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High-Resolution Storm Surge Alerting and Forecasting System

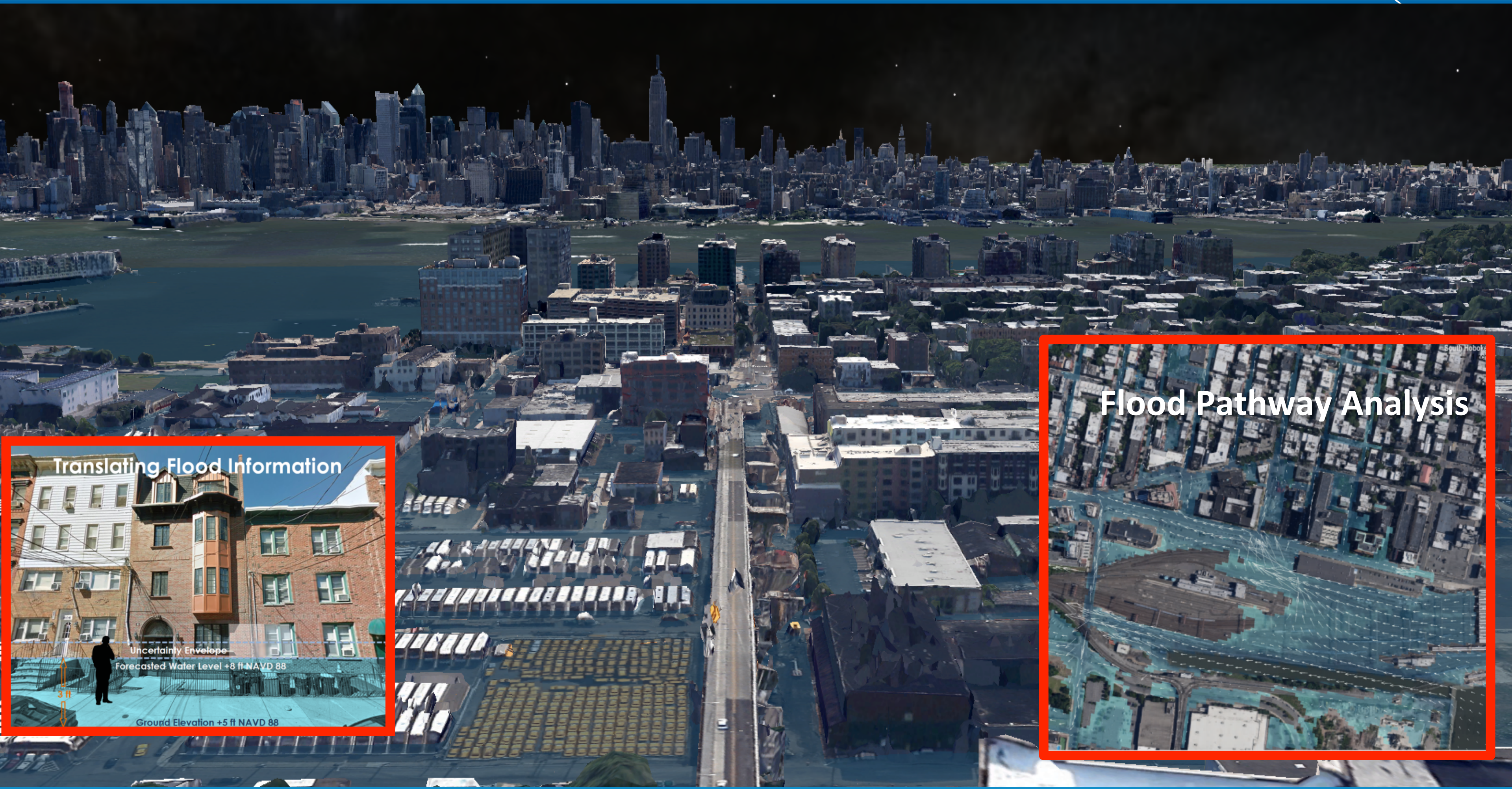
Thomas Herrington, Alan Blumberg & Nickitas Georgas
Davidson Laboratory, Stevens Institute of Technology

Integrating Coastal Flood Research, Modeling and Monitoring to Improve Coastal Resiliency in the Mid-Atlantic Workshop, September 16, 2015

Science Drivers

- Where will the water be?
  - when will it come? What streets? What depth?
- How will the urban infrastructure react?
  - transportation, power grid, food, water, healthcare, etc?
- How best to communicate risk and uncertainty?
  - visuals?
- What will be people's perceptions, expectations, and intentions?
  - government? industry? the public?

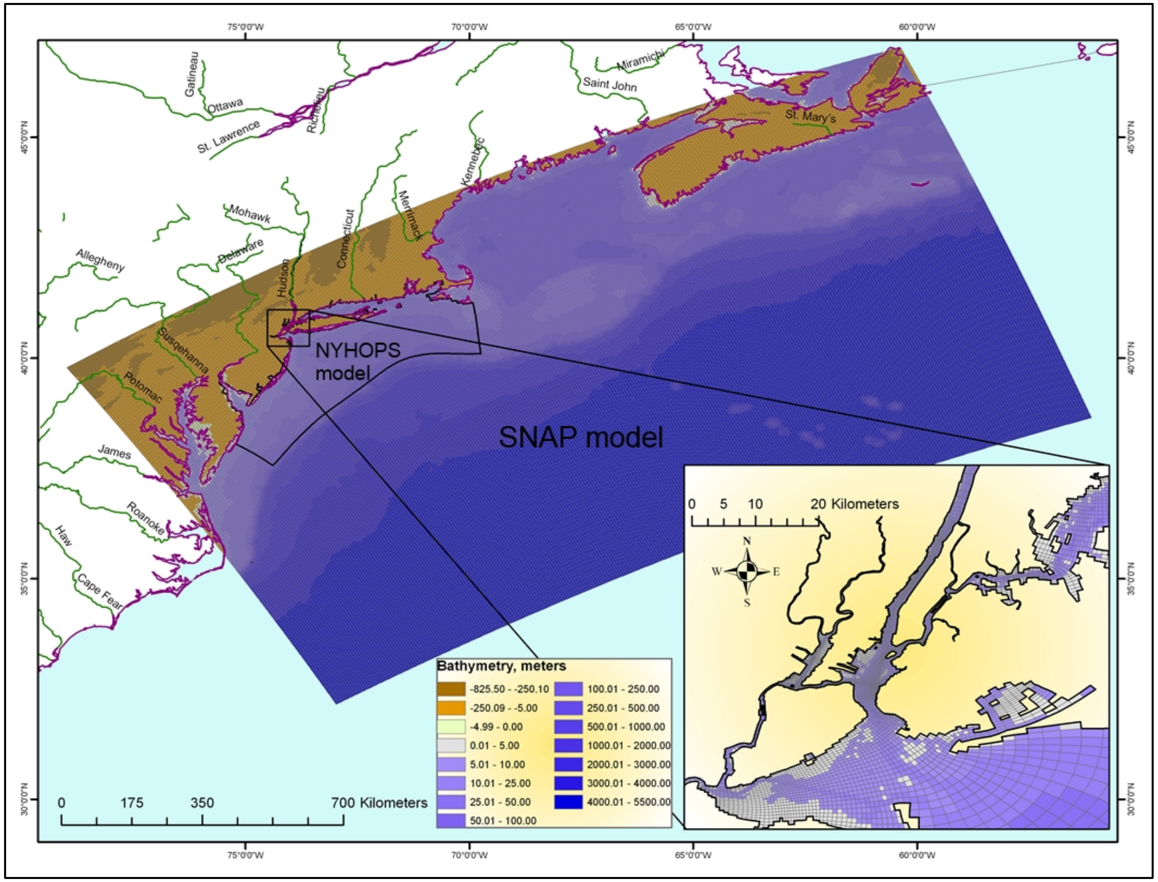
Flood Forecasting on the Human Scale



Move from the static, area-wide flood elevation forecasts and point forecasts to dynamic flood simulations for event preparation/response and long-term flood mitigation.

Development of a Dynamic Overland Inundation Modeling System for Preparation, Response and Coastal Resiliency Planning

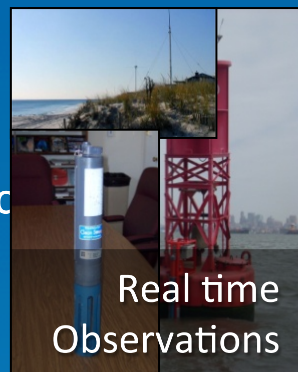
- Based on verified, operational ocean circulation model, NYHOPS (NY Harbor Observation and Prediction System)
- Derivative of the Princeton Ocean Model (POM)
- Verified Operational NOAA IOOS Forecast Model



Operational NYHOPS Forecast model
3D General Circulation and Surface Wind-Wave Model

Input forcing:

- ✓ Tides
- ✓ Offshore Surge and Steric
- ✓ Offshore Waves
- ✓ Surface Winds/Pressure
- ✓ Heating and Cooling
- ✓ 239 Rivers and Streams
- ✓ 280 Major Dischargers
- ✓ River Ice



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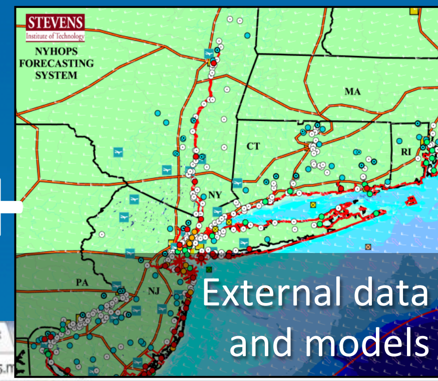

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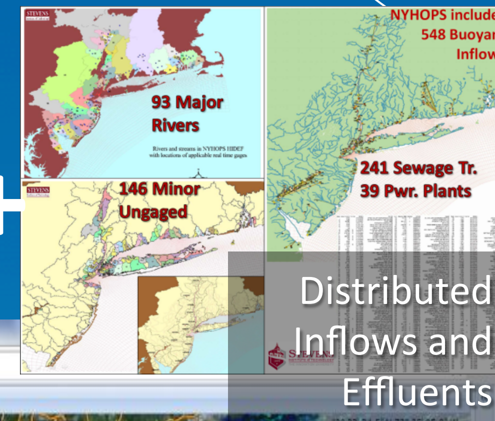
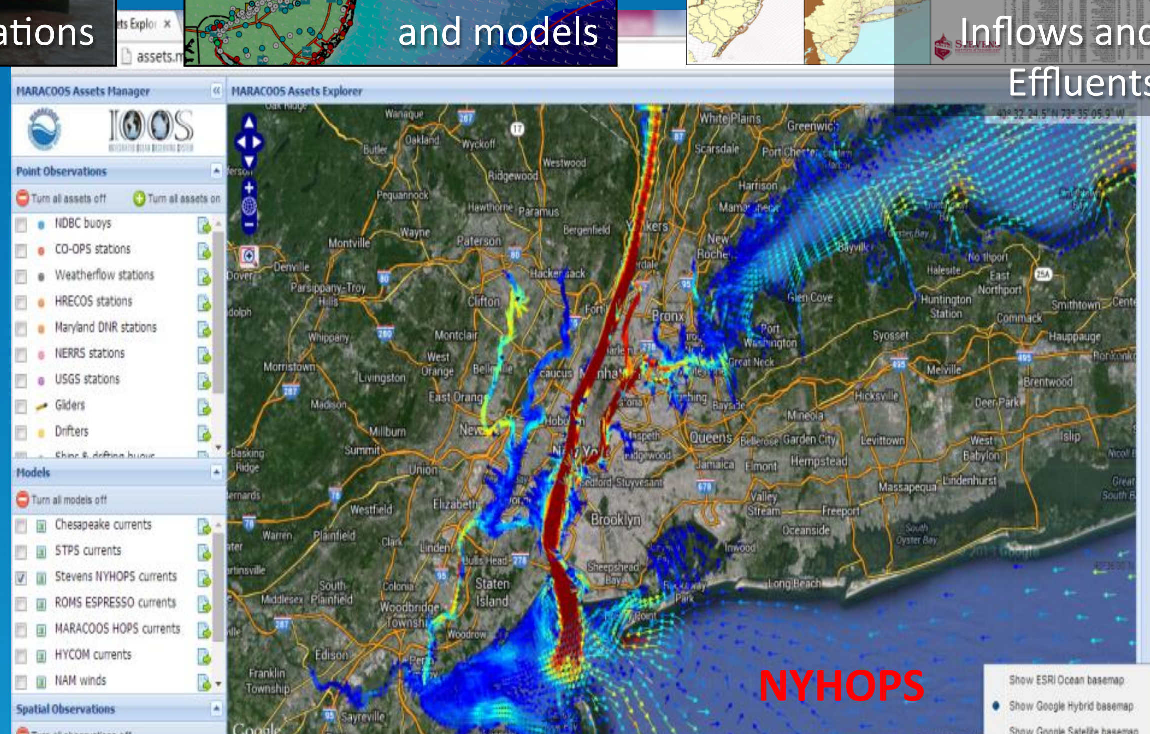


Output:

hindcasts+72-hr forecasts 4x/day

Results every 10min, since 2006.

- ➢Total water level.
- ➢3D Currents, Salinity, Temperature.
- ➢Significant wave height and wave period.



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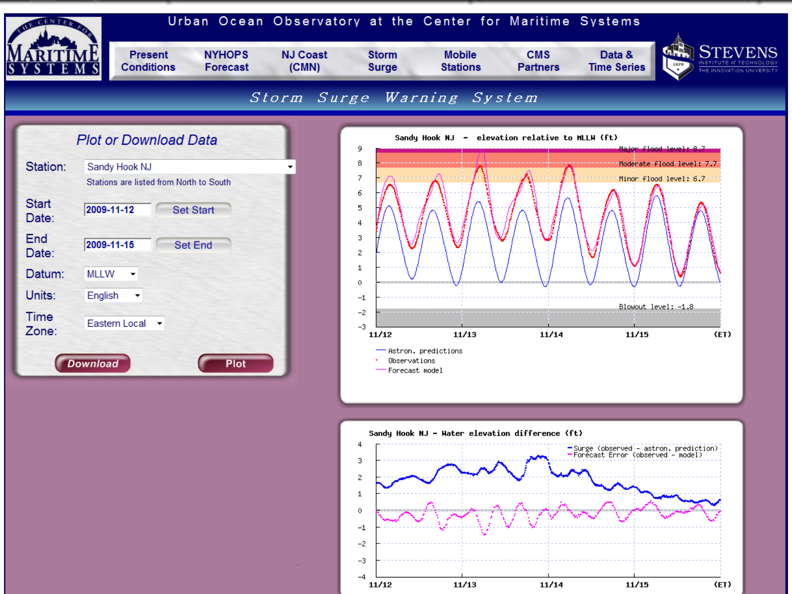
IOOS INTEGRATED OCEAN OBSERVING SYSTEM

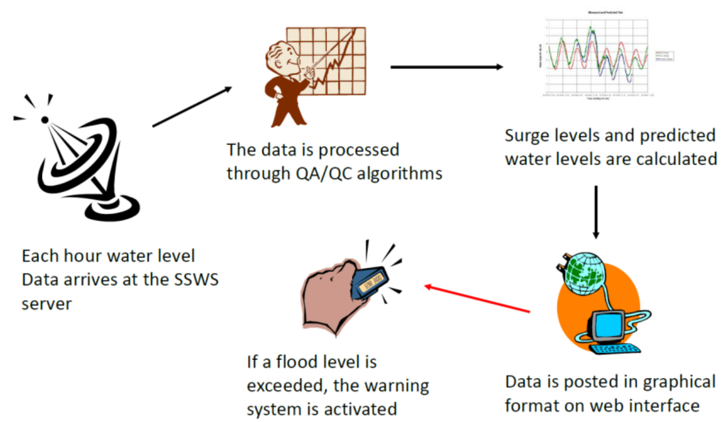
Existing Focused Products Supported by NYHOPS

MARACOOS
Ocean Information for a Changing World

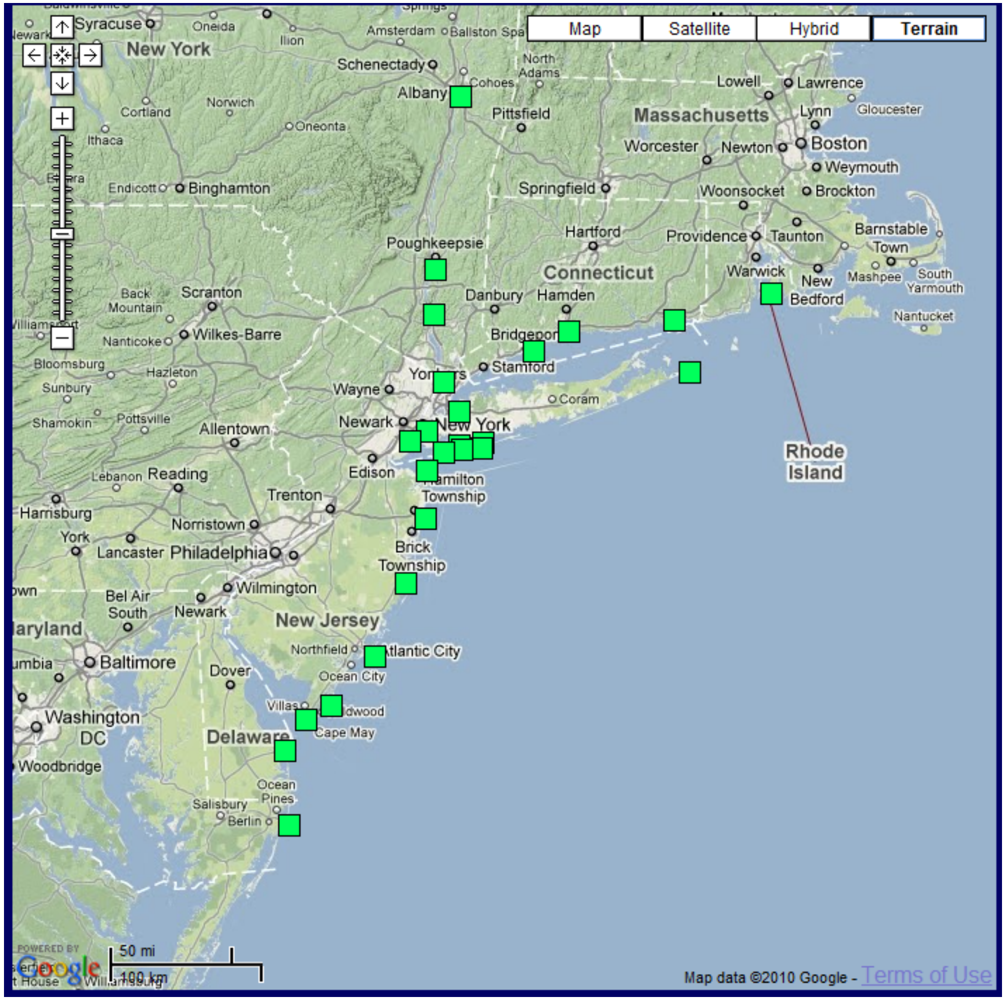
MACOORA Themes	MARCOOS Capabilities					
	Weather Mesonet	HF Radar Network	Statistical STPS Forecast	Satellite Imagery	Glider Surveys	Dynamical Ocean Forecasts
1. Maritime Safety	Operational input to USCG SAROPS	Operational input to USCG SAROPS	Operational input to USCG SAROPS			
2. Ecological Decision Support		Circulation and divergence maps for habitat		SST & Color for habitat	Subsurface T & S for habitat	3-D Fields of T, S, circulation for habitat
3. Water Quality	Winds for transport, river plumes, & upwelling	Surface currents for floatables, bacteria, spill response	Surface currents for floatables, bacteria, spill response	Ocean color for river plumes	Nearshore dissolved oxygen surveys	Surface currents for floatables, bacteria, spill response
4. Coastal Inundation	Weather forecast ensemble validation	Current forecast model validation				Nested forecast ensembles
5. Offshore Energy	Historical analysis & wind model validation	Historical current analysis & wind model validation		Historical analysis surface fronts & plumes for siting	Historical analysis subsurface fronts & plumes	Coupled ocean-atmosphere models for resource estimates



Storm Surge Warning System (SSWS) Architecture



Existing MARCOOS Storm Surge Products



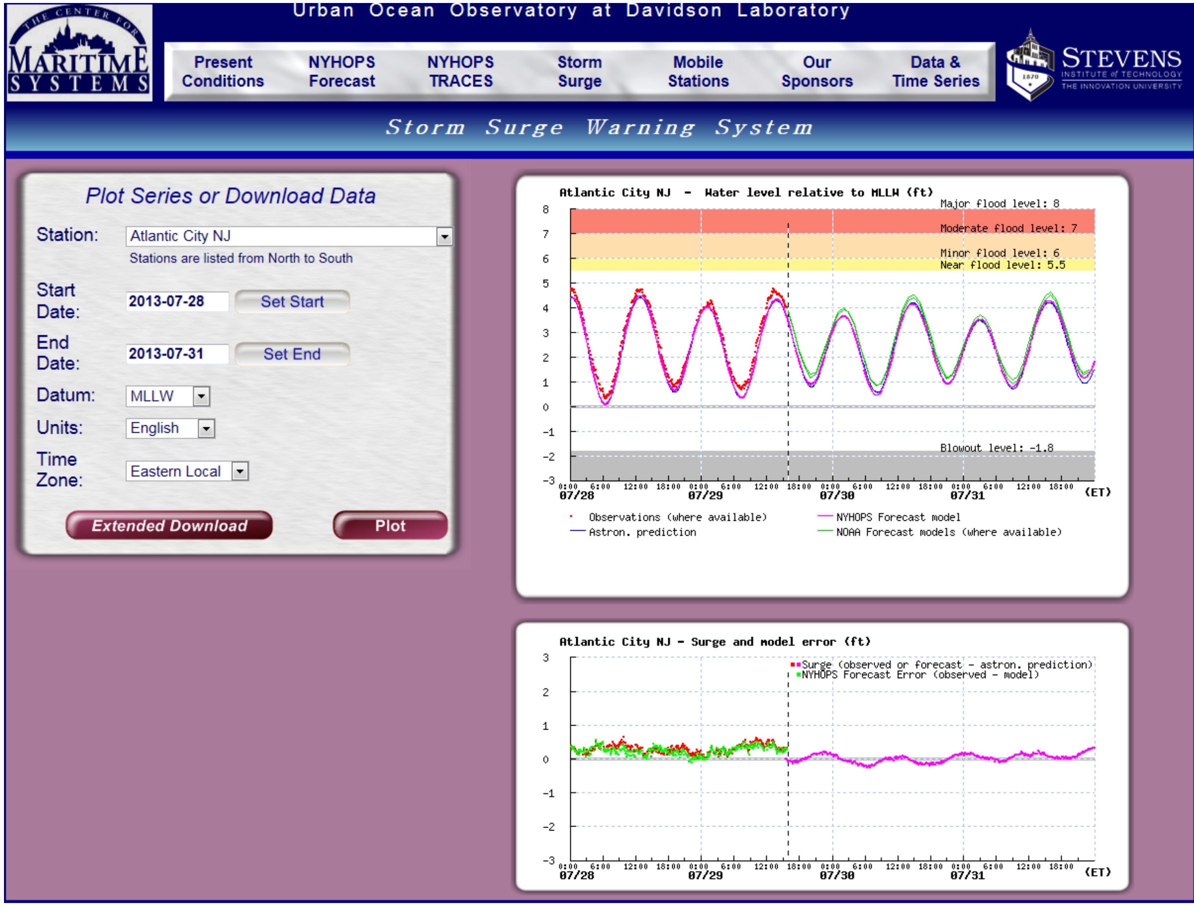
STORM SURGE WARNING SYSTEM

40 Existing Water Level Gauges in NYHOPS Domain

NOAA NOS
USGS
Stevens

Storm Surge Warning System

- SSWS constantly ingests and compares observed and NYHOPS forecasted water elevations
- If water elevation is predicted to exceed a set threshold over 72 hr forecast period, web-based and text alerts are automatically triggered



Surge Impact Table

- ***OCEAN COUNTY, New Jersey***

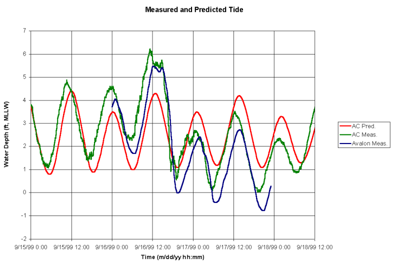
- *ALL HEIGHTS ARE IN MEAN LOWER LOW WATER (MLLW).*

9.3	*FT —*	*December 11, 1992.*
9.2	*FT —*	*September 14, 1944 (Hurricane).*
8.9	*FT —*	*September 27, 1985 (Hurricane Gloria).*
8.8	*FT —*	*March 6, 1962; August 9, 1976 (Hurricane Belle) and October 31,*
8.7	*FT —*	*SEVERE TIDAL FLOODING BEGINS.*
8.4	*FT —*	*March 29, 1984.*
8.2	*FT —*	*October 25, 1980.*
8.1	*FT —*	*January 4, 1992.*
7.9	*FT —*	*March 19, 1996.*
7.8	*FT —*	*March 2, 1994.*
7.7	*FT —*	*MODERATE TIDAL FLOODING BEGINS.*
7.6	*FT —*	*Bay View Avenue in Seaside Park begins to flood.**

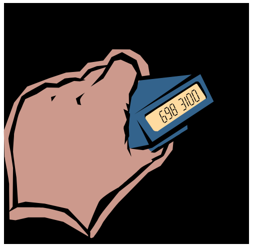
*Local roads in Ocean Gate (including Bay View Avenue) begin to flood.**

Historic water level observations and impacts tabulated by local NWS Forecast Office for each coastal county. Allows for the delineation of minor, moderate and sever flood levels relative to MLLW.

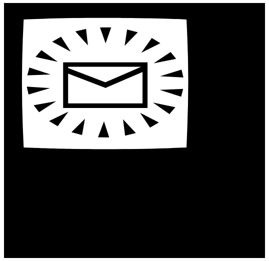
Storm Surge Warning Mode



YY	MM	DD	hh	WD	WSP	D GST	WVHT	DPD	APD	MWD	BAR	ATMP	WTMP
91	4	29	21	79	5.6	6.9	1.1	6.7	4.9	999	1022.6	8.9	8.6
91	4	29	22	90	3.5	4.3	1.2	5.9	5	999	1022.8	8.7	8.6
91	4	29	23	79	3.6	4.3	1.2	6.7	5.2	999	1022.1	8.7	8.6
91	4	30	0	75	3.4	4	1.1	6.7	5.2	999	1021.9	8.7	8.6
91	4	30	1	71	4.5	5.6	1	7.1	5.1	999	1022	8.9	8.6
91	4	30	2	76	4	4.6	1	7.1	5.1	999	1022.5	9	8.6
91	4	30	3	82	4	4.6	0.9	7.1	5.2	999	1021.9	8.9	8.6
91	4	30	4	82	4.8	5.5	0.8	6.7	5	999	1021.2	8.9	8.6
91	4	30	5	112	4.1	4.9	0.8	6.7	5.1	999	1020.4	9	8.6
91	4	30	6	111	2.6	3	0.8	6.2	5.1	999	1019.9	9	8.6
91	4	30	7	82	1.5	2	0.8	6.7	5.2	999	1019.6	9	8.6
91	4	30	8	48	2.8	3.3	0.9	7.1	5.3	999	1019.8	9	8.6
91	4	30	9	73	5.3	6.2	0.8	5.9	5.3	999	1019.1	8.7	8.6
91	4	30	10	93	3.4	4.1	0.8	7.1	5.3	999	1019.1	8.9	8.6
91	4	30	12	111	6.3	7	0.8	7.7	5.3	999	1017.3	9	8.6
91	4	30	13	113	5.7	6.7	0.8	6.7	5.1	999	1016.5	9.7	8.6
91	4	30	14	131	4.1	4.8	0.8	5.9	4.9	999	1015.9	9.7	8.6
91	4	30	15	123	1.6	1.9	0.8	6.2	5	999	1016.4	9.8	8.7
91	4	30	16	131	4.1	4.6	0.8	5.9	5.2	999	1015	10.3	8.7
91	4	30	17	132	4.9	5.5	0.8	7.7	5.3	999	1014.4	10.9	8.7
91	4	30	18	170	3.9	4.4	0.8	8.3	5.3	999	1013.9	10.8	8.7
91	4	30	19	169	3.1	3.5	99	99	99	999	1013.3	10.3	8.7
91	4	30	20	222	3.6	4.3	0.9	6.2	5.5	999	1012.7	10.5	8.9
91	4	30	21	261	2.9	3.5	0.9	6.2	5.6	999	1012.7	10.2	8.9
91	4	30	22	308	3.1	3.8	0.8	7.7	5.4	999	1012.6	11.2	8.9
91	4	30	23	349	2.5	2.8	0.8	6.7	5.6	999	1011.8	11.3	8.9
91	5	1	0	210	2.1	2.6	0.8	6.7	5.5	999	1012.5	10.3	8.9
91	5	1	1	200	1.5	1.9	0.8	6.2	5.4	999	1012.6	9.8	8.9
91	5	1	2	218	1	1.5	0.8	7.7	5.4	999	1012.9	9.9	8.9
91	5	1	3	28	1	1.6	0.8	8.3	5.3	999	1012.6	10.3	8.8
91	5	1	4	308	1	1.3	0.7	7.1	5.2	999	1012.7	9.5	8.7
91	5	1	5	28	3.1	3.4	0.7	5.9	5.2	999	1013.3	10.2	8.7
91	5	1	6	75	2.1	2.4	0.7	6.7	5.3	999	1013.5	10.3	8.7
91	5	1	7	114	0.9	1.7	0.7	6.7	5.4	999	1013.7	10.2	8.7



Pager

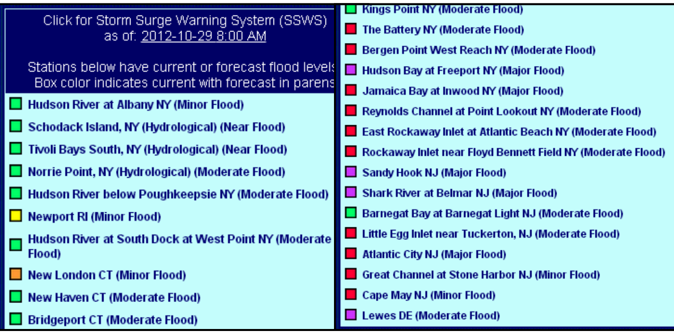


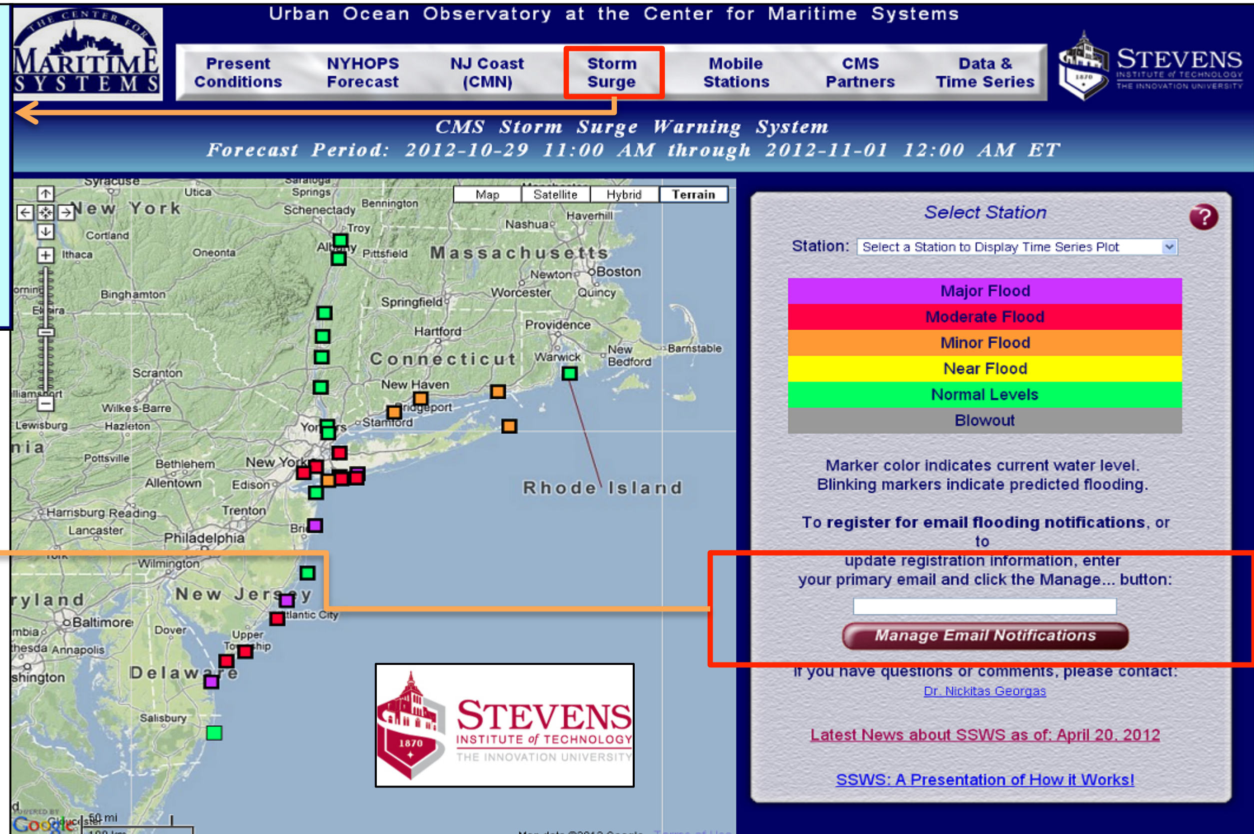
If surge levels are predicted
To exceed minor, moderate,
or severe flood level…

.. a subscriber database of contact
information is accessed and …

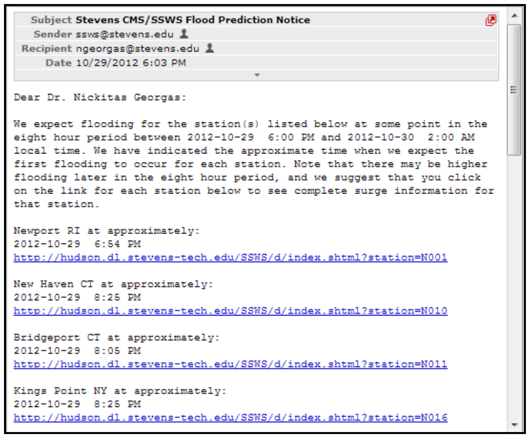
.. a tailored text message
is transmitted via email

Storm Surge Warning System





www.stevens.edu/SSWS



Subject Stevens CMS/SSWS Flood Prediction Notice
Sender ssws@stevens.edu
Recipient ngeorgas@stevens.edu
Date 10/29/2012 6:03 PM

Dear Dr. Nickitas Georgas:

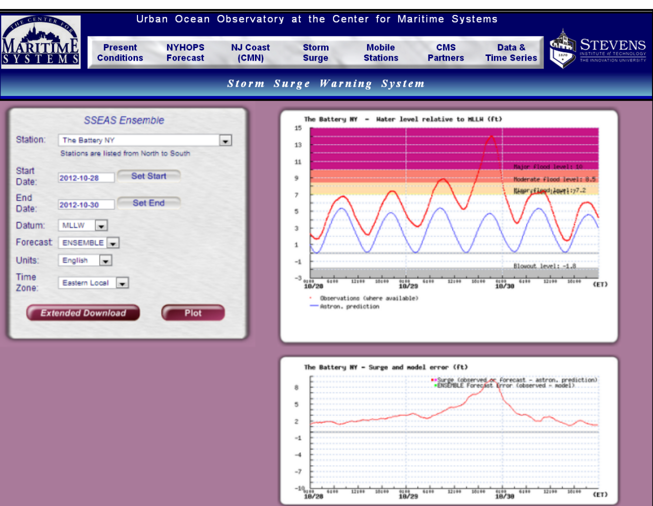
We expect flooding for the station(s) listed below at some point in the eight hour period between 2012-10-29 6:00 PM and 2012-10-30 2:00 AM local time. We have indicated the approximate time when we expect the first flooding to occur for each station. Note that there may be higher flooding later in the eight hour period, and we suggest that you click on the link for each station below to see complete surge information for that station.

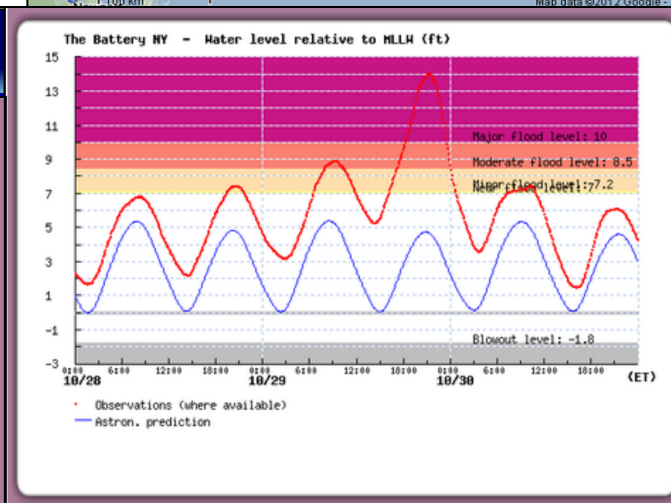
Newport RI at approximately:
2012-10-29 6:54 PM
http://hudson.dl.stevens-tech.edu/SSWS/d/index.shtml?station=N001

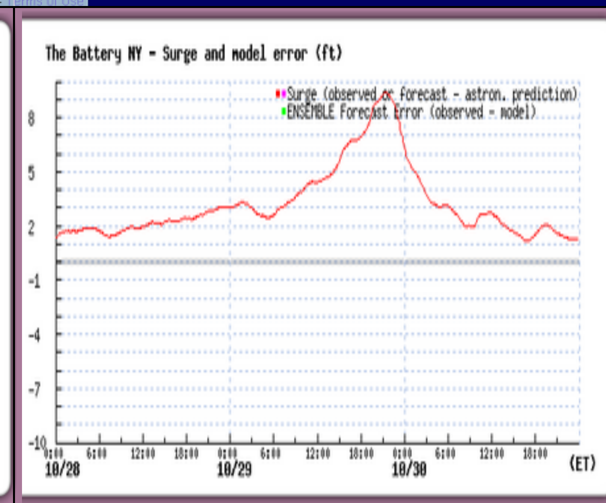
New Haven CT at approximately:
2012-10-29 8:25 PM
http://hudson.dl.stevens-tech.edu/SSWS/d/index.shtml?station=N010

Bridgeport CT at approximately:
2012-10-29 8:05 PM
http://hudson.dl.stevens-tech.edu/SSWS/d/index.shtml?station=N011

Kings Point NY at approximately:
2012-10-29 8:25 PM
http://hudson.dl.stevens-tech.edu/SSWS/d/index.shtml?station=N016







Overland Inundation Forecasting

- Model grid was expanded to include overland areas along NY Harbor urban coast.
- High-resolution LiDAR derived DEMs used define topography.
- Inundated model cells employ depth averaged flow equations to predict water levels and overland currents

Depth Integrated Equations of Motion

$$\bar{u} = \frac{1}{D}\int_{-h}^{\eta} u\,dz; \quad \bar{v} = \frac{1}{D}\int_{-h}^{\eta} v\,dz; \quad D = h+\eta$$

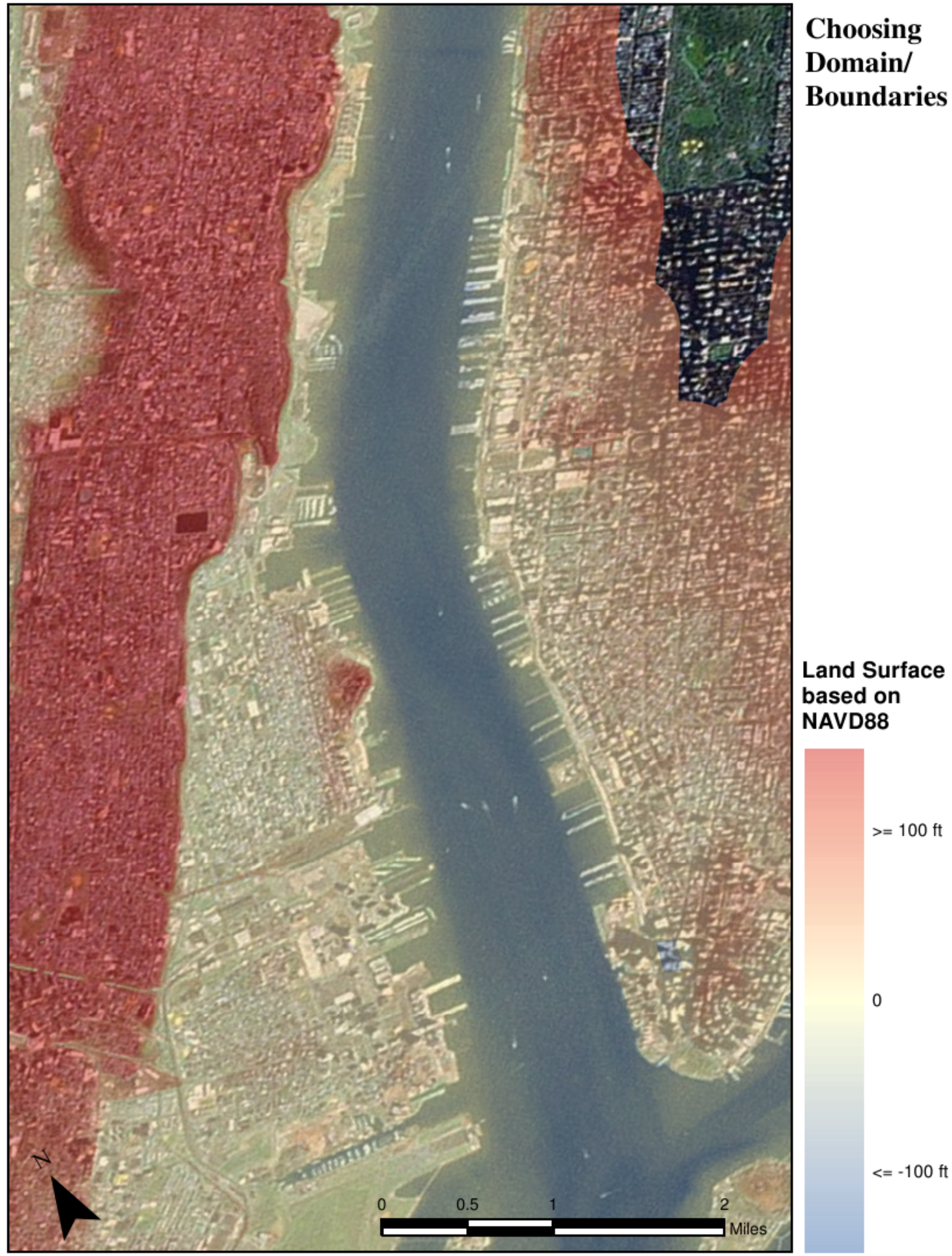
$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}(\bar{u}D) + \frac{\partial}{\partial y}(\bar{v}D) = 0$$

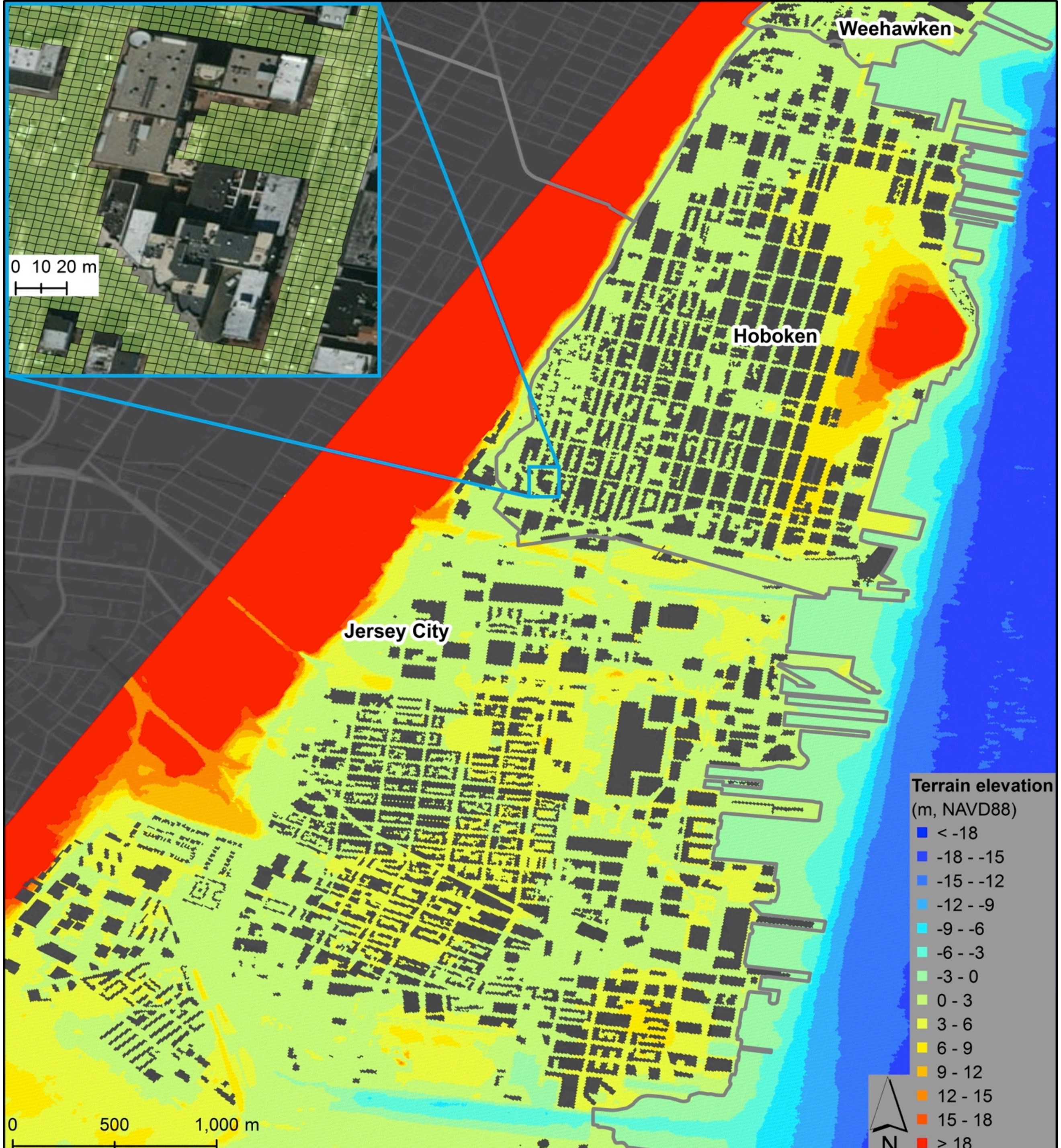
$$\frac{\partial \bar{u}}{\partial t} + \bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y} - f\,\bar{v} = -g\frac{\partial \eta}{\partial x} + \frac{\tau_{sx} - \tau_{bx}}{\rho_o D}$$

$$\frac{\partial \bar{v}}{\partial t} + \bar{u}\frac{\partial \bar{v}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial y} + f\,\bar{u} = -g\frac{\partial \eta}{\partial y} + \frac{\tau_{sy} - \tau_{by}}{\rho_o D}$$

The NJ Hudson River Waterfront Model Domain

3m horizontal resolution Digital Elevation Model

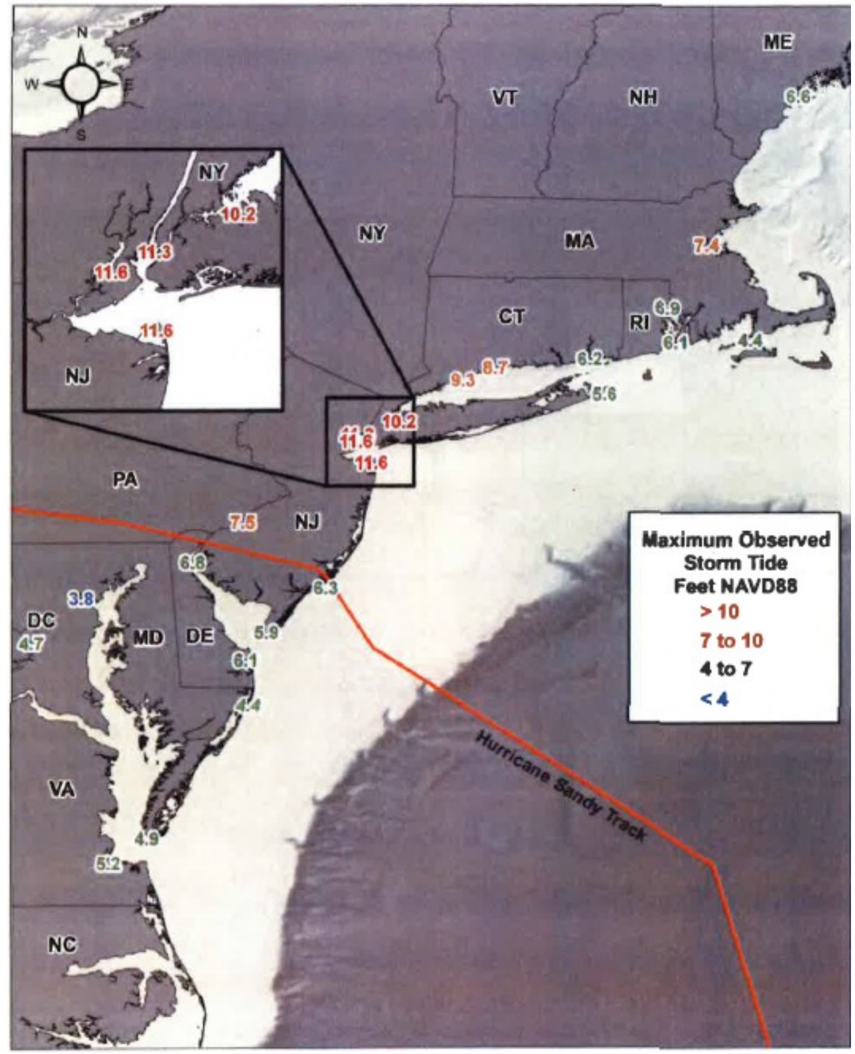




Weehawken
Hoboken
Jersey City
0 10 20 m
0 500 1,000 m
Terrain elevation
(m, NAVD88)
< -18
-18 - -15
-15 - -12
-12 - -9
-9 - -6
-6 - -3
-3 - 0
0 - 3
3 - 6
6 - 9
9 - 12
12 - 15
15 - 18
> 18
N

Model Calibration

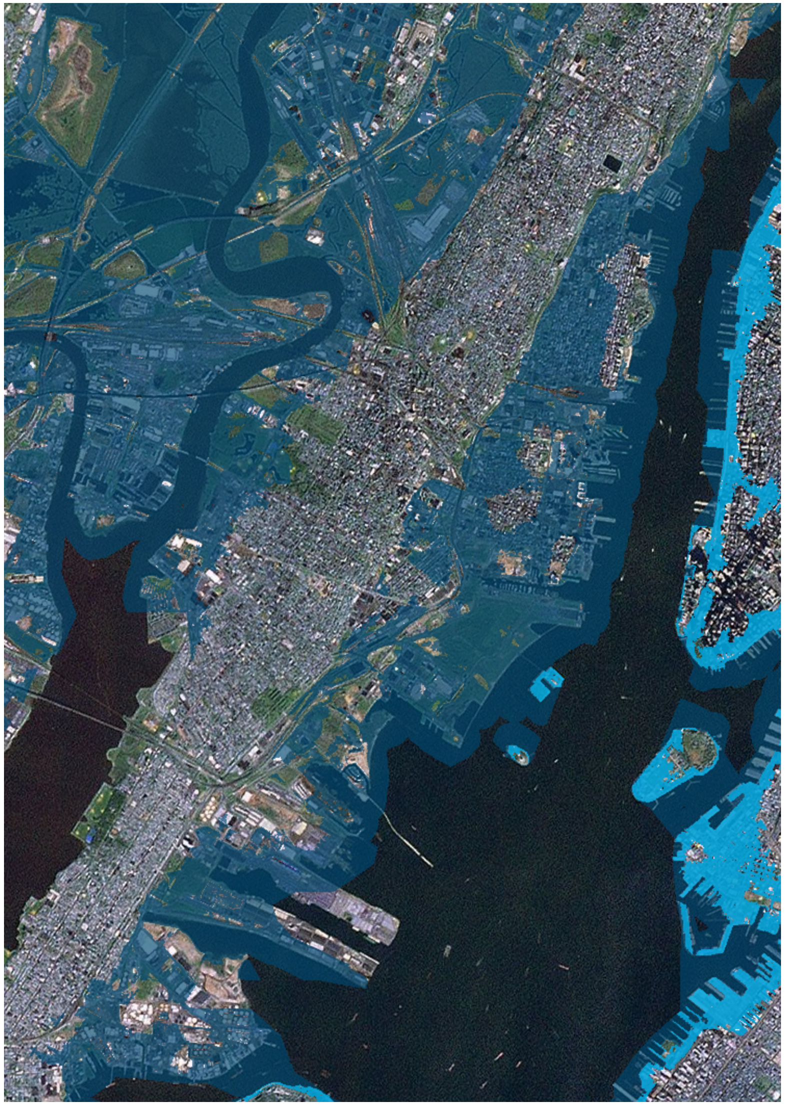
- Model calibrated with Sandy hindcast wind and pressure fields.
- Battery tide gauge used as calibration point in Upper Harbor.
- Available NOAA and USGS regional water level data used for NY Bight



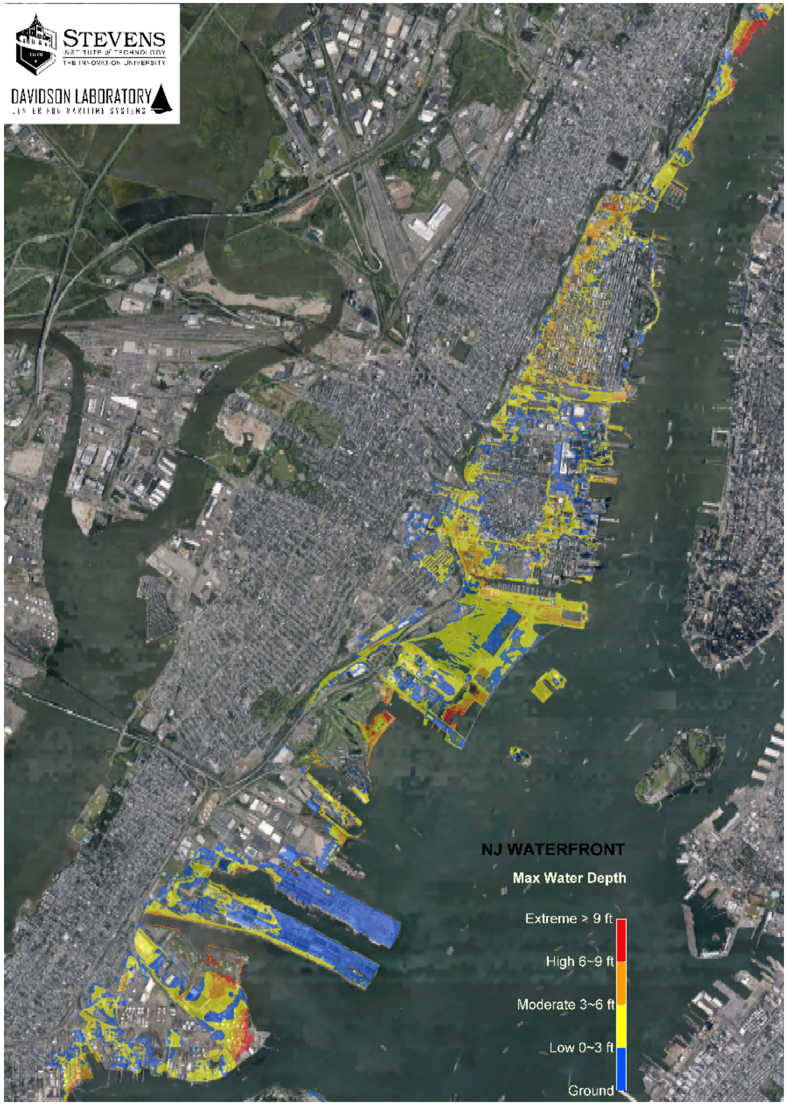
Model Validation

- Peak over ground water levels predicted by the model were compared to maximum storm surge extents published by USGS.
- Local water level data recorded by USGS water level sensors used for point verification
- Crowed sourcing used to estimate peak water levels.

Model Validation



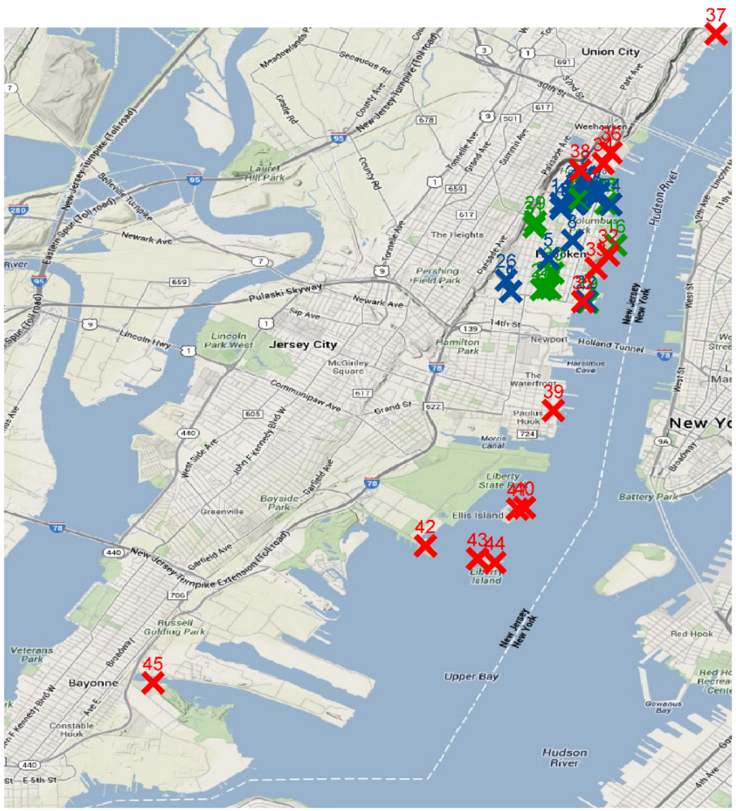
USGS Peak Surge Extent

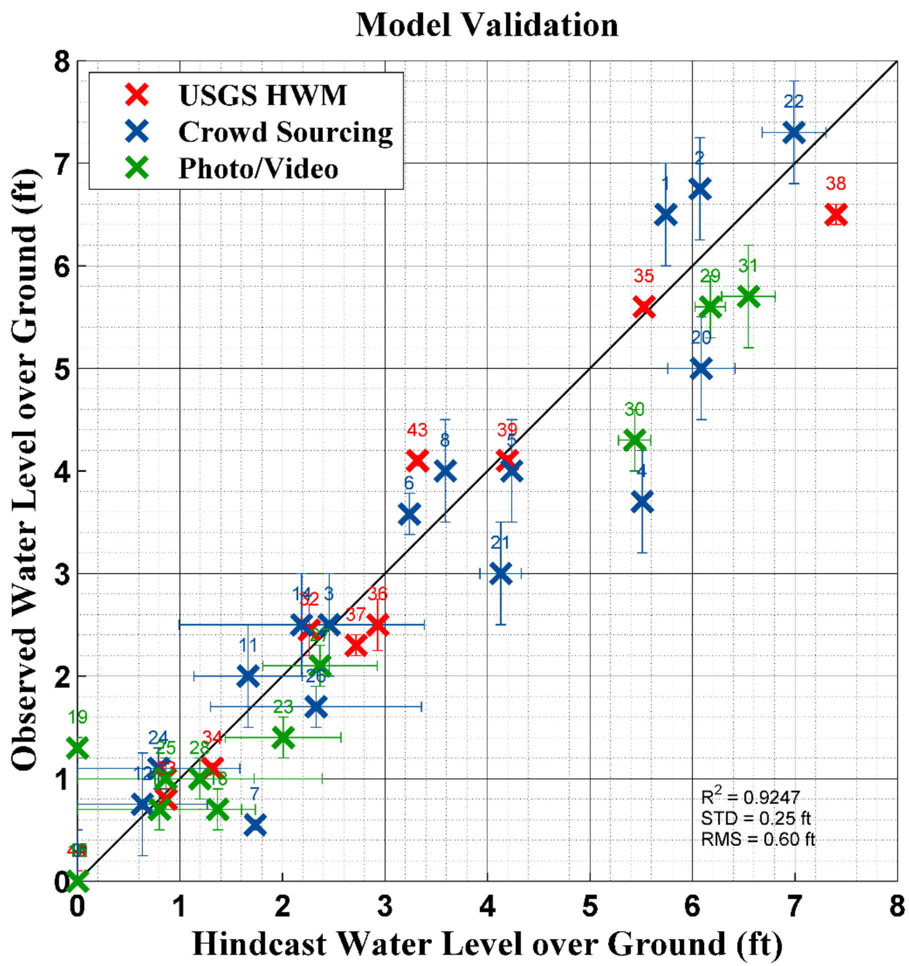


Predicted overland surge depth


STOP

Model Validation Points





The correlation coefficient (R^2) between the water mark observations and the model is 0.93.

The standard deviation of the residual error is 0.07 m.

The simulated inundation levels at 78% of the data measurement locations have <20% error.

Model Application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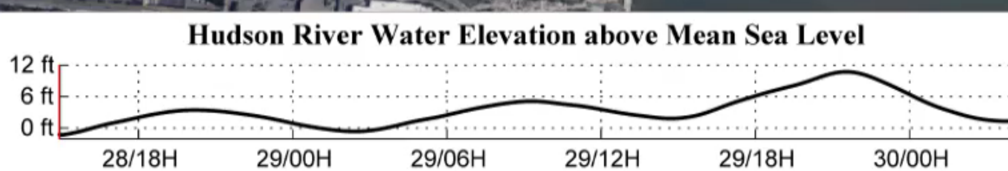
2012-10-28 14:55 EDT
N
HOBOKEN, NJ
Water Depth
Extreme > 9 ft
High 6~9 ft
Moderate 3~6 ft
Low 0~3 ft
Ground


Hudson River Water Elevation above Mean Sea Level
12 ft
6 ft
0 ft
28/18H
29/00H
29/06H
29/12H
29/18H
30/00H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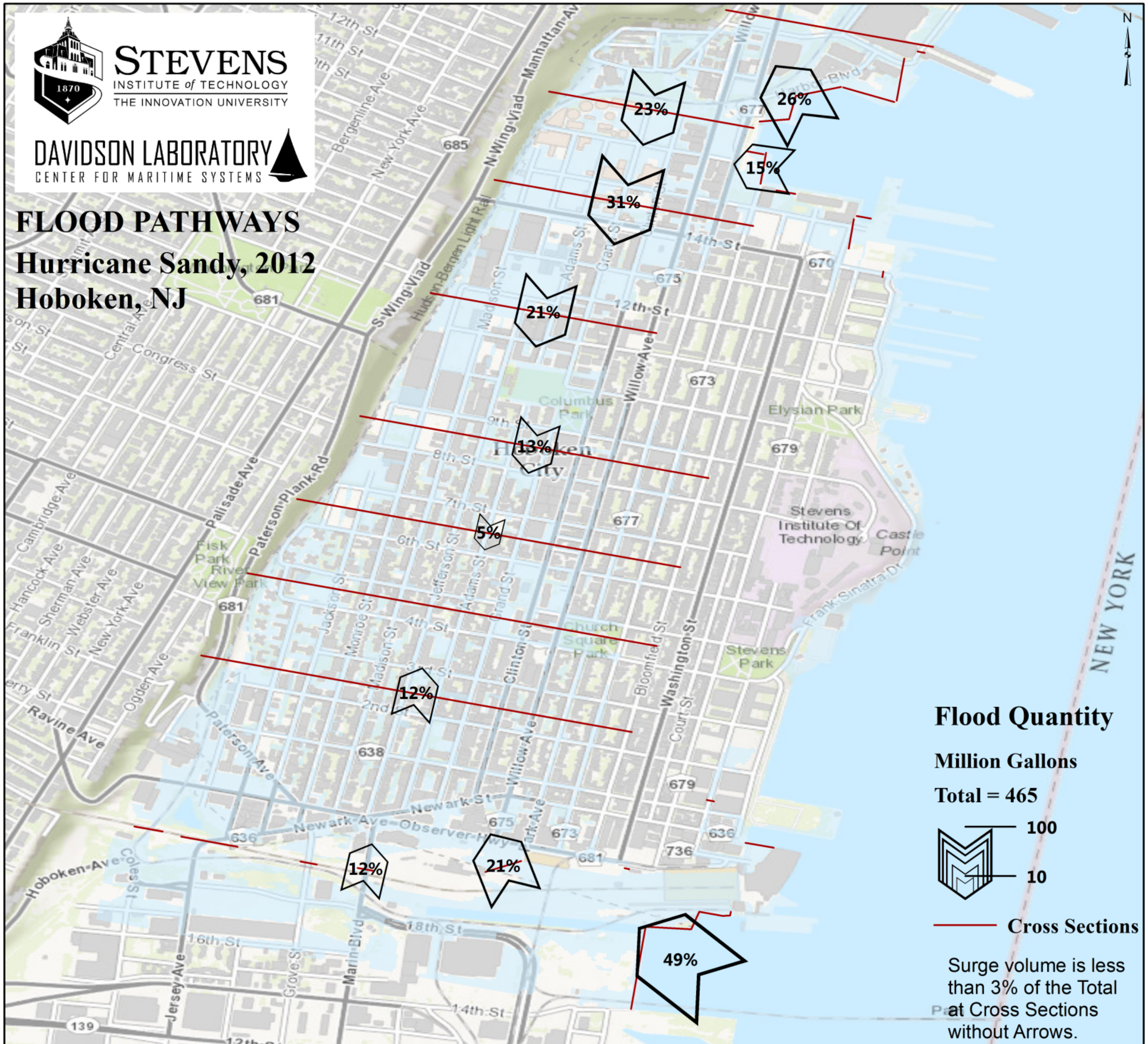
DAVIDSON LABORATORY
CENTER FOR MARITIME SYSTEMS
2012-10-29 21:30 EDT
N
HOBOKEN, NJ
Water Depth
Extreme > 9 ft
High 6~9 ft
Moderate 3~6 ft
Low 0~3 ft
Ground
Hudson River Water Elevation above Mean Sea Level
12 ft
6 ft
0 ft
28/00H
28/12H
29/00H
29/12H
30/00H
30/12H



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1870
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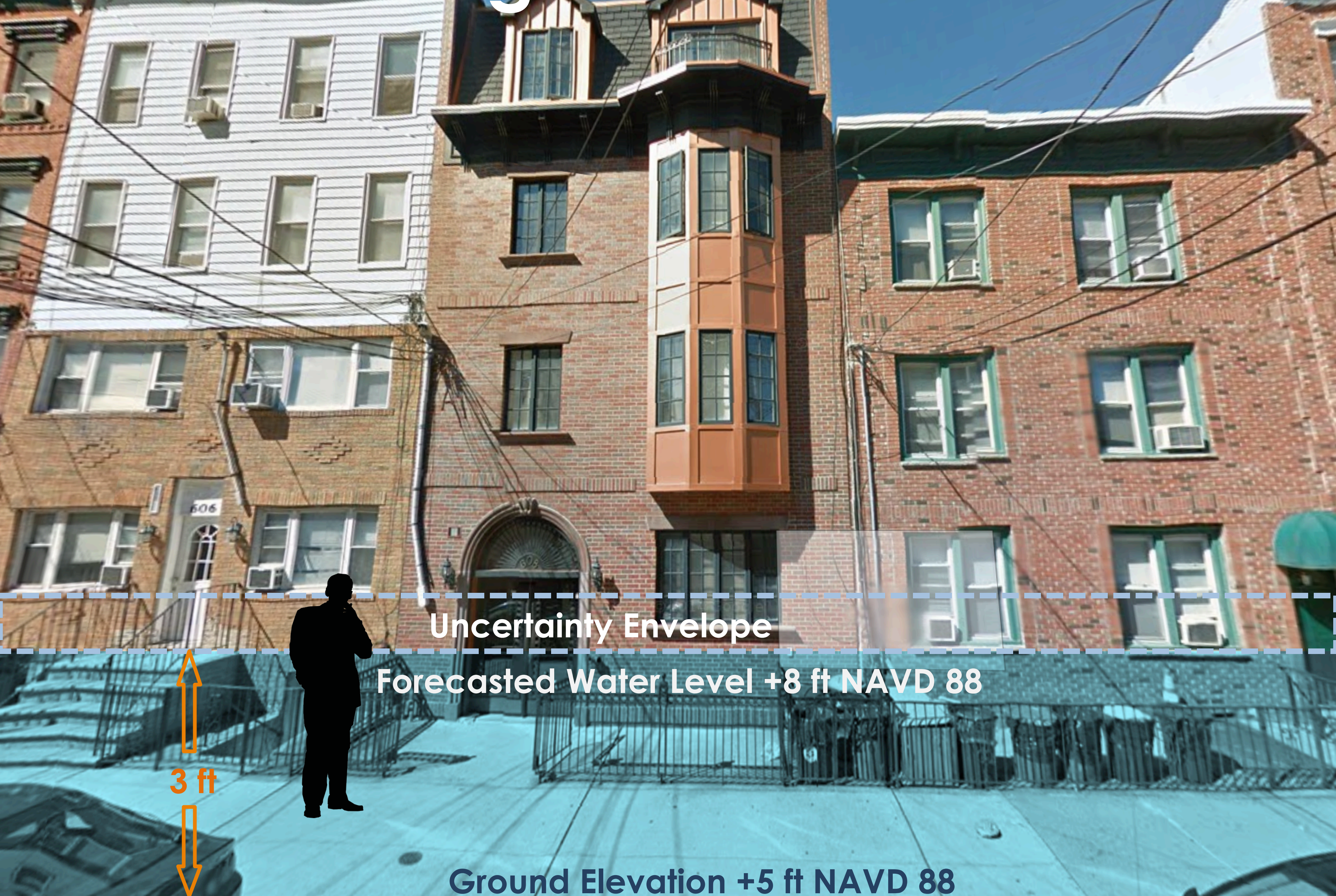
CENTER FOR MARITIME SYSTEMS
FLOOD PATHWAYS
Hurricane Sandy, 2012
Hoboken, NJ
N
23%
26%
15%
31%
21%
13%
5%
12%
12%
21%
49%
Flood Quantity
Million Gallons
Total = 465
100
10
Cross Sections
Surge volume is less than 3% of the Total at Cross Sections without Arrows.
Columbus Park
Elysian Park
Stevens Institute Of Technology
Castle Point
Church Square Park
Stevens Park
Fisk Park
River View Park
Washington St
Willow Ave
Clinton St
Bloomfield St
Court St
Grand St
Adams St
Jefferson St
Madison St
Monroe St
Jackson St
Paterson Plank Rd
Palisade Ave
Newark Ave
Observer Hwy
Hoboken Ave
Marin Blvd
Jersey Ave
Frank Sinatra Dr
14th St
12th St
8th St
7th St
6th St
4th St
2nd St
18th St
16th St
Ravine Ave
Ogden Ave
Congress St
Franklin St
New York Ave
Webster Ave
Sherman Ave
Hancock Ave
Cambridge Ave
Bergenline Ave
N Wing Viad
S Wing Viad
Hudson-Bergen Light Rail
Manhattan Ave
NEW YORK


THIN DAM
N
W
E
S
0
250
500
1,000 Yards

Where are we Headed?

Translating Flood Information



Acknowledgements

This research was supported by the Governor's Office of Recovery and Rebuilding. Additional support for data collection was provided by the NJDEP Bureau of Coastal Engineering and the National Science Foundation under grant 1318169.

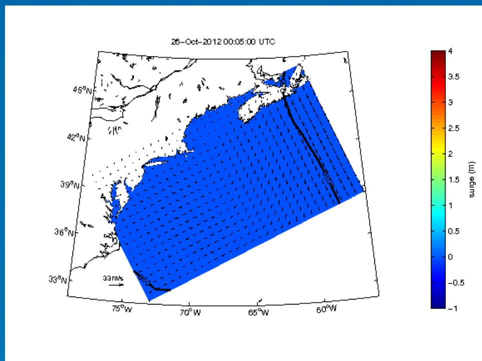
Special thanks to the US Geological Survey for providing verified Sandy storm tide data available for the verification of the model, as well as Mr. John P. Carey who provided much of the crowed source data. The authors gratefully acknowledge their colleagues Dr. Nickitas Georgas and Mr. Larry Yin for their tremendous efforts in making sure the model was running correctly and for working on the validation.

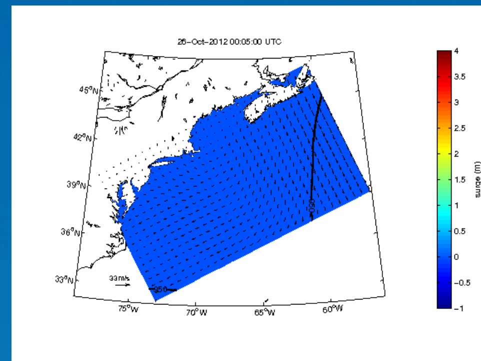
State of New Jersey
Governor's Office of Recovery and Rebuilding

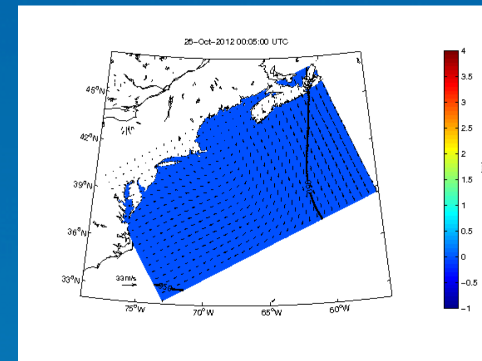
State of New Jersey
Department of Environmental Protection
Coastal Engineering

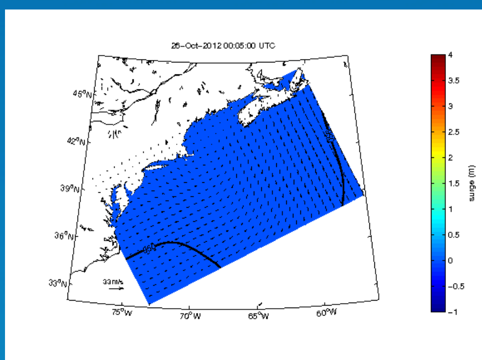
National Science Foundation
WHERE DISCOVERIES BEGIN

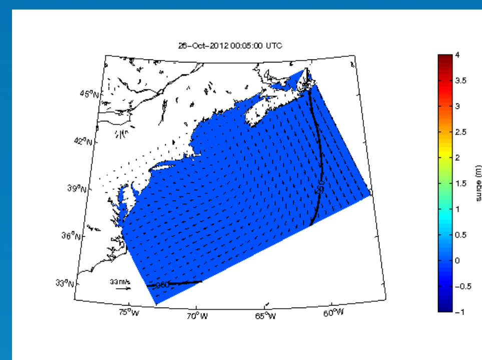
Ensemble Modeling: North Atlantic Forecasts

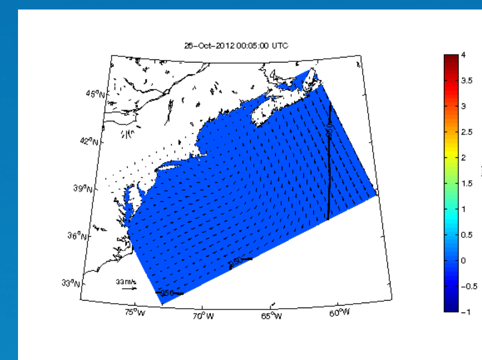


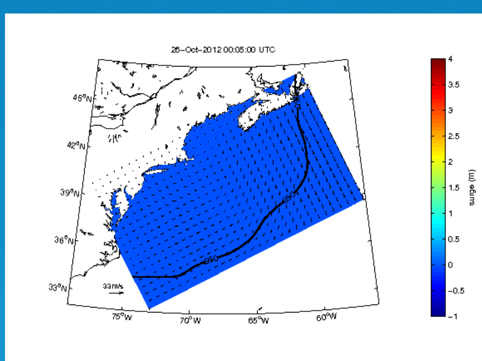


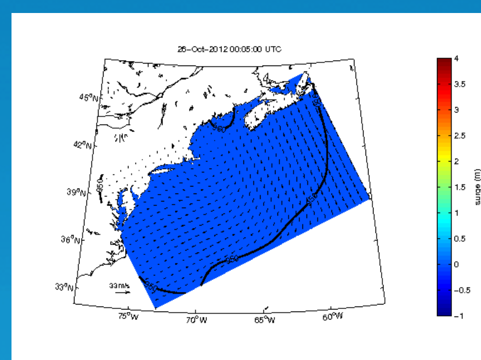


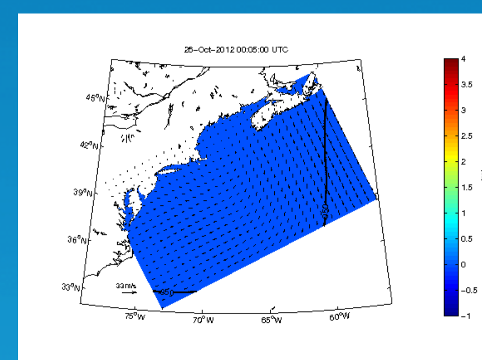




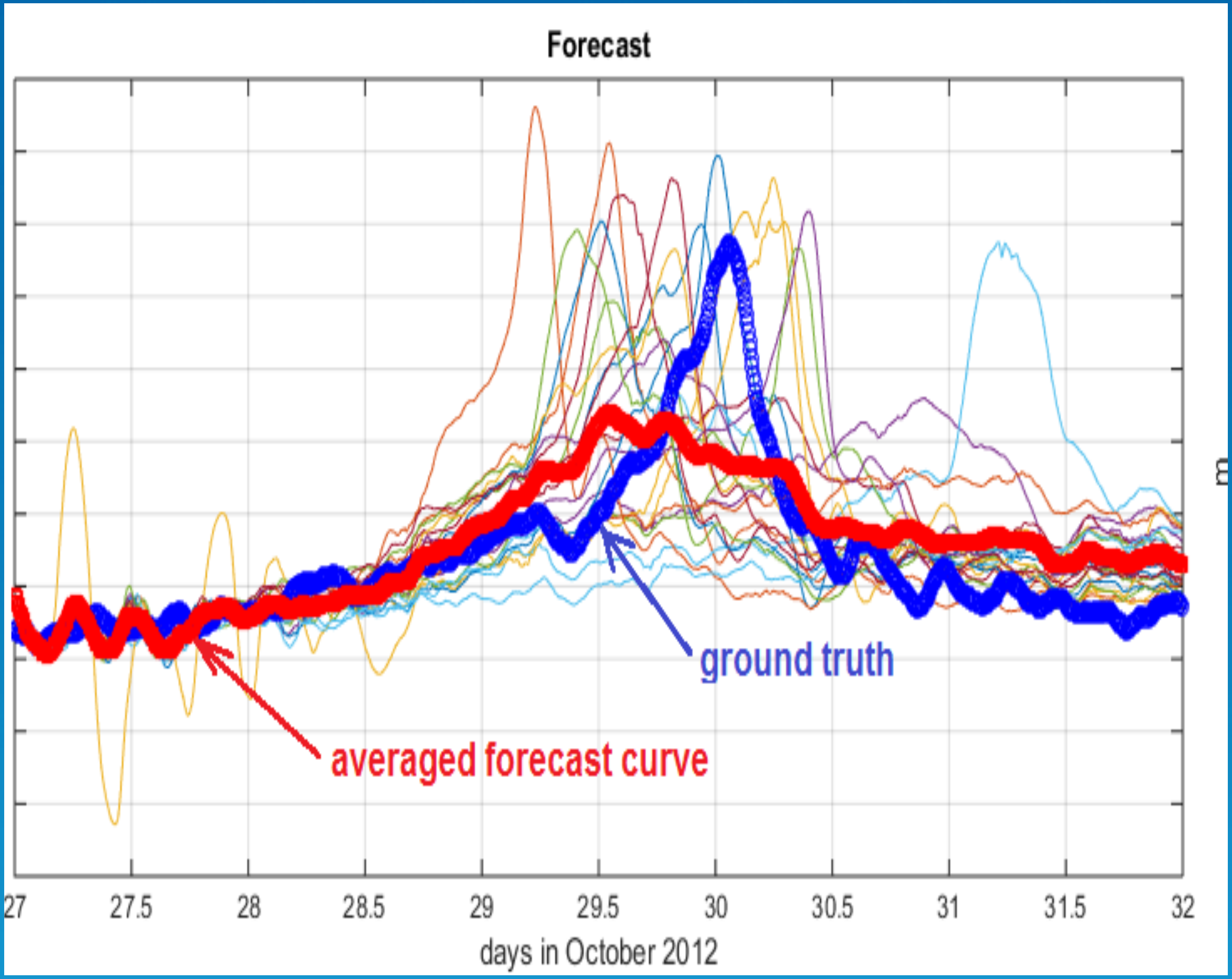








Research on Forecasts and Ensembles



Street-Scale Modeling of Storm Surge Inundation along the New Jersey Hudson River Waterfront

ALAN F. BLUMBERG, NICKITAS GEORGAS, LARRY YIN, THOMAS O. HERRINGTON, AND PHILIP M. ORTON

Stevens Institute of Technology, Hoboken, New Jersey

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ABSTRACT

A new, high-resolution, hydrodynamic model that encompasses the urban coastal waters of New Jersey along the Hudson River Waterfront opposite New York City, New York, has been developed and validated for simulating inundation during Hurricane Sandy. A 3.1-m-resolution square model grid combined with a high-resolution lidar elevation dataset permits a street-by-street focus to inundation modeling. The waterfront inundation model is a triple-nested Stevens Institute Estuarine and Coastal Ocean Hydrodynamic Model (sECOM) application; sECOM is a successor model to the Princeton Ocean Model family of models. Robust flooding and drying of land in the model physics provides for the dynamic prediction of flood elevations and velocities across land features during inundation events. The inundation model was forced by water levels from the extensively validated New York Harbor Observing and Prediction System (NYHOPS) hindcast of that hurricane.

Validation against 56 watermarks and 16 edgemarks provided via the USGS and through an extensive crowdsourcing effort consisting of photographs, videos, and personal stories shows that the model is capable of computing overland water elevations quite accurately throughout the entire surge event. The correlation coefficient (R^2) between the watermark observations and the model results is 0.92. The standard deviation of the residual error is 0.07 m. Comparisons to the 16 flood edgemarks suggest that the model was able to reproduce flood extent to within 20 m. Because the model was able to capture the spatial and temporal variation of water levels in the region observed during Hurricane Sandy, it was used to identify the flood pathways and suggest where flood-preventing interventions could be built.

1. Introduction

Storm surges are among the world's most costly and deadly disasters, and recent hurricanes like Sandy and Katrina and Typhoon Haiyan highlight the threat worldwide. Modeling inundation in coastal cities and towns (defined as the area within 100 km of a coastline) has become important because the world's inland rural population is moving to the coast (Creel 2003). Over 39% of the U.S. population lived in coastal shoreline counties in 2010 (NOAA 2013). Over 50% of the world population lives in coastal areas, and this percentage is projected to keep increasing for the foreseeable future (Creel 2003; Tibbetts 2002). In the largest coastal cities, the 136 port cities around the world that have more than 1 million inhabitants, there is a population of 400 million people (Hallegatte et al. 2013).

Increasing damage from coastal flooding is one of the most certain impacts of climate change, with storm surges coming on top of rising sea levels, and with the potential for intensified storms and increased rainfall in the northeastern United States (Walsh et al. 2014). Sea level rise is expected to accelerate over the twenty-first century, primarily due to increasing expansion of warming seawater and accelerated melting of land-based ice sheets. A conservative estimate of 30–60 cm for New York City, New York (NYC), by 2080 will change a 100-yr flood event to a 30-yr flood event; the latest localized projections show a 25% chance of sea level rising more than a meter over this period (Horton et al. 2015). Using recovered archival tide gauge data back to 1844 for New York Harbor, Talke et al. (2014) showed that flood levels in New York Harbor have been increasing due to rising sea levels and also due to increasing storm tides, the latter for unknown reasons. The annual likelihood of overtopping seawalls has

Corresponding author address: Alan F. Blumberg, Davidson Laboratory, Stevens Institute of Technology, Castle Point on Hudson, Hoboken, NJ 07030.
E-mail: alan.blumberg@stevens.edu

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