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# Simulation of Hurricane Loading for Proposed Offshore Windfarms off the US Northeast Coast

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**Abstract.** The development of offshore wind projects off the US northeast coast requires a comprehensive assessment of extreme loads generated by hurricanes. In this study, we demonstrated that using simplified methods based on observed data at nearby stations (e.g., measure-correlate-predict algorithms) to assess wind and wave loads during extreme conditions may lead to significant errors. We used an advanced ocean modeling system (COAWST: Coupled Ocean Atmosphere Wave Sediment Transport) to assess environmental loading at the proposed wind farm sites offshore Rhode Island and Massachusetts. After validation of the COAWST model using historical hurricanes (e.g., Hurricane Sandy in 2012), a number of synthetic tropical storms that represented wind with various probabilities (e.g., 50-year return period) were simulated. The spatial and temporal variability of the wind and wave loads within the proposed sites were assessed. Nearly 40% variability of wave loads was shown in the proposed sites. The results indicated the advantage of more advanced modeling systems for extreme load characterization, in which wind and wave fields in offshore wind farms can be resolved.

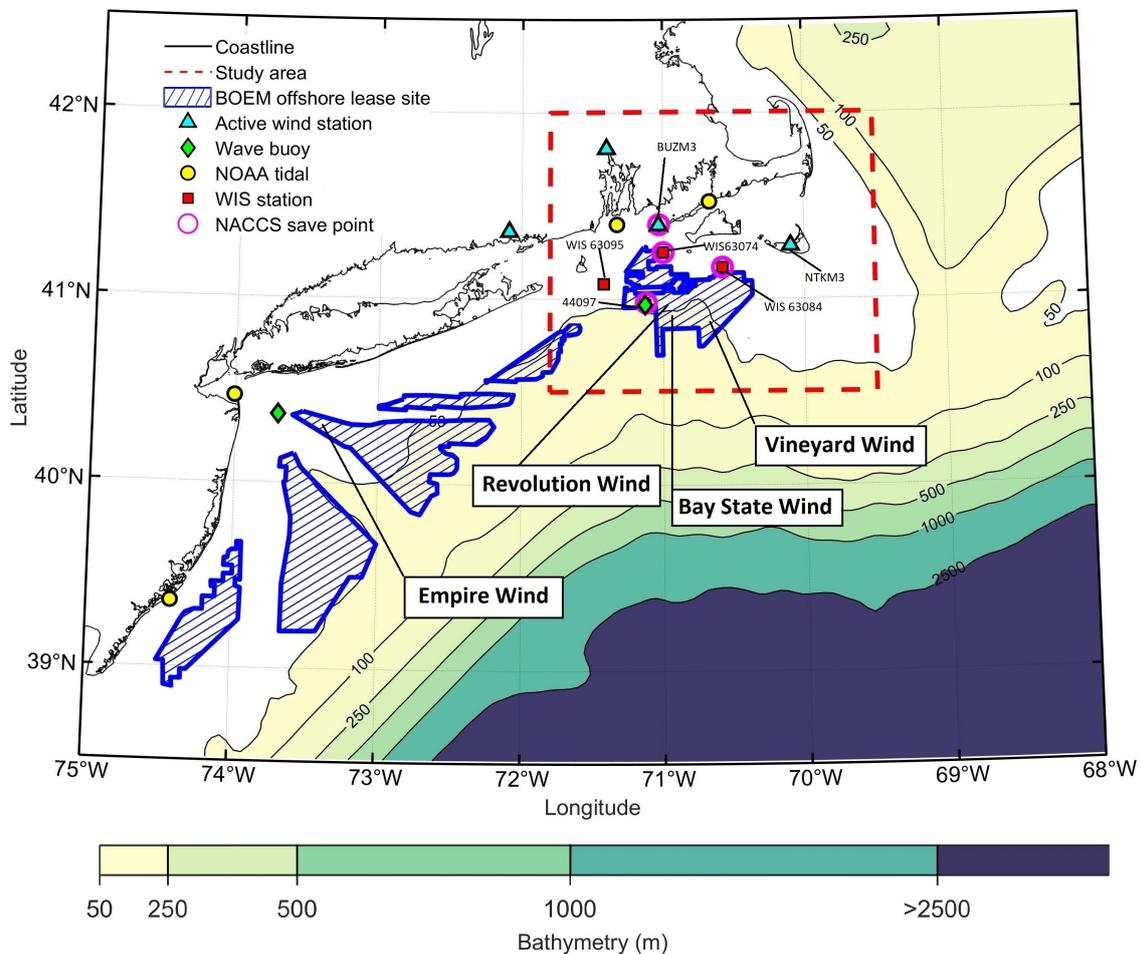
## 1. Introduction

The northeast coast of the US has a vast offshore energy resource that can potentially supply a large portion of the electricity demand of the coastal cities in this region. Following the success of the Block Island Wind Farm offshore Rhode Island, as the first offshore wind project in the US, several projects (e.g., Bay State Wind, Empire Wind, Revolution Wind, and Vineyard Wind <sup>1</sup>) have been planned by Rhode Island, Massachusetts, New Jersey, and other states in this region (see Fig. 1).

The exposure of offshore wind energy sites in the US east coast to strong tropical storms, hurricanes, and Nor'easters [2, 3, 4], as opposed to European offshore wind farms, requires additional considerations in the design procedure [5, 6]. Some studies have indicated the possibility of the failure of wind turbine structures during hurricanes [7]. Over the past decades, several hurricanes (e.g, Bob in 1991, Irene in 2011, Sandy in 2012) have impacted the northeastern US, causing severe damages [8]. Fewer hurricanes have made landfalls in the northeastern US compared with the southeastern US; therefore, there is more uncertainty about future hurricanes in this region due to less historical data. Additionally, recent studies suggest a change in the intensity and the frequency of hurricanes in a warming climate [9, 10, 11, 12].

<sup>1</sup> see: vineyardwind.com, baystatewind.com, equinor.com, dwwind.com, and www.boem.gov





**Figure 1.** Map of the US northeast coast and the BOEM offshore wind energy lease sites and projects (see [1] for details). The bathymetry of the region and a number of wind/wave observation stations or data points are shown on the map.

To characterize extreme wind and wave loads on offshore wind turbines (e.g., substructure and foundation), the wind engineering standards such as IEC 61400-3 and DNV-OS-J101 [13] implement the load and resistance factor design method (LRFD; [14]). A wind and/or a wave field with a specific return period is usually used to evaluate a loading combination (e.g, 50-year return period according to the IEC Standard [15]). To calculate wind and wave loading parameters at a proposed site, simplified methods such as measure-correlate-predict algorithm are implemented [16, 17]. These methods usually assume that the variability of the wind and wave conditions within a site is negligible (i.e., uniform). Also, due to the lack of measured data during extreme storms at a site, correlation in moderate conditions may be used to estimate the extreme wind and wave conditions. These simplifications may lead to significant errors that lead to under- or over-estimation of the design loads. A design based on inaccurate loading evaluation at an offshore wind farm can lead to structural safety issues or uneconomic designs.

Several global or regional ocean/atmospheric models provide the wind/wave field simulations in hindcast and/or forecast modes; e.g., North American Regional Reanalysis (NARR<sup>2</sup>, [18]);

<sup>2</sup> [www.emc.ncep.noaa.gov/mmb/rrean/](http://www.emc.ncep.noaa.gov/mmb/rrean/)

the European Centre for Medium-Range Weather Forecasts (ECMWF<sup>3</sup>, [19]); the Northeast Coastal Ocean Forecast System (NECOFS<sup>4</sup>). For the US coastal regions, the Wave Information Studies (WIS<sup>5</sup>, [20]) has provided long-term (decadal) wave and wind time series data based on numerical modeling. Fig. 1 shows a few WIS stations/nodes near the study area. While these databases provide valuable information about historical hurricanes, site specific modeling studies are required to better resolve the environmental loading at offshore energy sites.

Synthetic hurricanes can be used to study a storm with a certain probability (e.g., extreme analysis) at a site [21, 22]. Therefore, they can be useful in the loading stage of the structural designs of wind turbines; they can better represent a 50-year or a 100-year loading scenario. In 2015, the North Atlantic Coast Comprehensive Study (NACCS; [23]) was published in which 1050 synthetic tropical storms were simulated for the US east coast. The synthetic storms in this dataset were employed in this research.

In this study, a regional ocean model of the US northeast was developed to better characterize the wind and wave loads under hurricane condition. The modeling study was focused on the proposed wind farm sites offshore Rhode Island and Massachusetts. After validation of the model using Hurricane Sandy, two synthetic storms representing a hurricane with 2% exceeding probability (i.e., 50-year return period) were modeled. Spatial variabilities of the peak wind and wave loads in the site were discussed.

## 2. Methods

COAWST [24] was employed to develop a numerical model of the region (Fig. 1). COAWST is comprised of a toolkit to exchange data between an ocean model ROMS (Regional Ocean Modeling System), an atmosphere model WRF (Weather Research and Forecasting), and a wave model SWAN (Simulating WAVes Nearshore). COAWST allows various coupling configurations between modules (e.g., ROMS-WRF, SWAN-ROMS, WRF-SWAN, ROMS-SWAN-WRF) depending on the application. Physical processes/parameters such as ocean currents, tides, storm surge, salinity, temperature, wind, and waves can be simulated during tropical or extra-tropical storms as well as calm periods. In this study, a coupled ROMS-SWAN model (see Fig. 2) forced by external wind fields were used. While coupling with WRF could be used for hurricane simulations [25], for simplicity, we used decoupled wind modeled data to characterize the wind field.

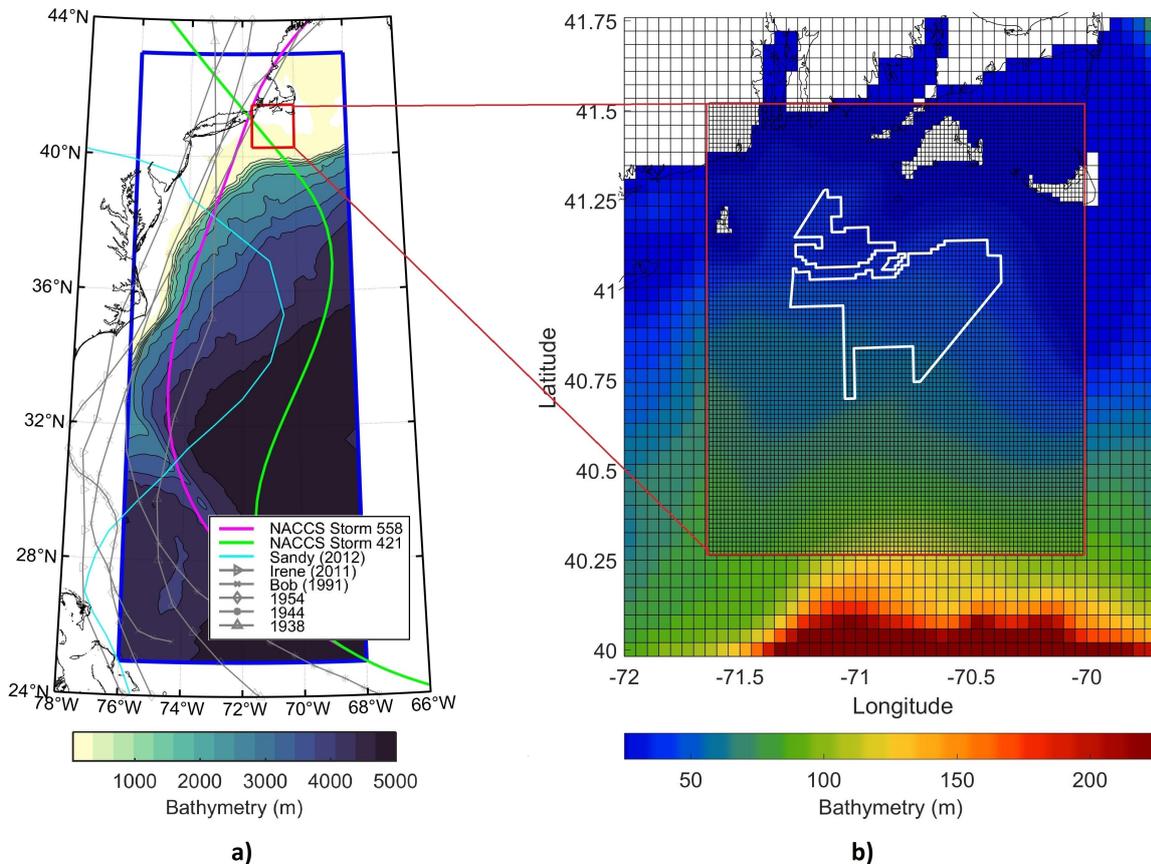
The computational domain was discretized using a two-way nested grid configuration (e.g., [26]) to increase the simulation accuracy in the area of interest while keeping the computational cost low [27]. Fig. 2 shows the computational grid and the bathymetry for the domain. The parent domain extends from 76° W to 68° W and 25° N to 43° N. The parent grid has a 3 arc-minutes (~5 km) horizontal resolution. The 1-arc minute (~1.5 km) ETOPO [28] bathymetry dataset was used. The nested child domain, which was focused on the offshore wind lease sites offshore Rhode Island and Massachusetts, was built at 1 arc-minute (~1.5 km) resolution. Both parent and child grids were discretized with 21  $\sigma$ -layers [29] in the vertical direction. The ROMS open ocean boundaries were forced with the tidal data (elevation and velocity); 10 tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, Mf, and Mm) were extracted from TPXO global tidal dataset [30] for each boundary point. Based on the previous application of ROMS in this region, the quadratic bottom drag coefficient was set to 0.003 [31]. In addition, the  $\kappa - \epsilon$  turbulence closure model ( $p = 3$ ,  $m = 1.5$ , and  $n = -1$ ; [32]) was implemented.

For wave simulations, swells propagating in the far-field were included at the boundaries, and wave generation (by wind) and propagation inside the domains (parent and child) were

<sup>3</sup> [www.ecmwf.int/](http://www.ecmwf.int/)

<sup>4</sup> [fvcom.smast.umassd.edu/necofs/](http://fvcom.smast.umassd.edu/necofs/)

<sup>5</sup> [wis.usace.army.mil](http://wis.usace.army.mil)



**Figure 2.** a) COAWST domains and b) grid configurations including the bathymetry. Blue and red rectangles illustrate the two-way nested configuration of parent (3-arc minute) and child (1-arc minute) grids. The zoomed view also shows the area for proposed wind energy project sites offshore Rhode Island and Massachusetts. The tracks of selected historic and synthetic hurricanes are plotted on Subfigure a.

simulated. The spectral wave information provided by NOAA WaveWatch-III model<sup>6</sup> were prescribed at the open ocean boundaries. The SWAN model was run in the third generation mode, with inclusion of wind generated waves, whitecapping, and quadruple wave-wave interactions. To configure coupling of ROMS and SWAN models, the COAWST toolbox<sup>7</sup> was used. This toolbox allows the information exchange between the wave and ocean model to include wave-circulation interactions (e.g., wave set-up and set-down, Doppler effect). The coupling time interval between ROMS and SWAN was set at 15 minutes which is suitable to capture temporal variations of wind or circulation (i.e., water elevation and currents).

COAWST was first validated for Hurricane Sandy. For simulation of the wind field during this historical hurricane, the NARR dataset was employed. Three hour interval was used for wind speed and pressure data. The simulation of Hurricane Sandy was carried out for 7 days from October 25, 2012 to November 1, 2012. Also, 2 days for ramping/warming up of the model was considered.

Two synthetic storms from NACCS database, Storm 421 and 558, were simulated. The tracks of historic and synthetic hurricanes are shown in Fig. 2. Table 1 shows how

<sup>6</sup> polar.ncep.noaa.gov

<sup>7</sup> coawstmodel-trac.sourcerepo.com

the peak wind speeds generated by these storms compare to the 50-year storms in the nearby stations (see Fig. 1). As this table shows, these storms can approximately represent a hurricane that generate a design wind speed (e.g., 50-year return period). The peak  $U_{10}$  of Storm 421 and 558 fall in the range of mean and the upper 95% confidence limit of 50-year wind at BUZM3 and WIS 63074. For synthetic storms, at first, the synthetic hurricane parameters from NACCS database were extracted. These parameters include the storm track, intensity, and pressure deficit. A parametric Asymmetric Holland Model [33, 34] was then applied to simulate the wind field over the domain.

### 3. Results

Using the COAWST model, a historical storm and two synthetic storms were simulated. Hurricane Sandy was simulated to assess/validate the model. Two synthetic storms were simulated to examine the spatial variability of the design wind speed and the design wave height within the proposed offshore wind sites.

**Table 1.** Extreme wind loads and the peak  $U_{10}$  of Storm 421 and 558 at BUZM3.

Location	50-year		100-year	
	Mean	Upper 95%	Mean	Upper 95%
BUZM3	33.2 m/s	44.8 m/s	34.5 m/s	49.9 m/s
WIS 63074	28.5 m/s	36.3 m/s	30.1 m/s	40.8 m/s
Peak $U_{10}$				
Storm 421	40 m/s			
Storm 558	37 m/s			

#### 3.1. Hurricane Sandy

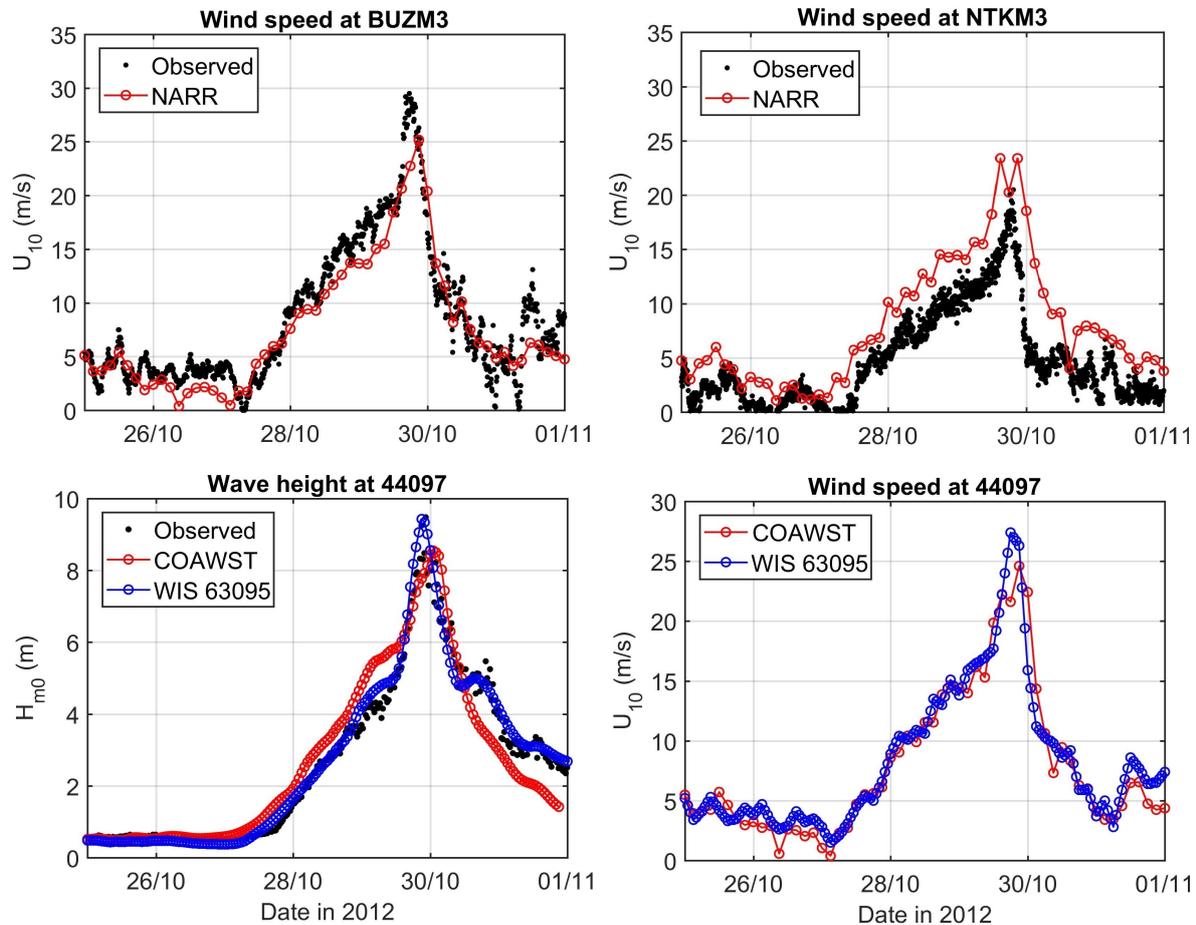
The time series of wind speed at 10 m elevation ( $U_{10}$ ) and significant wave height ( $H_{m0}$ ) were extracted at two wind stations and an observational wave buoy near the proposed sites. The wind stations are located at Buzzards Bay (BUZM3) and Nantucket (NTKM3). The wave buoy is located off Block Island: NDBC 44097. Figure 1 shows the locations of these stations.

Table 2 and Fig. 3 show the comparison of the modeled and simulated data. In general, the results show a relatively good agreement. However, the peak wind speed is underestimated near the Buzzards Bay Station which has led to underestimation of the significant wave height. This could be associated with the track of Sandy which was relatively far from these sites because some

**Table 2.** Comparison of modeled (COAWST) and observed data.

Location	Peak value			
	Observed	Simulated	Error	%Error
<b><math>U_{10}</math> (m/s)</b>				
BUZM3	31.20	25.17	-6.02	20 %
NTKM3	20.50	23.40	2.90	14 %
<b><math>H_{m0}</math> (m)</b>				
44097	9.48	8.11	-1.36	14 %

atmospheric models can not resolve the wind field very far from the track of hurricanes [34]. Referring to Fig. 3, the model shows a relatively convincing time series for wave simulation. At 44097 buoy, simulated maximum wave height is 8.11 m during Hurricane Sandy. The peak observed significant wave height is 9.48 m. Additionally,  $H_{m0}$  and  $U_{10}$  from the nearest WIS station, WIS 63095 were included in Fig. 3 for further assessment of the model performance. The peak  $U_{10}$  at WIS 63095 shows a better match to the observed wind speed, which consequently results in a better match of the wave height. The WIS project is based on another wind model (see [35] for more detail). Therefore, for a better simulation of historical hurricanes, a number of wind models should be compared [34] to select the best wind dataset. The NARR dataset may not be the best product. However, for the purpose of this study, it showed a relatively convincing results.



**Figure 3.** Comparison of the model results and the observed data for  $U_{10}$  and  $H_{m0}$ . The top panels show the comparison of wind speed at BUZM3 and NTKM3. The bottom panels show the comparison of wind speed and wave height at NBC 44097. The WIS 63095 (nearest WIS station to 44097) wind data were also included for further comparison as NDBC Buoy 44097 only have wave measurement data. The COAWST wind are provided by NARR.

### 3.2. Spatial variability of the wind and wave fields within the proposed sites; synthetic storms

The selected NACCS synthetic storms, Storm 421 and 558 were simulated in COAWST. Since the full NACSS wind fields were not available (only the time series at selected points, or Save Points, have been provided), we used an Asymmetrical Holland Model [33] to calculate the wind fields based on the storm parameters (i.e., track and intensity).

Table 3 shows the synthetic storm parameters for these storms. Fig. 4 shows a snapshot of the wind speed and the track of these synthetic storms. Storm 421 and 558 generated peak  $U_{10}$  of nearly 40 m/s and 37 m/s,

respectively. Note that 42.5 m/s is the border of Category 1 and Category 2 hurricanes according to the Saffir-Simpson scale. Storm 421 travels northward from the tropics with a translational speed of 59 km/h. The track of Storm 421 extends from the Caribbean to the Atlantic Ocean before its landfall in New England (see Fig. 2). Referring to Table 3, Storm 558 has less

**Table 3.** Parameters of synthetic storm 421 and 558.

Parameter	Storm 421	Storm 558
Heading direction ( $\theta$ , degree)	-40	20
Pressure deficit ( $\delta p$ , hPa)	78	73
Radius of maximum wind ( $R_{max}$ , km)	82	62
Translational speed ( $V_t$ , km/h)	59	65

strength compared with Storm 421 but travels faster and has a different track; Storm 558 is heading toward northeast while Storm 421 is heading northwest after landfall.

The COAWST simulation results for Storm 421 and 558 are presented in Fig. 5 and Fig. 6. Five points within the proposed sites were selected to assess the variability of the wind and the wave field in the area (Table 4). The results show that the storm/hurricane track and the radius of maximum wind play important roles in wave generation in the site. For instance, ‘the stronger’ Storm 421 produced smaller waves within the proposed site even though it carried higher wind speeds. During Storm 421, the maximum  $U_{10}$  reached to 40 m/s within the site. The maximum  $H_{m0}$  was 13.5 m within the site for this storm. Whereas, for Storm 558, the maximum  $U_{10}$  and  $H_{m0}$  were 37 m/s and 15 m, respectively.

To assess the spatial variability of the wind and the wave loads within the study area, ratios of  $U_{10}^2$  to its mean and  $H_{m0}^2$  to its mean over the site were calculated, and presented in Fig. 6. These ratios are proportional to the wind and the wave loads, respectively. For wind loading,  $U_{10}$  was used as wind observations are provided at this elevation. For wind speed/loading at the hub height ( $U_{hub}$ ) or on the tower, logarithmic distribution, power law, or other methods need to be implemented [36, 37, 38]. As this figure shows, up to 20% and 40% variation in the wind and the wave loads, respectively, can be expected. The variability of a load depends on the hurricane track and the radius of maximum wind.

**Table 4.** Summary of simulated wind and wave load within the proposed site (Fig. 5).

Points	Longitude	Latitude	Storm 421		Storm 558	
			$U_{10}$ (m/s)	$H_{m0}$ (m)	$U_{10}$ (m/s)	$H_{m0}$ (m)
P1	-71.00	40.75	38.29	11.31	35.96	14.53
P2	-70.75	40.95	39.17	12.99	35.34	13.94
P3	-70.50	41.12	40.08	12.21	34.34	11.52
P4	-71.15	41.25	38.65	11.30	35.44	11.39
P5	-70.60	40.85	39.34	13.35	34.07	14.09

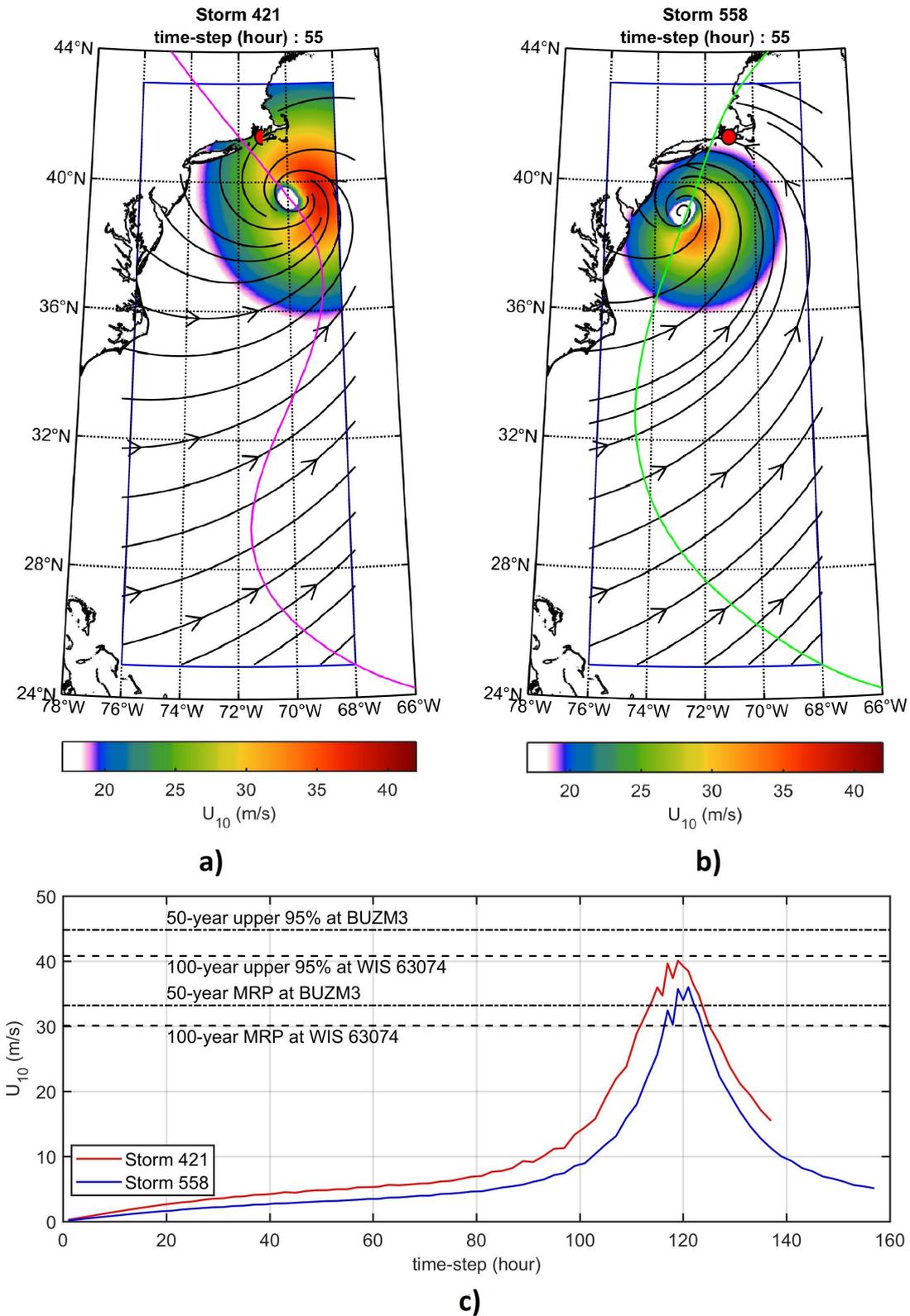
#### 4. Discussion

It was demonstrated that the spatial variability of wind and wave fields, and consequently their loads, can be significant within a farm. For instance, a turbine located at P1 (Fig. 5) is expected to experience a wave height of 14.53 m whereas another turbine located at P4 experiences wave height of 11.39 m during Storm 558. The spatial variation of wave loads would be more than that of significant wave heights; i.e., proportional to the square of wave height. Furthermore, results showed that the storm track plays an important role regarding the correlation of wind and wave loads in a site. This factor would be particularly important when wind and wave load combinations are used for the design of turbine substructures.

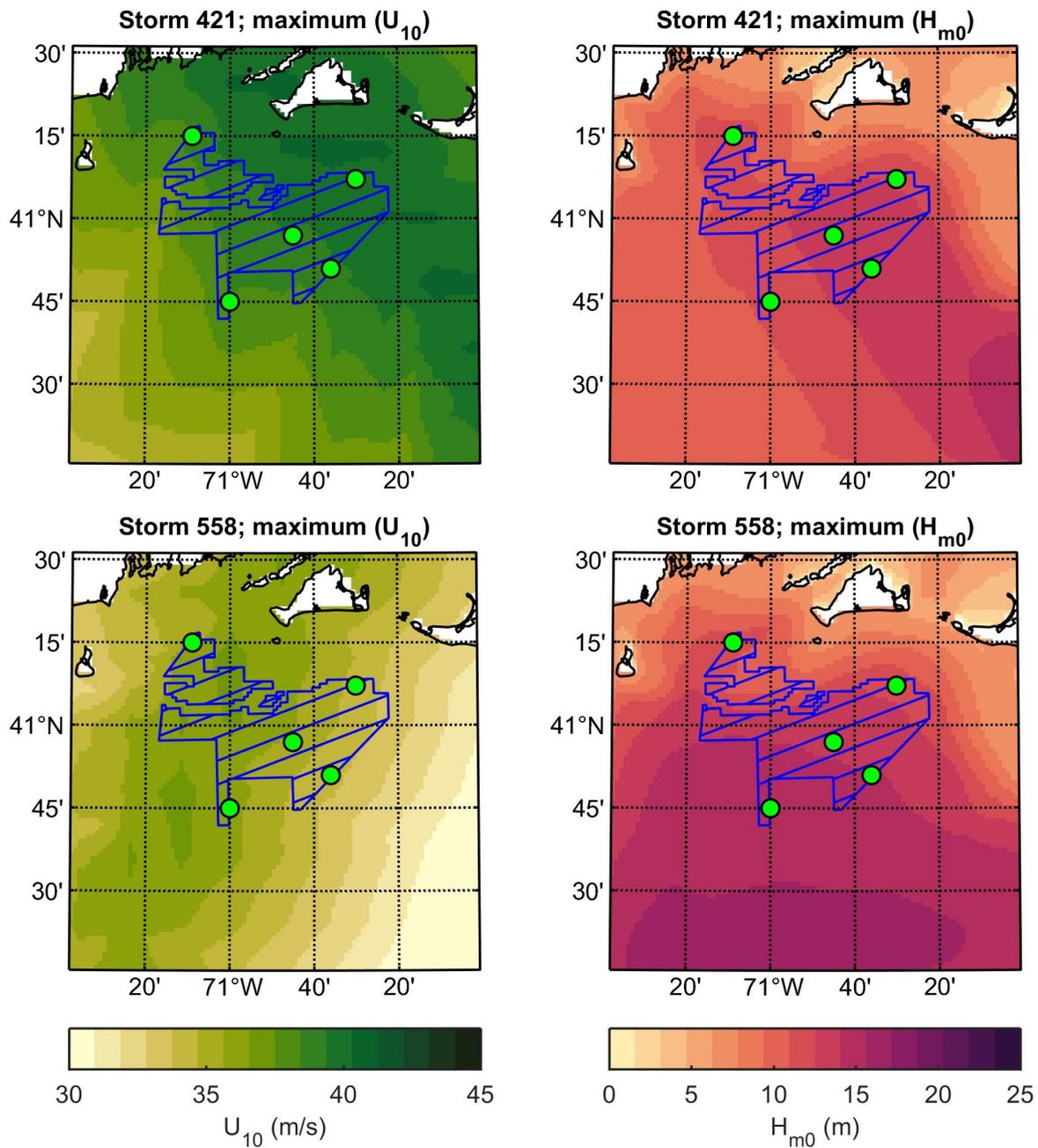
The measure-correlate-predict is a popular method to generate a long-term time series of wind/wave data at a site. This method uses the correlation between the wind/wave parameters at a proposed site and nearby stations that have long-term data records [39, 40, 41]. Measurements at a site of interest usually do not include extreme weather events; e.g., with return periods of 50-year and above. Therefore, simulation of synthetic storms that represent a more realistic spatial variation of storm parameters during extreme events provide a tool to better examine the validity of measure-correlate-predict methods.

In this study, the coupled ROMS-SWAN COAWST was implemented. Alternatively, ROMS-SWAN-WRF COAWST can be applied to better simulate the wind field, particularly for modeling historical storms [25]. Nevertheless, for synthetic storm simulations in which the wind field is dominated by the cyclone/hurricane core structure rather than the environmental wind field, the parametric wind model seems to be adequate.

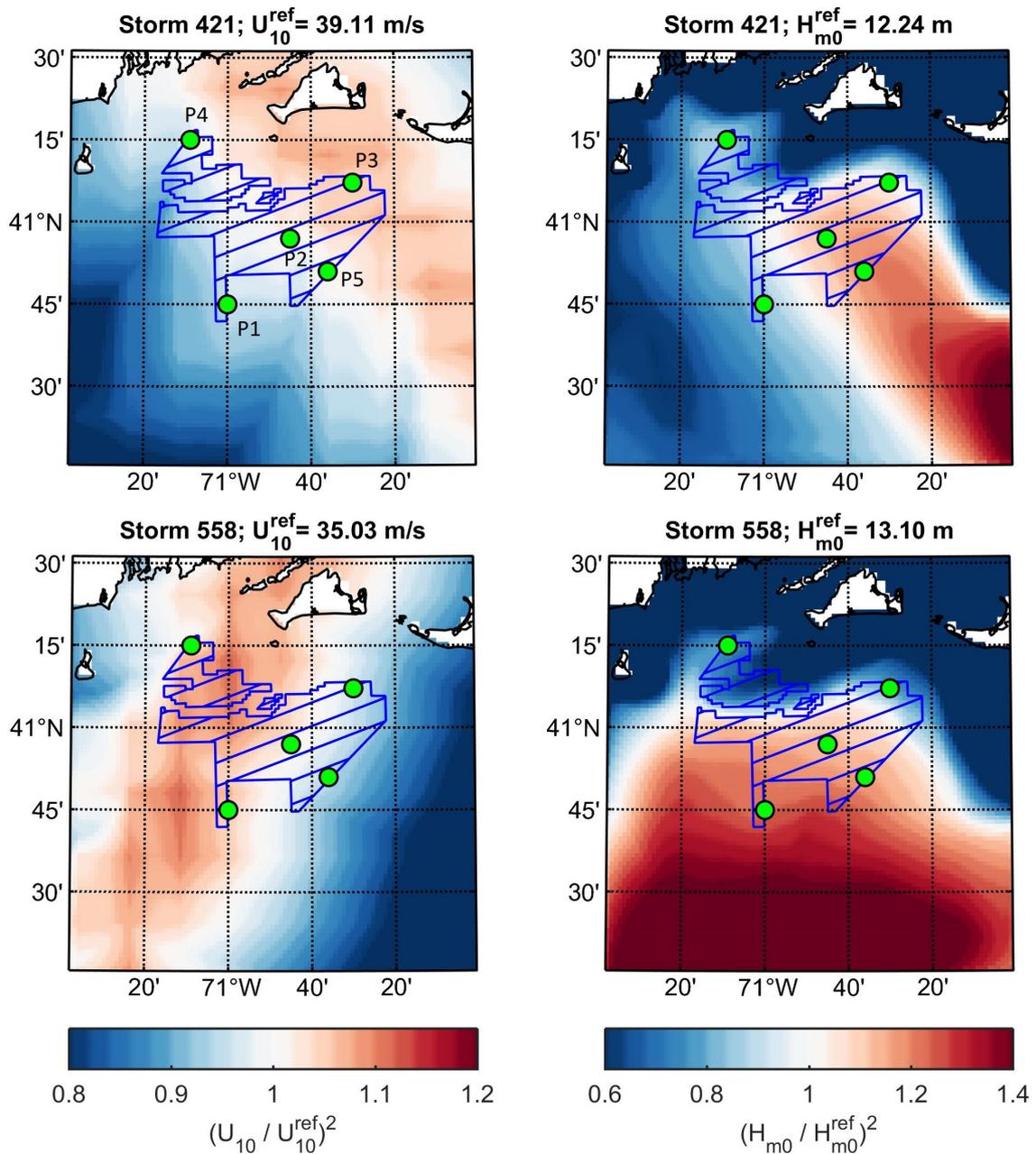
Further research is underway to simulate the wind and the wave fields at micro-scale levels (i.e., within a wind farm). CFD codes that include fluid-structure interaction [42] can be forced



**Figure 4.** The NACCS synthetic storm tracks and their wind fields: a) Storm 421; b) Storm 558; c) The time series of the wind speed at BUZM3 compared with 50-year and 100-year wind speeds at BUZM3.



**Figure 5.** Spatial variation of the peak wind speed and the peak wave height during Storm 421 and 558. Hatched areas illustrate the study area which covers some of the proposed Rhode Island and Massachusetts sites (see Fig. 1).



**Figure 6.** Spatial variation of the wind and wave loads during Storm 421 and 558. Color scales show the ratio of a variable to its average over the domain. It was assumed that wind and wave loads are approximately proportional to wind speed and wave height squared, respectively.

with regional ocean-atmospheric models for this purpose.

## 5. Conclusion

In this study, hurricane wind and wave fields within the proposed wind farm sites offshore Rhode Island and Massachusetts were simulated using the COAWST coupled ocean-atmosphere model. Results showed that the spatial variation of wind and wave loads during a hurricane are significant (up to 40% for wave loads). Also, the correlation of wind and wave loads depends on the track of the hurricane and the region (e.g. bathymetry and coastline). Using uniform wind/wave load based on simple statistical methods that ignore the structure and the track of hurricanes can lead to under- or overestimation of loads. Therefore, modeling synthetic storms that represent storms with certain return periods can result in better assessment of wind and wave loads in a proposed/planned offshore site.

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