

Structural effects of floating wind turbines based on typhoon-wave prediction

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SUMMARY

Joint wind-wave-current conditions frequently occur in strait regions, and neglecting their coupled characteristics may lead to non-conservative assessments of wind turbine structural responses. This study employs the COAWST (Coupled-Ocean-Atmosphere-Wave-Sediment Transport) mesoscale modeling system to reconstruct wind, wave, and current fields. The system integrates the WRF atmospheric model, SWAN wave model, and ROMS ocean circulation model, enabling fully coupled simulations of wind-wave-current interactions under complex meteorological forcing. Based on this high-resolution coupled modeling framework, joint probabilistic representations of extreme environmental conditions are established in a typical strait region. Using the resulting combined wind-wave-current scenarios, time-domain simulations are conducted to evaluate the structural responses of floating offshore wind turbines (FOWTs), including blade loads, tower responses, and platform motions. The results demonstrate that accounting for wind-wave-current coupling significantly modifies extreme response characteristics compared with conventional assumptions, underscoring the importance of joint environmental modeling for wind turbine design and safety assessment in strait regions.

Keywords: extreme wind-wave-current simulation, Joint probability distribution, Floating wind turbine, Structural effects

1. INTRODUCTION

Environmental loading acting on offshore wind turbines is inherently stochastic and strongly coupled (Taflanidis et al., 2013). In particular, offshore environments in strait regions are governed by complex interactions among atmospheric circulation, wave propagation, and ocean current systems, leading to pronounced statistical dependence among wind-wave-current processes (Villas et al., 2019). Nevertheless, most existing investigations of wind turbine structural responses under extreme marine conditions rely on prescribed or case-specific environmental combinations, which fail to systematically represent joint probabilistic characteristics and thus limit the identification of governing design scenarios (Bierbooms et al., 2024). To overcome these limitations, the COAWST mesoscale coupled modeling system, integrating the WRF atmospheric model, SWAN wave model, and ROMS ocean circulation model, is employed to resolve wind, wave, and current fields under complex meteorological forcing. In this study, a COAWST-based numerical framework driven by multi-source background data from ERA5, HYCOM, and TPXO8 is implemented to simulate multiple typhoon events in a representative strait region. The resulting high-resolution coupled environmental fields provide a physically consistent basis for constructing joint probabilistic wind-wave-current scenarios and for systematically investigating their effects on the structural responses of floating offshore wind turbines.

2. MESOSCALE SIMULATION

COAWST mesoscale models (coupled with WRF, SWAN, and ROMS) were used to simulate the passage of 40 historical typhoons across the Taiwan Strait (Kumar et al., 2012). ERA5 global reanalysis wind field data, HYCOM global ocean dataset, and TPXO8 tidal model data were used as initial and boundary conditions. Figure 1 illustrates the outlines of the simulation domain used in this study, which covers the waters surrounding the Taiwan Strait to capture the full range of interactions of wind, waves and TWLs during typhoon passages. The WRF model employs a two-way nested grid system: the outer domain provides a 9 km horizontal resolution (150×120 grid points), while the inner domain focuses on the study area with a refined 3 km resolution (124×106 grid points) and 50 vertical levels. For the oceanic and wave components, ROMS and SWAN share a common curvilinear grid covering the Taiwan Strait at a 3 km resolution (238×223 grid points). The vertical structure of ROMS is discretized into 30 terrain-following sigma layers. During the coupled simulation, state variables and fluxes are exchanged among the sub-models every 10 minutes to ensure physical consistency across the air-sea interface. The selected typhoon groups, which are the focus of this study's simulations, are shown in Figure 2.

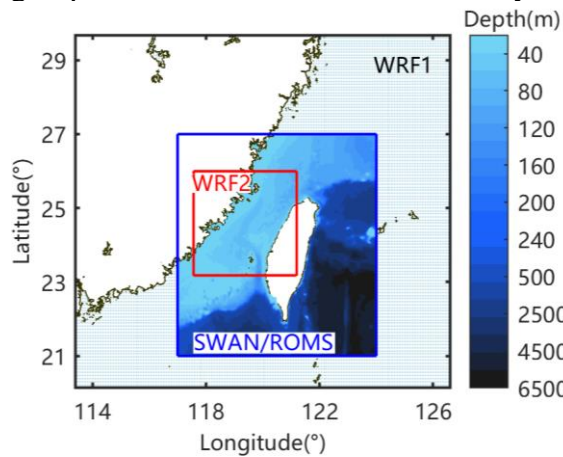


Figure 1: Simulation domain

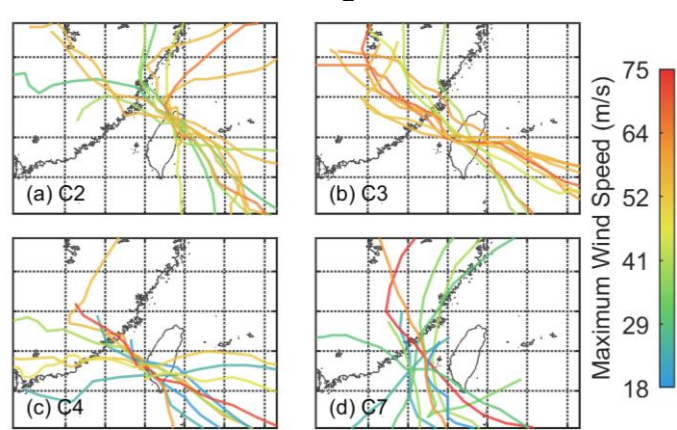


Figure 2: Simulated tracks

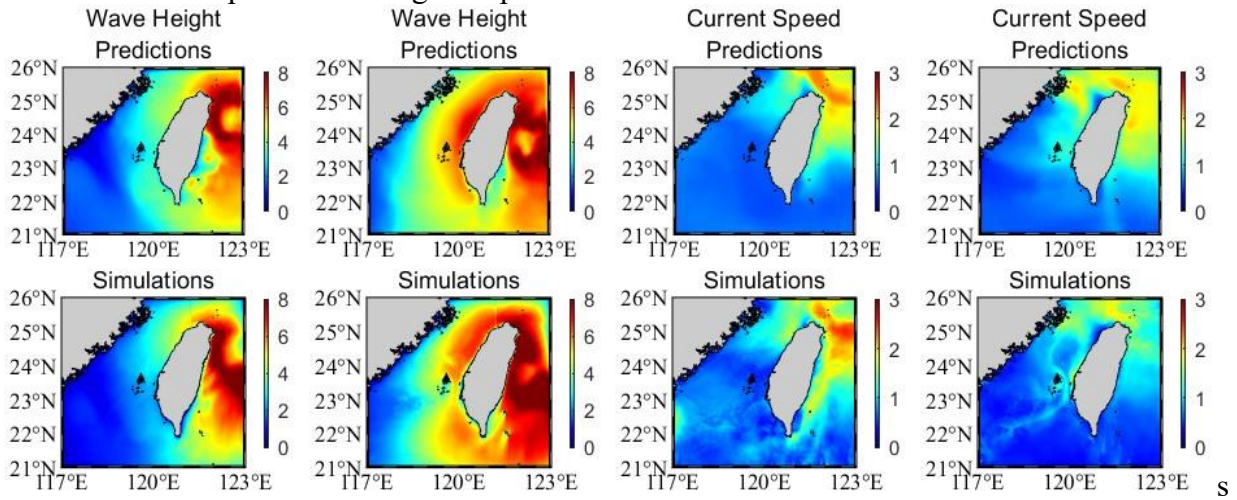
3. TYPHOON-WAVE COUPLING PREDICTION

The ConvLSTM model replaces the fully connected operations in traditional LSTM networks with convolutional operations, enabling the model to capture spatial information while processing spatiotemporal sequence data (Shi et al., 2015). The model uses two input channels (the eastward and northward wind speed components) and a learning rate of 0.001. It employs two types of 2D convolution layers: Conv2D(64, 5) and Conv2D(128, 3), with the final layer being Conv2D(128, 3). The model is trained on 11 training samples, 1 validation sample, and 2 test samples, respectively. The model achieved an R^2 of 0.886 on the training set and 0.881 on the test set. Figure 3 shows the comparison between the predictions and the simulation results.

4. RANDOM RESPONSE OF FLOATING WIND TURBINES

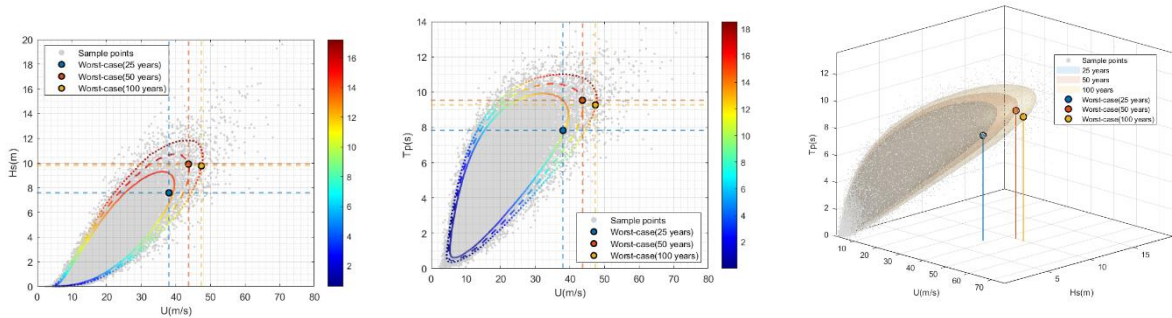
To further capture the dependence among typhoon-induced environmental parameters, a joint probabilistic model of wind speed, significant wave height, and peak wave period is constructed. Figure 4 presents the distributions of structural responses under combined wind-wave conditions corresponding to different return periods, with Figure 4(a) showing the blade tip deflection and

Figure 4(b) illustrating the platform pitch response. The response surfaces are mapped onto the joint wind–wave parameter space, enabling a direct comparison of response patterns under varying environmental severity. It can be observed that, as the return period increases, the worst-response points shift consistently toward regions characterized by larger wind speeds and wave heights, indicating a coherent dependence of both responses on extreme environmental loading. Notably, the distributions of blade tip deflection and platform pitch exhibit similar geometric features and trends across the wind–wave parameter space, suggesting a strong correlation between the upper-structure blade response and the global platform motion.

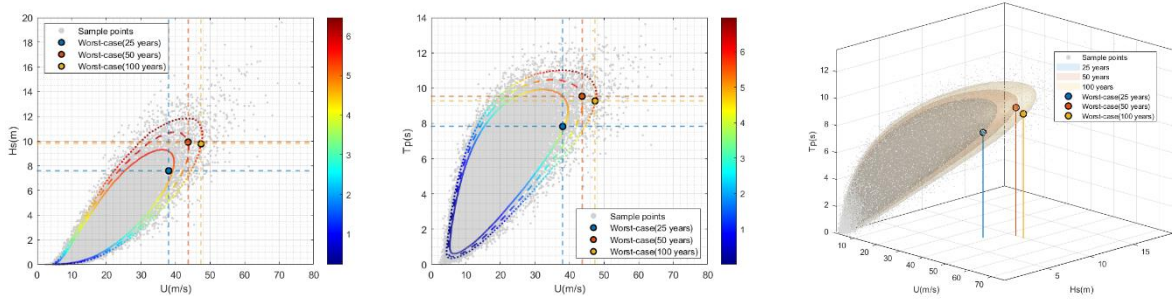


(a) Test Set 1 (b) Test Set 2

Figure 3: Comparison of ConvLSTM Test Set Performance.



(a) Blade tip deflection



(b) Platform pitch

Figure 4: Worst response surfaces with different return periods

5. CONCLUSIONS

This study investigated the structural responses of floating offshore wind turbines under coupled wind-wave-current conditions in a typical strait region using a probabilistic framework. High-resolution wind, wave, and current fields were simulated with the COAWST system and employed to construct joint probabilistic environmental scenarios. Time-domain analyses revealed that turbine scale significantly influences response characteristics, with blade and tower responses increasingly governed by low-frequency wave excitation and platform motions. Probabilistic response surfaces further demonstrated that extreme structural demands shift toward combined high wind and wave conditions as the return period increases. The strong correlation between blade responses and platform motions highlights the necessity of joint environmental modeling for reliable design and safety assessment of floating wind turbines in strait regions.

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