P1.40 **SLOSH MODEL HINDCAST OF HURRICANE IRENE (2011) SURGE**

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1. INTRODUCTION

Hurricane Irene (2011) had the potential to be an extremely catastrophic Northeast hurricane with devastating wind and storm surge affecting coastal regions from North Carolina to New York. Fortunately, this impact was never realized and Irene weakened to a minimal Category 1 on the Saffir-Simpson Hurricane Wind Scale (SSHWS) prior to landfall in North Carolina and further weakened to tropical storm status by landfall in New Jersey and subsequently New York. For storm tracks that traverse the eastern seaboard, it is imperative that storm surge estimates are accurate for evacuation planning and mitigation. On the opposite spectrum, a catastrophe risk model must accurately predict both wind speeds and surge to estimate insured losses, and ultimately provide a quality assessment of risk for insurance portfolio management and ratemaking.

Operationally, the National Hurricane Center (NHC) uses the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model to estimate the storm surge impact from an impending tropical system. SLOSH is a numerical model developed by the National Weather Service (NWS) and can be run in various modes to estimate the surge for a particular tropical cyclone. It is well known that SLOSH predicts surge heights reasonably well, but was not designed to model overland wind speeds (Jelesnianski et al. 1992). For catastrophe risk modeling, it is critical that both ocean winds (which, in part, generates the surge) and inland winds (which causes building damage) are accurately modeled over the entire storm track, since these models are tightly coupled. As such, the hurricane wind field developed by AIR Worldwide Corporation (hereafter, AIR), has been adapted into the SLOSH model framework and is evaluated herein for the case of Hurricane Irene.

This work analyses and validates hindcasts of Hurricane Irene's surge using the SLOSH model (v4.00) and the SLOSH model adapted to use the AIR hurricane wind model. The SLOSH wind model assumes a surface wind profile in the pressure equation. AIR uses the gradient wind profile defined in Willoughby et al. (2006) and estimates winds speeds at the surface using the latest research and methodologies. The SLOSH surge hindcasts are compared to observed water levels from NOAA tide gauges located along the east coast of the US. It is shown that adopting the AIR wind field not only produces comparable surge estimates to the operational SLOSH model, but also estimates inland wind speeds in general agreement with observations.

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2. HURRICANE IRENE

Hurricane Irene was the first hurricane and major hurricane of the 2011 hurricane season. Irene originated from a well-defined tropical wave that exited the coast of West Africa on August 15. Initially, the wave struggled to organize and late on August 20 tropical storm Irene formed just east of Martinique. With favorable atmospheric conditions, Irene crossed St. Croix and the eastern shore of Puerto Rico and was upgraded to a Category 1 hurricane. After passing Hispaniola, Irene strengthened to a Category 3 hurricane with maximum sustained winds of 54 m s^{-1}, a central pressure of 957 hPa, and an eye diameter of 33 km at 1200 UTC on August 24.

Irene then turned more towards the north as the subtropical ridge shifted eastward while Irene crossed the central and northwestern Bahamas. After which, Irene weakened, and on August 27, made landfall near Cape Lookout, NC with winds of 40 m s^{-1}. Irene crossed back into the Atlantic Ocean and made a second landfall on the east coast near Atlantic City, NJ at 0935 UTC on August 27 with maximum wind speeds of 39 m s^{-1}. Irene tracked north-northeast and made a third landfall near Coney Island, NY at 1300 UTC on August 28 with winds of 28 m s^{-1}. Irene continued north over New England, became extratropical, and then emerged into the Labrador Sea late on August 29 to be absorbed by an extratropical cyclone the following day. The NHC best track path line for Hurricane Irene is shown in Fig. 1 (Avila and Cangialosi 2011).

Hurricane Irene generated a storm surge that affected the entire eastern seaboard from Florida to Maine. Storm surge residuals, which are the difference between the observed water levels (storm tide) and the predicted astronomical tide, are shown in Fig. 1. These water level data were obtained from McCallum et al. (2012) and represent data collected by the National Oceanic and Atmospheric Administration (NOAA) permanent monitoring sites. Residuals show only the effects of the storm (i.e., storm surge) on the observed water levels. Other factors, such as the non-linear interaction between the surge and tide are also captured in the surge residual.

The highest storm surge residual observed was 2.161 m at Oregon Inlet Marina, NC at 0354 UTC on August 28. From FL to SC, residuals ranged from 0.464 m to 1.02 m, and along the east coast from VA to NY residuals ranged from 1.00 m to 1.48 m. In Atlantic City, where Irene made a second landfall, a residual of 1.00 m was observed. Near Chesapeake Bay, residuals ranged from 0.55 m to 1.48 m. Around Irene's third landfall in NY, a maximum residual of 1.441 m was measured at King's Point, NJ.

3. SLOSH MODEL

The SLOSH model is a computationally efficient storm surge model designed to predict water levels for impending tropical cyclones for evacuation planning and emergency management (Jelesnianski et al. 1992). It is a dynamic 2-D numerical model that steps through the depth-averaged, quasi-linear shallow water equations of motion and the continuity equation applied to a rotating fluid with a free surface. Advective terms are ignored but the model does include finite amplitude effects and some nonlinear terms. The coastline is considered a physical boundary and, provided that a grid is of sufficient size, SLOSH can resolve coastal-trapped Kelvin waves.

To capture water levels at a high resolution for an area of interest (e.g., along the coast, in bays, etc.), SLOSH employs curvilinear polar, elliptical, or hyperbolic telescoping grids. Sub-grid scale water features and topographic obstructions such as channels, rivers, and cuts and levees, barriers, and roads, respectively are parameterized to improve the modeled water levels. The model ignores river flow, rainfall, ocean waves, and the explicit modeling of astronomical tides. The latter can be specified as an initial water level adjustment, but the periodicity in the signal is ignored. This limitation in the SLOSH model makes it advantageous to compare modeled water levels to storm surge residuals, as this removes the primary tidal component in the surge signal.

Verification of SLOSH modeled water levels was performed by Jelesnianski et al. (1992). For 13 storms, they found that SLOSH is typically accurate to within ± 20% for significant surges, but larger errors can exist. The NHC reports that SLOSH model performance was nearly ± 5% compared to 'excellent' high water marks (HWM) obtained after Hurricane Katrina. The latter demonstrates that the quality and type of HWM can greatly affect the validation and values must be rigorously inspected for accuracy and quality assurance. On the contrary, water level data from permanent NOAA gauges do not have such problems and can typically be used as reported.

3.1 SLOSH Parametric Wind Field Model

The SLOSH model uses a parametric wind field that is computed using the location of a storm (i.e., for translational motion), central pressure deficit, and radius of maximum wind (R_{max}). Asymmetry is applied to the circularly-symmetric wind field by vectorially adding the forward speed of the storm. The maximum correction allowed for storm motion is half the vector forward speed, which occurs at R_{max} (values approach zero at the storm center and r=∞). Regardless of forward motion, the circulation center is located at the geometric center of the storm. The total wind speed vector for the SLOSH parametric wind field is computed, in polar coordinates (r,θ), as the vector sum of Eq. (1) vector wind for a stationary storm and Eq. (2) for the example of a northward moving storm (and θ=0º is east):

$$\vec{V} = V_{\max} \frac{2R_{\max} r}{R_{\max}^2 + r^2} e^{i[\pi/2 + \theta + \Phi(r)]} , \qquad (1)$$

$$\vec{V}_1 = \left|\vec{U}_s\right| \frac{R_{\max} r}{R_{\max}^2 + r^2} e^{i[\pi/2]} , \qquad (2)$$

where V_{max} is the maximum wind speed based on the central pressure deficit, r is the distance from the storm center, $\Phi(r)$ is the inflow angle, θ is the storm angle, and U_s is the storm speed. A constant drag coefficient (C_D) of $3X10^{-6}$ is employed in the surface stress (τ) computation, defined as:

$$\vec{\tau} = C_D \frac{\rho_a}{\rho_w} (\vec{V} + \vec{V}_1)^2 . \qquad (3)$$

The model wind friction coefficients have been developed based on over water values in order to accurately predict storm surge. As noted by Jelesnianski et al. (1992), the friction coefficients were not designed to produce an accurate wind field over the land surface. The wind friction coefficients for ocean winds in the tangential *ks* and radial *kn* directions are specified as:

$$k_s = 1.15 k_n = \left(\frac{10^{-4} R_{\max}}{0.3 V_{\max} + 60} \right). \qquad (4)$$

4. AIR HURRICANE WIND MODEL

The parametric AIR wind model computes the maximum gradient level wind speed assuming gradient wind balance. The radial variation in gradient wind speed follows Willoughby et al (2006). The profile is based on reconnaissance data from 493 hurricanes in the Atlantic and eastern Pacific basins from 1977 to 2000. This calculation requires that the storm location (latitude), R_{max}, and V_{max} are known. The profile is defined by three equations: Eq. (5) inside the eyewall, Eq. (6) in the eyewall region, and Eq. (7) outside of the eyewall:

$$V(r) = V_i = V_{\max} \left(\tfrac{r}{R_{\max}} \right)^n , \qquad (5)$$

$$V(r) = V_i(1-w) + V_o\, w\,, \tag{6}$$

$$V(r) = V_o = V_{\max}[(1-A)\exp(-\tfrac{r-R_{\max}}{X_1}) + A\exp(-\tfrac{r-R_{\max}}{X_2})]\,, \tag{7}$$

where V_i and V_o are the tangential wind component in the eye region and beyond the transition zone, respectively, X_1 and X_2 control the decay of the wind profile outside R_{max}, n is the exponent for the power law inside the eye, w is the weighting function, and A sets the proportion of the two exponentials in the wind profile. The wind profile defined by Willoughby et al. (2006), for latitude 20°N, is compared to that of Jelesnianski et al. (1992) in Fig. 2. It can be seen that the latter profile is broader about R_{max} and that the wind speeds decrease more rapidly with increasing distance beyond approximately twice the R_{max}.

To compute winds at the surface, the AIR wind model adjusts for the storm slant and a reduction of the winds from gradient level to 10 m (the latter captures momentum transfer), friction and turbulence characteristics using high-resolution USGS land use land cover data, asymmetry due to storm speed, and statistical decay functions after landfall. This methodology allows the intricacies of the surface wind speed footprint to be accurately modeled both spatially and temporally along the entire path of the storm. The AIR wind model has been extensively validated against many historical storms and certified by the Florida Commission on Hurricane Loss Projection Methodology.

5. METHODOLOGY

Hurricane Irene hindcasts were conducted using nine tropical SLOSH basins spanning the US east coast from SC to ME and the large extratropical domain EX2, as shown in Fig. 3. Surface stresses were forced by both the wind model inherent to SLOSH and the AIR hurricane wind model. Hindcast water levels were compared to storm surge residuals observed by NOAA gauges (McCallum et al. 2012) located in NC through southern MA. Observations that were located in the far south and north were omitted from the analysis as these they were not significantly impacted by the storm. Based on these criteria, a total of 37 observations were used in the analyses. The observations range from NOAA gauges that are located offshore and exposed to the open ocean to those located in channel locks.

The modeled water levels were compared to storm surge residuals, which allowed the SLOSH hindcasts to be run without a specified initial water displacement. However, this methodology ignores the nonlinear interaction between tide and surge, which is included in the surge residuals, but not the SLOSH hindcast water levels. These additional displacements are relatively small in magnitude compared to the overall surge and can be ignored for this work.

For the analysis, hindcast water levels were only compared to observations in which the grid cell is defined as water in the SLOSH basin data file. Using this methodology, datum differences (such as NGVD29 versus NAVD88) become irrelevant. Observations are matched to the closest SLOSH grid cell with no interpolation. In addition, model validation statistics are only computed for locations in which non-zero surge levels were hindcast for each independent simulation and SLOSH basin.

6. RESULTS / DISUCSSION

Hurricane Irene maximum wind speed footprints for the SLOSH wind field (computed using basin EX2) and AIR wind hurricane wind model are shown in Fig. 4. As designed, the AIR wind model is able to capture inland wind speeds at a high resolution and with much detail. It can be seen that the SLOSH model wind friction coefficients are quite high and do not allow for overland wind speeds to be modeled. Reliable over land wind speed estimates are critical for risk modeling at AIR, and accurate wind speeds must be predicted both over land and over water.

Compared to the SLOSH wind radii, it is shown that the AIR wind model produces a narrower footprint for all radii. A similar result is seen when comparing the wind footprints to the NHC wind extents (Fig. 4 b,d). It should be noted that the NHC wind swath extents tend to be biased high as they are a forecaster's best estimate at the time, and not based completely on observations. Therefore, this result does not necessarily imply that the AIR wind field is incorrect, but is rather another estimate of the wind field.

Further analysis using observed wind speeds are needed to perform a complete evaluation of the wind speed footprints estimated using the different methodologies. The variations in the two wind fields, and ultimately the resulting momentum transfer from the air to the sea via shear stresses, results in different views of the hindcast water levels.

Maximum hindcast water levels for the AIR and SLOSH wind models are similar, but differ spatially in magnitude, as shown in Fig. 5. In the Chesapeake region, stronger winds are modeled offshore by the SLOSH wind model and this results in a higher surge than that produced by the AIR wind model. This is also true for the New York region, but the increase in hindcast water levels is a consequence of the SLOSH wind model producing a larger wind field. In other locations, small differences in the distribution and magnitude of the wind speeds results in different surge patterns.

Modeled versus observed water level statistics for the ten SLOSH basins used in the analysis are shown in Table 1 and scatterplots for the aggregate, tropical, and extratropical basin EX2 are shown in Fig. 6. Due to sample size restrictions, validation data points were aggregated to quantify the overall performance of the wind field models adapted to SLOSH.

In general, the large extratropical domain does a good job in predicting water levels along the entire US east coast. A possible reason for this outcome includes, but is not limited to the fact that larger domain allows sufficient time for the model physics to spin-up. The smaller tropical domains suffer from this affect, especially on the periphery of the domains. When inland inundation is not of primary concern, this course mesh provides a relatively accurate and aggregate view of the offshore water levels. This basin can also serve as a guide to determine areas that will be most significantly impacted and thus simulated at a higher resolution. Also, basin EX2 could be used to provide boundary conditions for the smaller domains and thus limit errors due to domain size.

For both the aggregated tropical basins and all basins, the SLOSH model adapted with the AIR wind model validates more favorably than the SLOSH wind model for this particular case study. An average coefficient of determination for the AIR and SLOSH wind models is 0.34 and 0.26, respectively. This result gives confidence that the AIR wind model (at least) performs comparably to SLOSH, which was the purpose of this work. However a greater sample size of storms is needed to further test these results. Also, inclusion of the surveyed HWM into the dataset will provide significantly more points for validation.

7. FUTURE WORK

This work provides the framework for a more extensive examination of SLOSH hindcast storm surge (forced by SLOSH and AIR hurricane wind models) for Hurricane Irene and other historic storms. Some of the future work is listed below:

- Storm tide water elevation time series collected by the permanent NOAA gauges will be compared to SLOSH model hindcasts with inclusion of the astronomical tide levels as an initial water height displacement in SLOSH.
- The observation dataset will be extended to include HWM collected over land by the USGS. SLOSH will be run with an initial water displacement for each basin and results will be compared to the offshore validation.
- Various methods to estimate Irene's R_{max} along the track will be examined (e.g., satellite-derived, WSR-88D, etc.) as the size of the storm offshore is critical to accurately predicated water levels.
- For the SLOSH model adapted with the AIR wind model, extensive inland wind speed validation will be conducted to ensure that accurate wind speeds are being modeled over land (and over water).

8. REFERENCES

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TABLE 1. Modeled versus observed water level statistics for the ten SLOSH basins, an aggregate of the nine tropical basins ('Tropical'), and an aggregate of all basins ('All') for the AIR (shaded) and SLOSH hurricane wind models.

Basin	Count	Count	R^2	R^2	Mean Obs	Mean Model	Mean Model	St. Dev Obs	St. Dev Model	St. Dev Model	MBE	MBE	MAE	MAE	MSE	MSE
ACY	7	7	0.66	0.84	3.71	4.40	5.34	0.50	1.37	1.07	0.69	1.63	0.71	1.63	1.35	3.02
CP4	16	16	0.48	0.27	3.59	3.09	4.05	1.23	1.31	1.69	-0.50	0.46	0.80	1.22	1.16	2.28
DE3	7	7	0.71	0.81	3.77	4.56	5.31	0.56	1.95	1.42	0.79	1.55	1.03	1.55	2.55	3.16
HT2	10	10	0.00	0.01	4.09	3.53	4.59	1.29	1.17	1.72	-0.56	0.50	1.06	1.78	3.02	4.75
ORF	14	14	0.28	0.10	3.58	2.75	4.00	1.31	1.47	1.97	-0.83	0.42	0.97	1.60	2.41	3.88
IL3	2	2	1.00	1.00	2.04	1.05	1.05	1.62	1.06	1.34	-0.99	-0.99	0.99	0.99	1.13	1.01
NY3	6	6	0.43	0.80	4.05	4.80	5.72	0.66	1.66	1.71	0.75	1.67	1.04	1.67	2.02	3.90
OCE	3	3	0.16	0.02	3.43	3.63	4.37	0.18	0.91	0.49	0.20	0.94	0.68	0.94	0.70	1.05
PV2	8	8	0.19	0.42	4.47	4.19	5.28	0.37	1.22	1.35	-0.29	0.80	0.88	1.24	1.16	1.79
EX2	31	30	0.51	0.36	3.56	2.84	4.15	1.12	1.62	2.11	-0.72	0.50	1.05	1.46	1.77	3.06
Tropical	73	73	0.27	0.22	3.77	3.58	4.56	1.07	1.57	1.76	-0.19	0.79	0.91	1.46	1.86	3.07
All	104	103	0.34	0.26	3.71	3.36	4.44	1.08	1.61	1.87	-0.35	0.71	0.95	1.46	1.83	3.07

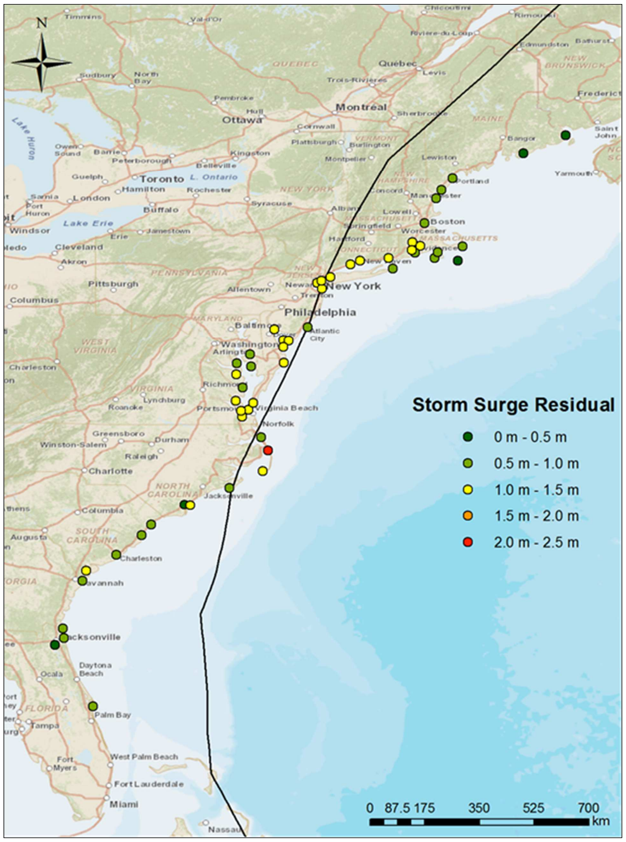

FIG. 1. Hurricane Irene (2011) storm surge residuals (McCallum et al. 2012) and NHC best track path line (Avila and Cangialosi 2011).

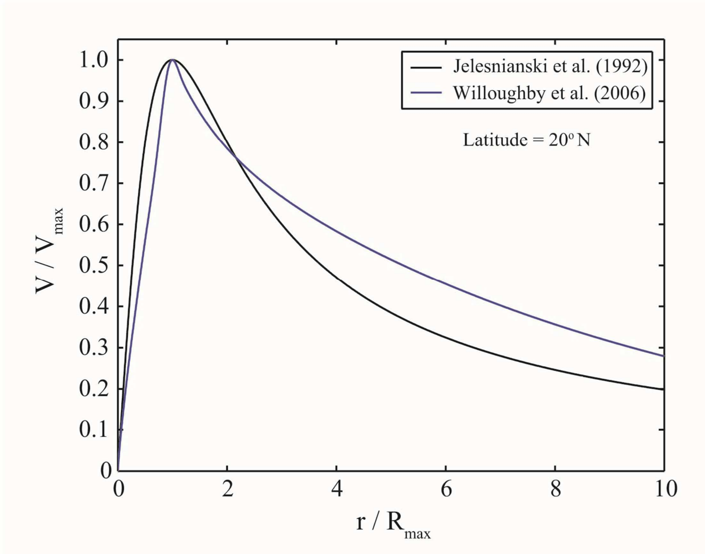

FIG. 2. Radial wind profile comparisons between Jelesnianski et al. (1992) and Willoughby et al (2006).

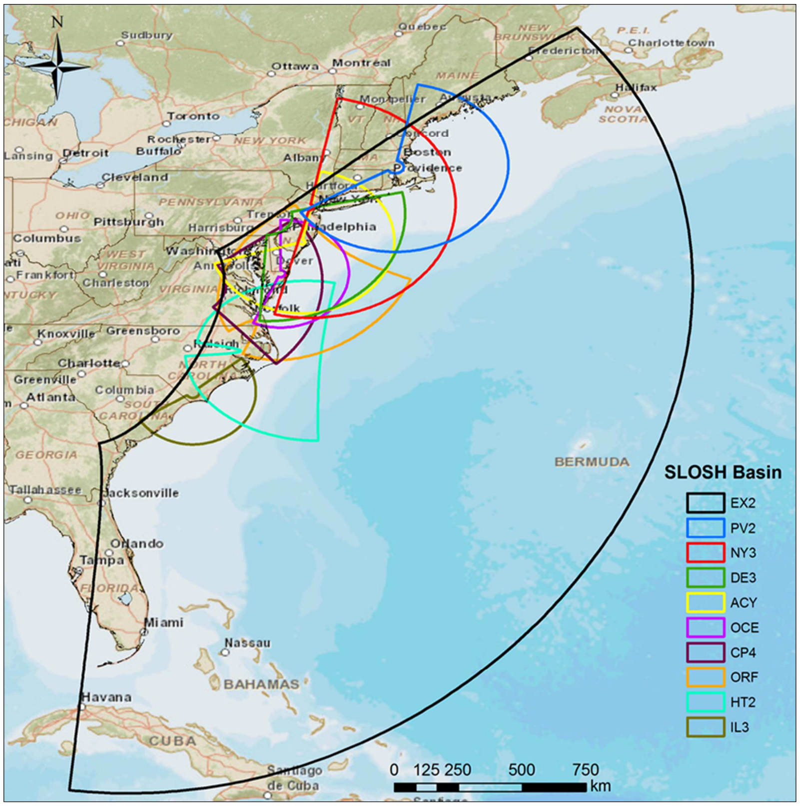

FIG. 3. SLOSH basins used in the analysis.

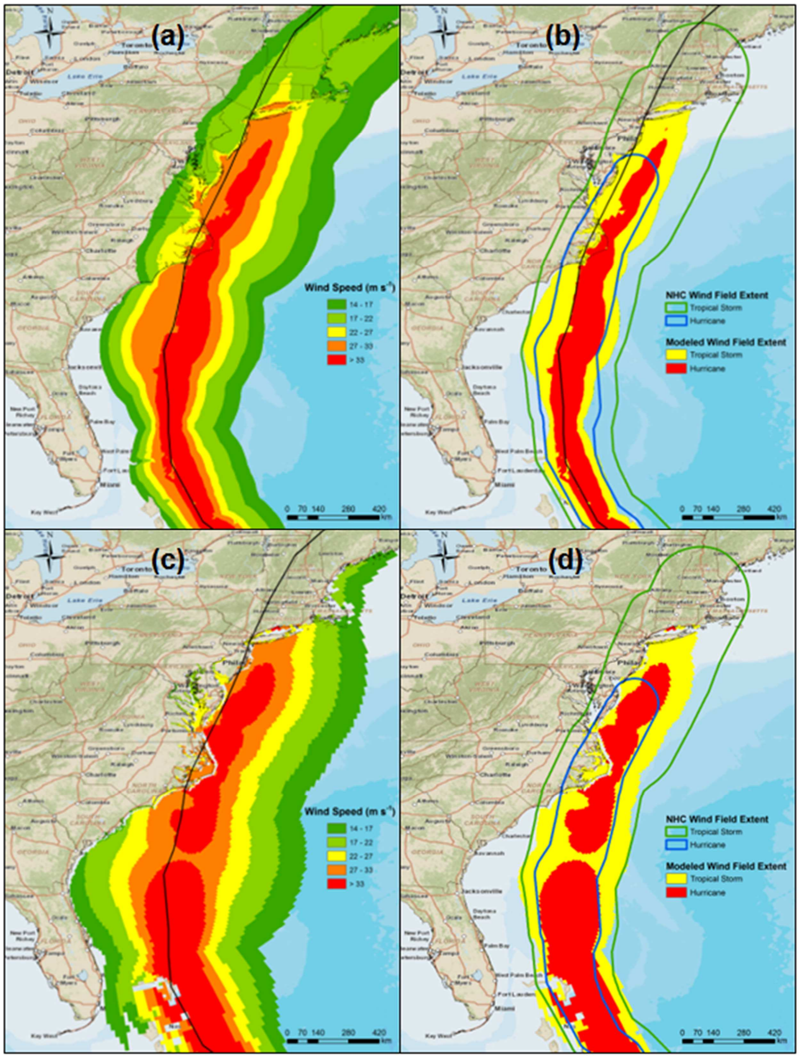

FIG. 4. Maximum wind speed footprints (left) and comparison to NHC extents (right) for the AIR (upper) and SLOSH (lower) wind models.

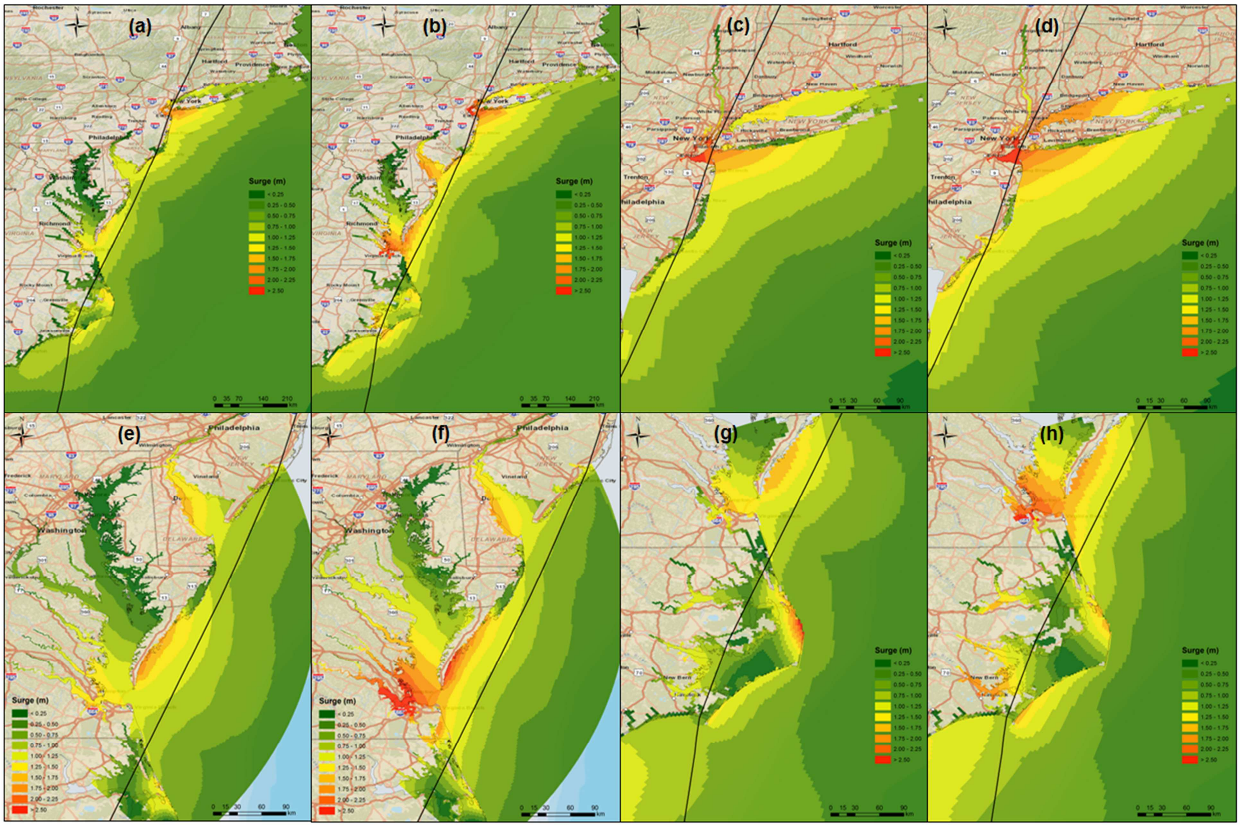

FIG. 5. Maximum SLOSH hindcast water levels for basin EX2 (a,b), NY3 (c,d), CP4 (e,f), and HT2 (g,h) using the AIR (left panel for each basin) and SLOSH (right panel for each basin) hurricane wind models.

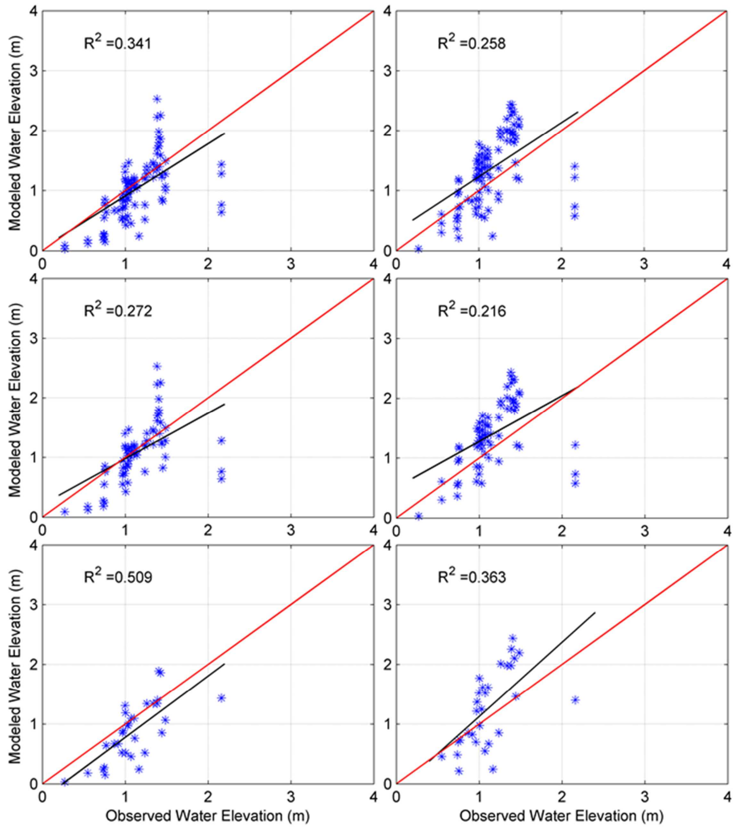

FIG. 6. Modeled versus observed water levels for SLOSH adapted with AIR (left) and SLOSH (right) wind models for all basins (top), tropical (middle), and extratropical (bottom).