A Perfect Storm: The Collision of Tropical Cyclones, Climate Change and Coastal Population Growth

Jeff Donnelly
Woods Hole Oceanographic Institution
• Background on hurricanes and climate
• Putting Hurricane Sandy in context
• Hurricane history in eastern MA
• What the long term (prehistoric) record tells us
What is a tropical cyclone?

Conditions for genesis

- Warm tropical waters > 26°C, 80°F
- Minimal Wind Shear Aloft
- Prior disturbance
- Coriolis Deflection
Where do they occur?

Tracks and Intensity of All Tropical Storms

Saffir-Simpson Hurricane Intensity Scale
# Intensity

## Saffir-Simpson Scale for Hurricane Classification

<table>
<thead>
<tr>
<th>Strength</th>
<th>Wind Speed (Kts)</th>
<th>Wind Speed (MPH)</th>
<th>Pressure (Millibars)</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 1</td>
<td>64-82 kts</td>
<td>74-95 mph</td>
<td>&gt;980 mb</td>
<td>28.94 &quot;Hg</td>
</tr>
<tr>
<td>Category 2</td>
<td>83-95 kts</td>
<td>96-110 mph</td>
<td>965-979 mb</td>
<td>28.50-28.91 &quot;Hg</td>
</tr>
<tr>
<td>Category 3</td>
<td>96-113 kts</td>
<td>111-130 mph</td>
<td>945-964 mb</td>
<td>27.91-28.47 &quot;Hg</td>
</tr>
<tr>
<td>Category 4</td>
<td>114-135 kts</td>
<td>131-155 mph</td>
<td>920-944 mb</td>
<td>27.17-27.88 &quot;Hg</td>
</tr>
<tr>
<td>Category 5</td>
<td>&gt;135 kts</td>
<td>&gt;155 mph</td>
<td>919 mb</td>
<td>27.16 &quot;Hg</td>
</tr>
</tbody>
</table>

## Tropical Cyclone Classification

<table>
<thead>
<tr>
<th>Category</th>
<th>Wind Speed</th>
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</thead>
<tbody>
<tr>
<td>Tropical Depression</td>
<td>20-34 kts</td>
</tr>
<tr>
<td>Tropical Storm</td>
<td>35-63 kts</td>
</tr>
<tr>
<td>Hurricane</td>
<td>64+ kts or 74+ mph</td>
</tr>
</tbody>
</table>
Tropical cyclones come in different sizes.
What Might the Future Hold?

N. Atl. Tropical SST
N. Atl. Tropical Cyclones
N. Hem. Mean Temp

From Coumou and Rahmstorf, 2012
Nature Climate Change
What Might the Future Hold?

Frequency of hurricanes may increase (particularly intense storms)

Using IPCC AR4 models

“Best Case”

“Worst Case”

Modern

N. Atl. Tropical SST
N. Atl. Tropical Cyclones
N. Hem. Mean Temp

Temperature anomaly (°C)

Year

Power dissipation index

U.S. East Coast Hurricanes per Decade

NCEP (1981 - 2000 A.D.)
ECHAM (2181 - 2200 A.D.)
GFDL (2181 - 2200 A.D.)

Modern
What Might the Future Hold?

Frequency of hurricanes may increase (particularly intense storms)

From Emanuel, 2013 PNAS
Using IPCC AR5 models
What Might the Future Hold?

Rate of sea-level rise will continue to accelerate

IPCC AR5
Hurricane Sandy 2012
68 billion in damage
148 fatalities
Historical Northeast US Hurricanes

Black = cat 1 and 2
Red ≥ cat 3
Historical Northeast US Hurricanes

Black = cat 1 and 2
Red ≥ cat 3

- 1788
- 1821
- 1838
- 1893
- 1815
- 1869
- 1954
- 1960
- 1944
- 1635

Sandy
1821 Hurricane SLOSH Simulation

SLOSH input
Track: ~known
Translation speed: ~known (~65 km/hr (40 MPH))
Radius of maximum winds: ?
Intensity: ?

Though some inferences can be drawn from damage

William C. Redfield
1789-1857

RMW = 46 km
Intensity = 51 m/s (115 MPH)
1821 Hurricane vs. Sandy
1821 Hurricane vs. Sandy in NYC

1821

Sandy

Water level relative to mean sea level in 1821 (m)

Water level relative to mean sea level in 2012 (m)

Time September 3, 1821

Time October 29, 2012

predicted tide

surge+tide

predicted tide

surge+tide

Water level relative to mean sea level in 1821 (m)

Water level relative to mean sea level in 2012 (m)

0:00 4:00 8:00 12:00 16:00 20:00 24:00

0:00 4:00 8:00 12:00 16:00 20:00 24:00

-3 -2 -1 0 1 2 3 4

-3 -2 -1 0 1 2 3 4
1821 Hurricane vs. Sandy in NYC

1821 Hurricane

- ~4 m of surge

Sandy Hurricane

- ~2.75 m of surge

Water level relative to mean sea level in 1821 (m)

Water level relative to mean sea level in 2012 (m)

Time September 3, 1821

Time October 29, 2012
Storm tides in lower Manhattan

<table>
<thead>
<tr>
<th>Date</th>
<th>Maximum Water Level above MSL (m)</th>
</tr>
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<tbody>
<tr>
<td>1788</td>
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<tr>
<td>1851</td>
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<td>1883</td>
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<tr>
<td>2012</td>
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- Hurricanes: Red bars
- Winter Storm: Yellow bars
Storm tides in lower Manhattan

If 1821 hit at high tide

If Sandy hit at low tide

Maximum Water Level above MSL (m)

Date

- 1788
- 1821
- 1893
- 1938
- 1944
- 1950
- 1960
- 1966
- 1968
- 1984
- 1985
- 1987
- 1991
- 1992
- 1993
- 1996
- 2012

Hurricanes
Winter Storm
Hurricane Sandy Storm Tide

Storm Tide Heights
Meters Above NAVD88

- 1.5
- 1.8
- 2.1
- 2.4
- 2.7
- 3.0
- 3.3
- 3.6
- 3.9
- 4.2
- 4.5
- >4.5

USGS High Water Measurements
Hurricane Sandy Storm Tide

Storm Tide Heights
Meters Above NAVD88

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- >4.5

USGS High Water Measurements

Long Beach
Long Beach Washover

Pre Sandy

Post Sandy
TBD LONG BEACH BLVD, LONG BEACH TWP, NJ 08008

$2,200,000

Lot Size: 24 Acres sq. ft.

MLS ID: 3063835

- Request Information
- Save this Listing
- Schedule Showing
- Make Notes
- Print Property Report
- View Photo Full-Size
What if Sandy hit SE New England?
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~1.4 m of surge at Woods Hole
What if Sandy hit SE New England?

Woods Hole, MA

- Monthly highest water Woods Hole tide gauge (above MHW)
- SLOSH simulation for Woods Hole (above MHW)
- SLOSH simulation for Woods Hole (above astronomical tide)
- Hypothetical SE New England Sandy landfall

What if Sandy hit SE New England?

Boldt et al. (2010)
Why so much damage from Sandy?
Why so much damage from Sandy?

Future home of Atlantic City (ca. 1833)

today
Why so much damage from Sandy?

Source: New Jersey Department of Labor and Workforce Development
From Pielke et al., 2008
1900-2013 US Hurricane Damage in 2005 USD

But what if these storms were to strike today?

From Pielke et al., 2008
1900-2013 US Hurricane Damage in 2005 USD

Damage accounting for increased wealth and population

From Pielke et al., 2008
1900-2013 US Hurricane Damage in 2005 USD

Damage accounting for increased wealth and population

From Pielke et al., 2008
Sea-Level Rise

From Kemp and Horton, 2013 *Journal of Quaternary Science*
What about eastern MA?

Hurricane Bob (1991) Storm Surge
What about eastern MA?

Storm surge from the Great Colonial Hurricane of 1635
Storm surge from the Great Colonial Hurricane of 1635

John Winthrop  
(Governor of Massachusetts Bay Colony)

“The tide rose at Narragansett fourteen feet higher than ordinary, and drowned eight Indians flying from their wigwams”

William Bradford (Governor of Plymouth Colony)

“...a mighty storm of wind and rain as none living in these parts, either English or Indians ever saw”

“It caused the sea to swell to the south wind of this place above 20 foot right up and down, and made many of the Indians to climb into trees for their safety”

“It blew down many hundred thousands of trees, turning up the stronger by the roots and breaking the higher pine trees off in the middle”
Sedimentary Records of Hurricane Strikes

Overwash sand layer

Overwash sand layer

Overwash sand layer

1 foot
Prehistoric Hurricanes and Climate

Hurricane-induced Sand Layers

Event deposits
Salt Pond, MA

1675
1635
1991

Age (years CE)

Coarse anomaly (% > 63 μm)
Prehistoric Hurricanes and Climate

a - Event deposits
Salt Pond, MA

- Event deposits
- Salt Pond, MA

λ = 0.9
(0.002)

Age (years CE)

0 500 1000 1500 2000

Events/century

Coarse anomaly (%>63 μm)

0.01
(0.06)
(0.2)
(0.6)
(1)

0 500 1000 1500 2000

0 5 10 15 20 25 30 35

Case
(%) average

0 5 10 15 20 25 30 35
Prehistoric Hurricanes and Climate

- Event deposits
  - Salt Pond, MA

- $\lambda = 0.9 (0.002)$

- 0.01

- (0.06)

- (0.2)

- (0.6)

- 0

- Basin-wide increases related to warm SST anomaly in deep tropics

- Increased activity driven by warm SST anomaly off East Coast

- Age (years CE)
  - 0
  - 500
  - 1000
  - 1500
  - 2000

- Events/century
  - 0
  - 500
  - 1000
  - 1500
  - 2000

- Coarse anomaly (%>63 $\mu$m)
Prehistoric Hurricanes and Climate

a - Event deposits
Salt Pond, MA

λ = 0.9 (0.002)

b - Inlet Formation Outer Banks, NC

Landscape Impacts

Cummulative Events

Prehistoric Hurricanes and Climate

Age (years CE)

0 500 1000 1500 2000

Events/century

0 5 10 15 20 25 30 35

Coarse anomaly (%>63 μm)

0.01

0.06

0.2

0.6

0.9

(0.01)

(0.06)

(0.2)

(0.6)

(1)

(0.002)
Landscape Impacts

17th Century erosion event Pattagansett Marsh, CT
(van de Plassche et al. 2006)

- Erosive boundary potentially related to the Great Colonial Hurricane of 1635
- Radiocarbon dated samples
Summary

NJ/NYC were fortunate throughout the 20th century (unfortunately this was a time of unprecedented coastal development)
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Storms of far greater intensity than Hurricane Sandy (and Bob) impacted the area historically (and prehistorically)
Summary

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Storms of far greater intensity than Hurricane Sandy (and Bob) impacted the area historically (and prehistorically)

Over the last two millennium historically unprecedented intense hurricane activity occurred during intervals of elevated sea surface temperatures
Summary

The impacts of future hurricane activity will be greatly exacerbated by continuing sea-level rise and coastal population growth, regardless of whether or not we experience significant increases in hurricane landfalls.
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Intervals of more frequent intense hurricane strikes significantly altered coastal landforms and ecosystems.
Thank you!

For more info see: www.whoi.edu/science/GG/coastal/
Redfield (1831) - Water rose 13 feet (4 m) in lower Manhattan.
Cat 3 curving west and making landfall in SE MA
Summary

The impacts of future hurricane activity will be greatly exacerbated by continuing sea-level rise and coastal population growth, regardless of whether or not we experience significant increases in hurricane landfalls.

Intervals of more frequent intense hurricane strikes significantly altered coastal landforms and ecosystems.

We may see a loss of the protective services these landforms provide if we return to an active hurricane regime.