1.2 DEVELOPMENT OF THE NWS' PROBABILISTIC EXTRA-TROPICAL STORM SURGE MODEL AND POST PROCESSING METHODOLOGY

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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., 2006) to provide guidance for Coastal Flood watches and warnings. To provide total water level guidance, MDL developed in 2000, a post-processing methodology which added at tide gauges, the surge guidance to the tide prediction and a statistical estimate of other water level components such as sea level rise, disruptions of currents, waves, river flooding and model error.

More recently, in anticipation of the overland requirements of a potential extra-tropical storm surge watch and warning, MDL enhanced the ETSS model to operationally provide deterministic inundation guidance based on storm surge and tide, four times a day, in coastal areas along the United States' Eastern and Western Seaboards, the Gulf of Mexico and Alaska. These enhancements included: in October 2014, switching to 0.5 degree (versus 1.0 degree) Global Forecast System (GFS) winds and pressure as inputs (Taylor et al. 2015), in May 2015, nesting the finer resolution overland tropical grids within the coarser but broader extra-tropical grids (Liu et al. 2015), in November 2015, modifying ETSS's inundation calculations to consider both surge and tide (Liu et al. 2016) and in December 2017, improving the tidal simulation along the coasts of Alaska and the Gulf of Mexico (Liu and Taylor 2018).

However, storm surge guidance has various uncertainties associated with it such as: the atmospheric forcing (wind speed, wind direction and atmospheric pressure), the initial water conditions, the included physical processes, the numerical scheme, etc. While some of these can be reduced by enhancing the storm surge model, others, such as atmospheric forcing, rely on external inputs. Uncertainty in atmospheric forcing is of particular importance as it is the main source of uncertainty in storm surge based inundation guidance. Hurricane Joaquin (2015) (Fig. 1) is a good example of this. Slight variations in the atmospheric forcing can result in considerable variations in the deterministic storm surge model results (Fig. 2).

Ensemble techniques combining atmospheric forcing and storm surge modeling are necessary to produce quantitative estimates of storm surge based inundation risk. MDL first did this with Probabilistic Tropical Cyclone Storm Surge (P-Surge) (Taylor and Glahn 2008); however this method requires a way of parameterizing the atmospheric forcing. Something else is needed for extra-tropical cases or tropical cases that are not easily represented by a parametric wind model (Taylor et al. 2014). MDL has recently implemented such an ensemble technique in the form of the Probabilistic Extra-Tropical Storm Surge (P-ETSS) model. P-ETSS uses the 21 ensemble members from the Global Ensemble Forecast System (GEFS) as atmospheric input to the ETSS model. It then equally weights the resulting set of inundation guidance. Since the inundation model does not account for water level components such as sea level rise, waves, and river flooding; a statistical post processing methodology, similar to ETSS', is used at stations to enhance the overall guidance and account for model bias.

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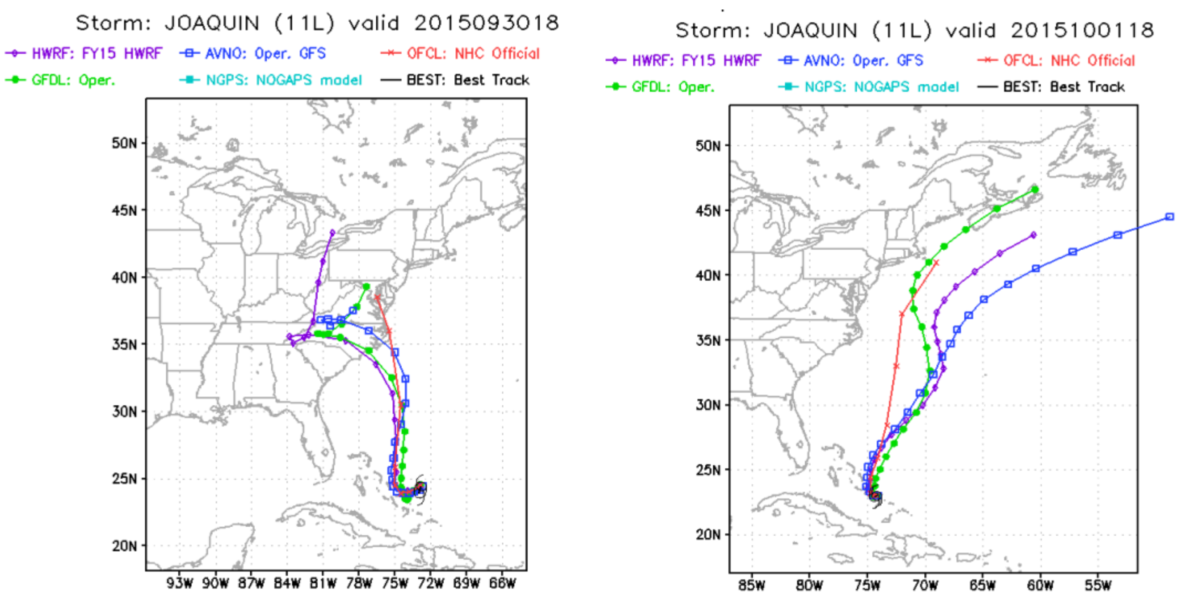


Fig. 1 Hurricane Joaquin track forecast from GFS (blue), other models (HWRF, GFDL) and NHC's forecast (OFCL) at 18Z, Sep. 30, 2015 (left) and at 18Z, Oct. 1, 2015 (right). (From NCEP Operational HWRF Forecast Guidance for Storm JOAQUIN)

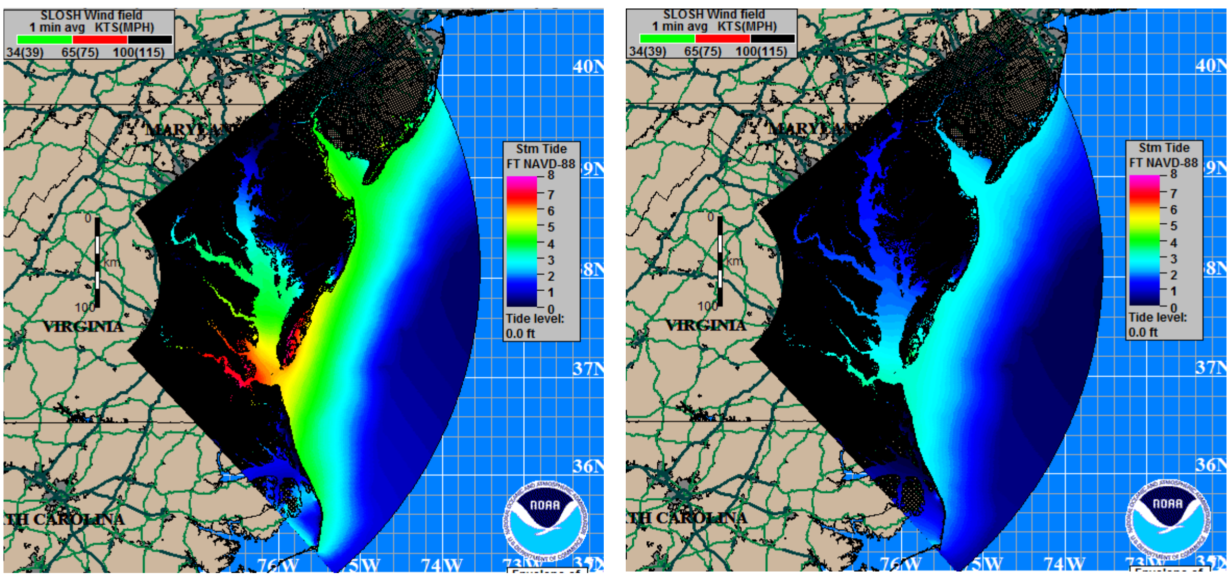
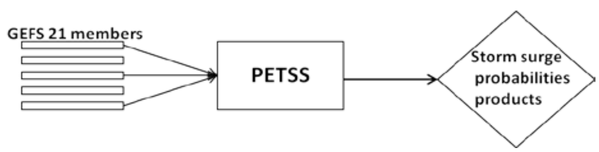


Fig.2 ETSS2.1 maximum storm surge + tide for the next 96 hours starting at 18Z, Sep. 30, 2015 (left) and 18Z, Oct. 1, 2015 (right).

This paper describes the details of this effort and evaluates P-ETSS results from five historical events. Section 2 describes P-ETSS' methodology and products. Section 3 lists the historical storms along with observations used to validate the P-ETSS results. Section 4 presents the results. Section 5 discusses the post processing adjustment. Section 6 discusses Hurricane Irma and how P-ETSS and P-Surge can be used together. The paper concludes with a summary and discussion in Section 7.

2. METHODOLOGY AND PRODUCTS



As the diagram shows, P-ETSS uses the 21 ensemble members from the GEFS as atmospheric input to the ETSS model. In each grid cell, the surge + tide values from each ensemble run are sorted in ascending order. The probability and exceedance products are created from this sorted set.

Specifically for the **Probability of Surge + Tide** greater than X products for X in {0, 1, 2, 3, 6, 7, 8, 9, 10, 13 and 16 feet above datum or ground level}, it counts in each grid cell the number (N) of ensemble runs greater than X. The probability in that grid cell is then: N*100/21. See Fig. 3 for an example where the probability of > 1 feet is 80%.

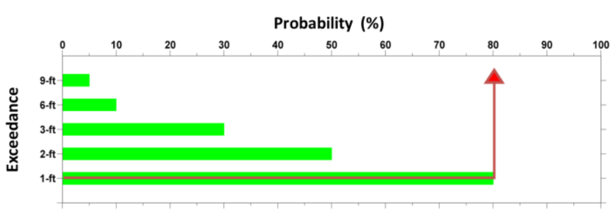


Fig. 3 is an example of using the number of values with surge + tide greater than a threshold to determine the probability

For the **X% Exceedance Height** products, for X in {10, 20, 30, 40, 50, 90}, it searches down the sorted list for the height (above datum or ground level) in the "correct" spot. For example, the 10% exceedance with 21 members is the value that is matched or exceeded by 2.1 ensemble members, so we want the 2^{nd} spot in the sorted list (Fig 4). Thus the "correct" spots for {10, 20, 30, 40, 50, 90%} are {2^{nd}, 4^{th}, 6^{th}, 8^{th}, 10^{th}, 19^{th}} respectively.

The final P-ETSS product is the **Ensemble Mean, Minimum and Maximum** computed by taking the algebraic mean, minimum and maximum values in each grid cell respectively, in feet above datum or ground level.

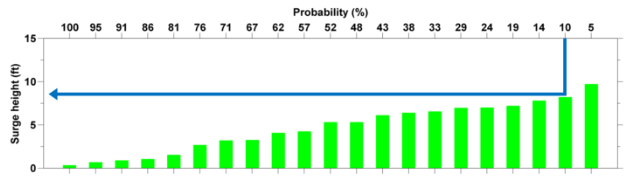


Fig. 4 is an example of determining the 10% exceedance value from a specific element in the stored list of surge + tide values.

3. HISTORICAL STORMS

To compare P-ETSS and ETSS, a quantitative analysis using retrospective model runs was made over the past two years. The two year limitation was chosen because the GEFS underwent a major upgrade in December 2015 with the introduction of 0.5 degree wind resolution grids, so GEFS model runs before that were deemed unrepresentative of the current model. Of the interesting storms over the last two years, we chose to evaluate model performance with the following five: Tropical Storm Colin 2016, Hurricane Hermine 2016, Hurricane Matthew 2016, Hurricane Harvey 2017 and Hurricane Irma 2017. From these five storms, we identified a total of 57 pertinent tide gauge observation time frames.

P-ETSS and ETSS skill scores for 12-hr, 24-hr, 36-hr, 48-hr, 60-hr, 72-hr, 84-hr and 96-hr projection windows were evaluated against the 57 tide gauge observation time frames based on statistical scores calculated from a 96-hr time series. The 96-hr time series was created by splicing together 6-hr projections from consecutive model runs. For example, the 24-hr projection window spliced hours 19 to 24 from one model run to hours 19 to 24 from the next consecutive model run. This results in a relatively constant projection thereby reducing the impact of errors within different projections on the surge model assessment.

Model performance was then assessed based on the average of the following scores over the various tide gauge observation time frames:

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),

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

4. RESULTS

The average RMSE and PAE for the 57 tide gauge observation time frames for the 12-hr, 24-hr, 36-hr, 48-hr, 60-hr, 72-hr, 84-hr and 96-hr projection windows are shown in Fig. 5. During the short term (24 hours or less) projection windows, the P-ETSS ensemble mean and ETSS model performed similarly with regards to average RMSE and PAE. However, as the projection hour increased, the P-ETSS ensemble mean's RMSE and PAE remained relatively constant, while they increased for the ETSS model. Thus for projection hours greater than 24, the P-ETSS ensemble mean outperformed the ETSS model.

Scatter diagrams of the peak surge versus observation for the 24-hr, 48-hr, 72-hr and 96-hr projections from the 57 tide gauge observation time frames are plotted in Fig 6. The figure indicates that the P-ETSS ensemble mean's peak surge guidance is better than the ETSS model's and improves with increased projection hour. The P-ETSS ensemble mean is also more stable in terms of peak surge guidance than the ETSS model. However, Fig. 6 demonstrates that both ETSS and P-ETSS are under forecasting in many cases. Forecasters require accurate peak storm surge guidance to enable them to forecast the inundation extent for a storm surge watch/warning, so we introduce a post processing adjustment at stations in the next section to further improve the peak surge forecast.

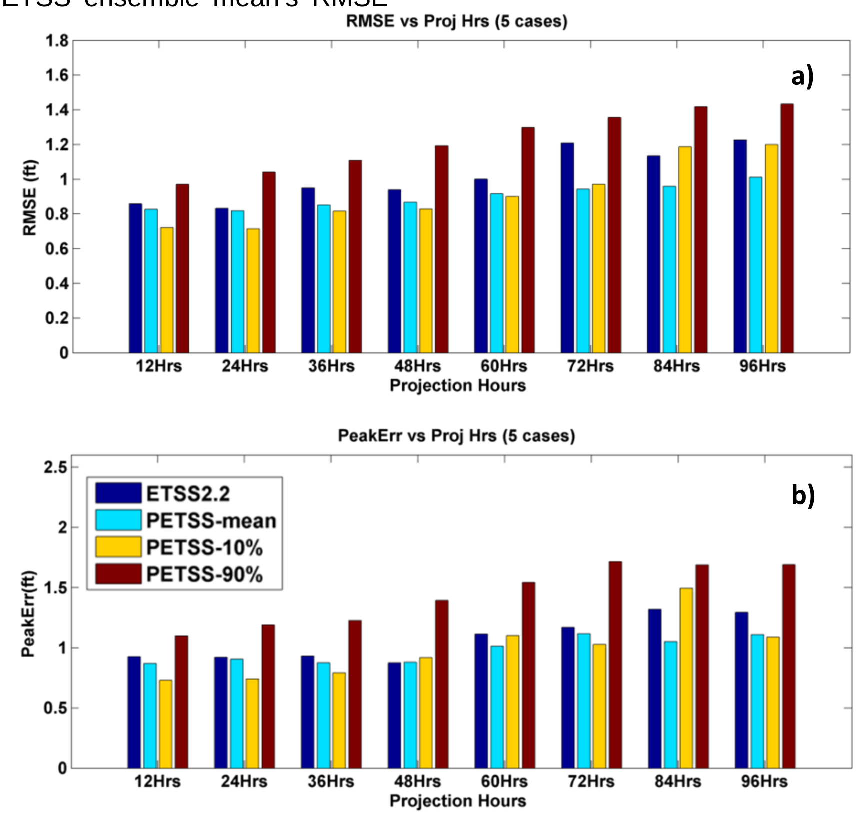


Fig. 5. a) Average RMSE over the 57 stations for the 5 events for different projection hours from P-ETSS and ETSS b) Average PAE over the 57 stations for the 5 events for different projection hours from P-ETSS and ETSS

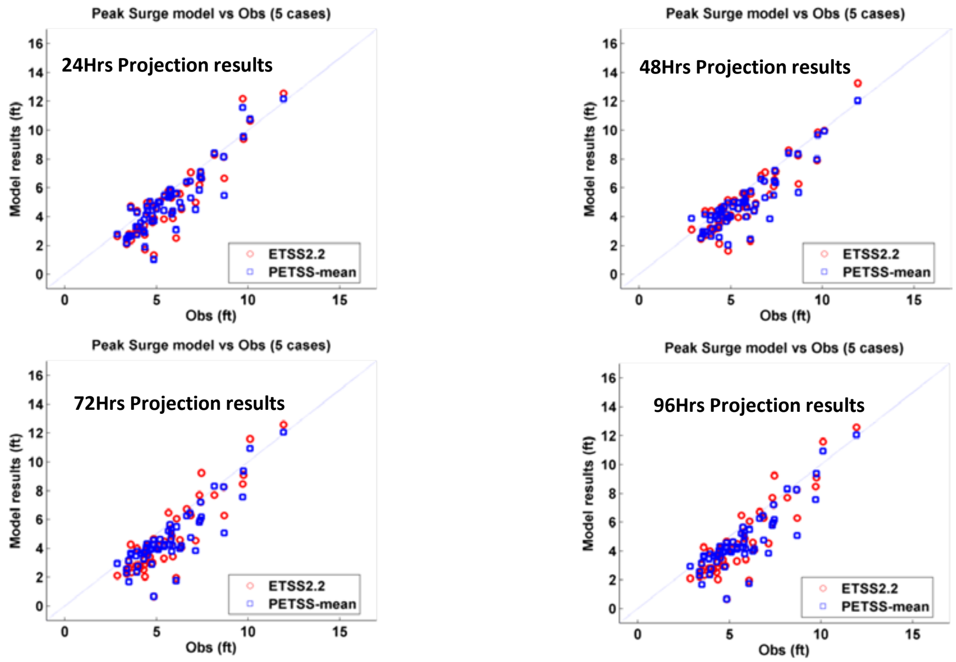


Fig. 6. Peak surge scatter plot at 57 tidal stations for the five events for 24-hr, 48-hr, 72-hr and 96-hr projections. Red dots are ETSS2.2 result and blue dots are the P-ETSS ensemble mean.

5. POST PROCESSING ADJUSTMENT

As mentioned previously, the peak surge scatter plots indicated that the P-ETSS ensemble mean and ETSS model under forecast the observations at certain stations. Possible causes for this include: omitting wave setup and run-up, errors in the wind forcing (GFS/GEFS), omitting flooding from rain, omitting sea level rise, model bias, etc.

The ETSS model incorporated a simple and efficient post processing methodology as a way to account for these omissions and errors (Schuster and Taylor 2015). A similar technique is used within P-ETSS to account for the same thing. Specifically the P-ETSS post processing uses observations, tides, and surge guidance (P-ETSS ensemble mean instead of ETSS) to calculate the average anomaly over the past 5 days. It then adds, for the first 12 hours, a linearly interpolated anomaly (from the instantaneous anomaly value to the 5-day average anomaly value) to the P-ETSS ensemble mean, 10% exceedance and 90% exceedance water levels at a particular station. After 12 hours, it adds the 5-day average anomaly to those same products.

To demonstrate the impact of post processing the P-ETSS model results, we performed post processing for Hurricanes Harvey 2017 and Irma 2017. The average RMSE and PAE for the model results with and without post processing for those two events are shown in Fig. 7 and Fig. 8. In both cases, post processing improved the skill scores at all projections.

6. HURRICANE IRMA, P-ETSS AND P-SURGE

It is worth noting that the RMSE and PAE values for Hurricane Irma 2017 are much larger than for other events. For example, the range of the RMSE for Hurricane Harvey 2017, as well as the range of the average RMSE over all 5 cases was 0 to 1.8 feet, while it was 0 to 2.5 feet for Hurricane Irma. From this one might conclude that P-ETSS did poorly for Hurricane Irma; however, we received very positive feedback for P-ETSS' performance from the Charleston, SC Weather Forecast Office (WFO), who used it for their tropical storm surge watch/warning along the coasts of SC and GA.

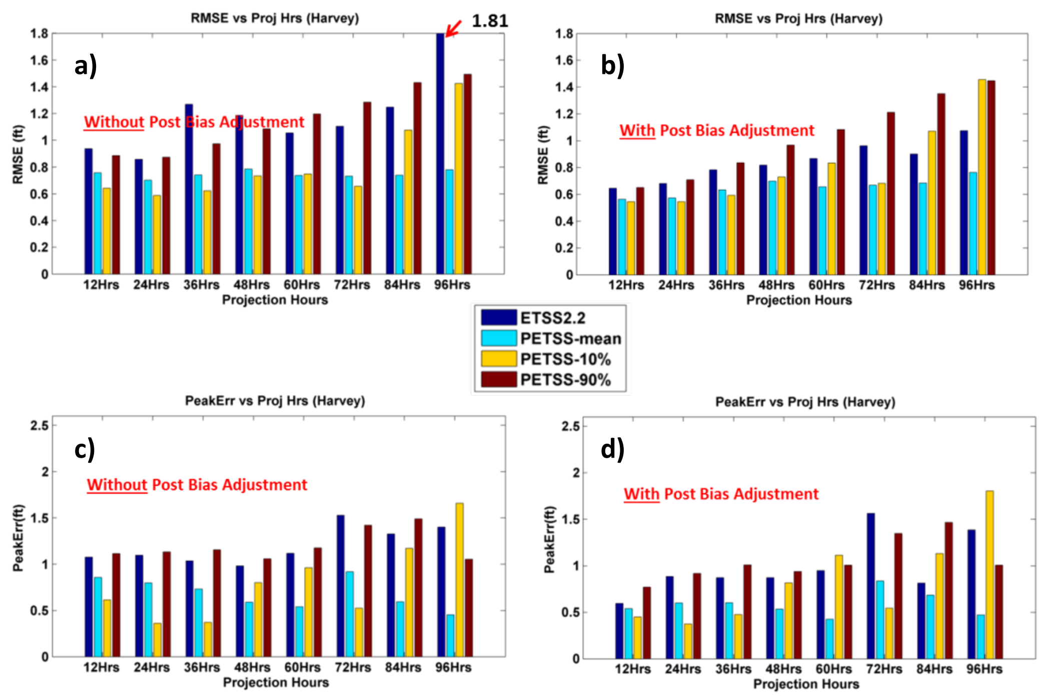


Fig. 7. a) average RMSE over the 9 stations of Hurricane Harvey 2017 **without** post-processing, b) average RMSE **with** post-processing, c) average PAE **without** post-processing and d) average PAE **without** post-processing

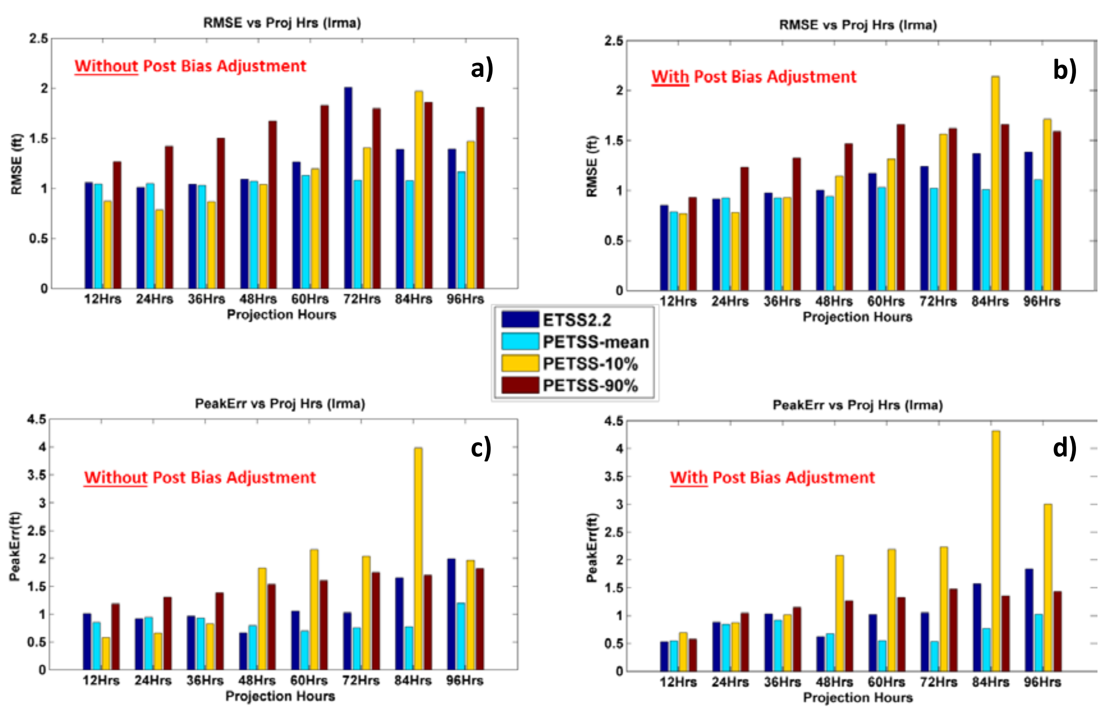
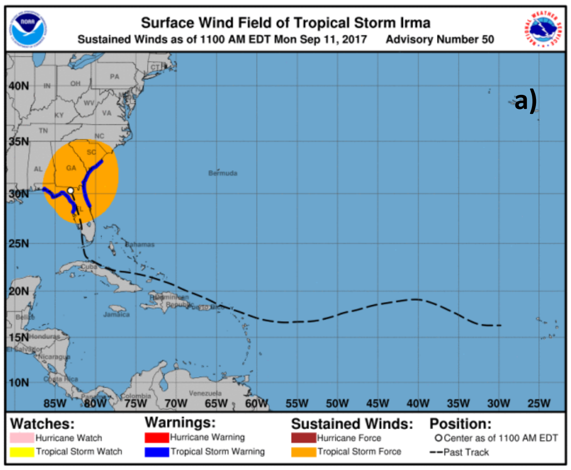


Fig. 8. Same as **Fig. 7** but for Hurricane Irma 2017.

The explanation for this dichotomy can be seen in the track of Hurricane Irma (Fig. 9a). When Hurricane Irma is in the Gulf of Mexico, it has a symmetric wind structure typical of tropical storms; however when it crosses land and returns to the Atlantic, its winds are broader and less symmetric. P-Surge is the best model for it when it is in the Gulf of Mexico and P-ETSS is the best for it when it is back in the Atlantic.

To quantitatively demonstrate this, we split the stations (Fig. 9b) into two groups and calculated the resulting average RMSE and PAE. The group along the Gulf of Mexico had 5 stations, while the group along the Atlantic had 7 stations. The average RMSE and PAE of these two groups of stations are shown in Fig. 10. Both RMSE and PAE indicate that for this case, P-ETSS does a much better job along the Atlantic than along the Gulf of Mexico.



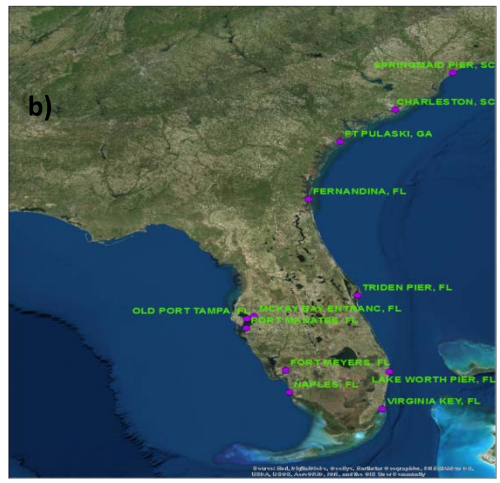


Fig. 9a) Surface wind field from Advisory 50 of Hurricane Irma 2017. **Fig. 9b**) Stations used in P-ETSS.

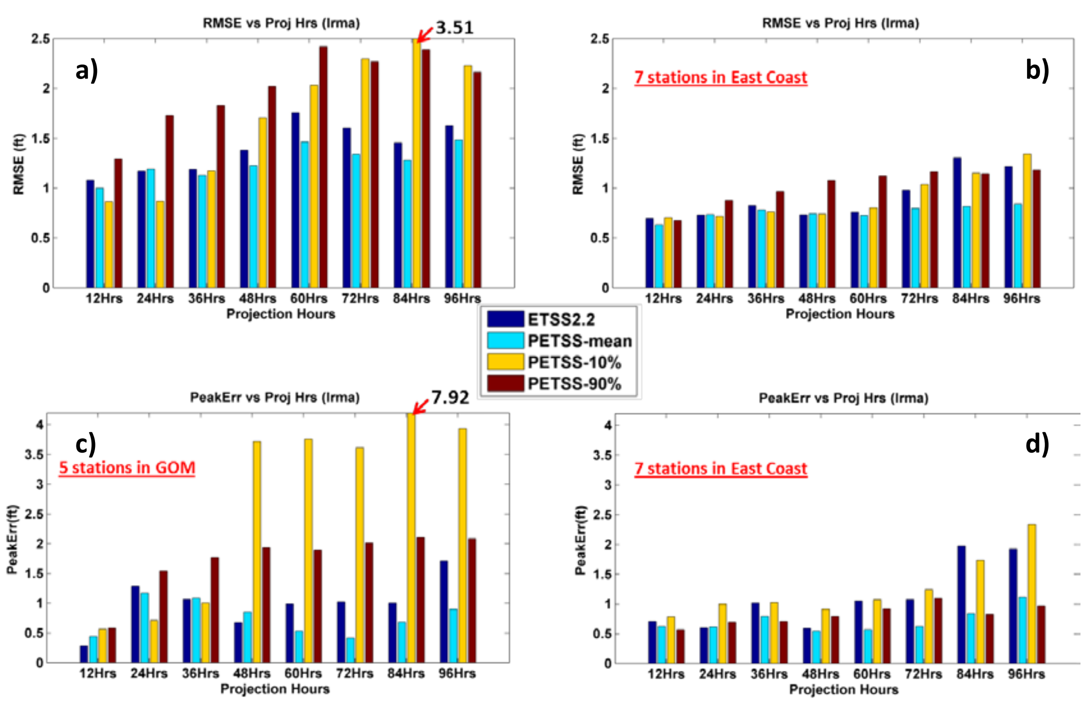


Fig. 10. a) average RMSE of 5 stations along the Gulf of Mexico, b) average RMSE of 7 stations along East Coast of the United States, c) same as a) but for PAE and d) same as b) but for PAE.

7. SUMMARY AND DISCUSSION

In these five cases, P-ETSS guidance provides a more consistent message than ETSS deterministic guidance for all projection hours from 12 to 96. Furthermore, the P-ETSS ensemble mean is better than the ETSS model, especially for longer range projections. The post processing adjustment provides an efficient way to account for omitted physical terms and adjust for model bias. Finally Hurricane Irma 2017 provides a good example for how P-ETSS can complement P-Surge for issuing storm surge watches and warnings. P-Surge guidance can be used for narrower, more symmetric, tropical storms, while P-ETSS guidance can be used for broader, more asymmetric, extra-tropical storms.

A number of actions can be undertaken to improve P-ETSS' performance. In the short term, MDL plans to extend the East Coast computational domain to cover Puerto Rico and the Virgin Islands. Additionally, MDL plans to expand the spread of the input forcing by using the 42 members of the North American Ensemble Forecast System (NAEFS). In the longer term, MDL plans to incorporate a fast wave model when one becomes available. MDL would also like to incorporate rainfall model output along the river boundary. Finally, MDL would like to add other fast storm surge models into the P-ETSS scheme to create multi storm surge model ensemble products.

8. ACKNOWLEDGEMENTS

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