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Derivation of Met-Ocean Conditions for the Simulation of Floating Wind Turbines: a European case study

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Abstract. Offshore wind turbines are subject not only to varying wind conditions during their lifetime, but also sea conditions. Therefore, in addition to wind speed, other sea-related quantities need to be considered to characterize a specific installation site. International standards suggest that, at a minimum, significant wave height, peak spectral period and wind/wave misalignment must be considered. In order to have a statistically significant description of the potential installation site, the long-term distributions of the three environmental variables must be determined. In this context, the objectives of the present work are twofold: firstly, to demonstrate the procedure trough which environmental conditions including wind and wave information can be derived using open-source tools. Secondly, an exemplary dataset is provided. The dataset is used both do demonstrate the procedure and provided as a ready-made example for use in future studies. The provided dataset is used in the EU-funded Horizon 2020 project FLOATECH.

1. Introduction

Wind turbines are designed with decades-long service life in mind. During their service life, these machines operate with as little as possible maintenance in order to maximize Levelized Cost of Energy (LCOE). Unlike most fossil-fuel based power generation systems however, that typically operate within the specifications provided by designers, the operating conditions a wind turbine experiences are non-deterministic. In fact, wind turbines are subject to a vast range of environmental conditions during their lifetime such as tropical storms or tempests.

From a general perspective, even in a non-deterministic design space, engineers need a way of estimating fatigue loads and a way of estimating extreme loads. This objective can be achieved by having a statistical representation of the installation site by treating relevant environmental variables as stochastic. Events with high probability of occurrence are fatigue-driving while the tails of the probability distributions can be used to estimate the likelihood of extreme weather events that cause high structural loading. Extremely sporadic events that have little statistical significance such as tornadoes need to be accounted for separately and will not be discussed in this study. For onshore wind turbines, the design driving parameters are the mean 10-minute wind speed at hub height (U) and the turbulence intensity (*ti*). In practice however, in order to simplify the design process, design standards [1,2] prescribe *ti* to be determined based on the mean wind speed, reducing the environmental aleatoric variables to just one. Moreover, to favor standardization and industrialization of wind turbine designs, international standards prescribe a series of design *classes* for onshore wind turbines. For each *class* the long term wind speed distribution is assumed to follow a Raileigh [1] probability density function (PDF) with a prescribed mean, and a deterministic law is prescribed for turbulence intensity. Once a turbine is designed for a specific *class* it can operate in sites with less severe inflow conditions than the design class.

An offshore wind turbine however is subject not only to varying inflow conditions but also to varying sea conditions. The formers are typically referred to as meteorological conditions, while the latter as ocean conditions. The combination of the two will be referred to as met-ocean conditions throughout this work. For sake of completeness, meteorological conditions for the purpose of wind turbine design are summarized. They are defined based on wind speed and direction, with the latter parameter being previously neglected under the assumption that the wind turbine is able to yaw. Ocean waves on the other hand are modelled by superimposing individual regular waves with a certain amplitude (H), period (T) and direction. The combination of these wave trains defines a sea state. Design standards assume that an individual sea state can be modelled with three aleatoric variables: the mean amplitude of the highest third of the waves (significant wave height H_S), the peak spectral period of the waves (T_P) and the mean wave direction. If we combine wind and wave direction by defining wind-wave misalignment (M_{WW}), a generic offshore site can be statistically modelled with four aleatoric variables U, H_S, T_P, M_{WW}.

While this approach allows for a complete characterization of an offshore site, it is not exempt from limitations. For instance, it does not allow for modelling two or three-peak wave spectra, which may arise in sites where the contribution of swell is significant [3]. Moreover, condensing wind and wave direction into one parameter (M_{WW}) implicitly assumes that the Floating Offshore Wind Turbine's (FOWT) floater and mooring lines are symmetrical, which is often not the case.

Currently, no specific design classes are prescribed for offshore wind turbines and therefore each turbine-floater combination must be verified in site-specific installation conditions. To do so, a wind turbine designer must construct a joint probabilistic model of the installation site to have a representation of the long-term probability distributions of H_S, T_P and M_{WW}. "Extreme" combinations of the environmental variables can be found by defining an environmental contour; a collection of environmental parameters corresponding to a certain return period [4].

High quality data sources to build such environmental contours are scarce. In fact to obtain a high quality representation of an installation site, long-term measurement of environmental conditions are required and only recently governments and research institutions have started to gather measurements of ocean and meteorological parameters together, as is the case for the Italian government-funded RMN initiative [5]. At the same time however, realistic environmental conditions could help to improve future FOWT designs, helping researchers to overcome potential issues of turbine upscaling, as highlighted in [6]. For researchers looking into analyzing marine structures installed in relatively shallow waters, such as fixed-bottom offshore wind turbines, the FINO monitoring platforms [7,8] provide an exceptional high-quality public dataset. For researcher focusing on deep-water installations such as in Floating Offshore Wind Turbines (FOWTs) however, this dataset is affected by the interaction of the waves with the seabed, causing changes to the ocean parameters that are not representative of deep-water sites.

Some examples of processed ready-to-use datasets for FOWT research are available in the literature. Stewart et al. [9] created a comprehensive dataset for sites off the coasts of the United States by creating full long-term joint probability distributions of the environmental parameters in terms of conditional PDFs for the examined sites. The authors then combined them to create generic sites for researchers to use. The approach used by the authors derives conditional distributions based on data bins which can render the creation of environmental contours difficult. Turning to available data for European sites, Li et al. [10] defined long-term probability representations of five European sites based on hindcast data. Wind-wave misalignment, which can introduce relevant loading FOWTs [11], was not considered by the authors. Authors report 3-D contours of U-H_S-T_P that, in the case of FOWT design, are suitable to derived extreme met-ocean conditions in a parked configuration. Severe-Sea-States (SSS) in operational conditions cannot be derived from the data presented alone without requiring additional processing, a non-trivial task for many. The COREWIND [12] and LIFEs50+ [13,14] design basis provide processed met-ocean data that was used in the two EU-funded projects. In both cases, because post-processing has already been performed on these datasets, their resolution is often coarse, and not suitable for the derivation of additional quantities that may be of interest.

In this context, the current study aims at tackling the highlighted issues by presenting and demonstrating a procedure to obtain met-ocean data for a given offshore location and process it to obtain a long-term description of the site in terms of marginal conditional PDFs for U, H_S, T_P and M_{WW}. High quality hindcast data is obtained through the open-source database ERA-5 [15,16]. The post-processing procedure is developed in Python and is based on the open-source tool Virocon [17], that is also used to compute environmental contours. The open-source nature of the procedure makes it possible for other researchers to replicate and apply it to different data or in a different way to obtain additional quantities of interest. The procedure is demonstrated on an exemplary dataset, for which statistical representation is provided, together with post-processed quantities compliant with current international standards for wind turbine designs. The procedure that was used to process the data as well as the post processed data are made publicly available as reported at the bottom of the paper.

2. Met-ocean data for FOWT design

In this section, the entire procedure that was adopted is explained step by step. Results of the application of the procedure to an exemplary location are discussed at each step. After discussing the source of the raw data used in this study, the necessary met-ocean quantities (referenced as sea states) for the design of a FOWT are explained. Each sea state is then analyzed and commented.

2.1. Hindcast environmental conditions

Hindcast atmospheric models, also known as re-analysis models, combine short-term forecast data obtained through numerical modelling techniques, with observations, to obtain a physically consistent representation of the atmosphere. In simple terms, the observations are used to calibrate the model system and bring the existing forecast closer to the observations. The updated forecast is referred to as reanalysis and is used as starting point for a new forecast [18]. For the scope of deriving met-ocean conditions for FOWTs, the ERA-5 Reanalysis database [15] can be used, and is suggested in this article. In fact, the dataset contains reanalysis data of both atmospheric and oceanographic parameters, spans a total of more than 40 years, and has been thoroughly validated with observations. Moreover, data can be obtained worldwide on a 31km grid, a reasonably fine spacing for offshore applications, and most importantly, is available open source.

The site that was chosen for this study is a sea leg west of the Scottish isle of Barra (56.886ºN, 7.948ºW). This site was indicated by Marine Scotland among potential sites for offshore wind development and is located on the European Continental shelf [14]. Water depths are in excess of 120 m, thus representative of the range of depths that are currently being proposed for FOWT installation. This site is also used in the EU-funded projects COREWIND and LifeS50+, and it is characterized by severe wind and wave conditions, a preferred characteristic in the context of the EU-funded FLOATECH project [19]. Twenty-two years of data are used in the analysis, from January 1979 to December 2000. This period of time was chosen to be as consistent as possible with the data used in LifeS50+ [14]. The following variables were obtained from the ERA5 database:

i. *100m u-component of wind and 100m v-component of wind* – combined to find a 100m wind magnitude (U) and direction
ii. *Significant wave height of combined wind waves and swell* (H_S)
iii. *Peak wave period* (T_P)
iv. *Mean wave direction* - combined with mean wind direction to find wind-wave misalignment (M_{WW})

2.2. Design-driving environmental conditions

Although apparently simple machines, wind turbines operate in several manners reacting to the non-deterministic environment around them. The different operating conditions may be damaging for different components; therefore, design standards require component loads to be computed in different operating conditions. In very simple terms, IEC 61400-3 [20,21] requires the definition of three families of sea-states for the design of an offshore wind turbine. The Normal Sea State (NSS) refers to the combination of H_S, T_P and M_{WW} that the turbine normally experiences during power production. This sea state is used for both fatigue and ultimate load estimation. When computing ultimate loads, the expected values of H_S conditioned on U (H_S|U) and the expected value of T_P conditioned on H_S E(T_P|H_S) may be used. A M_{WW} of 0° is considered, as the condition of aligned wind and waves is considered to be unfavorable for peak loading. On the other hand, when evaluating fatigue loads the joint probability distribution of H_S, T_P and M_{WW} must be considered in the definition of the NSS to use, resulting in a variety of ocean conditions as shown in detail in the following part of the study.

Severe Sea State (SSS) refers to the sea state with a recurrence period of 50 years conditioned on the wind speed. As discussed previously, areas of the design space with low probability of occurrence, relevant for component ultimate loading are taken in account here. Wind speeds between cut-in and cut-out shall be considered, and the turbine is modelled as operational in these conditions. IEC 61400-3 suggest using an environmental contour, specifically the IFORM [22] method to derive SSS conditions, as demonstrated later on.

Extreme Sea State (ESS) refers to the combination of wind and wave conditions with recurrence period of 50 years. The turbine will typically be parked in these conditions. As demonstrated in the following, these conditions can also be derived based on environmental contours for the site in exam.

2.3. Normal Sea State

Normal Sea State parameters are found by building a joint probability model of the West of Barra site. Because the environmental variables in exam are not statistically independent, a hierarchical model is used. The joint probability density function is therefore expressed as:

$$f_{U,H_S,T_P,M_{ww}}(U,H_s,T_p,M_{ww}) = f_U(U) f_{H_s}(H_s|U) f_{T_P}(T_p|H_s) f_{M_{ww}}(M_{ww}|U) \quad (1)$$

The wind speed is modelled as an independent random variable, H_S is conditioned on U, T_P is conditioned on H_S and M_{WW} is conditioned on U. These pdfs are referred to as conditional because their parameters are dependent or conditioned on the conditioning parameter. In more detail, if μ_i and σ_i are the parameters of a conditional distribution (the mean and variance of a normal distribution for instance), then these parameters will be modelled with dependence functions:

$$\begin{aligned} \mu_i &= f(x_{i-1}, c_1, \dots, c_n) \\ \sigma_i &= f(x_{i-1}, c_1, \dots, c_n) \end{aligned} \quad (2)$$

where x_{i-1} is the conditioning parameter (for instance U in the case of H_S) and c_n are fit coefficients. To fit the analytical model, data is binned in the dimension of the conditioning variable. For each bin a pdf is fitted, and the best fit pdf parameters are found (such as $\mu_i(x_{i-1})$ and $\sigma_i(x_{i-1})$ in the current example). The set of values $\mu_i(x_{i-1})$ and $\sigma_i(x_{i-1})$ are then used to find the coefficients c_n of the dependence functions, obtaining a continuous joint probability model. The procedure is illustrated schematically in figure 1 for a couple of environmental conditions: wind speed as an independent parameter and significant wave height conditioned on the wind speed. It is important to note that the procedure is general and can be extended to a n-dimensional probability space.

The approach proposed by Haselsteiner et al. [23] is followed to derive marginal PDFs for wind speed, significant wave height and peak spectral period. Wind speed is modelled using an Exponentiated Weibull distribution [23]. H_S is modelled with an Exponentiated Weibull distribution conditioned on U:

$$f_{H_s}(H_s|U) = \left(1 - e^{\left[-\left(\frac{H_s}{\alpha_{hs}}\right)^{\beta_{hs}}\right]}\right)^{\delta_{hs}} \quad (3)$$

Physically speaking, Hs is conditioned on U in order to include wind-generated waves, one of the main wave-generating mechanisms [24], in the hierarchical model .

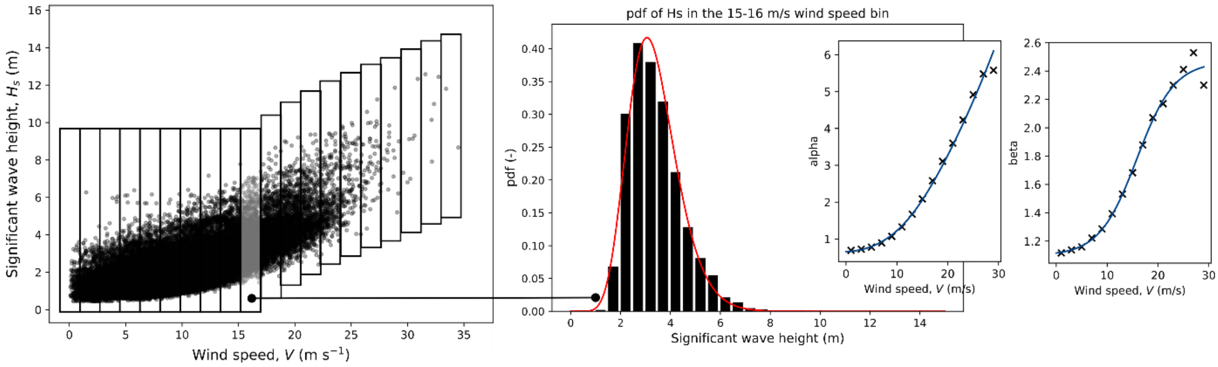

Figure 1: Schematic illustration of the procedure to derive a join probability model. i) data is binned based on values of the independent parameter (U), ii) for each bin a best-fit distribution of the conditioned parameter (Hs) is found iii) best-fit parameters of Hs are fit with a dependence function

The median wave height is modelled as an exponential function $\widetilde{H_s} = c_1 + c_2 U^{c_3}$ that relates the wind speed at the sites to physical theories on wind-generated waves. The shape parameter β_{H_s} is modelled as a logistics function. From the definition of median of the exponentiated Weibull distribution follows the value of the scale parameter $\alpha_{H_s} = H_s/2.0445^{1/\beta_{H_s}}$. T_P is modelled with a log-normal distribution conditioned on H_S:

$$f_{H_s}(T_p|H_s) = \frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{lnT_p - \mu_{Tp}}{\sqrt{2}\sigma^2}\right)\right) \tag{4}$$

The peak spectral period median is considered to be proportional to the square root of H_S, and the variance is considered to be asymptotically decreasing:

$$\widetilde{T_p} = c_8 + c_9\sqrt{\frac{H_s}{g}} = e^{\mu_{Tp}}$$
$$\sigma_{T_p} = c_{10} + c_{11}e^{-c_{12}H_s} \tag{5}$$

Finally, M_{WW} is modelled using a Von Mises distribution as proposed by Stewart et al. [9], also known as circular normal distribution. This distribution is periodic on the support [-π, π] and is thus suitable to model wind-wave misalignment. At the time of writing, this distribution is not available in Virocon, thus it was implemented and tested by the authors:

$$f_{wwm}(wwm|U) = \frac{e^{k\cos(M_{WW} - \mu_W)}}{2\pi I_0(k)} \tag{6}$$

Where I_0 is the modified Bessel function of order zero. The shape parameter k is modelled with a logistics distribution while mean value μ_w is modelled with a secondo order polynomial. Both functions were chosen as they provided the best fit to the data. Best-fit coefficients for the West of Barra site are shown in table 1, where the fit-functions that were used are also listed. The goodness of fit can be examined by looking at the Q-Q plots and fit functions in fig. 2.

The best fit value of c_3, which is derived based on the median value of significant wave heigh $\widetilde{H_s} = c_1 + c_2 U^{c_3}$, is very close to two, indicating that the sea states at the site are fully developed, pointing to the fact that the wave amplitude spectrum can be modelled with a Pierson-Moskovitz spectrum [23].

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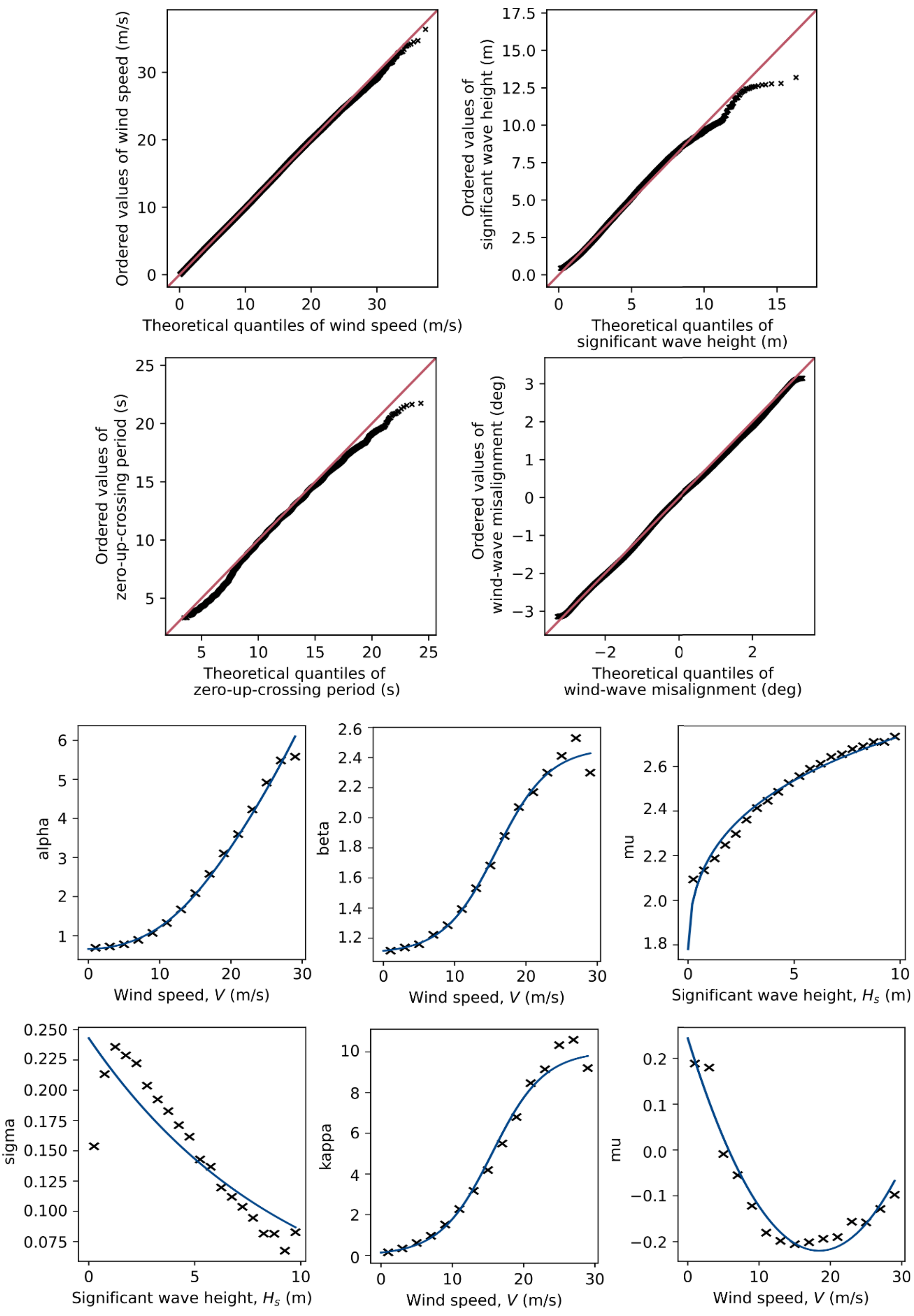

Figure 2: (top) Q-Q plots of the four environmental variables (bottom) Fit functions for the parameters of the marginal pdfs. Values and functions specified in table 1.

Table 1: Fitted statistical model

	parameter		distribution		best fit coefficients	
independent variables	wind speed (U)		$f(U) = \left(1-e^{\left(\frac{U}{\alpha}\right)^{\beta}}\right)^{\delta}$		$\alpha = 12.773$ $\beta = 2.345$ $\delta = 0.880$	
conditional variables	$\mathbf{H_S \mid U}$		$\mathbf{T_P \mid H_S}$		$M_{WW} \mid \mathbf{U}$	
distribution	exponentiated Weibull $\left(1-e^{\left[-\left(\frac{H_s}{\alpha_{H_s}}\right)^{\beta_{H_s}}\right]}\right)^{5}$		Log-Normal $\frac{1}{2}\left(1+\mathrm{erf}\left(\frac{\ln T_p-\mu_{Tp}}{\sqrt{2}\sigma^2}\right)\right)$		Von Mises $\frac{e^{k\cos(M_{ww}-\mu_w)}}{2\pi I_0(k)}$	
parameter	α_{H_S}	β_{H_s}	μ_{Tp}	σ_{T_p}	k_w	μ_w
f(x)	$\frac{c_1+c_2U^{c_3}}{2.0445^{\frac{1}{\beta_{H_s}}}}$	$c_4+\frac{c_5}{1+e^{-c_6(U-c_7)}}$	$\ln\left(c_8+c_9\sqrt{\frac{H_s}{g}}\right)$	$c_{10}+c_{11}e^{-c_{12}H_s}$	$c_{12}+\frac{c_{13}}{1+e^{-c_{14}(U-c_{15})}}$	$c_{16}+c_{17}U+c_{18}U^2$
c_1	1.25	1.1	5.94	0	0	0.24
c_2	0.01	1.37	9.42	0.24	10.04	-0.05
c_3	1.98	-0.27	-	0.11	-0.28	0.0014
c_4	-	-15.86	-	-	-15.89	-

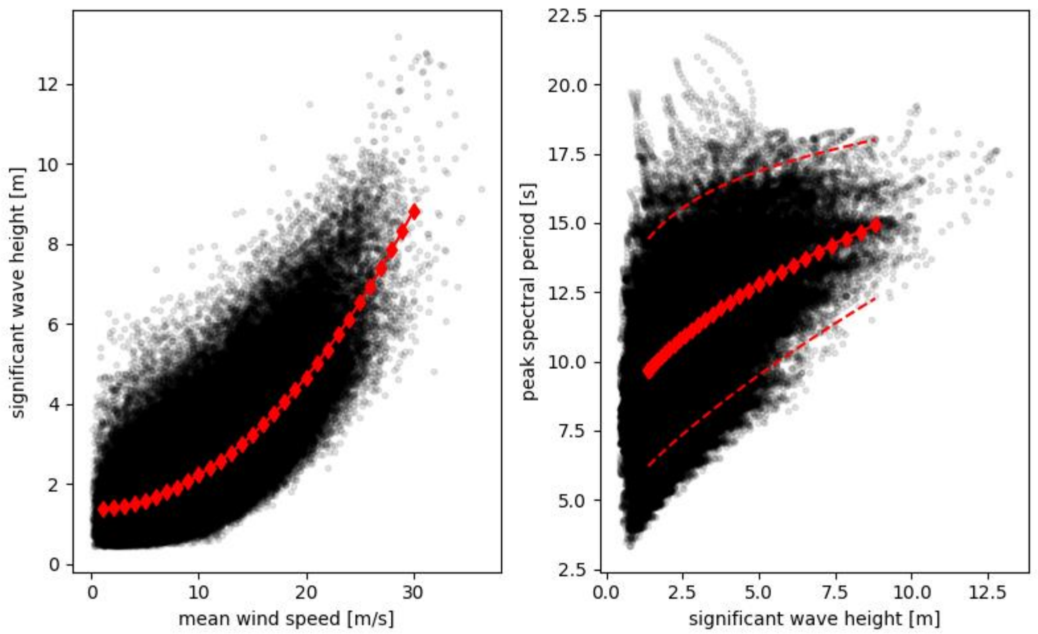

Figure 3: Expected values of H_S and T_P for west of Barra site corresponding to NSS conditions for extreme load calculation (in red), $\pm 2\sigma_{T_p}(H_s)$ range (red dashed lines) and scatter data from ERA5 database [15]

Moreover, using the coefficients in Table 1, median wave height for the west of Barra site can be expressed as height $\widetilde{H_s} = 1.25 + 0.01U^{1.98}$. If we were to physically interpret this dependence function, the first term of this expression indicates that median significant wave height is independent from U and is swell-driven, while the latter highlights the contribution of wind-generated waves [23].

2.3.1. NSS for ultimate load calculations. For ultimate load DLCs that require a NSS, according to IEC 61400-3, wind and waves may be considered aligned, effectively neglecting M_{WW}. This simplification is considered acceptable to limit the number of required model evaluations, as the condition of aligned wind and waves is considered the worst loading condition for FOWTs. For each wind speed the expected value of significant wave height can be used, while a "range of peak spectral period, T_P, appropriate to each significant wave height" must be considered. Considering the statistical model that was built in table 1:

$$E(Hs|U) = E\left(f_{H_s}(H_s|U)\right)$$
$$E(T_p|H_s) = E\left(f_{T_P}(T_p|H_s)\right) \pm 2\sigma_{T_p}(H_s) \tag{7}$$

Therefore, for each wind speed the expected value of significant wave height is readily found. Based on the latter, a range of peak spectral periods can be found by considering the expected value of T_P and a range of +/- two standard deviations, enclosing 95% of the T_P population. For the West of Barra site, expected values for NSS are shown in fig. 3.

2.3.2. NSS for fatigue load calculations. When evaluating fatigue loads, the full long-term distribution of the met-ocean parameters must be considered. The probability space must be divided in a number of bins, and the FOWT model must be evaluated a certain number of times within each bin to get an estimation of the fatigue loading in the considered condition. Finally, lifetime fatigue loads are found by weighing the per-bin loads by the bin's cumulative probability. The cumulative probability of a given bin, can be found by integrating eq. 1 between the bins upper and lower limits:

$$F(bin) = \int_{U_1}^{U_2}\int_{Hs_1}^{Hs_2}\int_{Tp_1}^{Tp_2}\int_{M_{ww_2}}^{M_{ww_2}} f_{H_s}(H_s|U) f_{T_P}(T_p|H_s) f_{M_{ww}}(M_{ww}|U)\, dU dH_s dT_p dM_{ww} \tag{8}$$

Because the distributions are conditional, we cannot simply multiply the cumulative density functions (CDF) of each variable independently, and eq. 8 must be solved analytically or numerically. Alternatively, if raw data is available, the probability of each bin can be found by counting the number of times a combination of the environmental variables is within the ranges of the specific bin:

$$F(bin) = n(\, x_1 =]x_{1_1}, x_{1_2}], \ldots, x_n =]x_{n_1}, x_{n_2}]\,)/N \tag{9}$$

where $n(\, x_1, .. x_n)$ is the number of occurrences recorded in the bin with upper and lows limits for the n-th aleatoric variable x_{n_1}, x_{n_2}, and N is the total number of events. The latter approach was followed in the current study.

Table 2: Bin ranges and width

Parameter	Range	bin width IEC	bin width
U (m/s)	4-26	2	2
H_S (m)	0-14	0.5	2
T_P (s)	3-21	0.5	2
M_{WW} (°)	-180 - 180	15	60
total bins	-	252747	4158

It is important to choose bin width wisely, as at least one model evaluation will be required per each bin. As shown in table 2, using the bin width ranges recommended by IEC standards, would result in an unreasonable number of model evaluations. Therefore, two strategies are combined to reduce the number of model evaluations as proposed by Stewart [11]. The first is to increase bin width; this is shown in table 2 and allows for a reduction in bin number of two orders of magnitude. The second is based on the observation that many bins contain a very low number of samples and thus have a very low probability of occurrence, only marginally influencing fatigue loads. Therefore, the bins with the lowest probability of occurrence are excluded, with the constraint that the CDF of the remaining bins is at least 90%. By combining the two strategies the total number of bins for the examined data was reduced to 251.

2.4. Severe Sea State

As IEC 61400-3 (Annex F) suggests, SSS met-ocean conditions may be found using an environmental contour method. In more detail the Inverse First-Order Reliability Method (IFORM) is suggested to obtain a 2-D contour of wind speed and significant wave height. The IFORM method physically assumes that the conditions with recurrence probability greater than the threshold to be located beyond any possible line tangent to the contour [25]. In fig. 4, examples of such lines are shown as dashed lines. The 50-yrs and 1-yr environmental contours of U-H_S are shown as solid lines. SSS is defined by the points of the 50-yrs contour that are between cut-in and cut-out (in black in fig. 4) The physical interpretation of environmental contours, and alternative methods to the IFORM, as well as the mathematical procedure involved in deriving such contours, are discussed in detail in [4,17,25–27].

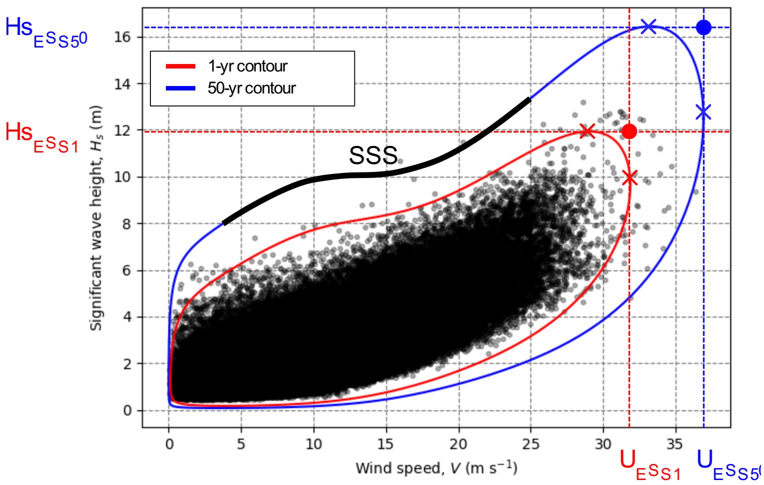

Figure 4: wind speed – significant wave height environmental contours compute with IFORM method in Virocon for the West of Barra site. 1-D exceedance values of wind speed and significant wave height in dashed lines, corresponding to ESS conditions.

2.5. Extreme Sea State

Like the SSS, IEC 61400-3 defines the conditions corresponding to an extreme sea state as *"combined global environmental actions with return periods of 1 year and 50 years*". As discussed in detail in [28], several ways of estimating these extreme conditions exist. In this work the simplest and most conservative way of estimating ESS conditions is proposed as it requires the least number of model evaluations. An alternative method is also discussed, and the interested reader is referred to [28] for further discussion on the topic.

The simplest way of determining ESS conditions is to determine the 1-D exceedance of U and H_S without considering the joint environmental distribution. In other terms the 1-D exceedance value of the random variable x_i can be expressed in terms of it's cdf F_{x_i} as:

$$x_i(r) = F_{x_i}^{-1}(1 - r) \tag{10}$$

where r is the probability of exceeding a certain return period of a certain length. For instance, the probability of exceedance for a 1-hour sea state during a 50-year period can be defined as:

$$r_{50} = 1/(50 * 365.25 * 24) \quad (11)$$

Based on what has discussed in section 2.5, $x_i(r)$ can be determined by finding the tangent lines to the IFORM environmental contour in the dimensions of interest, as shown in figure 4. By applying this procedure, we can determine the combination of U and H_S with a 1yr and 50yr recurrence period (table 3). A range of peak spectral periods consistent with IEC 61400-3 guidelines can be determined as shown by [28] as:

$$11.7\sqrt{Hs/g} \leq T_p \leq 17.2\sqrt{Hs/g} \quad (12)$$

The application of these considerations to the West of Barra data results in the conditions shown in table 3. This requires the FOWT model to be evaluated in one point only if the mean value of T_P is chosen, or in a limited set of conditions if multiple T_P are tested. Because the joint distribution of the environmental variables is considered, this method is thought to introduce a certain degree of conservatism in the design.

Table 3: ESS parameters

Recurrence	U (m/s)	H_S (m)	T_P (s)
1 year	31.9	11.93	12.9 – 19
50 years	36.92	16.42	15.1 – 22.25

Alternatively, the points of maximum 1-D exceedance can be combined with the joint probability distribution of the environmental variables. By applying this method ESS conditions result in the conditions indicated by an “X” symbol in fig. 4. While this approach does account for the joint probability of the examined met-ocean parameters, it requires double the model evaluations than the previous method.

In conclusion, the definitions of NSS for ultimate and fatigue load calculations, SSS and ESS for ultimate load calculations, fulfill all the requirements of IEC 61400-3 for Offshore wind turbine design and could potentially be used in a complete turbine certification study.

3. Conclusions

In this study current requirements in terms on metocean data for FOWT design are analysed in detail. International standards require a certain number of Sea States to be defined for a given installation site. Normal Sea State conditions for the analysis of ultimate and fatigue loading, as well as Severe Sea State and Extreme Sea State environmental conditions for the analysis of ultimate loads are deriver for an European site using open-source tools. While the tools themselves were not developed specifically in the current study, this work provides *i)* a demonstration of a complete workflow, from the sourcing of raw data to final ready-to-use metocean conditions *ii)* an extension to existing open-source tools, namely the integration of a Von Mises distribution to Virocon *iii)* a ready-to-use dataset for FOWT research. Due to the open-source nature of the presented toolchain, the guidelines and procedures detailed in this paper can be expanded or integrated into more vast data processing procedures if required. This is seen as a key point of novelty, as it allows researchers that are not accustomed to the fields of reliability or environmental contour definition, to adapt the procedure to their needs, if the data presented in this work does not fulfil them. Finally, the date presented in this work is used to define a code-to-code comparison dataset in the EU-funded H2020 project FLOATECH.

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Data Availability The tools developed to process the data as well as the post processed data are available at https://doi.org/10.5281/zenodo.6972014

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