Quantifying Tropical Cyclone-Generated Waves in Extreme-Value-Derived Design Input for Offshore Wind Projects

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Track 14: Ocean Sciences

Introductory Summary

Limited guidance is provided in major offshore standards (API RP 2MET, 2019; DNV, 2018; IEC-614000-3, 2019) for the minimum requirements of ocean models and methods for ocean-model-derived design parameters. This study investigates representation of significant wave height in the mixed-storm climate of the US Atlantic coast for use in offshore wind project N-year design values. Contributing factors are discussed and recommendations provided.

Keywords: *Tropical Cyclone, Extreme Value Analysis (EVA), design values*

Introduction

As offshore wind energy expands to new regions of the world, the representation of tropical cyclones in multi-decade metocean models is increasingly central to the sustainable planning and design of offshore wind projects. Traditionally, local, high-fidelity metocean models for the design and operation of offshore wind projects consist of coupled wind, wave, and hydrodynamic components, with model boundary conditions from global reanalysis data sets, such as in [5]. When evaluating model skill in capturing tropical cyclones, extra-tropical cyclones, and the combination of both, different models may result in notably different return period values employed in design; however, no best practices have been established for the industry.

Various studies have quantified extreme conditions on the US East Coast [1, 2, 3, 7] or modeled specific events [6], however, the translation of these events into oceanographic extremes - the statistical analysis of a large number of directly-modeled tropical cyclones on the Atlantic coast - have been less studied [7, 4]. This paper investigates the representation of these extremes in terms of statistical method, model design, and model capability by investigating model performance at two locations, Kitty Hawk Wind, in the Mid-Atlantic Bight, and New England Wind, in the North Atlantic, as compared to the extensively-validated GROW-Fine East Coast tropical cyclone and extra-tropical cyclone models [8]. These locations are chosen for their different storm climates, including maximum tropical cyclone intensity, tropical cyclone frequency, and ratio of tropical-to-extra-tropical events.

Methods

Two separate high-resolution models are investigated in this study. Return period results from all four models (a high-resolution model in the North Atlantic and in the Mid-Atlantic Bight, each, the GROW-Fine tropical-cyclone-only model, and the GROW-Fine extra-tropical-cyclone-only model) are calculated by the Block Maxima method with a Gumbel-Graphical fit. Block maxima was selected after values were calculated with Peaks-Over-Threshold and Half-Max methods, using both 3-parameter Weibull and Gumbel-graphical fits, with 4% or less variation between return values.

Model	Resolution	Boundary Conditions	Duration
CFSR	22km spatial (2D) 2-hour	CFSR	42 years
WRF	9km spatial (3D) 1-hour	CFSR	30 years
Tropical Boundary Layer Model	5.5km spatial (3D) 15-minute	*Wind*: Satellite reconstruction *Pressure*: Far-field tropical reconstruction	*Trop*: 100 years *Extra-Trop*: 75 years

Table 1: Wind parameterization

The North Atlantic model comprises 42 years of Climate Forecast System Reanalysis (CFSR) winds forcing a MIKE21 spectral wave and MIKE21 hydrodynamics hindcast, with one-way coupling from hydrodynamics to waves. Model skill is assessed with a number of buoy observations, including wind and waves at the Vineyard Wind 1 FLiDAR and at NDBC buoy 44097. Data is presented for 40.8N, 70.7W, the deepest and most southern location in the New England Wind Energy Area.

Model	Resolution	Boundary Conditions	Coupling	Spectral Parameterization	Tidal Included
MIKE21	600m wave (2D) 600m hydro (2D) 1-hour	DHI Global Waves (waves) DHI East Coast (hydro)	1-way, hydro to waves	36 directions 32 freq. bins 0.033 Hz min, freq.	Yes
SWAN + DELFT3D	400m wave (2D) 400m hydro (3D) 1-hour	ERA5 (waves) HYCOM (hydro)	2-way	36 directions 24 freq. bins 0.005 Hz min, freq.	Yes
OWI3G + ADCIRC	5.5km wave (2D) 5.5km hydro (2D) 15-minute	GROW2012 (waves) Prevost '08 (hydro)	No dynamic coupling. Reanalysis of each modeled storm.	48 directions 26 freq. bins 0.0029 Hz min, freq.	Yes

Table 2: Wave and hydrodynamic parameterization

The Mid-Atlantic Bight model comprises 30 years of Weather Research and Forecasting (WRF) winds forcing a SWAN spectral wave and Delft3D hydrodynamics hindcast, with two-way coupling between the hydrodynamic and wave models. Model skill is assessed with a number of regional NDBC buoy observations, including 28 years at buoy 44014. Data is presented for 36.2N, 75.0W, the southernmost location in the Kitty Hawk Wind Energy Area.

After simulation and calibration to observations in the modeled timeframe, EVA is calculated over the full time period available (mixed-type storm events), on separated storm sets (post-processed), and over a shortened GROW-Fine storm basis (from 100 years to the hindcast length for tropical cyclones, and from 75 years to the hindcast length for extra-tropical cyclones).

Results and Conclusions

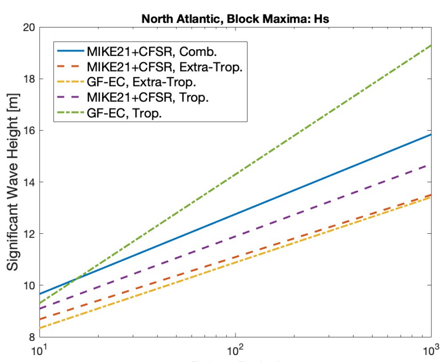

Figure 1. Significant wave height extremes at 40.8N, 70.7W, by block maxima with gumbel-graphical fit.

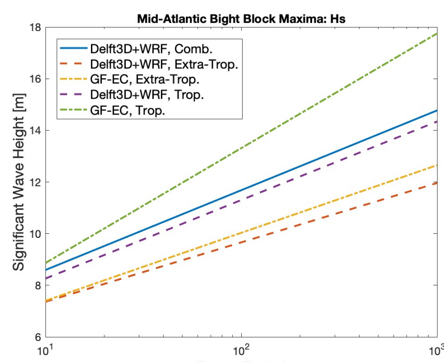

Figure 2. Significant wave height extremes at 36.2N, 75.0W, by block maxima with gumbel-graphical fit.

Overall, return values due to extra-tropical events are shown in this study to be well-resolved by established methods of metocean modeling with CFSR- or WRF-generated winds and ERA5-/MIKE21-boundary conditions. However, the differences in extreme value trends between tropical cyclone cases suggests that under-representation by these typical models of return values can not be mitigated by calibration alone, both due to nonlinear factors and to the limited duration of observations of smaller-radius, lower-frequency events. While both high-resolution models, with different wind forcing, model design, and boundary conditions, captured a number of tropical cyclone peak significant wave height within 1m, the effect of the shorter storm basis and single analysis of mixed events resulted in an under-estimation of 100-, 1,000- and 10,000-year design values, at both locations on the US east coast with varying storm frequencies and intensities (see Figure 1 and Figure 2).

For more accurate determination of return values for offshore design in areas with tropical cyclone activity, analysis of a point or range of points with 100km or less proximity to multiple storm centers is recommended. When analyzing these extremes, statistics should be carried out on a data set of single storm types; single analysis of mixed species, despite variations in frequency and intensity in the two locations investigated, resulted in a reduction of the magnitude of longer-term return values. Finally, while a 30- to 40-year hindcast period is sufficient in both locations to capture extremes due to extra-tropical events, it is not sufficient in the investigated scenarios to determine extremes due to tropical cyclones. A longer period, either as a single hindcast or as a pooled data set, is likely necessary for characterizing extreme wave events for offshore wind infrastructure design on the US East Coast.

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