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

Doug Marcy
Coastal Hazards Specialist
NOAA Office for Coastal Management
Increase in Global Temperature

Global Temperature and Carbon Dioxide

- Global Temperature (°F)
- CO₂ Concentration (ppm)

Year

1880 1900 1920 1940 1960 1980 2000

58.0
57.5
57.0
56.5
56.0
260 280 300 320 340 360 380 400

CO₂ Concentration
10 Indicators of a Warming World

- Sea Ice
- Ocean Heat Content
- Sea Level
- Temperature Over Oceans
- Water Vapor
- Air Temperature Near Surface (Troposphere)
- Glaciers and Ice Sheets
- Snow Cover
- Temperature Over Land
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).
Recent Sea Level Rise

23 Annual Tide Gauge Records

- Three Year Average
- Satellite Altimetry

1.7mm/year
2.9mm/year
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
Monitoring Sea Level Locally
Monitoring Sea Level Globally
Future Temperature
IPCC Estimates

IPCC (2001, 2007, and 2013) acknowledge that there is an unknown additional potential contribution from major ice sheets that is not included in the range shown here.

Sea Level Rise (meters)

- Rahmstorf 2007
- Horton 2008
- Pfeffer 2008
- Vermeer 2009
- Jevrejeva 2010
- Katsman 2011
- NRC 2012
- NOAA 2012
- USACE 2013
“Consensus Scenarios” that fed the NCA 3rd Assessment

Parris et al., 2012
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

![Sea Level Trends Map](image)

- **TOPEX, J1, and J2**
- **1992.96 – 2015.60**

- **NOAA/Laboratory for Satellite Altimetry**
- **Sea level trends (mm/yr)**

- **Office for Coastal Management**
- **Digital Coast**
Land Motion Plays a Big Part Too
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.
How are We Tracking?

[Graph displaying global sea level trends over time, with different scenarios indicated by lines.]

NOAA CO-OPS
New Global and Regional Scenarios


<table>
<thead>
<tr>
<th>GMSL Scenario (meters)</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
<th>2060</th>
<th>2070</th>
<th>2080</th>
<th>2090</th>
<th>2100</th>
<th>2120</th>
<th>2150</th>
<th>2200</th>
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<tbody>
<tr>
<td>Low</td>
<td>0.03</td>
<td>0.06</td>
<td>0.09</td>
<td>0.13</td>
<td>0.16</td>
<td>0.19</td>
<td>0.22</td>
<td>0.25</td>
<td>0.28</td>
<td>0.30</td>
<td>0.34</td>
<td>0.37</td>
<td>0.39</td>
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<tr>
<td>Intermediate-Low</td>
<td>0.04</td>
<td>0.08</td>
<td>0.13</td>
<td>0.18</td>
<td>0.24</td>
<td>0.29</td>
<td>0.35</td>
<td>0.4</td>
<td>0.45</td>
<td>0.50</td>
<td>0.60</td>
<td>0.73</td>
<td>0.95</td>
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<tr>
<td>Intermediate-High</td>
<td>0.05</td>
<td>0.10</td>
<td>0.16</td>
<td>0.25</td>
<td>0.34</td>
<td>0.45</td>
<td>0.57</td>
<td>0.71</td>
<td>0.85</td>
<td>1.0</td>
<td>1.3</td>
<td>1.8</td>
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<tr>
<td>High</td>
<td>0.05</td>
<td>0.11</td>
<td>0.21</td>
<td>0.36</td>
<td>0.54</td>
<td>0.77</td>
<td>1.0</td>
<td>1.3</td>
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<tr>
<td>Extreme</td>
<td>0.04</td>
<td>0.11</td>
<td>0.24</td>
<td>0.41</td>
<td>0.63</td>
<td>0.90</td>
<td>1.2</td>
<td>1.6</td>
<td>2.0</td>
<td>2.5</td>
<td>3.6</td>
<td>5.5</td>
<td>9.7</td>
</tr>
</tbody>
</table>

GLOBAL AND REGIONAL SEA LEVEL RISE SCENARIOS FOR THE UNITED STATES

NOAA Technical Report NOS CO-OPS 083

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

NOAA Tech Report NOS CO-OPS 083
Probabilities Related to RCPs

NOAA Global Mean Sea Level (GMSL) Scenarios for 2100

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

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

NOAA Tech Report NOS CO-OPS 083
Greatest source of uncertainty?

MAIN CAUSES OF SEA LEVEL RISE
2002 - 2014

- Antarctic ice sheet melt: 0.26 mm/yr
- Glacier melt: 0.38 mm/yr
- Greenland ice sheet melt: 0.73 mm/yr
- Expansion from ocean warming: 1.38 mm/yr

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

OFFICE FOR COASTAL MANAGEMENT
DIGITAL COAST
Relative Sea Level Rise

GMSL adjusted for

1.) Oceanographic Factors

2.) Gravity Changes due to Melting Land Based Ice

3.) Vertical Land Movement
Deterministic, Probabilistic, Scenarios

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DoD CARSWG Report
Hall et al., 2016
Compare with New Scenarios
Previous Curves

Estimated Relative Sea Level Change from 2015 To 2100
Gauge: 8685530, Charleston, SC (3.15 mm/yr)

<table>
<thead>
<tr>
<th>Year</th>
<th>NOAA Low</th>
<th>NOAA Int Low</th>
<th>NOAA Int High</th>
<th>NOAA High</th>
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<td>2015</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
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<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>2025</td>
<td>0.1</td>
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<td>0.4</td>
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<td>0.6</td>
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<tr>
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<td>0.4</td>
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<tr>
<td>2045</td>
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<td>0.5</td>
<td>1.0</td>
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<tr>
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<td>0.4</td>
<td>0.6</td>
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<tr>
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<td>0.5</td>
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<td>1.9</td>
<td>3.0</td>
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<td>2100</td>
<td>0.9</td>
<td>1.9</td>
<td>4.1</td>
<td>6.6</td>
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</tbody>
</table>

Print Table
New Curves

USGCRP Relative Sea Level Change Scenarios for: CHARLESTON I

Enter Project Name
Scenarios for CHARLESTON I
USGCRP VLM: 0.00417 feet/yr
All values are expressed in feet

<table>
<thead>
<tr>
<th>Year</th>
<th>USGCRP VLM</th>
<th>USGCRP Low</th>
<th>USGCRP Int-Low</th>
<th>USGCRP Intermediate</th>
<th>USGCRP Int-High</th>
<th>USGCRP High</th>
<th>USGCRP Extreme</th>
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<td>0.00</td>
<td>0.00</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<td>2060</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>2070</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>2080</td>
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<tr>
<td>2090</td>
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<td>0.00</td>
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<tr>
<td>2100</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Year
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
NCA3 Scenarios for Charleston, SC

- NOAA Low
- NOAA Int Low
- NOAA Int High
- NOAA High
NCA4 Scenarios for Charleston, SC

- NOAA2017 Low
- NOAA2017 Int-Low
- NOAA2017 Intermediate
- NOAA2017 Int-High
- NOAA2017 High
- NOAA2017 Extreme
Critical Thresholds Are Being Reached More Often

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

What is nuisance flooding?
Floods which cause 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.

In 1950 it would take a considerable amount of water caused by a large storm such as a hurricane to cause nuisance flooding. Nuisance flooding was infrequent.

In 2010, with higher relative sea level, it no longer takes a strong storm or hurricane to cause flooding. Now, nuisance flooding is frequent and can be caused merely by high tide.

How is local elevation important to nuisance flooding?
The relationship between local elevation and the high tide line determines the rate of nuisance flooding. If they are close to the same in elevation, flooding is frequent. If they are not close, flooding is infrequent.
High Tide Events

**PERIGEAN-SPRING TIDE**
A perigean spring tide occurs when the moon is either new or full and closest to Earth.

**NEW MOON**
- Moon closest to Earth in monthly orbit (perigee)
- Moon in alignment with sun
- Moon between Earth and sun

**FULL MOON**
- Moon closest to Earth in monthly orbit (perigee)
- Moon in alignment with sun
- Earth between moon and sun

*Not to scale.*
High Tide (nuisance) Flooding

CHARLESTON HARBOR TIDE GAGE
Universal Time (UTC)

Latest observed value: 6.55 ft at 10:48 AM EDT 27-Oct-2015. Flood Stage is 7 ft

Record: 12.6'

Major: 8.0'
Moderate: 7.5'
Minor: 7.0'
Action: 6.5'

Observations courtesy of NOAA National Ocean Service
Stormwater 101

Head – difference in elevation of two water surfaces

Large Head Difference – water will drain quickly from the surface

Small Head Difference – water will drain slowly from the surface

Increase in Events

From Sweet et al., 2014
Extreme Precipitation
Combined Events – October 2015
## Top Ten U.S. Areas with an Increase in Nuisance Flooding

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


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

Mycoast.org/SC

From Sweet et al., 2014
# Top Ten U.S. Areas with an Increase in Nuisance Flooding

<table>
<thead>
<tr>
<th>Location</th>
<th>Nuisance Flood Level (meters above MHHW)</th>
<th>&gt;30 days/year with Nuisance Flooding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilmington, NC</td>
<td>0.25</td>
<td>Past</td>
</tr>
<tr>
<td>Annapolis, MD</td>
<td>0.29</td>
<td>Past</td>
</tr>
<tr>
<td>Washington D.C.</td>
<td>0.31</td>
<td>Past</td>
</tr>
<tr>
<td>Port Isabel, TX</td>
<td>0.34</td>
<td>By 2020</td>
</tr>
<tr>
<td>Charleston, SC</td>
<td><strong>0.38</strong></td>
<td><strong>By 2020</strong></td>
</tr>
<tr>
<td>Lewes, DE</td>
<td>0.41</td>
<td>By 2020</td>
</tr>
<tr>
<td>Baltimore, MD</td>
<td>0.41</td>
<td>By 2020</td>
</tr>
<tr>
<td>Atlantic City, NJ</td>
<td>0.43</td>
<td>By 2020</td>
</tr>
<tr>
<td>Sandy Hook, NJ</td>
<td>0.45</td>
<td>By 2020</td>
</tr>
<tr>
<td>Kings Point, NY</td>
<td>0.52</td>
<td>By 2020</td>
</tr>
<tr>
<td>Key West, FL</td>
<td>0.33</td>
<td>By 2030</td>
</tr>
<tr>
<td>San Francisco, CA</td>
<td>0.35</td>
<td>By 2030</td>
</tr>
<tr>
<td>Savannah (Fl. Pulaski), GA</td>
<td>0.46</td>
<td>By 2030</td>
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<tr>
<td>Philadelphia, PA</td>
<td>0.49</td>
<td>By 2030</td>
</tr>
<tr>
<td>Mayport, FL</td>
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</tr>
<tr>
<td>La Jolla, CA</td>
<td>0.51</td>
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<tr>
<td>Norfolk, VA</td>
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<td>Boston, MA</td>
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<td>New London, CT</td>
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<td>2031-2060</td>
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<tr>
<td>St. Petersburg, FL</td>
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<td>2051-2100</td>
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</tbody>
</table>

*Sea level projections include local subsidence rates and regional gravity/tilt signatures from Kopp et al. (2014) and are based upon a 1.9 - 4.6 ºC range in future global warming under Regional Concentration Pathways (RCPs 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)


From Sweet and Park, 2014
Hurricanes

Tropical Cyclones (1985-2005)
Sea level sets a baseline for storm surge—the potentially destructive rise in sea height that occurs during a coastal storm. As local sea level rises, so does that baseline, allowing coastal storm surges to penetrate farther inland. With higher global sea levels in 2050 and 2100, areas much farther inland would be at risk of being flooded. The extent of local flooding also depends on factors like tides, natural and artificial barriers, and the contours of coastal land.

Local factors such as tides and coastal profile will influence extent of floodplain.
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

cost.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?

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