51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition
07 - 10 January 2013, Grapevine (Dallas/Ft. Worth Region), Texas

AIAA 2013-0198

Coupled Atmosphere-Wave-Ocean Modeling to Characterize Hurricane Load Cases for Offshore Wind Turbines

Milan Curcic,* Eungsoo Kim,† Lance Manuel,†
Shuyi Chen,* Mark Donelan,* John Michalakes‡

We report on work in progress that is seeking to define hurricane load cases for the design of offshore wind turbines. A software tool, CHAISE (Coupled Hydro-Aerodynamic Interface for Storm Environments), is being developed that will integrate a fully coupled atmospheric-wave-ocean model, referred to as the University of Miami Coupled Model (UMCM), with downscaling using computational fluid dynamics (CFD) tools and, ultimately, with turbine aeroelastic loads computation. The goal is to simulate turbine rotor, tower, and support structure loads on an offshore wind turbine throughout the evolution of a hurricane. We present various elements of this end-to-end simulation capability that is under development.

I. INTRODUCTION

In order to assess the risks to potential U.S. offshore wind farms from the destructive wind, wave, and current conditions induced by hurricanes in the Gulf of Mexico and the Eastern seaboard, a state-of-the-art numerical simulation tool, CHAISE (Coupled Hydro-Aerodynamic Interface for Storm Environments), is under development. The principal objective of CHAISE is to provide accurate estimates of hurricane-induced forces on offshore wind turbine structures at high temporal and spatial resolution; its capabilities are expected to exceed the reliability and applicability afforded by today's design standards. The CHAISE software is composed of several geophysical modeling components that simulate the environment at various scales. The University of Miami Coupled Model (UMCM) is a fully coupled atmosphere-wave-ocean model that is used to simulate the storm and associated environmental fields at spatial and temporal resolutions of the order of 1 kilometer and several seconds, respectively; the model is able to represent relevant physical processes at the air-sea interface at those scales. The UMCM output is used as input to a Large-Eddy Simulation (LES) model (OpenFOAM and WRF-LES) that will achieve the needed downscaling and solve the Naiver-Stokes equations at 5-10 meter spatial scales. Finally, these finely scaled fields will be used as input to FAST, an established wind turbine design tool, that provides accurate estimates of loads on the offshore wind turbine structure of interest. A schematic diagram describing CHAISE is shown on Figure 1. We describe the methodology, application, and some results of the work in progress that uses the CHAISE tool.

II. THE COUPLED ATMOSPHERE-WAVE-OCEAN MODEL

The University of Miami Coupled Model (UMCM) consists of atmosphere, ocean surface wave, and ocean component models. One of the unique features of UMCM is a unified air-sea interface module that is designed to encompass physically based air-sea coupling processes including surface waves as well as communication among the different model components. It is based on the Earth System Modeling Framework (ESMF),[1] which is a software library that facilitates the coupling of various geophysical models. The UMCM component models are:

*The Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149, USA
†Dept. of Civil, Architectural, and Environmental Engineering, University of Texas, Austin, TX 78712, USA
‡National Renewable Energy Laboratory, Golden, CO 80410, USA

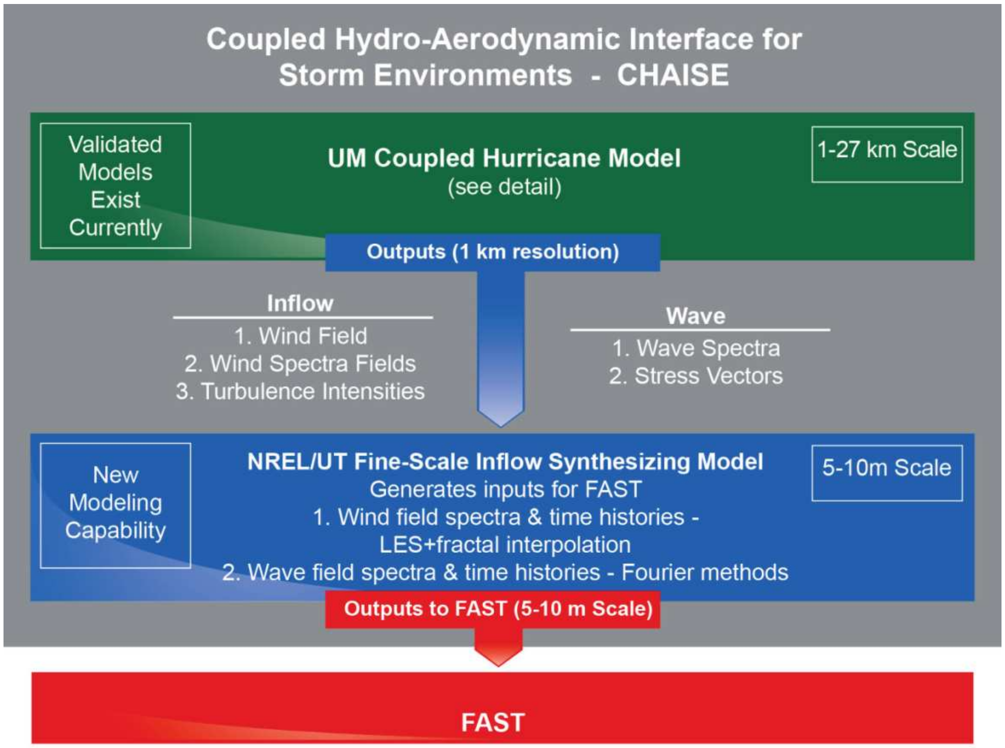


Figure 1. The University of Miami Coupled Model (UMCM) in CHAISE simulates the complex physics of wind-wave-ocean interaction at meteorological scales (1 km) and produces correlated wind, wave, and current fields for use with a scale-bridging software module that is being developed. CHAISE employs the fine-scale output as input to NREL's open-source FAST computer-aided engineering tool.

(a) Atmosphere model - Advanced Research Weather Research and Forecasting (WRF) model,[2] Version 3.4.1, is a three-dimensional primitive-equations model with the capability of movable, hurricane-following, high-resolution nested grids.

(b) Ocean surface wave model - University of Miami Wave Model (UMWM),[3] Version 1.0.1, is a physically based, computationally efficient spectral wave model that solves the wave energy balance equation. It takes the input of surface winds and ocean currents from the atmosphere and ocean model, and predicts 2-dimensional wave variance spectra and momentum fluxes between the atmosphere and ocean.

(c) Ocean circulation model - HYbrid Coordinate Ocean Model (HYCOM),[4] Version 2.2.34, is a primitive-equation ocean model whose vertical coordinate is a hybrid between the z coordinate in shallow water, isopycnal in intermediate water, and sigma (terrain-following) in deep water.

The interface module is responsible for communication and field regridding between component models and is designed to compute the air-sea fluxes in an energetically consistent manner. Wind-wave stress (form drag) is computed by UMWM, and is coupled with WRF at every time step (one minute). Skin drag and wave dissipation contribute to momentum flux vector to the ocean. Thus, momentum fluxes from wind to waves and from waves to currents may vary in directions and magnitudes. Surface currents from HYCOM are passed to UMWM; these act to advect and refract surface waves. Wave-induced residual current (Stokes drift) is applied at each step to advect 3-dimensional momentum and scalar quantities in HYCOM.

A schematic diagram for UMCM is shown in Figure 2. Results from the fully coupled atmosphere-wave-ocean model for a 5-day simulation of Hurricane Ike (2008) are presented here. UMCM is initialized at 1200 UTC on 8 September 2008. WRF is configured with a fixed outer domain and two inner storm-following moving nests with horizontal grid resolutions of 12 km, 4 km, and 1.3 km, respectively. It has 36 vertical levels. Initial and lateral boundary conditions are from the National Center for Environmental Prediction (NCEP) global analysis fields with 1-degree and 6-hour spatial and temporal resolutions, respectively. HYCOM is configured with a domain that is similar to the WRF outer domain, except for the use of a 1/24-degree horizontal resolution and 32 hybrid vertical levels. The initial and lateral boundary conditions are from a

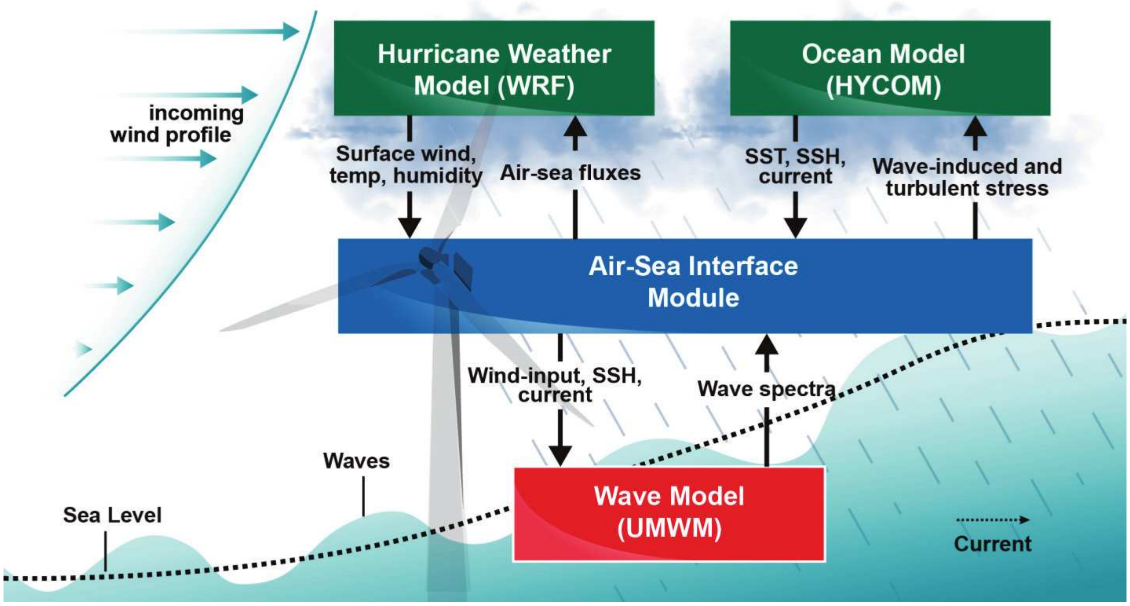


Figure 2. A schematic diagram of components and physical processes in UMCM.

daily 1/12-degree data-assimilated global HYCOM model output. The UMWM setup is described in more detail in the next section.

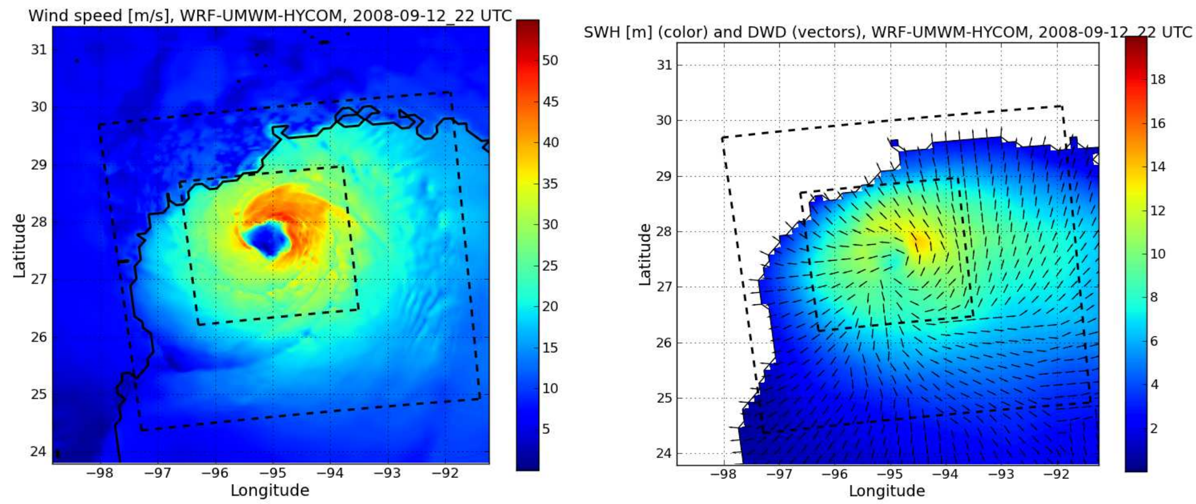
Figure 3(a) shows wind speeds at the time when Hurricane Ike is about to make landfall near the Texas coast. The dashed boxes show the edges of the inner storm-following WRF domains at 4 km and 1.3 km resolutions. The maximum wind speed at this time exceeds 52 m/s. Figure 3(b) shows significant wave heights (SWH) induced by strong hurricane winds. SWH is defined as the average of the highest third of all waves. The characteristic asymmetric shape of surface waves in moving hurricanes is evident. Waves that are generated on the right-hand side of the storm experience a longer apparent fetch and, thus, are higher and longer compared to those on the left-hand side. The maximum SWH at this time exceeds 13 m, while the individual waves may be significantly higher.

III. HURRICANE WAVE KINEMATICS

The wave spectrum in UMCM consists of 36 directional bins and 37 frequency bins in the range of 0.0313 Hz to 2 Hz, where frequencies are logarithmically spaced. Because the model is initiated from a calm state, it takes around 24 hours for the full spectrum to develop and some swell waves that originated from the storm at points in time before 12:00 UTC 8 September do not exist in the model, but they do in reality.[3] Thus, wave spectrum data extracted from the first 24 hours of simulation after 12:00 UTC 8 September are excluded in this study. As an illustration of the development of wave inputs for turbine loads analysis, we present in Figure 4 the simulated track of Hurricane Ike. We select locations (denoted as A and B) 60 km to the right and left of the hurricane track where the water depth is 20 meters. In Figure 5, we present directional wave spectra obtained from UMCM, that apply to these two locations at the left and right sides, at 100 hours after the start of the simulation. Based on the directional wave spectra obtained from UMCM, the irregular sea surface elevation process and associated wave kinematics can be simulated.

A. Unidirectional Linear Irregular Waves

In this study, the response of a selected wind turbine subjected to hurricane wind and waves is evaluated using the wind turbine simulation software, FAST, which had been developed at the National Renewable Energy Laboratory (NREL). In the current version of FAST, only unidirectional linear irregular waves can be modeled. It is common practice to model the irregular sea surface elevation process as a Gaussian random process using linear Airy wave theory. In reality, waves, especially in shallow water, generally have steeper crests and shallower troughs than are predicted by linear theory.[5] Agarwal and Manuel[6] studied



(a) (b)

Figure 3. (a) Wind speed (m/s) and (b) significant wave height (m) as simulated by UMCM at the time when Hurricane Ike was approaching the coast of Texas.

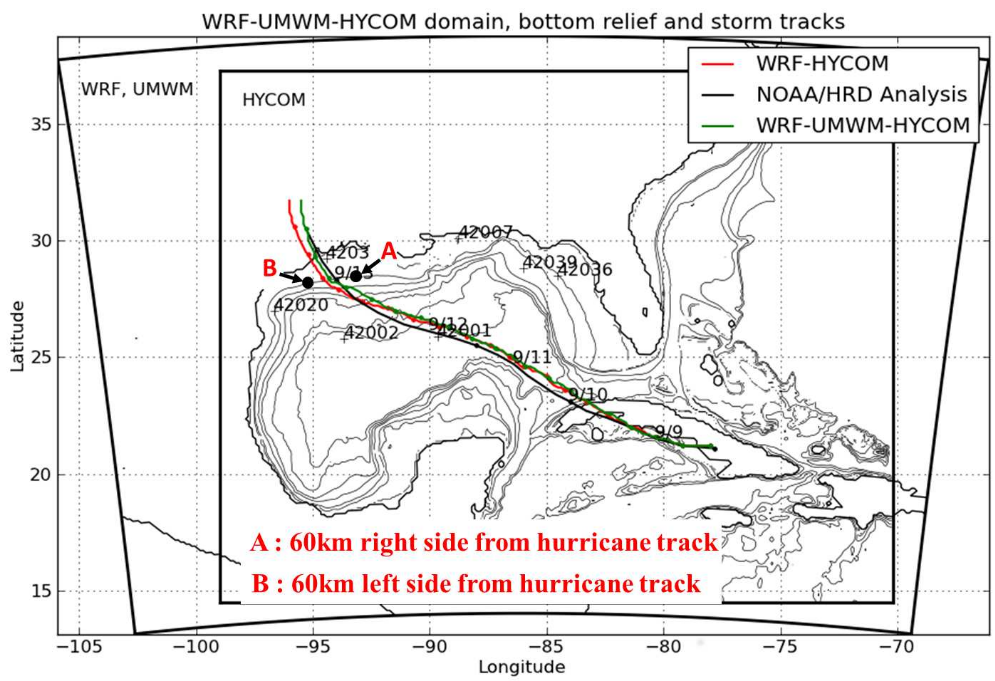
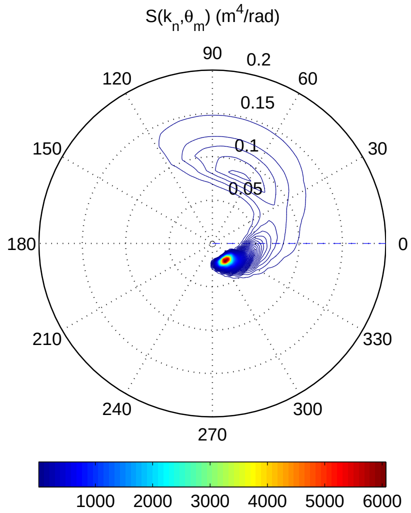


Figure 4. Track of Hurricane Ike and selected locations of two sites, one to the left and the other to the right of the track where the water depth is 20 m.

the influence of alternative wave modeling assumptions on short-term and long-term loads on offshore wind turbines. They found that modeling nonlinear irregular waves can significantly increase hydrodynamic loads experienced by offshore wind turbine support structures in shallow waters (compared to models that rely on linear wave theory). Besides the availability of only linear wave modeling, waves can only be modeled as unidirectional waves in FAST; this is not appropriate for storm-generated seas where wave directionality is obviously important as is evident in Figure 5. Several studies[7–10] have discussed how wave directionality can influence the response of offshore structures.



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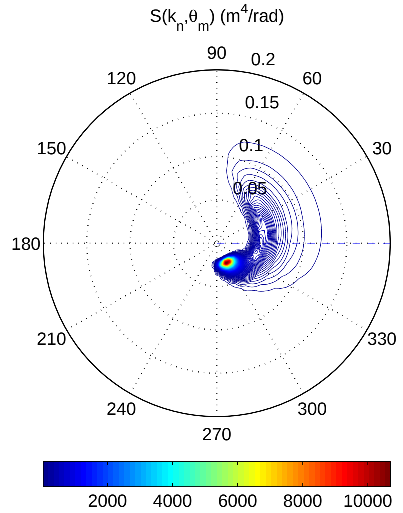


(b)

Figure 5. Wave spectra (at the two selected sites) 100 hours after the start of the simulation of the storm at the two selected locations: (a) left of the track; (b) right of the track.

B. Omnidirectional Nonlinear Irregular Waves

To generate realistic hurricane wave fields, it is essential to account for both wave directionality and nonlinearity. In this study, directionality and nonlinearity of waves is accounted for by employing directional irregular second-order wave formulations extended by Sharma and Dean[7] for finite water depths; the second-order wave theory is an extension of the theory developed by Longuet-Higgins[11] for waters of infinite depth to apply to waters of arbitrary depth. Using wave steepness as a perturbation parameter, Stokes[12] provided solutions for the analysis of regular waves. In Stokes' study, only the sum frequencies of first-order waves are considered. For irregular waves, however, not only the sum frequencies appear but also the difference frequencies at second order are considered. The second-order wave solutions for infinite water depth including the contribution of the difference frequencies were provided by Longuet-Higgins;[11] Sharma and Dean[7] extended the theory for infinite water depth to intermediate water depths.

C. Wave Simulation Example

We simulate a single sea surface elevation process and associated kinematics based on different wave theories using the directional wave spectrum for a location on the right side of the track of Hurricane Ike (see Site A on Fig. 4), as obtained from UMCM at 100 hours after the start of the simulation; the significant wave height at that time is about 7.2 m. The effect of wave directionality and nonlinearity is assessed by studying the response of a bottom-supported 5-MW wind turbine in 20 m of water that is subjected to loading from the waves. We match the energy of the simulated nonlinear waves (including first- and second-order components) with that of the total energy indicated by the UMCM wave spectrum. Wave kinematics simulated in a separate computational module are provided as input to FAST; the fore-aft tower base shear and bending moment are evaluated in time-domain dynamic analyses without considering rotor aerodynamics for now. In Table 1, including the nonlinearity of the waves (Case 1 $\rightarrow$ Case 3 and Case 2 $\rightarrow$ Case 4) leads to a reduction in the tower base response by 12-27%, while accounting for wave directionality (Case 1 $\rightarrow$ Case 2 and Case 3 $\rightarrow$ Case 4) reduces the tower base response by about 18-29%. The simultaneous consideration of both wave nonlinearity and directionality over more commonly used linear long-crested unidirectional waves (Case 1 $\rightarrow$ Case 4) results in a decrease in the tower base response by 38-43%.

IV. HURRICANE WIND FIELDS

In this study, mean wind speed data obtained from UMCM are generated at a 1.33 km grid resolution. This large-scale mean wind field data must be down-scaled using a scale-bridging technique to provide the

Table 1. Comparison of tower base response maxima for alternative wave modeling approaches based on simulations (without aerodynamic loads).

Maximum Response	Linear waves		Nonlinear waves	
	Unidirectional (Case 1)	Omnidirectional (Case 2)	Unidirectional (Case 3)	Omnidirectional (Case 4)
Tower Base Shear force (kN)	4895	3802	3829	2771
Tower Base Moment (MN-m)	105.1	74.1	79.5	64.7

needed wind field at 10 m resolution around the rotor to allow meaningful aerodynamic load computations. Work is underway towards the use of Large-Eddy Simulation (LES) with the Weather Research and Forecast (WRF) model to achieve this down-scaling.

V. EFFECT OF COUPLED WIND-WAVE MODELS ON TURBINE RESPONSE

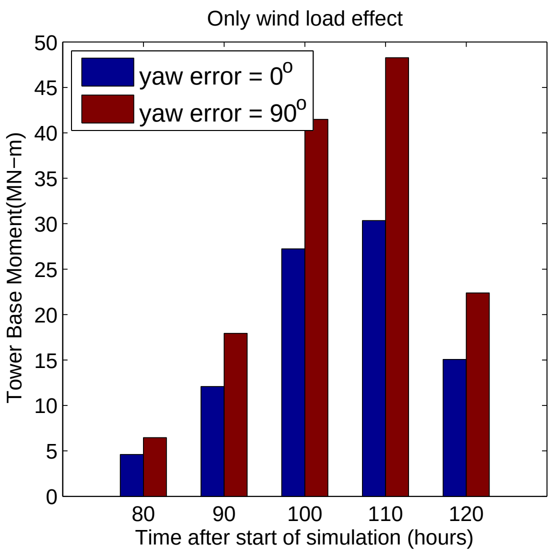
We now investigate how hurricane-generated wind and waves discussed above influence the response of an offshore wind turbine. A 5-MW wind turbine model developed at NREL closely representing utility-scale offshore wind turbines being manufactured today is considered. The turbine is a variable-speed, collective pitch-controlled machine with a maximum rotor speed of 12.1 rpm; its rated wind speed is 11.5 m/s. It is assumed to have a hub height of 90 meters (above the mean sea level) and a rotor diameter of 126 meters. It is assumed to be sited in 20 meters of water; it has a monopile support structure of 6 m diameter, which is assumed to be rigidly connected to the seafloor. Fundamental frequencies for tower fore-aft and side-to-side bending modes are around 0.32 Hz and 0.31 Hz, respectively. It is assumed that during the hurricane, the wind turbines are parked (standstill condition) and that all the blades are feathered, or turned to a 90-degree pitch angle, to minimize loads on the turbine blades

Although our ultimate goal is to develop a wind field down-scaling scheme and apply it to generate turbine-scale turbulent wind fields, in the present study, simpler stochastic simulation of turbulence using Fourier techniques is used. Turbulence spectra proposed by Kaimal et al.[13] and coherence functions, both of which are specified in the IEC 61400-1 standard,[14] are used to simulate the turbulent wind fields. In a comparison study of spectra for hurricane wind fields measured over a seaway and the spectral formulations of Davenport,[15] Kaimal et al.,[13] and Kareem,[16] Ochi[17] reported that the average spectra based on measured hurricane data over a seaway displayed greater low-frequency energy than any of the other spectral formulations. The differences become significant for frequencies below 0.03 Hz. Since important natural frequencies of our offshore wind turbine model with monopile-type support structure lie between 0.2 Hz (the 1-per-rev or 1P frequency at rated conditions) and important resonant frequencies such as those associated with the tower bending modes (around 0.3 Hz)—all significantly higher than 0.03 Hz—it is expected that discrepancies at the low frequencies of standard spectra from those in hurricane wind fields may not greatly influence turbine response.

In the following, we investigate load effects for following two different turbine states: (i) where the turbine maintains yaw control and can track the changing wind direction perfectly; and (ii) where the turbine experiences yaw misalignment or yaw error (note that this may also represent an intentional rotation of the rotor plane so as to have the rotor plane oriented orthogonal to the dominant wind direction). We consider a turbine at location A in Figure 4. Yaw misalignment may occur in various conditions such as due to a fault in the yaw control system, loss of grid connection, lack of sufficient backup battery power supply, or rapid change in the local hurricane wind direction. Table 2 and Figure 6 illustrate the effect of yaw misalignment on turbine response. As the yaw error increases from 0 to 90 degrees, because the blades are all pitched to feather, the blade-root in-plane bending moment is systematically greater for the high yaw-error case. If the out-of-plane moment is combined with the in-plane moment to compute a resultant tower base moment, the general trend stays the same. As can be seen in Figure 6, yaw misalignment significantly increases tower base moments due to aerodynamic loads alone; tower base bending moment maxima increase by up to 48% due to yaw misalignment. The addition of wave loading to the aerodynamic loading also maintains the trend but the relative influence of increased yaw error on loads is less pronounced.

Table 2. **Comparison of tower base bending moment maxima (in MN-m) based on 5 simulations.**

	only wind load		wind + wave loads	
	yaw error= 0°	yaw error = 90°	yaw error = 0°	yaw error = 90°
$t = 80$ hrs	4.6	6.2	12.4	18.0
$t = 90$ hrs	12.0	15.9	23.6	38.1
$t = 100$ hrs	27.2	39.2	79.5	95.8
$t = 110$ hrs	30.3	44.9	105.8	127.4
$t = 120$ hrs	15.0	20.3	31.8	44.0



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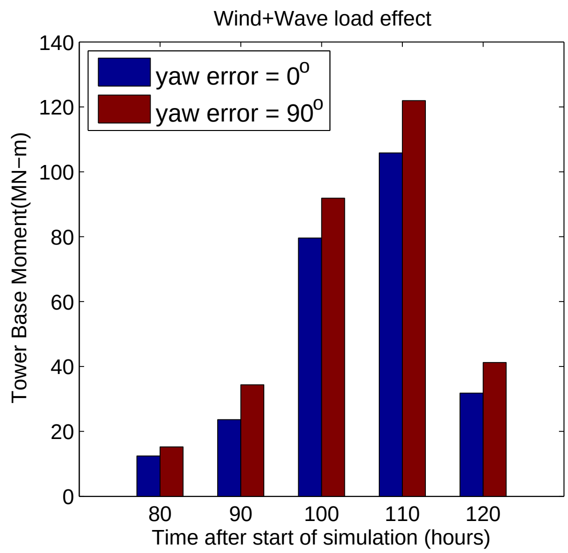

(b)

Figure 6. Tower base moment maxima for cases where (a) only aerodynamic loads are included; and (b) both aerodynamic and hydrodynamic loads are included.

VI. CONCLUDING REMARKS

We have described work in progress that is related to end-to-end simulation of hurricane-induced wind-wave-current fields and associated load computation for bottom-supported offshore wind turbines. Not all the constituent components are fully integrated. We have reported here on details related to the coupled atmosphere-waves-ocean model and the physical processes and computational frameworks involved therein. We have also presented some details related to wave modeling with considerations for nonlinear waves in shallow water and have demonstrated the importance of modeling directional seas. We also compared load statistics for selected locations of turbines close to the simulated track of Hurricane Ike. Future work will address integration of the many separate analyses that are needed for assessing risks to offshore wind turbines during hurricanes.

ACKNOWLEDGEMENTS

The authors are pleased to acknowledge financial support received from the U.S. Department of Energy (DE-FOA-0000415).

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