Impacts of Climate Change: Sea Level Rise and Coastal Flood Risk

Doug Marcy

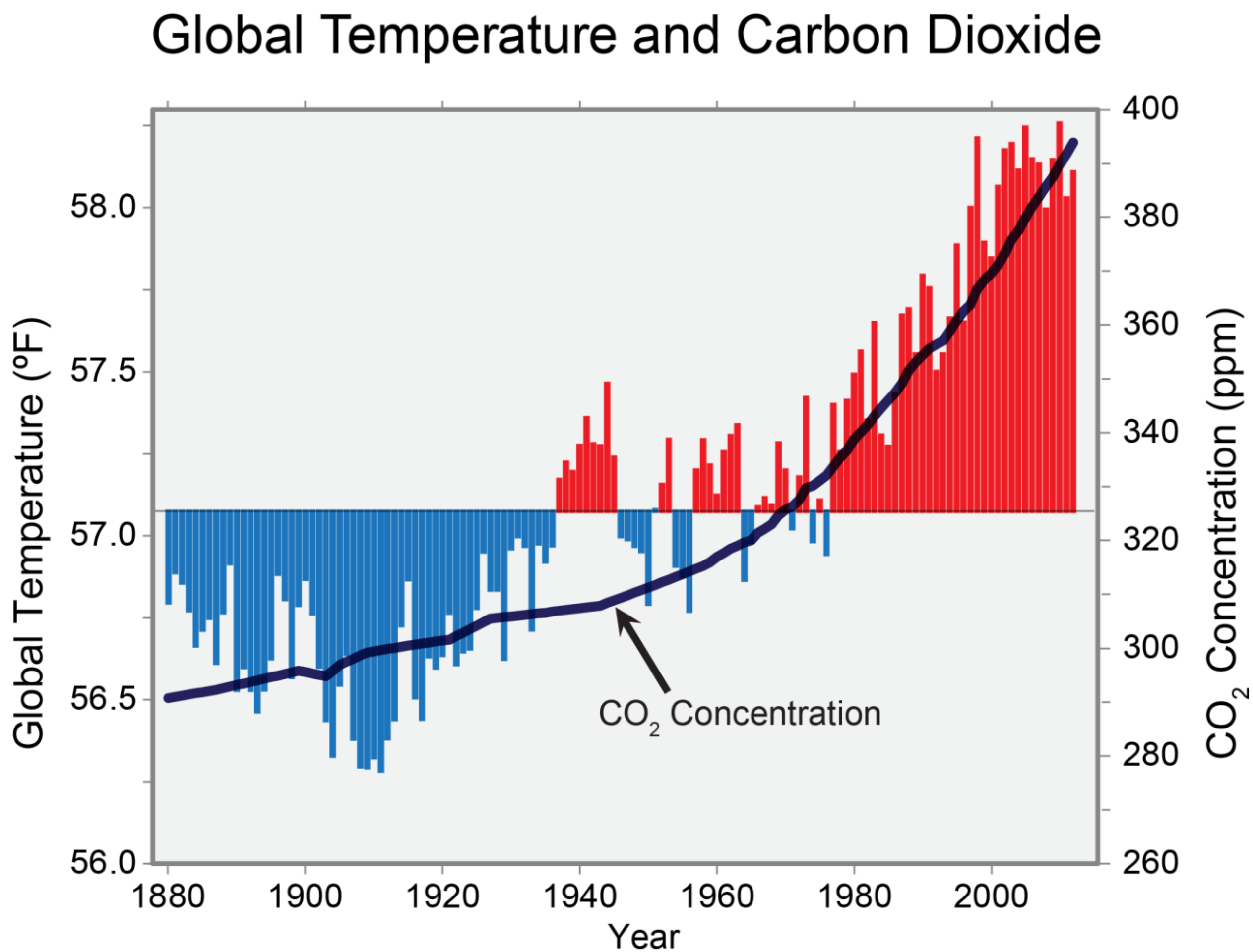
Coastal Hazards Specialist

NOAA Office for Coastal Management

OFFICE FOR COASTAL MANAGEMENT

DIGITAL COAST

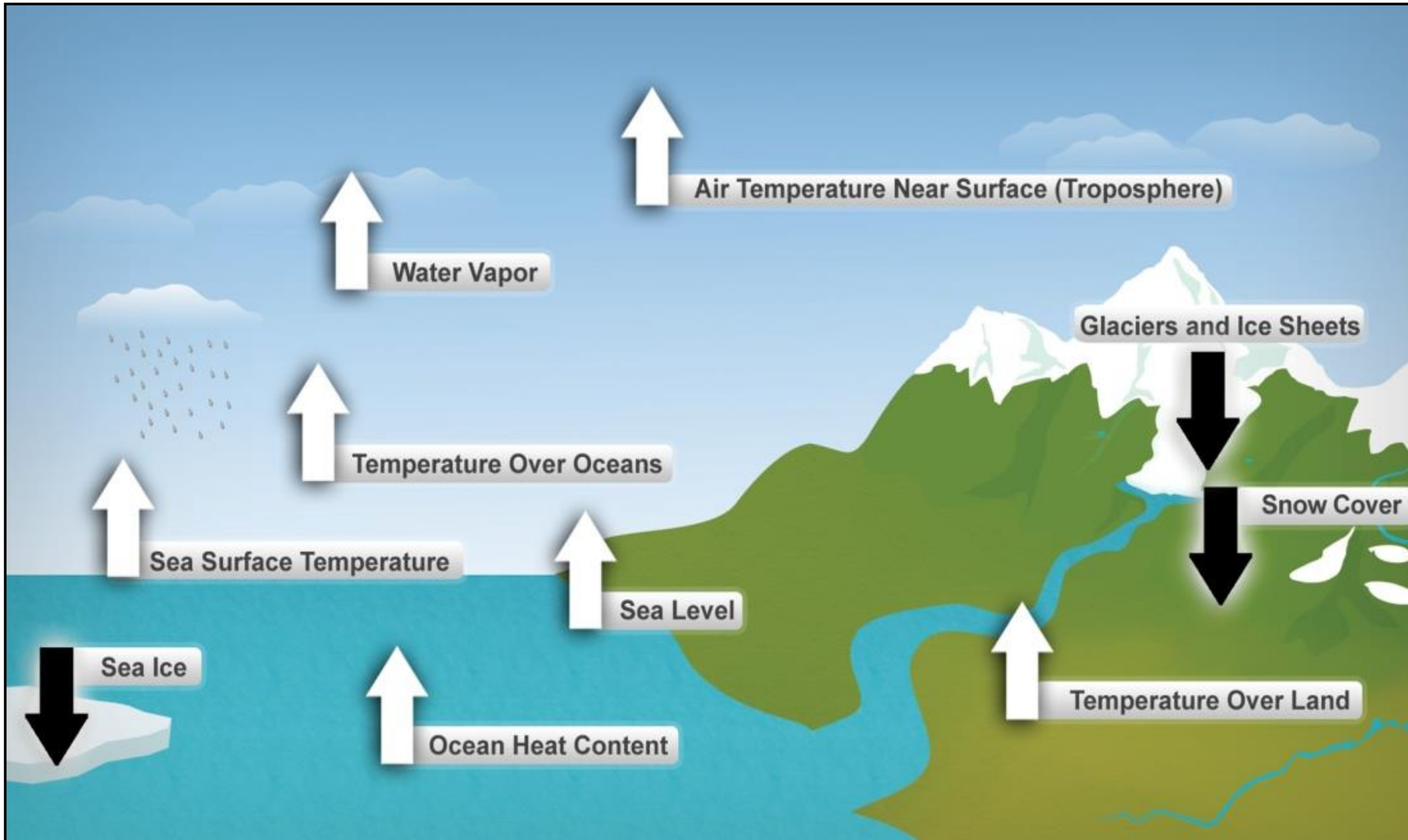
Increase in Global Temperature



NCA3

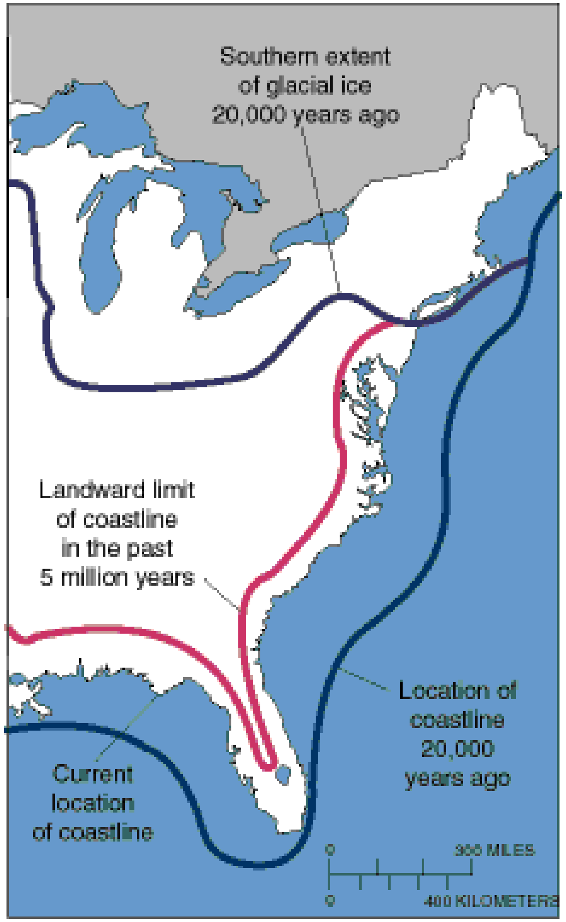
OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST

10 Indicators of a Warming World



NCA3

Sea Level has Changed Throughout Geologic History



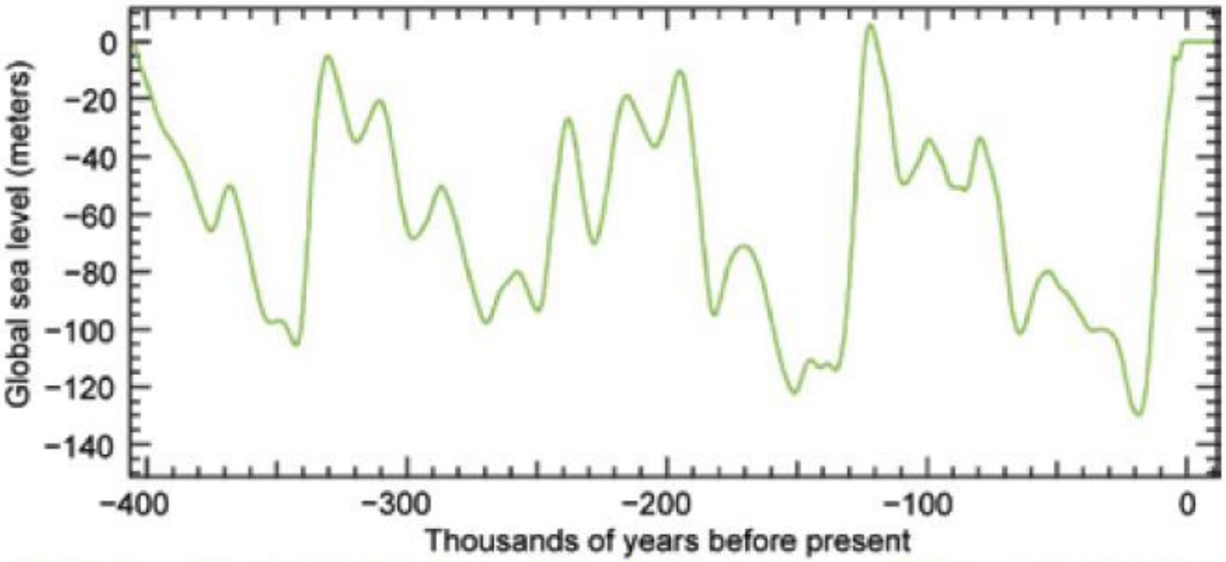
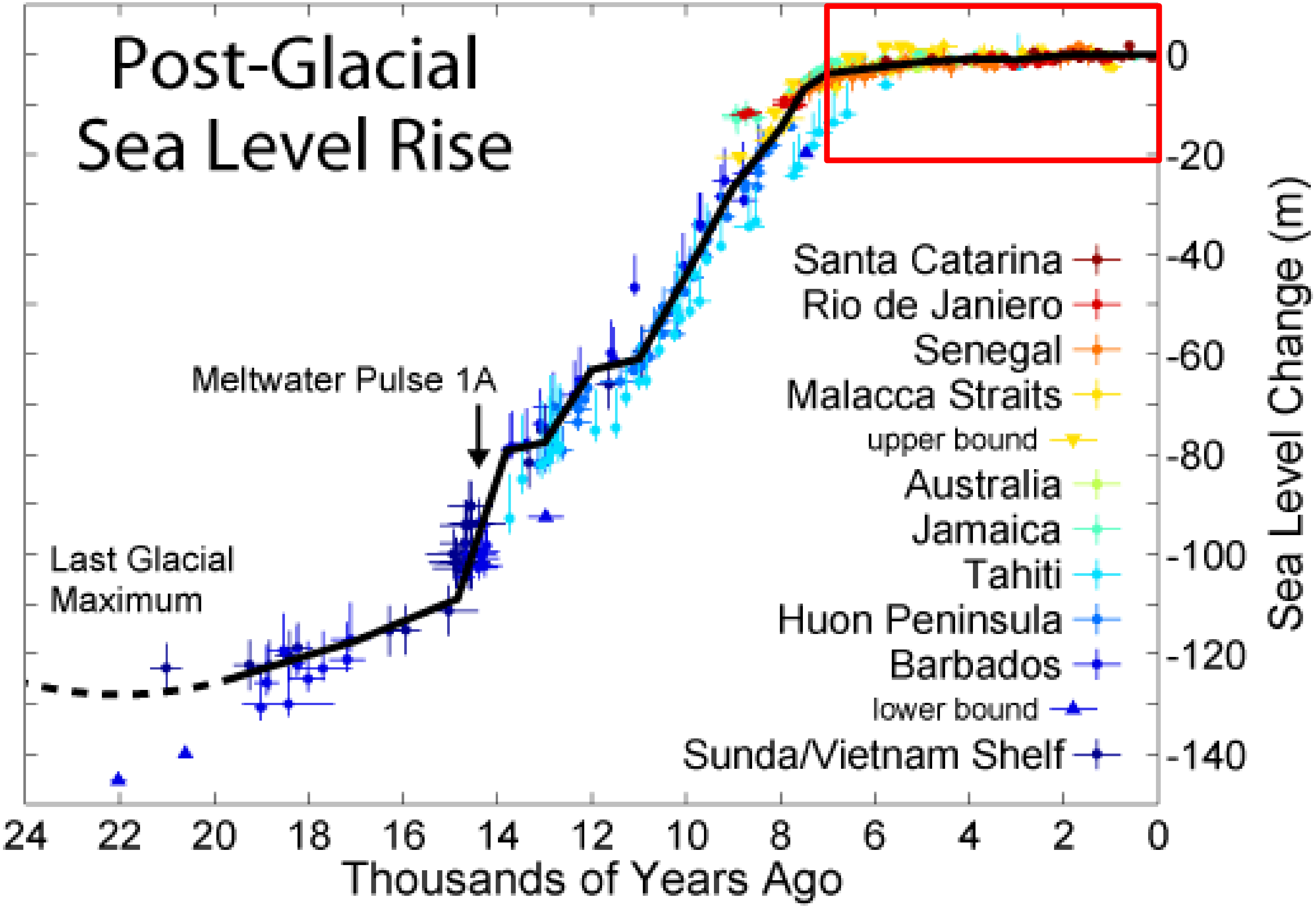
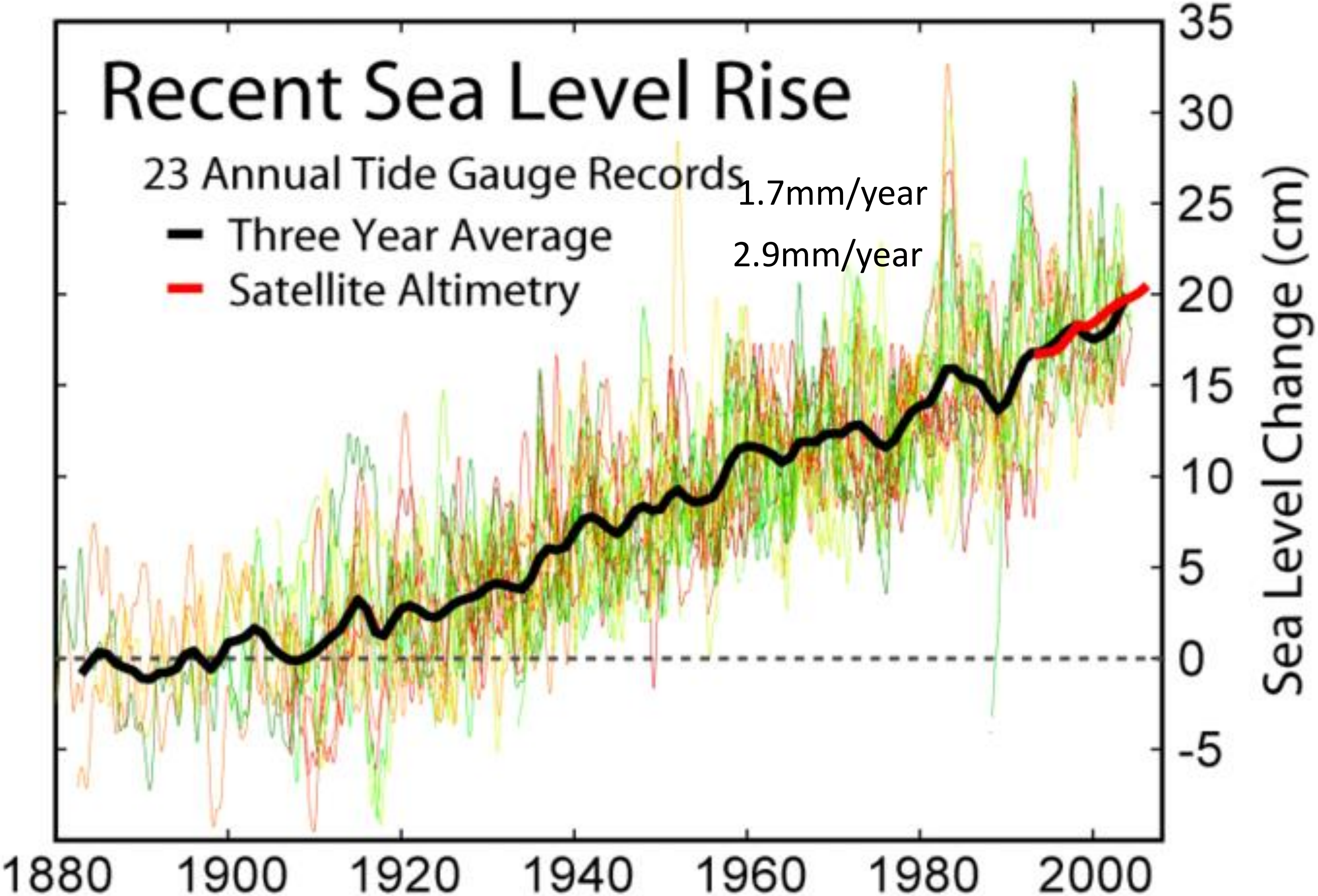


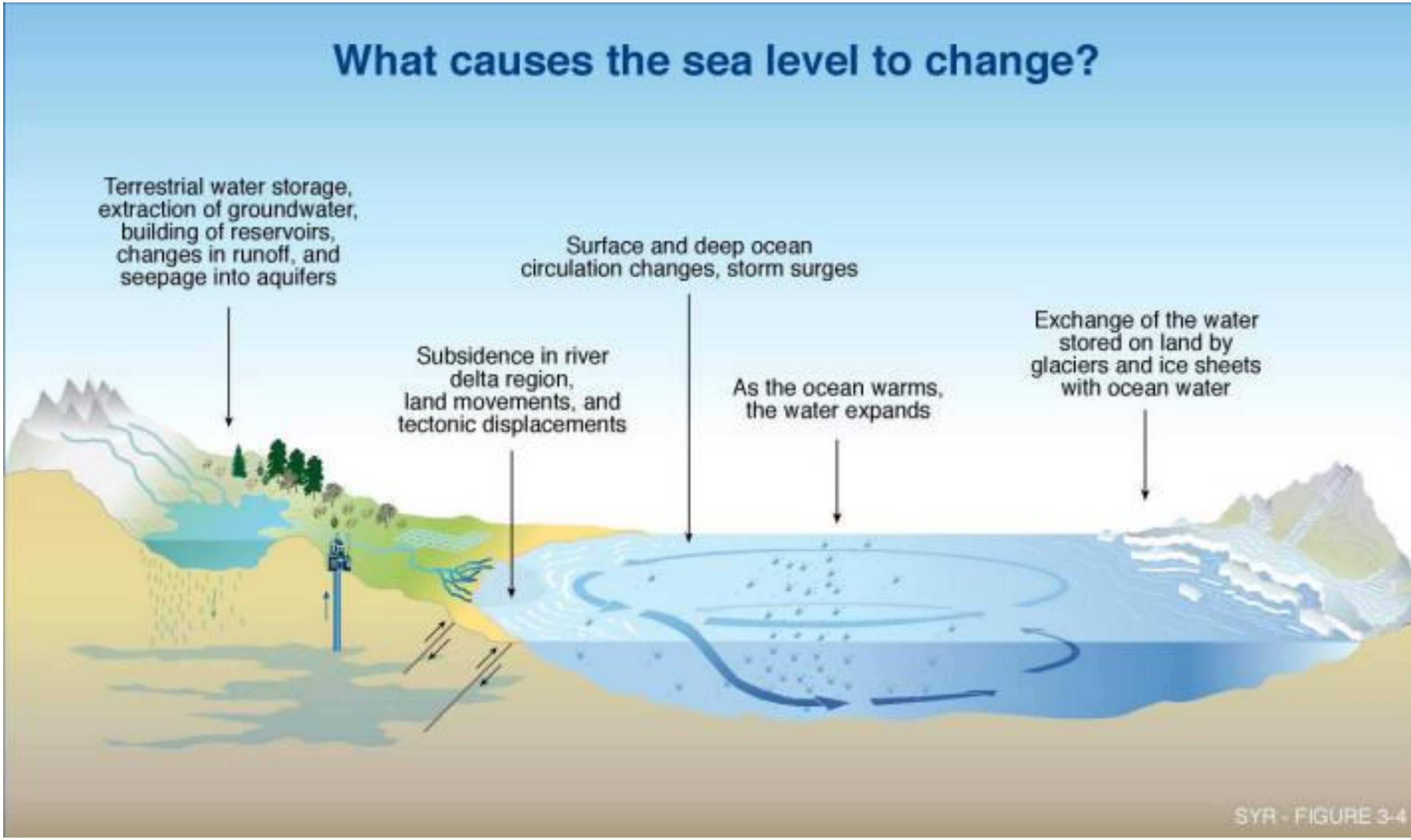
Figure 2.1. Global sea level change from 400,000 years ago to the present (Williams et al. 2009).



OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST



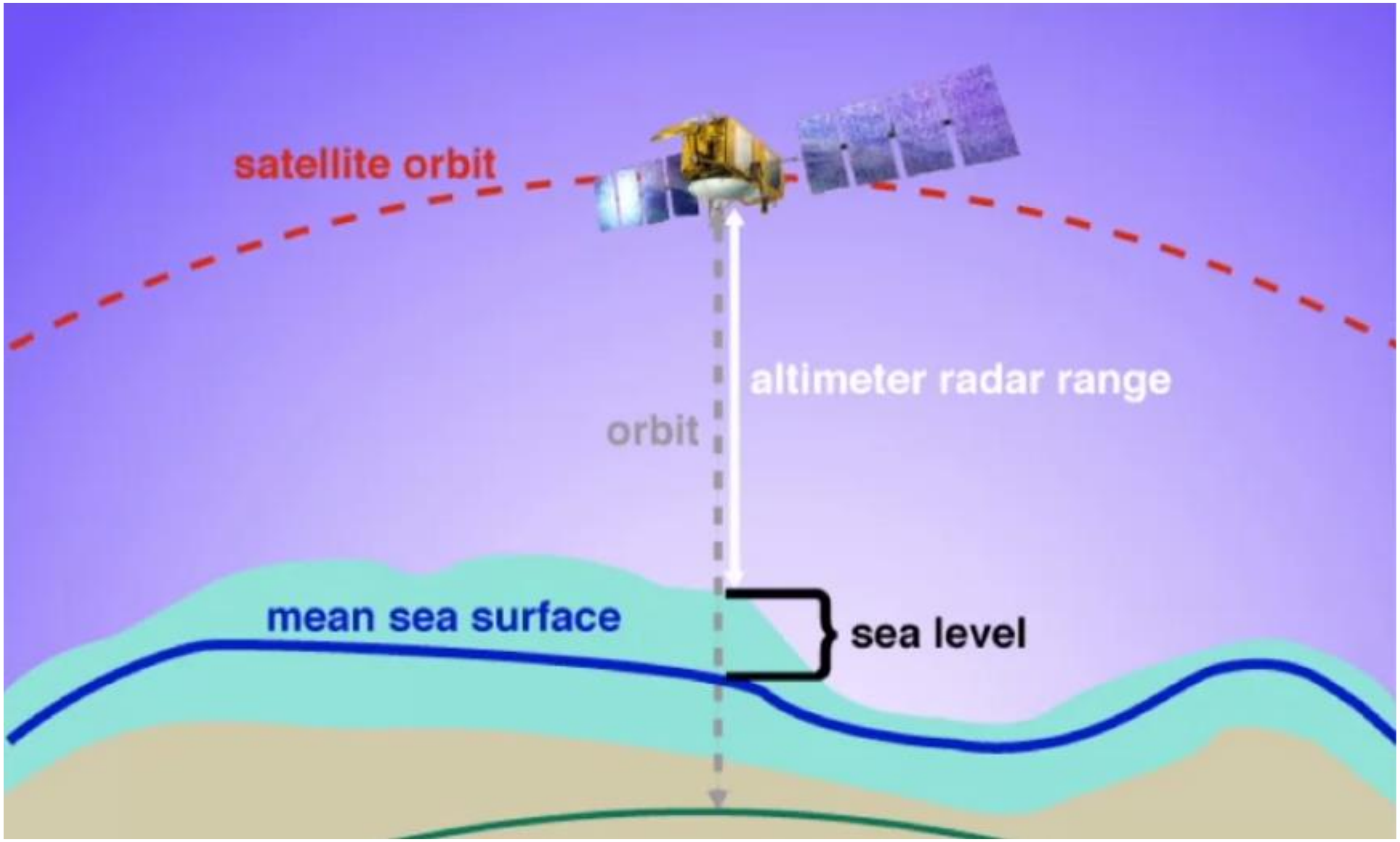
Recent Sea Level Rise
23 Annual Tide Gauge Records
Three Year Average
Satellite Altimetry
1.7mm/year
2.9mm/year
Sea Level Change (cm)
35
30
25
20
15
10
5
0
-5
1880
1900
1920
1940
1960
1980
2000


What causes the sea level to change?
Terrestrial water storage, extraction of groundwater, building of reservoirs, changes in runoff, and seepage into aquifers
Surface and deep ocean circulation changes, storm surges
Subsidence in river delta region, land movements, and tectonic displacements
As the ocean warms, the water expands
Exchange of the water stored on land by glaciers and ice sheets with ocean water
SYR - FIGURE 3-4

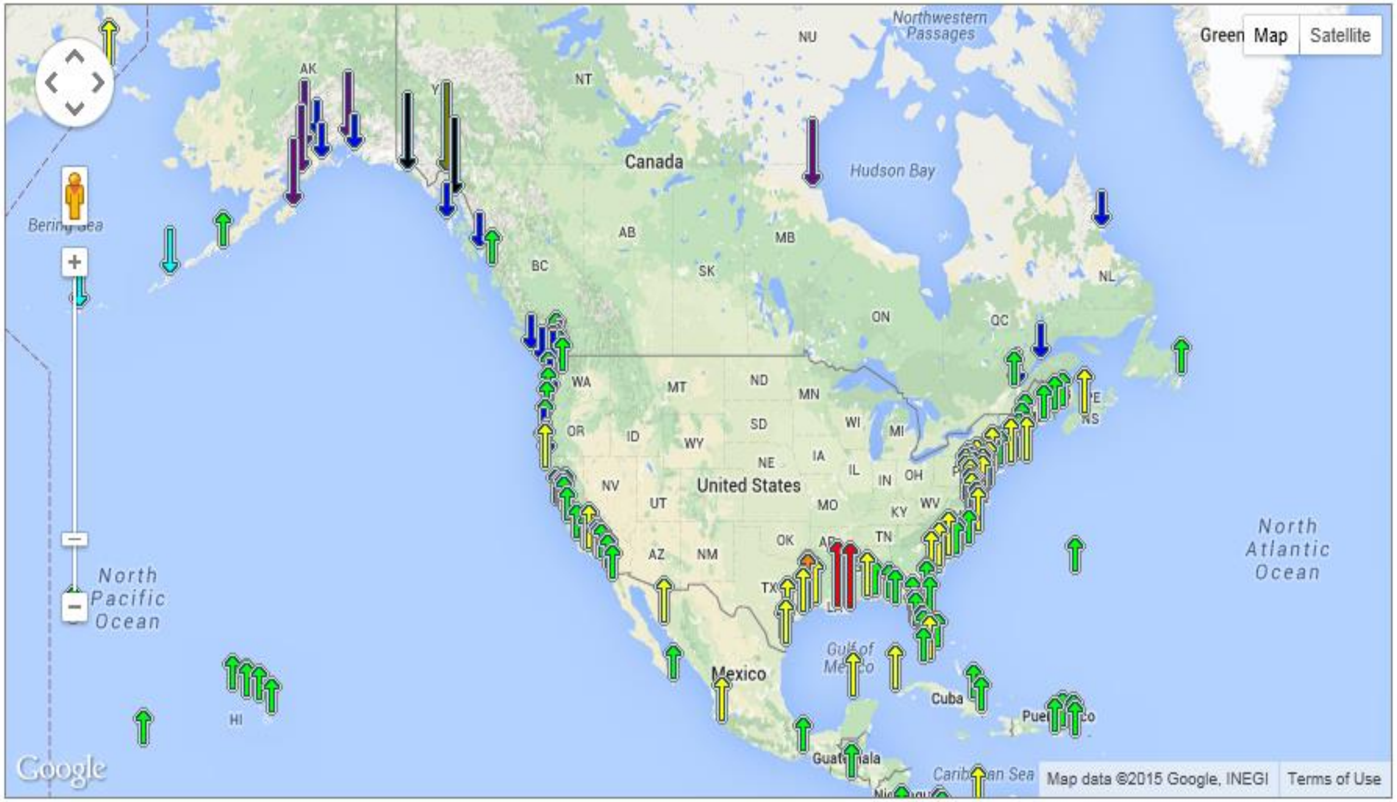
NCA3

Monitoring Sea Level Locally

Monitoring Sea Level Globally



Sea Level Trends



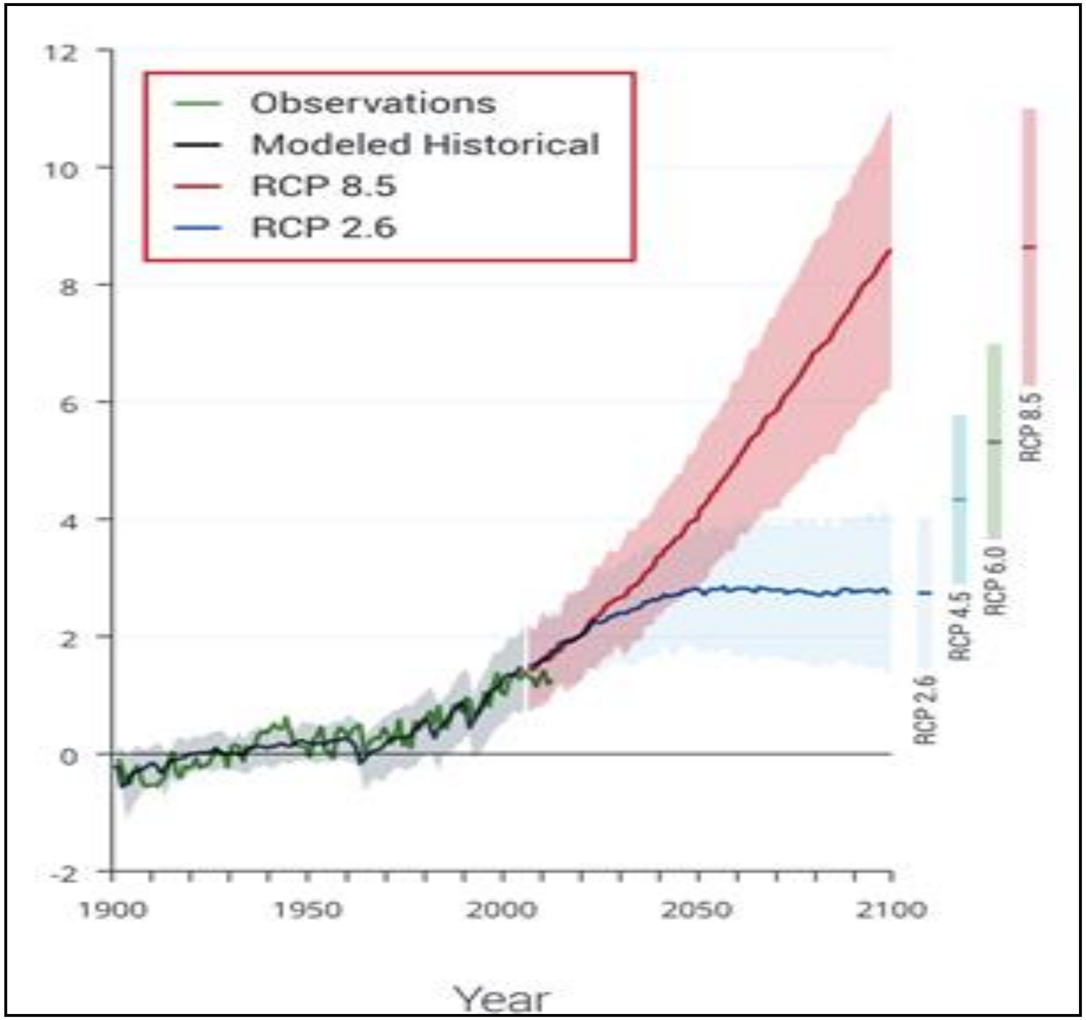
Sea Level Trends
mm/yr (feet/century)

15 to 21 (5 to 7)	6 to 9 (2 to 3)	-3 to 0 (-1 to 0)	-12 to -9 (-4 to -3)
12 to 15 (4 to 5)	3 to 6 (1 to 2)	-6 to -3 (-2 to -1)	-15 to -12 (-5 to -4)
9 to 12 (3 to 4)	0 to 3 (0 to 1)	-9 to -6 (-3 to -2)	-18 to -15 (-6 to -5)

https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST

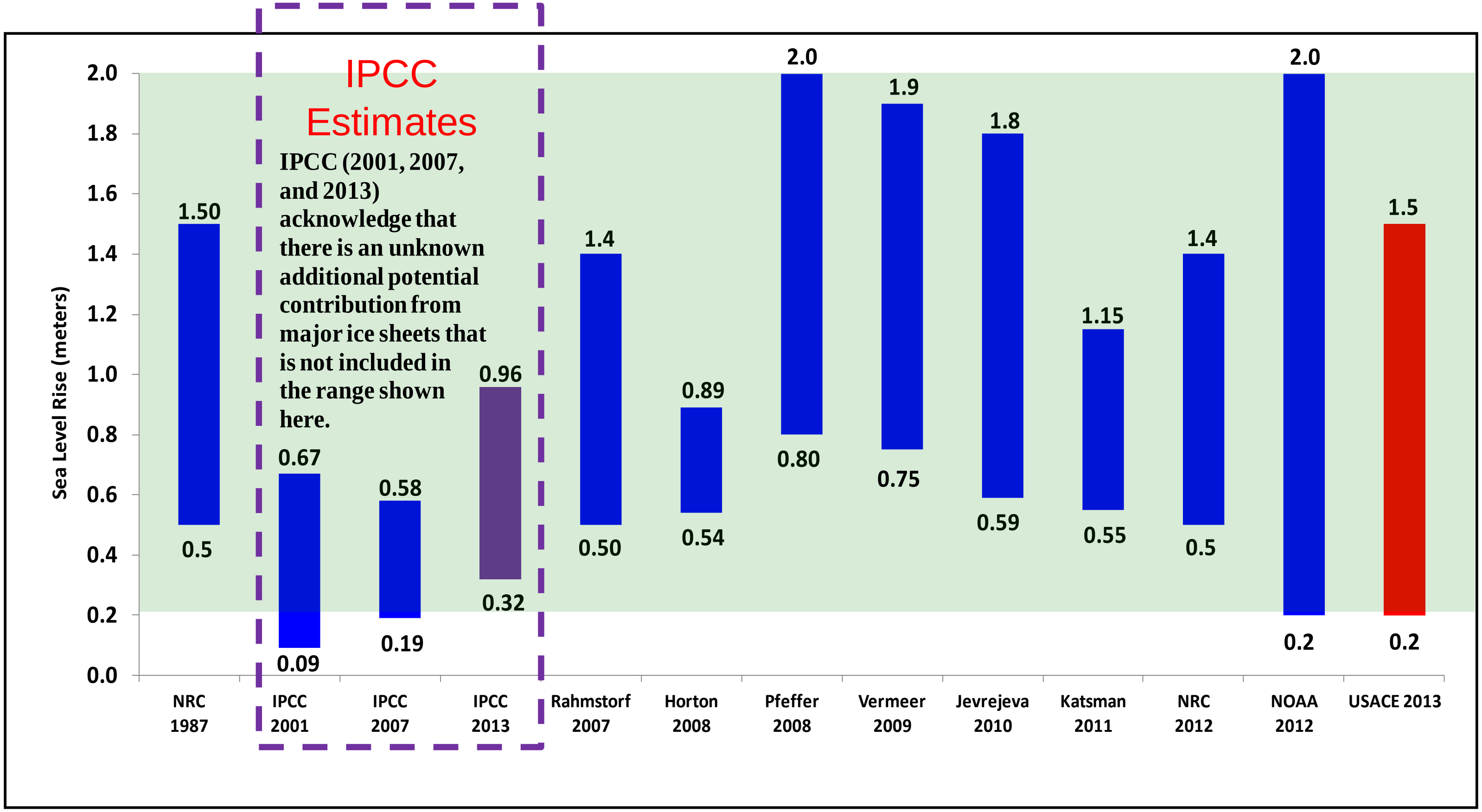
Future Temperature



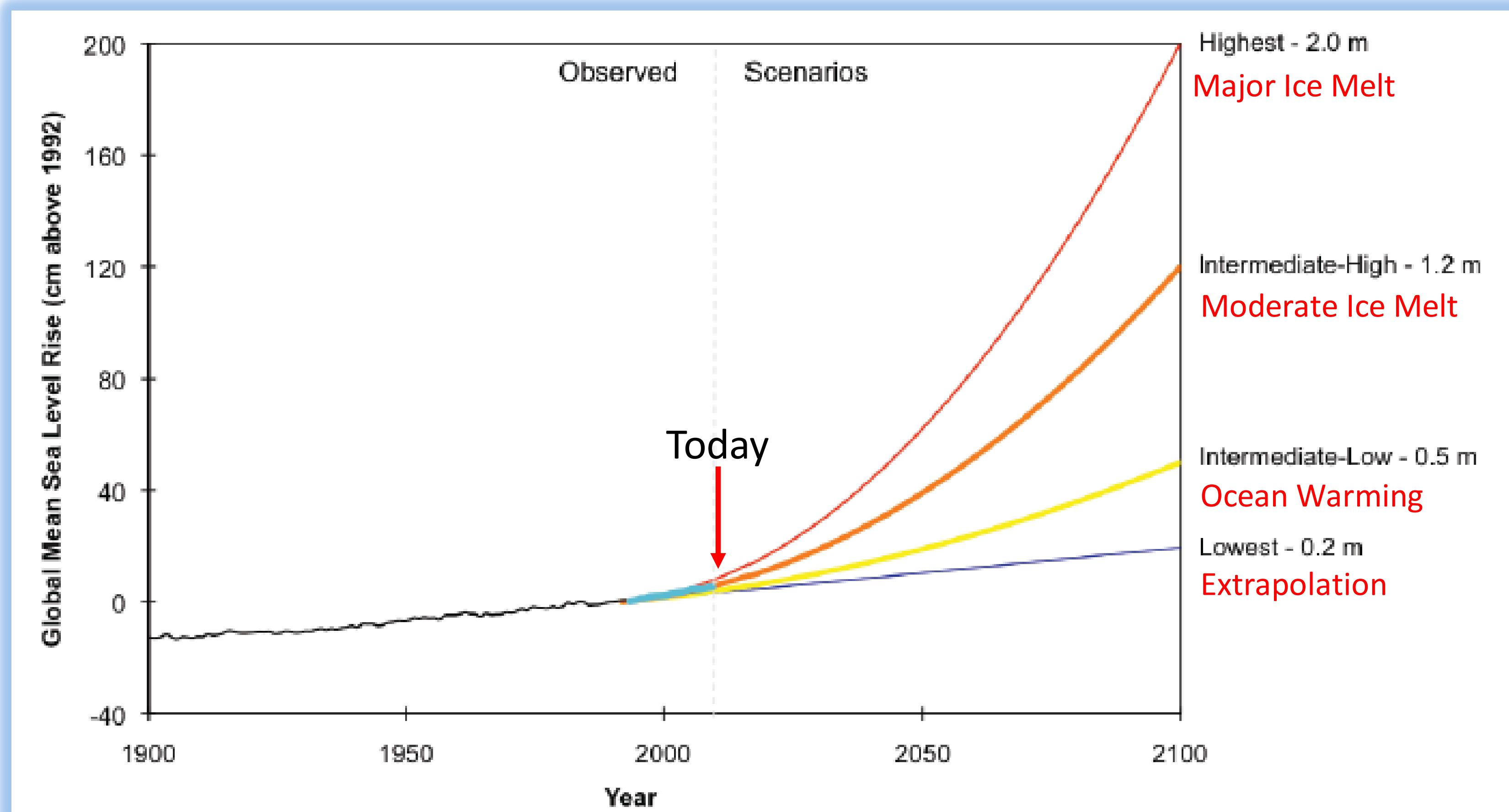
NCA3

OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST

Literature Review



“Consensus Scenarios” that fed the NCA 3rd Assessment



Parris et al., 2012

OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST

Past, Present, and Future

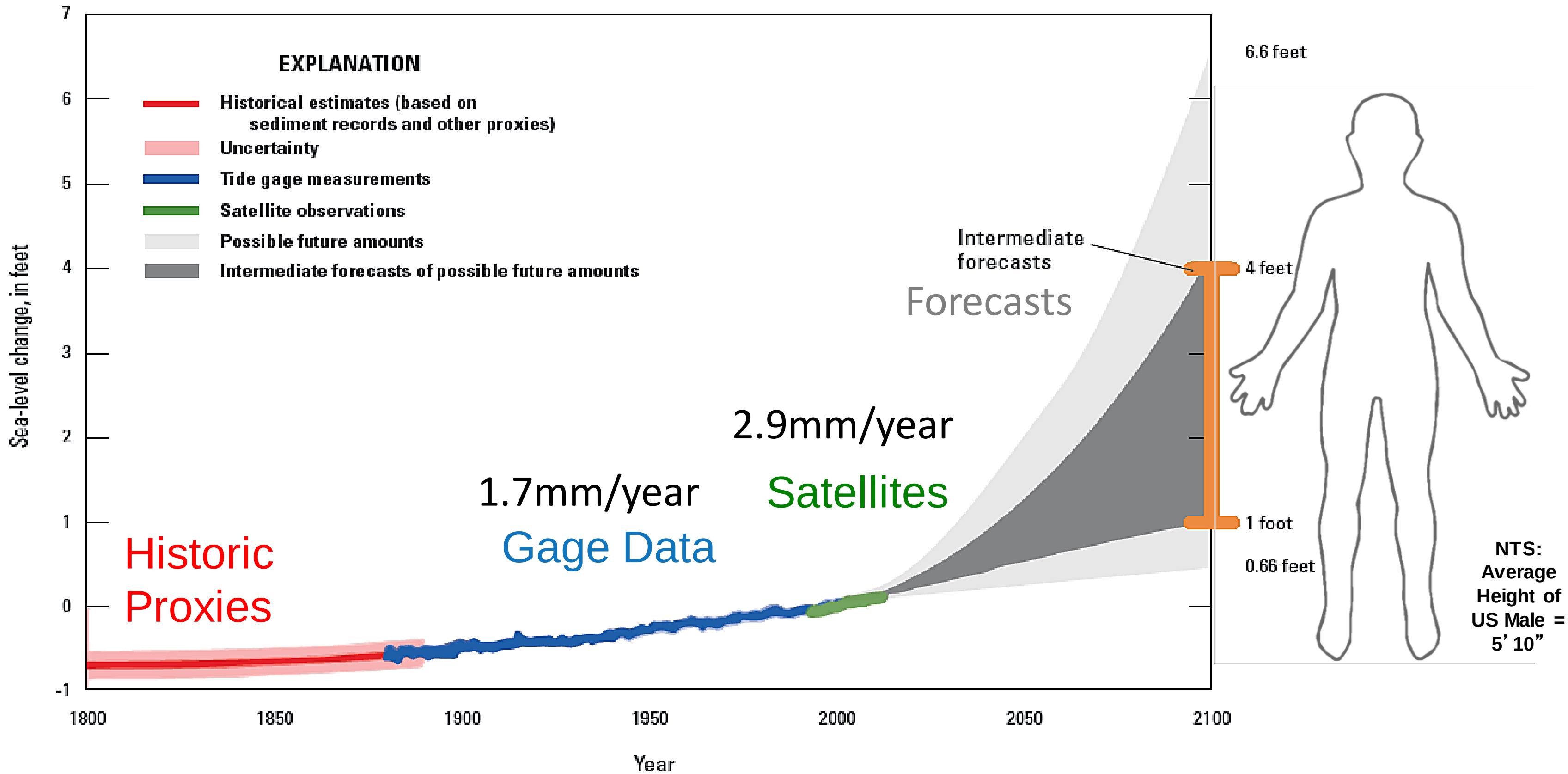
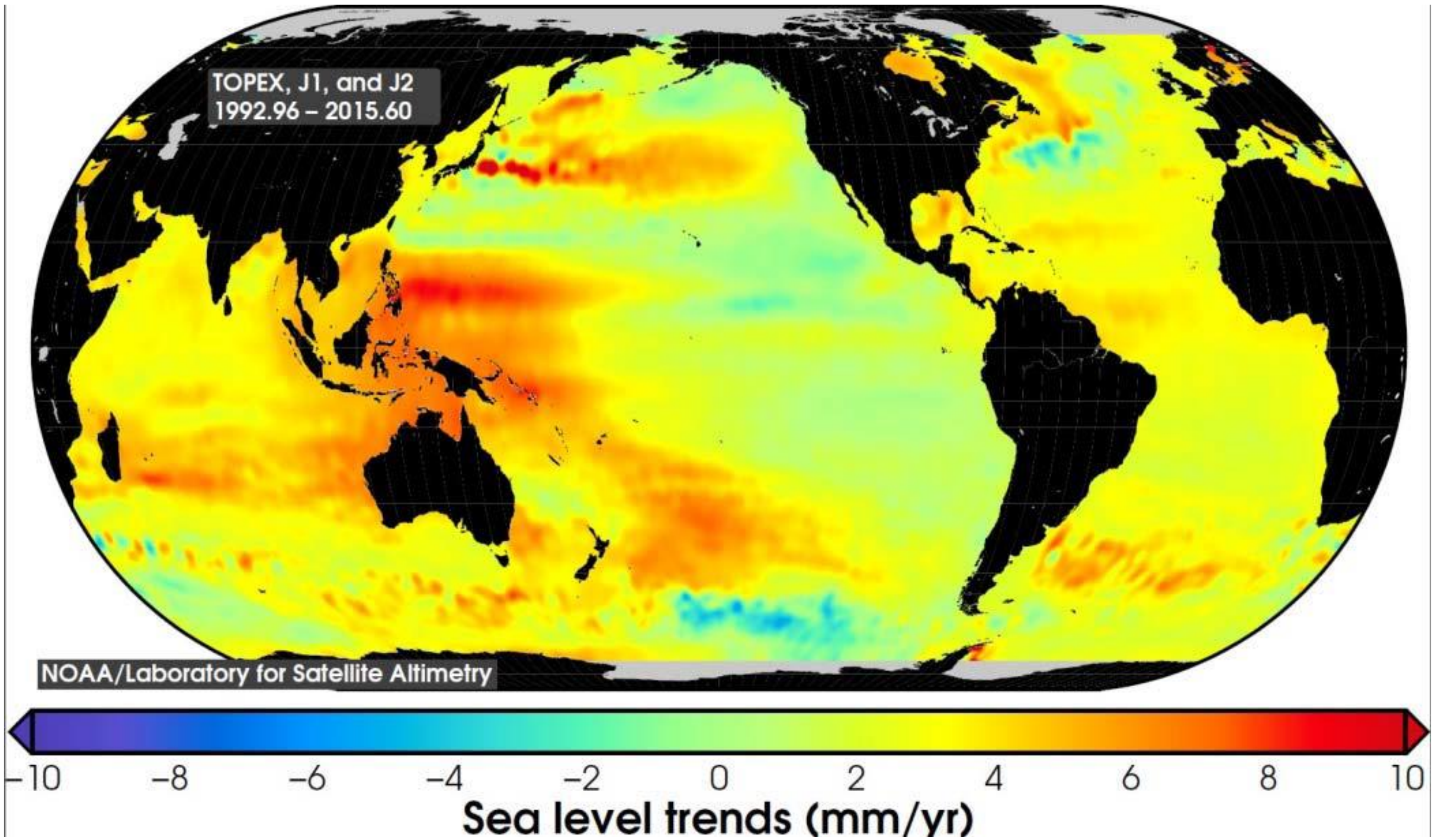
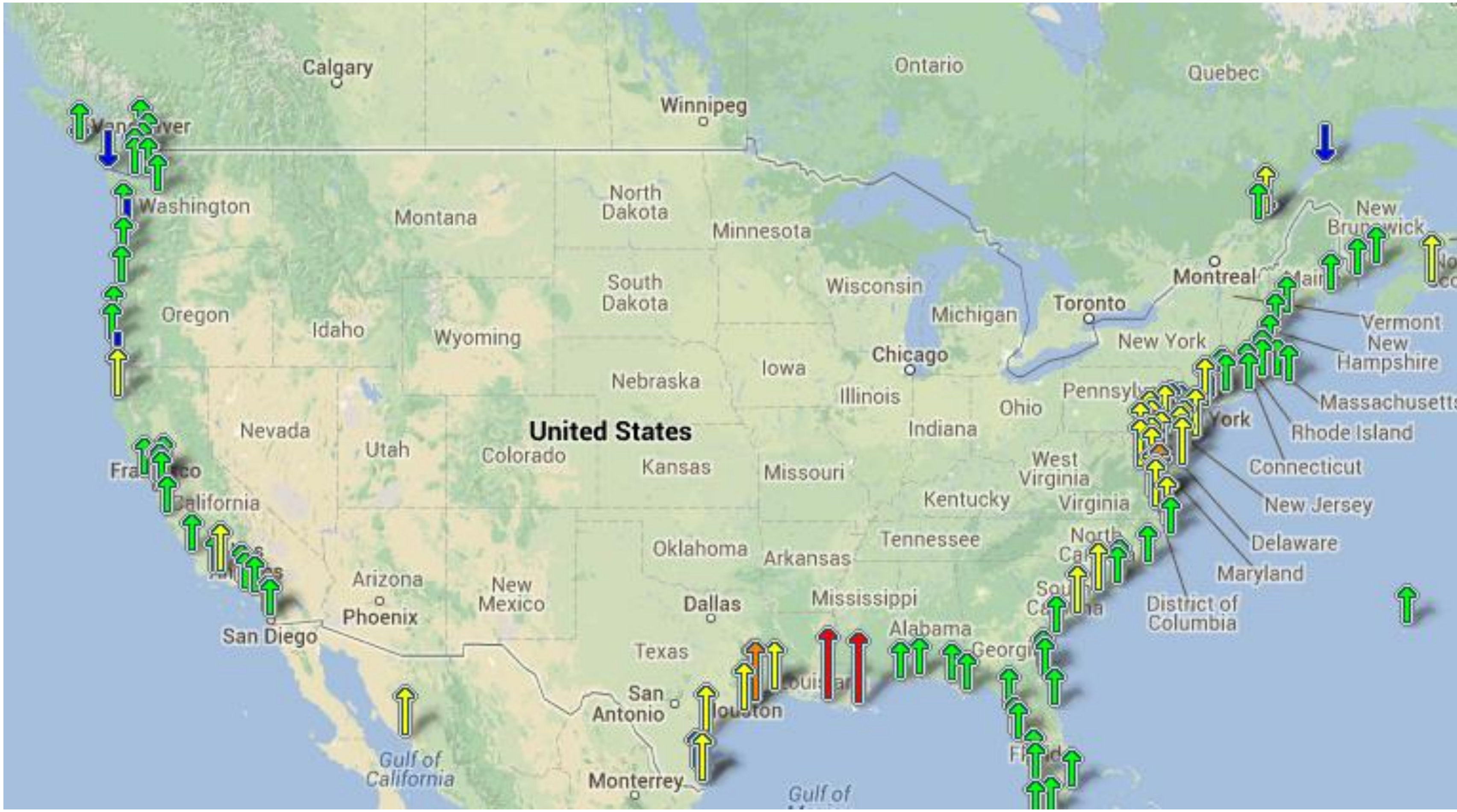


Figure 9. Historical, observed, and possible future amounts of global sea-level rise from 1800 to 2100 (from Melillo and others, 2014). Historical estimates (based on sediment records and other proxies) are shown in red (pink band shows uncertainty range), tide gage measurements in blue, and satellite observations in green.

Sea Level is Not Rising at the Same Rate Everywhere



Land Motion Plays a Big Part Too

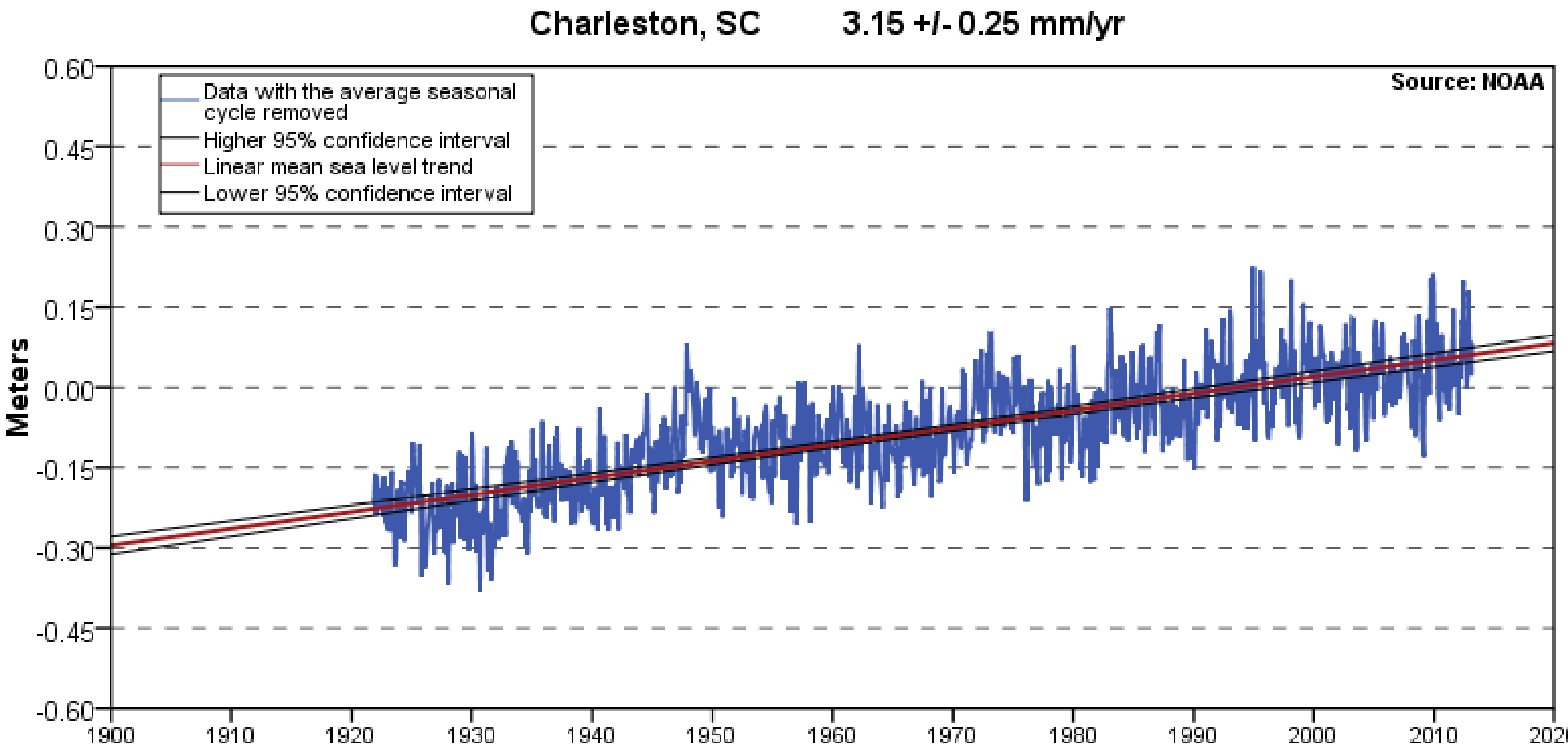


Sea Level Trends

mm/yr (feet/century)

15 to 21 (5 to 7)	6 to 9 (2 to 3)	-3 to 0 (-1 to 0)	-12 to -9 (-4 to -3)
12 to 15 (4 to 5)	3 to 6 (1 to 2)	-6 to -3 (-2 to -1)	-15 to -12 (-5 to -4)
9 to 12 (3 to 4)	0 to 3 (0 to 1)	-9 to -6 (-3 to -2)	-18 to -15 (-6 to -5)

Local Sea Level Rise

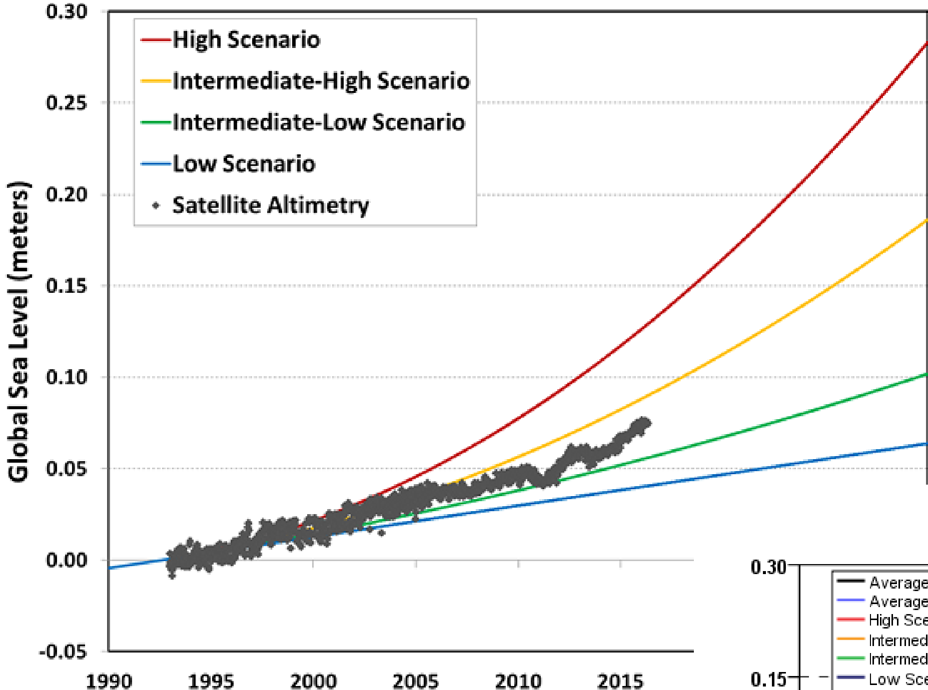


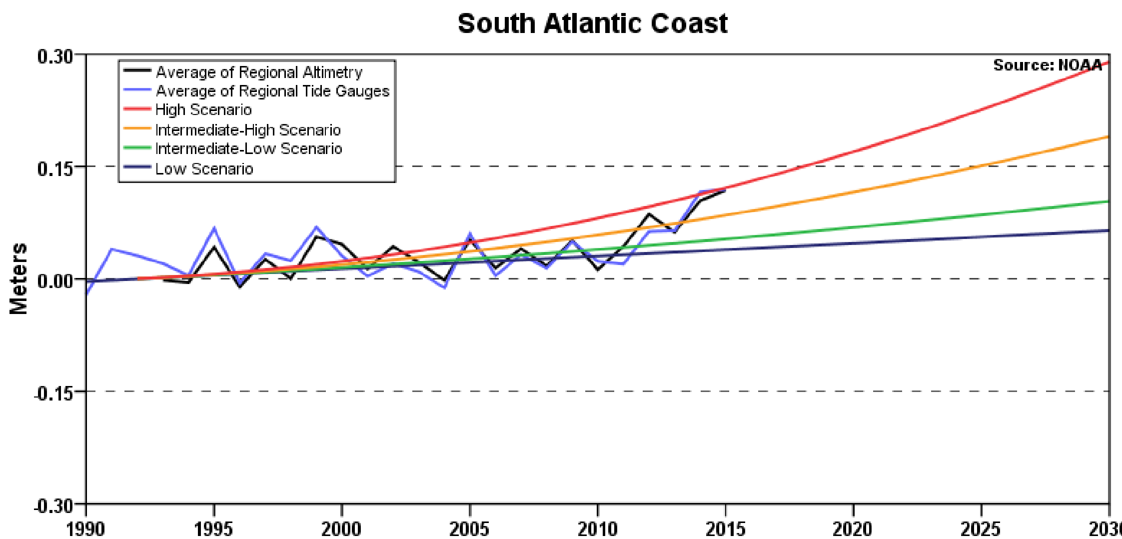
The mean sea level trend is 3.15 millimeters/year with a 95% confidence interval of +/- 0.25 mm/yr based on monthly mean sea level data from 1921 to 2006 which is equivalent to a change of 1.03 feet in 100 years.

NOAA CO-OPS

OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST

How are We Tracking?



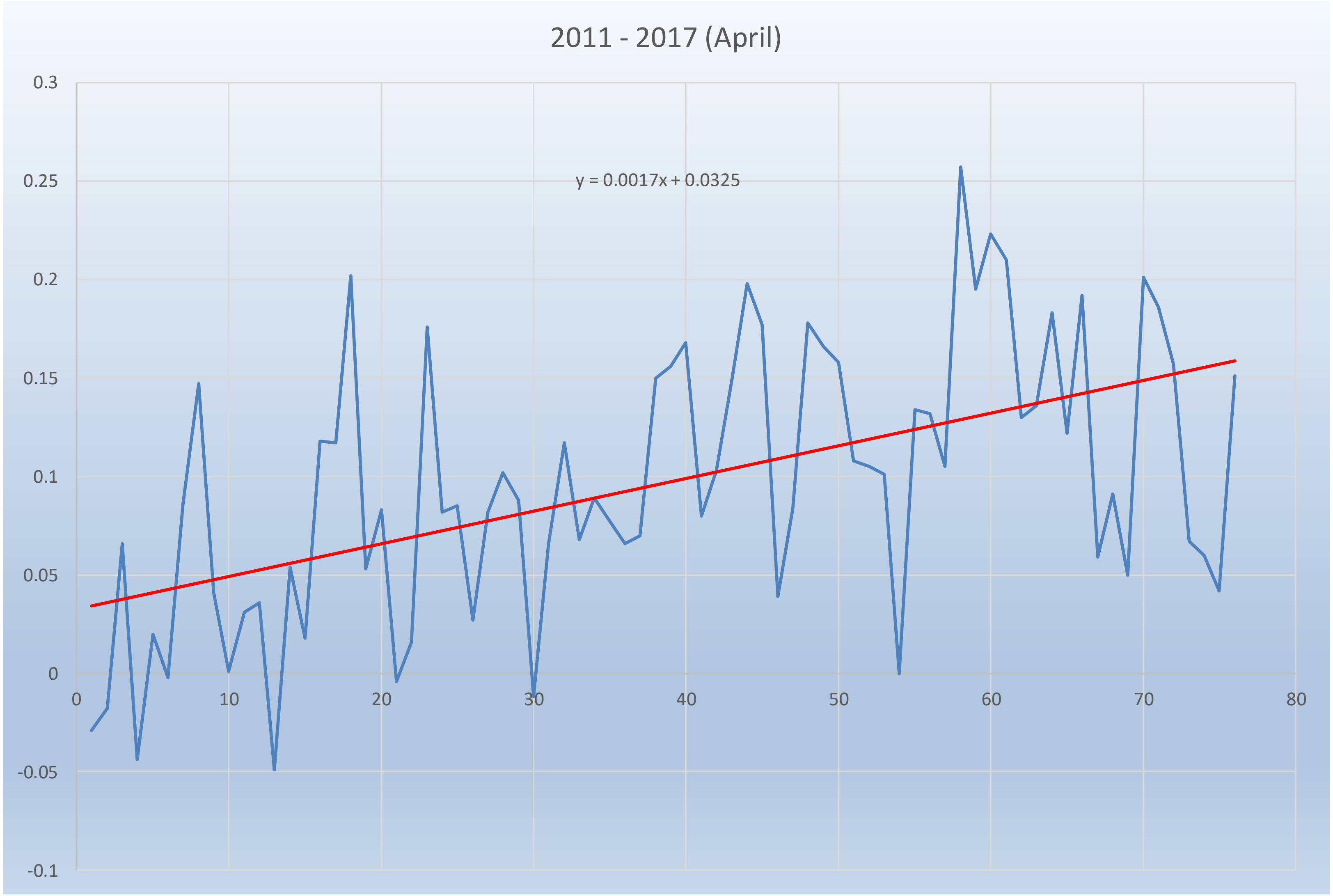


NOAA CO-OPS

OFFICE FOR COASTAL MANAGEMENT

DIGITAL COAST

Recent Increase



New Global and Regional Scenarios

https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf

GMSL Scenario (meters)	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2120	2150	2200
Low	0.03	0.06	0.09	0.13	0.16	0.19	0.22	0.25	0.28	0.30	0.34	0.37	0.39
Intermediate-Low	0.04	0.08	0.13	0.18	0.24	0.29	0.35	0.4	0.45	0.50	0.60	0.73	0.95
Intermediate	0.04	0.10	0.16	0.25	0.34	0.45	0.57	0.71	0.85	1.0	1.3	1.8	2.8
Intermediate-High	0.05	0.10	0.19	0.30	0.44	0.60	0.79	1.0	1.2	1.5	2.0	3.1	5.1
High	0.05	0.11	0.21	0.36	0.54	0.77	1.0	1.3	1.7	2.0	2.8	4.3	7.5
Extreme	0.04	0.11	0.24	0.41	0.63	0.90	1.2	1.6	2.0	2.5	3.6	5.5	9.7

GMSL Scenario Rates (mm/year)	2010	2020	2030	2040	2050	2060	2070	2080	2090
Low	3	3	3	3	3	3	3	3	3
Intermediate-Low	4	5	5	5	5	5	5	5	5
Intermediate	5	6	7	9	10	12	13	14	15
Intermediate-High	5	7	10	13	15	18	20	22	24
High	6	8	13	16	20	24	28	31	35
Extreme	6	10	15	20	25	30	35	40	44

NOAA Technical Report NOS CO-OPS 083

GLOBAL AND REGIONAL SEA LEVEL RISE SCENARIOS FOR THE UNITED STATES

Photo: Ocean City, Maryland

Silver Spring, Maryland
January 2017

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Center for Operational Oceanographic Products and Services

Probabilities Related to RCPs

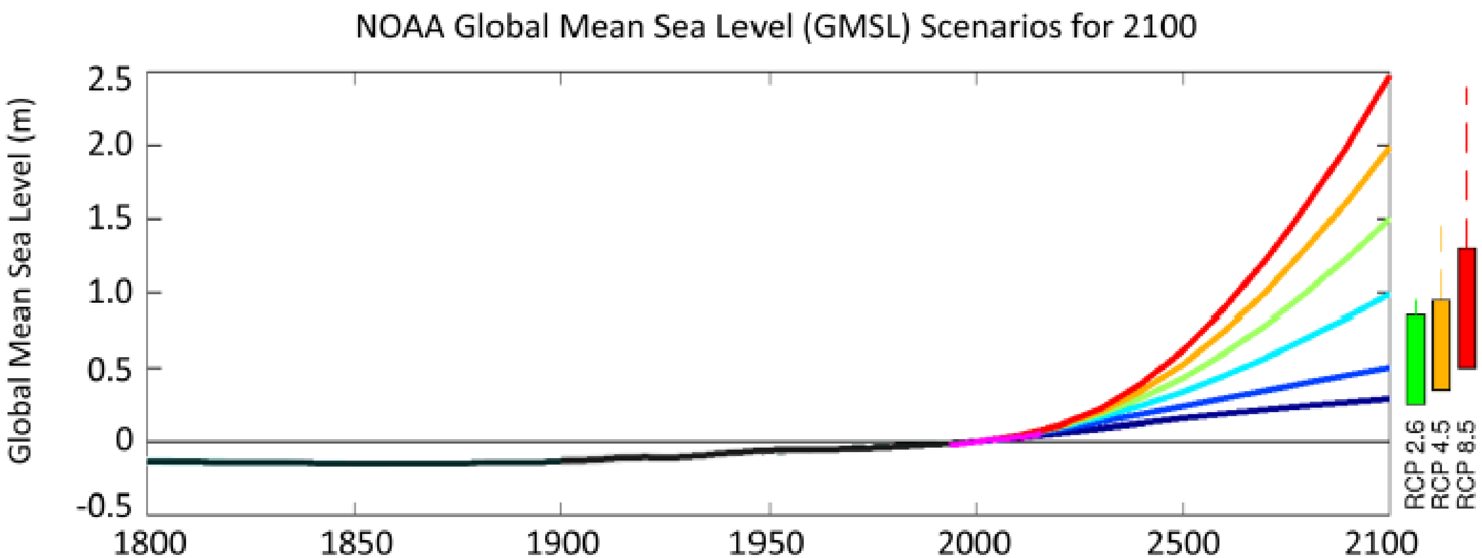
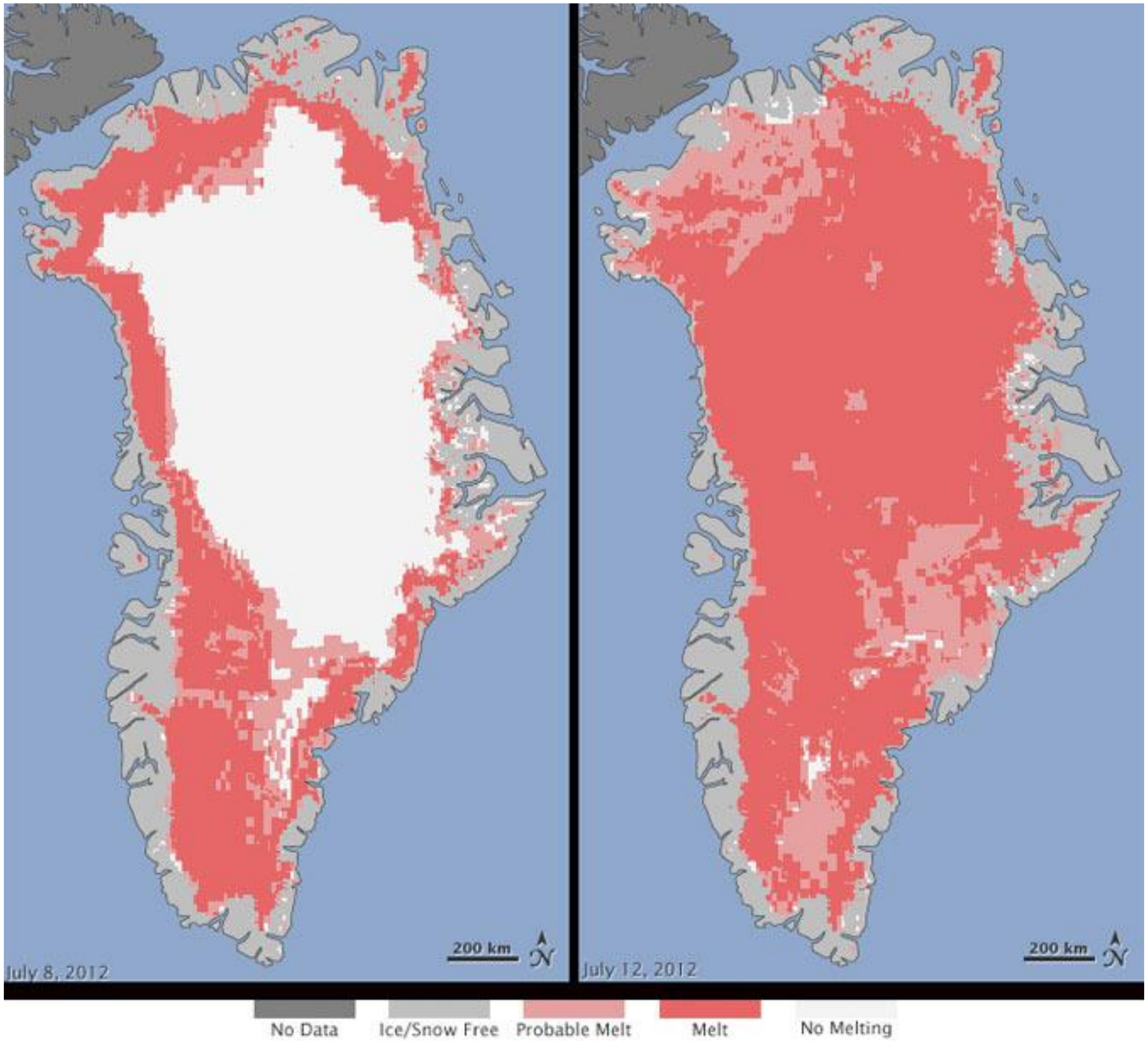
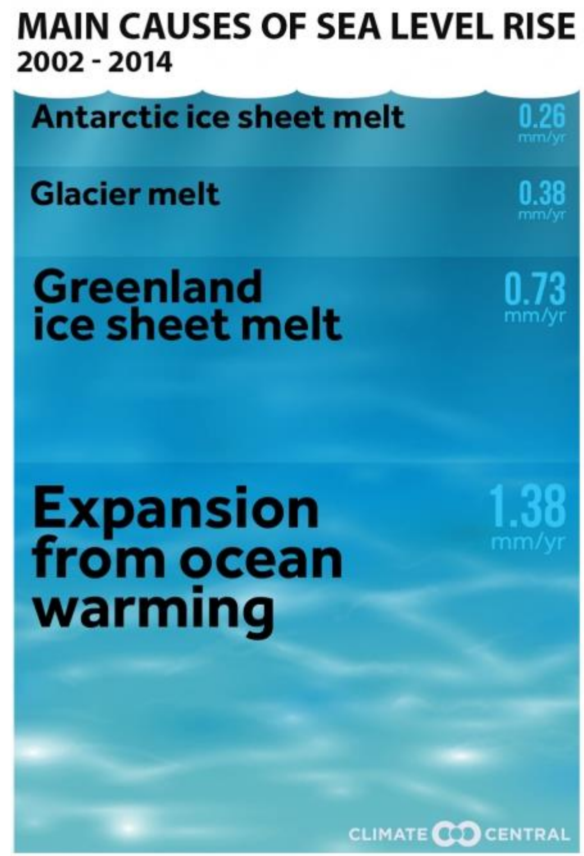


Table 4. Probability of exceeding GMSL (median value) scenarios in 2100 based upon Kopp et al. (2014).

GMSL rise Scenario	RCP2.6	RCP4.5	RCP8.5
Low (0.3 m)	94%	98%	100%
Intermediate-Low (0.5 m)	49%	73%	96%
Intermediate (1.0 m)	2%	3%	17%
Intermediate-High (1.5 m)	0.4%	0.5%	1.3%
High (2.0 m)	0.1%	0.1%	0.3%
Extreme (2.5 m)	0.05%	0.05%	0.1%

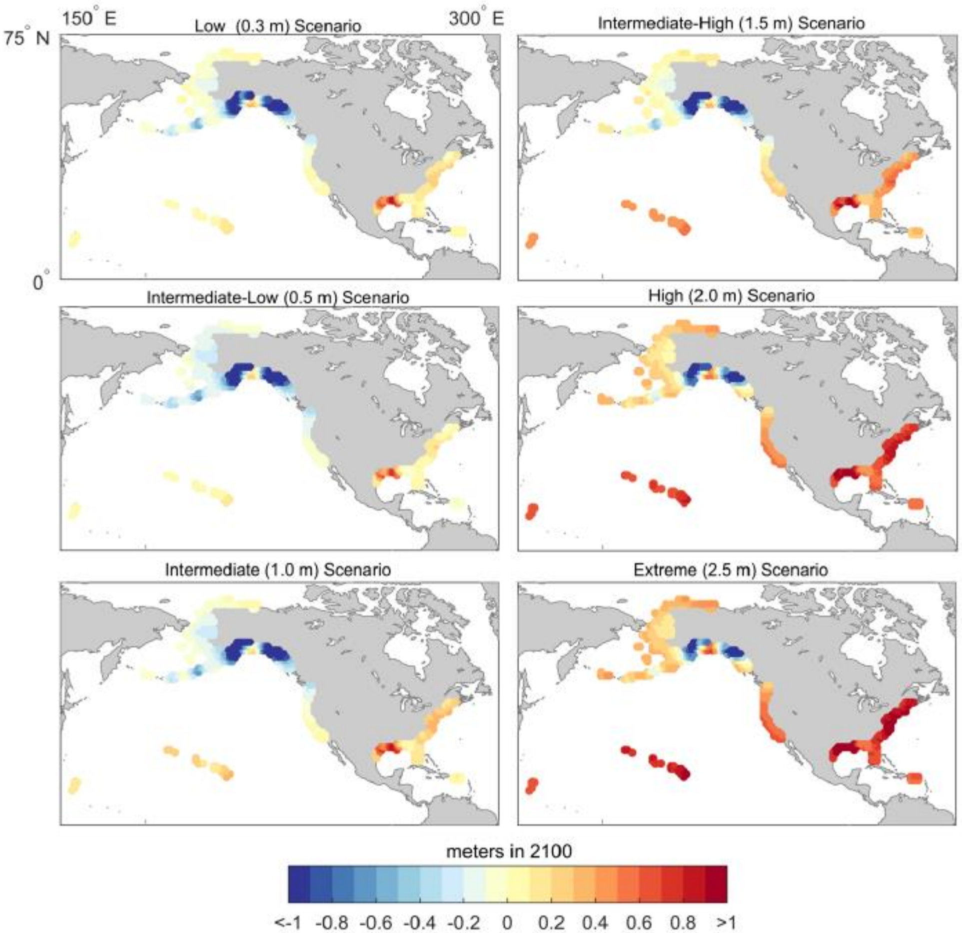
Greatest source of uncertainty?

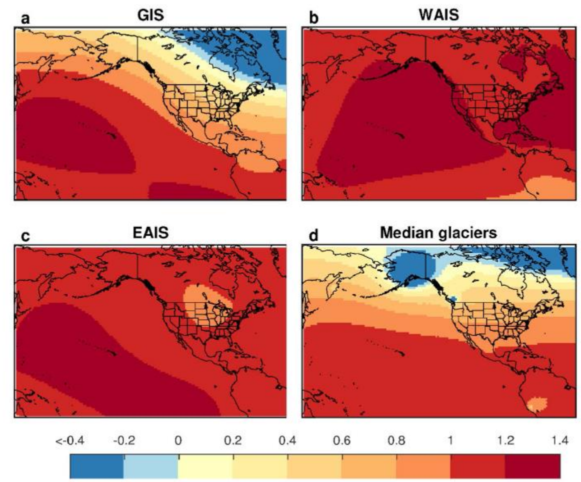




Source: Rietbroek et al., Revisiting the contemporary sea level budget on global and regional scales, PNAS

Relative Sea Level Rise





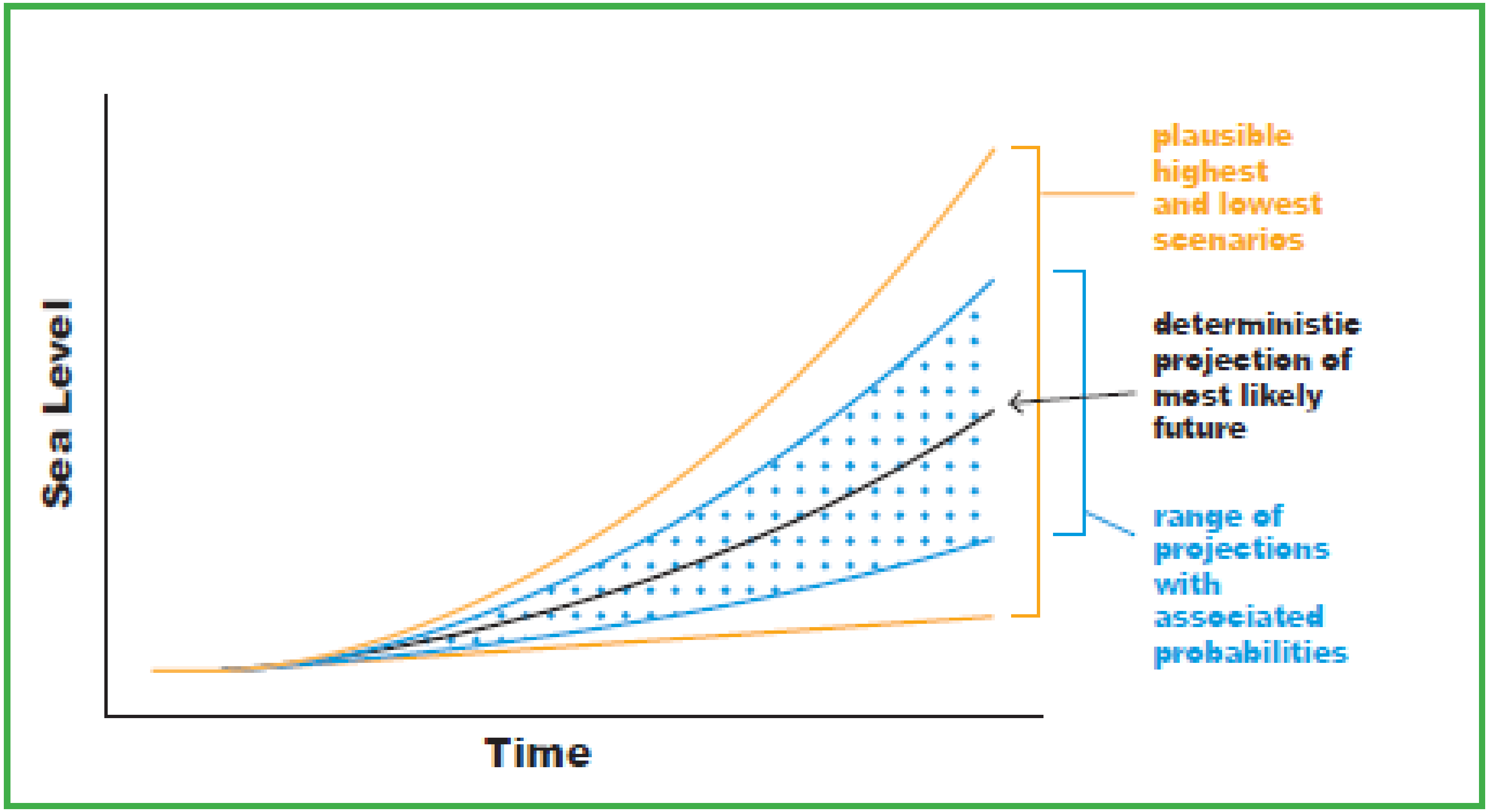
<u>GMSL adjusted for</u>

1.) Oceanographic Factors

2.) Gravity Changes due to Melting Land Based Ice

3.) Vertical Land Movement

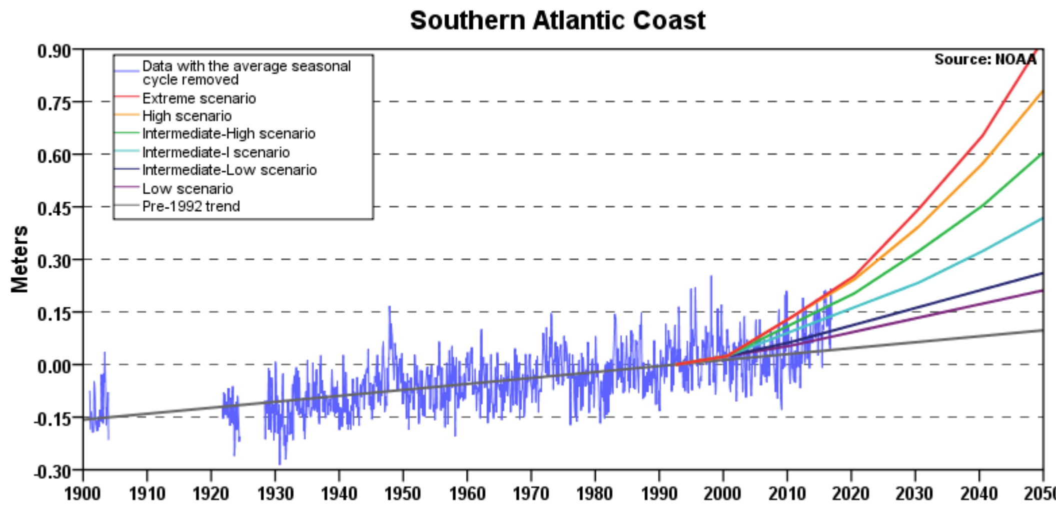
Deterministic, Probabilistic, Scenarios

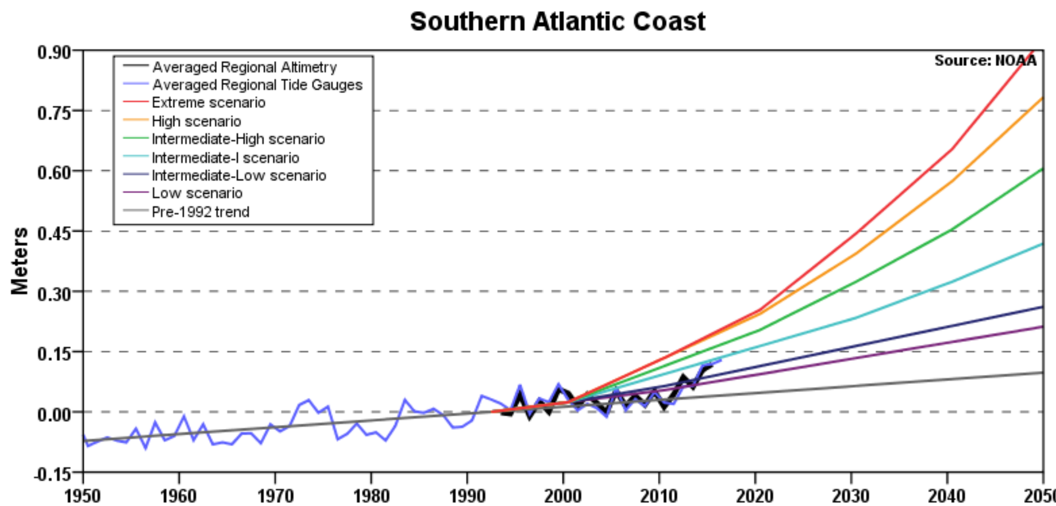


DoD CARSWG Report
Hall et al., 2016

OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST

Compare with New Scenarios





OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST

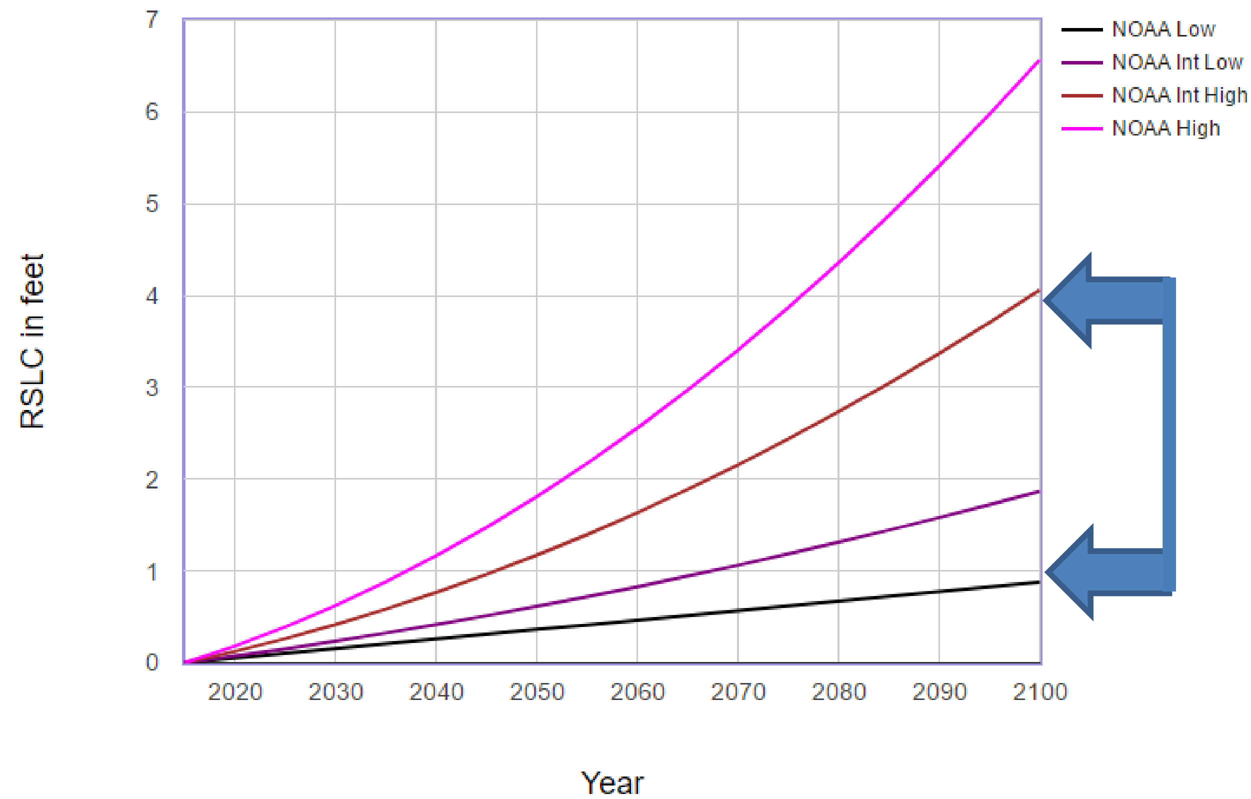
Previous Curves

Estimated Relative Sea Level Change from 2015 To 2100
8665530, Charleston, SC
NOAA's Published Rate: 0.01033 feet/yr
All values are expressed in feet

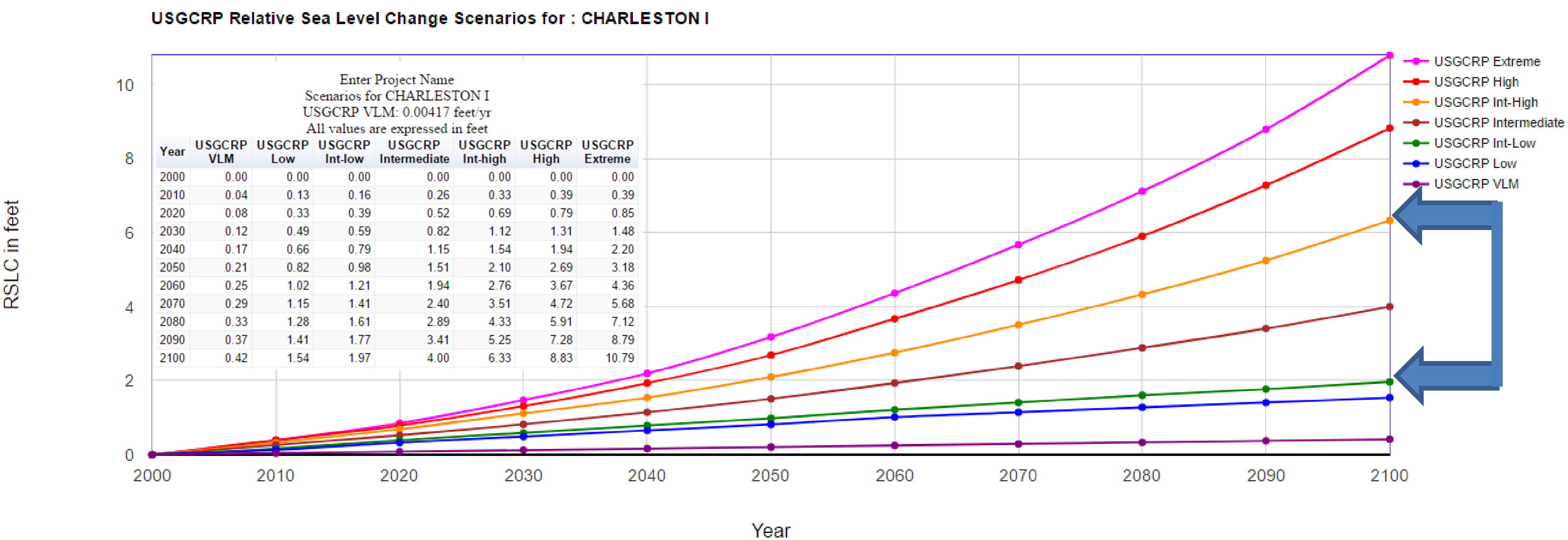
Year	NOAA Low	NOAA Int Low	NOAA Int High	NOAA High
2015	0.0	0.0	0.0	0.0
2020	0.1	0.1	0.1	0.2
2025	0.1	0.2	0.3	0.4
2030	0.2	0.2	0.4	0.6
2035	0.2	0.3	0.6	0.9
2040	0.3	0.4	0.8	1.2
2045	0.3	0.5	1.0	1.5
2050	0.4	0.6	1.2	1.8
2055	0.4	0.7	1.4	2.2
2060	0.5	0.8	1.6	2.6
2065	0.5	0.9	1.9	3.0
2070	0.6	1.1	2.2	3.4
2075	0.6	1.2	2.4	3.9
2080	0.7	1.3	2.7	4.4
2085	0.7	1.4	3.0	4.9
2090	0.8	1.6	3.4	5.4
2095	0.8	1.7	3.7	6.0
2100	0.9	1.9	4.1	6.6

Print Table

Estimated Relative Sea Level Change Projections From 2015 To 2100 - Gauge: 8665530, Charleston, SC (3.15 mm/yr)



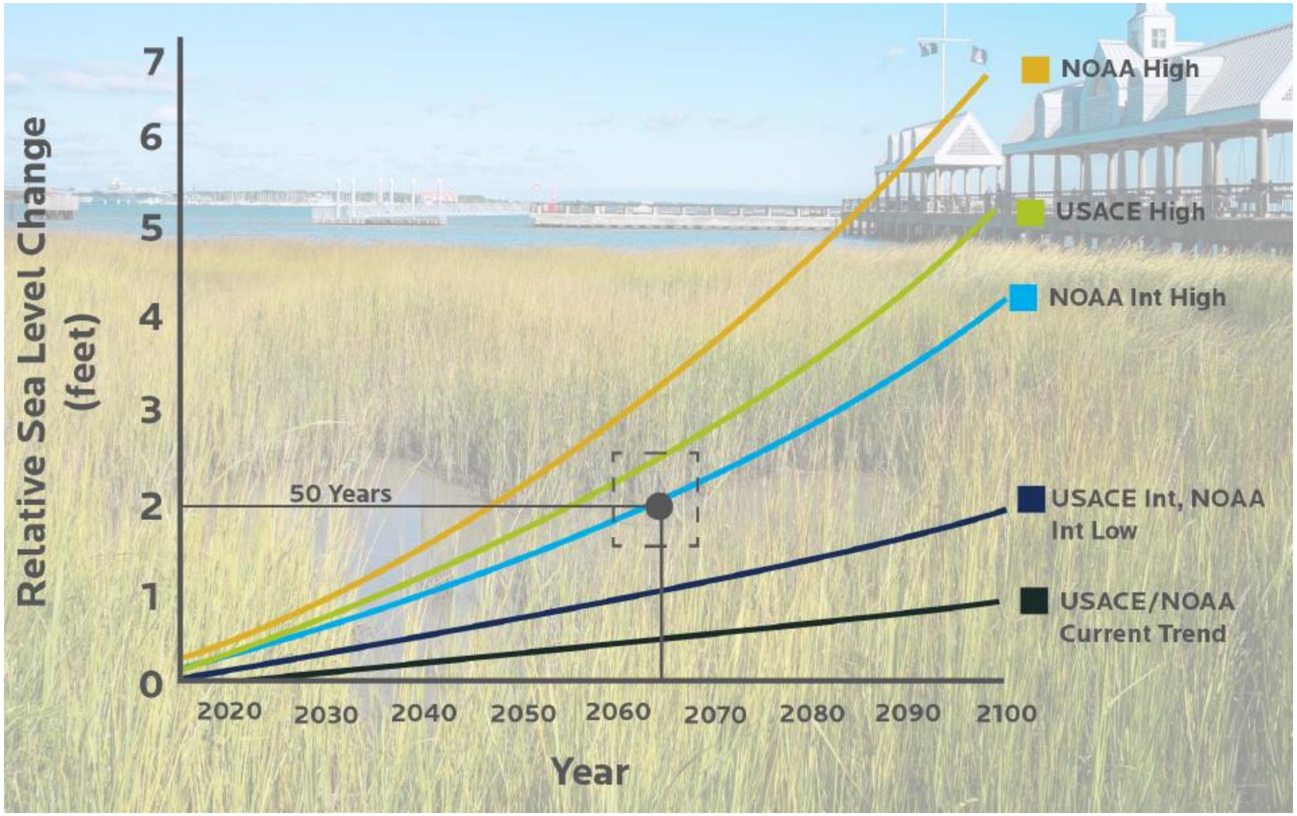
New Curves



Year	USGCRP VLM	USGCRP Low	USGCRP Int-low	USGCRP Intermediate	USGCRP Int-high	USGCRP High	USGCRP Extreme
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	0.04	0.13	0.16	0.26	0.33	0.39	0.39
2020	0.08	0.33	0.39	0.52	0.69	0.79	0.85
2030	0.12	0.49	0.59	0.82	1.12	1.31	1.48
2040	0.17	0.66	0.79	1.15	1.54	1.94	2.20
2050	0.21	0.82	0.98	1.51	2.10	2.69	3.18
2060	0.25	1.02	1.21	1.94	2.76	3.67	4.36
2070	0.29	1.15	1.41	2.40	3.51	4.72	5.68
2080	0.33	1.28	1.61	2.89	4.33	5.91	7.12
2090	0.37	1.41	1.77	3.41	5.25	7.28	8.79
2100	0.42	1.54	1.97	4.00	6.33	8.83	10.79

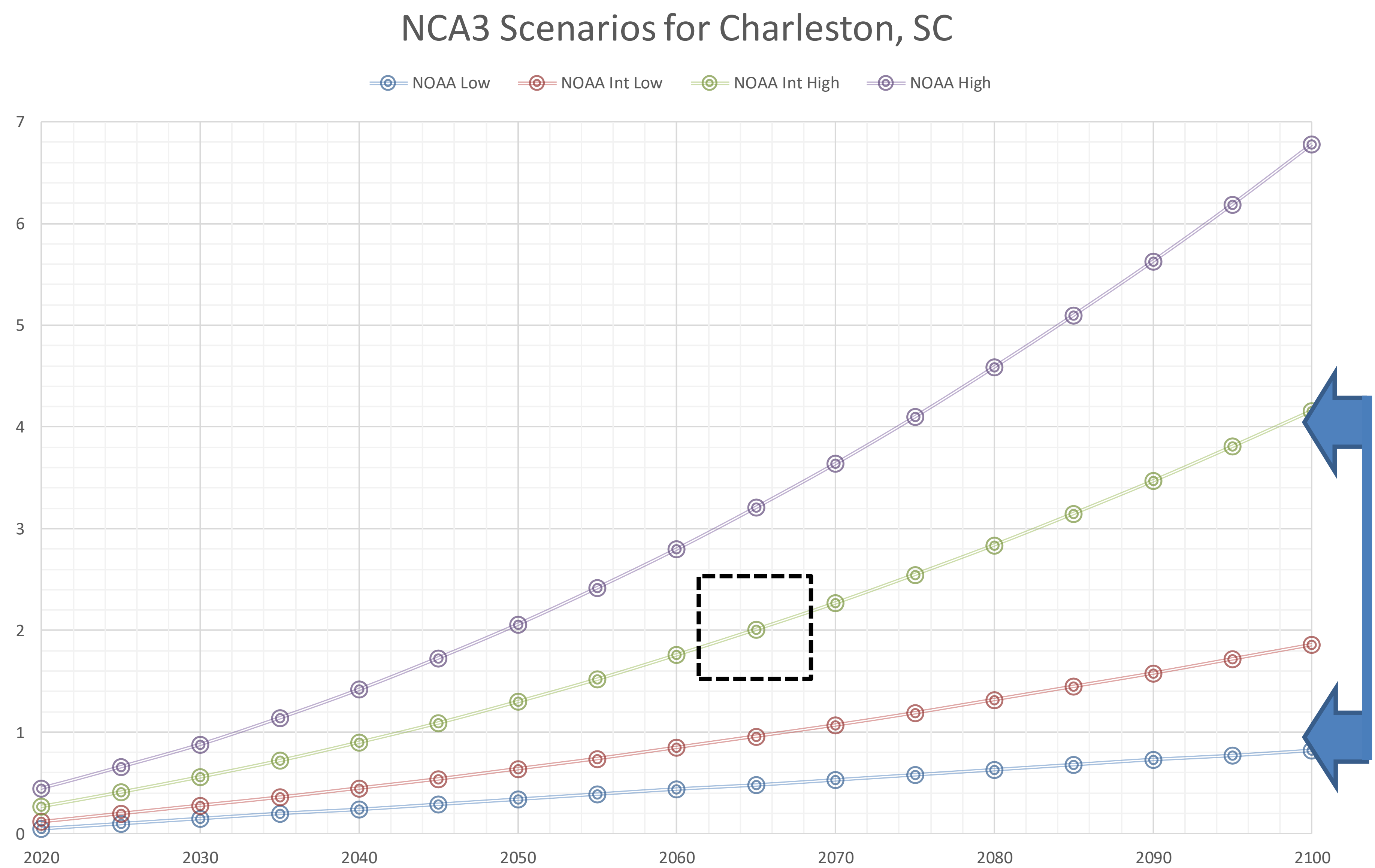
Selecting a SLR Scenario (example)

- A 1.5 foot increase will be used for short-term, less vulnerable investment, such as a parking lot.
- A 2.5 foot increase will be used for more critical longer term investments, such as emergency routes and public buildings.



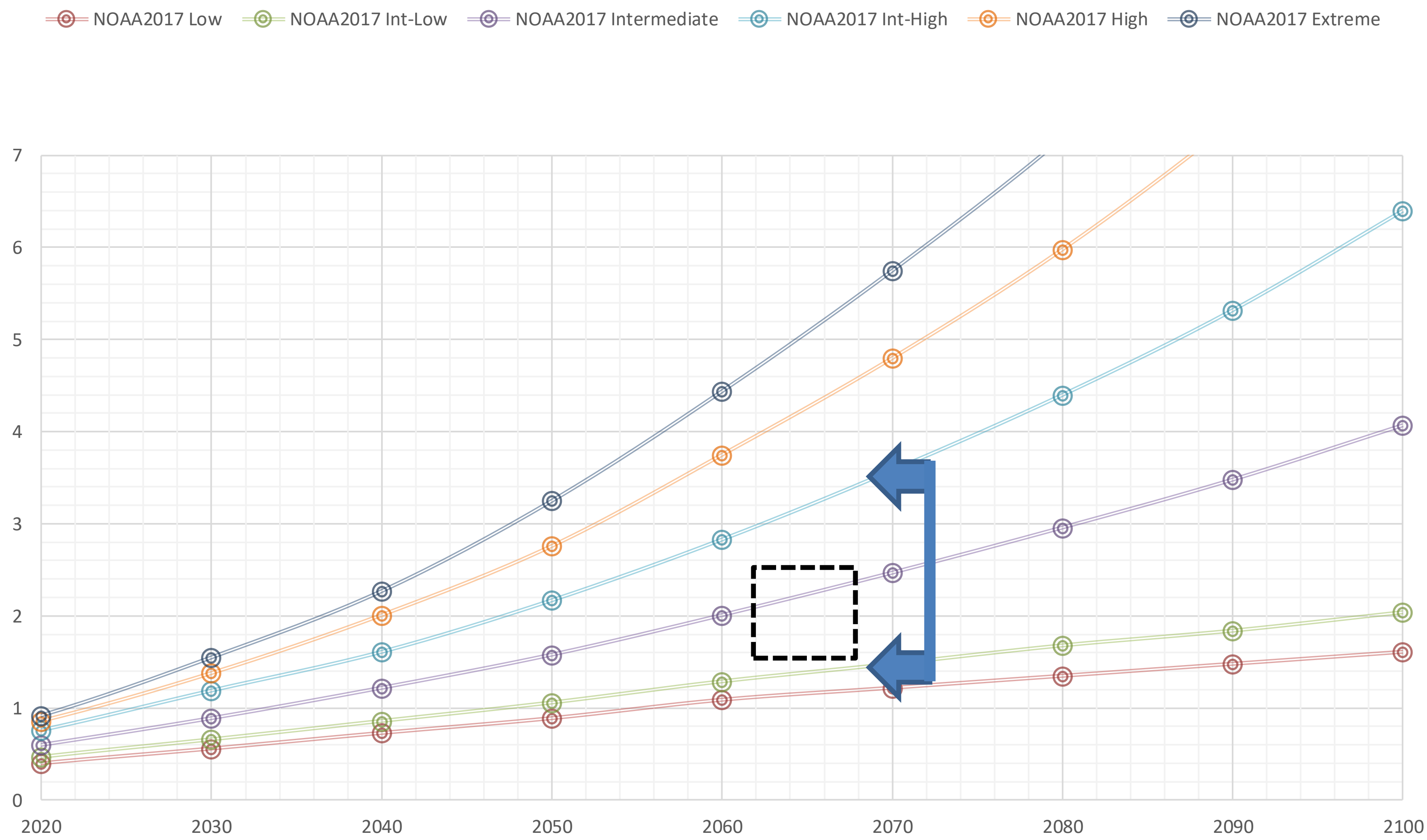
From City of Charleston Sea Level Rise Strategy Document

http://www.charleston-sc.gov/DocumentCenter/View/10089



OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST

NCA4 Scenarios for Charleston, SC



OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST

Critical Thresholds Are Being Reached More Often

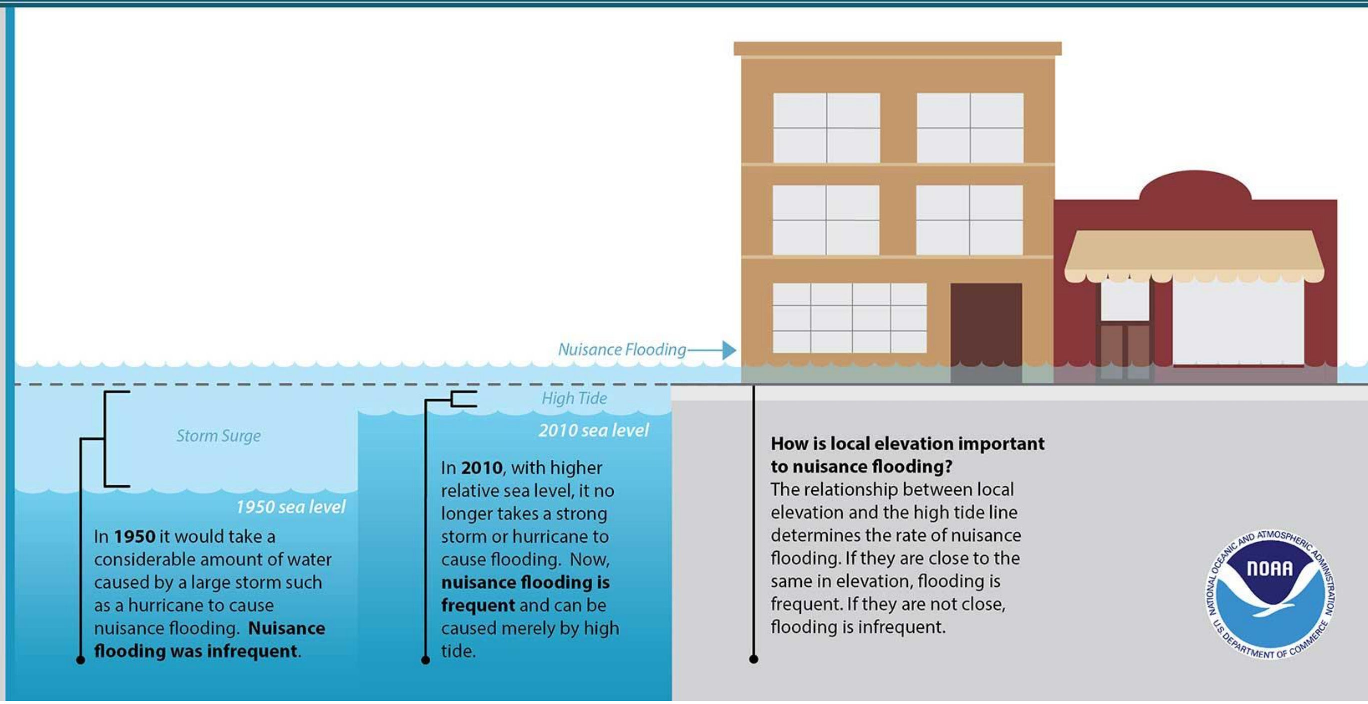
Nuisance Flood Events Are Significantly Increasing Around the U.S.

What is nuisance flooding?
Flooding which causes public inconvenience.

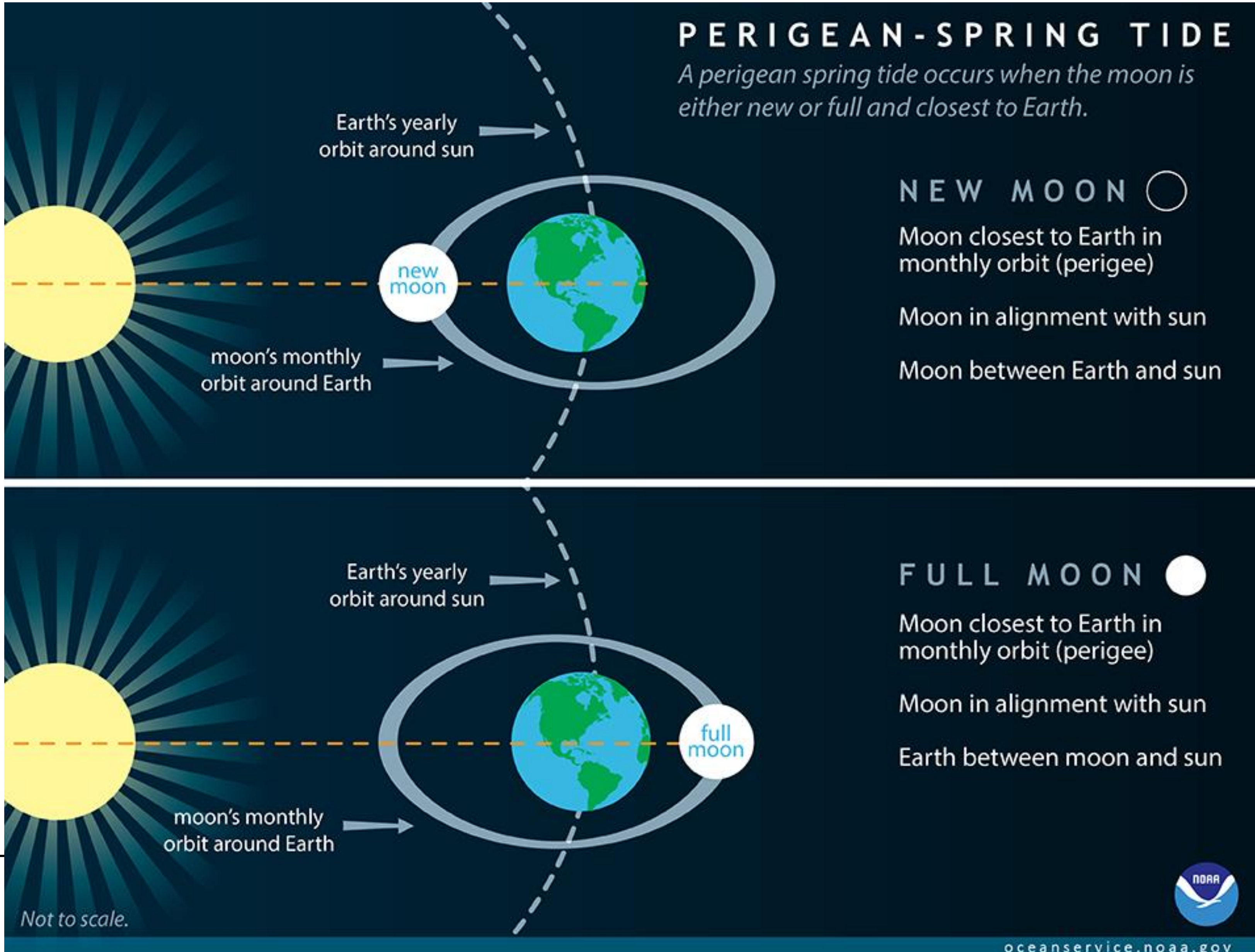
What are the impacts of nuisance flooding?
Frequent road closures, overwhelmed storm drains, and deterioration of infrastructure such as roads and rail.

Where is this happening?
Nuisance flooding is increasing around the coastal U.S., with more rapid acceleration along the East and Gulf Coasts.

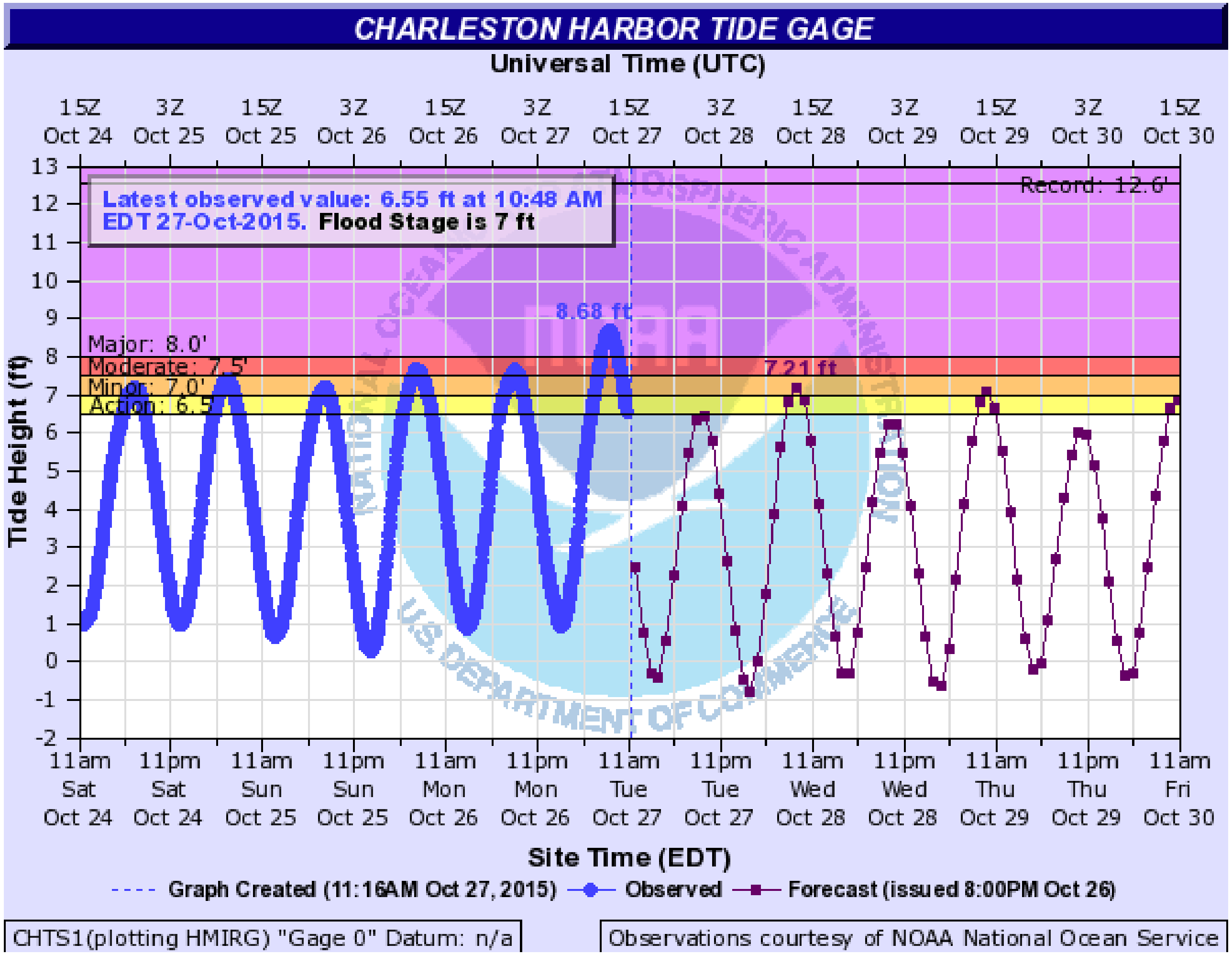
Why is this happening?
Nuisance flooding is increasing due to climate-related sea level rise and land subsidence (sinking) combined with loss of natural coastal barriers.



High Tide Events



High Tide (nuisance) Flooding



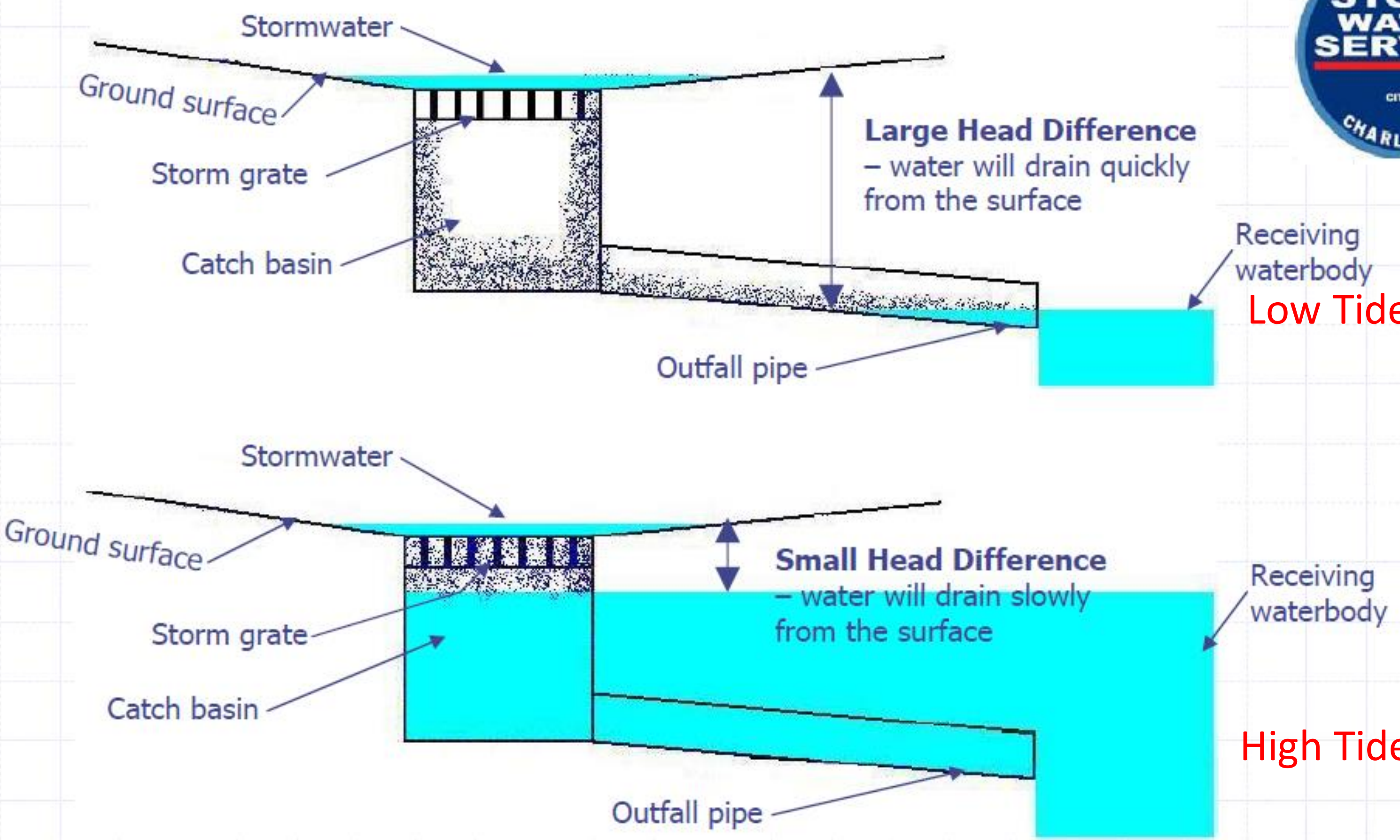
NOAA NWS AHPS

OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST


201
STOP
ALL WAY

Stormwater 101

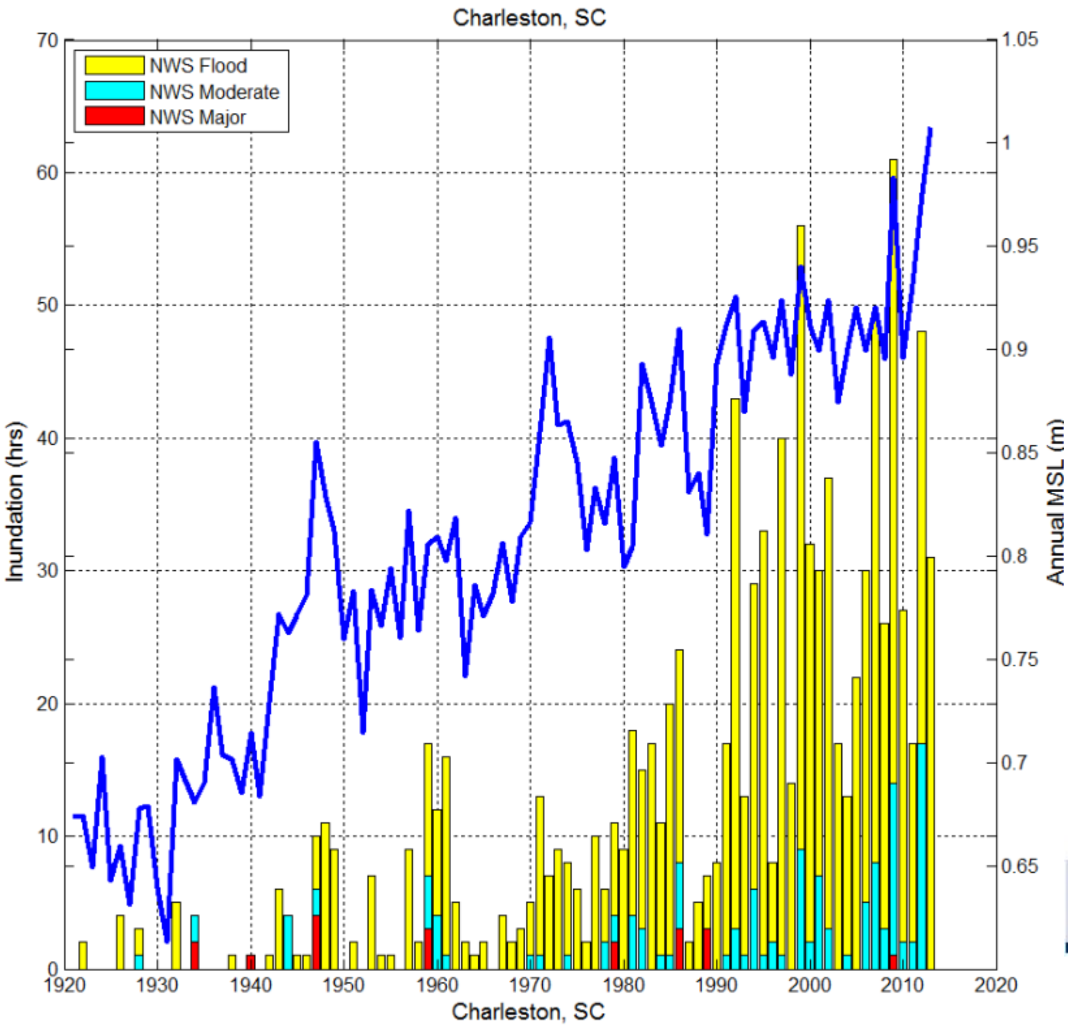
- Head – difference in elevation of two water surfaces

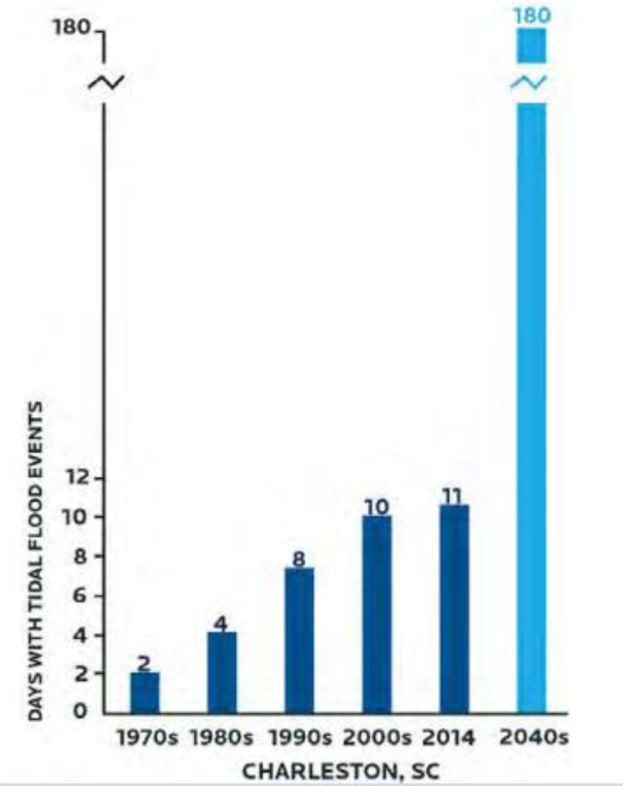


http://www.charleston-sc.gov/index.aspx?NID=588

OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST

Increase in Events



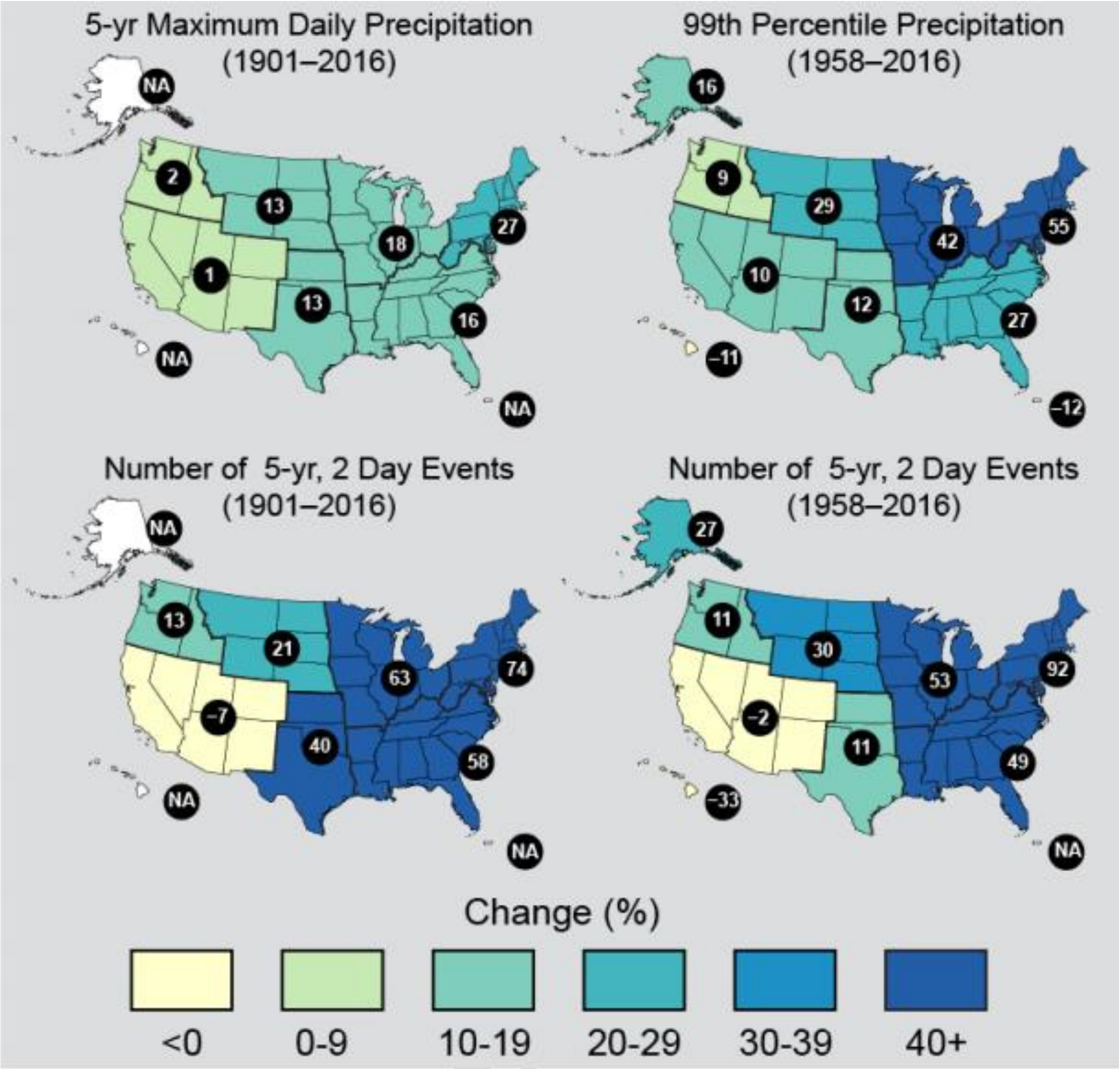


SOURCES: UCS Analysis; Morales and Alsheimer 2014; NOAA Tides and Currents 2013.

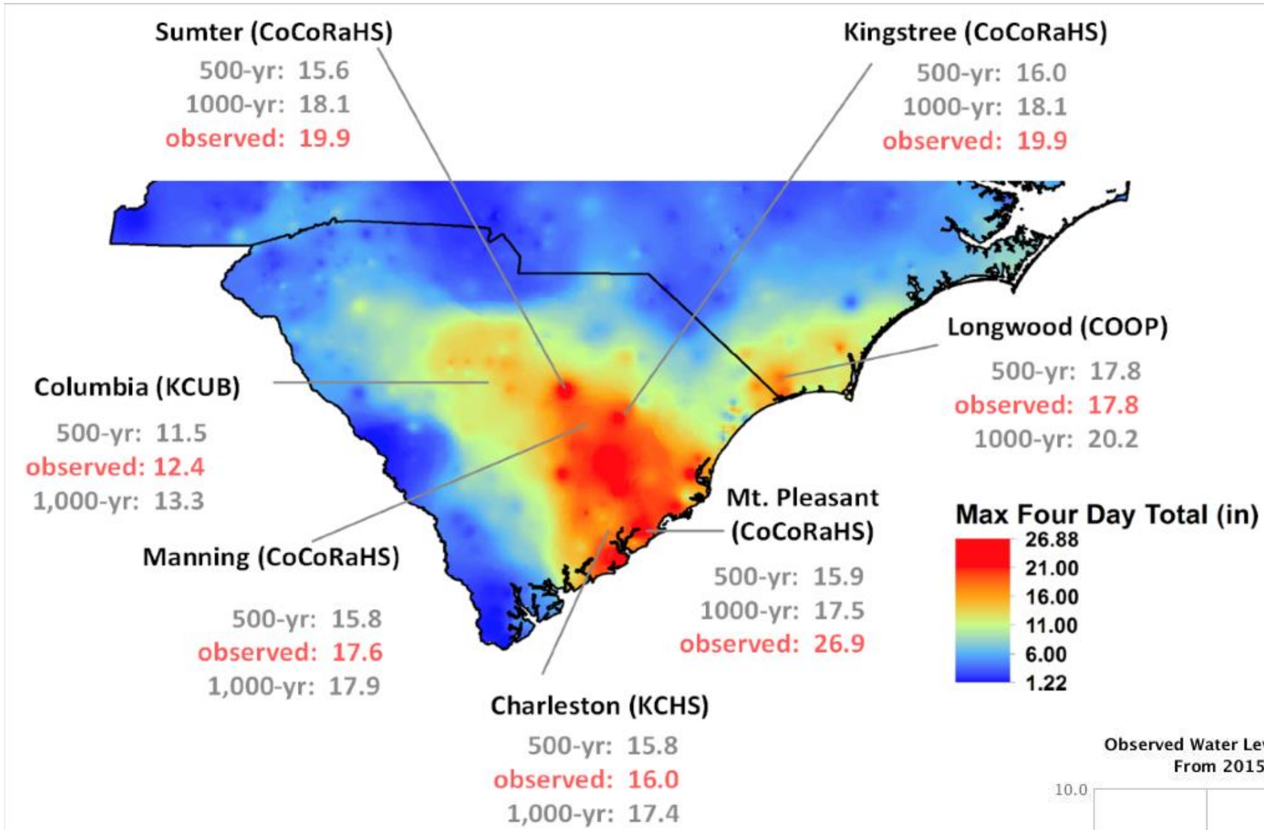
From Sweet et al., 2014

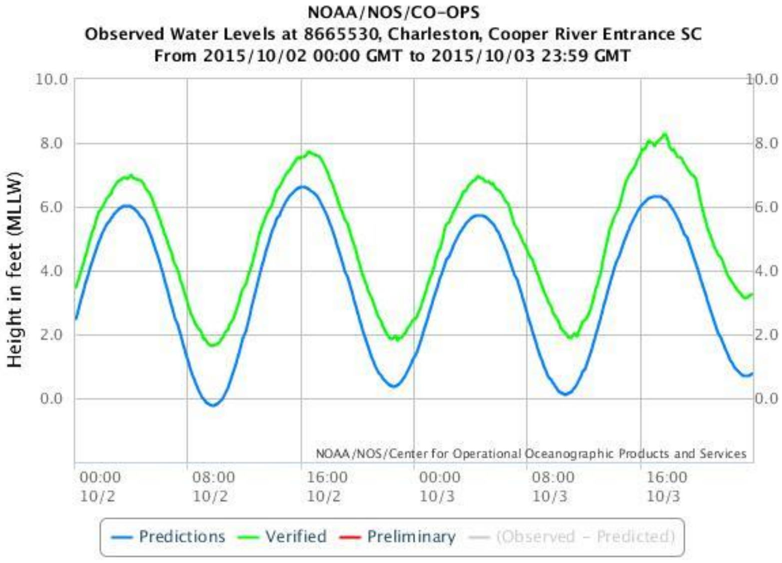
OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST

Extreme Precipitation



Combined Events – October 2015





Top Ten U.S. Areas with an Increase in Nuisance Flooding

	"Nuisance level": Meters above mean higher high water mark	Average nuisance flood days, 1957-1963	Average nuisance flood days, 2007-2013	Percent Increase
Annapolis, Md.	0.29	3.8	39.3	925
Baltimore, Md.	0.41	1.3	13.1	922
Atlantic City, N.J.	0.43	3.1	24.6	682
Philadelphia, Pa.	0.49	1.6	12.0	650
Sandy Hook, N.J.	0.45	3.3	23.9	626
Port Isabel, Texas	0.34	2.1	13.9	547
Charleston, S.C.	0.38	4.6	23.3	409
Washington, D.C.	0.31	6.3	29.7	373
San Francisco, Calif.	0.35	2.0	9.3	364
Norfolk, Va.	0.53	1.7	7.3	325

10/29/2015 | 10:56 am
Tide at Charleston Gauge
7.2' (observed)

Mycoast.org/SC

http://www.noaanews.noaa.gov/stories2014/20140728_nuisanceflooding.html

From Sweet et al., 2014

OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST

Top Ten U.S. Areas with an Increase in Nuisance Flooding

Decade(s) of Tipping Point Crossing under 4 Projections (0.5, 0.6, 0.8, 1.2 m) of Global Sea Level Rise by 2100*		
Location	Nuisance Flood Level (meters above MHHW)	>30 days/year with Nuisance Flooding
Wilmington, NC	0.25	Past
Annapolis, MD	0.29	Past
Washington D.C.	0.31	Past
Port Isabel, TX	0.34	By 2020
Charleston, SC	0.38	By 2020
Lewes, DE	0.41	By 2020
Baltimore, MD	0.41	By 2020
Atlantic City, NJ	0.43	By 2020
Sandy Hook, NJ	0.45	By 2020
Kings Point, NY	0.52	By 2020
Key West, FL	0.33	By 2030
San Francisco, CA	0.35	By 2030
Savannah (Ft. Pulaski), GA	0.46	By 2030
Philadelphia, PA	0.49	By 2030
Mayport, FL	0.44	2021-2040
La Jolla, CA	0.51	2021-2040
Norfolk, VA	0.53	2021-2040
Boston, MA	0.68	2021-2040
Montauk, NY	0.60	2021-2050
The Battery, NY	0.65	2021-2050
Fernandina Beach, FL	0.59	2031-2060
New London, CT	0.60	2031-2060
Providence, RI	0.66	2031-2060
Galveston Bay, TX	0.79	2041-2060
Seattle, WA	0.65	2051-2080
St. Petersburg, FL	0.84	2051-2100+

* Sea level projections include local subsidence rates and regional gravity/circulation fingerprints of Kopp et al. (2014) and are based upon a 1.9 - 5.4° C range in future global warming under Regional Concentration Pathways (RCP's 2.6, 4.5, 8.5) for greenhouse gas emissions from the 5th Assessment of the Intergovernmental Panel on Climate Change (IPCC).

10/29/2015 | 10:25 am
Tide at Charleston Gauge
7.4' (observed)

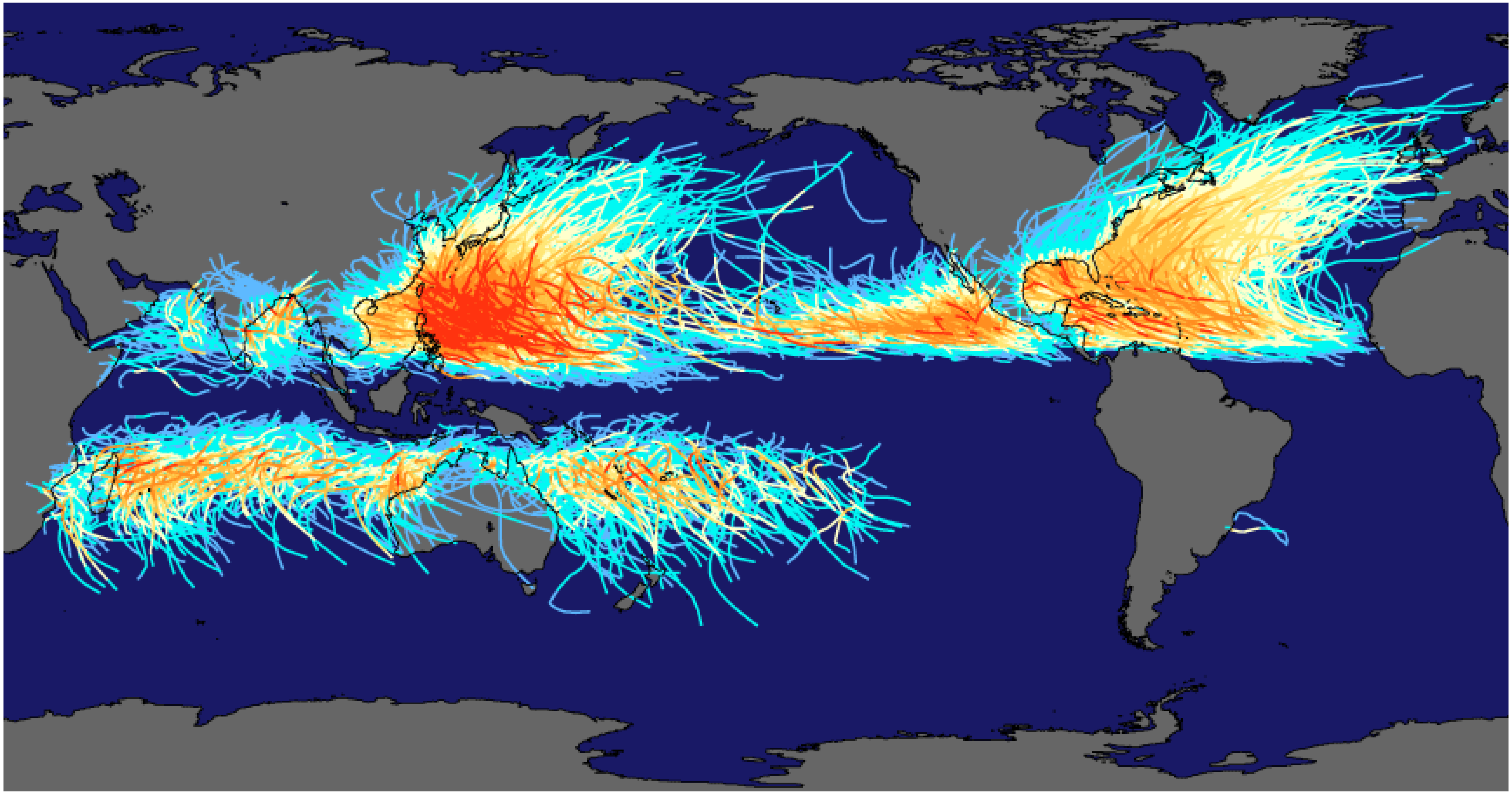
Mycoast.org/SC

http://www.noaanews.noaa.gov/stories2014/20141218_sealevelrise.html

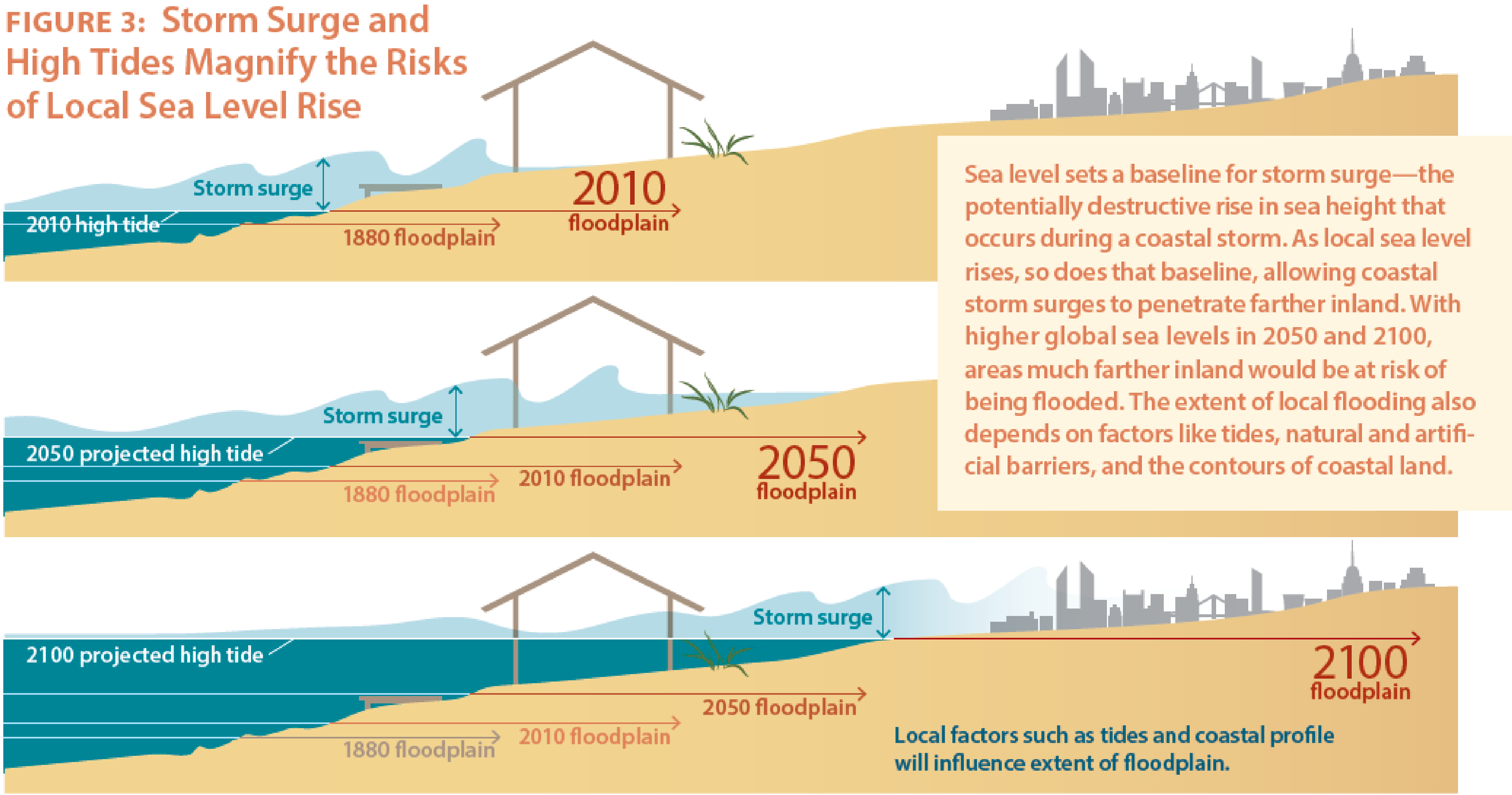
From Sweet and Park, 2014

Hurricanes

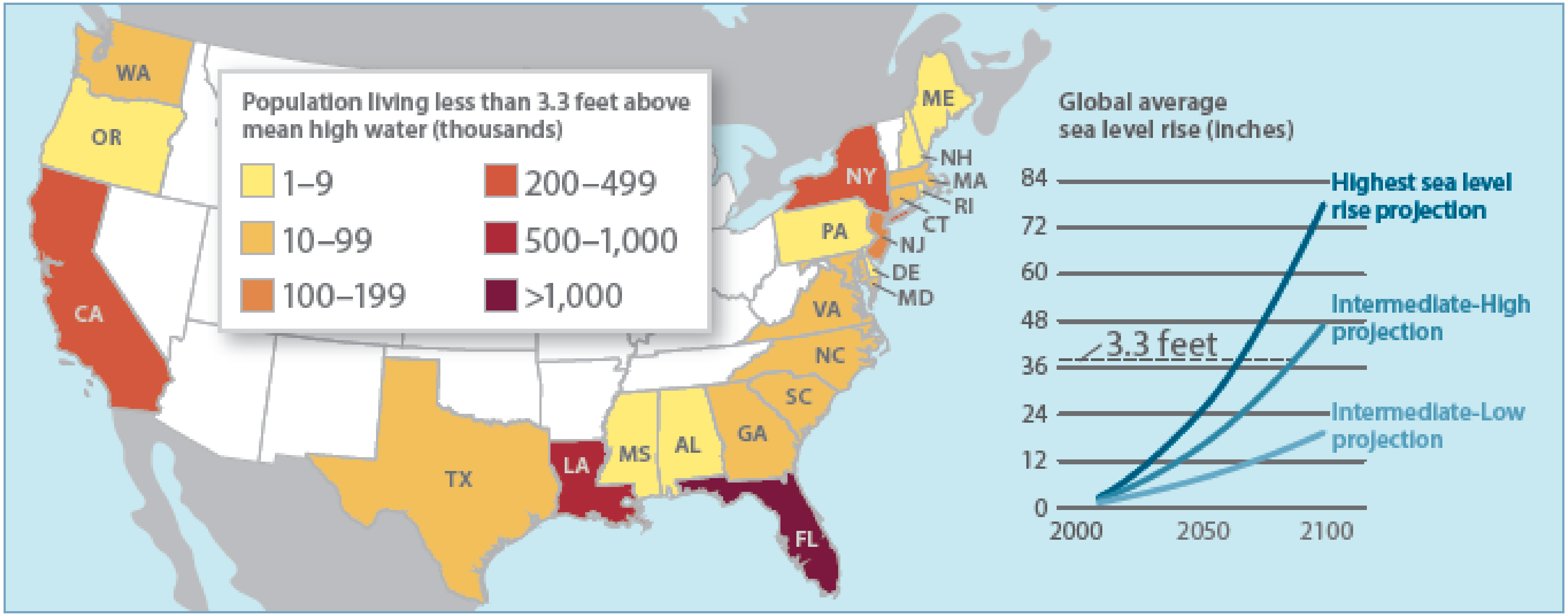
Tropical Cyclones (1985-2005)



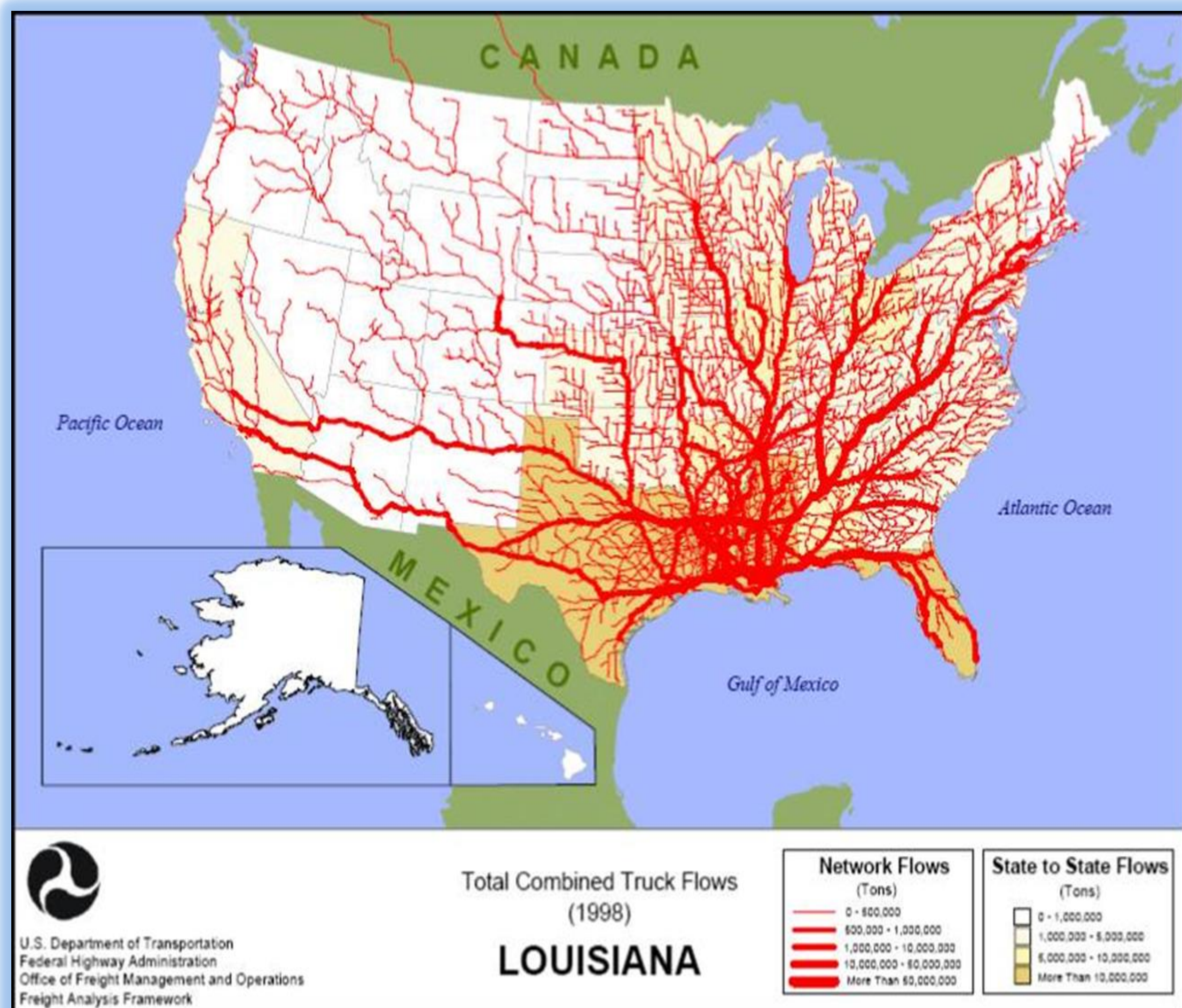
SLR Will Make Future Storms Worse



Lots of People Impacted



Coastal Nation – Even in the Heartland



What Are We Going To Do?

Steps to Resilience

1. *Focus on climate stressors that threaten people, buildings, natural resources, or the economy in your area.*
2. *Identify specific populations, locations, and infrastructure that may be impacted by the climate problem you identified.*
3. *Compile a list of potential solutions, drawing on the experiences of others who have addressed similar problems.*
4. *Consider risks and values to analyze the costs and benefits of favored options. Select the best solution for your situation and make a plan.*
5. *Implement your plan and monitor your progress. As necessary, adjust your plan to move toward your desired outcomes. Be prepared to iterate, if needed.*

From U.S. Climate Resilience Toolkit – toolkit.climate.gov

Sea Level Rise and Coastal Flooding Impacts Viewer

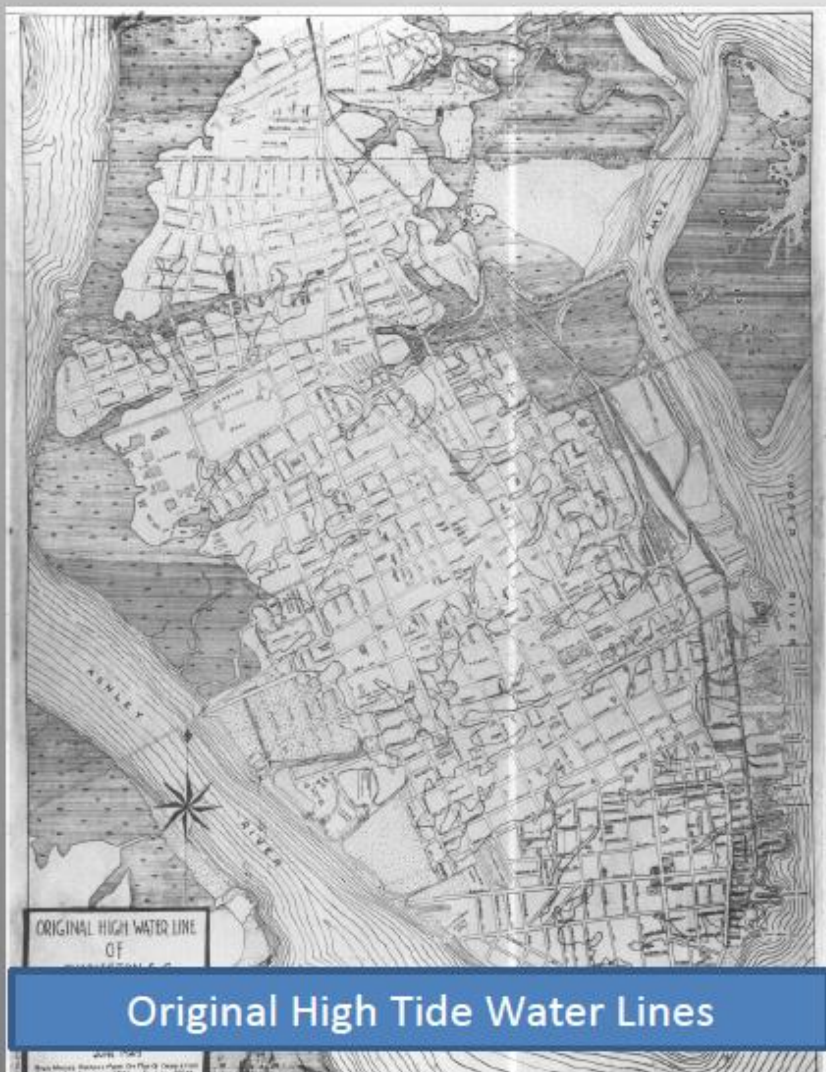
coast.noaa.gov/digitalcoast/tools/slr

Version 3.0

- **Displays** potential future sea levels
- **Provides** simulations of sea level rise at local landmarks
- **Communicates** the spatial uncertainty of mapped sea levels
- **Models** potential marsh migration due to sea level rise
- **Overlays** social and economic data onto potential sea level rise
- **Examines** how tidal flooding will become more frequent with sea level rise

Charleston Geography

Laura Cabiness, P.E., Director of Public Service, City of Charleston presentation to league of women voters 11/14/16



Original High Tide Water Lines

Charleston Today

Tunnel Collection and Pumping

Calhoun Street Drainage improvements

Completed 2001

10 ft. and 6 ft. Tunnels

Raising Roads, Armoring and Walls

$235,000,000 Capital Investment Between 1990 - 2020

- $81.1M Complete
- $27.2M Under construction
- $126.9M Funded

- $4.1 2016 Maintenance Budget

Questions?

Doug Marcy
doug.marcy@noaa.gov