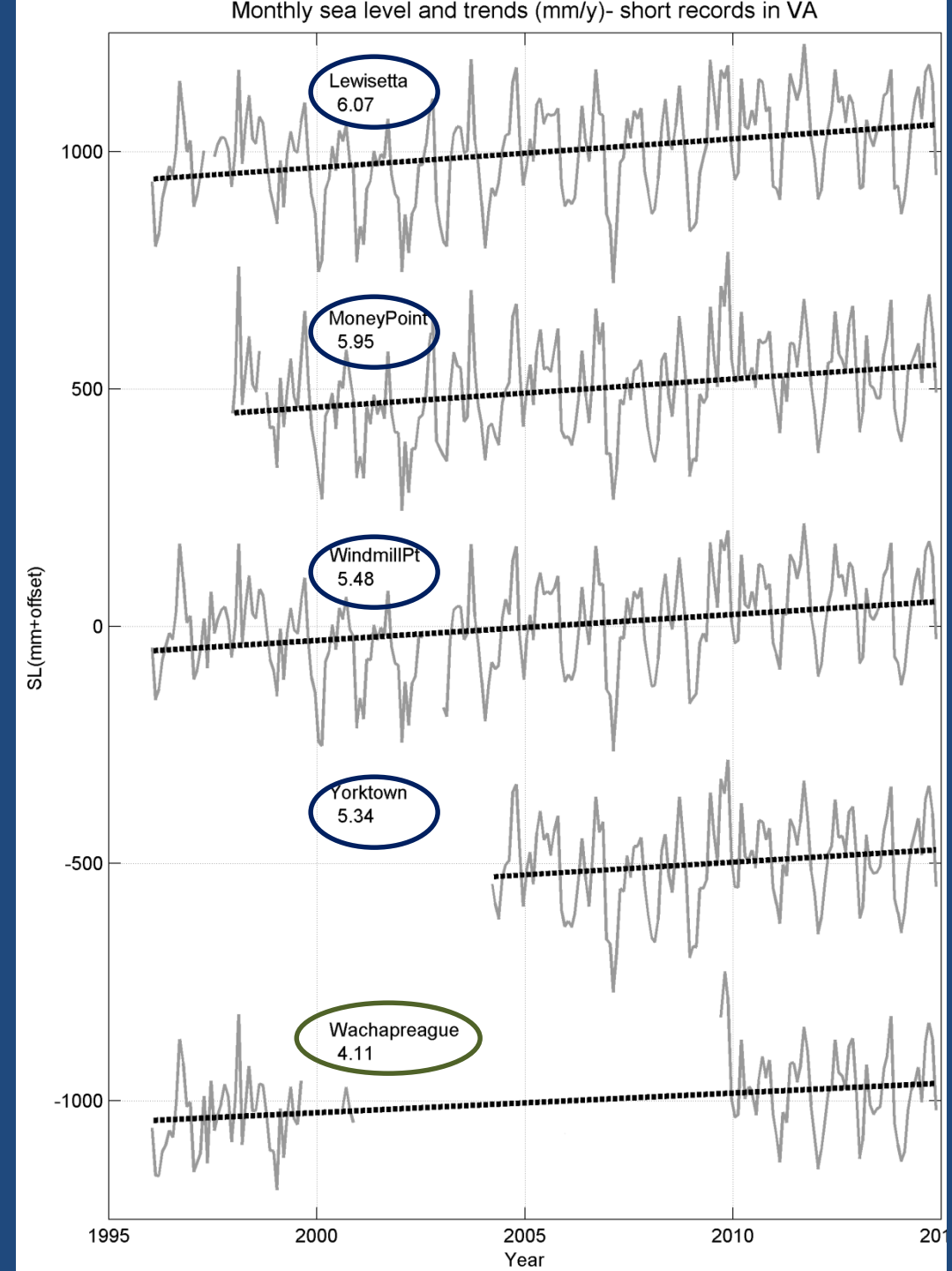




Long (40-110 yrs) sea level records:

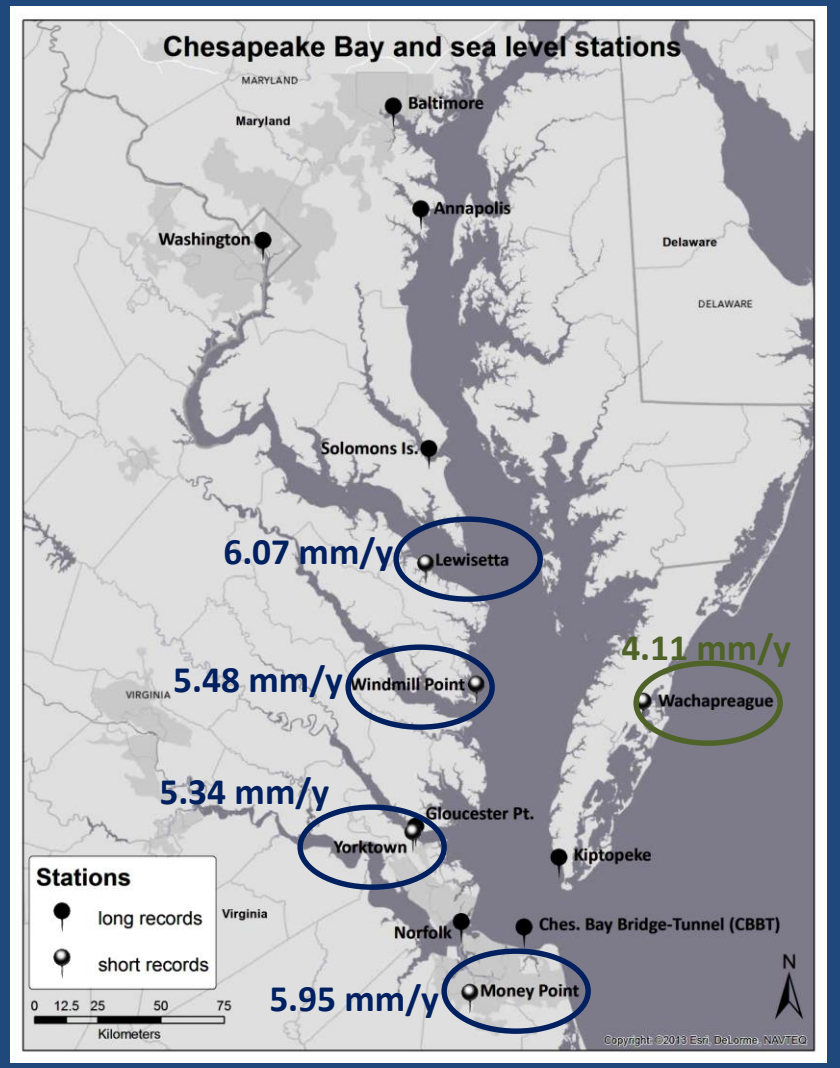
- increase SLR rate from ~**2.4 mm/y** (50s-80s) to ~**4.5 mm/y** (80s-today)
- higher SLR in lower CB, ~**5.3 mm/y**, than upper CB, ~**4.3 mm/y** and Eastern Shore Peninsula, **3.9 mm/y**



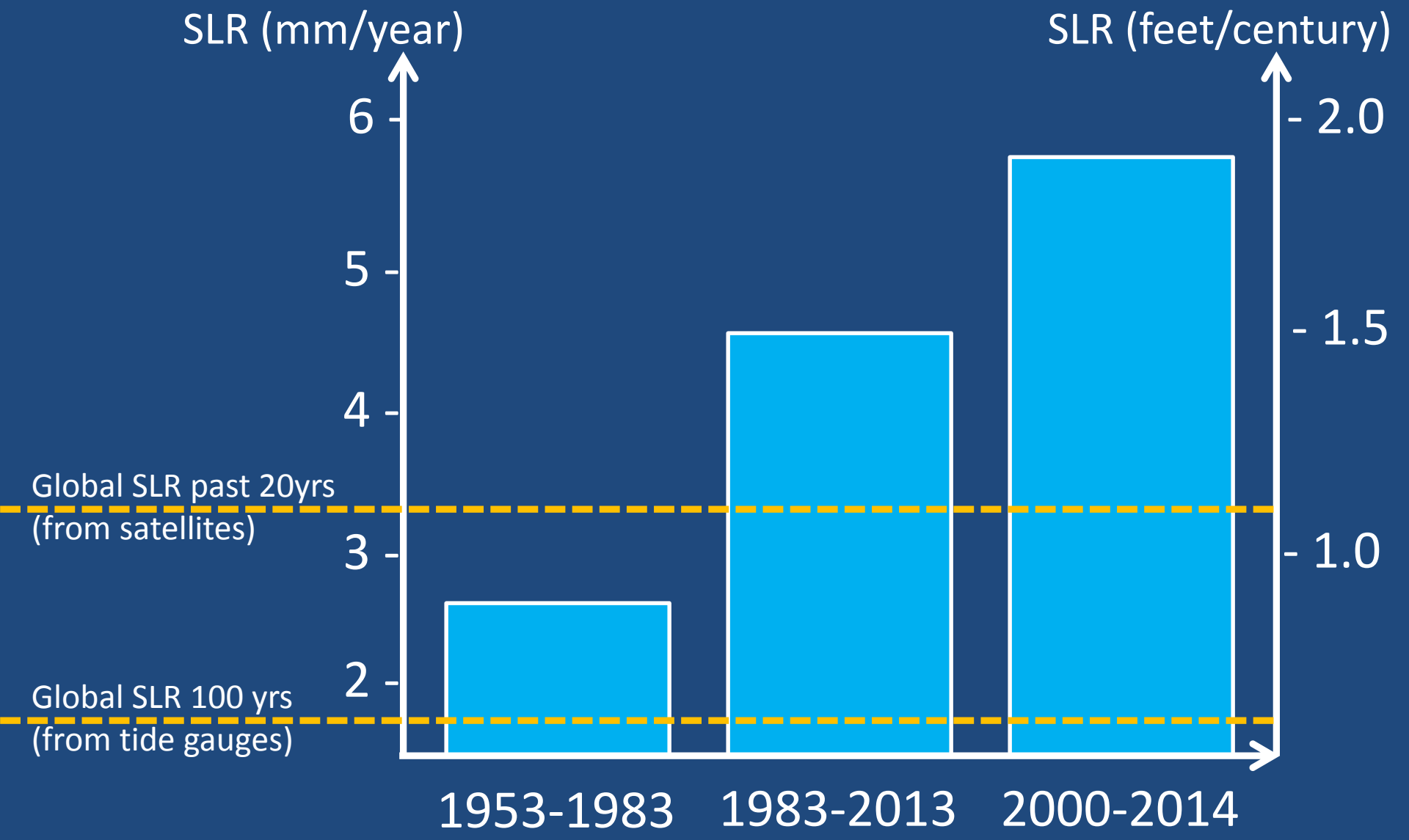


Short (10-20 yrs) sea level records in VA:

- even larger SLR rate, ~**5.7 mm/y** , in recent years than in long records

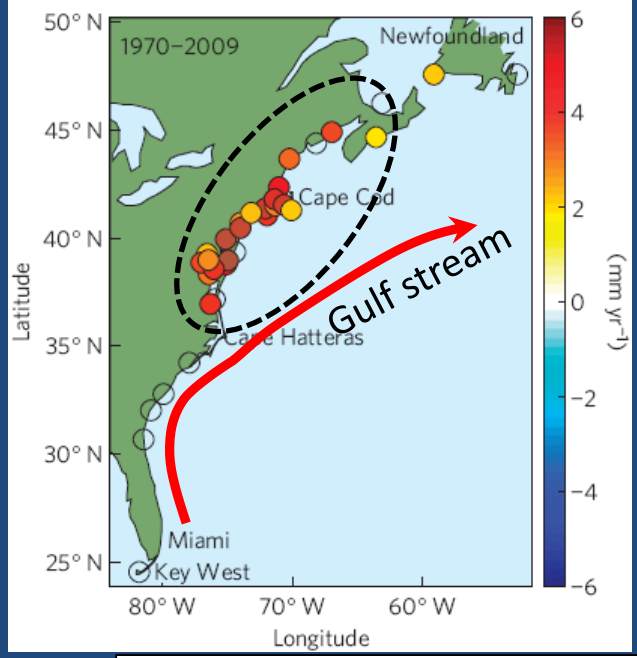


Summary of estimated sea level rise around the Chesapeake Bay: Rising faster than global SLR and rates increase (acceleration)



Impact of ocean dynamics on sea level rise:

Research triggered by 3 separate studies (2012) that indicate a "**hotspot of accelerated SLR"** in the mid-Atlantic coast north of Cape Hatteras.



nature climate change

LETTERS

PUBLISHED ONLINE: 24 JUNE 2012 | DOI: 10.1038/NCLIMATE1597

Hotspot of accelerated sea-level rise on the Atlantic coast of North America

Asbury H. Sallenger Jr*, Kara S. Doran and Peter A. Howd

USGS

(Method: linear trends over different periods)

Evidence of Sea Level Acceleration at U.S. and Canadian Tide Stations, Atlantic Coast, North America

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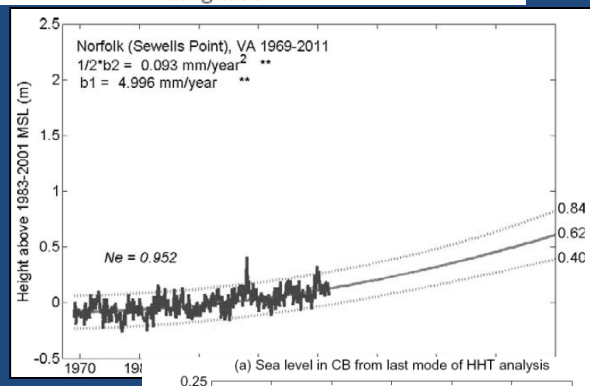
www.cerf-jcr.org

J. Coastal Res. 2012

VIMS



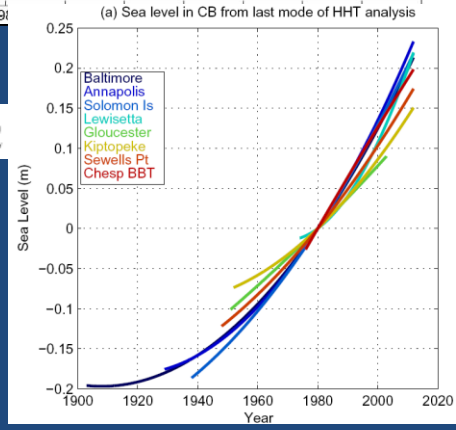
(Method: quadratic line fit)

GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L19605, doi:10.1029/2012GL053435, 2012

Is sea level rise accelerating in the Chesapeake Bay? A demonstration of a novel new approach for analyzing sea level data

Tal Ezer[1] and William Bryce Corlett[1,2]

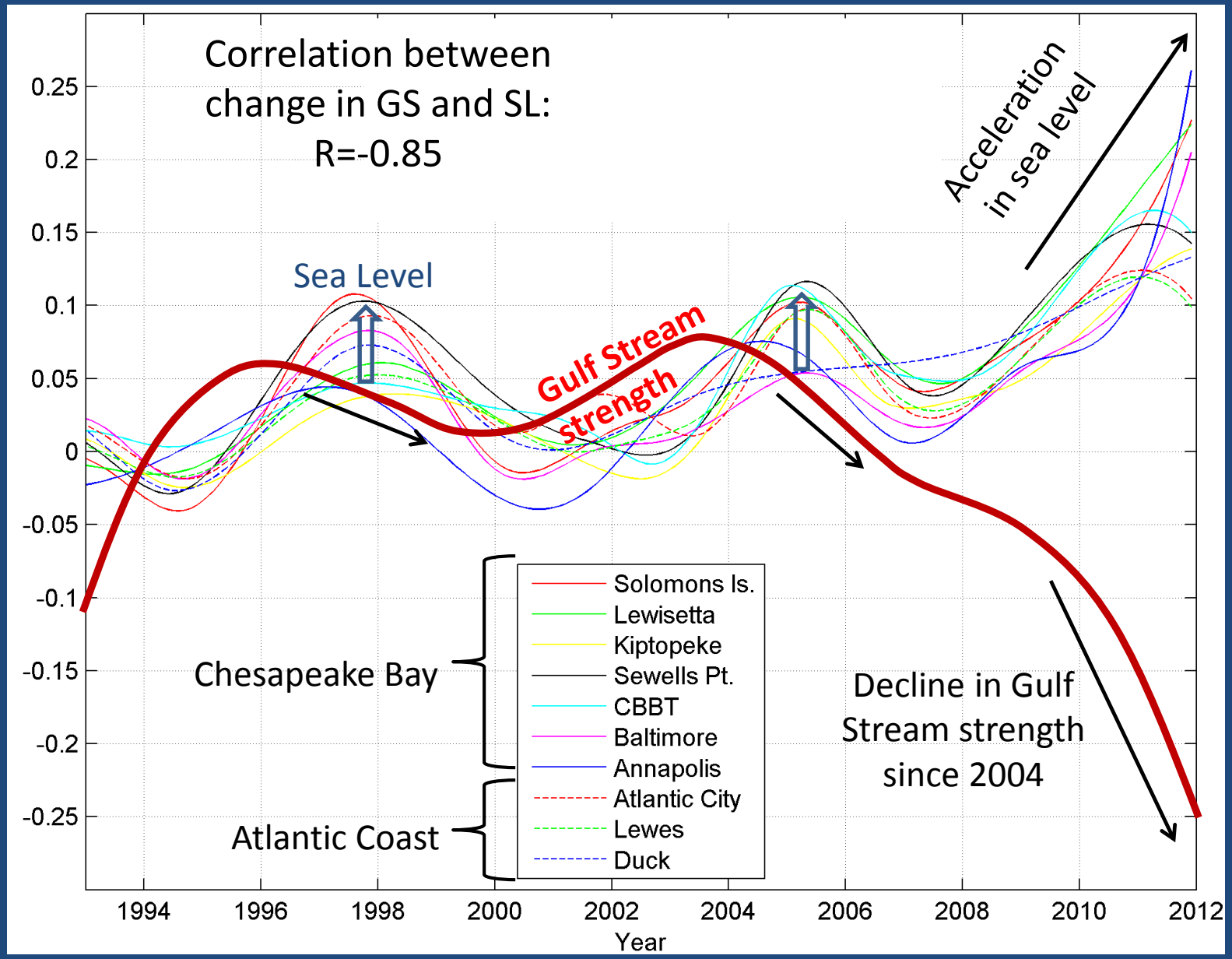
ODU



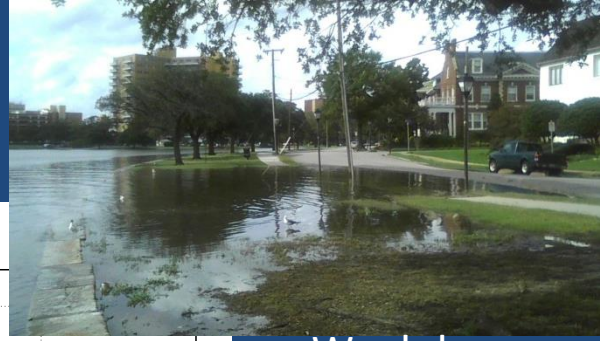
(Method: non-linear Empirical Mode Decomposition)

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

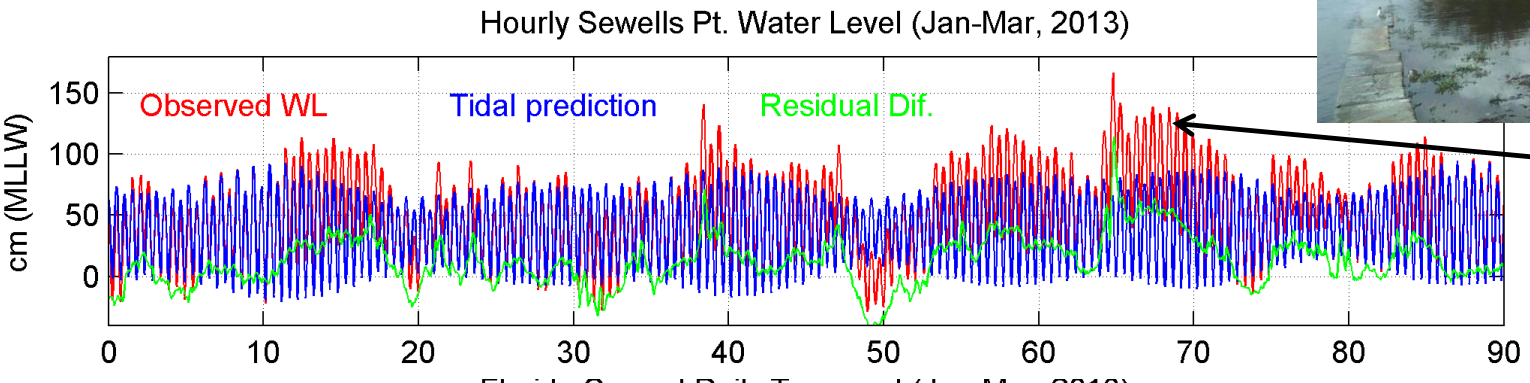
Why do stations in different locations show the same pattern?

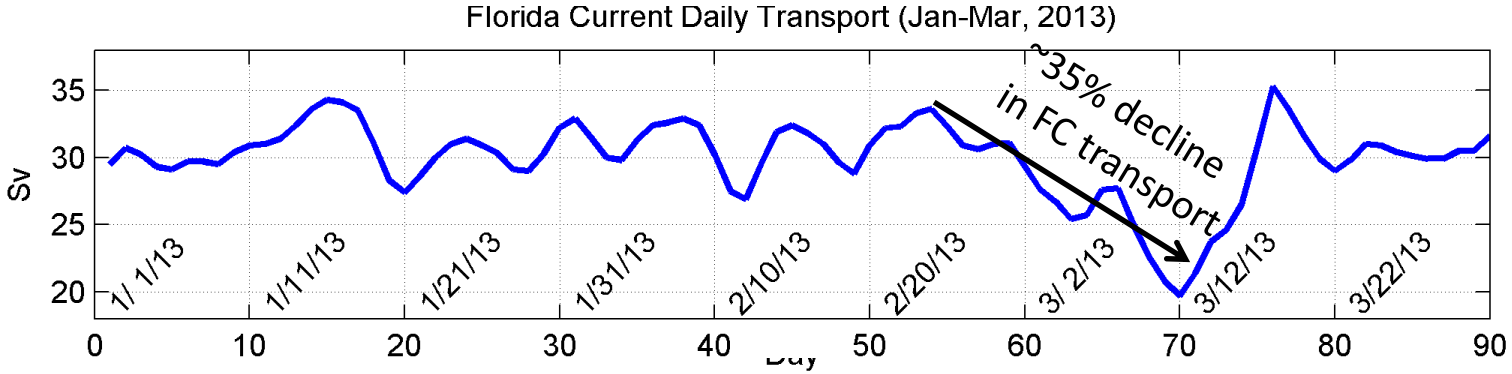


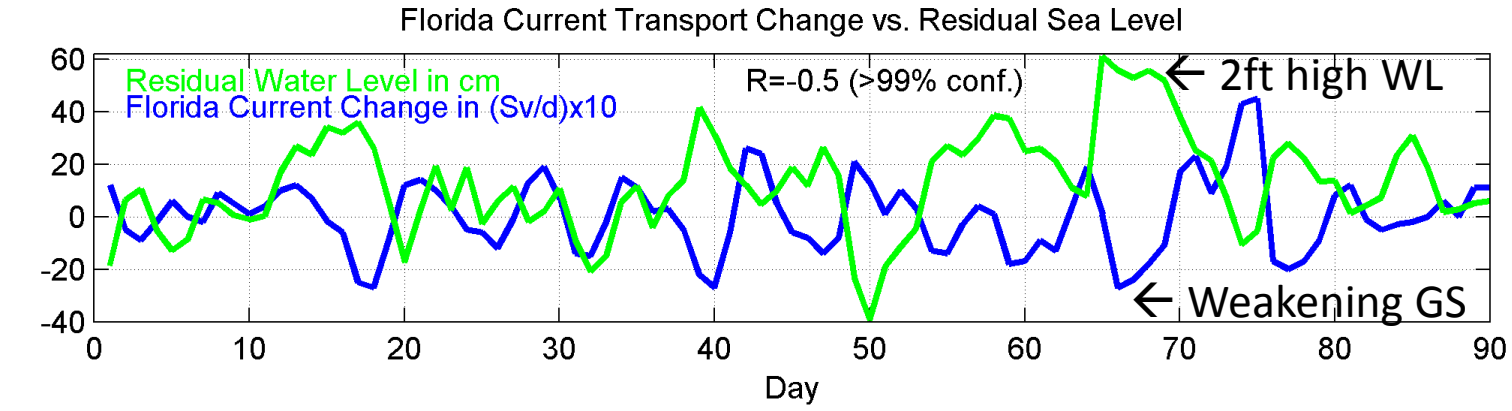
Short-term sea level variations:
also affected by the Gulf Stream?

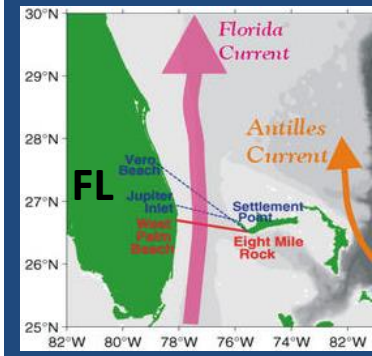


Week-long tidal flooding in Norfolk (no storms!!!)





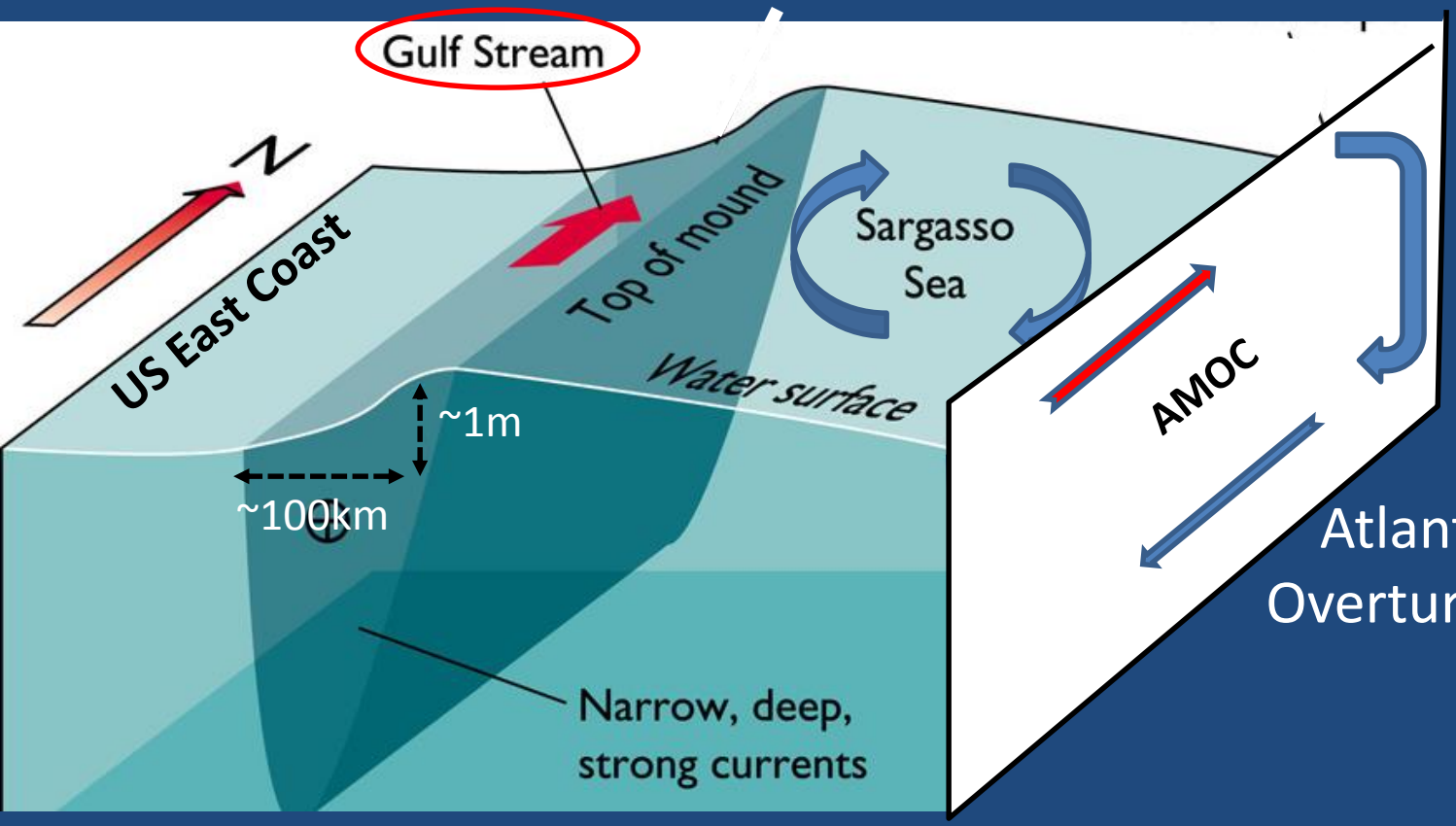




Weakening Gulf Stream across the Florida Strait is correlated with flooding in Norfolk…

How can ocean dynamics affect coastal sea level?

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



Atlantic Meridional Overturning Circulation (AMOC)

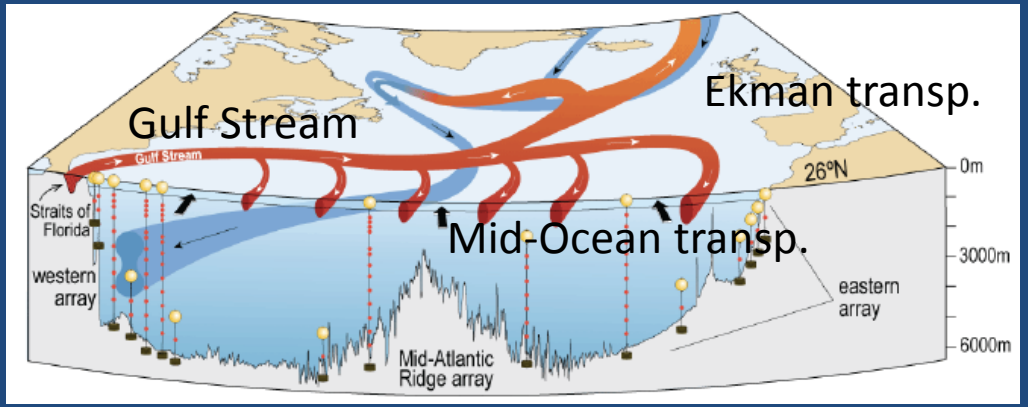
The Gulf Stream keeps sea level on the US East Coast ~1-1.5 m (3-5 feet) lower than water offshore → variations in GS strength or position will affect SL.

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!!!

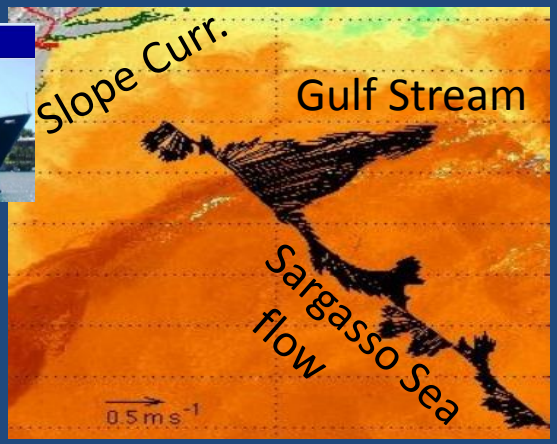
• Can we detect past climatic changes in the ocean?

• How can this information be used for future SLR projections?

• AMOC transport at 26°N from the RAPID project since 2004
(McCarthy et al, 2013) **~10yrs**

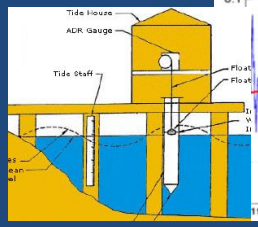


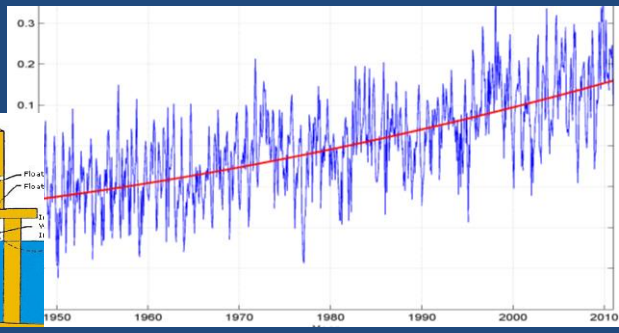
• Gulf Stream velocity from the Oleander project
(Rossby et al., 2010, 2014) **~20Yrs**



• Gulf Stream and sea level from altimeter data **~20Yrs**
(AVISO)

• Sea-Level data from tide gauges
(PSMSL) **~100yrs**





Ocean Sci. Discuss., 10, 1619–1645, 2013
www.ocean-sci-discuss.net/10/1619/2013/
doi:10.5194/osd-10-1619-2013
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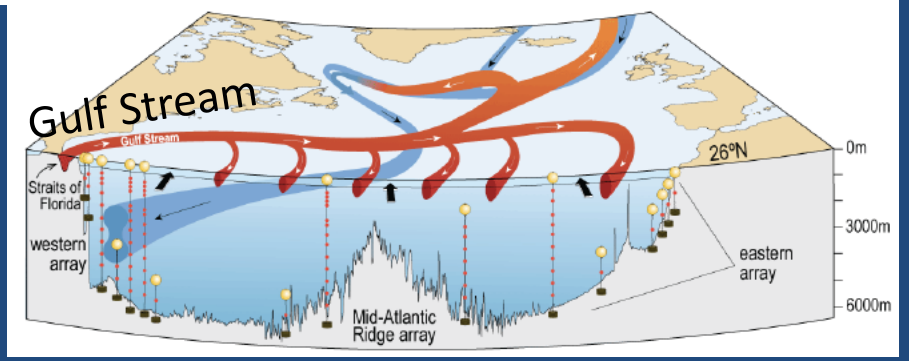
Ocean Science
Discussions
Open Access

This discussion paper is/has been under review for the journal Ocean Science (OS).
Please refer to the corresponding final paper in OS if available.

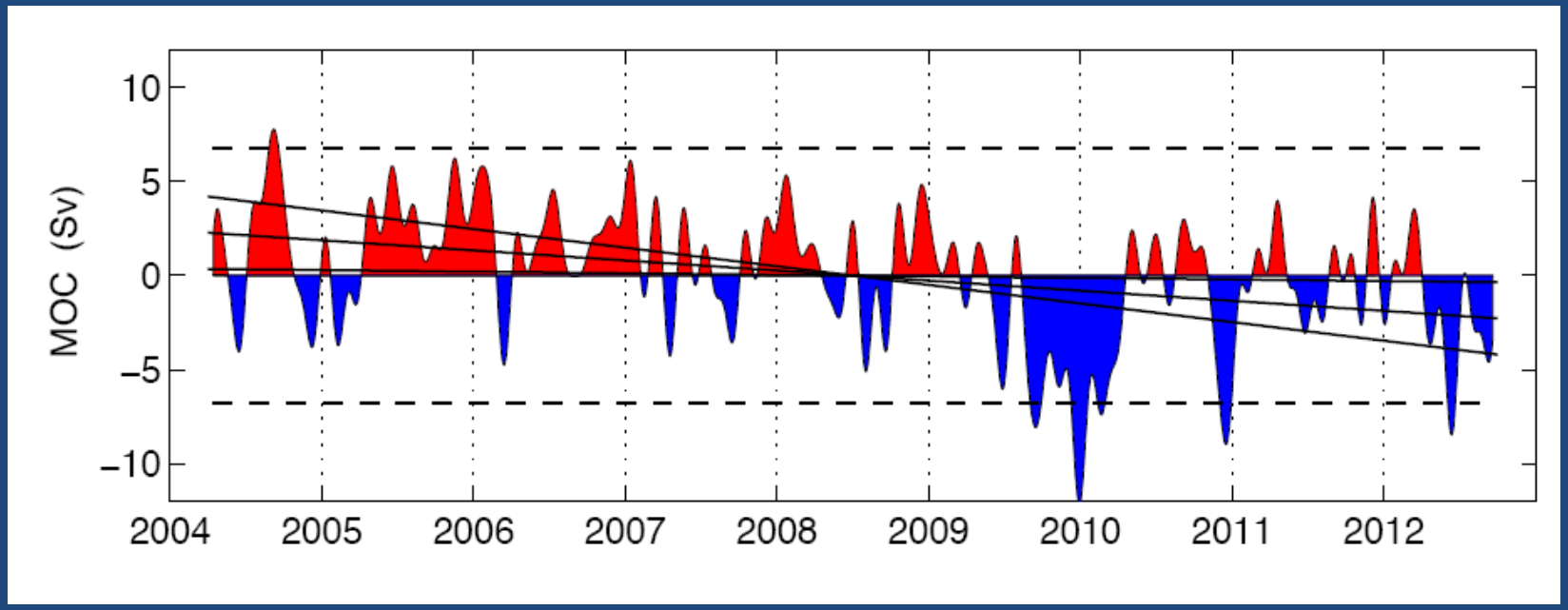
Observed decline of the Atlantic Meridional Overturning Circulation 2004 to 2012

D. A. Smeed[1], G. McCarthy[1], S. A. Cunningham[2], E. Frajka-Williams[3], D. Rayner[1], W. E. Johns[4], C. S. Meinen[5], M. O. Baringer[5], B. I. Moat[1], A. Duchez[1], and H. L. Bryden[3]

The 26° N RAPID-MOCHA-WBTS program



From April 2008 to March 2012 the AMOC was an average of 2.7 Sv weaker than in the first four years of observation (95 % confidence that the reduction is 0.3 Sv or more).

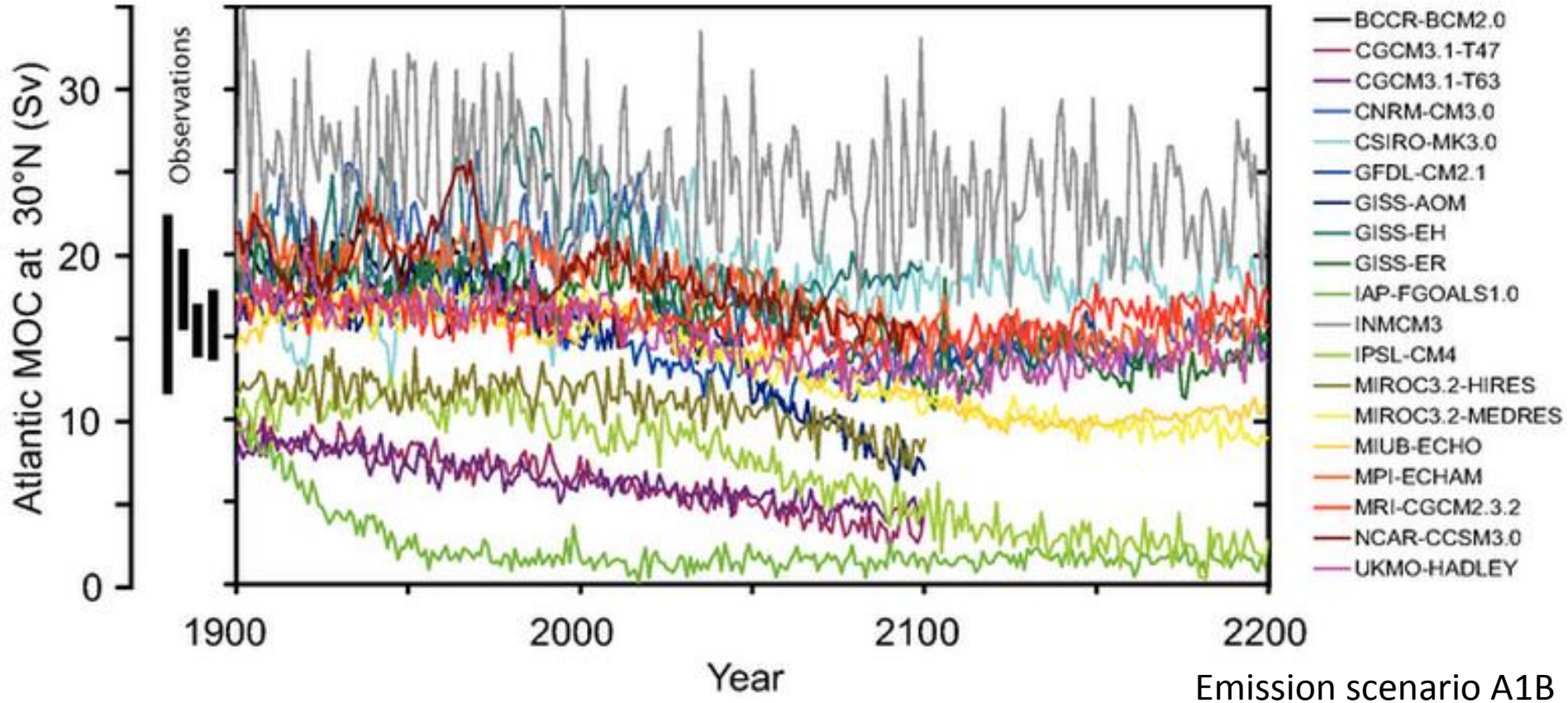


Impact of ocean dynamics on future sea level

IPCC Fourth Assessment Report: Climate Change 2007

Climate Change 2007: Working Group I: The Physical Science Basis

All climate models show some degree of weakening in the overturning circulation



Emission scenario A1B

Climate models predict future weakening of the Gulf Stream and increase sea level north of Cape Hatteras

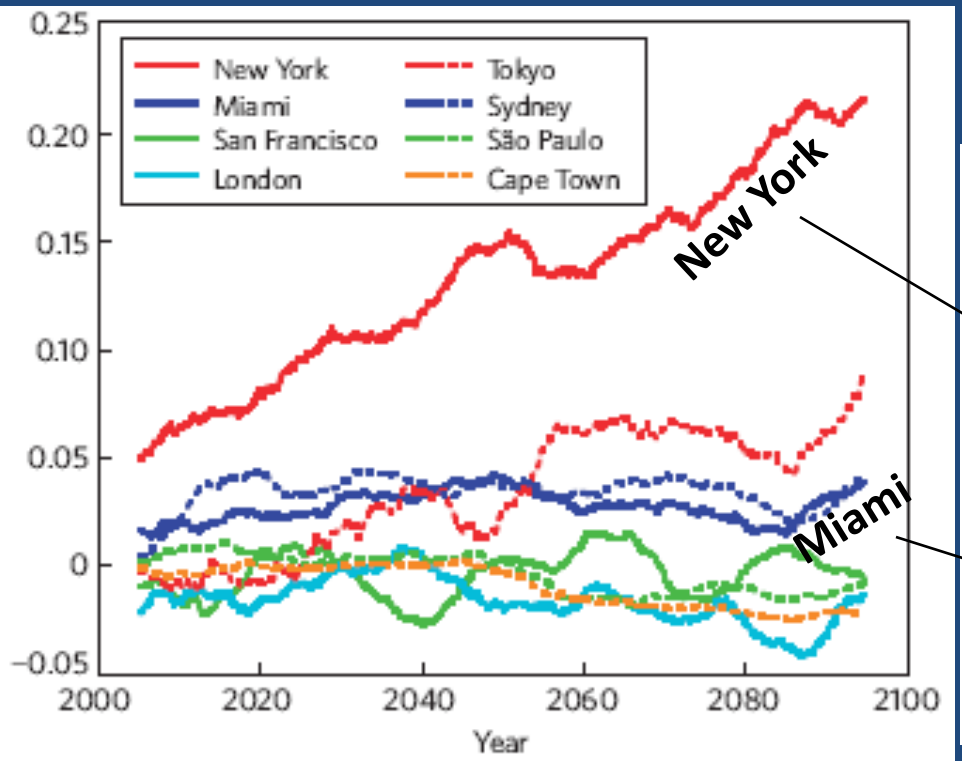
LETTERS
PUBLISHED ONLINE: 15 MARCH 2009 | DOI: 10.1038/NGEO462
nature geoscience

Model projections of rapid sea-level rise on the northeast coast of the United States

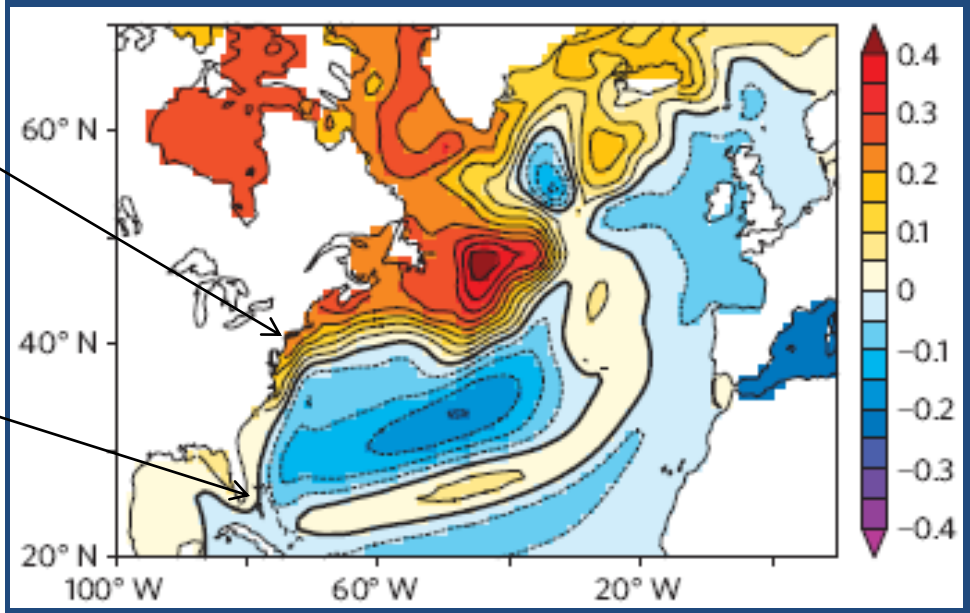
Jianjun Yin[1]*, Michael E. Schlesinger[2] and Ronald J. Stouffer[3]

Yin et al., 2009

Dynamic Sea Level Rise



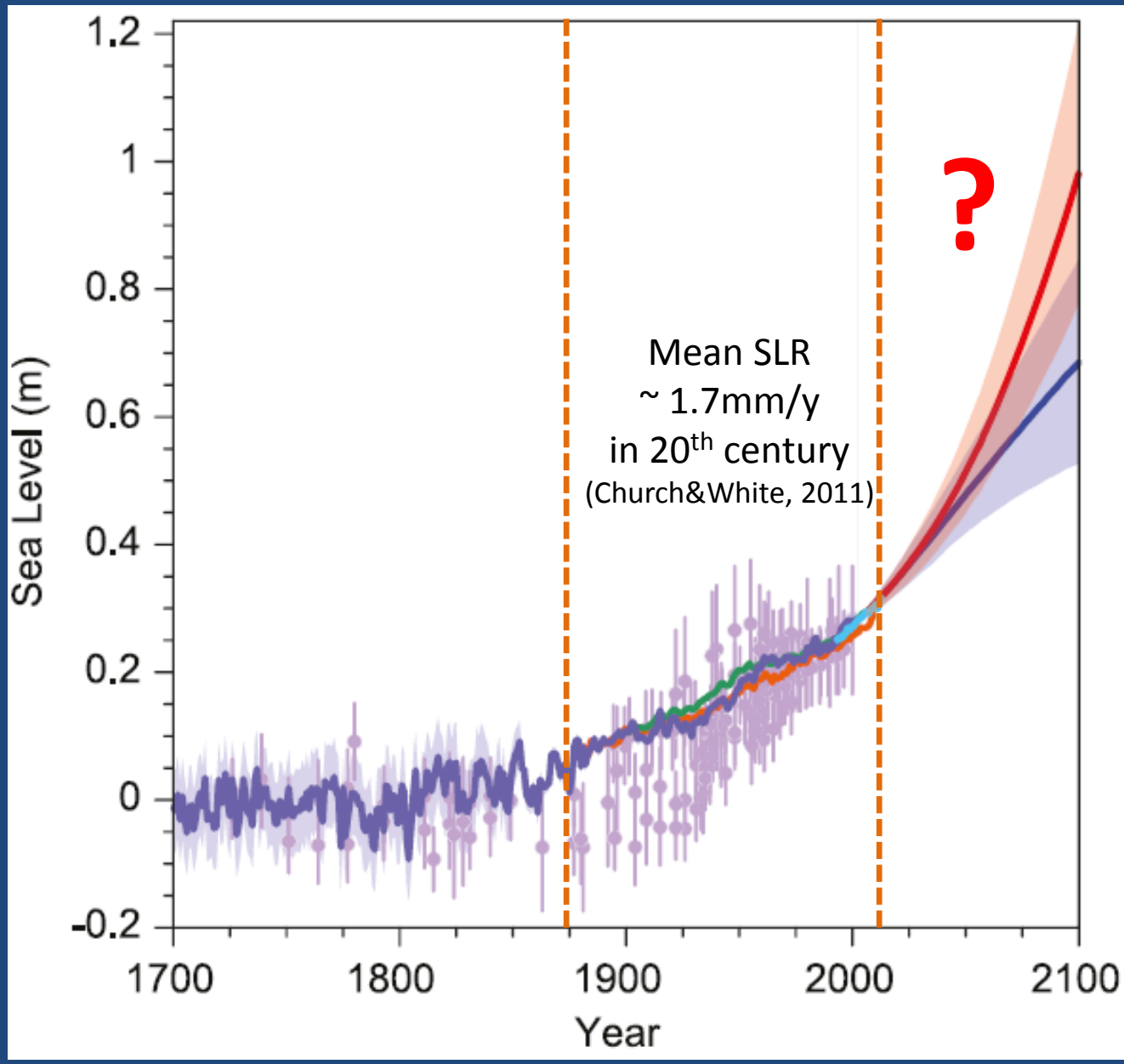
Projected SLR anomalies from 2000 to 2100



Global-Mean Sea-Level Rise: past 300 years and next 100 years

Past sea level:
paleo-sea-level data, tide gauge data, satellite altimeter data.

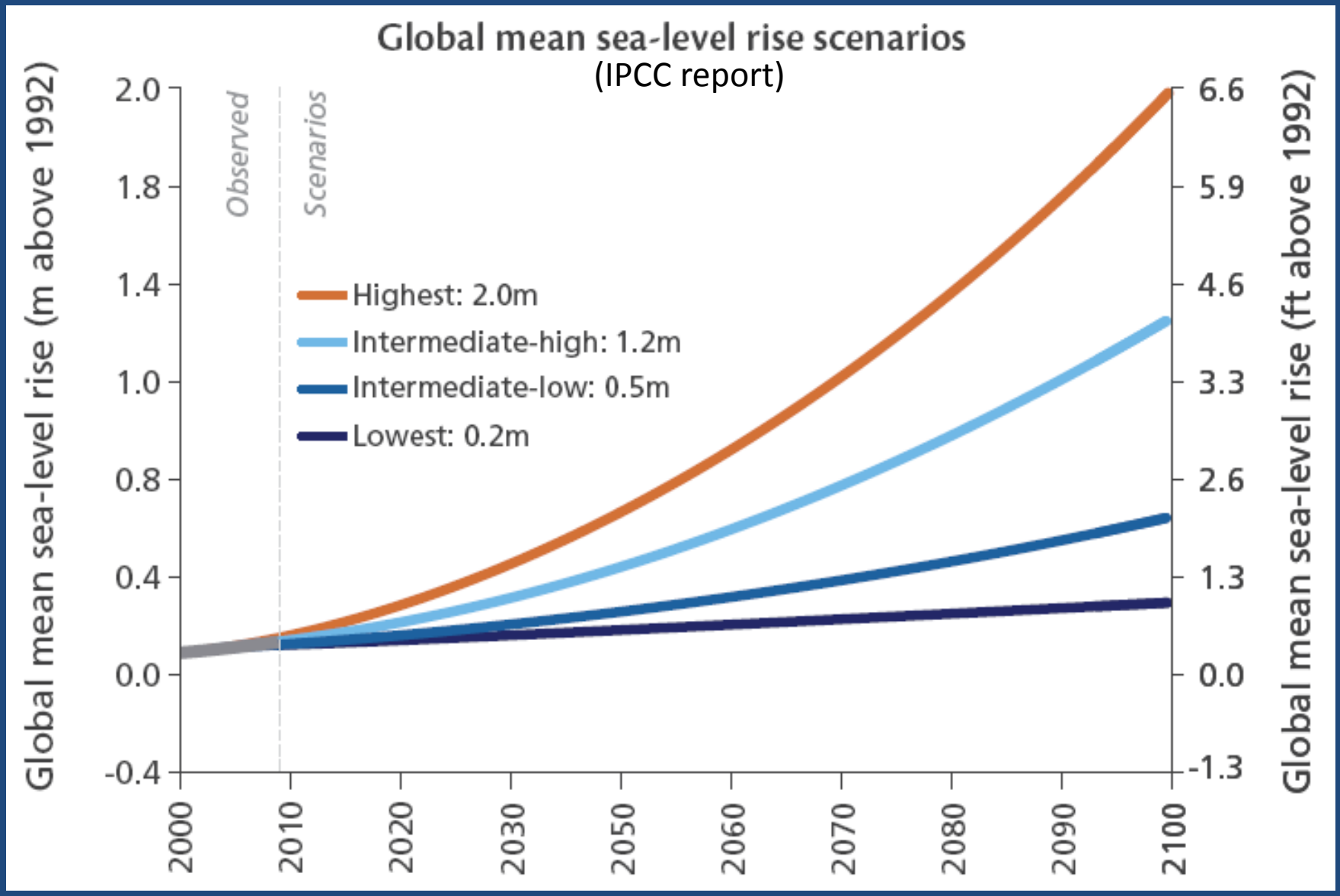
future estimates:
global climate models with different scenarios
RCP2.6 (blue) and
RCP8.5 (red)



Source: IPCC, 2013, AR5 WG1 (from Nicholls, 2013)

Projections of global sea level rise:

- too large range for practical local/regional planning
- neglect spatial variations due to land movements & ocean dynamics



What is the projected SLR for particular location? Many use the USACE SLR Calculator…

corpsclimate.us/ccaceslcurves.cfm

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US Army Corps of Engineers®

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Climate Change Adaptation

Comprehensive Evaluation of Projects with Respect to Sea-Level Change

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Respect to Sea-Level Change | Update Drought Contingency Plans | Updat

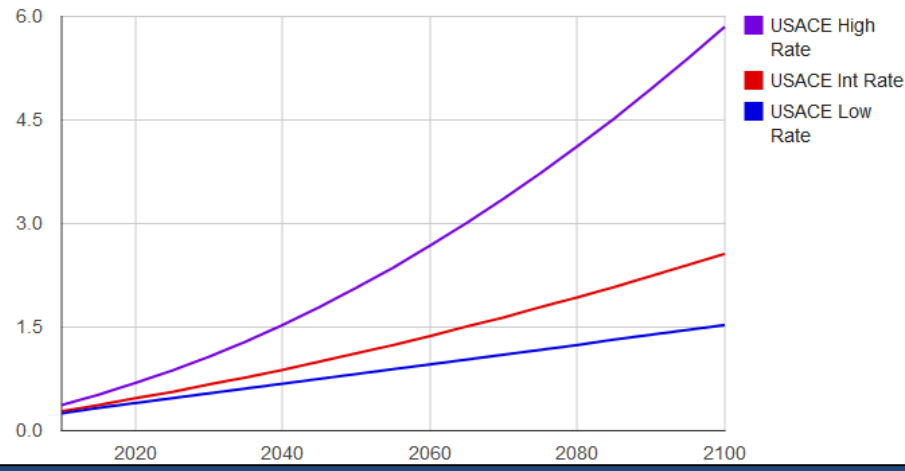
Sea-Level Change Curve Calculator

$E(t)=(\text{Land Subsidence}) \times t + (\text{global SLR}) \times t + (\text{acceleration}) \times t^2$

- no probability
- local land subsidence not accurate
- global acceleration- no local dynamics

USACE SLC Curves - Gauge VA, Sewells Point: 80 yrs
USACE Curves computed using criteria in EC 1165-2-212

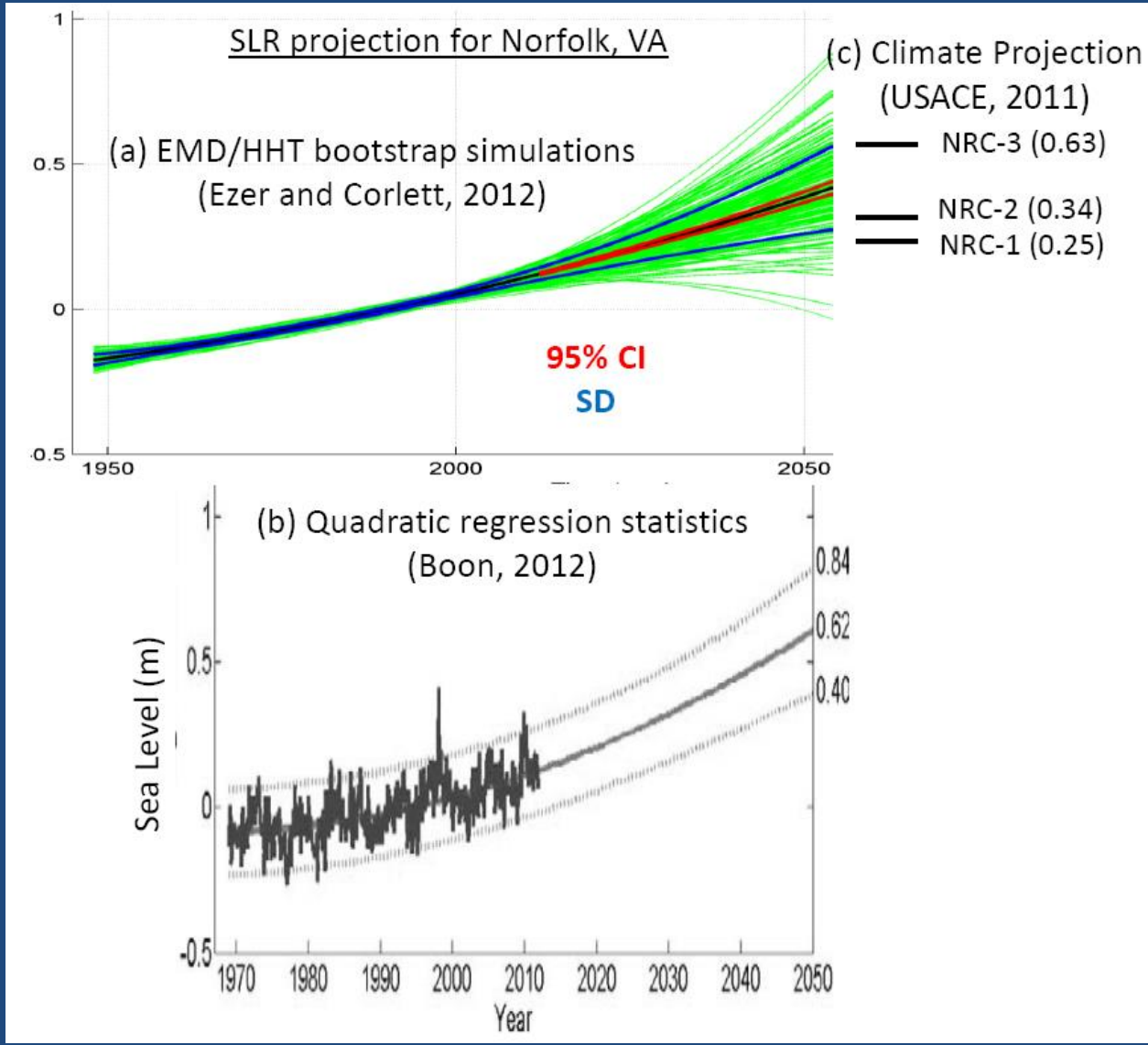
Projected SLR in Norfolk (ft)



Projections based on statistics of past sea level data:

- May be useful for short-term horizon (~20-50 years?)
- Do not take into account potential long-term changes:

- abrupt Greenland ice-melt
- future CO2 emissions
- other unexpected climate change and feedbacks



Probabilistic approaches in local SLR

Journal of Coastal Research	00	0	000–000	Coconut Creek, Florida	Month 0000

Nonlinear Change in Sea Level Observed at North American Tide Stations

John D. Boon* and Molly Mitchell

Virginia Institute of Marine Science
College of William & Mary
Gloucester Point, VA 23062, U.S.A.

www.cerf-jcr.org

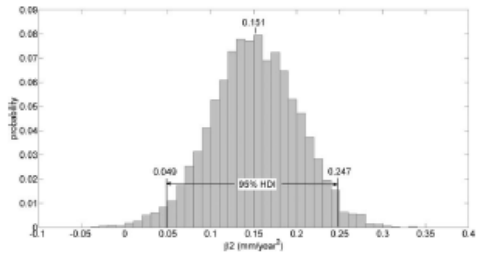
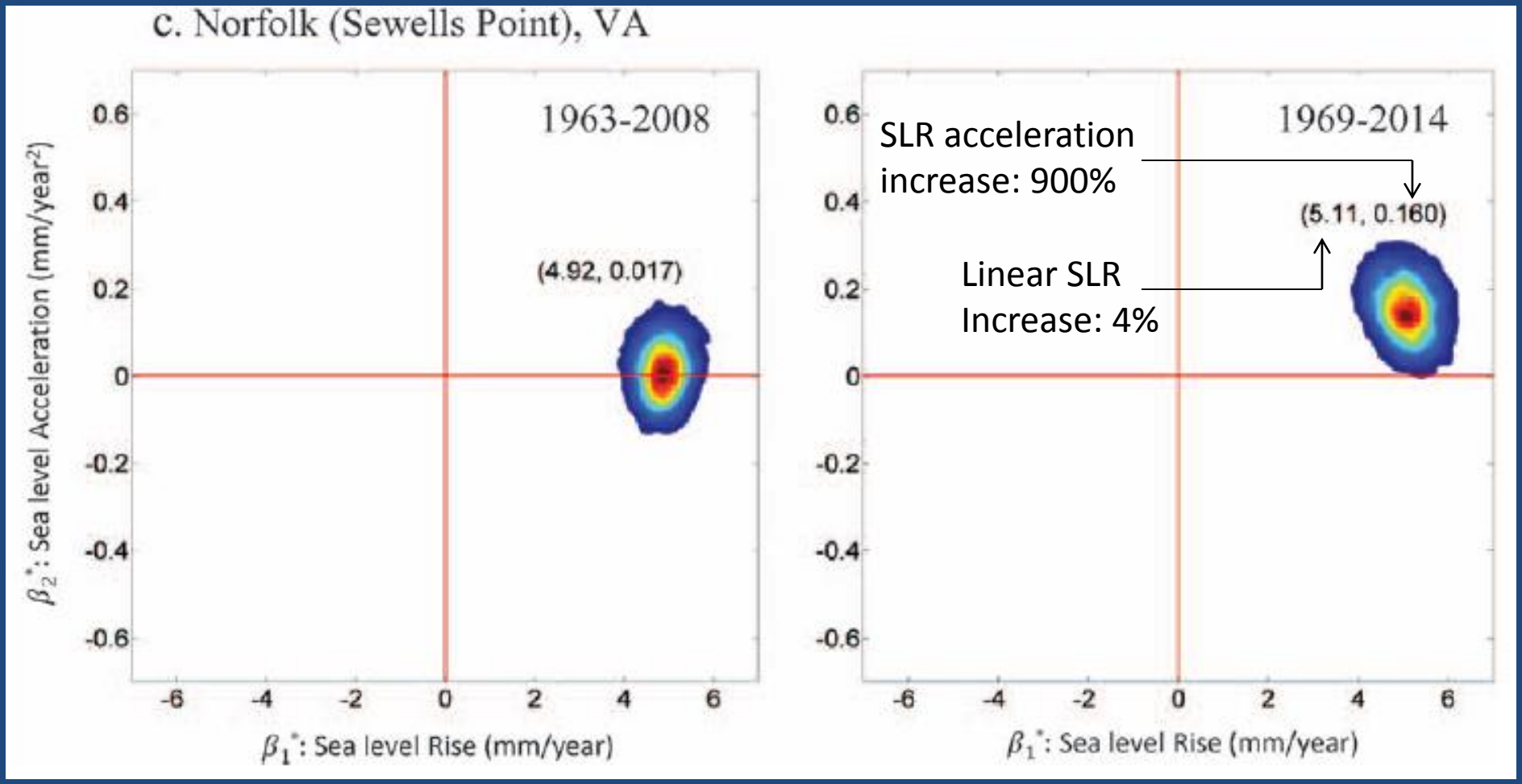


Figure 5. Marginal probability distribution for sea-level acceleration parameter illustrating median value $\beta_2^* = 0.151$ mm/y^2 and 95% HDI given 1969–2014 RMSL data at Baltimore. Note the 95% HDI between the 2.5 and 97.5 percentiles ($\beta_2^* = 0.049$ and 0.247 mm/y^2, respectively) does not include $\beta_2 = 0$.



Probabilistic approaches in projections of coastal risks based on climate models

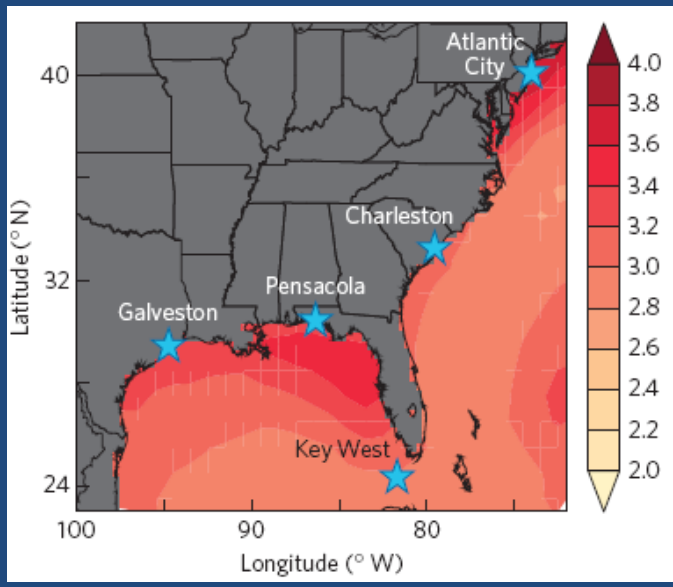
nature climate change

ARTICLES

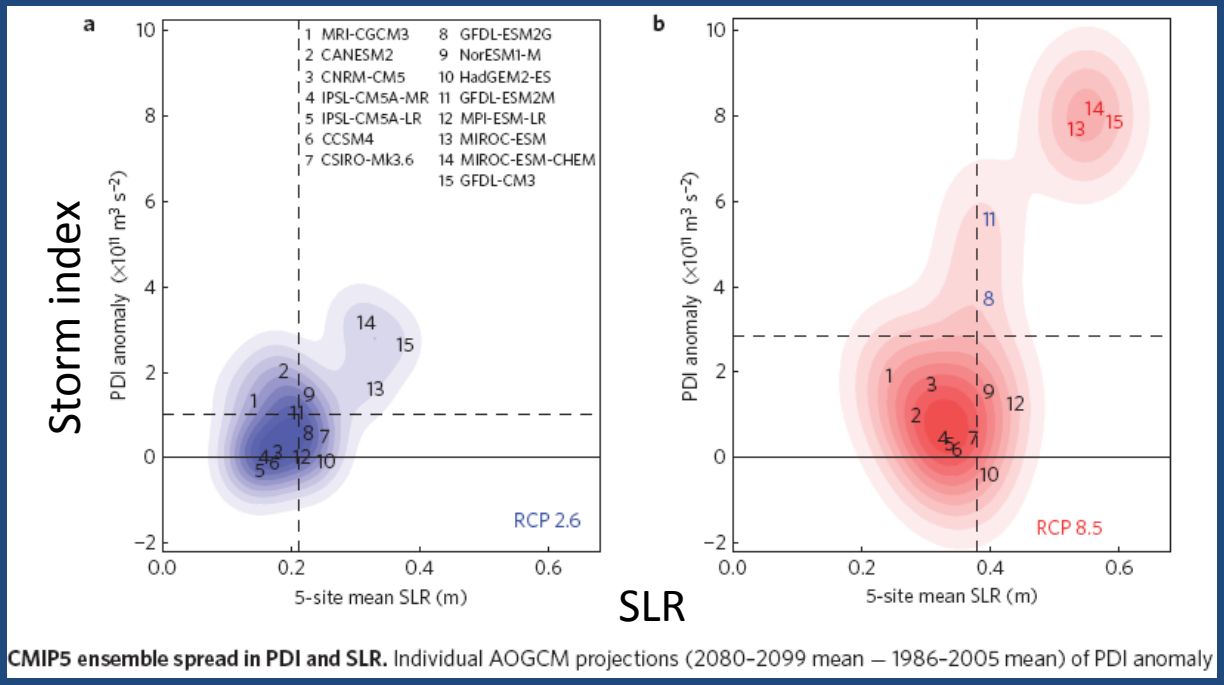
PUBLISHED ONLINE: 21 SEPTEMBER 2015 | DOI: 10.1038/NCLIMATE2801

Joint projections of US East Coast sea level and storm surge

Christopher M. Little[1*], Radley M. Horton[2], Robert E. Kopp[3], Michael Oppenheimer[4,5], Gabriel A. Vecchi[6] and Gabriele Villarini[7]

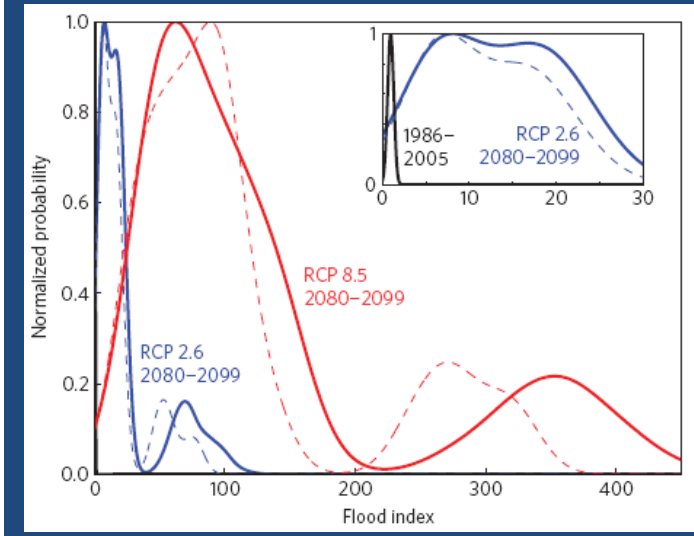


Climate models for two CO2 scenarios

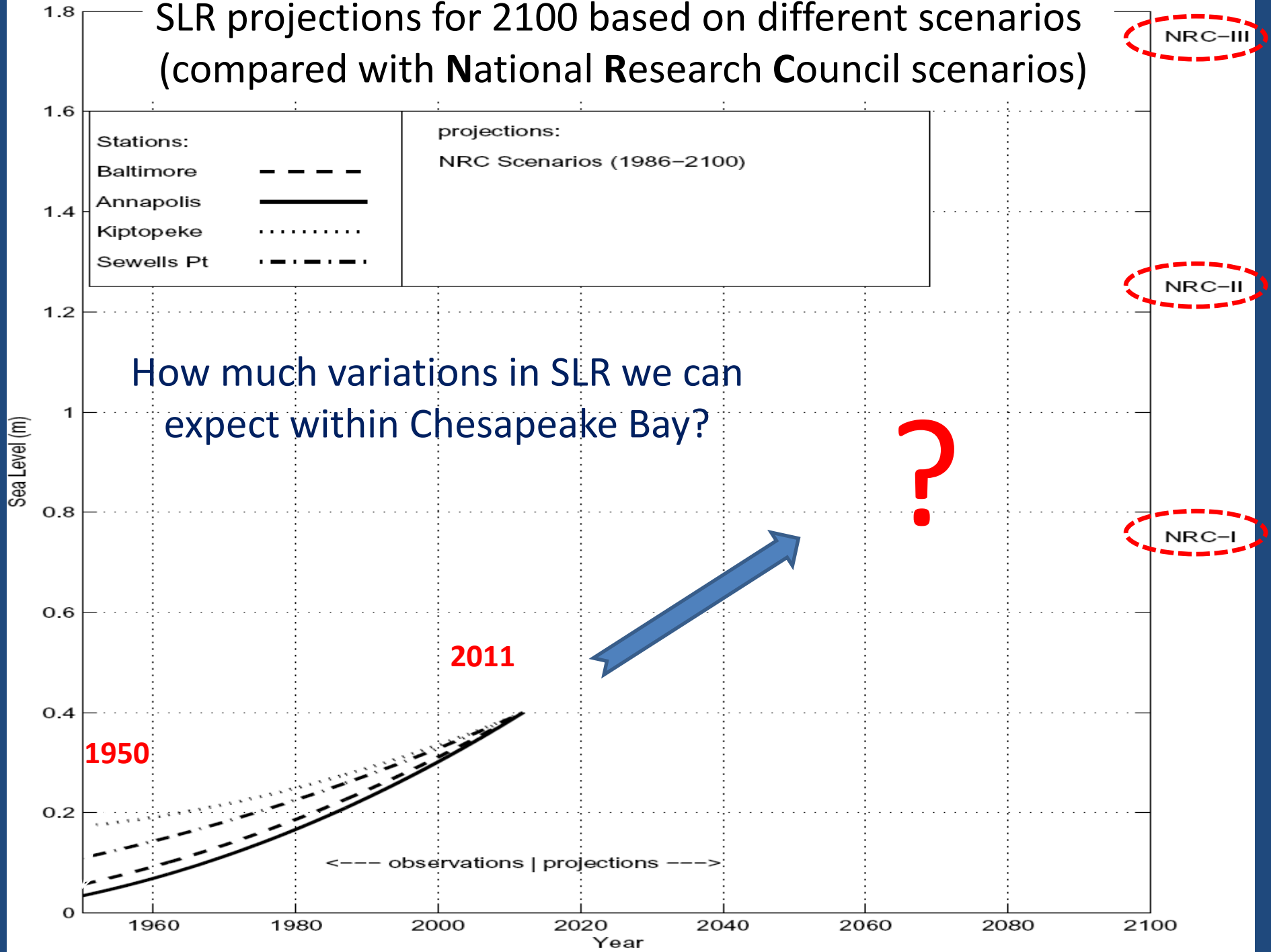


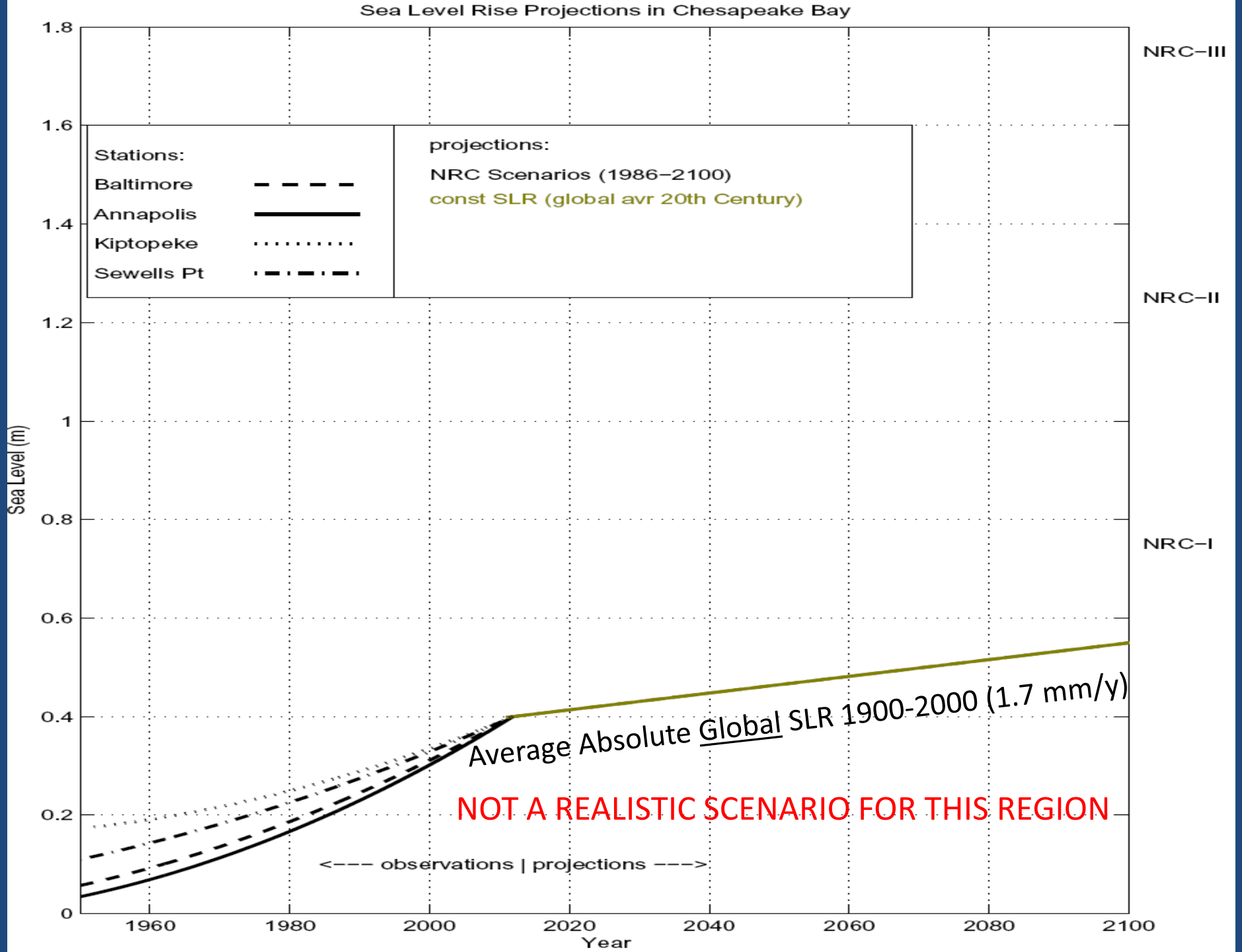
CMIP5 ensemble spread in PDI and SLR. Individual AOGCM projections (2080–2099 mean – 1986–2005 mean) of PDI anomaly

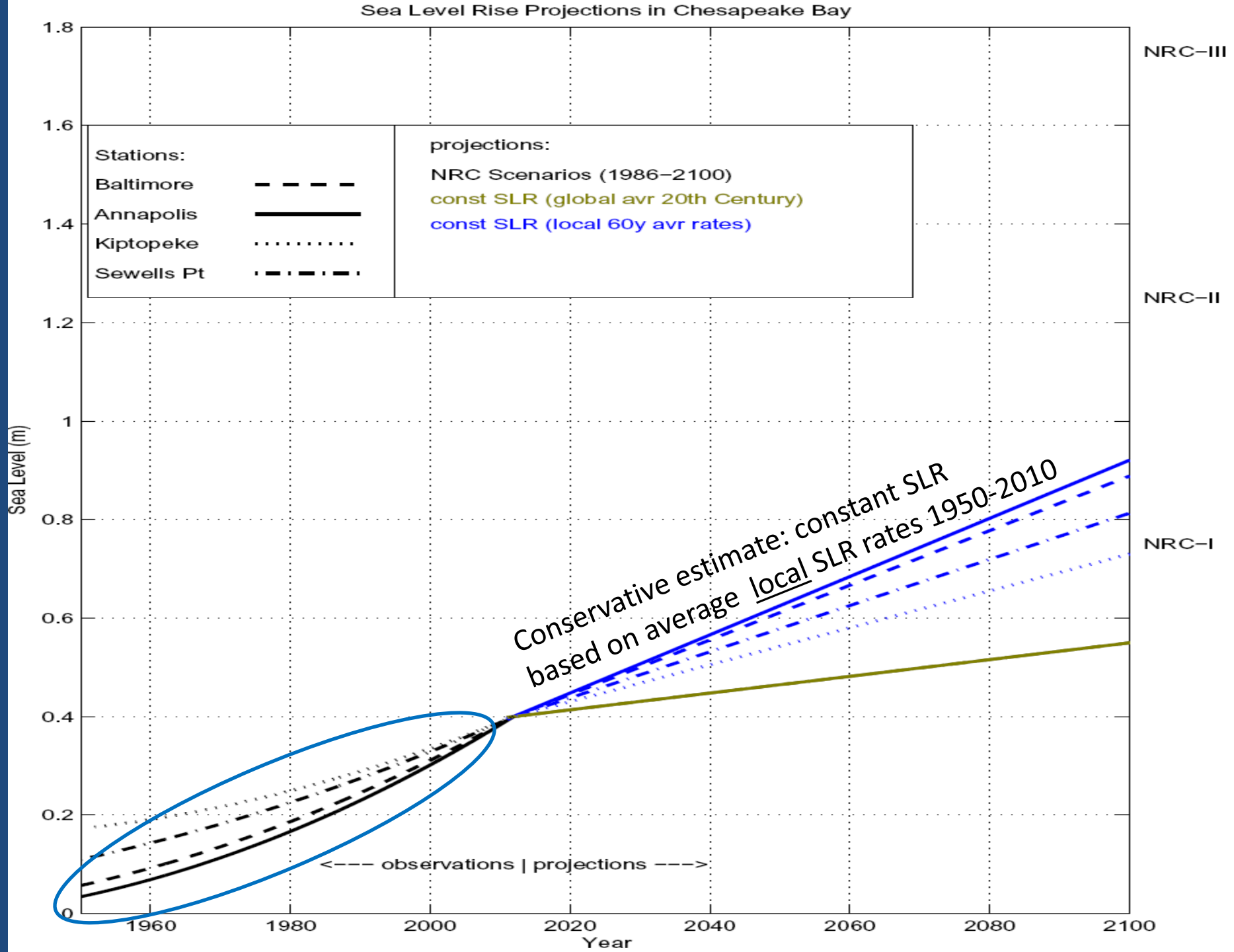
Probability vs. flood index

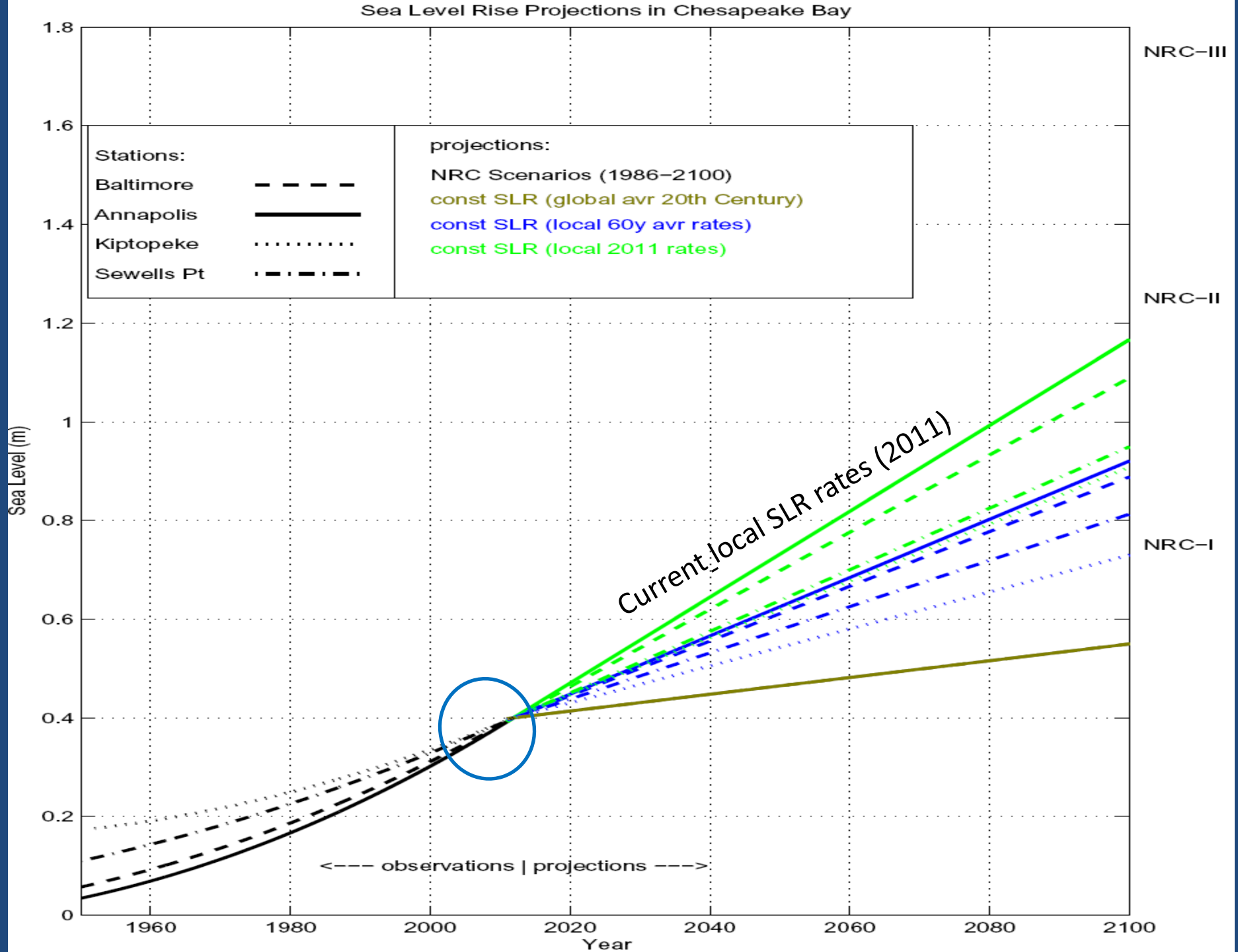


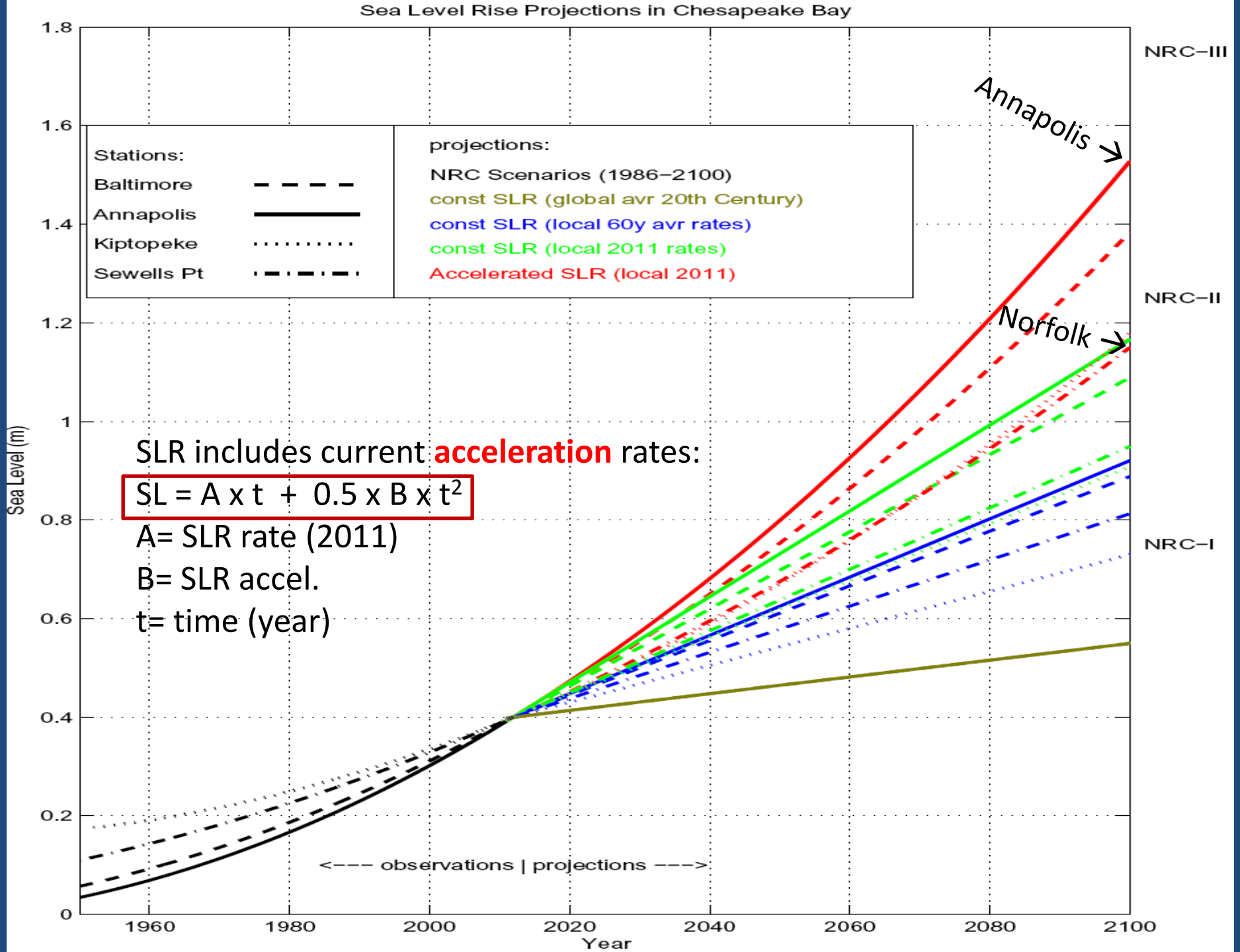
SLR projections for 2100 based on different scenarios (compared with **N**ational **R**esearch **C**ouncil scenarios)




Sea Level Rise Projections in Chesapeake Bay
Stations:
Baltimore
Annapolis
Kiptopeke
Sewells Pt
projections:
NRC Scenarios (1986–2100)
const SLR (global avr 20th Century)
NRC–III
NRC–II
NRC–I
Sea Level (m)
Year
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1960
1980
2000
2020
2040
2060
2080
2100
Average Absolute Global SLR 1900-2000 (1.7 mm/y)
NOT A REALISTIC SCENARIO FOR THIS REGION
<--- observations | projections --->
Sea Level (m)


Sea Level Rise Projections in Chesapeake Bay
Stations:
Baltimore
Annapolis
Kiptopeke
Sewells Pt
projections:
NRC Scenarios (1986–2100)
const SLR (global avr 20th Century)
const SLR (local 60y avr rates)
NRC–III
NRC–II
NRC–I
Conservative estimate: constant SLR
based on average local SLR rates 1950-2010
<--- observations | projections --->
Sea Level (m)
Year
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1960
1980
2000
2020
2040
2060
2080
2100


Sea Level Rise Projections in Chesapeake Bay
Stations:
Baltimore
Annapolis
Kiptopeke
Sewells Pt
projections:
NRC Scenarios (1986–2100)
const SLR (global avr 20th Century)
const SLR (local 60y avr rates)
const SLR (local 2011 rates)
NRC–III
NRC–II
NRC–I
Current local SLR rates (2011)
<--- observations | projections --->
Sea Level (m)
Year
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1960
1980
2000
2020
2040
2060
2080
2100


Sea Level Rise Projections in Chesapeake Bay
Stations:
Baltimore
Annapolis
Kiptopeke
Sewells Pt
projections:
NRC Scenarios (1986–2100)
const SLR (global avr 20th Century)
const SLR (local 60y avr rates)
const SLR (local 2011 rates)
Accelerated SLR (local 2011)
Annapolis
Norfolk
NRC–III
NRC–II
NRC–I
SLR includes current acceleration rates:
SL = A x t + 0.5 x B x t²
A= SLR rate (2011)
B= SLR accel.
t= time (year)
<--- observations | projections --->
Sea Level (m)
Year
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1960
1980
2000
2020
2040
2060
2080
2100

Comparison of local projections of SLR (m) 2000-2100

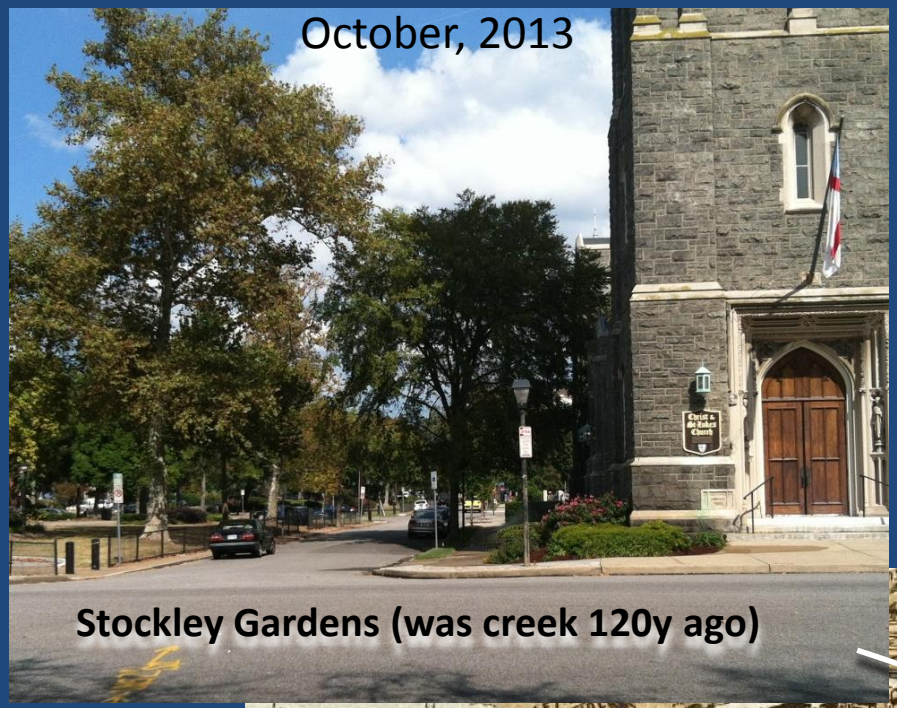
Method	Annapolis			Norfolk		
	Low	Mid	High	Low	Mid	High
USACE	0.35	0.67	1.67	0.4	0.72	1.72
EMD analysis (Ezer&Corlett, 2012)		1.2			0.85	
Quadratic fit (Boon&Mitchell, 2015)		1.4			1.44	

Summary of contributions to SLR in the Chesapeake Bay region:

SLR Process	Rate mm/y	Reference and notes
Subsidence – GIA	0.6-1.8 mm/yr	USGS; Engelhart & Horton (2012); Miller et al. (2013)
Subsidence – Ground water pumping	2-4.8 mm/yr (location dependent)	USGS; Eggleston & Pope (2013)
Subsidence – Impact crater	Probably small/unknown	USGS; Powars and Bruce (1999); Boon et al. (2010)
Ocean circulation	±5-10 mm/yr (includes decadal variations)	Ezer (2013); Ezer et al. (2013)
Global scale thermal expansion and land ice melt	1.7-3.2 mm/yr (larger recent rates)	Church and White (2011); Ezer (2013); many others.

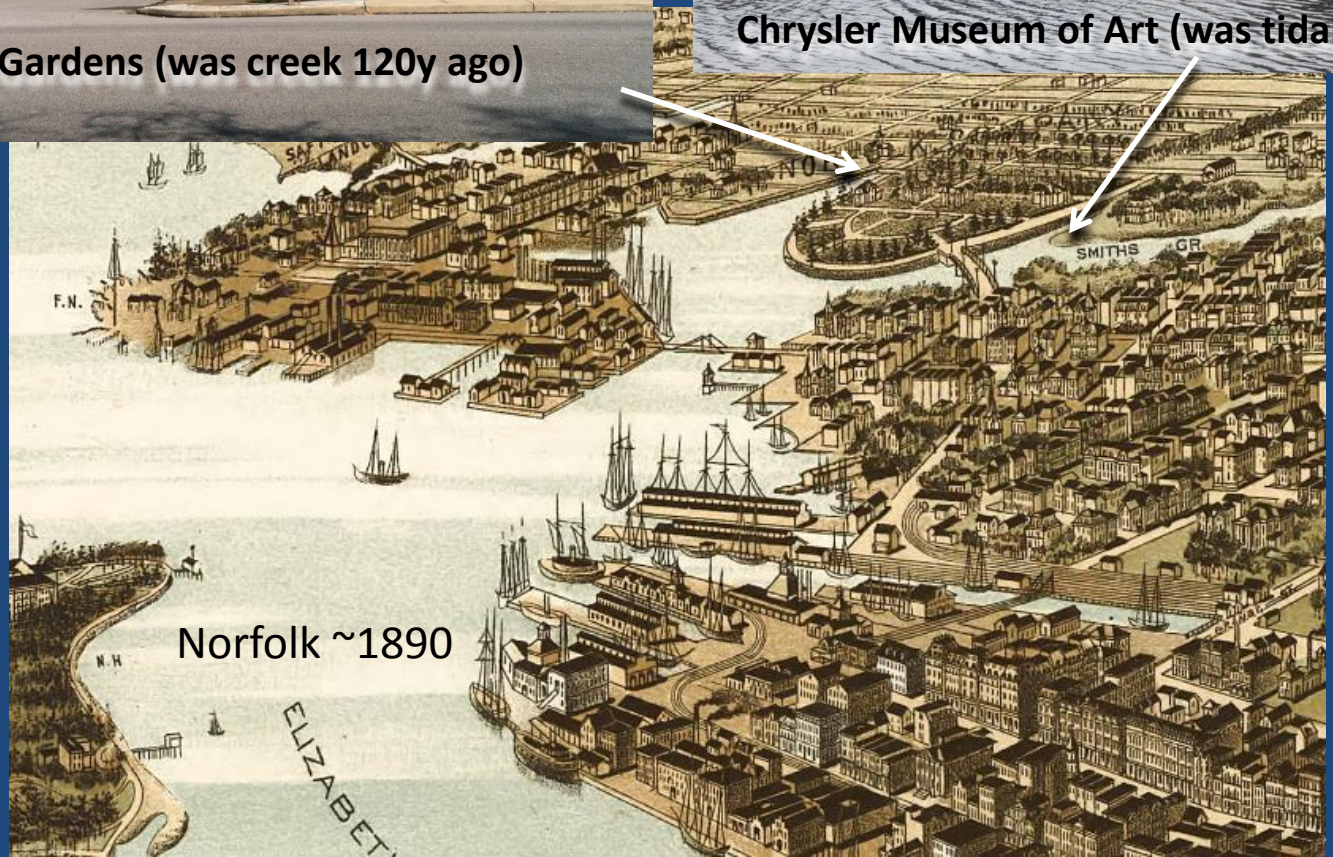
Future unknowns:
- Rapid Greenland ice sheet melt
- Gulf Stream slowdown

Local impact of climate change in the Chesapeake Bay region



Stockley Gardens (was creek 120y ago)

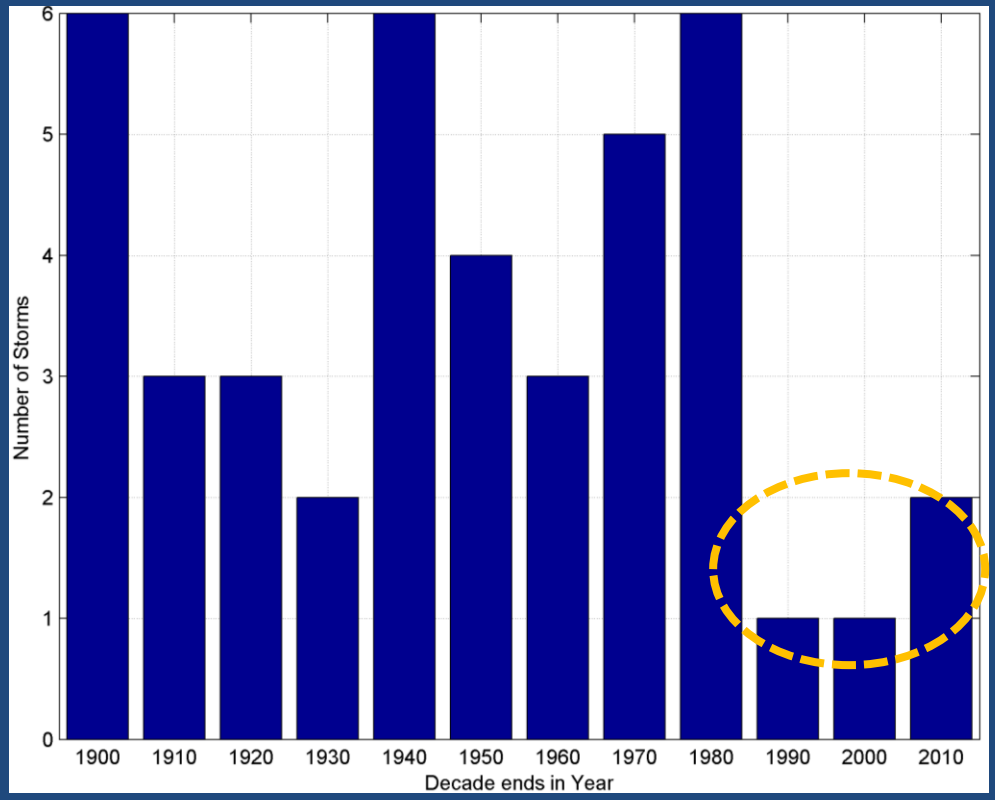
Chrysler Museum of Art (was tidal flat 120y ago)



Norfolk ~1890

Local impact of climate change in the Chesapeake Bay region

Number of big (>5 inch) snow storms per decade in Norfolk

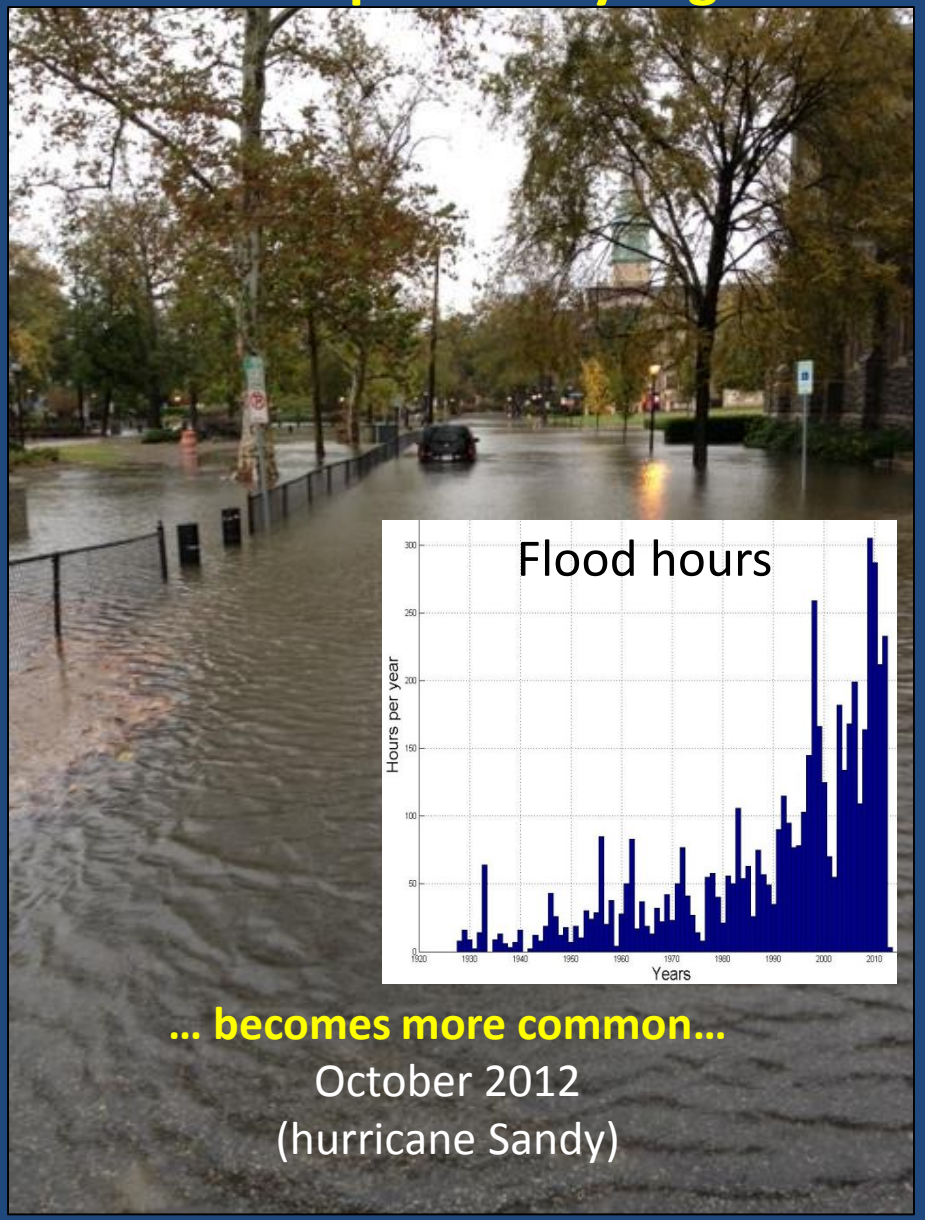


Local impact of climate change in the Chesapeake Bay region

January, 2013

… becomes very rare

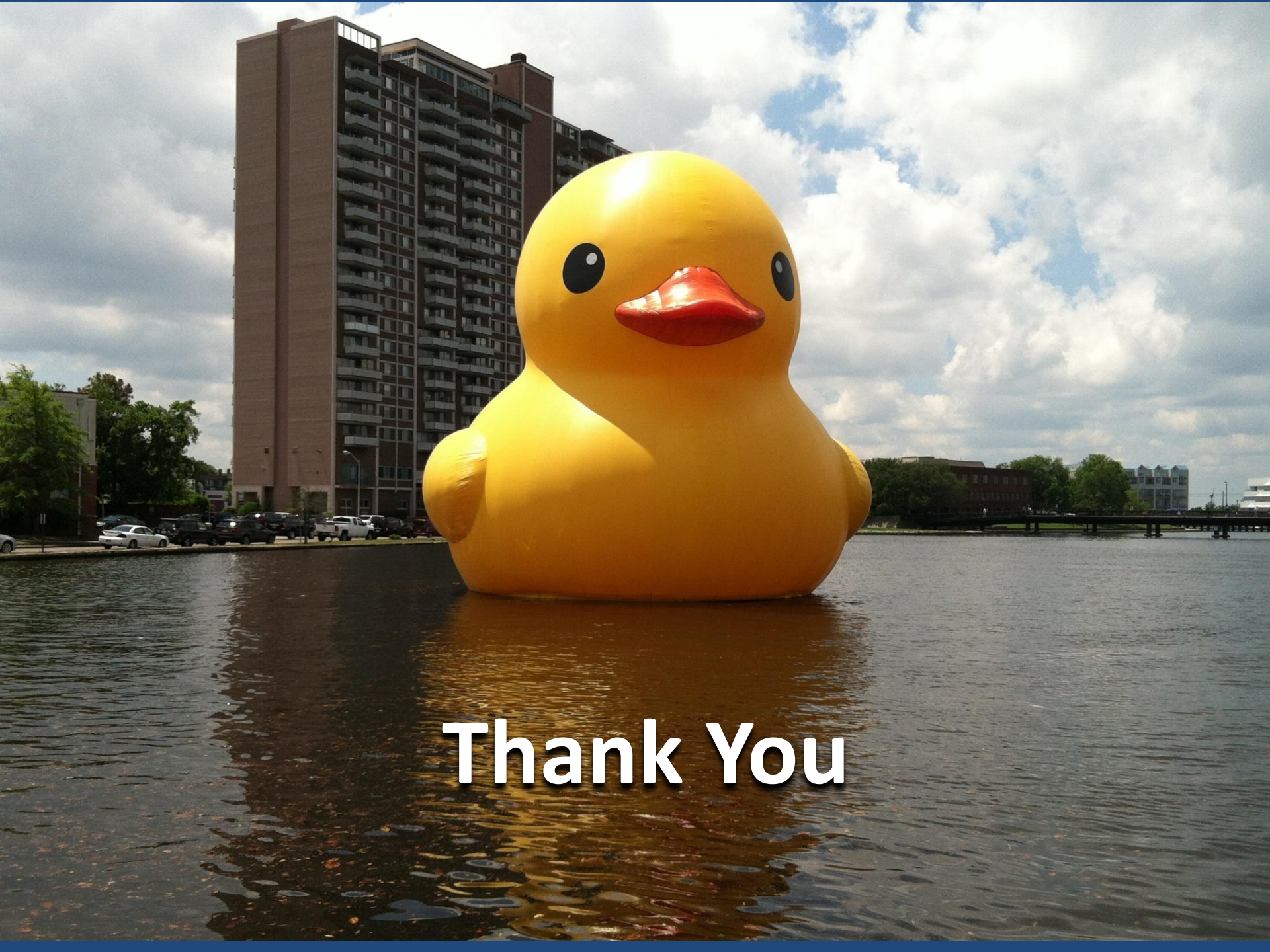
January, 2014



… becomes more common…

October 2012

(hurricane Sandy)


Thank You