Evaluation of surface wind fields for prediction of directional ocean wave spectra during Hurricane Sandy

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Abstract

Hurricane Sandy was the largest storm on historical record in the Atlantic Ocean basin with extensive coastal damage caused by large waves and high storm surge. In this study, three different spatially-varying surface wind and atmospheric pressure fields that are used for forecasting or hindcasting hurricane waves on the continental shelf are investigated. These wind fields include two 2D parametric wind models (Holland model, H80; Generalized Asymmetric Holland Model, GAHM), and a 3D atmospheric model with data assimilation (WeatherFlow Regional Atmospheric Modelling System, WRAMS). These wind fields are used to drive wave hindcasts using coupled Delft3D-SWAN hydrodynamic and ocean wave models on a regional grid, and the bulk wave statistics and the directional wave spectra are compared to observations at offshore wave buoys to investigate the impact of differences between the complex wind fields on predictions of the sea surface evolution.

The spatial and temporal distribution of bulk wave parameters are different for each wind field. The WRAMS wind field produces wave model predictions in the best agreement with significant wave height observations, followed by the GAHM and H80 wind fields, with mean correlation coefficients of 0.91, 0.82 and 0.75, respectively averaged

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over 9 sites. The directional wave spectra for Hurricane Sandy was bi-modal predominantly in the two left quadrants of the hurricane, in agreement with buoy observations. The results indicate that a regional atmospheric wind model that has the best description of the wind field is the most appropriate forcing for hindcasting hurricane waves when detailed observations are available. However a parametric vortex model that incorporates wind at multiple isotachs results in very good agreement with wave observations when used in the wave model, and is a useful tool for forecasting hurricane sea surface conditions. The results of this study are relevant for other tropical cyclones that undergo extratropical transition or are influenced by other atmospheric disturbances at mid-latitudes, resulting in storms with large spatial size and high asymmetry.

Keywords: hurricane winds, ocean surface waves, directional wave spectra, spectral wave model, SWAN

1. Introduction

Hurricanes, also known as tropical cyclones, are some of the world's most powerful and destructive weather events with strong winds that create large waves and high storm surges that can flood coastal areas and cause shoreline erosion. These storms are the costliest natural disasters in the USA (Emanuel, 2005), and have been increasing in frequency and intensity over the last 30 years due to climate change. Associated with climate change, an increase in average storm intensity is expected which will increase damage to coastal regions (Emanuel, 2005). Global climate model predictions indicate an increase in frequency of 2-11% by 2100 of the most intense tropical cyclones (Knutson et al., 2010). Goldenberg et al. (2001) describes the observed doubling of the number of cyclones since 1995 in the Atlantic basin and suggests that the changes are caused by higher sea surface temperatures and the lower vertical wind shear. A better understanding of tropical cyclone winds is needed to improve prediction of impacts and

14 mitigation of damage from the increasing intensity of these storms. Numerical mod-
15 elling of ocean wave and water level conditions is an important method of forecasting
16 costly and hazardous marine conditions from storms like hurricanes.

17 Atmospheric wind models combined with ocean circulation and wave models are
18 powerful tools to predict and better understand hurricane conditions. As an exam-
19 ple, hurricane waves are currently forecast using the Wavewatch III spectral wave
20 model (Tolman, 2009) by the U.S. National Weather Service (2016) where real-time
21 predictions of hurricane wave conditions are computed every 3 hours on a coarse
22 grid with a resolution of 0.25° (approximately 28 km). Hurricane waves are also
23 commonly hindcast using Wavewatch III, the Simulating Waves Nearshore (SWAN)
24 model (Booij et al., 1999), the Wave Model (WAM) or the steady-state spectral wave
25 (STWAVE) model (Jensen et al., 2016). Huang et al. (2013) used SWAN to test the
26 sensitivity of wind drag coefficients under hurricane conditions on deep water waves,
27 and determined that the default wind input settings are suitable for hurricanes and
28 produce reliable predictions in shallow water. Hu and Chen (2011) used SWAN to
29 study wave spectra for hurricane events in the Gulf of Mexico to obtain insight into
30 the controls on the shape of bi-modal wave spectra under complex hurricane winds.
31 Mori (2012) also used SWAN to simulate the waves under typhoon conditions near
32 the Japan coast, to investigate the occurrence of freak waves due to nonlinear four-
33 wave interactions in the different quadrants. Chen and Curcic (2015) used a coupled
34 atmosphere-wave-ocean model for Hurricanes Ike (2008) and Sandy (2012) to better
35 understand the spatial distribution of integrated mean wave properties and the direc-
36 tional spectra.

37 Wave models coupled with hydrodynamic models are also used to predict the com-
38 bined surface waves and storm surge. For example, Sebastian et al. (2014) used SWAN
39 coupled with the Advanced Circulation model (ADCIRC), to study how hurricanes
40 drive storm surge in Galveston Bay. Dietrich et al. (2011) validated ADCIRC coupled

41 with the unstructured mesh version of SWAN for Hurricanes Katrina (2005) and Rita
42 (2005). The Delft3D hydrodynamic model (Lesser et al., 2004) coupled to SWAN has
43 been used to investigate the estuarine response to hurricane storm surge and surface
44 waves in a shallow estuary (Mulligan et al., 2015). Several of these studies use the
45 parametric wind vortex model described by Holland (1980) to simulate the hurricane
46 wind field needed to force the hydrodynamic and wave models. In the present study
47 the goal is to simulate the ocean wave spectra generated by a hurricane wind field,
48 while in related work the coupled wave model circulation models are used to predict
49 storm surge and barrier island overwash (Bennett et al., 2017).

50 The focus of the present study is to investigate a strong storm event that generated
51 large surface waves in the coastal ocean, and had different wind characteristics than
52 typical storms that have been used to develop parametric hurricane wind models. The
53 SWAN spectral wave model is used to simulate Hurricane Sandy over a regional model
54 grid covering the western continental shelf of the Atlantic Ocean for the central United
55 States (Figure 1). Three different spatially-varying surface wind fields are evaluated
56 and compared to wind observations, including the parametric Holland model (H80),
57 a parametric Generalized Asymmetric Holland Model (GAHM), and results from the
58 WeatherFlow Regional Atmospheric Modelling System (WRAMS). These winds are
59 used to drive the spectral wave model, and the wave statistics and directional wave
60 spectra are compared to observations at offshore wave buoys to investigate the impact of
61 differences between the complex wind fields on predictions of the sea surface evolution.
62 It is hypothesized that the WRAMS wind field should produce the best agreement with
63 wave observations since this wind input has been developed using a 3D atmospheric
64 model that assimilates wind observations, where H80 and GAHM wind fields have been
65 developed from 2D parametric hurricane wind models. The influence of these different
66 wind fields on the generation of surface waves are investigated for Hurricane Sandy
67 because it was different in size and meteorological characteristics from typical north

68 Atlantic hurricanes.

69 **2. The Wind Field During Hurricane Sandy**

70 Hurricane Sandy formed in the southwestern Caribbean Sea (Blake et al., 2013) and
71 gained strength as it travelled northeast, parallel to the southeast United States coast-
72 line (Figure 1). The hurricane made a westward turn that is uncharacteristic of typical
73 tropical hurricane tracks (714 year chance of perpendicular landfall, Hall and Sobel
74 (2013)) and made landfall as a Category 1 hurricane on the Saffir-Simpson scale. Sandy
75 is also considered a hybrid “superstorm” due to the combination of tropical and non-
76 tropical characteristics as it approached the coast (Halverson and Rabenhorst, 2013),
77 since it acquired dual energy sources in the mid-Atlantic Ocean from warm tropical
78 waters (typical of a hurricane) and extratropical sources such as the cooler jet stream
79 trough in the middle and upper atmosphere (typical of a Nor’easter). Landfall oc-
80 curred just northeast of Atlantic City (AC), NJ, on October 29, 2012 at 2330 UTC
81 (Coordinated Universal Time), equivalent to Yearday 303.98 (where Yearday 1 is de-
82 fined as January 1, 2012) with 36 ms^{-1} maximum sustained surface winds that caused
83 a high storm surge along the coast of NJ and NY. The storm was nearly 2,000 km
84 in diameter with a radius to maximum wind speed up to 330 km near landfall, and
85 is described as the largest storm on historical record in the Atlantic Ocean and the
86 second costliest hurricane to hit the United States since 1900 (Blake et al., 2013) after
87 Hurricane Katrina (2005). Accurately simulating the Hurricane Sandy surface wind
88 field is important in predicting the ocean scale storm wave and surge properties that
89 led to extensive coastal damage. For this study, the wind field for Hurricane Sandy
90 was developed from three different wind models including H80, GAHM and WRAMS
91 to simulate the wind and pressure fields at a 10 m elevation above mean sea level.

92 **2.1. Holland (1980) Model (H80)**

93 The Holland (1980) model, is an analytical model of the radial profiles of sea level pres-
94 sure and wind velocity components in a tropical cyclone. This model uses hyperbolic
95 pressure profiles that are scaled and used in the gradient wind equations to define the
96 hurricane wind profile and the radius to maximum winds (R_{max}). The model requires
97 the “Best Track” parameters of the hurricane including the eye latitude, eye longitude,
98 R_{max} , wind speed U at R_{max} , the minimum central atmospheric pressure (P_{min}), the
99 ambient atmospheric pressure, and the ambient wind conditions. This wind model has
100 been successfully used in several studies to force hydrodynamic and wave models to
101 predict waves and storm surges (e.g. Mulligan et al., 2015; Hu and Chen, 2011) during
102 cyclonic storms.

103 The H80 wind model was implemented in MATLAB and used to generate winds for
104 Hurricane Sandy over a 3.5 day period from Oct. 28 at 0000 UTC to Oct. 31 at 1200
105 UTC (Yearday 302.0-303.5) on a spherical grid with 18 km horizontal resolution and
106 1-hour temporal resolution. The Best Track wind parameters were obtained every 6
107 hours from Landsea et al. (2016) and used to produce the wind field as indicated in
108 Figure 2a-b for two time steps corresponding to Yearday 303.3 (Oct. 29 at 0500) and
109 Yearday 303.9 (Oct. 29 at 2000). To achieve storm asymmetry, the forward moving
110 velocity (V_{fm}) is calculated from the average 6-hour storm speed and added to the
111 gradient wind velocity.

112 **2.2. Generalized Asymmetric Holland Model (GAHM)**

113 The GAHM model was adapted from the H80 model by Gao et al. (2013) by better
114 taking into account the asymmetry of a hurricane. It differs from H80 with modifi-
115 cations that include eliminating the assumption of cyclostrophic balance at R_{max} and
116 using multiple storm isotachs (e.g. wind speeds at several radii from the storm centre)

117 from National Hurricane Center (NHC) wind forecast advisories. These modifications
 118 allow GAHM to generate a more accurate representation of the wind field for a wider
 119 range of hurricanes, and ensure that the predicted winds match all available isotach in-
 120 formation. In contrast, the Holland model uses only the highest isotach at R_{max} while
 121 GAHM uses the radial distance to the 34, 50 and 64 knot isotachs. Gao et al. (2013)
 122 shows that GAHM is a better representation of 7 historical storms when compared
 123 with NHC’s best track information.

124 In the present study, the Hurricane Sandy wind field is generated from GAHM and is
 125 interpolated onto a grid at 18 km horizontal resolution and 1 hour temporal resolution.
 126 The wind field is shown in Figure 2c-d at two different time steps corresponding to
 127 Yearday 303.3 and 303.9 and is typically stronger over a larger area and more symmetric
 128 than the wind field produced by H80.

129 **2.3. WeatherFlow Regional Atmospheric Modelling System (WRAMS)**

130 The Regional Atmospheric Modelling System (RAMS) (Pielke et al., 1992; Cotton et al.,
 131 2003) is a 3D nonhydrostatic mesoscale meteorological modelling system with equa-
 132 tions for time dependent changes in velocity, pressure and cloud and ice microphysics.
 133 WeatherFlow has implemented the RAMS model (WRAMS) as an operational model
 134 on specific domains at high resolution (WeatherFlow, 2016). WRAMS is used to sim-
 135 ulate Hurricane Sandy by assimilating observational data from meteorological stations
 136 along the east coast of the United States. Data assimilation in RAMS (Federico, 2013)
 137 uses observations from WeatherFlow’s mesoscale observing network (HURRNET) of
 138 over 130 meteorological stations designed to withstand hurricane conditions. This data
 139 set uses the temporal evolution of 1-minute sustained winds, 3-second gusts and at-
 140 mospheric pressure recorded at 10 meters above ground level. The wind field has been
 141 used in a previous study of Hurricane Sandy to investigate inundation in New York City
 142 using a finite element storm surge model (Wang et al., 2014). The WRAMS Hurricane

143 Sandy hindcast was computed on a regional grid of North America with 33 vertical
 144 layers and a horizontal resolution of 18 km. In the present study the surface wind and
 145 atmospheric pressure fields are extracted at 1-hourly temporal resolution over the re-
 146 gion indicated in Figure 1. The wind field is shown in Figure 2e-f at two different time
 147 steps corresponding to Yearday 303.3 and 303.9, indicating that the storm size was
 148 significantly larger than predicted by the H80 and GAHM parametric wind models,
 149 with higher spatial variability.

150 **2.4. Comparison of Wind Fields**

151 The surface wind fields generated using the H80 model show a significantly stronger
 152 east side of the hurricane track and a much weaker west side with similar intensity
 153 on the north and south sides. The GAHM wind field is similar to the H80 but less
 154 asymmetric in shape and has a more significant decrease in wind speed in the eye of
 155 the hurricane. The most intense part of the hurricane is generally on the east side
 156 of the track, but changes from the southeast to the northeast as the storm moves
 157 northward and changes direction. The WRAMS wind field is the most representative
 158 of the actual winds during Hurricane Sandy, as it includes assimilated observations
 159 and a full physics-based set of equations to describe the atmospheric conditions. This
 160 is indicated in Figure 2 by the large region of high winds and the bands of different
 161 wind speeds within the hurricane. This model also includes the influence of land on
 162 the storm indicated by the significant decrease in wind speed as the storm moves over
 163 the continent (Figure 2f).

164 The predicted wind components and atmospheric pressures are compared to the
 165 observed data at six observation locations (Table 1) in Figure 3. H80 has the low-
 166 est agreement with observed wind components (U, V) but is in better agreement with
 167 the observed atmospheric pressure (P) in comparison to GAHM. GAHM indicates
 168 relatively good predictions of the wind components but has weaker agreement with

169 atmospheric pressure observations. WRAMS has the highest agreement with all ob-
 170 servations for U , V , and P , indicating that this wind field is likely the best forcing for
 171 wave and storm surge models.

172 3. Methods

173 3.1. Model Description

174 Delft3D-Wave is the SWAN model (Booij et al., 1999) that is coupled with the Delft3D-
 175 Flow hydrodynamic model (Lesser et al., 2004). SWAN is a third generation, phase-
 176 averaged wave model that uses the action balance equation to predict the evolution of
 177 the wave action density spectrum (N) in space and time. The action balance equation
 178 is given by:

$$\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma} \quad (1)$$

179 where the left side represents the change in wave action (N) over time (t) and the
 180 propagation of the wave action in geographical space (phase speeds are c_x and c_y in x
 181 and y space, respectively), the shifting of the relative frequency (σ) due to variations in
 182 depths and currents, and directional changes (θ) caused by depth- and current-induced
 183 refraction (turning rate c_θ). The right side of the equation (S_{tot}) represents processes
 184 that generate, dissipate or redistribute spectral wave energy (Zijlema, 2010)

$$S_{tot} = S_{in} + S_{wc} + S_{nl4} + S_{bot} + S_{brk} + S_{nl3} \quad (2)$$

185 where S_{in} is the transfer of wind energy to waves, S_{wc} is the dissipation of wave energy
 186 due to whitecapping, S_{nl4} is the nonlinear transfer of wave energy due to quadruplet
 187 interaction, S_{bot} is the dissipation due to bottom friction, S_{brk} is the dissipation due to
 188 wave breaking and S_{nl3} is the nonlinear triad interaction.

189 Delft3D-Flow is a hydrodynamic model (Lesser et al., 2004) used for predicting

currents and water levels that solves the unsteady shallow water equations derived from the Reynolds averaged Navier Stokes equations for an incompressible free surface flow. The system of equations includes the horizontal momentum equations, continuity equation, transport equation and a turbulence closure model.

3.2. Model Setup

The model was implemented on an orthogonal curvilinear grid in a two-dimensional (2D) spherical coordinate system extending from 30.5°N to 42.0°N and from -81.5°E to -66.0°E with a spatial resolution of 2.7 km. This resolution was determined to be ideal in resolving the ocean wave characteristics, and yielded results that were no different from models with coarser (5.4 km) or finer (1.8 km and 0.5 km) grids. The domain spans approximately 1,280 km N-S and 1,440 km E-W has open flow boundaries on the east and south sides. The bathymetry was obtained from the ETOPO1 (1 arc minute resolution) global relief model (Amante and Eakins, 2009) which has a horizontal resolution of approximately 1.8 km. The depth-averaged Delft3D-Flow model is applied on the same orthogonal curvilinear grid as SWAN to simulate the barotropic storm surge that influences the wave field. The model runs were initialized with a water level of $z = 0.0$ m and model parameters include fluid density of $\rho = 1025 \text{ kgm}^{-3}$, the default Chezy bottom friction coefficient of $C_z = 65$ applied uniformly and the default horizontal eddy viscosity of $A_H = 1 \text{ m}^2\text{s}^{-1}$. The present study focusses on ocean waves generated by the hurricane wind field, however the wave and circulation models are coupled to simulate the effect of the storm surge on the waves and for consistency with a study by Bennett et al. (2017) where storm surge is investigated in detail.

The spectral resolution in SWAN was configured with 49 frequency bins over a range of 0.05-3.00 Hz and directional bins of 10°. SWAN operates in 3rd generation mode with a default bottom friction of $C_f = 0.067 \text{ m}^2\text{s}^{-3}$ parameterized using the JONSWAP formulation (Hasselmann et al., 1973). Depth-induced breaking

in shallow water uses a dissipation coefficient $\alpha = 1.00$ and a breaking parameter $\gamma = 0.73$ (Battjes and Janssen, 1978). Whitecapping was modelled based on the van der Westhuysen et al. (2007) formulation, quadruplet interactions are based on the Discrete Interaction Approximation (Hasselmann et al., 1985) and all other parameters in SWAN are default values. Tests were conducted to investigate the sensitivity of the spatial grid resolution, the bottom roughness coefficient, and triad wave-wave interactions, with model results indicating negligible differences.

After sensitivity tests using default wind drag coefficients produced results that did not match observations, the drag coefficients were modified for hurricane conditions. The wind drag coefficient is defined as a function of wind speed and values of $C_d = 0.0020$, 0.0025 and 0.0040 were used for wind speeds of $U < 20 \text{ ms}^{-1}$, $20 - 30 \text{ ms}^{-1}$ and $> 30 \text{ ms}^{-1}$ respectively. These drag coefficients were selected from the results of Fan and Rogers (2016) who investigated the relationship between C_d and wave spectra for Hurricane Ivan (2004), based on the data and simulations presented in Fan et al. (2009) for wind speeds up to 75 ms^{-1} . This is consistent with the work of Holthuijsen et al. (2012) (in which a considerable reduction in drag coefficients for $U > 40 \text{ ms}^{-1}$ is defined) since the winds in Hurricane Sandy were $U \leq 36 \text{ ms}^{-1}$.

The model was run for a 3.5 day period from Oct. 28 0000 UTC to Oct. 31 1200 UTC (Yearday 302.0 and 305.5) with forcing prescribed hourly by the wind components and atmospheric pressure fields over the model domain. During this time Hurricane Sandy propagated from the southern boundary of the model domain, followed a northeastward track, turned northwestward, became extratropical at 38.8°N latitude and dissipated over land. The model time step is 1-minute and coupling between SWAN and Delft3D-Flow occurs every 60 minutes. The model is used to simulate three cases, corresponding to the surface wind and pressure generated from the three hurricane wind models.

3.3. Observations

Due to the large size and high intensity of Hurricane Sandy, many weather stations on the mid-Atlantic coast were damaged or failed to measure throughout the storm. Six stations listed in Table 1 were able to capture the wind and pressure time series and were used to calibrate the wind models including 4 NOAA buoys (National Oceanic and Atmospheric Administration 2016) at Nantucket (NT), New York Harbour (NYH), Long Island (LI) and Delaware Bay (DB) and 2 land-based weather stations at the Field Research Facility (FRF) in Duck NC, and Chesapeake Light (CL) shown in Figure 1. Data from 9 NOAA wave buoys listed in Table 1 are compared to the wave model results, including the 4 above-mentioned buoys and 5 others at Block Island (BI), Cape Henry (CH), Virginia Beach (VB), Oregon Inlet (OI) and East Hatteras (EH).

4. Results

The H80, GAHM and WRAMS hurricane wind and atmospheric pressure fields are each used as input to the models in separate simulations. The bulk wave statistics including the significant wave height (H_s), mean absolute wave period (T_{m01}), and peak direction (θ_P), and the wave spectra are compared to observations to determine the influence of each wind field on the ocean conditions.

4.1. Wave Statistics

The significant wave height for each wind field is shown in Figure 4 at the same times as the winds shown in Figure 2, and follow a similar cyclonic pattern. H80 produced the largest wave heights on the east side of the track just north of the strongest winds, with smaller waves on the southwest side of the hurricane south of the weakest winds. The GAHM wind field generated waves in a similar pattern with the largest waves north of the strongest winds in the southeast quadrant of the storm. The WRAMS wind field

generated waves a similar spatial distribution to the winds with slightly smaller wave heights that cover a larger area.

The predicted significant wave height is compared to the observed significant wave height at 9 buoys shown in Figure 5, with the largest H_s of over 10 m typically on the east side of the track at NYH, LI, BI, and NT. The model performance is assessed by calculating four statistics: the correlation coefficient (R), the root-mean-squared error (RMSE), the bias and the scatter index (SI) for the bulk wave characteristics (H_s, T_{m01}, θ_P). The RMSE is given by

$$RMSE = \left[\frac{1}{N_p} \sum_i (x_i - y_i)^2 \right]^{\frac{1}{2}}, \quad (3)$$

where x_i are observations, y_i are model predictions and N_p is the total number of points. The bias is the mean difference between the observations and the model results:

$$Bias = \frac{1}{N_p} \sum_i (x_i - y_i), \quad (4)$$

and the scatter index is

$$SI = \frac{RMSE}{\left[\frac{1}{N_p} (\sum_i x_i \sum_i y_i) \right]^{\frac{1}{2}}} \quad (5)$$

The statistical results for the simulated significant wave height are presented in Table 2 for each wind field. The H80 winds produced waves with the lowest agreement with observations with R ranging from 0.33 (NT) to 0.90 (CH) as indicated in Figure 6 with an average $\bar{R} = 0.75$ for all 9 sites (Table 2). Waves simulated using winds from GAHM indicate higher correlation with observations data with a range of R from 0.62 (DB) to 0.96 (BI) with an average $\bar{R} = 0.82$ for all 9 sites. Waves produced using the WRAMS wind field have the highest correlation with observations with a range of R from 0.77 (NT) to 0.98 (CH) with an average $\bar{R} = 0.91$.

The model results for the mean absolute wave period and peak wave direction are

285 compared with observations in Figure 7 and Figure 8. Similar to the significant wave
 286 height shown in Figure 5, the WRAMS and GAHM wind fields are in better agreement
 287 with measurements than the H80 wind field at most sites. The mean absolute wave
 288 period time series is similar to the significant wave height time series, with the longest
 289 wave periods up to 13 s observed during the strongest parts of the storm. In Figure 8
 290 a large change in the peak wave direction for the observations and wind fields is shown
 291 on Yearday 303.1 at EH and Yearday 303.9 at CH as the hurricane passes by and
 292 the wave direction shifts from 0° to 360° . The peak direction observations often vary
 293 greatly over a short period of time and shift between values, caused by the difference
 294 in spectral peaks from the local wind-generated waves and from swell that propagate
 295 in different directions at different frequencies.

296 **4.2. Wave Spectra**

297 The 1-dimensional (1D) wave spectra and the 2-dimensional (2D) directional wave
 298 spectra are presented in Figures 9-11 at selected buoys. Evolution of the wave energy
 299 density at Virginia Beach (VB) and Long Island (LI) throughout the storm indicate
 300 that the spectral observations (Figure 9a,c) are similar to model results produced using
 301 the WRAMS wind field (Figure 9b,d). Higher energy lower frequency swell ($f = 0.05$ -
 302 0.10 Hz) is observed during the storm, arriving first at VB since it is further south
 303 than LI. Higher frequency wind sea ($f > 0.1$ Hz) is a major component of the spectra
 304 especially at VB, since offshore hurricane winds (e.g. Figure 2f) primarily generate
 305 waves after passage of the eye of the storm (Yearday 303.5-304.5). The model results
 306 generated using the WRAMS wind field slightly under-predict the wave energy, and
 307 the duration of the storm compared to the observations.

308 The simulated 1D wave spectra for each wind field is compared to observations at
 309 four buoy locations in Figure 10 for three time steps indicated in Figure 9. The predic-
 310 tions indicate good general agreement with the observations, however the simulations

do not to capture the same magnitude of local wind-generated wave and swell peaks as observed by the buoys. The GAHM wind field produces very good agreement with the observations but tends to over predict the wave energy, consistent with the significant wave height data (Figure 5). In particular, the large increase in wave energy in Figure 10k is correlated with the large increase in wave height in Figure 5g at VB on Yearday 303.9. The H80 and the WRAMS wind fields produce very similar waves with lower correlation with H_s observations but with a better agreement in spectral shape, with bi-modal spectra at DB and VB (Figure 10e-h) driven by onshore hurricane swell and offshore wind sea.

The 2D directional wave spectra for observations and SWAN results using the WRAMS wind field are shown in Figure 11 at 3 locations. The WRAMS wind field produces directional spectra that are similar to observations in frequency and direction, but the predicted energy distribution is narrower and smoother than the observations. This suggests that the model predicts the peaks in directional spectra well, but misses the minor spectral components likely associated with local wind fluctuations resulting from the complex and chaotic sea surface under the hurricane.

5. Discussion

5.1. Influence of Wind Field on Waves

The three surface wind fields are different in size and shape. They each have a different spatial wind distribution with the highest wind speeds in different regions relative to the hurricane eye (Figure 2). This results in different spectral energy levels in different areas of the storm indicated by the significant wave height (Figure 4), *e.g.* to the east (H80), south (GAHM), and southeast/northeast (WRAMS) of the storm centre on Yearday 303.3. The time series indicate general agreement with the maximum value of H_S produced using all three wind fields (Figure 5), however the data-model agreement

336 is poor at buoys located furthest east (*e.g.* EH, BI, NT), particularly after the hurricane
 337 has passed. This is likely due to other swell events coming in from the greater Atlantic
 338 Ocean that are not simulated by the model, since the waves in the model are generated
 339 only by winds over the regional domain. The GAHM wind field produces significant
 340 wave height results that consistently over-predict the H_s observations with RMSE of
 341 1.3 m particularly after the peak of the storm has passed the buoys located close to
 342 the coast (NYH, LI, CH, DB, VB, OI) shown in Figure 5. The WRAMS and H80 wind
 343 fields consistently result in under-prediction of the H_s with RMSE of 1.33 m and 2.44
 344 m.

345 The right side of the hurricane typically has wave spectra that is uni-modal with
 346 higher energy closer to the storm centre (*e.g.* LI and NYH, Figure 10). The left side
 347 of the storm typically has bi-modal spectra (*e.g.* DB and VB, Figure 10) and is not
 348 always accurately predicted using these wind fields. The WRAMS wind field results
 349 in wave spectra that has good agreement with the shape of the observed spectra but
 350 does not produce the same energy magnitude. This is evident from the generally under-
 351 predicted significant wave height, the shorter duration of high frequency waves through
 352 the storm (Figure 9), and the distribution of the directional spectra (Figure 11). The
 353 GAHM wind field results in better agreement with the magnitude of the frequency
 354 spectra but not the same spectral shape compared to the observations (Figure 10).
 355 The H80 winds consistently under-predict the intensity of the hurricane and results in
 356 significant wave height and wave spectra that are not as accurate as those generated
 357 by GAHM or WRAMS.

358 **5.2. Directional Spectra of Hurricane Waves**

359 Many hurricanes produce wind fields that are well-described using simple parametric
 360 wind models. For tropical cyclones close to the coast of Australia, Young (2006)
 361 observed that spectra in most quadrants are dominated by swell generated near the

intense wind crescent of the hurricane at some earlier point in the storm and is mixed with the local wind-sea, resulting in a directionally skewed spectrum. Hurricane Sandy was different from typical tropical hurricanes in terms of its large size (Figure 12a), combination of tropical and no-tropical storm characteristics, and westward turn in track. However we observe the wave spectra in each quadrant during Hurricane Sandy is similar to tropical cyclones studied by others, suggesting that the dominant spectral features developed as a result of the hurricane characteristics of this superstorm.

The present results are compared to the Hu and Chen (2011) classification of hurricane wave spectra to investigate the difference compared to other events. Hu and Chen (2011) suggest that hurricane generated spectra are typically uni-modal, with some bi-modal spectra in specific geographic regions relative to the eye of the hurricane. To investigate this, the Hurricane Sandy directional spectra predicted using the WRAMS wind field is analyzed by dividing the storm into four quadrants (Q1-Q4) relative to north with the eye in the centre, where Q1 is the northeast quadrant and the other quadrants follow sequentially counter-clockwise as shown in Figure 12b. Even though the storm track was directed to the northwest at this time, the classification of quadrants relative to north is applied here since a significant component of the forward moving velocity is directed northward and the region of maximum wind speed and largest significant wave height is located east of the eye.

The simulated wave spectra are shown in Figure 12c-f, and are generally consistent with Hu and Chen (2011), indicating energy in the right-side (east, Q1, Q4) quadrants that is higher than in the left-side (west, Q2, Q3) quadrants due to asymmetry of the wind field. The results also show agreement that spectra in the two right quadrants are dominated by higher frequency waves, particularly in Q3. The highest H_s of up to 12 m occur in Q1 and Q4, and are swell-dominated with lower frequency wave energy.

Hu and Chen (2011) report that bi-modal spectra most prominently occur in Q2-Q3, and define four types of bi-modal hurricane spectra where: Type I is a large

distance ($>6 R_{max}$) from the hurricane centre; Type II has a large difference between
 wind and wave directions; Type III has sea and swell components from the same
 direction, and Type IV occurs due to shallow water coastal effects. The present model
 results indicate that Hurricane Sandy has bi-modal wave spectra, that are mainly
 Types II and III. Type II (Figure 10g-l) occurs at DB and VB that are located in
 Q2-Q3. The fetch-limitation by the coast is particularly evident on the shelf at VB,
 and combined with the distance from the storm centre this results in sea and swell
 from different directions (Figure 11c,f). LI and NYH are in Q2-Q1 and are dominated
 by uni-modal spectra. Compared to observations, the model results using WRAMS
 predicts the Type II bi-modal spectra at some locations and times (Figure 10g,h,j),
 however it does not always simulate two spectral peaks (Figure 10i,k,l). In addition,
 in the 2D wave spectra in Figure 11f (corresponding to 1D spectra in Figure 10k)
 shows a wide directional distribution similar to the observed 2D spectra (Figure 11c).
 This phenomenon is also shown in Figure 12e where the 1D spectra is uni-modal swell
 but the directional spectra indicates multi-directional wave energy. Type III bi-modal
 waves occur at LI (Figure 10b,e and Figure 11a,b) where the sea and swell energy
 peaks are close in frequency and from similar directions. Type I bi-modal waves occur
 early in the simulations, when the storm is further south and wave heights are small.
 Type IV bi-modal waves are not observed because none of the observation sites are in
 shallow water depths relative to the wave length.

6. Summary and Conclusions

Hurricane Sandy was a large storm with offshore waves up to $H_s = 12.0$ m in the
 open ocean. The storm made a westward turn, uncharacteristic of typical tropical
 cyclone tracks in the north Atlantic Ocean basin, and made landfall along a coastal
 region that is not typically struck by tropical cyclones. In this study three different

spatially-varying surface wind fields are evaluated and compared to wind observations, including the parametric Holland (1980) model (H80), the parametric Generalized Asymmetric Holland Model (GAHM), and results from the WeatherFlow Regional Atmospheric Modelling System (WRAMS). The winds are used to drive the SWAN spectral wave model, and the wave statistics and directional wave spectra are compared to observations at offshore wave buoys to investigate the impact of differences between the complex wind fields on predictions of the sea surface evolution.

The wave simulations for three different spatially-varying wind fields for Hurricane Sandy revealed important differences in surface wave conditions. The WRAMS wind field produced wave model predictions with the highest agreement with wave observations, followed by the GAHM and H80, with mean correlation coefficients of $\bar{R} = 0.91$, 0.82 and 0.75 and mean root-mean squared errors of $\text{RMSE} = 1.33$ m, 1.30 m and 2.44 m, respectively, averaged over 3.5 days at 9 sites. WRAMS and H80 tended to under-predict the bulk wave statistics while GAHM tended to over-predict the significant wave height, wave energy and water levels. The SWAN model results using WRAMS were used to classify the directional wave spectra for Hurricane Sandy, indicating that the model simulates bi-modal spectra in the two left quadrants of the hurricane in agreement with the observations. Closer to the hurricane centre, uni-modal spectra is observed and predicted, but a wide directional distribution in wave energy spectra suggests there are likely both sea and swell components in the spectra that have not had space to disperse. In the two right quadrants uni-modal spectra is observed and predicted.

The WRAMS wind field, developed from a 3D atmospheric model that assimilates meteorological observations, should be used to hindcast waves because it is the most representative of true hurricane wind and pressure conditions and produces the most accurate results in comparison to wave observations. The GAHM wind field, generated from a parametric vortex model that incorporates all available isotach information,

441 should be used to forecast wave conditions from Best Track hurricane predictions.
442 The H80 wind field, computed using a parametric vortex model that uses the wind
443 speed only at the radius to maximum winds, produces a useful surface wind field
444 that is simple to predict, but does not result in wave predictions in SWAN that are as
445 accurate as using the GAHM winds. Although the focus of this research is on Hurricane
446 Sandy, its meteorological characteristics were not unlike other tropical cyclones at mid-
447 latitudes that undergo extratropical transition or are influenced by other atmospheric
448 disturbances making the results applicable to other hurricanes with large spatial size
449 and high asymmetry. The results indicate that hurricane wind fields used to force
450 ocean-scale wave models can accurately predict the spatial and temporal variability
451 of surface waves needed to provide detailed boundary conditions to higher-resolution
452 models for coastal regions.

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Table 1: Observation sites used in this study

Location	Acronym	Latitude	Longitude	Wind	Wave	Water level
New York Harbour	NYH	40.369	−73.703	x	x	
Long Island	LI	40.251	−73.164	x	x	
Block Island	BI	40.969	−71.127		x	
Cape Henry	CH	36.915	−75.720		x	
Delaware Bay	DB	38.461	−74.703	x	x	
Nantucket	NT	40.503	−69.248	x	x	
Virginia Beach	VB	36.611	−74.842		x	
East Hatteras	EH	34.645	−72.695		x	
Oregon Inlet	OI	35.750	−75.330		x	
Chesapeake Light	CL	36.905	−75.713	x		
Field Research Facility	FRF	36.184	−75.746	x		

Table 2: Statistics for significant wave height

Location	Model	R	RMSE (m)	Bias (m)	SI
New York Harbour (NYH)	WRAMS	0.96	1.10	0.92	0.03
	H80	0.80	2.02	1.55	0.07
	GAHM	0.82	1.35	−0.43	0.04
Long Island (LI)	WRAMS	0.96	1.19	1.04	0.03
	H80	0.79	2.34	1.76	0.07
	GAHM	0.82	1.63	−0.84	0.03
Block Island (BI)	WRAMS	0.85	1.82	1.56	0.04
	H80	0.52	2.66	1.61	0.06
	GAHM	0.96	0.70	−0.48	0.01
Cape Henry (CH)	WRAMS	0.98	0.51	0.45	0.01
	H80	0.90	1.23	1.11	0.04
	GAHM	0.80	0.76	−0.24	0.02
Delaware Bay (DB)	WRAMS	0.96	1.15	1.02	0.04
	H80	0.90	1.85	1.59	0.06
	GAHM	0.62	1.27	−0.22	0.03
Nantucket (NT)	WRAMS	0.78	2.15	1.76	0.06
	H80	0.32	3.37	2.07	0.10
	GAHM	0.85	1.11	0.23	0.03
Virginia Beach (VB)	WRAMS	0.94	1.06	0.73	0.03
	H80	0.86	2.46	2.25	0.07
	GAHM	0.73	1.59	−0.07	0.03
East Hatteras (EH)	WRAMS	0.83	2.04	1.22	0.04
	H80	0.82	3.80	3.38	0.09
	GAHM	0.88	2.17	0.68	0.04
Oregon Inlet (OI)	WRAMS	0.95	1.26	1.03	0.03
	H80	0.87	2.38	2.04	0.06
	GAHM	0.93	1.01	0.44	0.02
Averaged over all sites	WRAMS	0.91	1.36	1.08	0.03
	H80	0.75	2.46	2.03	0.07
	GAHM	0.82	1.29	−0.1	0.03

Figure 1: Location map indicating the best track of Hurricane Sandy (thick black line) at 6-hr intervals (black circles) in the north Atlantic Ocean, with observation sites (see Table 1) indicated for waves (red dots), winds (red circles) and the location of the eye near Atlantic City (AC) at landfall (red triangle). This region corresponds to the numerical model domain with bathymetry in m relative to mean sea level (colour contours), the 200 m depth contour (magenta line) and the coastline (thin black line).

Figure 2: Wind fields for Hurricane Sandy at Yearday 303.3 and 303.9 generated from: a)-b) the Holland (1980) model; c)-d) the Generalized Asymmetric Holland Model; and d)-e) the WeatherFlow Regional Atmospheric Modeling System. The best track (thick black line) at 6-hr intervals (black circles), wind magnitude (colour contours), wind direction (black vectors), and coastline (thin black line) are shown.

Figure 3: Time series of the atmospheric conditions (U, V wind components and P atmospheric pressure) generated by the H80 wind model (blue line), the GAHM wind model (green line), and the WRAMS wind model (red line) at six wind observation sites (black dots). Observation site locations are indicated in Figure 1.

Figure 4: Significant wave height predicted by SWAN for Hurricane Sandy at Yearday 303.3 and 303.9 generated using different wind field models: a)-b) the H80 wind model; c)-d) GAHM wind model; e)-f) WRAMS wind model. Wave direction (black arrows), significant wave height (colour contours), $H_s=10\text{m}$ contour (red line) and coastline (thin black line) are shown.

Figure 5: Time series of predicted significant wave heights generated using the H80 wind model (blue line), the GAHM wind model (green line), and WRAMS wind model (red line) at nine wave observation (black line) sites.

Figure 6: Scatter plot of predicted significant wave heights compared to observations generated using H80 wind model (blue crosses, H), the GAHM wind model (green dots, G), and WRAMS wind model (red circles, W) at nine wave observation sites. Correlation coefficients (R) for each model are listed in each plot.

Figure 7: Time series of predicted mean absolute wave periods generated using the H80 wind model (blue line), the GAHM wind model (green line), and WRAMS wind model (red line) at six wave observation (black line) sites.

Figure 8: Time series of predicted peak wave directions generated using the H80 wind model (blue line), the GAHM wind model (green line), and WRAMS wind model (red line) at six wave observation (black line) sites.

Figure 9: Observations and simulations of wave spectral evolution for Hurricane Sandy using the WRAMS wind field at Long Island (LI) and Virginia Beach (VB) wave buoys. Energy contours at $10.5m^2Hz^{-1}$ (black line) and selected time steps shown in Figure 10 (red lines) at Yearday 303.70, 303.90 and 303.95 are shown.

Figure 10: Wave energy spectra for Hurricane Sandy at Yearday $t_1=303.70$, $t_2=303.90$ and $t_3=303.95$ generated using the H80 wind model (blue line), the GAHM wind model (green line), and the WRAMS wind model (red line) at four wave observation sites (black line).

Figure 11: Wave directional spectra plots for Hurricane Sandy at Yearday 303.7 from: a)-c) wave buoy observations d)-f) wave model predictions at three sites using the WRAMS wind forcing.

Figure 12: Predicted directional spectra during Hurricane Sandy generated by SWAN using the WRAMS wind field at Yearday 303.7; a) wind speed contours and wind direction vectors; b) significant wave height and wave direction vectors; with red circles that identify 1D and 2D wave spectra in each quadrant of the hurricane shown in c)-f).

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Figure1

Figure2

a) H80: Yearday 303.3

b) H80: Yearday 303.9

c) GAHM: Yearday 303.3

d) GAHM: Yearday 303.9

e) WRAMS: Yearday 303.3

f) WRAMS: Yearday 303.9

Figure3

Figure4

Figure5

Figure6

Figure7

Figure8

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Figure10

Figure11

Figure12