A geological perspective on sea-level rise and its impacts

K.G. Miller, R.E. Kopp, B.H. Horton, J.V. Browning, A.C. Kemp
Ash Wed. 1962 Nor’ easter Harvey Cedars
Hurricane Donna hits New York 1960

http://www.netquake.net/2012/10/photos-the-most-devastating-hurricanes-in-new-york-history/
The Battery, New York tide gauge

Governor Cuomo “There’s only so long you can say, this is once in a lifetime and it’s not going to happen again.”

Heights in blue relative to Mean Lower Low Water (FEMA standard)

- Sandy: 13.9 ft
- Irene: 9.5 ft
- Dec. '92: 9.8 ft
- Donna: 10 ft

Modified after Zervas (2005)
Causes of sea-level change

Global sea level raised by:
- temperature: warming expands seawater (less dense)
- ice volume: melt ice (mountain glaciers & ice sheets)

Milne et al. (2009)
Causes of sea-level change

Regional sea level

1) Subsidence (sinking) or uplift tectonics (e.g., Alaska uplift)
   includes glacial isostatic adjustment (GIA)
2) Oceanographic effects (e.g., El Nino, Gulf Stream changes)

Local sea level

Compaction due to natural processes & groundwater extraction

Milne et al. (2009)
Global sea-level rise past 20,000 years

Modified after Fairbanks (1989)

Barbados approximates global average sea level

Sea level was 390 ft (120 m) lower 20,000 yr ago

Rapid rises 14,000 & 12,000 yrs ago (MWP1)

Slow rise 7,000 to 3,000 yr ago (1,000 BCE)

Meltwater pulse 1B
110 inches/century
9 ft/century
27 mm/yr

Meltwater pulse 1A
190 inches/century
16 ft/century
47 mm/yr (Dechamps et al., 2012)

last glaciation 390 ft lower
120 m Fairbanks (1989)

7-5 kyr 15 inches/century
(3.8 mm/yr)

The Deglaciation of North America
21,400-1000 years ago

with additions from "The Last Great Ice Sheets", Denton & Hughes, ed., 1981,
Coastlines estimated using Barbados sea level curve after Bard et al., 1990
Great Basin Lakes from
Currey, Atwood, and Mabey, "Map 73: Major Levels … Lake Bonneville", 1984
Is modern sea-level rise part of a natural cycle?

Kemp et al. (2011)

Sea-Level Estimates
- Proxy reconstructions
- Observations (tide gauges)
- Model

1st millennium 0 rise; Medieval Warm 2.3 inches/century (0.6 mm/yr); Little Ice Age ~0 rise; 20th century 7 inches/century (1.7 mm/yr)
Global sea level is rising and accelerating

**Tide Gauges**
1880-2006
- 6.7 inches per century
- 1.7±0.4 mm/yr

Church & White (2006)

**Satellite data**
1993-2013
- 12 inches per century
- 3.2±0.4 mm/yr

http://sealevel.colorado.edu/
Why Is global sea level is rising today?

Thermal Expansion:
- Ocean has gained heat
- Warmer water is less dense
- Global temperature increase explains about 1/3 modern rise

Melting Glaciers & Ice Caps
- Melting land ice raises sea level, but not sea ice

[Graph: Global Ocean Heat Content (10^22 Joules) from 1960 to 2010]
- Pentadal average 0-700 m through 2009-2013
- Pentadal average 0-2000 m through 2009-2013

[Image: Surface Melt on Greenland]
- Melt descending into a moulin, a vertical shaft carrying water to ice sheet base.

http://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/
Why Is global sea level rising today?

~ 30% rise is due to melting mountain glaciers
Prior to 2003, < 15% sea level rise was from melting ice sheets, now greater
(Cazenave & Le Cozanne, 2014)

How much sea level is stored in ice sheets?
Greenland ~23 ft (7 m)
W. Antarctica ~16 ft (5 m)
E. Antarctica 170 ft (52 m)
Revised mass loss figures from ice sheets

Mass loss from Greenland and West Antarctica appears to be accelerating

Shepherd et al. (2012)
National Research Council projections 2012

Scenario-based projections of global sea-level rise by 2100 of 2.7 ft (range 1.7-4.6 feet)

Global versus Regional Effects

12 inches/century = 3 mm/yr
16 inches/century = 4 mm/yr

Mid-Atlantic tide gauges; blue = data, green = smoothed fit.
Kopp (2013) & Miller et al. (2013)
Global average tide gauges (pink) 6.7 inches/century (1.7 mm/yr) Church & White (2006)
GIA: Glacial Isostatic Adjustment

Melting of ice sheets results in a regional adjustment: sinking (blue) in some areas, uplift (red) in others.
Regional vs local sea level from tide gauges

Fall (red) line separates bedrock & coastal plain

Bedrock sites
- NYC/Bayonne, Phil./Camden, Baltimore, D.C.
- 12 inches/century (3 mm/yr) = global + GIA regional

Coastal plain sites
- Sandy Hook–Norfolk
- 16-18 in./century (3.5-4.5 mm/yr) = global + regional + compaction

Miller et al. (2013)
Subsidence and oceanographic effects

Mid-Atlantic subsidence
4-8 inches/century (1-2 mm/y)


Dynamic oceanographic effects
Reduction in Gulf Stream/MOC flow raises sea level in mid-Atlantic region by 4-8 inches by 2100 (10-20 cm)
Coastal plain > NYC (= GIA + global)

Local subsidence 4 inches/century due to compaction due to natural compaction and groundwater withdrawal

Miller et al. (2013)
Future sea-level rise mid-Atlantic US

Shore = Atlantic City, Cape May 1.5 ft by 2050, 3.5 ft by 2100
Bedrock = NYC, Phil., Baltimore, D.C.: 1.3 ft by 2050, 3.1 ft by 2100

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## Future sea-level rise mid-Atlantic US

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<th>Global</th>
<th>Bedrock</th>
<th>Shore</th>
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Miller et al. (2013)

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Effects of sea-level rise: Coastal flooding

By 2100, a “5 to 10-yr storm” will have the flooding of a modern “100-yr storm”

Atlantic City, New Jersey

Advisory Basal Flood Elevation (12.6 ft)

Water level reached in 2100

Water level reached in 2050

Water level reached during historic event

Meters (above MLLW)

Feet (above MLLW)


11/08/2012


11/08/2012

10 year

Reurrence Interval

Miller et al. (2013)

Department of Earth and Planetary Sciences
Institute of Marine and Coastal Sciences
Odds for a 2 ft rise on the Jersey shore by years

No significant greenhouse gas emissions reductions

2100-2200 2035-2055
2075-2100 2055-2075

Major global greenhouse gas emissions reductions

2035-2055
2075-2100

Slide provided by R. Kopp based on Kopp et al (2014)
Sea-level rise appears to be accelerating. By 2100 global average sea level will likely be more than 2.5 ft higher than it is today.

Storm surge is added to the sea-level rise: a 5-10 yr storm in 2100 will have the same effect a 100 yr storm has now.

FEMA/NOAA FIRM do not include sea-level rise.

Both regional and local effects add to sea-level rise. Mid-Atlantic region should plan for:

1. 1.5 ft sea level rise by 2050
2. >3 ft sea level rise by 2100

By 2100 we will face a fundamentally different Jersey shore.
Recommendations

2050 sea-level estimates for the NJ shore are 1.5 ft and range from 1.1-2.3 feet. Zoning for low-impact structures (e.g., housing) should target at least 1.5 ft above FEMA ABFE flood levels.

For municipal planning for structures with life spans beyond 40-50 years (e.g., transportation, water, wastewater, energy, communications) should use higher figures.

For purposes of planning infrastructure projects with significant public investments with life spans from 2050 to 2100, it is prudent to employ higher scenarios.
Thank you!
Questions?
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NYC in an ice-free world