4.4 Creating Storm Tide Inundation Guidance and Bridging the Bering Strait with NWS' ETSS Model

Huiqing Liu[1], Arthur Taylor[2*] and Christina Belton[1]
1. Ace Info Solutions, Reston, VA
2. NOAA / NWS / Office of Science and Technology Integration/ Meteorological Development Laboratory, Silver Spring, MD
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1. INTRODUCTION

The National Weather Service's (NWS) Meteorological Development Laboratory (MDL) developed the Extra-Tropical Storm Surge (ETSS) model in 1995 (Kim et al. 1996) by applying the Sea Lake and Overland Surges from Hurricanes (SLOSH) model (Jelesnianski 1992) to Extra-Tropical storms. Over the last two years, MDL, with Hurricane Sandy Supplemental funding, has enhanced the ETSS model to meet anticipated requirements for a potential extra-tropical storm surge watch and warning. These enhancements included (a) in October 2014, switching to 0.5 degree, instead of 1.0 degree, Global Forecast System (GFS) winds and pressure as inputs (Taylor et al. 2015) and (b) in May 2015, nesting the finer resolution overland tropical grids within the coarser but broader extra-tropical grids (Liu et al. 2015). These changes, combined with a reintroduction of the inundation algorithm, provide inundation guidance based on storm surge alone which allow NWS to consider an overland extra-tropical storm surge watch and warning.

To improve the accuracy of the overland flooding guidance, in November 2015, MDL modified ETSS's inundation calculations to consider both surge and tide. This was done by extracting tidal constituents from two tidal databases. Specifically, for the East Coast and Gulf of Mexico, 37 tidal constituents were derived from the ADvanced CIRCulation (ADCIRC) EC-2014 tidal database, and for the West Coast and Alaska, 13 tidal constituents were derived from Oregon State University's TOPEX/Poseidon Global Tidal model (TPXO). Having tidal constituents at each grid cell allows ETSS to provide inundation guidance based on storm surge and tide in all of its model domains. Additionally, to increase the fidelity of the inundation product to the model results, MDL increased the resolution from 2.5 km to 625 m for the East Coast and Gulf of Mexico. Unfortunately the resolution of the computational domains for the West Coast and Alaska do not support higher resolution outputs.

In November 2015, MDL also addressed the fact that water could not flow through the Bering Strait due to using separate model domains. This was a significant failing in the accuracy of guidance in the Bering, Beaufort and Chukchi (BBC) seas. The solution was to replace the two separate grids with a single large BBC basin with the latest bathymetry and topography data.

This paper describes the details of both efforts and evaluates the resulting upgrade with case studies of historical events. The details of incorporating tide calculations into SLOSH are described by Fritz (Fritz et al. 2014), so they are omitted here. Section 2 discusses the impacts of including tides and producing finer resolution (625 m) output on inundation guidance using Hurricane Sandy-2012 as an example. Section 3 describes efforts to improve accuracy of guidance in the Alaska region. Section 4 describes historical storms and observations used for validation of the Alaska improvements. Results are presented in section 5 and discussion in Section 6.

2. Tide and output resolution impact on inundation

Accurate prediction of overland flooding requires inundation computed from water levels based on surge and tide. As of May 2015, ETSS did not model tides. Fortunately, in 2012, a tidal calculation capability was added to the SLOSH model and applied to the tropical basins along the East Coast and Gulf of Mexico. This was done by extracting at each grid cell, 37 tidal constituents from the ADCIRC EC-2014 tidal database. MDL adapted this method when creating ETSS version 2.1 (ETSS2.1) in November 2015. Unfortunately for the West Coast Alaska, there were no high resolution tidal databases available in time to be incorporated, so 13 tidal constituents were derived from TPXO. For details of TPXO, please see:

* Corresponding Author: Arthur Taylor, 1325 East-West Hwy, Silver Spring, MD 20910-3280; e-mail: arthur.taylor@noaa.gov

http://volkov.oce.orst.edu/tides/global.html.

ETSS produces products on an interpolated grid with 2.5 km resolution rather than its native grid. This allows easier use of the products, but at a cost in terms of fidelity to the model. For the East Coast and Gulf of Mexico, the native grids are fine

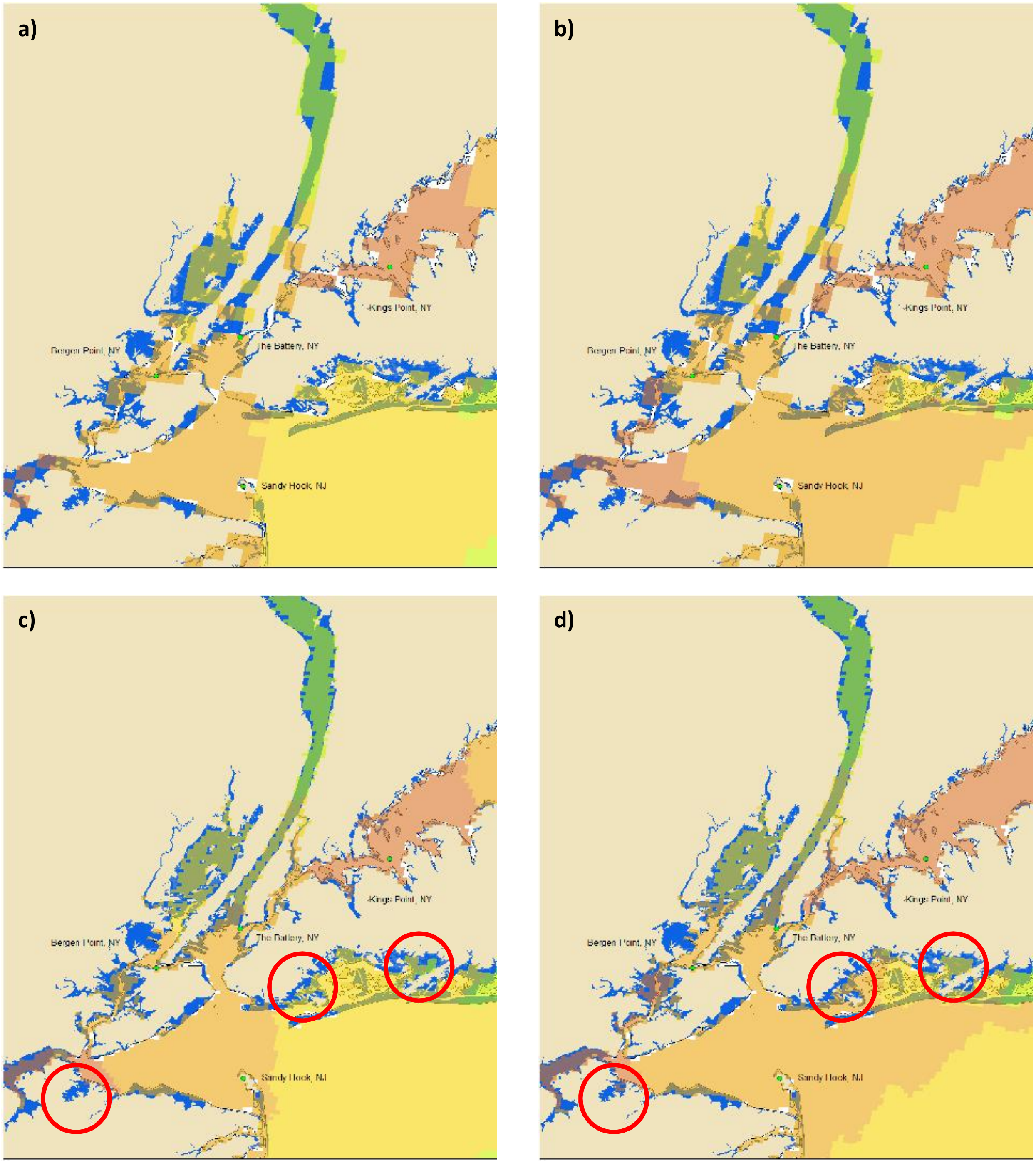

Fig. 1. Inundation map for Hurricane Sandy-2012 with field verified inundation data in blue. a) ETSS without tide at 2.5 km resolution; b) ETSS with tide at 2.5 km resolution; c) ETSS without tide at 625 m resolution; d) ETSS with tide at 625 m resolution.

enough to support 625 m resolution products, so ETSS2.1 created them to support users who can handle the larger files and grid sizes. Unfortunately, we cannot repeat this work for the West Coast or Alaska until finer native resolution grids exist.

To show the impact of including tides and higher resolution on ETSS inundation guidance, four ETSS2.1 flooding maps at 2.5 km and 625 m resolution with and without tide were created for Hurricane Sandy-2012 and compared with field verified observation data. Note that while ETSS is intended for extra-tropical rather than tropical storms, Hurricane Sandy was use since it was a large storm that was transitioning to extra-tropical at landfall. Fig. 1 shows these four inundation maps. The maps without tides are in Fig. 1a (2.5 km) and 1c (625 m), while those with tides are in Fig. 1b (2.5 km) and 1d (625 m).

The 625 m maps clearly resemble the field verified observations more closely than the 2.5 km maps. It is also hard to detect the impacts of including tide on the 2.5 km maps, whereas including the tides has a noticeable difference in the results on the 625 m maps (red circled areas in Fig. 1c and Fig. 1d). This shows that incorporating tides and interpolating to a higher resolution output grid improves the ETSS inundation product.

3. Improvements in Alaska Region

Before November 2015, ETSS used two separate non-communicating basins: OTZ and NOM on either side of the Bering Strait to cover the Bering, Beaufort and Chukchi Seas region (Fig. 2 shows OTZ in purple and NOM in blue). Unfortunately, this impacted the accuracy of ETSS storm surge guidance in the area as water was not allowed to flow through the Bering Strait. To resolve this, MDL created a single BBC (Bering, Beaufort and Chukchi Seas) basin (Fig 2. shows BBC in green) using the latest bathymetry and topography information. In ETSS version 2.1 the two decade old non-communicating basins were replaced with the BBC basin. Also, since the BBC basin contains coarse topography data, ETSS is now able to provide inundation guidance in the area.

While it is conceptually clear that water should flow through the Bering Strait, Fig. 3 shows the actual impact on the 48-hr forecast from the 06Z run on October 16, 2015. Figure 3a shows the forecast using the OTZ and NOM basins, whereas 3b shows the forecast using the BBC basin. This shows that there existed an unrealistic discontinuity on either side of Bering Strait. The quantitative assessment of this will be given in the next two sections.

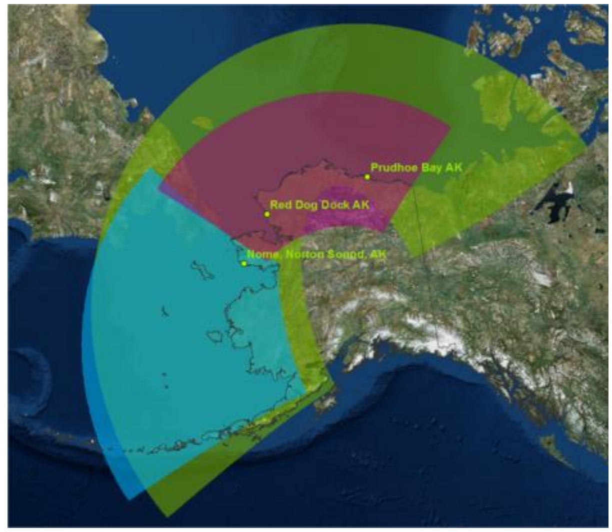

Fig. 2. ETSS basins: OTZ (purple), NOM (blue), BBC (green); in the Bering, Beaufort, and Chukchi Seas region.

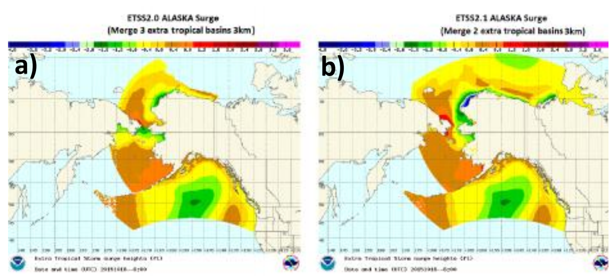

Fig. 3. 48-hr forecast from 06Z Oct 16, 2015 with (a) using OTZ and NOM basins and (b) using the BBC basin.

4. Historical Events

To do a quantitative analysis, retrospective model runs were made in the time frame from January 2006 to December 2014. To determine interesting events in that time frame, we looked through the water level observations at Nome (Fig. 4) for when either of the following two criteria applied. The first, intended to find storms with significant human impact, is when the water above ground, using Mean Higher High Water as a proxy, was taller than a child (3 feet). The second, intended to find storms interesting from a surge model's perspective, is when the water level without tide (aka Surge Only) was higher than 4 feet. Based on these criteria, 15 events were chosen for their human impacts and 2 events were chosen due to model impacts (Fig. 5) to evaluate the model performance. To avoid missing some historic events in other parts of the basin, the water level observations at the other two NOAA tidal stations (Prudhoe and Red Dog Dock) were checked using the same criteria. No new cases were found.

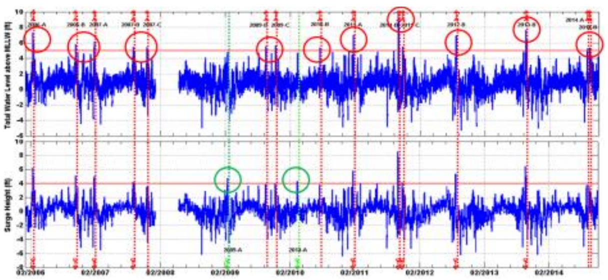

Fig. 4..Observed total water level (top) and surge height (bottom) from 2006 to 2014 at Nome.

Storm ID	Year	96 hour period (6 hour projection) over which RMSE, PAE is calculated	Storm ID	Year	96 hour period (6 hour projection) over which RMSE, PAE is calculated
2006-A	2006	FEB 12 01z – FEB 16 00z	2010-B	2010	AUG 14 01z – AUG 18 00z
2006-B	2006	OCT 15 01z – OCT 19 00z	2011-A	2011	FEB 23 01z – FEB 27 00z
2007-A	2007	JAN 29 01z – FEB 2 00z	2011-B	2011	NOV 8 13z – NOV 12 12z
2007-B	2007	SEP 9 01z – SEP 13 00z	2011-C	2011	DEC 3 01z – DEC 7 00z
2007-C	2007	NOV 28 01z – DEC 2 00z	2012-B	2012	OCT 4 13z – OCT 8 12z
2009-A	2009	MAR 4 01z – MAR 8 00z	2013-B	2013	NOV 8 01z – NOV 12 00z
2009-B	2009	OCT 10 01z – OCT 14 00z	2014-A	2014	OCT 25 01z – OCT 29 00z
2009-C	2009	DEC 5 01z – DEC 9 00z	2014-B	2014	NOV 9 01z – OCT 13 00z
2010-A	2010	APR 10 01z – APR 14 00z			

Fig. 5. Events with human impact (white) and model impact (green) from 2006 to 2014.

ETSS skill scores for 24-hr, 48-hr, 72-hr and 96-hr forecasts were evaluated at Nome, Prudhoe, and Red Dog Dock based on statistical scores calculated from a 96 hour time series. The 96 hour time series was created by splicing together 6 hour projections from consecutive model runs. For example, the 24-hr forecast used hours 19 to 24 from the consecutive model runs. Doing this reduces the impact of errors within different wind forecast cycles on the surge model assessment. Model performance was then assessed based on the average of the scores at the three stations.

Two statistical scores were used to assess model performance:

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),

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

5. RESULTS

Mean RMSE and Peak surge correlation scatter plot of 24-hr forecast window at these 3 stations for the 17 historical events are shown in Fig. 6. ETSS2.1 (green in Fig. 6) outperformed the previous version - ETSS2.0 (blue in Fig. 6) in 16 events and tied in one (Fig. 6a). The average RMSE for the 17 historical events are 0.82 feet and 1.00 feet for ETSS2.1 and ETSS2.0 respectively. Fig. 6b shows peak surge correlation between ETSS model and observation data at the three stations for the 17 historical events. The figure indicates peak surge skill improved in ETSS2.1 compared to ETSS2.0; however, many of the cases were below the 20% under forecast line. Simulating peak surge correctly is critical to determining inundation extent.

To further improve the peak surge skill, a revised wind drag coefficient formula was included in ETSS-2.1 model (ETSS2.1-WindDrag). The red color in Fig. 6 shows the resulting RMSE and peak surge correlation results for the 24-hr forecast. Using the revised wind drag formula, averaged RMSE for all 17 events is reduced to 0.72 feet. Furthermore, most of the peak surge under-forecast cases were pulled above the 20% under forecast line (Fig. 6b). Fig. 6b (Peak surge scatter plot) indicates that most of the peak surge simulations from ETSS2.1-WindDrag fall between the 20% over forecast line and the 20% under forecast line. The mean statistical scores (RMSE, PAE) of 3 stations of 24-hr forecast from each of 17 events are presented in Table 1.

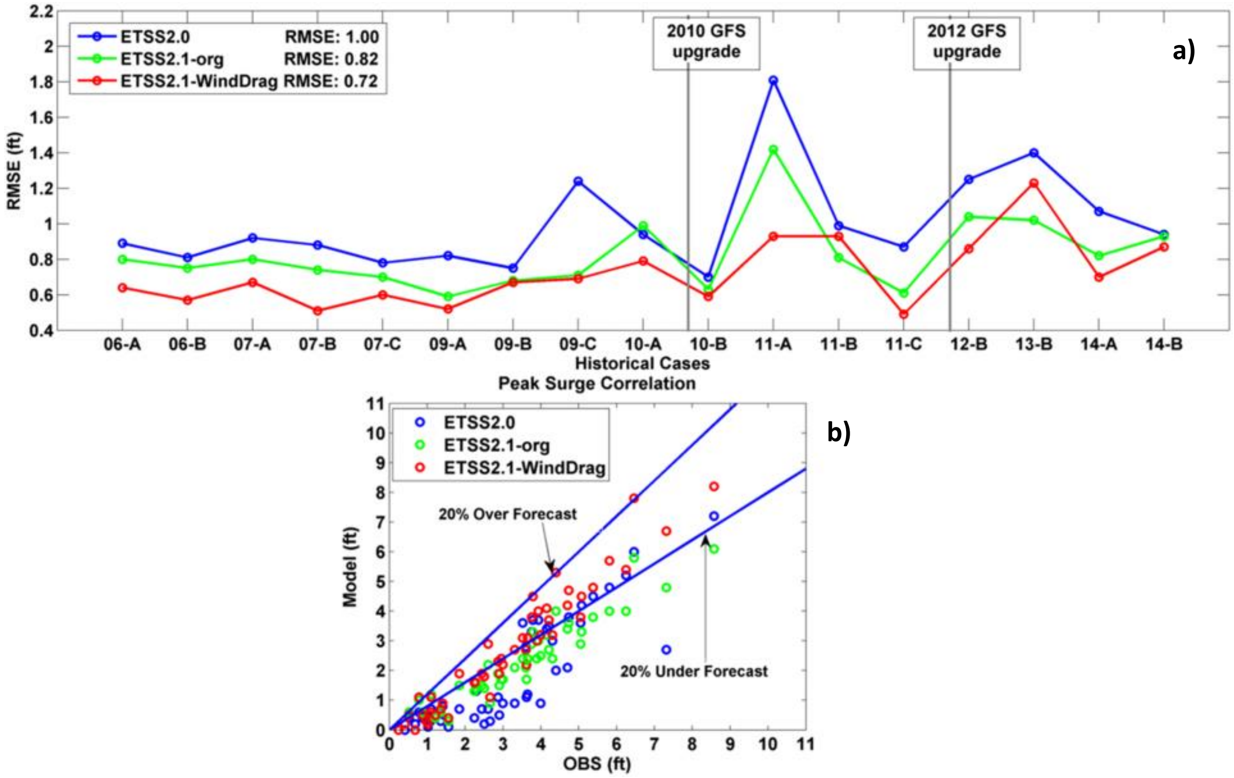

Fig. 6. 24-hr forecast window results. a) Average RMSE over the 3 stations plot from ETSS2.0, ETSS2.1 and ETSS2.1 with modified wind drag coefficient of 17 events and b) peak surge scatter plot at 3 tidal stations of 17 events.

Table 1 Average of the RMSE and PAE over the 3 stations for 17 events.

RMSE (feet)	2006 A	2006 B	2007 A	2007 B	2007 C	2009 A	2009 B	2009 C	2010 A	2010 B	2011 A	2011 B	2011 C	2012 B	2013 B	2014 A	2014 B
ETSS 2.0	0.89	0.81	0.92	0.88	0.78	0.82	0.75	1.24	0.94	0.70	1.81	0.99	0.87	1.25	1.40	1.07	0.94
ETSS 2.1	0.80	0.75	0.80	0.74	0.70	0.59	0.68	0.71	0.99	0.63	1.42	0.81	0.61	1.04	1.02	0.82	0.93
ETSS 2.1 New wind Drag	0.64	0.57	0.67	0.51	0.60	0.52	0.67	0.69	0.79	0.59	0.93	0.93	0.49	0.86	1.23	0.70	0.87

PAE (feet)	2006 A	2006 B	2007 A	2007 B	2007 C	2009 A	2009 B	2009 C	2010 A	2010 B	2011 A	2011 B	2011 C	2012 B	2013 B	2014 A	2014 B
ETSS 2.0	1.15	1.35	1.39	1.04	0.57	1.29	1.22	1.45	1.34	0.59	2.71	1.48	0.88	1.58	1.90	1.41	1.28
ETSS 2.1	0.98	1.22	1.15	1.04	0.72	1.02	1.08	1.02	1.24	0.48	2.08	1.31	0.67	1.35	1.26	0.91	1.28
ETSS 2.1 New wind Drag	0.50	0.69	0.72	0.57	0.46	0.42	0.78	0.50	0.80	0.14	0.71	0.32	0.21	0.78	1.13	0.72	1.01

Mean RMSE of 48-hr, 72-hr and 96-hr forecast at 3 stations for the 17 historical events are shown in Fig. 7. RMSE indicates that overall performance of ETSS2.1 with all enhancements is improved compared to ETSS2.0 in all forecast periods. The improvement decreases with increasing forecast hours, likely due to increased uncertainty of the wind forecast. Fig. 8 shows the peak surge scatter plot for the 24-hr, 48-hr, 72-hr and 96-hr forecasts and matches the trend seen with the

RMSE score. For the 48-hr forecast, ETSS2.1 shows a significant improvement over ETSS2.0; however, the skill decreases with increased forecast hours. In the 72-hr and 96-hr forecast results, ETSS2.1 was in some cases above the 20% over forecast line for peak surge (Fig. 8).

6. SUMMARY AND DISCUSSION

ETSS2.1 is a significant improvement over the previous version of the model. The incorporated tide simulation and high resolution 625 m output grid at US East Coast and Gulf of Mexico produce more realistic inundation guidance. The Bering Strait discontinuity has been resolved and the bathymetry has been updated and topography added to allow for inundation calculations. The new basin combined with a revised wind drag formula produces better skill scores for the Bering, Beaufort and Chukchi Seas. It is worth noting that the revised wind drag formulation was only applied to the BBC basin.

A number of actions can be undertaken to further improve ETSS performance. In the near term, the separate Gulf of Alaska and West Coast computational basins will be replaced with a single new grid, allowing water to flow along the Canadian coastline into the West Coast regions. Additionally, as with Probabilistic Hurricane Storm Surge (Taylor and Glahn 2008; Taylor et al. 2014), MDL will develop and implement Probabilistic Extra-Tropical Storm Surge (P-ETSS) guidance in 2016, to address the uncertainty of wind forecasting. Initially it will use an equal weight of 21 GFS ensemble members to generate probabilistic storm surge and tide guidance. After the initial version of P-ETSS, we plan to include more ensemble members (as resources permit), and explore other methods of producing probabilistic products from the ensemble members.

In the long term, MDL may improve ETSS to: (a) model the impacts of ice (northern regions), waves and river flow on storm surge, (b) improve the spatial interpolation method for the wind field from the GFS grid to ETSS basin, (c) apply the new revised wind drag coefficients to all ETSS basins (based on the results of retrospective runs), and (d) utilize spatially varying bottom friction coefficients dependent on different types of sea bottoms and water depth.

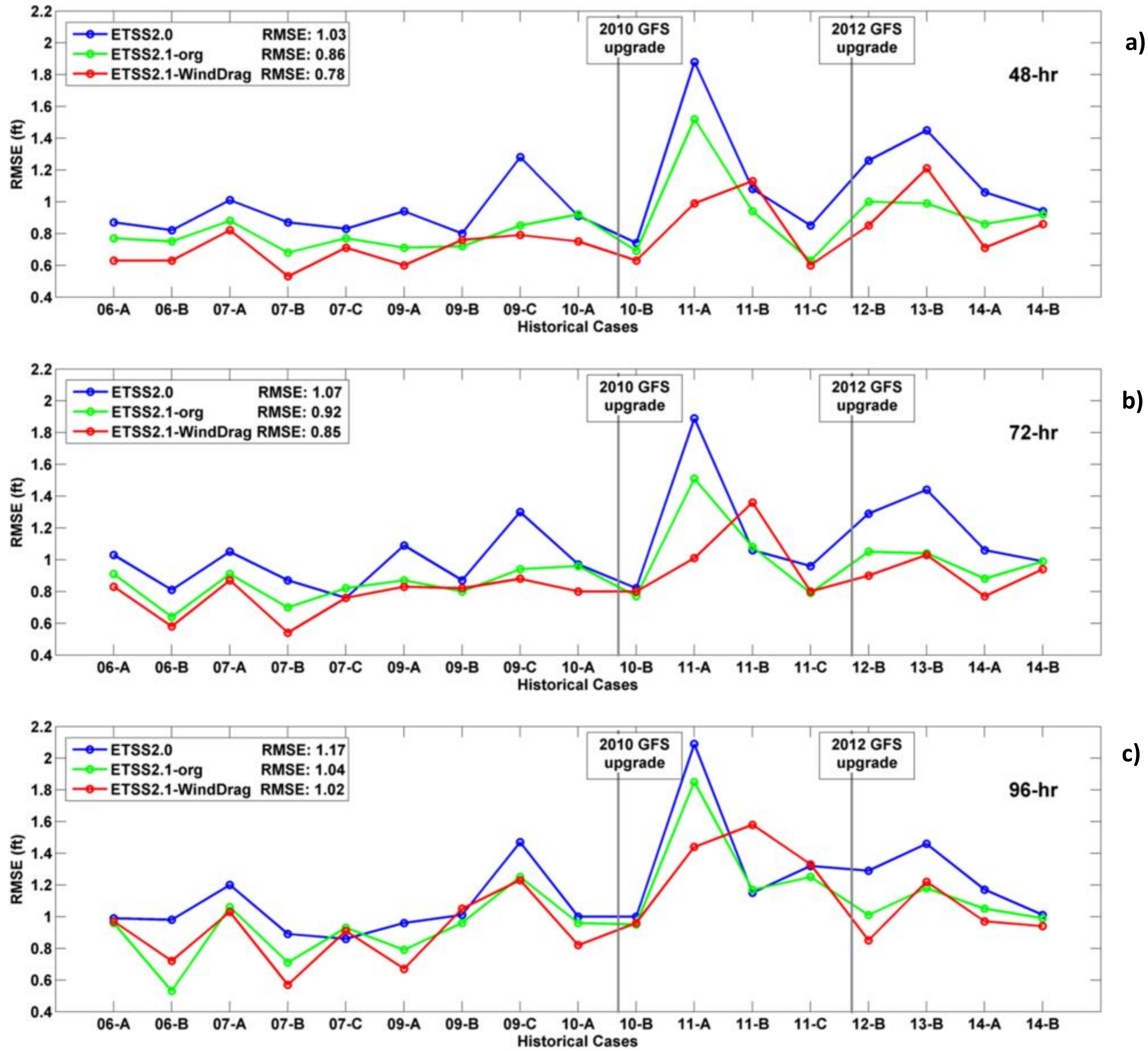

Fig. 7. Average RMSE over the 3 stations from ETSS2.0, ETSS2.1 and ETSS2.1 with modified wind drag coefficient of 17 events for a) 48-hr; b) 72-hr and c) 96-hr forecast window results.

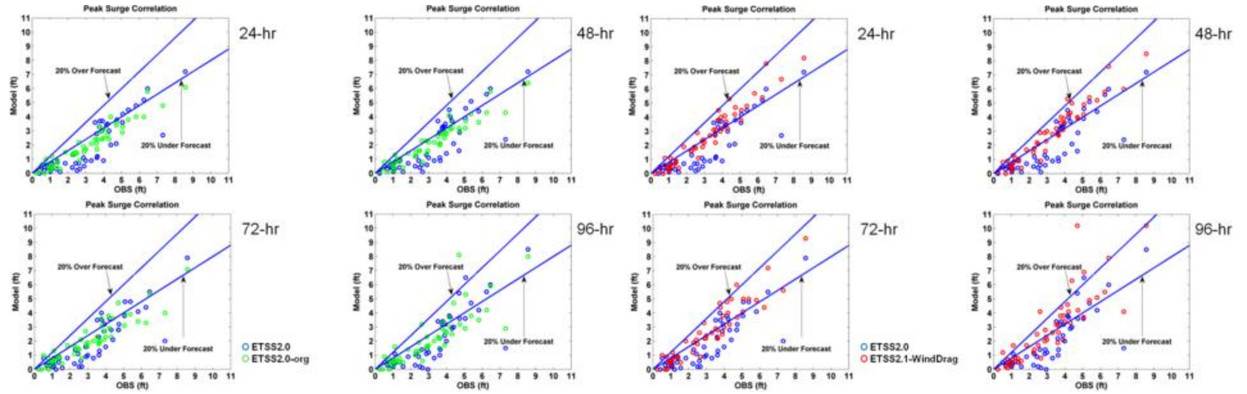

Fig. 8. Peak surge scatter plot at 3 tidal stations of 17 events for 24-hr, 48-hr, 72-hr and 96-hr forecast window. Blue dot is ETSS2.0 result, green dot is ETSS2.1 result and red dot is ETSS2.1 with modified wind drag coefficient.

7. ACKNOWLEDGEMENTS

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