Sea Level Rise and Storm Surge

Geospatial Data for Preparation, Recovery and Assessing Future Threats

Keeping History Above Water
Newport RI
April, 2016

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Geospatial Data for Assessing Threats, Preparation and Recovery

- **Accuracy & Uncertainty**
  - Error in Geospatial Data
- **Key Geospatial Data**
  - Elevation
  - Bathymetry
  - Inundation
    - Measurements
    - Models
    - Products
  - Also nice to have: Features & Imagery
- **Hx Sandy**
  - STLI/ELIS & GATE
  - ICT priorities & Mapping Needs
  - Post Hx Sandy: Planning & Reconstruction
- Elevation Data – NED/Lidar/RTK
  - RTK projects
  - Other related projects
- **The Long View**
Accuracy and Uncertainty

• Know your data = trust your data

• Error in Geospatial Data
  – What
  – Where

Figure 5: DEMs show how sea level rise will translate to coastal inundation near Verrazano Bridge, Assateague Island, MD. A. With 0.6 meters of sea level rise, the bridge and other coastal features are still above sea level. B. Sea level rise up to one meter would partially cover the shoreline as well as a portion of road near the bridge, as indicated by the blue shading over the southern road segment. C. After two meters of sea level rise, most of the island would be inundated, including a significant portion of the road.
Attribute Error

In field data, such as features mapped with GPS

What feature is this man standing beside?

Unexploded Ordinance found at Sandy Hook!

In interpreted data, such as from aerial photography

Would these unexpected features be correctly interpreted?

Boats at Forsythe National Wildlife Refuge were washed away from a nearby marina
Credit: USFWS

House pushed into the marsh on Staten Island
Credit: Adrees Laif, Reuters
Errors in model output

• Models cannot accommodate all the parameters of reality
  • SLOSH does not model waves on top of the surge or account for normal river flow and rain flooding, although these are in development*

• Models are highly dependent on input data
  • SLOSH surge heights are variously measured as correct to within 5**-20%***. Error is largely attributed to the difficulty of establishing & predicting meteorological inputs.

* Sea, Lake, and Overland Surges from Hurricanes (SLOSH)
  http://www.nhc.noaa.gov/surge/slosh.php

**National Weather Digest, Vol 33, #1, August 2009 (specifically, page 6 of this publication) http://slosh.nws.noaa.gov/sloshPub/pubs/Vol-33-Nu1-Glahn.pdf

***SLOSH model overview on NWS website.
  http://slosh.nws.noaa.gov/sloshPub/index.php#sloshDsp
Errors in model output
This has been declared a Severe Marine Debris Event
Pixel Value/Placement

(Plus/minus 30 cm Vertical!)

Satellite Imagery

- Georeferenced, Terrain Corrected
  - swaps around which other pixels they are beside
- Radiometrically corrected to eliminate atmospheric attenuation & resampled
  - changes pixel values

(LiDAR-derived DEM Vertical accuracy 95% confidence: +- 0.30m)

(Details about processing levels of all Landsat data products can be found on http://landsat.usgs.gov/Landsat_Processing_Details.php)

(Pixels move AND change value!)
Data Error - Locational

• Getting the datum right
  – On what shape are you measuring distance?
  – Where are you measuring from?

Horizontal
• A geodetic datum is a coordinate system with a set of reference points, used to locate places on the earth. Each starts with a spheroid as a base from which it defines X, Y horizontal coordinates. Different spheroids result in different XY coordinates for a given location.
• Geospatial data layers in different datums will not register with each other since they use different spheroids. Sometimes this is obvious, as when a stable and the horse within it have their locations reported in two different datum. Other times it isn’t so obvious, and especially with large raster datasets that do not have a strong relationship to familiar landscape features. The data inputs to models, such as DEM, and model outputs, such as the storm surge heights from SLOSH, are data layers for which this is the case.

Vertical
• The vertical datum is equally important when Z values are involved. An easy way to think of this is that the vertical datum defines the surface from which a height is measured. Sea level (or mean sea level) is a common reference for a vertical datum. It uses the midpoint between mean low and mean high tide at a particular location as the “standard sea level” from which rise or surge is measured. All your data must be in the same vertical datum, such as NVGD88.
Errors in Databased Content

John Fitzgerald Kennedy National Historic Site
Brookline, MA

Ellis Island and Statue of Liberty
New York Harbor
Locational Error in Field Data

Some things are tough to map without a GPS, or even with one.

*Old Inlet Dock at Fire Island NS*
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    Measurements
    Models
    Products
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  – RTK projects
  – Other related projects

• The Long View
Key Geospatial Data

- Elevation
- Sea Levels, Rise & Surge
- Bathymetry
- Inundation
- Features
- Imagery

<table>
<thead>
<tr>
<th>Additional Data – Related Considerations</th>
<th>Storm Surge</th>
<th>SLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteorology of Specific Storms</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Tidal regime</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>How future storms will alter the type, shape and character of the coastline</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>How the climate will change</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>How much sea level will rise</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>How vegetation will change</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>
Key Geospatial Data - Elevation

What’s out there

• National Elevation Dataset (NED)
  – Contours (1:24k)
  – Seamless raster elevation of US with continuous update
  – Resolution varies depending on source data: 1/9 arc second – 2 arc second.
  – RMSE for CONUS 1/3 arc second NED overall, as measured against 25,310 NGS benchmarks, was 1.55 as of April, 2013 (an improvement from 2.44 as measured 10 years previously)
  – Check the USGS National Map Viewer for current details of a specific area: http://viewer.nationalmap.gov/viewer/

TNM Elevation Tools:
• Spot elevation
• Profile tool
• Quick profile tool
• Bulk point query

Brown - 1 m extent
Orange - 1/9 arc second extent
(All of New England has 1/3 arc second NED coverage)
What’s out there – Lidar

• Lidar Participation
  • Use the USGS 2012 lidar specifications w/quality levels 5 – 139 cm. (vertical accuracy). Hans Karl Heidemann.
  • See also the Guidelines for Digital Elevations Data (NDEP), 2004, but designed to be technology-independent http://www.ndep.gov/TechSubComm.html
  • Participate in the annual 3DEP (3D Data Acquisition Partnership) for Lidar in which USGS coordinates lidar investments for critical mass.
    – http://nationalmap.gov/3dep/
What’s out there - Lidar

- Civilian Elevation Sites (Lidar and more)
  - National Digital Elevation Program (Coordination)
  - US Interagency Elevation Inventory (data discovery, incl to state & local repositories)
    - [https://coast.noaa.gov/inventory/](https://coast.noaa.gov/inventory/)
  - OpenTopography (NSF-funded with international holdings, includes Radar topo)
  - Digital Coast (NOAA, data viewer for coastal zone data of all sorts.
    - [https://coast.noaa.gov/dataviewer/#](https://coast.noaa.gov/dataviewer/#)
  - TNM Lidar holdings that are source data for NED
  - Best Fed Site: (opinion) USGS EarthExplorer now includes CLICK (Ctr for Lidar Coordination & Knowledge) for current Lidar holdings of all types for all federal gov’t agencies (many co-funded with state/local gov’t)

Blue – NPS>0.7
Green – NPS 0.36-0.35
Brown – NPS unknown
What’s out there/possible
– RTK GPS for elevation
  • Nail down local geodetic benchmarks and other points
    with up to cm or even mm accuracy.
  • Develop local dense high resolution coverage for small
    areas.
  • Technology continues to come down in price and
    complexity, but this is still high end work involving
    professional technical skills.
  • Recreational and Mapping grade GPS are also
    improving but are not yet of the quality to improve on
    lidar. (e.g. phone, Garmin, and non-RTK/survey grade
    Trimble, Ashtec and similar)
  • The football of accuracy
Sea Levels & Tide Gauges

Tide gauges measure sea level through complex instruments located along our coasts, recording information about the precise patterns of rising and falling tides up and down the coasts. Sensors continuously record long-period water levels relative to a stable height reference surface such as the geoid. Measurements are provided in all major relevant vertical datum. The information is essential for establishing “sea level” (including calibrating altimeter readings in the open ocean), creating accurate elevation maps and making predictions about storm impacts in specific locations.

Hurricane Sandy damaged or destroyed 73 tide gauges on the U.S. east coast, leaving researchers with critical information gaps. Replacement of these gauges is necessary for accurate measurement of the vulnerability of coastal resources to inundation (rising water from sea level rise and storm surges).

http://tidesandcurrents.noaa.gov/datumstable.php?id=8531680
Sea Level Rise Scenarios

Sea Level Rise “data” input to inundation models is simply the selected scenario. The most commonly used are the IPCC scenarios associated with different levels of carbon emissions that result in predicted SLR of 60 cm, 1 m and 2 m.
Storm Surge Model Inputs

Meteorological inputs to storm surge models is extensive and complex and a primary driver of the results, along with geomorphology. Parameters include storm track, intensity, forward speed, size (~diameter), angle of approach and central air pressure. Further complicating matters is that storm characteristics are highly dynamic and difficult to predict. For example, the average errors in track and intensity can mean the difference between a Cat 1 storm in Pensacola and a Cat 3 storm in New Orleans!
IBTrACS is a source for tropical cyclone track data from all major sources, maintained by Nat’l Ctr on Atmospheric Research. The World Meteorological Organization sanctions one “answer” per storm.

https://climatedataguide.ucar.edu/climate-data/ibtracs-tropical-cyclone-best-track-data
**Key Geospatial Data - Bathymetry**

Comparison of Shallow Water Mapping Technologies, GOMMI 2009

**Technologies:** side-scan sonar, multibeam & single beam sonar, interferometric, topo-bathy lidar, AUV platforms & more.

**Fields:** dis/advantages, trade-offs/thresholds, data types & products, technical complexity of data, suitability for conditions (e.g. depth), costs, more information

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**Trade-offs/thresholds**

- Much more complex and expensive relative to single beam, but benefits in cost per unit effort and resolution can well outweigh the disadvantages.
- Swath widths shorter in single beam.

**Primary products**

- Seafloor morphology/shape of the seafloor/seafloor topography.
- Surficial geology classification from backscatter is imprecise.
- Classify format of structural environment.

**bathymetry**

- Yes
- Primary purpose.
- Excellent high-resolution bathymetry.
Key Geospatial Data - Bathymetry

NOAA’s National Centers for Environmental Education
http://maps.ngdc.noaa.gov/viewers/bathymetry/
Key Geospatial Data - Inundation

Measurements
USGS sensors deployed pre-Sandy
High water marks

Models
SLOSH, ADCIRC, SWAN, CHAMP

NHC products for storm preparation
MOMs, MEOWs, P Surge

FEMA products for planning & construction
FIRMs, BFE/ABFE
USGS deployed a temporary monitoring network of water-level and barometric pressure sensors at 224 locations along the Atlantic coast from Virginia to Maine to continuously record the timing, areal extent, and magnitude of hurricane storm tide and coastal flooding generated by Hx Sandy. These records were greatly supplemented by an extensive post-flood high-water mark (HWM) flagging and surveying campaign from November to December 2012 involving more than 950 HWMs.

The resulting data constitute an extensive collection of continuous water-level records documenting a single, landfall hurricane and can be used to evaluate the performance of storm-tide models for maximum and incremental water level and flood extent, and for site-specific effects of storm tide.

Data available in tab-delineated, ASCII format by site for each sensor by using a USGS interactive storm-tide mapper at http://water.usgs.gov/floods/events/2012/sandy/sandymapper.html.
Inundation Models - SLOSH

• **Sea, Lake, and Overland Surge Height:** [http://www.nhc.noaa.gov/surge](http://www.nhc.noaa.gov/surge) estimate storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes. Developed by NWS. Primary model for FEMA, NOAA, USACE.

**Try SLOSH at home!**

- Computationally efficient (fast)
- Resolves flow through barriers, gaps & passes and inland inundation
- Resolves overtopping of barrier systems, levees and roads
- Resolves coastal reflections of surge

**Inputs:**

- **Bathymetry** for shape & character of coastline and for width & slope of the continental shelf.
  - NWS provides SLOSH basins, varying resolutions, updates
- **Meteorological data** (storm specific) for intensity, forward speed, size (~diameter), angle of approach, central air pressure. (NOTE: “There is more inaccuracy in the input wind parameters to surge models than in the models themselves.” – SLOSH Disclaimer. (see model error, above)
- **Land elevation data** Lidar-derived DEM (see Elevation sources, above)
Modeling Approaches

**Deterministic** Single simulation using a perfect forecast for a specific event.

**Probabilistic** Incorporate statistics of past forecast performances to generate an ensemble of runs.

**Composite** Incorporate statistics of hypothetical storms to generate several thousands of runs under different conditions.

SLOSH Products

- Maximum Envelope of Water
- Max of the MEOWs
- P-Surge
Inundation Models - ADCIRC

- **Advance Circulation** [http://adcirc.org/](http://adcirc.org/)
  Predict storm surge, flooding, model tides, wind driven circulation & more. Developed at University of North Carolina. More complex than SLOSH. Widely used.

- **Inputs:** bathymetry, topography, boundary information, tidal characteristics, nodal attributes (often based on land use data), river inflow, meteorological forcing input, wave radiation stress forcing, and others depending on the geographical area of interest.

- **Products:** time varying & spatially varying water surface elevation, water velocity, wind velocity, & atmospheric pressure, 2D or 3D as specified in the input.

**ADCIRC Bootcamp in May:**
Inundation Models – Wave Action

Simulating Waves Nearshore – SWAN

http://swanmodel.sourceforge.net/
Delft University of Technology

What it models:
• Wave propagation in time and space, shoaling, refraction, frequency shifting
• Wave generation by wind
• Three- and four-wave interactions
• Whitecapping, bottom friction & depth-induced breaking
• Dissipation due to aquatic vegetation, turbulent flow and viscous fluid mud
• Propagation from laboratory up to global scales
• Wave-induced set-up
• Transmission through and reflection against obstacles
• Diffraction

Coastal Hazard Analysis Modeling Program – CHAMP*

http://www.fema.gov/media-library/assets/documents/11551
FEMA

What it models:
(for 2%, 1% or 0.2% SWEL)
• Storm-induced erosion
• Wave height & period
• Wave runup

*CHAMPS now incorporates WHAFIS (Wave Height Analysis for Flood Insurance)
The National Hurricane Center’s Inundation
NWS, NOAA

**Storm-specific advisories based on SLOSH and other analyses**

- Predicted storm surge for specific events is highly dependent on meteorological input, hence the NHC “decision wedge”
- MEOWs and MOMs both provide regional worst case storm surge estimates
- Average errors in storm track and intensity can mean the difference between a Cat 1 in Pensacola or a Cat 3 in New Orleans.
- Probabilistic Storm Surge accommodates uncertainties
- Hurricane Local Statements address local conditions w/in 48 hrs
- Coastal areas susceptible to storm floods (not storm specific)
Federal Emergency Management Agency’s Inundation

DHS

FEMA starts with field reconnaissance (shoreline type, condition, presence of protection structures, buildings, vegetation, esp. marsh grass type, density & height). Next they use inundation models (SLOSH, ADCIRC) to delineate stillwater elevation (SWEL) for storm surge events of the 10%, 2%, 1% and 0.2% annual chance magnitudes. The third step adds runup, wave action and related variables on top of the SWEL. The last step is to compare the final water elevations, with waves, to the land elevation data and identify Special Flood Hazard Areas (SFHA) and other flood zones based on these Base Flood Elevations (BFE).

<table>
<thead>
<tr>
<th>Annual chance magnitude</th>
<th>Common name</th>
<th>Annual likelihood</th>
<th>Frequency</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 %</td>
<td>“500 year flood”</td>
<td>The flood with a 0.2% chance of being equaled or exceeded every year.</td>
<td>There is a 100% chance of such a flood during any 500 year span.</td>
<td>0.2 * 500 = 100</td>
</tr>
<tr>
<td>1%</td>
<td>“100 year flood” or “base flood”</td>
<td>The flood with a 1% chance of being equaled or exceeded every year.</td>
<td>There is a 100% chance of such a flood during any 100 year span.</td>
<td>1 * 100 = 100</td>
</tr>
<tr>
<td>2%</td>
<td>“50 year flood”</td>
<td>The flood with a 2% chance of being equaled or exceeded every year.</td>
<td>There is a 100% chance of such a flood during any 50 year span.</td>
<td>2 * 50 = 100</td>
</tr>
<tr>
<td>10%</td>
<td>“10 year flood”</td>
<td>The flood with a 10% chance of being equaled or exceeded every year.</td>
<td>There is a 100% chance of such a flood during any 10 year span.</td>
<td>10 * 10 = 100</td>
</tr>
</tbody>
</table>
Federal Emergency Management Agency’s Inundation
(p.2)

The Zones

- **Moderate flood hazard areas**, labeled Zone B or Zone X (shaded) are also shown on the FIRM, and are the areas between the limits of the base flood and the 0.2-percent-annual-chance (or 500-year) flood.
- **Minimal flood hazard areas**, which are the areas outside the SFHA and higher than the elevation of the 0.2-percent-annual-chance flood, are labeled Zone C or Zone X (unshaded).

**Regarding Updates**

- Not unusual to see a several foot increase in BFEs and a large landward shift in the VE zones with new flood study using updated data (e.g. longer storm history with big events, more refined storm surge grid), better models, and better topo.
- Not unusual to have an AE Zone adjacent to or encircled by a VE Zone of the same whole-foot elevation. It just means that the wave height component of the total flood elevation dropped below the 3’ threshold of the VE Zone. Probably due to a small change in topo (sub-foot), so the SWEL is reduced to < the 4’minimum for 3’ waves.
Within the SFHA

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Inundation

A NOAA online inundation tool (not geospatial):

– The data input for this tool is 6-minute water level data time series and the tabulated times and heights of the high tides over a user specified time period, relative to a desired tidal datum or user-specified datum.

– The data output of this tool provides summary statistics, which includes the number of occurrences of inundation above the threshold (events) and length of duration of inundation of each events above the threshold elevation for a specified time period.

– http://tidesandcurrents.noaa.gov/inundation/
Inundation

A USGS online tool:
- Sea Level Rise
  - Coastal Vulnerability Index
  - Shoreline Change Forecasts
- Shoreline Change
  - Long term change rates
  - Short term change rates
  - Historical shoreline positions
- Extreme Storms
  - Coastal change hazards
  - Beach morphology
- Nor’easters
  - Erosion probabilities and related content
Additional Geospatial Data Considerations

Imagery from both before and after a storm event

Ground Features
- resources of special interest
- general context

Infrastructure
- utilities
- power / communication systems
- access / transportation

Potential Danger Zones

This photo, taken just after Hurricane Sandy, shows Fire Island’s dunes blown back onto the inner barrier in overwash fans.
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**Hx Sandy**

**Recovery, Reconstruction, Planning & Mitigation**
- What we used and how
- What we wished for
- Geospatial data products

**First Priorities:** Safety, community assistance, identify access impediments and safety concerns, prevent further damage, remove or stabilize hazmat, stabilize structures, re-establish access to critical areas.

**Concurrent Concerns:** Remove sand and debris, remove portable resources, mold prevention, assess bridges, roads and piers along access routes, assess damage and additional threats to specific resources and structures.
History Below Water

Three quarters of Liberty Island and all of Ellis Island were underwater. Almost all buildings were flooded. The storm had destroyed most of the infrastructure on both islands, including primary and back-up power, HVAC, water, sewer, communications and security systems as well as piers and walkways.

The Statue itself was not damaged, but museum collections as well as nearly every other historic feature on these islands was affected.

At ELIS, a team of dozens of curators from across the NPS would move over 1 million archival documents and historic artifacts down three flights of stairs by hand for eventual temporary relocation in Maryland.
History Below Water

At Gateway’s three units, Jamaica Bay, Staten Island and Sandy Hook, the staff and community were further shaken by traumatic incidents such as the fires in Far Rockaway and the 12+ feet of water on Staten Island.
What to do & What’s been done

**Safety:**
Daily and sometimes hourly updated maps identifying areas, routes and structures that are unsafe or need a safety assessment.

**Access:**
Routes open/closed with the specific locations and nature of existing impediments and potential impasses.

**Resource Status:**
Status of specific areas and features.

**Team Briefings:**
Daily and more maps to accompany team briefings, both general and site specific.

**Logistics & Local Info for ICT staff:**
- Housing assignments
- Getting around
- Where to eat, do laundry, charge phones, etc.

**Work Assignments:**
Teams for debris and sand removal, etc.

**Damage Assessment Activity:**
Areas evaluated and by whom. Prioritized assignments for the different kinds of evaluation teams. Coordinating transportation

**Reporting:**
Daily and more maps to inform WASO, etc.
Incident Command Team
Geospatial Data Needs

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Boardwalk damage at Fire Island
Work Assignments
Gateway NRA, Sandy Hook Unit
Sand Removal from Visitor Center parking lot
Fire Island National Seashore

Hurricane Sandy not only introduced a lower, wider beach, it also uncovered a bit of history. Filled with coal and headed to Newfoundland, the Bessie White ran aground close to Smith Point County Park in the 1922. Waves carried the remains of the ship west, to its present-day location near Skunk Hollow in the Otis Pike Fire Island High Dune Wilderness. Winter storms occasionally reveal the wreck but for most of the year, the beach keeps this ship a buried treasure.
Floyd Bennett Field conditions are subject to change. Please see Liaison Officer for the most up to date information.
Hx Sandy Planning & Reconstruction Projects

A 2012 web map application displayed pre-Sandy imagery. Park and ICT staff delineated impact areas associated with specific recovery, rehabilitation and mitigation projects. Resulting maps were very helpful when sorting out overlapping project requests.
A 2013 project to establish the First Floor Elevations (FFE) for every building at GATE, Statue and Ellis with RTK GPS and total stations by the numbers:

- Buildings FFE’d: >500
- RTK shots: >1,500
- Staff: 8
- Days: 5
- Cost: $5,354.12

Repeated for FIIS FFE in 2014.
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Comparing Elevation Data Sources

- **USGS NED**
  - Vertical accuracy
  - 95% confidence: ± 2.4m

- **LiDAR-derived DEM**
  - Vertical accuracy
  - 95% confidence: ± 0.30m

- **Geodetic-grade GPS**
  - Vertical accuracy
  - 95% confidence: ± 0.02m

1 meter of sea level rise

Sea level
Mapping Elevation for Park Planning and Resource Protection

The NPS and the University of Rhode Island are engaged in a series of valuable high resolution elevation mapping projects utilizing RTK GPS:

• **“The Backbone”** Establish a network of high quality geodetic benchmarks through ten coastal National Parks in the northeast, providing comprehensive coverage at 5 km spacing so future projects can include high res elevation for all features using GPS.

• **“Sentinel Sites”** Use the Backbone to map an additional 15-20 selected features in each park with nearly as high vertical accuracy to demonstrate the backbone-based mapping process.

• **Hx Sandy Sentinel Site Elevation Data Collection** for marshes, beaches, dunes, archaeological sites, buildings...you name it!

*All the Backbone sites are shared publicly on OPUS, NGS’ centralized repository.*
All the Backbone sites are shared publicly on OPUS, NGS’ centralized repository.
Storm Surge, Sea Level Rise and Web Maps

Academic expertise has a central role in collecting, modeling and analyzing data and information on storm surge and sea level rise in National Parks. Among the current projects:

- Develop an emergency preparedness and response system to guide spatial data acquisition, analysis and archiving before, during and after extreme storm events. University of Rhode Island. [http://www.edc.uri.edu/sandy/home](http://www.edc.uri.edu/sandy/home)

- Evaluate vulnerability of site specific resources and infrastructure to inundation for coastal parks with reference to FEMA Flood Hazard Maps and known exposure.

- Quantify the dimensions of geomorphological change caused by the storm, including analysis of volumetric and 3D change. Rutgers University.
The Long View

Coastal zone threats are heightened in the mid-Atlantic U.S., where unique geology and a combination of climatic forces have accelerated the rate of sea level rise. Dubbed the Atlantic “hot spot,” the stretch of coastline from Cape Hatteras, NC to Boston, MA, saw rates of sea level rise increase three to four times faster than the global average between 1980 and 2009, according to a U.S. Geological Survey report.