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PREDICTION AND VERIFICATION OF STORM SURGE DURING HURRICANE SANDY WITH THE NWS SLOSH MODEL

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1. INTRODUCTION

Hurricane ("Superstorm") Sandy (Blake et al. 2012), the second-costliest Atlantic hurricane on record, formed in the western Caribbean, south of the island of Jamaica in a region of low wind shear, warm water and a broad area of low pressure on October 22, 2012. It reached its peak intensity of 185 kph (115 mph, 100 kts) just before making landfall in Cuba at 05:25 UTC on October 25 as a category 3 hurricane. Sandy then weakened and began expanding in size, reaching a radius of maximum winds (RMW) larger than 185 km (100 nm) over the Bahamas. It re-intensified over the warm Gulf Stream waters as it turned northwest towards the mid-Atlantic states. An anomalous blocking high over the North Atlantic prevented Sandy from moving out to sea, while a baroclinic trough associated with an early winter storm deepened over the southeast US. This accelerated the storm's forward speed to 37 kph (20 kts) and steered it northwest, where it encountered cold water and transitioned to an extratropical cyclone 83 km (45 nm) southeast of Atlantic City, NJ (Blake et al. 2012) , 2.5 hours prior to its final landfall.

Sandy approached the coast as a category 1 hurricane and made landfall at 23:30 UTC Monday October 29, 2012, near Brigantine, NJ (northeast of Atlantic City) as a post-tropical cyclone, with maximum sustained winds of 130 kph (80 mph, 70 kts) and a central pressure of 945 mb. The lowest pressure found was 940 mb (dropsonde estimate) a few hours before landfall in NJ (Blake et al. 2012) and a warm front developed in the storm's northeast quadrant.

One of the most dangerous aspects of Hurricane Sandy was its large size, approximately 1,150 miles (1,850 km) in diameter, with a wind field that created a significant storm tide threat to vast areas along the Atlantic coastline and inland. After Hurricane Sandy made landfall in NJ, its sustained winds increased as an effect of the winter storm approaching from the west. The combination of both the hurricane and the winter storm, timed with the full-moon high tide on the night of October 29, worsened the storm-tide flooding along the NJ, NY and CT coastlines and caused significant flooding far inland along the Delaware and Hudson Rivers (McCallum et al. 2013).

Table 1 summarizes the maximum total, tide (referenced to various vertical datums) and surge water levels reached during Hurricane Sandy at three NOAA stations at the coast: The Battery, Bergen Point and Kings Point. At The Battery total water levels crested at the same time as the surge, even though the highest tides arrived half an hour earlier. At Bergen Point the maximum surge arrived half an hour after the highest total water level, while at Kings Point the

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maximum surge arrived two hours before the highest total water level.

Station (ID)	Time / Vertical Datum	Maximum Total Water Level m [ft]	Maximum Tide m [ft]	Maximum Surge Above Astronomical Tide m [ft]
The Battery, NY (8518750)	Time	Oct. 30, 2012 01:24 UTC	Oct. 30, 2012 00:54 UTC	Oct. 30, 2012 01:24 UTC
	MHHW	2.74 [8.999]	-0.10 [-0.315]	2.87 [9.40]
	NAVD88	3.44 [11.280]	0.60 [1.965]	
	MSL	3.50 [11.486]	0.66 [2.172]	
	MLW	4.22 [13.848]	1.38 [4.534]	
	MLLW	4.28 [14.055]	1.44 [4.741]	
Bergen Point, NY (8519483)	Time	Oct. 30, 2012 01:24 UTC	Oct. 30, 2012 00:54 UTC	Oct. 30, 2012 02:00 UTC
	MHHW	2.76 [9.065]	-0.80 [-0.259]	2.91 [9.56]
	NAVD88*	3.54 [11.623]	0.70 [2.299]	
	MSL	3.60 [11.801]	0.75 [2.477]	
	MLW	4.38 [14.367]	1.54 [5.042]	
	MLLW	4.43 [14.577]	1.60 [5.252]	
Kings Point, NY (8516945)	Time	Oct. 30, 2012 02:06 UTC	Oct. 30, 2012 04:24 UTC	Oct. 29, 2012 23:06 UTC
	MHHW	1.98 [6.509]	-0.07 [-0.224]	3.86 [12.65]
	NAVD88†	3.11 [10.201]	1.06 [3.468]	
	MSL	3.18 [10.423]	1.12 [3.690]	
	MLW	4.28 [14.035]	2.22 [7.302]	
	MLLW	4.36 [14.311]	2.31 [7.578]	

MHHW = Mean Higher High Water
MSL = Mean Sea Level
MLW = Mean Low Water
MLLW = Mean Lower Low Water
NAVD88 = North American Vertical Datum of 1988
* NOAA/NOS/CO-OPS personal communication NAVD88-MSL = 0.0542 m (0.178 ft)
† NOAA/NOS/CO-OPS personal communication NAVD88-MSL = 0.0676 m (0.222 ft)

Table 1. Maximum total, tide (referenced to various vertical datums) and surge water levels reached at three NOAA tide gauge stations at the coast: The Battery, Bergen Point and Kings Point, NY (from Forbes et al. 2014).

High Water Marks measured by USGS sensors recorded the highest water level inland, a value of 2.71 m (8.9 ft) above ground level (AGL), at the US Coast Guard Station in Sandy Hook, NJ, followed by 2.44 m (8.0 ft) AGL at the South Street Seaport near the Brooklyn Bridge and 2.41 m (7.9 ft) AGL in the Oakwood neighborhood of Staten Island and on the south side of Raritan Bay.

These various measurements depict the difficulty in assessing the storm surge threat because water level values might be referenced to different vertical datums or the quoted water surface elevations might represent only partial components of the total water level (e.g. tide or surge). According to a recent NHC technical memorandum (NOAA 2013), inundation is defined as the total water level that occurs on normally dry ground as a result of the storm tide. It is expressed in terms of height of water, in feet AGL. NHC's public advisories were modified to include values of inundation above ground level at the peak of high tide so the public would better understand the storm surge threat.

Operational storm surge forecasts during the storm and post-storm hindcast simulations of Hurricane Sandy were run by forecasters in NHC's Storm Surge Unit using the National Weather Service (NWS) Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model. This manuscript describes the operational forecasts of Hurricane Sandy run in the SLOSH ny3 basin (Figure 1), the improvements to the surge forecasting system implemented during 2013, and how the storm would have been predicted had the recently enhanced system been available in 2012. Hindcast simulations of Hurricane Sandy were run for analysis and verification. Comparisons of observed water levels at NOAA tide gauge stations, by USGS temporary storm surge sensors (SSS) and high water marks (HWM) were compared with the numerically simulated water levels to assess model performance.

The objective of this study is to quantify the ability of the NWS SLOSH storm surge prediction model (Jelesnianski et al. 1992) to replicate the height, timing, evolution and extent of the storm tide that occurred along the US Atlantic coastline during Hurricane Sandy (2012). It will also provide an assessment of the storm surge forecast skill during the storm compared to the model improvements incorporated in the model since. This analysis will serve as a baseline for the evaluation of further enhancements to SLOSH and for comparisons against the results from other modeling systems as NWS moves toward a multi-model ensemble.

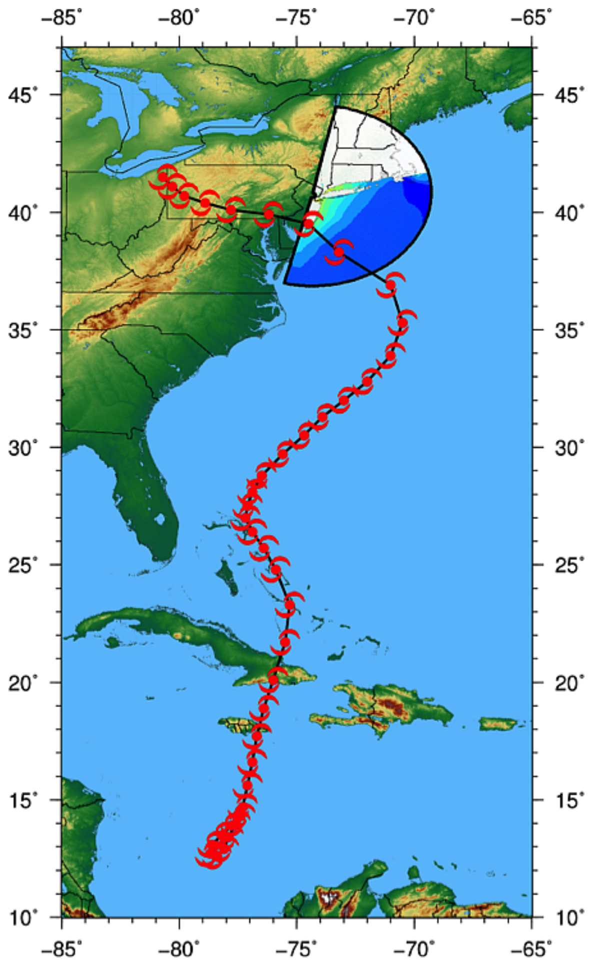

Figure 1. Hurricane Sandy track and the storm tide (m) simulated by the SLOSH numerical storm surge prediction model in the ny3 basin.

2. MODEL

SLOSH (Jelesnianski et al. 1992) is a numerical coastal ocean model used by the National Weather Service to run: 1) real-time operational, 2) hypothetical (for evacuation planning), 3) historical (for validation purposes), 4) probabilistic (Taylor and Glahn 2008), and 5) extratropical storm surge prediction simulations.

It is an extremely computationally efficient, 2-D explicit, finite-difference model, formulated on a semi-staggered Arakawa B-grid (Arakawa and Lamb 1977). The horizontal transport equations are solved through the application of the Navier-Stokes momentum equations for incompressible and turbulent flow (Platzman 1963, Jelesnianski 1967). The governing equations are integrated over the entire depth of the water column. At every time step, the horizontal transports are solved from the pressure, Coriolis and frictional forces. These transports generate an updated level of surge at every model grid point. SLOSH includes a wetting-and-drying algorithm to predict inland inundation.

SLOSH basins (grids in local geographic areas) have different shapes (hyperbolic, elliptical or polar) that can be customized for specific coastline geometries, with higher resolution near the coast and grid cells that telescope outward concentrically to lower resolution offshore. There are 37 operational SLOSH basins that cover the east coast of the US, the Gulf of Mexico, the Bahamas, Puerto Rico and the Virgin Islands.

An automated, event-triggered, storm surge prediction system, AutoSurge (Forbes and Rhome 2012), was developed at NHC in 2010 to accelerate forecaster workflows by eliminating labor-intensive tasks, computing storm parameters with greater accuracy and preventing human input error. The system runs the SLOSH model; the input is determined objectively and consistently for all operational simulations. AutoSurge automatically generates a vast array of products from the SLOSH model output to provide internal guidance to the Storm Surge Specialists during a tropical cyclone event.

3. FORECASTS

As soon as a tropical disturbance with the potential of developing into a tropical cyclone in the subsequent 48-hours is identified in the Atlantic Ocean, Caribbean Sea, or the Gulf of Mexico, AutoSurge begins generating storm surge forecast simulations using the SLOSH model. The system alerts the Storm Surge Specialists at NHC, sending guidance products via e-mail, and the results are available on an internal web site, both in tabular and graphical format. Graphics of the ensemble maximum envelope of water, model track spread, individual ensemble member maximum water levels, wind intensity, the radius of maximum winds, and forecast trends are generated to depict the expected range of the storm surge forecasts to account for variability in the atmospheric forcing.

AutoSurge was run in surge-only mode during the 2012 hurricane season. More than 1,000 AutoSurge numerical simulations were run during Hurricane Sandy using the Best Track and the internal NHC model guidance used to create the official track (OFCL). The ensembles are derived from the suite of statistical, dynamical and consensus track and intensity models that NHC's Hurricane Specialists use to create their forecasts. This meteorological forcing was used to drive the SLOSH storm surge prediction model over multiple SLOSH basins, from Puerto Rico to the Bahamas and along the US. East Coast. Results for the ny3 basin will be described and the model output graphics will be shown. These ensemble simulations are run in conjunction with the probabilistic P-Surge modeling system (Taylor and Glahn 2008) developed at NOAA/Meteorological Development Laboratory (MDL), which runs an ensemble of storm surge simulations using historical error statistics of the wind parameters to generate the forecast tracks.

Enhancements made to AutoSurge in 2013 include: a new version of the tides (V. 2), model results relative to both the NAVD88 (North American Vertical Datum of 1988) datum and above ground level, Mini-MEOW (Maximum Envelope Of Water) simulations (a handful of ensembles created by permutations of the OFCL track), ensemble maximum water level ranges and trends, and calculations of inundation area.

The new version of SLOSH+Tides (V. 2) incorporates the tides dynamically at every time step and at every SLOSH model grid point (Taylor et al. 2013, Haase et al. 2012). The location-dependent amplitudes and phases of 37 tidal constituents were selected to be consistent with NOAA/NOS station data and had recently been extracted from the new, updated experimental EC2013 ADCIRC tidal database (Szpilka et al. 2013)

Due to the limited amount of time available to complete the numerical forecasts, the model runtime has to be short to be able to construct the storm surge prediction ensembles. The runtime performance for a typical SLOSH model simulation run over the ny3 basin on a typical desktop PC or Linux workstation is approximately 1 min 49 sec, 3 min 14 sec, 4 min for surge only-runs, for surge+tide runs and surge+tides+graphics, respectively.

SLOSH surge-only simulations (without tides) were run operationally in 2012 for Hurricane Sandy, as described above. Figure 2 shows an example of the model tracks used by NHC's Hurricane Specialists as guidance to determine the OFCL track for Hurricane Sandy 48-hours prior to landfall. It depicts a large spread in the model tracks with various intensities, sizes and storm center locations. This guidance is used to run the ensemble SLOSH simulations.

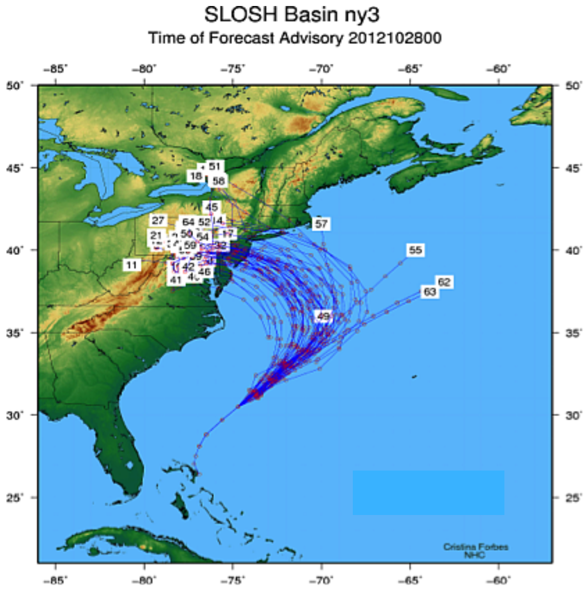

Figure 2. Example of the model tracks used by the Hurricane Specialists at NHC to develop the OFCL forecast track for Hurricane Sandy. It depicts the large spread in the model tracks with various wind intensities, sizes and track locations. This meteorological guidance is used as forcing to run the SLOSH ensemble storm surge simulations.

As the storm evolved in time, the AutoSurge forecast system calculated the trend of maximum water elevation above NAVD88 for all the ensemble members at each synoptic time, as shown in Figure 3 (a). The predicted maximum water elevation levels converge to 3.8 m (12.4 ft) relative to the NAVD88 vertical datum. During Hurricane Sandy the Storm Surge Specialists had to add the tide and convert values to above ground level to create the text that was issued in the forecast advisories.

If Hurricane Sandy were forecast today with the enhancements described earlier, then the SLOSH model simulations would have tides included in the hydrodynamic equations and would depict the total above ground water levels (inundation). The forecast trends of the surge-plus-tides simulations are shown in Figure 3 (b). The water level values converge to 2.6 m (8.5 ft) AGL (3.9 m or 12.9 ft relative to NAVD88). The light yellow polygon delineates the range of water levels issued in real-time by NHC in its forecast advisories, which encompasses the maximum inundation actually recorded during this storm event of 2.71 m (8.9 ft) AGL.

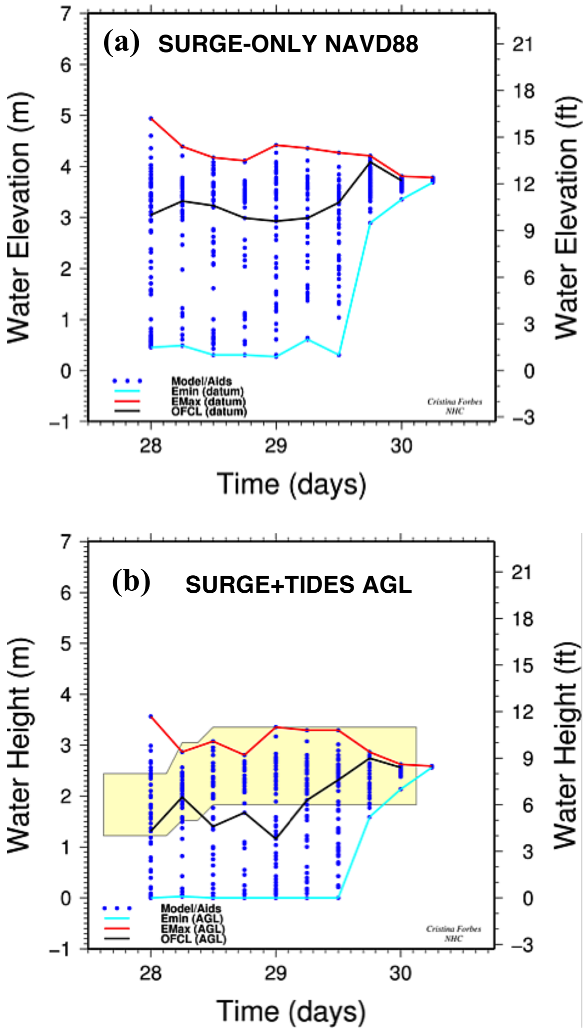

Figure 3. Trend of **(a)** maximum water elevation in the entire SLOSH basin relative to the NAVD88 vertical datum for all ensemble members in the SLOSH storm surge-only simulations, and **(b)** the water height above ground level (AGL) for all the ensemble members for the surge + tides simulations. The time in days (horizontal axis) denotes the initial time of the model forecasts. The light yellow polygon delineates the range of water levels issued in real-time by NHC in its forecast advisories, which encompasses the maximum inundation actually recorded during this storm event (figure from Forbes et al. 2014).

4. HINDCASTS

Post-storm hindcast surge-plus-tides simulations were run for the SLOSH ny3 basin and were forced by wind parameters from the Hurricane Sandy Best Track to determine the accuracy of the results. First, tides were spun up for 720 hours. After this 30-day spin-up period with tides alone, a 100-hour SLOSH hindcast simulation was run with both tides and Best Track wind forcing.

The results were then compared with the water surface elevations recorded at NOAA tide gauge stations, measurements from temporary USGS storm surge sensors (SSS) and high water mark (HWM) estimates made by the USGS.

The total water levels were extracted from 13 NOAA stations located in New York (NY), New Jersey (NJ), Rhode Island (RI), Connecticut (CT), and Massachusetts (MA) within the ny3 basin area and compared to the SLOSH water levels from the surge-plus-tide hindcast simulation.

Examples of the time evolution of the observed vs. modeled water levels are shown in Figure 4. The total water levels (surge-plus-tides) at the NY stations are in good agreement with the observations, with calculated root mean square errors (RMSE) of 0.19-0.51 (Table 2). The RMSE ranges from 0.19-0.35 m at CT stations. The modeled total water levels are slightly underestimated at RI and MA stations, with RMSEs of 0.22-0.26 m. The simulated water surface elevations at NJ stations are characterized by RMSEs between 0.33-0.47 m.

Table 2 shows a summary of the NOAA stations and SLOSH simulation results.

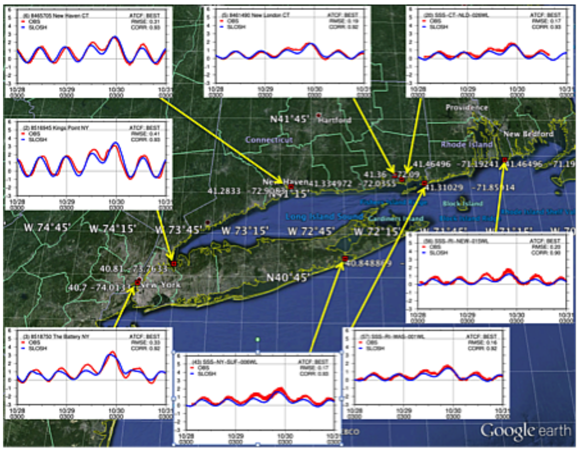

Figure 4. Map of NOAA tide gauge station locations with hydrographs of surge surge + tides at NOAA stations (red) vs. SLOSH simulations (blue) with RMS error and correlation calculated between the two time series. Time is in month/day and hours UTC (horizontal axis) and water elevations are in meters (vertical axis).

For the most part, the timing of the observed peaks was replicated in the SLOSH simulations to within one hour. The RMS errors range from 0.19-0.51 m. The correlations range from 0.81-0.95 (excluding Cape May which is located at the boundary of the basin).

Station ID	Station Name	Lon (deg)	Lat (deg)	Obs Peak Time (hrs)	Model Peak Time (hrs)	Obs Max Elev (m)	Model Max Elev (m)	RMSE (m)	CORR
8510560	Montauk, NY	-71.96	41.04	69.2	69.50	1.69	1.57	**0.19**	0.91
8516945	Kings Pt., NY	-73.76	40.81	71.1	71.50	3.11	3.47	0.41	0.93
8518750	The Battery, NY	-74.01	40.70	70.4	68.33	3.44	3.05	0.33	0.92
8519483	Bergen Pt., NY	-74.14	40.63	70.4	69.16	3.54	3.24	0.51	0.81
8461490	New London CT	-72.09	41.36	69.2	69.66	1.88	1.80	**0.19**	0.92
8465705	New Haven, CT	-72.90	41.28	70.5	71.33	2.65	2.73	0.31	0.93
8467150	Bridgeport, CT	-73.18	41.17	71.1	71.16	2.83	2.92	0.35	0.93
8531680	Sandy Hook, NJ	-74.00	40.46	68.6	67.99	3.18	3.20	NA	NA
8534720	Atlantic City, NJ	-74.41	39.35	69.4	66.16	1.91	2.57	0.32	0.86
8536110	Cape May, NJ	-74.96	38.96	58.7	66.16	1.80	2.02	0.47	0.64
8452660	Newport, RI	-71.32	41.50	68	67.99	1.87	1.25	0.25	0.91
8447435	Chatham, MA	-69.95	41.68	61	61.33	1.79	1.04	0.26	0.95
8449130	Nantucket I. MA	-70.09	41.28	61.1	61.66	1.18	0.67	0.22	0.89

Table 2. Summary of the NOAA stations vs. SLOSH surge (S) and surge-plus-tides (ST) simulation results. Times are in elapsed hours from the start of the model run – 03:00 UTC, October 27, 2012.

The panels in Figure 5 (a) display the maximum water levels and (b) the time-of-arrival of the peaks for surge-plus-tides, measured at NOAA stations (red squares), USGS sensors (blue triangles) and USGS High Water Marks (purple circles) vs. those simulated by SLOSH. Figure 5 (a) shows the SLOSH peak values at the station locations that fall within the 10% (dark orange), 20% (orange) and 30% (yellow) height error cones. In Figure 5 (b) the SLOSH values at the station locations that fall in the ± 3 hour error range for the time-of-arrival of the peak are within the orange band and the ± 6 hour error range are within the yellow band.

The simulated surge-plus-tides water surface elevation errors at most station locations in Figure 5 (a) are within the 10-20% range. Most of the simulated peak arrival times are accurate within 3 hours of the observed arrival times.

The simulated peak arrival times at most NOAA stations locations (red squares in Figure 4 b) are within 3 hours of that which was observed, except at stations in RI and MA far from the landfall location, and at Cape May (station 8536110) because, as mentioned above, the station is located too close to the model boundary.

The USGS deployed a temporary network of water level and barometric pressure sensors at 224 locations along the Eastern US Atlantic coast from Virginia (VA) to Maine (MN). This temporary monitoring network augmented the existing tide gauge networks and helped characterize the height, extent and timing of the storm tides. This was the second-largest deployment of storm-tide sensors after Hurricane Irene (2011), which made landfall in the same area of the US (M^cCallum et al. 2013). 145 water level and 9 wave height sensors were deployed at 147 locations while 8 rapid deployment gauges (RDGs) and 62 barometric pressure sensors were deployed at additional locations. The water level sensors recorded water levels in feet above NAVD88 at 30-second intervals.

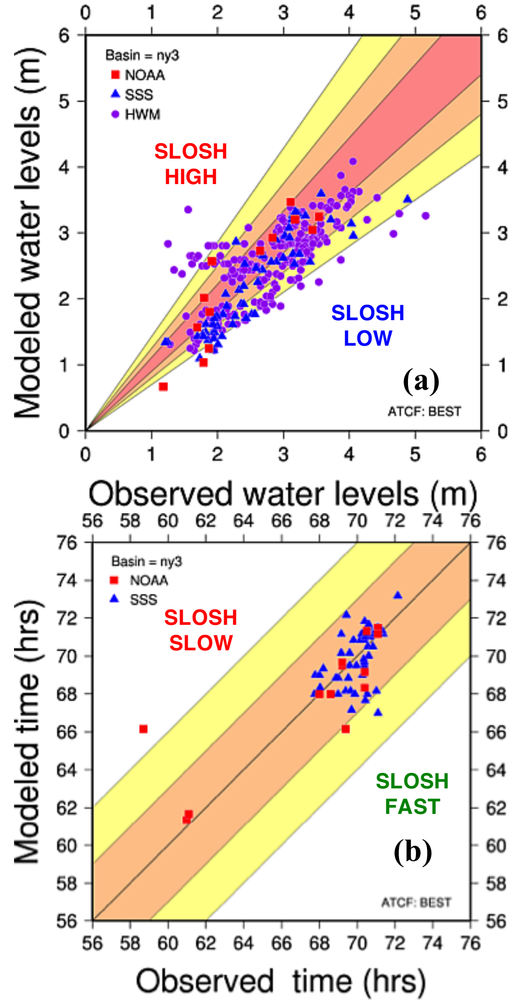

Figure 5. Comparison of **(a)** water levels (m) at all NOAA tidal gauges, USGS storm surge sensors (SSS) and USGS High Water Marks (HWMs) and **(b)** the time-of-arrival of the peak water levels at all NOAA tidal gauges, USGS storm surge sensors (SSS) vs. SLOSH for surge-plus-tides model-simulations. In **(a)** the dark orange cone depicts 10% error, the orange cone depicts 20% error and the yellow cone depicts 30% error. The simulated surge-plus-tides water surface elevation errors at most station locations are within the 10-20% range. In panel **(b)** the stations and sensors that fall in the ± 3 hour error range for the time-of-arrival of the peak are within the orange band and the ± 6 hour error range are within the yellow band. The simulated peak arrival times at most sensor locations are within 3 hours of that which was observed.

Of the 154 sensors, 73 were located outside the ny3 basin, 9 sensors that recorded high-frequency wave heights were not used for verification purposes (this version of the modeling system does not include waves) and 12 sensors were close to the SLOSH basin boundary or were sited in locations that were contaminated by local effects (buried under the sand in narrow alleys between buildings, etc.) which are not modeled or resolved by the SLOSH grid, so those sensors were not employed in the verification process. Therefore, 60 SSS sensors were compared with the model results.

The hydrographs at the SSS stations show excellent agreement in both amplitude and phase with the SLOSH model-simulated surge-plus-tides results (see examples in Figure 4).

The SLOSH-simulated surge-plus-tides values at most USGS sensor locations (blue triangles in Figure 5 a) are within the 10-20% error range. Figure 5 (b) shows that most of the sensors that fall in the ± 3 hour error range in the arrival time of the peak (orange) and one in the ± 6 hour error zone (yellow).

The RMSE of the USGS SSS vs. SLOSH-simulated water levels show that 80% of the values simulated at station locations are less than 0.5 m (1.6 ft) in error and have correlations greater than 0.60. The SLOSH-simulated relative errors are less than 0.30 at 92% of the SSS sensor locations.

The observational measurements for Hurricane Sandy were supplemented by an extensive dataset of post-storm high water marks (HWMs). Of 950 USGS HWMs flagged, surveyed and collected, 650 were classified to be independent (greater than 1,000 ft apart from each other), and 257 flagged in CT, RI and MA were not surveyed due to lack of funding. 559 HWMs were inside the SLOSH ny3 basin, and 312 had valid data, so excluding those near the SLOSH boundaries, 284 HWMs were analyzed and 17 outliers (a HWM estimated from a streak on the wall of a steel shipping container, another identified by a mud line inside a small enclosed room under an air-conditioning unit, etc.) were removed. The remaining 268 HWMs were then compared to SLOSH-simulated inundation values AGL. A comparison of the HWM estimates vs. SLOSH surge-plus-tides maximum water levels is shown in Figure 5. 34% of the simulated height at HWM locations have relative errors less than 10% (dark orange), 72% have errors less than or equal to 20% (orange cone) and almost 90% have relative errors less than or equal to 30% (yellow cone).

In summary, quantitative comparisons (Table 3) of SLOSH simulation results against water surface peak elevations measured at all 13 NOAA tide gauge stations, by 60 storm surge sensors deployed by the USGS prior to the storm, and from 268 HWMs collected by USGS – a total of 341 observations – reveal that the SLOSH model-simulated water levels at approximately one third (34%) of the data measurement locations have less than 10% relative error (dark orange cone), while 71% (89%) have less than 20% (30%) relative error (orange and yellow cones, respectively).

Rel Err	NOAA	%	SSS	%	HWM	%	NOAA +HWM +SSS	%
<= .10	6	46	21	35	90	34	117	**34**
<= .20	9	69	40	67	192	72	241	**71**
<= .30	9	69	55	92	238	89	302	**89**
<= .40	11	85	60	100	254	95	325	**95**
> .40)	13		60		268		341	**100**
Total	**13**		**60**		**268**		**341**	

Table 3. Partition of relative error between observed and SLOSH-simulated maximum water elevation for all measurements: NOAA tide gauge stations, USGS storm surge sensors (SSS) and USGS high water marks (HWM).

The RMS error between all the observed and modeled peak water levels is 0.47 m (1.5 ft) (Table 4).

	NOAA	SSS	HWM	ALL
# of Obs	13	60	268	341
RMSE	0.38 m (1.27 ft)	0.34 m (1.11 ft)	0.49 m (1.62 ft)	0.47 m (1.54 ft)

Table 4. Root mean square error between observed and SLOSH-simulated maximum water elevation for all measurements: NOAA tide gauge stations, USGS storm surge sensors (SSS) and USGS high water marks (HWM).

4.1. Horizontal Distribution of Observations vs. SLOSH

Figure 6 shows the SLOSH-simulated surge-plus-tides maximum envelope of water (relative to NAVD88) for Hurricane Sandy. Observations at NOAA stations (squares), SSS (triangles) and HWM (circles) have been added with the same color range for comparison.

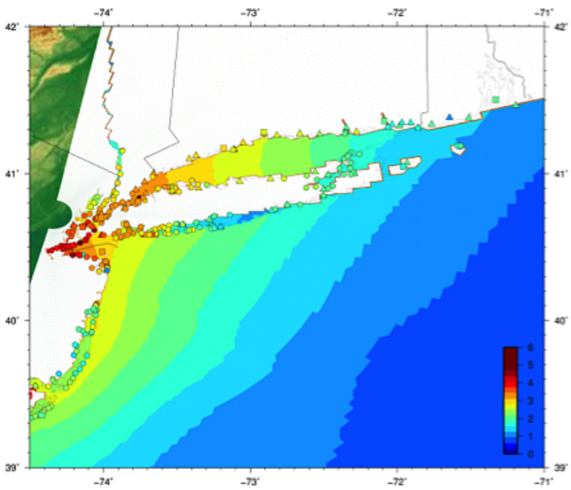

Figure 6. SLOSH model-simulated surge-plus-tides maximum envelope of water (relative to the NAVD88 vertical datum) for Hurricane Sandy. Observations at NOAA stations (squares), SSS (triangles) and HWM (circles) have been added with the same color range for comparison. Water levels are in meters (figure from Forbes et al. 2014).

In general, the observations are in good agreement with the model results. Some HWMs have higher water level values than those simulated (red circles), particularly in west Raritan Bay, NY. Examining the simulation more closely, it appears the water in the East River is not flowing through the grid properly. More detailed investigation will be conducted and a new New York basin grid might need to be built to remedy this retardation of the water flow.

In Figure 7 the SLOSH model-simulated surge-plus-tides AGL results over land and maximum envelope of water over the ocean are compared to the FEMA Modeling Task Force (MOTF) field-verified, "ground-truth" Hurricane Sandy Impact Analysis graphic (FEMA 2012), which depicts the final high-resolution storm surge extent (grey) and very high-resolution extent in NYC (blue) to provide a more detailed verification of the inundation area.

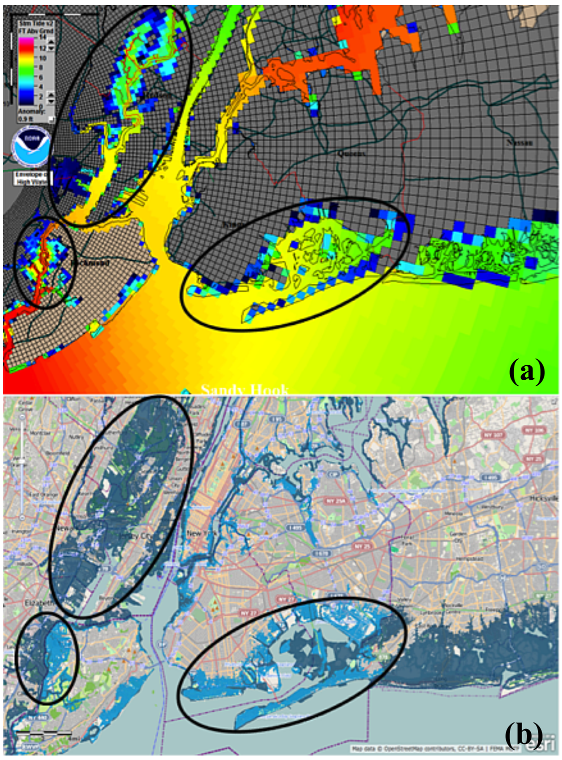

Figure 7. (a) SLOSH model-simulated inundation (ft) above ground level (AGL) over land and maximum envelope of water over the ocean, as rendered by the interactive SLOSH Display Program, and (b) Modeling Task Force (MOTF) field-verified, "ground-truth" Hurricane Sandy Impact Analysis graphic (courtesy of FEMA), which depicts the final high-resolution storm surge extent (grey) and very high-resolution extent in NYC (blue).

The simulated geographical patterns of inundation agree well, especially at Breezy Point, Rockaway, the low-lying areas surrounding JFK airport and further east along the shores of East Bay and South Oyster Bay. The SLOSH wetting-and-drying algorithm performs skillfully inland to the west, in the area extending from south to north along the west bank of the Hudson River from Hoboken to Union City, NJ and further west in the larger Jersey City, Secaucus and Ridgefield area. Flooding over the river banks is also accurately simulated to the south along the Raritan River, the Washington Canal and the South River. The inundation area calculated from the SLOSH Best Track hindcast simulation was 561 km^2 (216 sq mi).

4.2. Horizontal Distribution of Winds vs. SLOSH

Figure 8 shows a comparison between the winds produced by the SLOSH parametric wind model and the real-time multi-platform satellite surface wind analysis at 00 UTC on October 30, 2012 from the NOAA National Environmental Satellite, Data and Information Service (NESDIS), the Cooperative Institute for Research in the Atmosphere (CIRA) Regional and Mesoscale Meteorology Branch (RAMMB) at Colorado State University (CSU) (NESDIS, 2012) as Hurricane Sandy made landfall northeast of Atlantic City, NJ. Despite the simplicity of the SLOSH parametric wind model, the simulated winds are remarkably realistic and exhibit a strong wavenumber 1 asymmetry due to the storm's forward motion. The 50 kt (25.72 ms^{-1}) isotachs in panels (a) and (b) are similar in orientation, shape and extent. The SLOSH surface friction simulates a reduction in wind speed of about 10 knots (5.14 ms^{-1}) over Long Island Sound due to the downwind effects of the Long Island land cover. The wind directions in both panels also compare quite favorably.

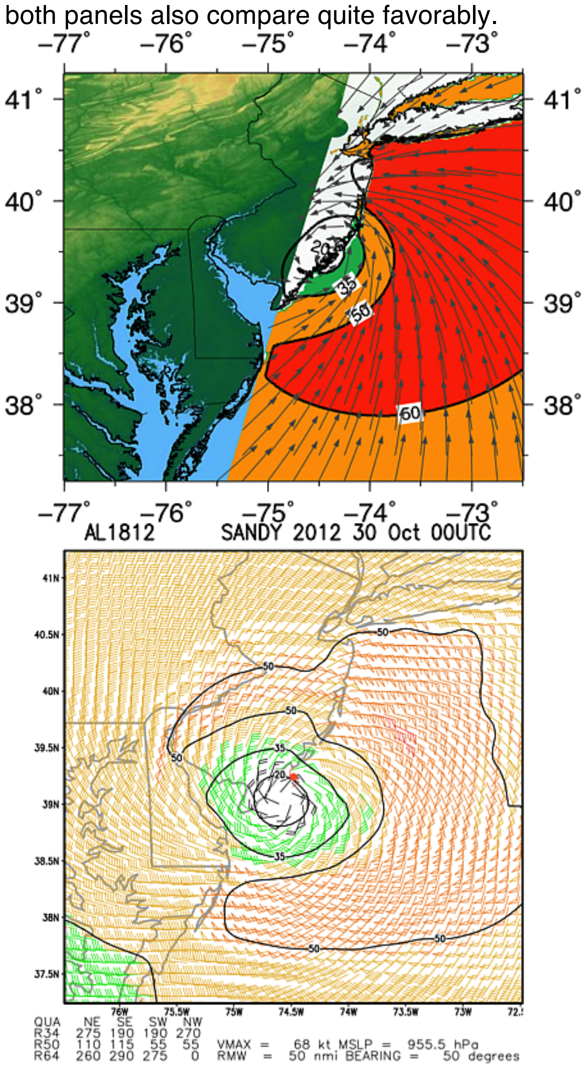

Figure 8. Comparison of wind speeds from (a) the SLOSH parametric wind model and (b) the multi-platform surface wind analysis (courtesy of NOAA/NESDIS and CSU/CIRA/RAMMB). Wind speeds are in kts (1 kt = 0.52 ms^{-1}) for comparison.

5. CONCLUSIONS

Numerical simulations of the storm tide that flooded the US Atlantic coastline during Hurricane Sandy (2012) were carried out using the NWS SLOSH storm surge prediction model. The verification analyses conducted in this study show that the NWS SLOSH storm surge prediction model is able to simulate the height, timing, evolution and extent of the water that was driven ashore by Hurricane Sandy (2012) with a high degree of fidelity. Upgrades to the numerical model in 2013, including the incorporation of astronomical tides with 37 harmonic constituents, have increased its hindcast accuracy and will enable forecasters to better predict the timing and extent of the total water level and inundation.

It is shown, through comprehensive verifications of SLOSH simulation results against peak water surface elevations measured at 13 NOAA tide gauge stations, by 60 storm surge sensors deployed by USGS and 268 high water marks collected by the USGS, that the SLOSH-simulated water levels at 34%, 71%, 89% of the data measurement locations have less than 10%, 20% and 30% relative error, respectively. The RMS error between all observed and modeled peak water levels is 0.47 m (1.5 ft).

In addition, the model's extreme computational efficiency enables it to run large, automated ensembles of predictions in real-time to account for the high variability in atmospheric forcing that can occur in tropical cyclone forecasts, which makes the guidance designed to alert the public and prevent the loss of life more robust and reliable.

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