3.1 FINER WIND FIELD RESOLUTION FOR NWS'S EXTRA-TROPICAL STORM SURGE MODEL

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1. INTRODUCTION

The National Weather Service (NWS) is developing tropical storm surge watch and warning products. Its goal in 2015 is to produce experimental graphics for watches and warnings that show at 2.5 km resolution where life threatening surge could occur (Tew et al. 2015). The agency has already developed a companion product, the tropical storm surge inundation graphic, to depict a forecast of how much water above ground could occur at a resolution of less than 100 m. The watch and warning products and inundation graphic product are intended to depict the threat of tropical storm surge overland. Results from the Probabilistic hurricane storm Surge (P-Surge) model provide the primary guidance for both products (Taylor and Glahn 2008).

To provide consistent service for storm surge events regardless of the cause, the NWS is considering developing extra-tropical storm surge watch and warning products, as well as an inundation graphic product. Much of the forecasting and collaboration infrastructure investment used to develop the tropical storm surge watch and warning can be leveraged for extra-tropical products; however, comparable model guidance is needed.

Operational extra-tropical storm surge guidance produced by the NWS consists of output from two deterministic models: the Extra-Tropical Storm Surge (ETSS) model and the Extratropical Surge and Tide Operational Forecast System (ESTOFS) model. For a detailed description of ESTOFS, please see Funakoshi et al. (2012). The ETSS model was developed by the NWS's Meteorological Development Laboratory (MDL) in 1995 by applying the Sea Lake and Overland Surges from Hurricanes (SLOSH) model (Jelesnianski et al. 1992) to extra-tropical storms. To do so, MDL (a) replaced SLOSH's parametric wind model with the Global Forecast System (GFS) winds and pressure on a 1 degree grid and (b) removed the computation of inundation based on surge (Kim et al. 1996). The latter change allowed the model to run efficiently on operational computers of the time. Both ETSS and ESTOFS run four times daily and create either 96 hourly forecasts (ETSS) or 168 hourly forecasts (ESTOFS) for the US East and West Coasts, US portion of the Gulf of Mexico, and the Gulf of Alaska. In addition, ETSS provides guidance for the US portion of the Bering Sea and Arctic. Unfortunately, the guidance from both models is not as comprehensive as P-Surge since (a) they compute surge to the coastline but not overland; and (b) they do not address uncertainty in the input wind and pressure fields.

As seen in Fig. 1, P-Surge 2.0 is based on three modeling developments which improved MDL's tropical guidance, but were not applied to MDL's extra-tropical guidance. Currently, ETSS is most comparable to the Special Programs to List Amplitudes of Surges from Hurricanes (SPLASH) model which provided storm surge guidance to the coastline but not overland (Jelesnianski et al. 1972). The first modeling development, the introduction of overland flooding based on storm surge alone, occurred in 1984 when SLOSH replaced SPLASH (Jelesnianski et al. 1984). The second modeling development, the application of ensemble modeling concepts to account for forecast uncertainty, occurred in 1986 with the

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introduction of climatological ensembles (Maximum Envelope of Water (MEOW) and Maximum of MEOWs (MOM)) to evaluate an area's potential storm surge risk for evacuation planning (Shaffer et al. 1986). Ensemble modeling concepts were applied again in 2008 with the development of real-time ensembles (e.g. P-surge) based on varying NHC official forecasts and associated average forecast errors (Taylor and Glahn 2008). The third modeling development, the ability to provide inundation based on surge and tide, began in 2012 with the introduction of gridded tide calculations in SLOSH (Haase et al. 2012), and culminated in 2014 with the P-Surge 2.0 system (Taylor et al. 2014).

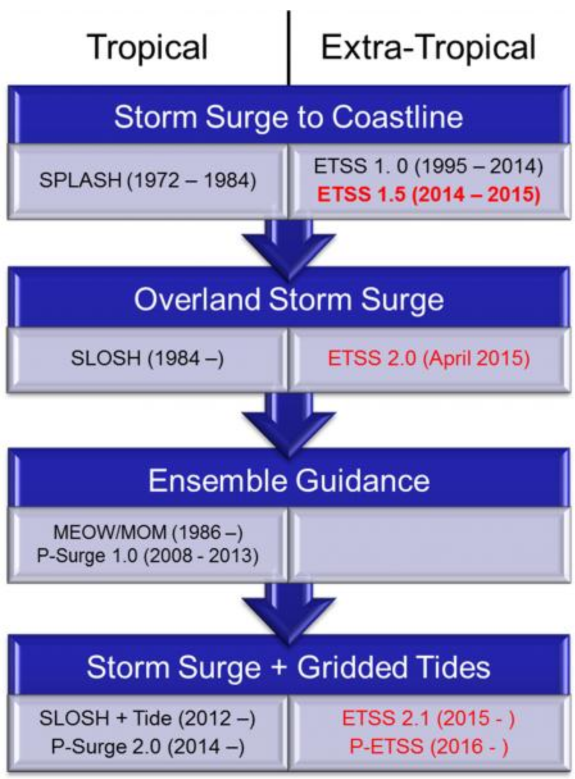

Fig. 1. Evolution of MDL's Tropical and Extra-Tropical guidance capabilities. Blue arrows indicate model developments and red text indicate recent or future products.

MDL, aided by Hurricane Sandy Supplemental funding, is applying those three modeling developments to ETSS with the goal of applying real-time ensemble concepts to a storm surge model which efficiently computes overland flooding based on surge and tide. Like the tropical improvements, extra-tropical improvements will occur in stages: (1) modify ETSS to compute overland flooding based on surge (Liu et al. 2015), (2) enable ETSS to compute inundation based on surge and gridded tides, and (3) develop Probabilistic Extra-Tropical Storm Surge (P-ETSS) initially by using the 21 GFS ensemble members to drive the improved ETSS model, but potentially including other atmospheric modeling systems.

2. OCTOBER 2014 IMPLEMENTATION

To prepare for these enhancements, in October 2014, MDL and National Centers for Environmental Prediction's (NCEP) NCEP Central Operations (NCO) upgraded ETSS. The implementation had several objectives including: (1) improve Alaska gridded guidance by selecting values from the Gulf of Alaska computational grid north of the Aleutian Islands, which act as a barrier to surge, rather than from the Bering Sea computational grid (Fig. 2); (2) use finer resolution output grids (from 5 km to 2.5 km for the CONUS and from 6 km to 3 km for Alaska); (3) make various coding improvements; and (4) switch the atmospheric input from 1 degree to 0.5 degree GFS gridded wind and pressure fields. Only objective (4) was hypothesized to improve the result and needed to be validated.

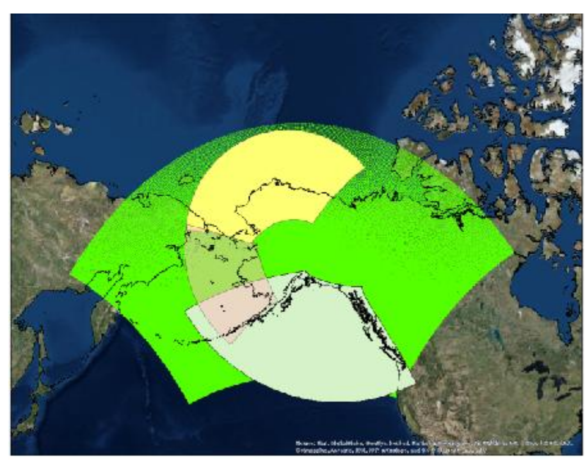

Fig. 2. Alaska merged grid (green) now derives values in the overlap area (pink) from the Bering Sea grid (dark green) instead of Gulf of Alaska grid (light green).

3. VALIDATION METHODOLOGY

Four storms (Hurricane Irene-2011, Hurricane Sandy-2012, extra-tropical March-2013, extra-tropical February-2013) were chosen to validate model performance at 31 Center for Operational Oceanographic Products and Services (COOPS) tide gauges (Fig. 3). While ETSS is intended to provide guidance for extra-tropical rather than tropical storms, using Hurricanes Sandy and Irene to expand the number of test cases is justified here as both were large storms at landfall and were captured well in the GFS wind and pressure fields.

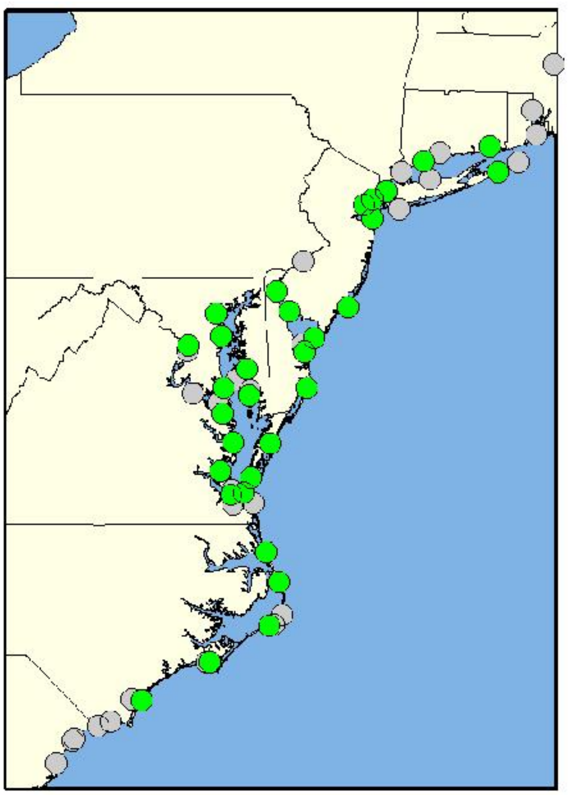

Fig. 3. Model output stations in the study area which are included (green) or omitted (gray).

As Fig. 3 indicates, the ETSS model outputs storm surge time series at a number of stations in the study area. Gray stations were excluded from the validation effort due to any of the following: (a) the station had been retired by COOPS, so observations were unavailable; (b) the station failed during the storm, so observations were unavailable for the full assessment period; and (c) the station was too far from the storms to be affected. Thus model performance was only assessed at the 31 stations shown in green Fig. 3.

A 48-h skill assessment period was chosen which covered the occurrence of peak surge at the 31 stations. To reduce the impact of variations among wind forecast cycles on the evaluation of model performance, the model was run with five different start times for the forecast wind and pressure inputs. Those start times correspond with GFS runs 0, 6, 12, 18, and 24 hours before the start of the 48 hour period. Storm surge output from all five model runs was averaged together to assess model performance. Assessment periods for each of the storms began on:

- August 27 for hurricane Irene-2011,
- October 29 for hurricane Sandy-2012,
- March 6 for extra-tropical March-2013,
- February 12 for extra-tropical February-2014

Statistical measures used to validate performance were:

1) Root Mean Squared Error (RMSE):

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

2) Peak Absolute Error (PAE):

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

Averaging the five model runs means that surge guidance at the beginning of the assessment period is based on an average of 0-, 6-, 12-, 18-, and 24-h old forecasts, whereas at the end of the period it is based on an average of 48-, 54-, 60-, 66-, and 72-h old forecasts. Wind and pressure forecast errors, and therefore storm surge model error, should increase with lead time. Thus, skill at a particular station is a function of how long it takes for a surge event to occur for that station and storm. While making model-to-model comparisons at a specific station is not a problem, as the models receive wind and pressure inputs from similar time windows and have comparable errors, station-to-station comparisons do pose a challenge.

4. RESULTS

Figures 4, 5, 6, and 7 provide hydrographs at representative stations for Hurricane Irene, Hurricane Sandy, extra-tropical March-2013 and extra-tropical February-2014, respectively. These hydrographs are typical in that surge guidance from the newest model version (ETSS 1.5) is closer to the observations (when the tidal signal is removed) than surge guidance from the original model (ETSS 1.0).

RMSE and PAE were calculated and averaged over all 31 stations during the 48-hour skill assessment periods. RMSE measures how well guidance and observations matched over the whole period, while PAE measures how well the guidance captured the critical maximum value. Table 1 contains the averaged RMSEs and PAEs.

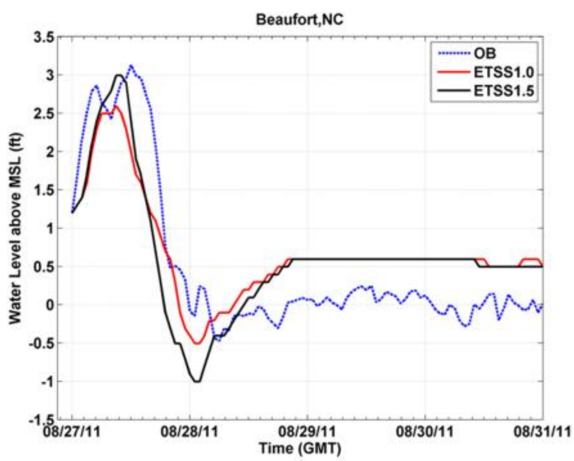

Fig. 4. Hydrograph for Hurricane Irene-2011 at Beaufort, NC. Observations without tide are in blue, original model is in red and new model is in black.

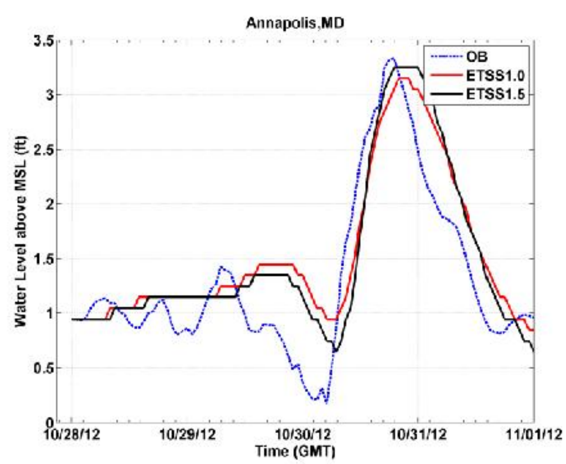

Fig. 5. Hydrograph for Hurricane Sandy-2012 at Annapolis, MD. Observations without tide are in blue, original model is in red and new model is in black.

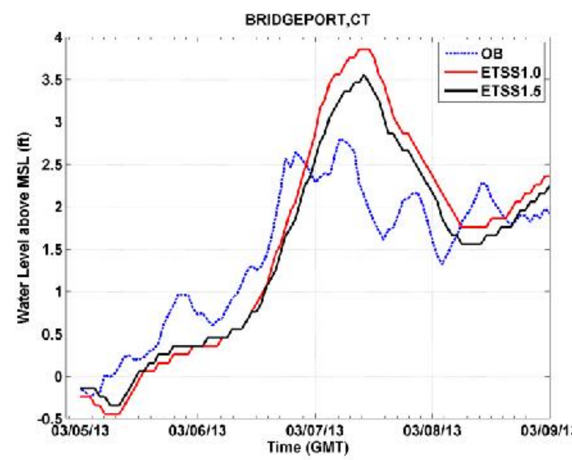

Fig. 6. Hydrograph for extra-tropical March-2013 at Bridgeport, CT. Observations without tide are in blue, original model is in red and new model is in black.

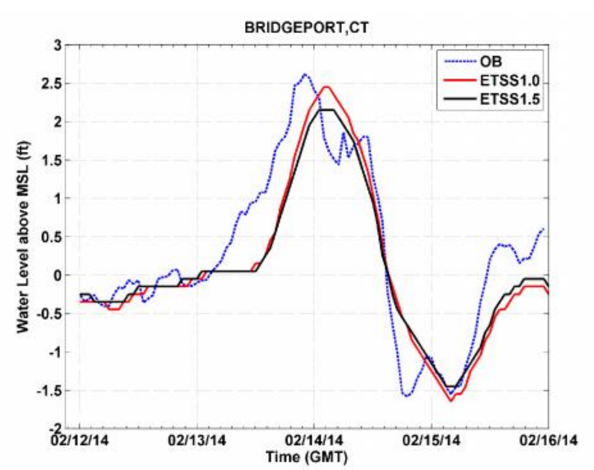

Fig. 7. Hydrograph for extra-tropical February-2014 at Bridgeport, CT. Observations without tide are in blue, original model is in red and new model is in black.

Score	Hurricane Irene-2011	Hurricane Sandy-2012	Extra-Tropical March-2013	Extra-Tropical February-2013
RMSE-ETSS 1.0	**0.65 feet**	**1.16 feet**	0.85 feet	**0.77 feet**
RMSE-ETSS 1.5	0.67 feet	1.23 feet	**0.82 feet**	0.78 feet
PAE-ETSS 1.0	1.14 feet	1.53 feet	1.02 feet	1.05 feet
PAE-ETSS 1.5	**1.02 feet**	**1.52 feet**	**0.96 feet**	**1.04 feet**
Overall	ETSS 1.5	ETSS 1.0	ETSS 1.5	Tie

Table 1. Average of the scores calculated for each assessment period over the 31 stations. Bold indicates a better score. Green indicates an improvement of more than 10%.

5. SUMMARY AND DISCUSSION

The higher fidelity to the GFS wind and pressure fields used in the October 2014 implementation is for the most part beneficial. The hydrographs indicated general improvement overall, however ETSS 1.0 was better in some locations. RMSEs were better for ETSS 1.0 in three of the four cases; however the differences are very small, with the largest being 6%. Alternatively, PAEs show ETSS 1.5 was always better than ETSS 1.0 (by more than 10% in one case). Therefore, the October 2014 implementation, by using higher resolution GFS wind and pressure fields, did not harm, and was beneficial to, the model performance.

Surprisingly, using higher resolution winds did not provide as much of an improvement as we expected. One thought is that higher fidelity to wind and pressure fields cause ETSS 1.5 to be more susceptible to errors in those fields. Consistent improvements in PAEs were reassuring, as correctly predicting peak surge is essential for inundation calculations. Future work with the model, such as nesting the finer tropical storm surge grids, may improve surge timing and RMSEs.

The GFS model continues to evolve with plans to produce grids at 0.25 degrees (26 km) and 0.125 degrees (13 km), but not initially disseminate the 0.125 degree results. This study could be repeated with the four different resolution wind and pressure fields along with the latest version of ETSS to determine the best choice for GFS input resolution.

6. ACKNOWLEDGEMENTS

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