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3.1 ENHANCEMENTS TO NWPS TO PROVIDE COASTAL AND OVERLAND HURRICANE WAVE GUIDANCE

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1. INTRODUCTION

The Nearshore Wave Prediction System (NWPS, Van der Westhuysen et al., 2013) is currently being developed to provide on-demand, high-resolution nearshore wave guidance to the coastal forecasters of the National Weather Service (NWS). It is designed to run locally at NWS's coastal Weather Forecast Offices (WFOs), covering their forecast domains of responsibility (Figure 1), and is driven by forecaster-developed wind grids from the Advanced Weather Interactive Processing System's (AWIPS) Graphical Forecast Editor (GFE). The nearshore wave model applied is SWAN (Booij et al., 1999), and alternatively a nearshore version of WAVEWATCH III (Tolman et al., 2002). During extra-tropical conditions, wave boundary conditions are received from the National Centers for Environmental Prediction's (NCEP) global WAVEWATCH III model, surface currents are ingested from RTOFS Global and water levels are taken from the Extratropical Surge and Tide Operational Forecast System (ESTOFS, Feyen et al., 2013). NWPS produces various types of output, including fields of integral wave parameters, spectra and individual partitioned and tracked wave systems. This model guidance is subsequently ingested into AWIPS to aid in the generation of detailed coastal marine forecasts.

In response to the devastation caused by Superstorm Sandy (2012), various enhancements have been implemented in NWPS to provide improved coastal wave guidance during tropical cyclone events, which are discussed in this paper. Flexible unstructured grids with increased nearshore resolution have been included in order to adequately resolve coastal wave processes. During a tropical cyclone event, the NWS's National Hurricane Center (NHC) issues a Tropical Forecast/Advisory Message (TCM) featuring a mandated wind forecast. Under these conditions, NWPS is forced with forecaster wind fields prepared with the TCMWindTool inside of AWIPS/GFE, and wave boundary conditions are provided by an NWPS implementation running at NCEP/NHC's Tropical Analysis and Forecast Branch (TAFB, Gibbs et al., 2014). Due to the high uncertainty in hurricane wind forcing, NHC gives preference to probabilistic surge model guidance, currently proved by the SLOSH-based

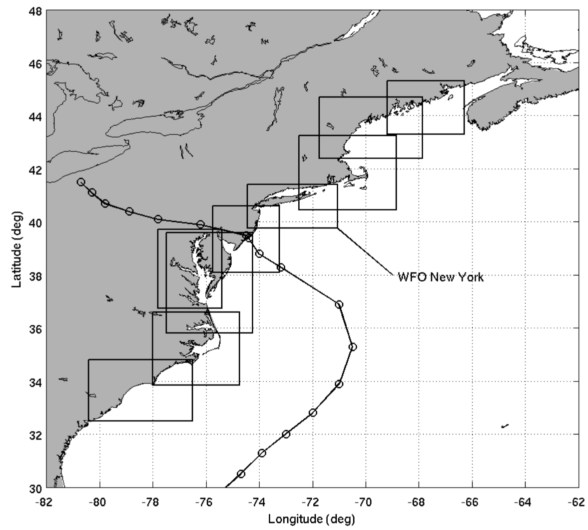

Figure 1: Example of the coverage of NWPS at coastal WFOs domains within NWS's Eastern Region, including WFO New York. Also shown is the best track of Superstorm Sandy (Blake et al. 2013).

P-Surge model (Taylor and Glahn, 2008). This paper discusses how time-dependent P-Surge fields are ingested in NWPS to provide nearshore wave conditions that are consistent with the probabilistic surge advisories issued by NHC's Storm Surge Unit.

In the sections below, background to NWPS and P-Surge is given (Section 2), the inclusion the P-Surge water level fields into NWPS is discussed (Section 3), and implementation is validated using the field case of Superstorm Sandy (Section 4). Section 5 closes the paper with conclusions.

2. BACKGROUND: SLOSH AND PROBABILISTIC STORM SURGE

The Sea, Lake and Overland Surge from Hurricanes model (SLOSH, Jelesnianski et al. 1992) computes storm surge heights from tropical cyclones using a parametric wind model featuring the track of the storm, the time series of radius of maximum winds (Rmax), and

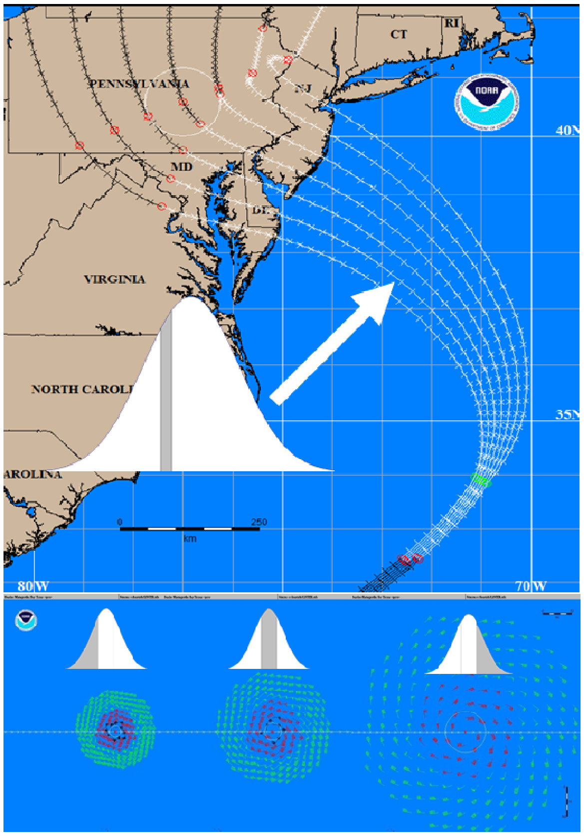

Figure 2: Example of the variation in the track, radius of maximum winds, and central pressure difference in the P-Surge ensemble.

the time series of pressure difference between the center of the storm and the ambient pressure (DelP). Thus, using parameters in the NHC's official advisory, NHC forecasters can produce a storm surge forecast. However, the uncertainties in these hurricane forecasts typically far exceed the modeling uncertainties (numerical and physical) within surge models such as SLOSH. Therefore, instead of using a single run of the model based on the current NHC hurricane forecast, an ensemble of hypothetical storms are used that are based on both the current NHC hurricane forecast and combinations of error distributions derived from historic NHC advisories, using the P-Surge model.

The set of hypothetical storms in P-Surge is created by permuting the hurricane's position, size, and intensity based on past errors of the advisories. Since each hypothetical storm represents a specific combination of errors in these parameters, the chance of that combination occurring is assigned to that hypothetical storm. P-surge then joins the results of running the hypothetical storms through SLOSH, along with their associated chance, in a probabilistic manner. In order to create an ensemble of hypothetical storms, the P-surge model needs the error distributions associated with NHC's forecast. These are provided by analyzing the average errors of NHC's hurricane forecasts over the last few years, and estimating what they might be in the near future. The specific average errors that are estimated are the cross-track (perpendicular to the motion of the storm), along-track, and intensity errors. The P-surge model then combines them with an assumption that the errors follow a normal distribution to compute three permutations of speed (along-track error) and intensity (Figure 2). Once all the error distributions are established, the P-surge model creates one hypothetical storm for each category of error, and assigns that hypothetical storm a weight, which is the product of the probability of each error.

After the set of hypothetical storms is created, the storms are run and the maximum surge value a particular area (typically 500-1000 m across) attains at any time due to each hypothetical storm is calculated. The maximum surge values for all the areas are assigned the weight associated with the hypothetical storm which caused them. The surge values and associated weights from all the hypothetical storms are then combined to create probabilistic storm surge. For more details see Taylor and Glahn (2008).

Recently time-dependent, incremental probabilities of surge levels have been made available, which now also include tides. In this approach, 13 incremental probability fields are produced, defined as the probability the event will occur at each grid cell in a 6 hour window during the next 78 hours (e.g. 0-6 hours, 6-12, 12-18 to 72-78). The P-Surge output is available in two formats: (i) probability of storm surge and tide above datum: fields of probabilities, in percent, of storm surge with tide exceeding 2 through 25 feet above North American Vertical Datum of 1988 (NAVD 88). (ii) exceedance height of storm surge and tide above datum: fields of heights of storm surge with tide, in feet above NAVD88, which will be exceeded by a given percentage of storms (10-50%). When issuing tropical storm surge forecasts based on the guidance product category (ii), forecasters typically vary the exceedance level during the course of a cyclone event. When the cyclone is far from landfall (e.g. 48 h), small exceedances (e.g. 10%) are typically applied in order to produce a conservative forcast. However, as the cyclone nears landfall and the uncertainty reduces, higher levels of exceedance are used (up to 50%).

3. INCLUSION OF P-SURGE RESULTS IN NWPS

NWPS is currently run in one-way coupled mode, receiving wind input, surface currents and water level information, without feedback to these various processes. Under extra-tropical conditions, NWPS is forced by forecaster-developed wind fields, and ingests water levels from the deterministic ESTOFS model. Under tropical conditions, NHC issues a TCM, which all affected WFOs are mandated to use. As explained above, uncertainties in the hurricane wind forcing calls for a probabilistic surge modeling approach. Because of

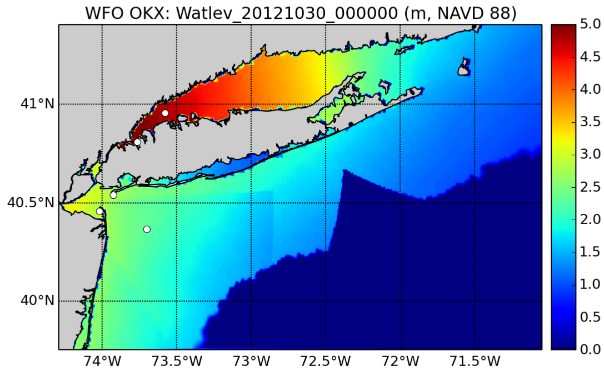

Figure 3: Example of a time-dependent P-Surge water level field extracted for WFO New York (OKX). Advisory 27 with an incremental probability of exceedance of 10%, at the peak surge (October 30, 00:00 UTC) soon after the landfall of Superstorm Sandy near Brigantine, NJ. Dots indicate observation stations (see Figure 4).

the computational efficiency of SLOSH, the P-Surge approach, with thousands of ensemble members, is operationally feasible. A two-way coupling mechanism between SLOSH and SWAN has recently been developed. In this coupled system, both the influence of the storm surge on the waves (increased water levels) and the effect of the wind waves on the storm surge (radiation stresses) are taken into account. However, the state-of-the-art, third-generation spectral model SWAN is computationally much more expensive than SLOSH, making a large ensemble simulation such as in P-Surge with this coupled system operationally unfeasible at present.

As a practical mid-way, it is proposed here to include the final, time-dependent probabilistic surge levels (product category (ii) above) from an uncoupled P-Surge run into a single determinstic SWAN run inside of NWPS, forced with the NHC best track forecast. This approach neglects relevant wave-related processes in the surge calculation, as well as the uncertainty in the wind forcing on the wave model output. However, it does ensure consistency between the P-Surge guidance issued by NHC, the mandated TCM wind fields and the wave model guidance produced by NWPS. Since only a single SWAN model run is involved, it also remains operationally feasible.

Scripting was written to extract P-Surge data on NCEP's production machine for each WFO affected by a given hurricane advisory. This water level output, interpolated from the native curvilinear SLOSH grids onto regular grids, are made available to WFOs for download and ingesting into NWPS (e.g. Figure 3). This process is repeated for every advisory issued, and for each incremental exceedence level published (10-50%). Hence, during a tropical cyclone event, NWPS will switch from ingesting ESTOFS water level fields to ingesting P-Surge fields. For consistency, WFOs should ensure that NWPS receives the same P-Surge exceedance level used to issue their storm surge forecast. To force the wave model, the parametric information from the TCM is converted into hourly wind fields using the TCMWindTool inside of AWIPS/GFE, and superimposed onto a background model field. Consistent wave boundary conditions are received from the basin-scale implementation of NWPS that is run on demand at NHC/TAFB.

4. SUPERSTORM SANDY VALIDATION CASE

4.1 Conditions

Given the magnitude and surge impact of the recent Supertorm Sandy (October 22-30, 2012), it is considered an ideal case with which evaluate the impacts of inclusion of P-Surge fields into the wave model guidance of NWPS. Blake et al. (2013) summerize the event as follows: Sandy was a classic late-season hurricane in the southwestern Caribbean Sea. The system restrengthened into a hurricane while it moved northeastward, parallel to the coast of the southeastern United States, and reached a secondary peak intensity of 85 kt while it turned northwestward toward the mid-Atlantic states. Sandy weakened somewhat and then made landfall as a post-tropical cyclone near Brigantine, New Jersey (Figure 1) on October 30 at 23:30 UTC, with 70-kt maximum sustained winds. Because of its tremendous size, however, Sandy drove a catastrophic storm surge into the New Jersey and New York coastlines. There were at least 147 direct deaths recorded across the Atlantic basin due to Sandy, with 72 of these fatalities occurring in the mid-Atlantic and northeastern United States. See also Sullivan and Uccellini (2013) for an assessment of the service level provided by NWS during this event.

4.2 Model setup

The study area chosen is WFO New York's domain of responsibility, which includes Long Island Sound, New York Harbor and Northern New Jersey, all regions strongly affected by Sandy (Figures 1 and 4). Figure 4 (top panel) shows the unstructured mesh developed for this domain, which features 165,536 vertices and a resolution that varies from 4 arc-min in the offshore to 250 m in the nearshore. The bottom panel of Figure 4 shows the bathymetry used for this domain, taken from the 3 arc-second Coastal Relief Model (NOAA NGDC, 2013). The study area includes significant shallow regions inside of Long Island Sound, along Long Island's southern shore, the New York Harbor area and Northern New Jersey.

Atmospheric forcing was taken from two sources. The first represents the operational forcing that would be applied at a WFO during a tropical cyclone event, based on the TCM This parametric information is converted into hourly wind fields using the TCMWindTool, and

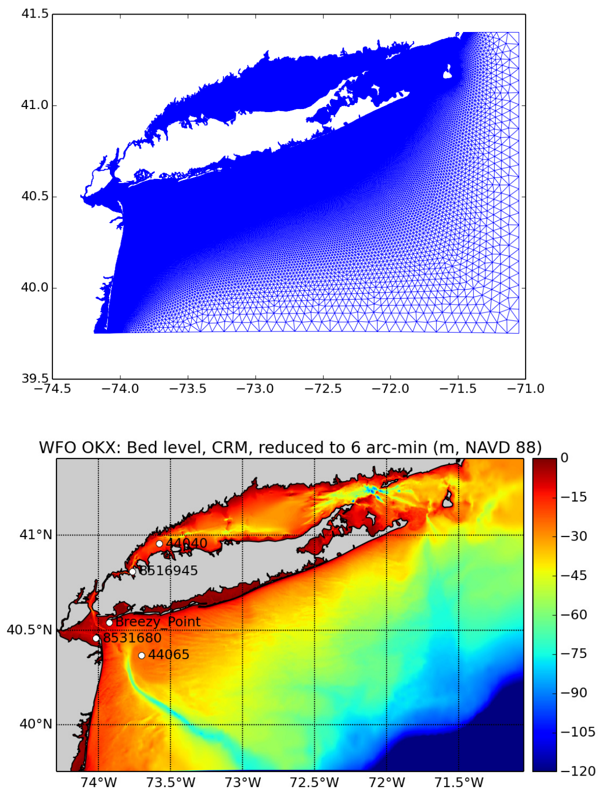

Figure 4: NWPS domain for WFO New York (OKX), featuring an unstructured model mesh with resolutions varying from 4 arc-min in the offshore to 250 m in the nearshore (top), and bathymetry (bottom). Dots indicate observation stations.

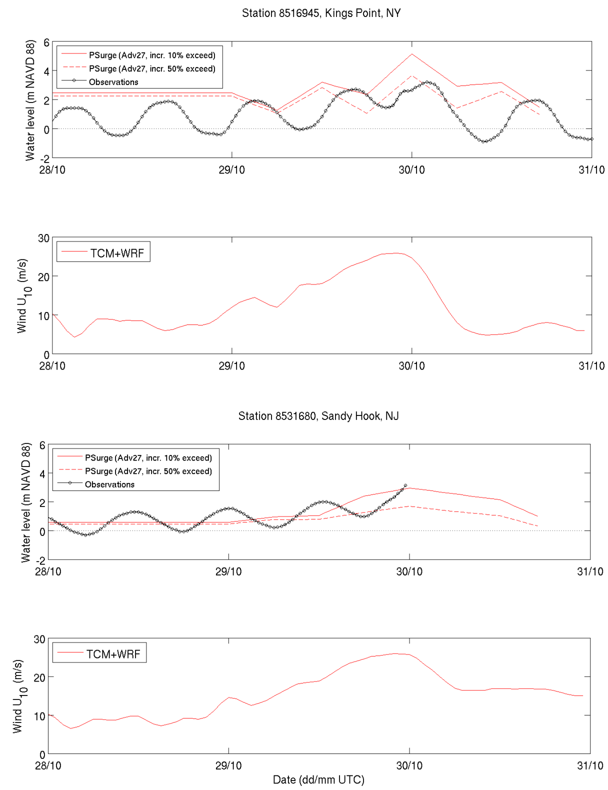

Figure 5: Time-series of P-Surge water levels from Advisory 27, with incremental exceedances of 10% and 50%, extracted at King's Point, NY (station 8516945) and Sandy Hook, NJ (station 8531680) and compared to CO-OPS observations.

superimposed onto a background model field. Only the first (analysis) hour from each TCM advisory was applied. The background fields were taken from a 9 km resolution, North Atlantic WRF ARW 60 Ensemble Member model (Zhang et al., 2011; Weng and Zhang, 2012.) were applied. Two runs from this model were combined, namely the 20121023_00z (initial 48 h) and 20121025_00z (remainder up to landfall) cycles. Sandy was a unique case in that the TCM advisories stopped leading up to landfall since it was then declared a post-tropical cyclone. As a result, the subsequent time steps reverted back to the background guidance, in this case from the WRF ARW 60 Ensemble Member model. At the time, this operational procedure received much criticism and has since been corrected. The second source of atmospheric forcing applied was hourly analysis H*Wind fields (Powell et al., 1998), again superimposed onto the above-mentioned background WRF model fields. This second set represents an analysis-grade forcing, included here to study the accuracy of the operational TCM forecast, and its impact on the wave guidance.

Wave boundary conditions along the WFO New York study domain were generated by running basin-scale simulations with NCEP's global WW3 model at a 1/2 degree resolution starting at October 23, 00:00 UTC. Two sets were computed, using the TCM+WRF and H*Wind+WRF composite wind fields, respectively. The former case represents the boundary conditions that the WFO would receive from the basin-scale implementation of NWPS run at NHC/TAFB. Water levels over the WFO New York domain, including the tide and cyclone-induced probabilisitic surge, where taken from the 6-hourly P-Surge fields, as discussed above. Here the results from P-Surge Advisory 27 were applied, which were valid from October 29 at 00:00 UTC. NWPS was spun up from October 27 at 00:00 UTC, so that before the onset of Advisory 27 water levels were taken as stationary. No surface current input was applied. NWPS ran with SWAN, with the default physics and numerical settings described in Van der Westhuysen et al. (2013). The 1-hourly wind fields and 6-hourly P-Surge water level fields were linearly interpolated onto NWPS's 600 s time step during computation. Model field output was extracted every 3 hours and time series output every 1 hour.

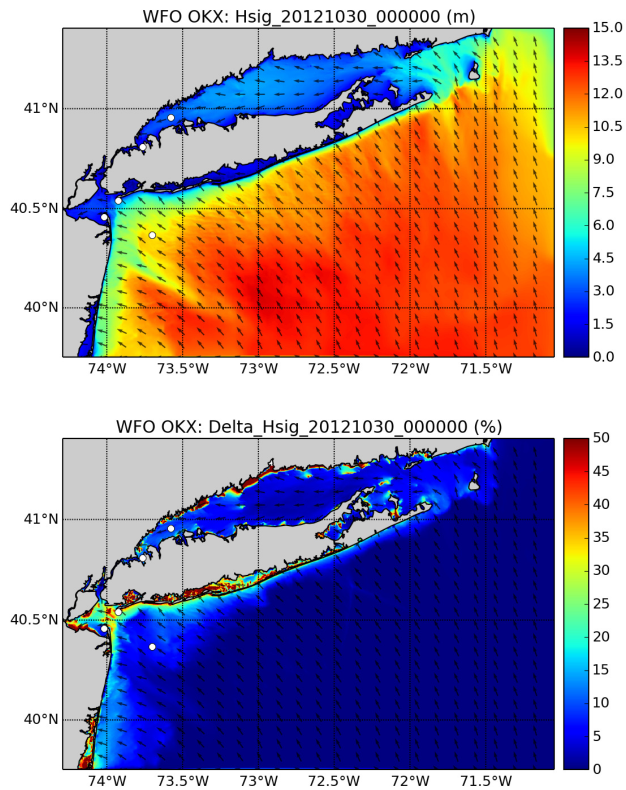

Figure 6: Hindcast results of NWPS over the WFO New York domain on October 30 at 00:00 UTC, soon after landfall of Superstorm Sandy near Brigantine, NJ. NWPS forced by TCM+WRF winds and includes P-Surge water levels (Advisory 27, 10% incremental exceedance). Top: Significant wave height and mean wave direction (vectors). Bottom: Percentage difference in the significant wave height due to the inclusion of the P-Surge water levels, and mean wave direction (vectors). Dots indicate observations stations (see Figure 4).

4.3 Results

Figure 5 compares the probabilistic time series output of P-Surge (10% and 50% incremental exceedance) with observations at two stations strongly affected by storm surge, namely King's Point, NY and Sandy Hook, NJ. Observed surge levels at King's Point reached 3 m (above NAVD 88), and those at Sandy Hook reached 3.5 m before the instrument failed. Modeled 10 m elevation winds (U10) at the two locations reached roughly the same speed, around 25 m/s. The P-Surge Advisory 27, with 50% incremental exceedance (an estimate of the expected value) gives a good estimate of the peak surge at King's Point, but tends to underestimate the observations at Sandy Hook. By contrast, the 10% exceedance fields yield more realistic results at Sandy Hook, but overestimate the observations at King's Point by about 2 m. It can also be seen that the 6-hourly temporal resolution in the P-

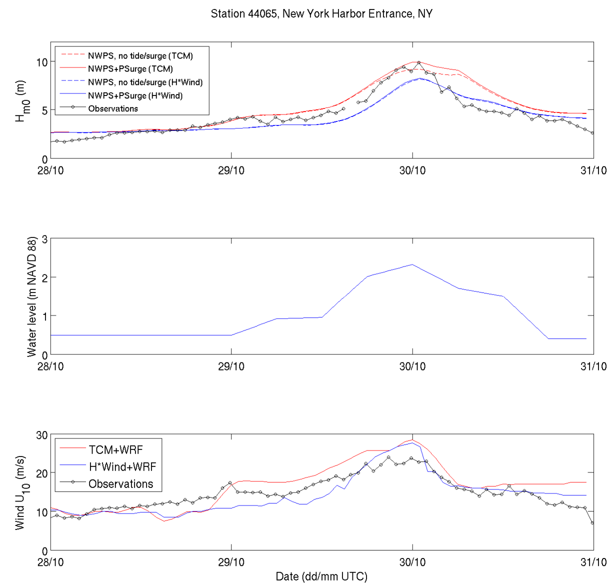

Figure 7: Time-series results at NDBC 44065 (New York Harbor) during Superstorm Sandy. Top: Significant wave height from NWPS with and without P-Surge water levels (Adv 27, 10% incremental exceedance) using winds from respectively the TCMWindTool and H*Wind, compared to to observations. Center: P-Surge water levels. Bottom: Comparison between the wind speed at 10 m elevation from the two model wind sources with observations.

Surge output captures the general variation of the surge during the course of the storm, but is insufficient to resolve the tidal variation. In the remainder, we will study the impact of the conservative 10% exceedance levels on the wave model results.

Figure 6 (top panel) shows the wave field results of NWPS/SWAN including the P-Surge fields over the WFO New York domain just after landfall. Very strong southeasterly waves can be seen along the south coast of Long Island and the north coast of New Jersey, with significant wave heights of Hm0 = 10 m at New York Harbor Entrance (NDBC buoy 44065). By contrast, due to the narrow entrance and shallow water, wave heights in Long Island Sound reached only Hm0 = 2-3 m, even though its long axis was aligned with the wind direction to the north of the landfalling cyclone. Along the more sheltered southeastern side of Staten Island modeled wave heights reached Hm0 = 1 m.

The bottom panel of Figure 6 shows the impact on the significant wave heights of including the P-Surge water levels (10% exceedance). As expected, the influence of including coastal surge levels is restricted to the shoaling regions and nearshore areas. Large impacts are seen along the southern coast of Long Island, including the inner waters behind the barrier islands,

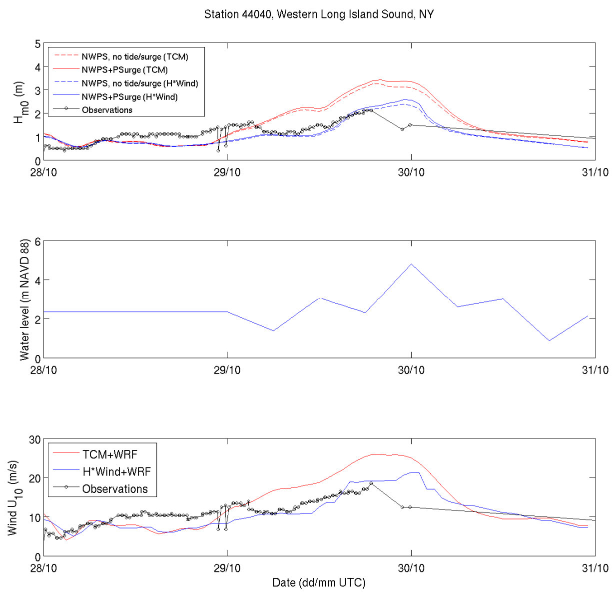

Figure 8: As in Figure 7, but for NDBC 44040 (Western Long Island Sound).

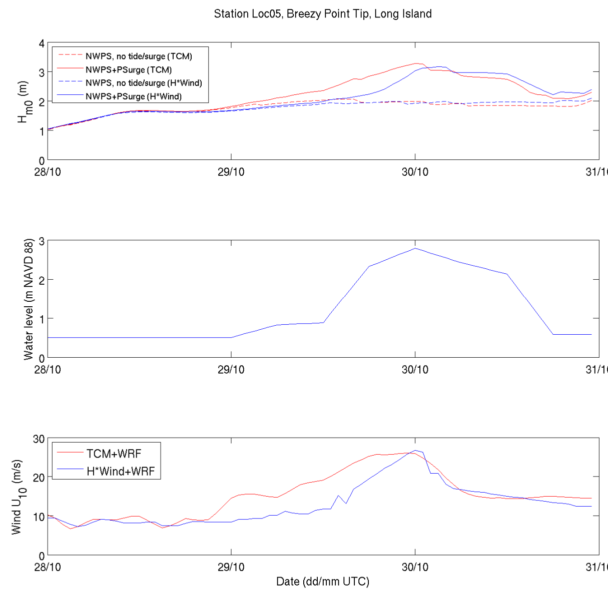

Figure 9: As in Figure 7, but for Breezy Point, Long Island, NY (40.542° N; 73.928° W). No observations available.

where energetic waves encounter shallow waters. Increases in significant wave height of up to 50% are found here. Increases of 50% can also be seen in New York Harbor's Lower Bay along Staten Island. Similar impacts are seen along the northern shore of Long Island Sound. However, within the Sound, despite having reached levels of up to 5 m NAVD 88, the relative depth is too great for the waves to feel substantial impact from the surge.

Figures 7-9 show the impact of the P-Surge fields (runs with/without) on the time series results of NWPS/SWAN at a few key locations. To evaluate the impact of the choice of atmospheric forcing, results of both the TCM+WRF and H*Wind+WRF wave runs are included. Figure 7 shows the time series wave height, water level and U_{10} wind results at the New York Harbor Entrance (NDBC buoy 44065). Regarding the quality of the wind forcing (bottom panel), the TCM+WRF winds consistently overestimate the observations, whereas the H*Wind fields tend to underestimate the observed winds leading up to landfall, and then overestimate them at landfall. Note that the results of these two sources are essentially the same prior to October 29, 00:00 UTC, since up to this time the background WRF field dominates. Using the TCM+WRF inputs, NWPS/SWAN yields accurate estimates of significant wave height up to landfall, whereas with H*Wind+WRF peak wave heights are underestimated (top panel). The dashed lines show the results of the run without P-Surge. At this intermediate depth location, the influence of including the probabilistic surge levels is visible, but modest (compare Figure 6).

Figure 8 shows the corresponding results for Western Long Island Sound (NDBC buoy 44040). The TCM+WRF winds are again higher relative to the H*Wind+WRF winds. However, here the former strongly overestimate the observations (until the instrument failed), whereas the H*Wind+WRF winds show good agreement. These differences are considered to be due to land influences at this location, which are not as well represented in the TCMWindTool. These differences in the wind forcing translate to large differences in the wave model results. Here runs forced with H*Wind+WRF wind agree well with the observed significant wave heights, whereas the TCM+WRF results in an overestimation of about 60% at landfall. At this location the influence of including the probabilistic storm surge fields from P-Surge can again be seen, but remains limited. Even though the surge levels here are significant (up to 5 m NAVD 88), the water depth remains deep in a non-dimensional sense, so that the effect on the waves are limited.

Finally, Figure 9 presents the model results at the tip of the south-facing Breezy Point, Long Island, NY, near the entrance to New York Harbor. No wind or wave observations are available for validation at this location. However, being in shallow water close to the coast, wave model output from both the TCM- and H*Wind-driven runs show large impact of the inclusion of surge water levels, exceeding 50% of H_{m0} (1 m) at landfall. Note, however, that since this result is associated with the P-Surge 10% exceedance levels, this should be considered an upper bound of the influence.

5. CONCLUSIONS

This study investigated the inclusion of probabilistic storm surge water level fields from the SLOSH-based P-Surge model into the Nearhsore Wave Prediction System (NWPS) to more accurately predict nearshore wave conditions during tropical cyclone landfall events. From the results of this study, the following can be concluded:

- The time-dependent water level output from P-Surge, with incremetnal exceedance probabilities of 10% and 50%, give a fair representation of the observed time-varying storm surge water levels in the nearshore during the landfall of Superstorm Sandy. For the conservative 10% exceedance level, some locations show an overestimation by the model.
- Although time-dependent trend in the P-Surge output is realistic when compared to observations, the temporal resolution of 6 h is too coarse to capture the tidal modulation well, and should be increased.
- Wind fields created using the TCMWindTool within AWIPS/GFE were found to yield acceptable accuracy at coastal stations relatively far away from land influence, but tend to overestimate stations close to the shore.
- NWPS/SWAN yields generally accurate wave parameter output for the studied Superstorm Sandy case, given that the applied wind forcing is accurate.
- Probabilistic water levels from P-Surge were found to have a significant impact on nearshore wave heights, exceeding 50% in regions close to the shore. The WFO-based model meshes in NWPS are currently being extended overland to include wave guidance in inundation zones.

6. ACKNOWLEDGEMENT

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