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Multivariate analysis of extreme metocean conditions for offshore wind turbines

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ABSTRACT

Most offshore wind turbines (OWTs) are designed according to the international standard IEC 61400-3 which requires consideration of several design load cases under 50-year extreme storm conditions during which the wind turbine is not operational (i.e. the rotor is parked and blades are feathered). Each of these load cases depends on combinations of at least three jointly distributed metocean parameters, the mean wind speed, the significant wave height, and the peak spectral period. In practice, these variables are commonly estimated for the 50-year extreme storm using a simple but coarse method, wherein 50-year values of wind speed and wave height are calculated independently and combined with a range of peak spectral period conditioned on the 50-year wave height. The IEC Standard does not provide detailed guidance on how to calculate the appropriate range of peak spectral period. Given the varying correlation of these parameters from site-to-site, this approach is clearly an approximation which is assumed to overestimate structural loads since wind and wave are combined without regard to their correlation. In this paper, we introduce an alternative multivariate method for assessing extreme storm conditions. The method is based on the Nataf model and the Inverse First Order Reliability Method (IFORM) and uses measurements or hindcasts of wind speed, wave height and peak spectral period to estimate an environmental surface which defines combinations of these parameters with a particular recurrence period. The method is illustrated using three sites along the U.S. Atlantic coast near Maine, Delaware and Georgia. Mudline moments are calculated using this new multivariate method for a hypothetical 5 MW OWT supported by a monopile and compared with mudline moments calculated using simpler univariate approaches. The results of the comparison highlight the importance of selecting an appropriate range of the peak spectral period when using the simpler univariate approaches.

1. Introduction

Offshore wind is a vast resource with the potential to transform the energy economy of the world. In the United States, the National Renewable Energy Laboratory (NREL) has stated that an optimal (i.e. least cost) strategy for the U.S. to achieve its target of generating 20% of its electricity demand from wind energy by 2030 [1] should include the development of 54 GW of offshore wind capacity. Obtainment of this ambitious goal will require a significant reduction in the cost of energy which currently exceeds traditional, carbon-based energy sources by more than a factor of two [2]. Ways to reduce the cost of offshore wind energy include reducing financing and underwriting costs and eliminating excessive conservatism from design requirements, each of which would reduce capital costs. A possible means to such a reduction in capital costs is to more realistically model and estimate extreme metocean

Abbreviations: OWT, offshore wind turbine; V, hourly mean wind speed at elevation of 5 m above sea surface; H_s, significant wave height; T_p, wave peak spectral period; IFORM, Inverse First Order Reliability Method; NOAA, National Oceanic and Atmospheric Administration (USA); NREL, National Renewable Energy Laboratory (USA); R-LOS, R Largest Order Statistics; R, annual rate of occurrence; t_{lag}, time lag between the measurement of maximum V and the maximum H_s during an extreme event; CDF, cumulative distribution function; GEV, generalized extreme value; μ, location parameter of GEV distribution; σ, scale parameter of GEV distribution; ξ, shape parameter of GEV distribution; x_N, magnitude of a variable x with a recurrence period N, e.g. V_{50} is the 50-year wind speed; g, gravitational acceleration; T, extreme wave period; N, recurrence period; β, Radius of the sphere in standard uncorrelated normal space used in IFORM; Φ, cumulative distribution function for standard normal distribution.

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conditions and their associated loads on offshore wind turbines (OWTs), thereby minimizing uncertainty in extreme loading and design conservatism.

The most widely used international standard for the design of OWTs is IEC 61400-3 [3]. This Standard prescribes a suite of design load cases which require an estimation of loads during a variety of operational and metocean conditions. One subset of these load cases considers extreme loads under 50-year storm conditions during which the wind turbine is not operational (i.e. the rotor is parked and blades are feathered). The extreme loads depend on estimation of the 50-year magnitudes of two metocean parameters: the one-hour mean wind speed V and the significant wave height H_s. Often, in practice, the 50-year values of these parameters, V_{50} and $H_{s,50}$, are estimated independently using extreme value analysis based on a hindcast, typically spanning more than a decade at the installation location. The IEC Standard also permits selection of these 50-year wind and wave parameters based on the long term joint probability distribution of extreme wind and waves, but it does not provide any specific guidance on how to execute such an analysis.

The parameters, V_{50} and $H_{s,50}$, are used as inputs to simulate stochastic time series corresponding to extreme turbulent winds and the extreme sea state. A structural model is then analyzed, for six one-hour realizations of both time series simultaneously, and the average of the maximum structural response from each of the six analyses is recorded as a design demand. The wave time series for the extreme sea state is typically based on the JONSWAP spectral model [3], which requires an additional metocean parameter, the peak spectral period T_p. Note that the IEC Standard also requires consideration of loads due to swell, tides and currents, but these metocean parameters are neglected here for simplification.

In this paper, we discuss three methods to estimate the 50-year extreme values of V, H_s and T_p. The first, termed herein as "1D Exceedance," is a univariate method, commonly used in practice, wherein 50-year values of V and H_s are calculated independently along with a range of T_p deterministically conditioned on the 50-year H_s, and these conditions are assumed to occur simultaneously. The second is also univariate and referred to herein as "1D Reduced Combination." In this method, which is based on Annex F of ISO-2394 [4], a dominant metocean parameter is selected (either V or H_s) and a 50-year extreme value of this parameter is combined with a reduced value of the other parameter. Again, as with 1D Exceedance, a range of T_p conditioned on H_s is calculated deterministically. The third method is multivariate, considers the long term joint probability distribution of V, H_s and T_p, and is referred to herein as the 3D Inverse First Order Reliability Method or "3D IFORM."

IFORM is a general method for extrapolation of metocean parameters and is usually applied to joint distributions of two random variables. The result is an "environmental contour," which defines, in a sense, combinations of the two random variables that have a particular recurrence period [5]. In this paper, IFORM is applied to three jointly distributed random variables resulting in an "environmental surface" which provides, in a sense, combinations of three random variables which have a particular recurrence period. IFORM has been applied in 3D by other researchers [6,7] who have used this method to generate an environmental surface of wind speed, turbulence intensity and bending moments for calculating the design moment at the root of a wind turbine blade. In that case of 3D IFORM, which considers plentiful 10 min measurements of the joint data, the joint distribution of the three random variables is expressed through a series of conditional distributions which can be estimated directly from the measured data. Similarly, in the original introduction of IFORM [5], joint distributions were estimated based on distributions developed for the northern North Sea based on 3-h measurements of the significant wave height (modeled with a Weibull distribution) and the peak spectral period conditioned on significant wave height distribution (modeled as a lognormal distribution) [8]. The 3D IFORM method discussed here is a straightforward extension of IFORM as presented in [5], but the application presented here is novel in that it is based on sparse sets of extreme value data and therefore requires an approximation of the joint distribution, which, in this case, is approximated using the Nataf model. Extreme value data and distributions are favored here because such an approach more accurately represents distribution tail behavior which often is determined by different physical mechanisms than what determines the vast majority of hourly data [12]. In fact, the authors considered using hourly measurements modeled with the distributions proposed in [5], and found that, for the examples considered here, such distributions did not accurately represent the tails of the measurements.

As an example, we present results for all three methods at three sites along the Atlantic Coast where the U.S. National Oceanic and Atmospheric Administration (NOAA) maintains buoys which have multiple decades of wind and wave measurements. For each of the three sites, all three methods are compared by searching all combinations of V, H_s and T_p that are associated with a 50-year recurrence period to find the critical combination, defined as the combination resulting in the maximum structural effect. In this paper, the structural effect considered is the mudline base moment which is estimated by analyzing a structural model of the 5 MW National Renewable Energy Laboratory (NREL) reference offshore wind turbine supported by a monopile foundation [9].

The paper is organized as follows: first, some general background is presented on univariate and multivariate metocean assessment for structural design. The next section introduces and describes three example offshore locations which are located near the U.S. Atlantic Coast where NOAA buoys have been measuring metocean conditions for multiple decades. Next, the methods for identifying extreme values from measured data and then extrapolating these values to 50-year parameters using 1D Exceedance, 1D Reduced Combination and 3D IFORM are presented. The following section presents comparative results for each of the locations and each of the methods. The paper ends with discussion on the results and a summary of conclusions.

2. Background

The design of OWTs, and all engineered structures generally, relies on the estimation of load effects associated with environmental conditions that occur at a particular recurrence period. For many structures, the intensity of metocean conditions for different load types can be modeled independently and the likelihood of simultaneity of load types can be considered through prescriptive load combinations (e.g. ASCE 7-05 for buildings [10]), which typically combine extreme values for one load type and expected values from all other load types. In many cases, this is a reasonable assumption because statistics of different load types are often accurately characterized as independent (e.g. earthquake combined with wind loads) and the chance of extreme values of these load types occurring simultaneously is negligible.

In offshore engineering, the impact and variability of the correlation of metocean conditions from wind and wave influence design significantly, and methods for modeling such conditions as multivariate are described conceptually in design standards [3]. The extreme offshore environment is commonly characterized by statistical measures of coupled wind and wave random processes that are assumed to be stationary. In particular, the statistical measures employed by IEC 61400-3 are the mean hourly wind speed V, the significant wave height H_s and the peak spectral period T_p. These three measures are jointly correlated random variables and the degree of correlation can vary significantly from site to site [11].

Despite the presence of multivariate methods in the IEC Standard, OWTs are commonly designed by what is considered a conservative approach: independently modeling extreme value marginal distributions of V and H_s, calculating their 50-year values, considering a deterministic range of T_p conditioned on H_s, and assuming that these conditions all occur simultaneously. This approach is referred to herein as "1D Exceedance" and is described in more detail in the following section. In reality, these three parameters are correlated to varying degrees, and so this approach is clearly an approximation. The approach is exact only for the case when the three parameters are fully correlated and the degree of the approximation increases with decreasing correlation. A more realistic approach involves using the joint probability distribution of the metocean parameters to estimate combinations with a 50-year recurrence period. The concept of a recurrence period is more complex for multivariate situations, because there are multiple combinations of variables corresponding to a particular recurrence period and because there are multiple algorithms for defining the joint exceedance condition for the variables.

3. Site selection and metocean data

Results of this paper are presented for three sites along the U.S. coast. The sites are selected based on a combination of geographic features and the availability of metocean data. Specifically regarding geographic criteria, sites have been selected along the Atlantic Coast of the U.S. with added attention being given to the mid-Atlantic and Northeastern coasts where the wind resource is rich and where many current proposed sites for offshore wind farms in the U.S. are located. Regarding data availability, sites have been selected to correspond to the location of metocean data buoys deployed and maintained by NOAA that have at least 20 years of data available. Given these considerations, three sites have been selected that lie off the coasts of the states of Maine, Delaware, and Georgia. In the remainder of this paper the sites are identified by their two letter postal abbreviation codes – ME, DE, and GA.

Table 1 gives the general characteristics of the sites including their latitude and longitude, distance from shore, water depth, NOAA site identifier, abbreviation and the duration of measurements. The sites have water depths ranging from 20 m to 30 m which covers the upper range of depths for which monopile support structures are expected to be suitable. With the exception of the ME site, the locations are all 20–30 km offshore.

The measured data used in this paper consists of the hourly wind speed V measured at 5 m above sea level, the significant wave height H_s, defined as usual to be the average of the top one third of recorded wave heights in a given time interval and the peak spectral period T_p, defined as the period of the sea state corresponding to the greatest power spectral density. Wind speed measurements reflect the 8 min average wind speed and are reported hourly. The significant wave heights are determined based on a 20 min time interval and are also reported hourly. Before applying the wind data to OWT design, therefore, corrections must be made to account for the higher elevation of the rotor hub and the different averaging periods specified by the relevant design standards [12]. All wind speeds reported in this paper are presented as hourly values at a height of 5 m.

4. Methodology

This section is divided into three subsections. The first describes the method that was employed to identify extreme events from the wind and wave measurements obtained from NOAA buoys. The second section defines three methods, 1D Exceedance, 1D Reduced Combination and 3D IFORM, to generate 50-year combinations of V, H_s and T_p. The final section defines the structural model which is used to convert specific combinations of V, H_s and T_p into a mudline moment for a particular OWT structure.

4.1. Identification of extreme events and extreme values

Extreme value analysis of metocean parameters requires identification of extreme events (i.e. storms) from either a hindcast of metocean conditions or, as in the case of this paper, measurements of such conditions. Each event then provides a set of extreme values, in this case, values of V, H_s and T_p, which are used to define the joint probability characteristics of the extreme values. There are several methods for defining extreme events, for example, annual maxima, Method of Independent Storms [13], or R Largest Order Statistics or R-LOS [14,15]. In this paper, R-LOS is applied with an R of 7, meaning that 7 extreme events are considered per year. Specifically, the method employed here for identifying extreme events starts by finding the 7 largest measurements of the wind speed V during each year of measurement. The 7 measurements of V from each year are assumed to be from independent events by requiring that each measurement be spaced more than 72 h apart. Next, the maximum H_s occurring within ±36 h of each of the 7 largest wind measurements and the T_p occurring simultaneously with the H_s are paired with the V measurement. These seven triplets of V, H_s and T_p determine the coupled extreme values for the 7 extreme events per year. The process is then repeated for each year of available measurements, resulting in a set of 7 times the number of years of data of V, H_s and T_p coupled values.

Although the method described above does not guarantee that the wind and wave measurements occur simultaneously (i.e. during the same hour), this method conservatively ensures that information from the highest wind speed and significant wave height for a particular storm are included in the analysis. If extreme values were strictly required to occur simultaneously, then the extreme values would be sensitive to whether extreme values are selected based on wind or wave. While this may make sense for structures which are known to be loaded predominately by wind or wave, the intent here is to provide information on metocean hazard which is not tied *a priori* to structural characteristics. For structures which are loaded predominately by wind or wave, the conservatism of the method is expected to be minimal since the combined loads will not be strongly influenced by whether the secondary extreme value is taken as a maximum or as a simultaneous value. For the structure considered in the numerical example in Section 5, the degree of wind and wave dominance is

Table 1
Site information.

Site	Postal Abbrev	NOAA ID	Lat	Long	Water depth (m)	Dist. to shore (km)	Duration (Years)
Maine	ME	44007	43.53° N	70.14° W	24	5.60	31
Delaware	DE	44009	38.46° N	74.70° W	30	30.3	27
Georgia	GA	41008	31.40° N	80.87° W	20	32.3	20

assessed. It is clear that this approach will, if anything, overestimate the hazard, however, in most cases, the approach roughly approximates simultaneous conditions, as suggested by Fig. 1. Fig. 1a shows a cumulative distribution function (CDF) of the absolute value of t_{lag}, the time lag, in hours, between the measurement of maximum V and the measurement of maximum H_s during an extreme event. The data show that, for all three stations, 72% of measurements have $|t_{lag}| < 6$ h and the probability of the maximum V and H_s occurring simultaneously is 17%. Moreover, for most storms observed at these sites, the maximum V and H_s remain relatively constant for several hours before and after the peak. This behavior is shown in Fig. 1b, which shows the hourly measurements of V and H_s taken during a specific event, a September 1999 storm at the GA station.

4.2. Calculation of 50-year extreme metocean conditions

In this section, three methods are described for using measurements of extreme values of V, H_s and T_p to calculate combinations of these values that have a particular recurrence period. The first and second methods, used commonly in practice, are based on univariate or 1D distributions of the extreme value data, and the third method which is proposed in this paper is based on a multivariate or joint (in this case, 3D) distribution of the extreme value data.

4.2.1. Univariate – 1D Exceedance

In this approach, V_{50} and $H_{s,50}$ are calculated independently, a range of T_p is deterministically conditioned on $H_{s,50}$ and all three conditions are assumed to occur simultaneously. IEC 61400-3 describes this approach as "in the absence of information defining the long term joint probability distribution of extreme wind and waves, it shall be assumed that the extreme 10-min mean wind speed with a 50-year recurrence period occurs during the extreme 3-h sea state with a 50-year recurrence period."

To calculate 50-year values of V and H_s, the measured extreme values of these parameters are modeled independently with generalized extreme value (GEV) distributions, which have the following cumulative distribution function for random variable X,

$$F_X(x) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} \tag{1}$$

where μ is the location parameter, σ is the scale parameter ξ is the shape parameter. The three GEV parameters are selected to best-fit the data using a maximum likelihood approach [16]. The magnitude of X with a 50-year recurrence period x_{50} can be calculated by solving the following equation for x_{50},

$$F_X(x_{50}) = 1 - 1/(R \cdot 50) \tag{2}$$

where R is the number of extreme values recorded per year (in this case, $R = 7$). A GEV distribution is selected following standard recommendations for most accurately modeling environmental parameters at long recurrence periods [12].

After fitting independent GEV distributions to the extreme value measurements of V and H_s and using Eq. (2) to calculate V_{50} and $H_{s,50}$, calculations of corresponding values of T_p are required. The IEC Standard states that the extreme sea state should "take account of the range of T_p appropriate to $H_{s,50}$" and that "design calculations should be based on values of the peak spectral period which result in the highest loads acting on an offshore wind turbine." The IEC Standard does not elaborate on how to calculate a range of peak spectral period appropriate to the significant wave height, although the Standard does provide a range of wave periods, relevant to a separate design load case, which requires deterministic simulation of the extreme wave with period T within the extreme sea state. This range, which is conditioned on H_s and gravity g is expressed as,

$$11.1\sqrt{H_s/g} \leqslant T \leqslant 14.3\sqrt{H_s/g} \tag{3}$$

and can be converted to a range of T_p using published empirical relationships between T and T_p for a sea state. API documents [17,18] suggest that the range of the expected ratio between the peak spectral period T_p and the period of the maximum wave T, is between 1.05 and 1.2. The range of T provided in Eq. (3) can be converted to a range of T_p by multiplying the lower bound of the range in Eq. (3) by 1.05 and the upper bound of the range by 1.20, resulting in a range for T_p given as,

$$11.7\sqrt{H_s/g} \leqslant T_p \leqslant 17.2\sqrt{H_s/g} \tag{4}$$

Thus, this method results in scalar 50-year values for H_s and V and a corresponding range of T_p defined by Eq. (4).

4.2.2. Univariate – 1D Reduced Combination

In this approach, a dominant metocean parameter is selected (either V or H_s) and a 50-year value of this parameter is calculated and combined with a reduced value of the other parameter and a range of T_p that is deterministically conditioned on H_s according to Eq. (4). The dominant metocean parameter is defined as the parameter which has the largest contribution to structural load effects. This method is described in ISO 2394, Annex F and aims to avoid the conservatism of combining V_{50} and $H_{s,50}$ while still maintaining the convenience of modeling only the marginal distributions of V and H_s. In this paper, two situations are considered: one where V is the dominant parameter and one where H_s is the dominant parameter.

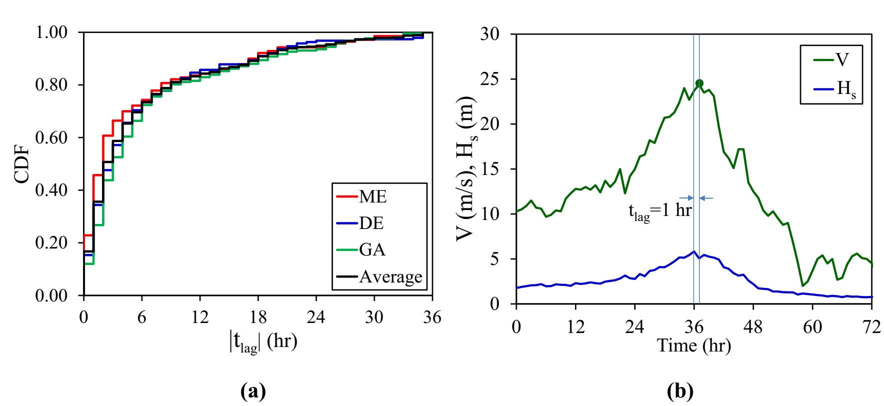

Fig. 1. Measurements of t_{lag} during extreme events including (a) cumulative distribution function of $|t_{lag}|$ for all extreme events at three NOAA buoys and (b) representative time history of V and H_s for a particular extreme event in September 1999 at the GA buoy.

4.2.3. Multivariate – 3D IFORM

The methods described in the previous sections are univariate methods and only require modeling of the marginal distributions of V and H_s. In contrast, the method described in this section is multivariate and considers the joint distribution of extreme values of V, H_s, and T_p. The marginal distributions of all three parameters are assumed to be a GEV distribution. For all three parameters, the GEV distributions were found to accurately fit the marginal data considered here. Because extreme value data is characteristically sparse, it is unlikely that sufficient data will exist to directly calculate the joint distribution of the data using approaches such as those recommended by the IEC Standard or employed by other researchers [3,5]. Rather, the joint distribution should be estimated approximately. One model for creating a joint distribution of multiple random variables is the Nataf model [19,20], which approximates the joint distribution of random variables by matching their marginal distributions and linear covariance [21]. It is worth noting that it is permissible to apply the Nataf model to random variables with extreme value marginal distributions for correlation coefficients less than 0.89 (this bound is specific to Type I Largest distributions, but other extreme value distributions have a similar bound which depends on the variance of the distribution) [19]. This condition it met for all data considered here.

It is important to note at this stage that the Nataf model is not able to capture asymptotic correlations of random variables due to its reliance on transformation of an underlying correlated Gaussian vector the components of which are asymptotically independent for large values of the random variables. Fifty year mean return period values of the conditions, the quantities of interest in this paper, do not lie particularly far into the upper tail of the joint distribution of the wind speed, wave height and peak spectral period and therefore the Nataf model is selected due to its simplicity. If the goal were to develop environmental conditions at much longer return periods the Nataf model would no longer be appropriate, but it is emphasized that design approaches for offshore wind turbines require primarily 50 year conditions.

After calculation of an approximate joint distribution of V, H_s, and T_p, the next step is to associate combinations of these variables with a recurrence period. Unlike univariate metocean measures, multivariate measures do not have a unique rank order nor a unique association between parameters and recurrence period. One method for associating recurrence periods with joint random variables is the Inverse First Order Reliability Method, or IFORM [5], which is also described for two random variables in Annex G of the IEC Standard. For two random variables, the method results in an "environmental contour," which define combinations of joint random variables that have, in a sense, identical recurrence periods. For three random variables, as is the case here, the "environmental contours" become an "environmental surface." The environmental surface is calculated by transforming a hyperspherical surface with a constant radius β in uncorrelated standard normal space to the physical joint random variable space using methods such as the Rosenblatt transformation [22]. For example, consider a hyperspherical surface with radius β for uncorrelated standard normal random variables u_1, u_2 and u_3. This surface is expressed analytically as,

$$u_1^2 + u_2^2 + u_3^2 = \beta^2 \tag{5}$$

The recurrence period (N) associated with this surface is calculated as,

$$N \cdot R = \frac{1}{1 - \Phi(\beta)} \tag{6}$$

where R is the annual rate of occurrence of the random variables. Each combination of u_1, u_2 and u_3 on the hypersphere is then transformed to the physical joint random variable space and defines combinations of the physical random variables (in this case, V, H_s and T_p) with an identical recurrence period N. For the case considered here, where $N = 50$ and $R = 7$, $\beta = 2.76$. More details of this method are available in Annex G of the IEC Standard [3].

4.3. Structural analysis of 5 MW NREL reference offshore turbine

For all three considered methods, the NREL 5 MW offshore reference turbine, supported by a monopile foundation, is analyzed in the program FAST to calculate mudline moments for specific combinations of V, H_s and T_p. FAST is an open source program developed by NREL for the analysis of onshore and offshore wind turbines. For all analyses, the turbine is modeled in a parked condition (i.e. the rotor is stationary and blades are feathered) as is prescribed by the IEC Standard for extreme conditions. In particular, the turbine is modeled for the IEC Design Load Case 6.1 which requires consideration of yaw errors of ±8°. Waves are modeled as irregular and linear, following a JONSWAP spectrum defined by H_s and T_p. Wind is modeled following the RisØ Smooth Terrain turbulence model [23,24], defined by the average wind speed V and the turbulence intensity. For each combination of these parameters, six one-hour analyses are simulated and the average of the maximum moment at the mudline from each of the six simulations is recorded.

Key specifications of the NREL 5 MW reference OWT are provided in Table 2. The height of the monopile is set equal to the water depth at each of the three NOAA buoy locations. The first period of the structure is 3.7 s, 3.9 s and 3.6 s for ME, DE and GA, respectively.

5. Numerical examples

In this section, we apply the three methods described in the previous section to each of the three NOAA buoy locations and the results are summarized. First, statistics of the measured data are provided for each of the three sites. Table 3 lists the best-fitting GEV distribution parameters and the correlation coefficients for V, H_s and T_p at each of the three stations. For all sites, the largest correlation coefficient is between H_s and T_p (0.68 for ME, 0.80 for DE and 0.65 for GA), the second largest correlation coefficient is between H_s and V (0.29 for ME, 0.43 for DE and 0.54 for GA) and the smallest correlation coefficient is between V and T_p (0.22 for ME, 0.36 for DE and 0.27 for GA). Fig. 2 shows projections of the joint distributions approximated by the Nataf model for each of the three sites. The projections clearly show the site-to-site variability between the correlations of metocean parameters, with the DE site having the strongest pair-wise correlations among all variables compared to the other sites. The T_p–H_s projections presented in the far right column of Fig. 2 are superimposed with the upper and lower bounds of Eq. (4), and it is clear that there are many instances of the measured data beyond these boundaries. The range of Eq. (4) is based on a range provided in the IEC Standard, see Eq. (3). This equation originated in [25], which was focused on North Sea conditions. Moreover, it is not clear what

Table 2
Properties of 5 MW NREL offshore wind turbine.

Rotor orientation, configuration	Upwind, 3 blades
Control	Variable speed, collective pitch
Rotor, hub diameter	126 m, 3 m
Hub height (relative to MSL)	90 m
Monopile diameter, thickness	6 m, 0.027 m
Cut in, rated, cut out wind speed	3 m/s, 11.4 m/s, 25 m/s
Rotor, nacelle, tower mass	110 t, 240 t, 347 t

Table 3
Best-fitting GEV marginal distribution parameters and linear correlation coefficients for V, H_s and T_p at the three NOAA buoys.

Site		ξ	σ	μ	Linear correlation coefficients		
					V	H_s	T_p
ME	V	0.09	1.50	16.2	1.00	0.29	0.22
	H_s	−0.13	1.45	3.23		1.00	0.68
	T_p	−0.29	2.05	8.39			1.00
DE	V	0.01	1.41	16.7	1.00	0.43	0.36
	H_s	0.10	0.95	2.99		1.00	0.80
	T_p	0.21	1.34	6.91			1.00
GA	V	0.03	1.31	14.8	1.00	0.54	0.27
	H_s	−0.13	0.74	2.29		1.00	0.65
	T_p	0.04	1.29	5.89			1.00

confidence interval is intended by the provided range. For the sites considered here, the range in Eq. (4) represents an average confidence interval of 81%, 80% and 70% for ME, DE, and GA, respectively. For all sites, the confidence interval of Eq. (4) is roughly centered on the data (i.e. the likelihood of being above the upper bound is roughly equal to the likelihood of being below the lower bound), however, Fig. 2 shows that the variability of the measurements above the upper bound is much larger than the variability of measurements below the lower bound. This has important implications, because, at least for the structures considered here, the response is much more sensitive to peak spectral periods below the lower bound than to period above the upper bound.

Fig. 3 shows 50-year recurrence combinations of V, H_s and T_p based on the 1D Exceedance, 1D Reduced Combination and 3D IFORM methods. The combinations are projected onto H_s–V space. In this space, the 50-year combinations from 1D Exceedance and 1D Reduced Combination are represented as points with the corresponding range of T_p indicated with text. The 50-year environmental surfaces from 3D IFORM are represented as H_s–V contours with constant T_p. Several critical points are indicated on these contours including the maximum and minimum T_p, the maximum V and the maximum H_s. Both the location and shape of the projections of the environmental surfaces vary significantly from site to site, as expected based on the variability observed in the joint distributions presented in Fig. 2. As seen in the Figure, the projection of the 50-year environmental surface is required to be circumscribed by a rectangle defined by V_{50} and $H_{s,50}$, and the point defined by V_{50} and $H_{s,50}$ is required to be contained within an environmental surface that has a longer recurrence period than 50 years. In general, the range of T_p included on the environmental surface is much larger than the range provided in Eq. (4). For all sites, the lower bound of T_p on the environmental surface is much lower than the lower bound of Eq. (4) for the 1D Exceedance point. For ME and GA, the upper bound of T_p on the environmental surface is slightly larger than the upper bound of Eq. (4) for the 1D Exceedance point, but not for DE, where the

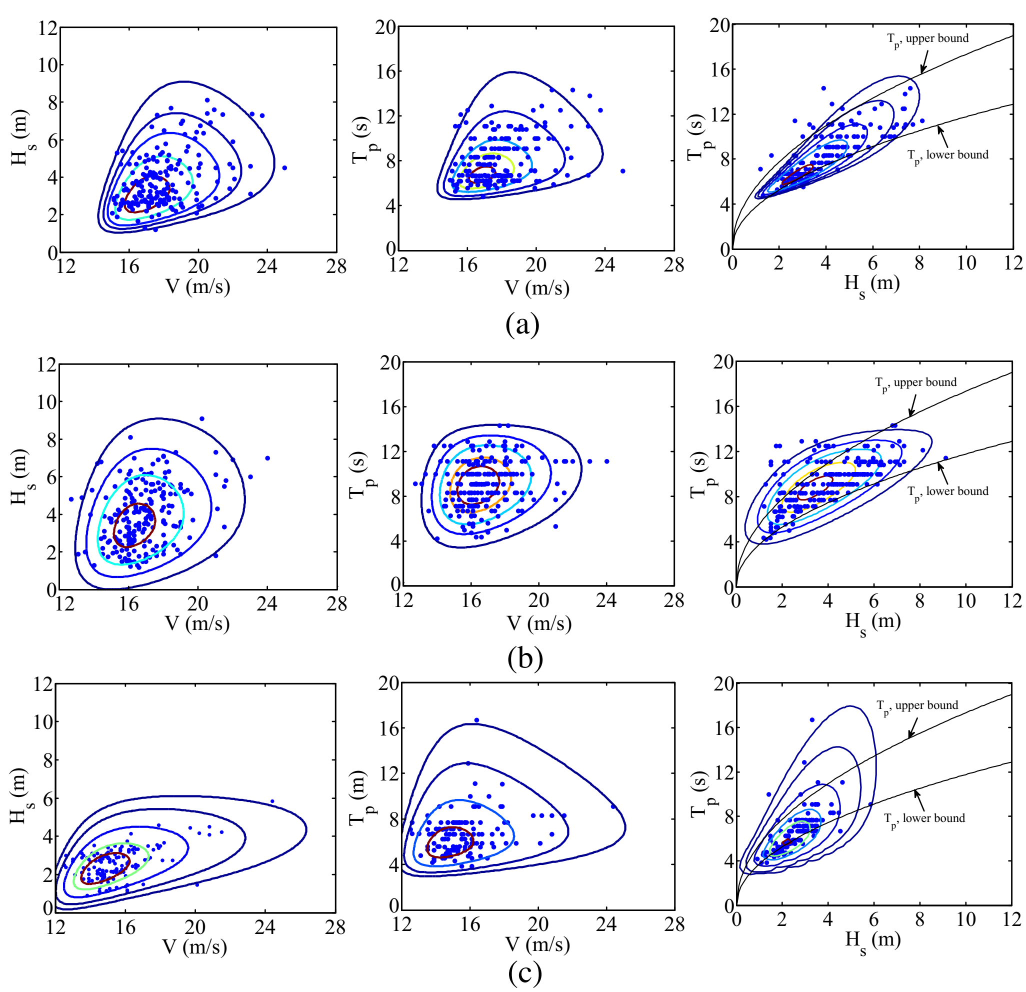

Fig. 2. Projections of the 3D joint distributions of V, H_s and T_p based on the Nataf model for NOAA sites (a) ME, (b) DE and (c) GA.

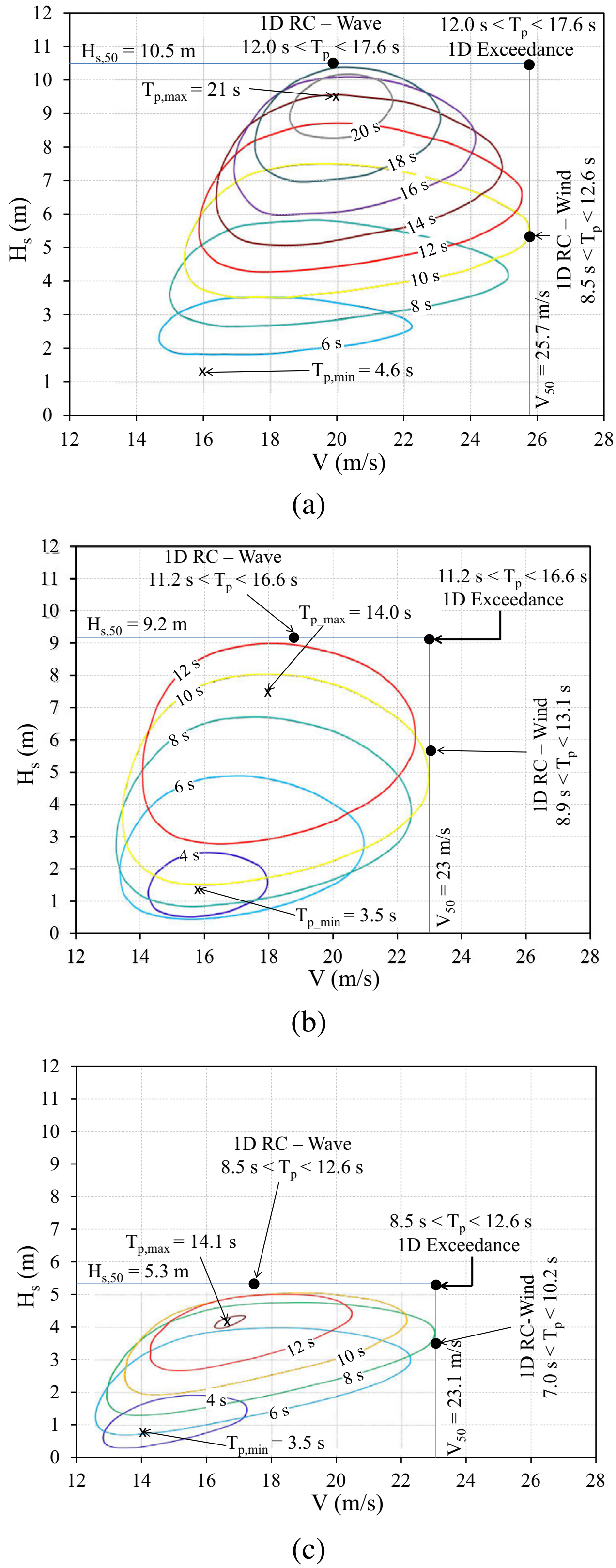

Fig. 3. 50-year recurrence combinations of V, H_s and T_p based on 1D Exceedance and 1D Reduced Combination (1D-RC), indicated with black circles and text defining the T_p range, and 3D IFORM, indicated with contours of constant T_p, for (a) ME, (b) DE and (c) GA.

measured data show that it is unlikely for T_p to exceed the upper bound. This observation is also evident in Fig. 2b.

The 50-year mudline moment is estimated for each site, for yaw positions of 0° and 8°, and for the metocean conditions defined by the three considered methods. For the 3D IFORM method, a structural analysis is conducted for all combinations of V, H_s and T_p defined by the environmental surfaces provided in Fig. 3. The combination of V, H_s and T_p resulting in the highest mudline moment is termed the critical point on the environmental surface. Searching the entire environmental surface for the critical point can be computationally expensive, however, in this case, only a portion of the surface needs to be considered when determining the critical point because it is expected that mudline moments will be higher, on average, for higher values of wind speed and significant wave height and for peak spectral periods closer to the first structural period, which in this case means a lower peak spectral period. Specifically, the search for the critical point can be reduced by first defining a plane that passes through the points on the environmental surface corresponding to the maximum significant wave height, maximum wind speed and minimum peak spectral period, and then limiting the search to the portion of the environmental surface on the side of the plane with more severe conditions (in this case, higher wind, higher wave and lower peak spectral period). For the 1D Exceedance and 1D Reduced Combination methods, a structural analysis is conducted for wind and wave time series defined by V, H_s and the associated range of T_p specified by Eq. (4). In all cases, the mudline moments are, on average, the highest for the lower bound of the period range which is closest to the first period of the structure for each location. Thus the peak spectral period of the critical point for the 1D Exceedance and 1D Reduced Combination methods is equal to $T_{p,\text{lower bound}}$.

Table 4 provides the values of V, H_s and T_p for the critical point for each site and yaw position for all three methods, including two cases, wind-dominated and wave-dominated, for the 1D Reduced Combination Method. Fig. 4 shows the environmental surface for each site and yaw position with the color of the surface indicating the magnitude of the mudline moment corresponding to a particular combination of V, H_s and T_p.

Regarding Table 4 and Fig. 4, several interesting observations can be made. First, for all three sites, the critical point on the environmental surface does not correspond to the point with the maximum wind speed or significant wave height. This is because the peak spectral period plays an important role in determining the location of the critical point. The influence of the peak spectral period can be seen clearly for site GA, Yaw = 0° (Fig. 4.c.1), where the critical point is located at a peak spectral period close to the first period of the structure, even though this point corresponds to relatively smaller wind speeds and significant wave heights. Second, a yaw position of 8° increases the contribution of loading due to wind compared to a yaw position of 0°. This can be seen by comparing the critical point between the two yaw positions and noting that, for all sites, the critical point shifts to a higher wind speed for a yaw position of 8°. Specifically, for site GA (Fig. 4.c.2), the critical point shifts from a wind speed close to the minimum value on the environmental surface to a wind speed close to the maximum value. For the DE and ME sites, which have larger water depths than the GA site, the loading due to waves is dominant. This can be seen by noting that the critical point moves minimally between the 0° and 8° yaw positions and noting that the wave height of the critical point is close to $H_{s,50}$. In general, the critical point moves toward the extreme of the parameter with the strongest influence on the structural response. Third, for every case except for the ME site and an 8° yaw position, the peak spec-

Table 4
Values of the critical point based on 1D Exceedance, 1D Reduced Combination and 3D IFORM for yaw errors of 0° and 8°.

Station	1D Exceedance			1D Reduced Combination				3D IFORM			
	V (m/s)	H_s (m)	T_p (s)	Dominant parameter	V (m/s)	H_s (m)	T_p (s)	Yaw Error	V (m/s)	H_s (m)	T_p (s)
ME	25.7	10.5	12.0	Wind	25.7	5.3	8.5	0°	20.8	8.8	11.4
				Wave	19.8	10.5	12.0	8°	21.5	10.4	15.9
DE	23.0	9.2	11.2	Wind	23.0	5.7	8.9	0°	19.2	7.8	9.9
				Wave	18.8	9.2	11.2	8°	19.5	8.2	10.7
GA	23.1	5.3	8.5	Wind	23.1	3.5	7.0	0°	15.0	2.1	3.9
				Wave	17.4	5.3	8.5	8°	23.0	4.1	7.4

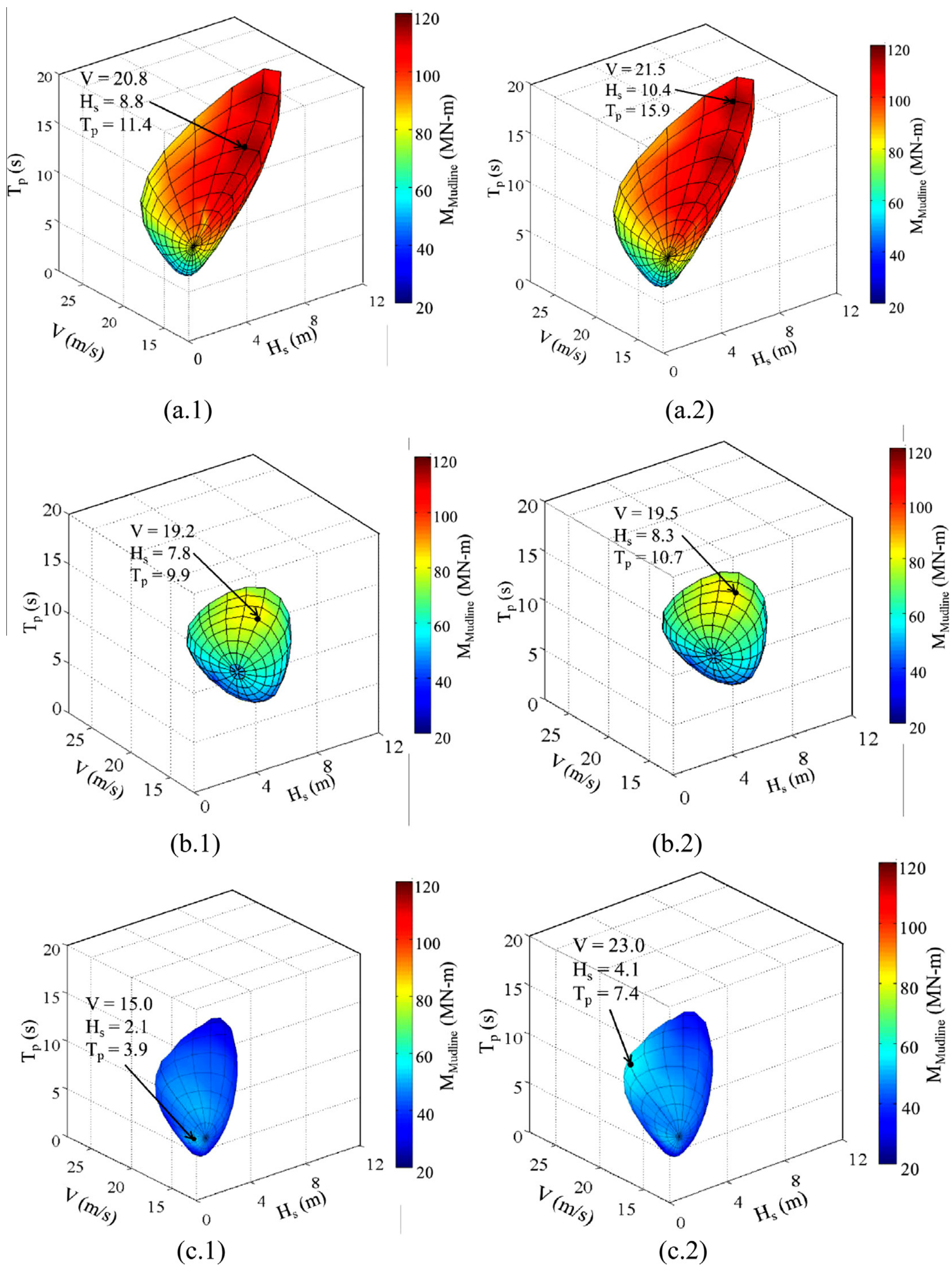

Fig. 4. Contours of the the mudline moment at all locations on the environmental surface for (a.1) Site = ME, Yaw = 0°, (a.2) Site = ME, Yaw = 8°, (b.1) Site = DE, Yaw = 0°, (b.2) Site = DE, Yaw = 8°, (c.1) Site = GA, Yaw = 0° and (c.2) Site = GA, Yaw = 8°.

Table 5
Average of the six maximum mudline bending moments from six one hour simulations of turbulent winds coupled with linear irregular waves defined by the critical point specified in Table 4.

Station	Yaw position	Mudline moment (MN-m)			
		1D Exceedance	1D Reduced Combination		3D IFORM
			Wind dominant	Wave dominant	
ME	0°	131	95	125	115
	8°	128	97	126	116
DE	0°	88	66	83	82
	8°	91	69	84	83
GA	0°	48	44	47	52
	8°	56	52	48	57

tral period of the critical point based on 3D IFORM is lower than the lower bound peak spectral period considered in 1D Exceedance. For both yaw positions and the ME and DE sites, the difference between these peak spectral periods is less than 12%, however, for the GA site and a 0° yaw position, the peak spectral period of the critical point from 3D IFORM is more than 50% lower than the lower bound.

The average maximum mudline moment for the critical point based on all methods are presented in Table 5 for the three sites and two yaw positions. For the ME and DE sites, the 1D Exceedance method results in a higher moment (7–12% higher) than 3D IFORM for both yaw positions. However, for the GA site, the 3D IFORM method results in a higher moment (2–8% higher), even though 1D Exceedance considers a more severe combination of V and H_s than any of the combinations on the environmental surface. For the ME and DE sites, as shown in Table 4, the critical point on the environmental surface has a peak spectral period that is much closer to the lower bound of the range considered in 1D Exceedance. So, at these sites, the more severe combination of V and H_s inherent to 1D Exceedance increases mudline moments by more than the lower peak spectral periods possible with 3D IFORM. However, for the GA site, the peak spectral period for 3D IFORM is much lower than the lower bound of the range considered in 1D Exceedance, and so, in this case, the lower peak spectral periods possible with 3D IFORM increases the mudline moment by more than the more severe combination of V and H_s inherent to 1D Exceedance. This result is conditioned on the simple method applied in this paper for estimating the range of peak spectral period for the 1D Exceedance method. Certainly, a more rigorous method could result in a more appropriate range which would avoid the non-conservative behavior shown here. Nevertheless, if a method similar to 1D Exceedance is used, the result emphasizes the importance of appropriate consideration of the peak spectral period range. The moments resulting from the 1D Reduced Combination method for the wave dominant condition range between 86% and 98% of the corresponding moments from 1D Exceedance. The result show that for all cases except for the GA site and 8° yaw error, the wave dominant condition results in higher moments. For all of cases with 0° yaw error, wave dominant conditions result in higher moments (32% higher for the ME site, 26% higher for the DE site and 7% higher for the GA site).

6. Conclusions and future work

In this paper, a multivariate, jointly probabilistic method for assessing extreme metocean conditions is proposed and examined for three sites along the U.S. Atlantic Coast near Maine (ME), Delaware (DE) and Georgia (GA). The method is based on the Nataf model and the Inverse First Order Reliability Method (IFORM) and uses measurements or hindcasts of multiple metocean parameters to estimate an environmental surface which defines combinations of these parameters with a particular recurrence period. For the examined sites, buoy measurements of extreme values of three parameters, the hourly wind speed, the significant wave height and the peak spectral period are integrated into the Nataf model to approximate a joint distribution of these data which is then converted to an environmental surface using 3D IFORM. The environmental surface is analyzed to find the critical point, defined as the combination of metocean parameters causing the largest mudline moment for a model of the NREL 5 MW offshore wind turbine supported by a monopile. The location of the critical point as well as the magnitude of the mudline moment is compared to results obtained using two simpler univariate methods, termed here as 1D Exceedance and 1D Reduced Combination. The comparison showed that, for one of the three considered sites (GA), the mudline moments based on 3D IFORM were greater than both other methods, even though the 1D Exceedance method, by definition, considers a more severe combination of wind and wave than does 3D IFORM. The reason for this result is that, for this site, the larger and more rational range of peak spectral period considered by the 3D IFORM method included wave loading with dominant frequency close to the first mode natural frequency of the offshore wind turbine and this effect more than offset the differences caused by considering a more severe combination of wind and wave. For this case, a design based on either 1D Exceedance or 1D Reduced Combination Methods would be non-conservative, even though it is commonly assumed that calculating moments based on combining the 50-year wind and wave is always conservative. At the other two sites (ME and DE), the 1D Exceedance and 1D Reduced Combination approaches predict mudline moments greater than 3D IFORM, and, in these two cases, some material savings may be possible if 3D IFORM were used.

It is important to emphasize that the results presented in this paper for 1D Exceedance and 1D Reduced Combination are conditioned on the simple method to estimate the appropriate range of peak spectral period, and that a more rigorous (and site-specific) method could have been selected which would have assured that, for all sites, the mudline moments were larger for both univariate methods. However, the results highlight the importance of selecting an appropriate range of the peak spectral period. Given that calculating a site-specific range of peak spectral period appropriate to the 1D Exceedance and 1D Reduced Combination methods is not a trivial exercise and given that the IEC Standard does not clearly specify how to estimate such a range, the authors believe that the added complexity, but greater rigor of 3D IFORM may be justified in practice.

The authors are currently exploring rational methods for expanding 3D IFORM to consider the influence of hurricanes which, at some sites along the U.S. Atlantic Coast, can dominate the metocean hazard at long return periods. The extent of this dominance cannot be reliably estimated using only multiple decades of buoy measurements or hindcasts.

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