6.1 CASE STUDY: SLOSH USING GRIDDED WIND FIELDS FOR HURRICANES IRENE-2011 AND SANDY-2012

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[*] *Presented at the 95th AMS Annual Meeting, Phoenix, AZ, January 7, 2015*

1. INTRODUCTION

Storm surge, the water pushed onshore by winds from tropical and extra-tropical cyclones, is one of the most devastating natural phenomena affecting coastal areas. As demonstrated by Hurricane Sandy in 2012, the impact of storm surge is enhanced when the surge coincides with high tide, which can result in entire communities being wiped out in a matter of hours. Accurate and timely forecasts of, and responses to, the storm surge threat are critical to saving lives and protecting property in the coastal community.

The National Weather Service's (NWS) operational hurricane storm surge guidance is based on the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model. The SLOSH model was developed by NWS's Meteorological Development Laboratory (MDL) in the 1980s (Jelesnianski et al. 1984) to provide overland storm surge guidance. Since SLOSH was intended to be used operationally, the various inputs had to be readily available, assumed or parameterized. Of prime importance was the wind model to drive the surge. "Such winds could come from a large-scale dynamic atmospheric model, but they would represent that model's forecast of the hurricane, not the National Hurricane Center's (NHC). So, Chester Jelesnianski (the primary SLOSH developer) chose to use a simplified parametric wind model (Jelesnianski and Taylor 1973) that could be driven with forecasts routinely made by NHC" (Glahn et al. 2009). SLOSH's parametric wind model has served it well for: (1) deterministic forecasting, (2) climatological ensemble forecasting a.k.a. SLOSH simulation runs and (3) real-time ensemble forecasting a.k.a. probabilistic storm surge forecasts (Glahn et al. 2009).

Sole reliance on a parametric wind model has its drawbacks, so MDL has recently enhanced SLOSH to also use gridded wind vector and atmospheric pressure fields to drive the surge model. This will enable: (1) SLOSH developers to improve the model by utilizing more accurate historic wind guidance; (2) NWS forecasters (and others) to better educate the public on the interactions of wind and storm surge via more accurate historic wind and storm surge analyses; and (3) SLOSH developers to provide SLOSH model guidance driven by various large-scale dynamic atmospheric models or hurricane specific atmospheric models such as the Hurricane Weather Research and Forecast System (HWRF) model (Tallapragada et al. 2013). With regards to (3), forecasters would then be able to select SLOSH model results based on the hurricane model they trust most for a given storm and advisory.

To evaluate the new capabilities and examine the performance of SLOSH with various gridded wind inputs, we selected Hurricane Sandy-2012 and Hurricane Irene-2011 as test cases. Results of running SLOSH with these storms in both forecast and hindcast mode are presented in sections 3 and 4 (following a brief description of the methods and data used in this study). A discussion of the results is provided in section 5.

2 MODEL, METHODS AND DATA

SLOSH is a 2-dimensional finite difference model based on an integrated form of the governing equations of motion. The finite difference schemes use an Arakawa-b grid and are centered in time and one-sided second order

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differenced in space (Jelesnianski et al. 1992). The transport equations were developed by Platzman (1963) and modified with a bottom slip coefficient by Jelesnianski (1967). SLOSH uses a constant surface wind drag coefficient and a constant eddy stress coefficient (Jelesnianski et al. 1992). It is able to model sub-grid features such as flows through channels or rivers, and levies, elevated roads or other barriers (Jelesnianski et al. 1992). Finally, as the name indicates, SLOSH computes overland inundation, which was originally based on surge alone, but can now also be based on surge and tide (Haase et al. 2012). The latter version was applied in this study.

To better represent critical areas and guarantee computational efficiency, SLOSH uses structured curvilinear grids with higher resolution overland and lower resolution offshore (Fig. 1). The grid, combined with the underlying bathymetry, topography, and sub-grid features, forms a SLOSH basin. The parametric wind model, based on (1) the position and forward speed of the storm center, (2) the pressure difference between the ambient environment and the storm center, and (3) the radius of maximum winds, computes wind vectors and atmospheric pressures at SLOSH basin grid cells. Thus, gridded wind and pressure inputs must be translated to SLOSH basin grid cells.

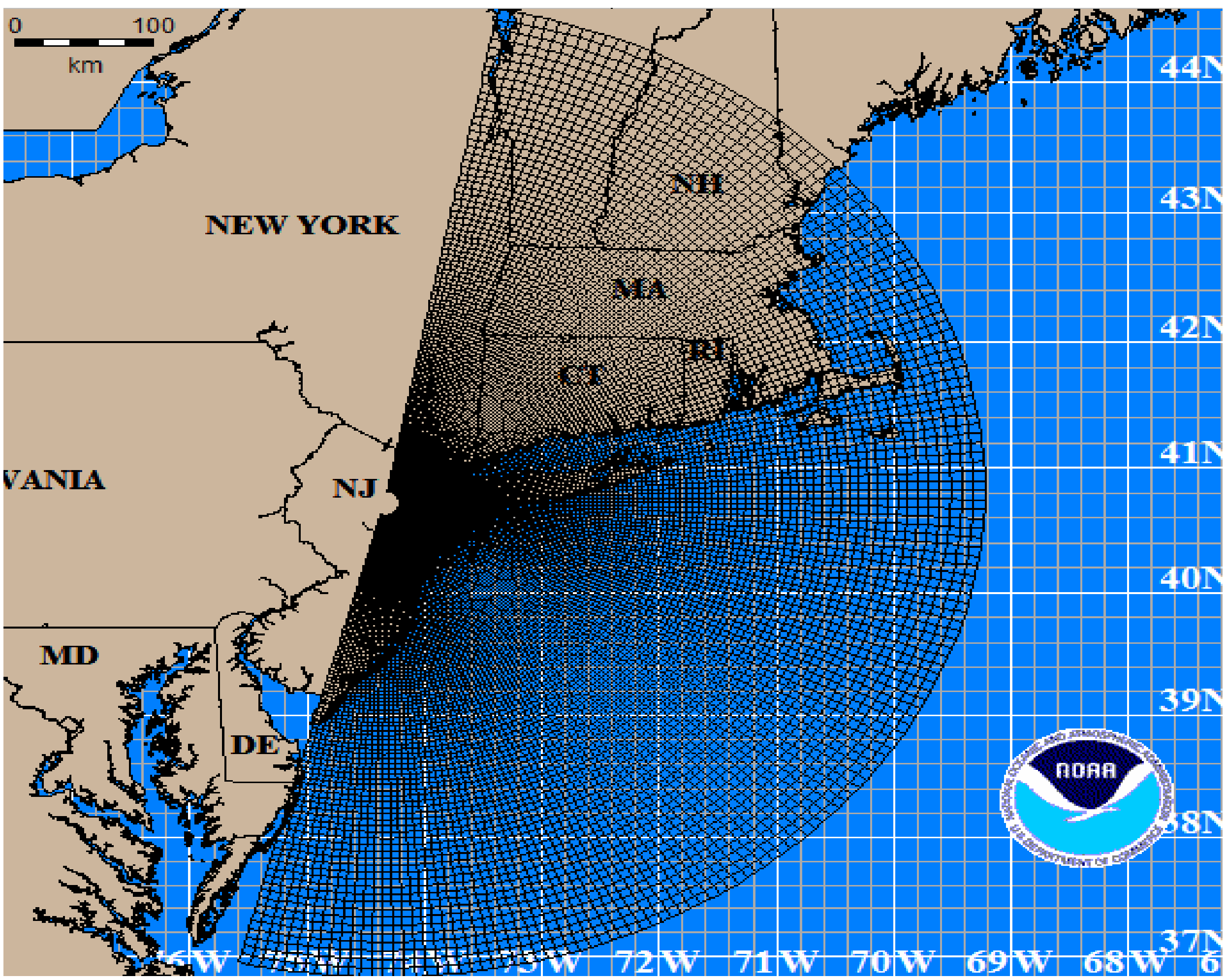

Fig. 1. Example of a SLOSH curvilinear grid (New York basin).

This study used HWRF and NOAA's Hurricane Research Division's (HRD) Real-time Hurricane Wind Analysis System (H*Wind) (Powell et al. 1998) gridded wind products to explore methods for translating gridded winds to SLOSH basin grids. Both products are output on uniform rectangular grids, but the domain characteristics are different. HWRF has a fixed basin-scale domain, while H*Wind has several time-varying, storm-track following domains with much smaller size. To work with HWRF products, a storm-specific subdomain is chosen which covers all areas of interest that are potentially affected by the storm (Fig. 2). To work with H*Wind products, a storm-specific subdomain is chosen in the form of an outer box which covers all of the H*Wind storm-track following domains (Fig. 3). Values within the storm-specific domains are interpolated to the appropriate SLOSH basin grids.

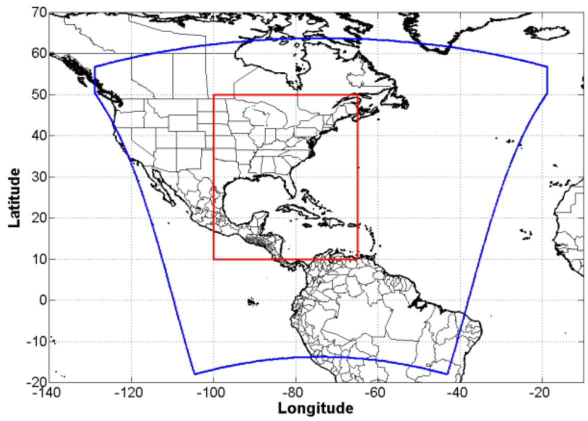

Fig. 2. Storm specific domain (red) contained within the HWRF domain (blue).

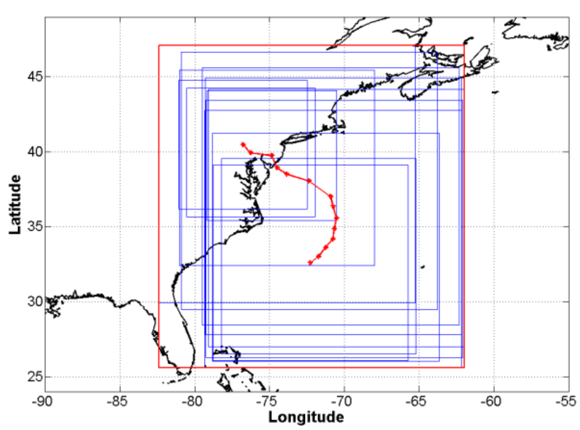

Fig. 3. Storm specific domain (red) which contains the H*Wind storm-track following domains (blue).

The storm-specific domain for H*Wind is larger than its native domain, so missing data was provided by extracting information from the 0.5° Global Forecast System (GFS, Environmental Modeling Center 2003) nowcast wind product. Additionally, H*Wind does not provide an atmospheric pressure field, which SLOSH requires to compute inverse barometric heights. To resolve this, we explored creating a pressure field for H*Wind by both: (1) extracting it from the GFS atmospheric pressure field (H*Wind + GFS), and (2) using the SLOSH parametric wind model to compute it from NHC's "Best Track Data (HURDAT2)" (http://www.nhc.noaa.gov/data) which consists of analyses of historic storms' (a) positions, (b) central pressures, and (c) maximum wind velocity (H*Wind + BT). As mentioned earlier, the SLOSH parametric wind model requires radius of maximum winds, however given maximum wind velocity the wind model can reverse engineer the radius of maximum winds.

The ability to use both HWRF and H*Wind allows us to run SLOSH in several forecast and hindcast modes. The two forecast modes used here are based on driving SLOSH with: (1) HWRF's gridded wind and pressure fields (HWRF Grid) and (2) SLOSH's own parametric wind model based on HWRF's forecast storm positions, central pressures and maximum velocity of winds (HWRF Track). The two gridded hindcast modes used here are based on driving SLOSH with the two H*Wind permutations described above (H*Wind + GFS, and H*Wind + BT). The parametric hindcast mode used here is based on driving SLOSH with its own parametric wind model based on NHC's best track data (Best Track).

To evaluate the performance of the various forecast and hindcast modes, model results have been compared with COOPS water level observations based on two metrics:

1) Root Mean Squared Error (RMSE),

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{n}}$$

2) Peak surge Error (PE),

$$PE = abs(\max(X_{obs,i}) - \max(X_{model,i}))$$

Where $X_{obs,i}$ and $X_{model,i}$ represent time series of observed and modeled water levels respectively.

3. HURRICANE SANDY-2012

Hurricane Sandy made landfall near Brigantine, NJ at approximately 23:30Z on October 29 after a complex evolution and growth (Blake et al. 2012). Due to its large size it produced catastrophic storm surge on the coastlines of New Jersey and New York. Three SLOSH basins: New York, Delaware and Chesapeake were used for simulating Sandy and results were compared with observations at 16 COOPS tidal gauges (Fig. 4).

SLOSH was run in forecast mode for 54 hours based on a single HWRF forecast which started at 0Z on October 29. It was run in hindcast mode for 51 hours starting at 1:30Z on October 28. The gridded forecast mode (HWRF Grid) outperformed the parametric forecast mode (HWRF Track) in terms of both RMSE and PE. Both gridded hindcast modes outperformed the parametric hindcast mode with (H*Wind + GFS) doing the best overall (Table 1).

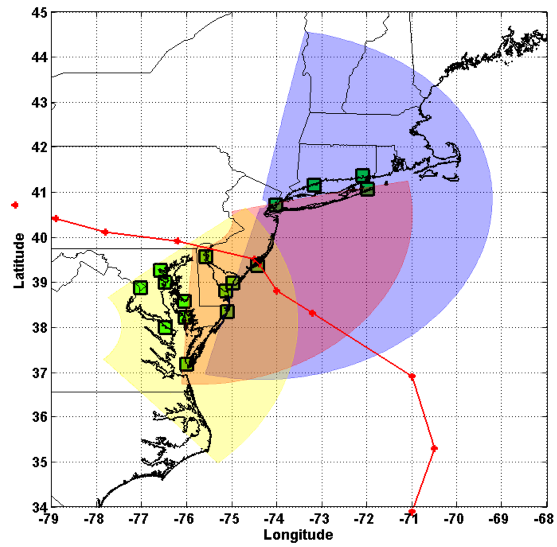

Fig. 4. Storm track (red line), observation stations (green squares), and SLOSH basins used (shaded areas) for Sandy-2012.

In addition to the statistical comparison, hydrographs of the forecast mode results were created at sample observation sites (Fig. 5). The hydrograph for The Battery, NY shows that both forecast modes under predicted the peak surge. While the parametric forecast mode was slightly better at capturing the peak surge, the gridded forecast mode was much better during the previous tide cycle. The hydrographs at Cape May, NJ; Bishops Head, MD; and Kiptopeke, VA, show that the gridded forecast mode improved the peak surge forecasts significantly compared to the parametric forecast mode.

The peak surge at The Battery, NY was again under predicted by all of the hindcast modes (Fig. 6). At the other three sites, the gridded hindcast modes, especially the one with GFS atmospheric pressure (H*Wind + GFS), had much better skill in terms of both overall agreement with the observations and peak surge simulation.

	HWRF Grid	HWRF Track	H*Wind + GFS	H*Wind + BT	Best Track
RMSE Mean	1.29	1.59	0.86	0.93	1.11
RMSE Range	0.79-2.13	0.98-2.21	0.61-1.23	0.63-1.41	0.62-1.62
PE Mean	0.91	1.48	0.98	1.08	0.98
PE Range	0.71-2.48	0.52-2.62	0.07-3.58	0.03-3.38	0.05-2.22

Table 1. Skill scores, in feet, for simulating Hurricane Sandy-2012 via the various forecast and hindcast modes.

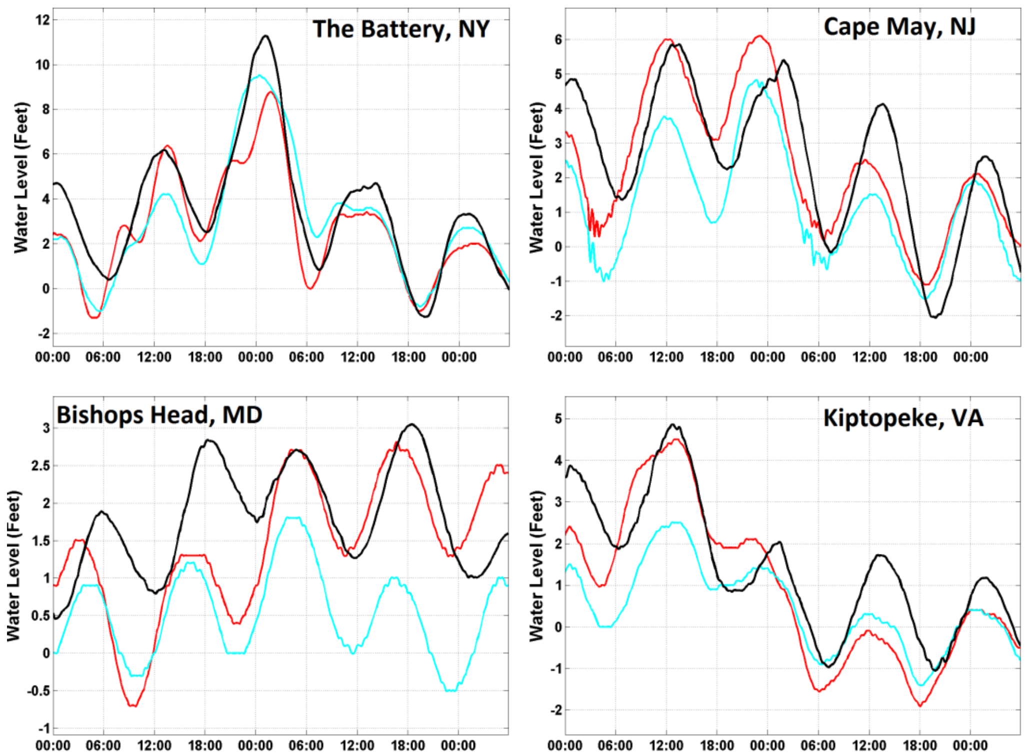

Fig. 5. Time series of NAVD88 water level during Sandy-2012 (0Z, Oct. 29 – 06Z, Oct. 31). Observation: black; SLOSH with gridded HWRF forecast: red; SLOSH with parametric HWRF forecast: blue.

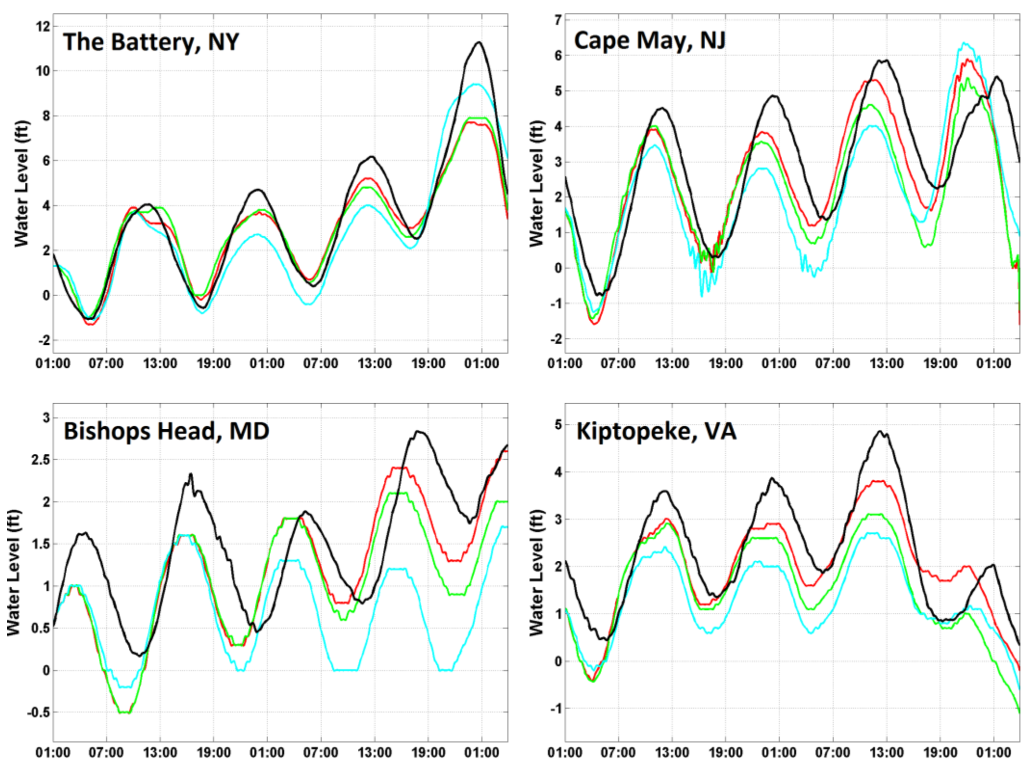

Fig. 6. Time series of NAVD88 water level during Sandy-2012 (01:30Z, Oct. 28 – 04:30Z, Oct. 30). Observation: black; SLOSH with: gridded H*Wind + GFS: red; gridded H*Wind + BT: green; parametric best track: blue.

4. HURRICANE IRENE-2011

Hurricane Irene made landfall at Cape Lookout, NC, Brigantine Island, NJ, and finally Coney Island, NY (Avila et al. 2011). The same three SLOSH basins used to simulate Sandy were used for Irene, and the model results were compared with observations at 18 COOPS tidal gauges (Fig. 7).

SLOSH was run in forecast modes for 54 hours based on a single run of the HWRF model starting at 12Z on August 27. It was run in hindcast mode for 41 hours starting at 01:30Z on August 27. The duration of the Hurricane Irene hindcast was limited by the availability of H*Wind. The parametric forecast mode outperformed the gridded one in RMSE (Table 2). The gridded forecast mode improved the prediction of peak surge (PE skill score), but based on the hydrographs and the RMSE score, it had worse overall agreement with observations (Fig. 8). The parametric hindcast mode was consistently better overall for the RMSE and PE skill scores (Table 2), as well as the hydrographs (Fig. 9).

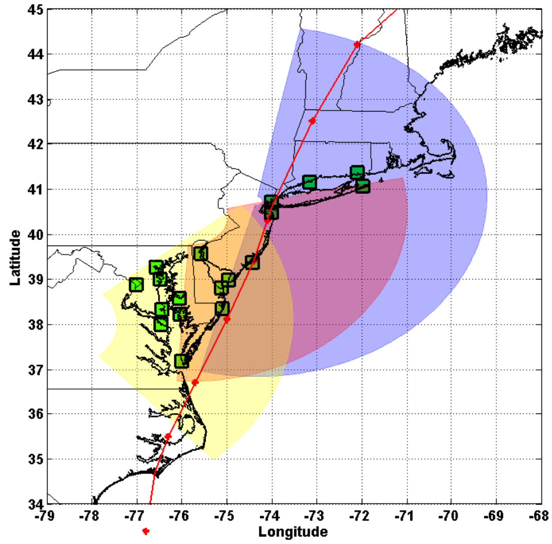

Fig. 7. Storm track (red line), observation stations (green squares), and SLOSH basins (shaded areas) applied for case Irene–2011.

	HWRF Grid	HWRF Track	H*Wind + GFS	H*Wind + BT	Best Track
RMSE Mean	1.08	0.98	0.91	0.82	0.81
RMSE Range	0.51-2.11	0.55-1.61	0.45-1.39	0.43-1.17	0.38-1.65
PE Mean	0.49	0.61	0.93	0.72	0.45
PE Range	0.15-1.75	0.06-1.35	0.14-1.65	0.02-1.45	0.02-1.25

Table 2. Skill scores, in feet, for simulating Hurricane Irene-2011 via the various forecast and hindcast modes.

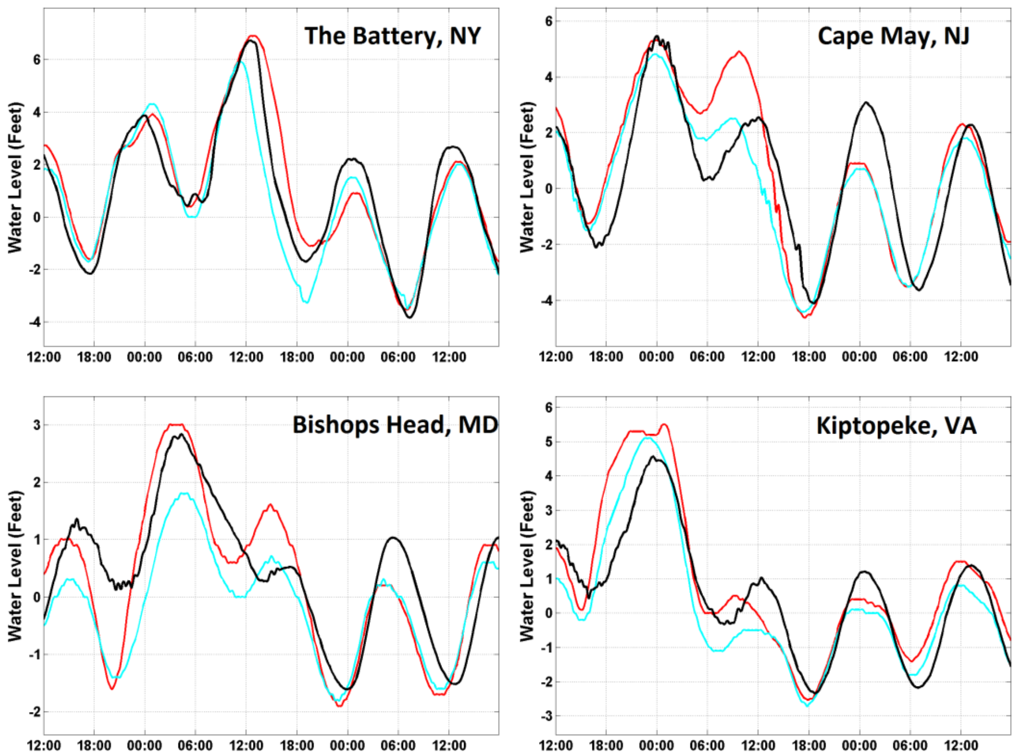

Fig. 8. Time series of NAVD88 water level during Irene-2011 (12Z, Aug. 27 – 18Z, Aug. 29). Observation: black; SLOSH with gridded HWRF: red; SLOSH with parametric HWRF forecast: blue.

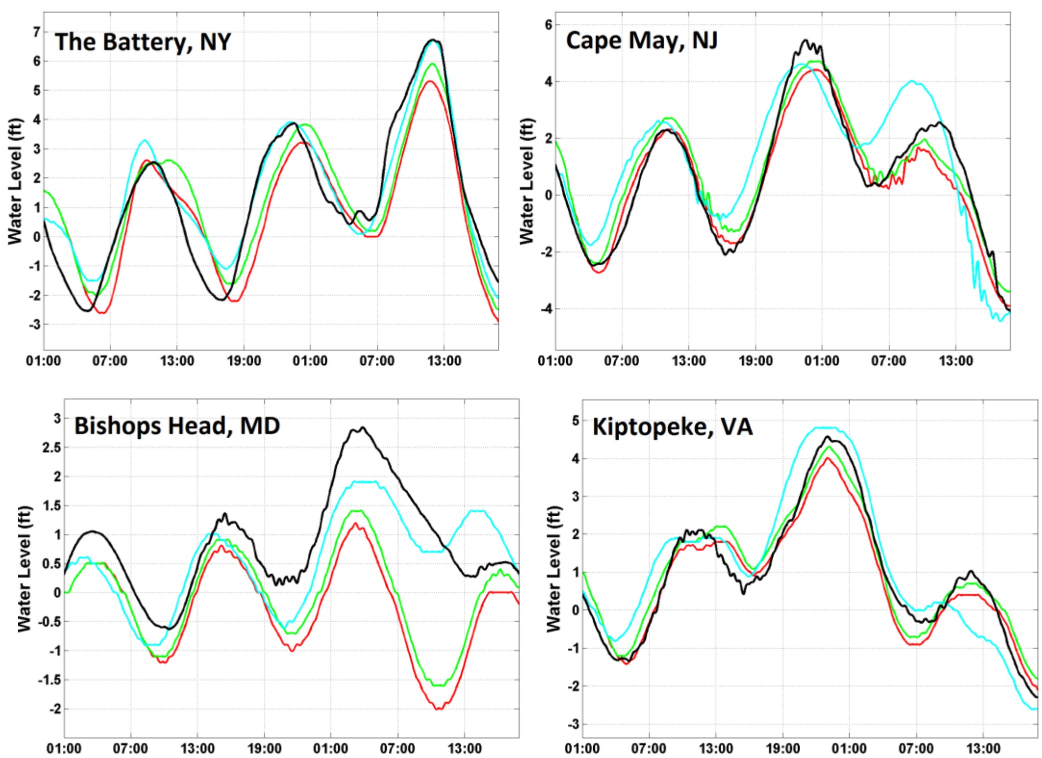

Fig. 9. Time series of NAVD88 water level during Irene-2011 (01:30Z, Aug. 27 – 18:30Z, Aug. 28). Observation: black; SLOSH with gridded H*Wind + GFS: red; gridded H*Wind + BT: green; parametric best track: blue.

5. DISCUSSION AND CONCLUSION

NWS's operational tropical storm surge model SLOSH has been upgraded to use gridded wind and pressure products as input, in addition to its original parametric wind model. The enhanced model has been tested in its various configurations by simulating Hurricane Sandy and Hurricane Irene. The performance of the various forecast and hindcast modes was analyzed based on comparisons with COOPS water level observations.

For asymmetric storms such as Hurricane Sandy, the gridded modes improved the storm surge results. This is because the gridded wind fields avoided the symmetric wind assumption made by the parametric wind model, thus providing more realistic inputs to the surge model.

For more symmetric storms such as Hurricane Irene, SLOSH with the original parametric wind model performed better because (a) the spatial interpolation of gridded wind fields from their original grids to SLOSH grids introduces errors and (b) the gridded wind models have errors. For a symmetric storm, the inaccuracies of the wind model and interpolation methods outweigh the inaccuracies of the parametric wind model.

ACKNOWLEDGEMENT

This study is supported by NOAA Sandy Supplemental Funding. The authors would like to note the contributions of Huiqing Liu for programming ideas.

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