Modified environmental contour method to determine the long-term extreme responses of a semi-submersible wind turbine

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ABSTRACT

In this paper, the modified environmental contour method (MECM) for long-term extreme response prediction are explained and tested for the OC4 DeepCwind 5-MW semi-submersible wind turbine with the environmental conditions at two different locations in the North Sea. MECM is a simplified method that is based on the original environmental contour method (ECM) but with modification to be better suited for offshore wind turbines or other systems in which active survival strategies are applied to reduce the system responses in extreme conditions. ECM is based on the short-term extreme probability distribution of an environmental conditions selected on the environmental contour with the same return period as the long-term extreme response (e.g. 50-year environmental contour for 50-year extreme responses). The MECM includes an additional contour within the operational region of the wind turbine and selects the design point on both contours that gives the largest response. The results of the MECM are compared with those of the full long-term analysis (FLTA), which are accurate but inefficient. It is found that the MECM is more computationally efficient than FLTA and significantly improves the accuracy of the prediction compared to ECM and its results are very close to the FLTA predictions.

Keywords: environmental contour method, inverse first order reliability method, semi-submersible wind turbines, long-term extreme response, statistical extrapolation

1 Introduction

Prediction of long-term extreme responses is very important for design of offshore wind turbines and their support structures. The accurate method is the full long-term analysis which combines the response distributions of all short-term environmental conditions according to their probability of occurrence. It has been used in many studies to determine the long-term extreme responses for wind turbines. Its disadvantage is that it requires simulations of a large number of environmental conditions and is thus not efficient. In an earlier study [1], a simplified long-term analysis for marine structures subjected

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to wave loads was applied and found that good accuracy can be achieved as long as important environmental conditions are included. A more efficient method applied for wave-induced responses is the environmental contour method (ECM) [2, 3], which uses a few conditions on the environmental contour and determine the relevant extreme response by taking the largest of the short-term maximas corresponding to a high fractile (e.g. 70% to 90%). The method has been widely used in design for offshore structures subjected to wave loading with good accuracy and is thus also used for the analysis offshore wind turbine [4, 5]. However, the results of the conventional ECM for some responses of wind turbines has been found to be largely under-predicting due to the inherent nature of the operation of wind turbines as showed in earlier studies [6–10]. Wind turbines either operate or park depending whether the hub-height wind speed is within the operational range (between cut-in and cut-out wind speed). Some of the responses are quite different when under operation or parked condition. This implies a discontinuity in the relation between extreme responses and the environmental parameters (e.g. wind speed). As a result, ECM cannot perform very well for wind turbines. Similarly, for other structures with different modes of operation and survival mechanism that changes the responses based on environmental conditions, ECM may not perform well either. For such systems, modified method was proposed and tested for a bottom-fixed offshore wind turbines with good accuracy.

In this paper, the modified environmental contour method (MECM) originally purposed in [10] is explained in detail and is applied for a floating wind turbine with statistics for environmental conditions from two different sites in the North Sea are. The predictions of ECM/MECM are compared with the full long-term analysis to determine their accuracy.

2 Full long-term analysis by short-term extremes

The full long-term analysis is an accurate method to determine the long-term extreme responses. It has been applied for extreme load prediction for wind turbines in many studies [11]. In this study, the long-term analysis is done by integrating the product of the cumulative distribution function (CDF) of the short-term extremes (maximum response of a short-term process) and the probability of occurrence of its environmental condition. Other approaches such as peak-over-threshold (POT) or up-crossing rate can also be used instead of short-term extremes. It has been found by [12, 13] that POT or up-crossing rate performs better than using extremes. Since the main focus is to investigate the performance ECM/MECM compared to the full long-term analysis, the selection of the short-term analysis method is irrelevant in this study as they do not change the applicability of ECM/MECM. Full long-term analysis is usually described by Equation 1 if one-hour extreme is used. The reference period is set to be one-hour to be consistent with the environmental data [14] used in this study as mentioned in Section 4. $F_X^{LT}(\xi)$ and $F_X^{ST}(\xi|U_w,H_s,T_p)$ are the long-term or short-term CDF respectively, which is the probability that X will have a value less than or equal to ξ. $f_{U_w,H_s,T_p}(u,h,t)$ is the probability density function of environmental condition ($U_w = u$, $H_s = h$, $T_p = t$). N is the return period in years.

$$F_X^{LT}(\xi) = \iiint F_X^{ST}(\xi|U_w,H_s,T_p)\, f_{U_w,H_s,T_p}(u,h,t)\,dudhdt = 1 - 1/(N * 365.25 * 24) \tag{1}$$

Equation 1 can also be re-written as Equation 2, where $Q_X(\xi) = 1 - F_X(\xi)$ is either the long-term or short-term exceedance probability, i.e. the probability of the value of X to be larger than ξ.

$$Q_X^{LT}(\xi) = \iiint Q_X^{ST}(\xi)\, f_{U_w,H_s,T_p}(u,h,t)\,dudhdt = 1/(N * 365.25 * 24) \tag{2}$$

However, it was discussed in [15], that Equation 1 is not an ergodic average and should be modified as Equation 3. The resulting differences between Equation 1 and 3 is found to be negligible for this study.

$$F_X^{LT}(\xi) = \exp\left(\iiint \ln F_X^{ST}(\xi)\, f_{U_w,H_s,T_p}(u,h,t)\,dudhdt\right) = 1 - 1/(N * 365.25 * 24) \tag{3}$$

3 Inverse first-order reliability method, environmental contour method and its modification

According to the discussion of Section 2, the full long-term analysis is time consuming and is not efficient because it requires many environmental conditions to simulate as shown in Equation 1. Most of the environmental conditions are not contributing to the prediction of the extreme responses. Generally, only a small number of them are important. Therefore, there are simpler alternative methods such as IFORM and ECM. It should be noted that the examples in this section have only mean wind speed at hub-height and significant wave height as environmental parameters for illustration purpose. The spectral peak period is ignored to keep the illustrations 3-dimensional (i.e. response, wind speed, significant wave height). It is considered for the results presented in Section 5.

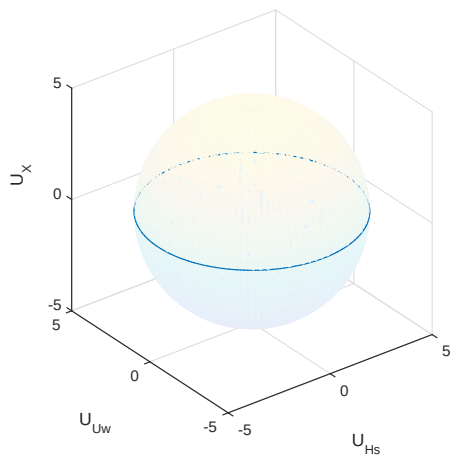

Fig. 1. The 50-year contour of the short-term extreme response, mean wind speeds and significant wave heights in the 3-D U-space. Peak spectral period is set to be the median value.

3.1 First order reliability method (FORM) and IFORM

The FORM is generally used in for the study of structural reliability problem but can also be used for extreme value predictions. The FORM and IFORM are based on the concept of standardized normal space (U-space), which is transformed from the physical space (X-space). The physical space involves response parameter (X), and environmental parameters (e.g. mean wind speed (U_W), significant wave height (H_S), spectral peak period (T_P), etc.). For each point in the physical space, the set (X, U_W, H_S, T_P) corresponds to a joint probability distribution. By Rosenblatt transformation [16], the CDF can be transformed to a space described as the U-space. Hence each point in X-space (X, U_W, H_S, T_P) corresponds to a (U_X, U_{U_W}, U_{H_S}, U_{T_P}) in U-space. Their relation can be described by Equation 4, where Φ^{-1} represents the inverse of the CDF of normal distribution.

$$\begin{aligned} U_{U_W} &= \Phi^{-1}(F(U_W)) \\ U_{H_S} &= \Phi^{-1}(F(H_S|U_W)) \\ U_{T_P} &= \Phi^{-1}(F(T_P|U_W,H_S)) \\ U_X &= \Phi^{-1}(F(X|U_W,H_S,T_P)) \end{aligned} \tag{4}$$

In the U-space, the distance to the origin is $U = (U_X^2 + U_{T_P}^2 + U_{H_S}^2 + U_{U_W}^2)^{0.5}$. $1-\Phi(U)$ is the exceedance probability of the combination of (U_X, U_{U_W}, U_{H_S}, U_{T_P}). For a return period of 50-year, with short-term process being 1 hours, $U = \Phi^{-1}(1-1/(50*365*24))$.

The FORM is a simplified method for calculating the exceedance or failure probability with a given response level. It approximates the failure curve or surface as a line or plane in the U-space. Then distance from the plane in U-space to the origin is used to calculate the failure probability. For extreme prediction, the plane is chosen such that the distance corresponds to the desired return period. Then the maximum response value of that plane is the predicted long-term extreme.

The IFORM is the inverse process of FORM. Instead of creating a plane of a known distance to origin, the IFORM creates a sphere in U-space with the distance as its radius. This sphere corresponds to the desired return period. By transforming the sphere into X-space, the largest value of the new surface in X-space is the predicted long-term extreme. It is better suited for extreme prediction since the return period is already given, i.e. radius of the sphere is known. It is easier to transform the U-space sphere to X-space rather than transforming the X-space plane to U-space as done by FORM.

On the transformed surface in X-space, the largest extreme response is considered as the long-term extreme of the given return period. Two examples shown by Figure 2 and 3 are the 50-year sphere shown in Figure 1 transformed to X-space. The largest extreme of the transformed contour is the 50-year extreme predicted by IFORM.

To summarize the IFORM, Equation 5 shows the main idea, which is to use a short-term extreme to approximate the long-term extreme. N is the return period in year. It should be noted that here the length of the short-term process is defined as 1-hour.

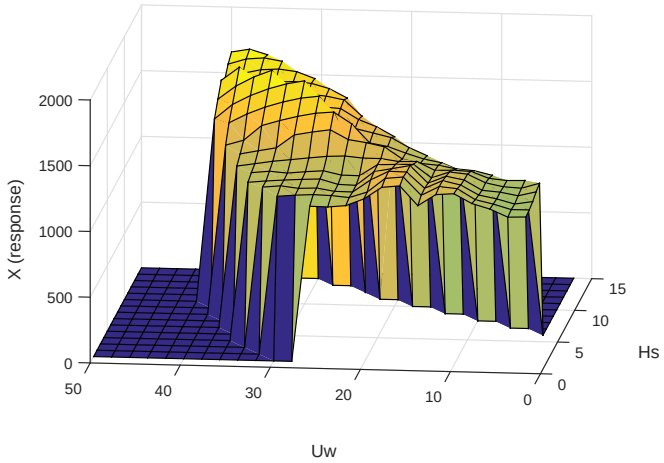

Fig. 2. The upper half of the transformed 50-year contour in the X-space for the IFORM. The response is the 1-hour extreme tension of mooring line 1. Peak spectral period is set to be the median value.

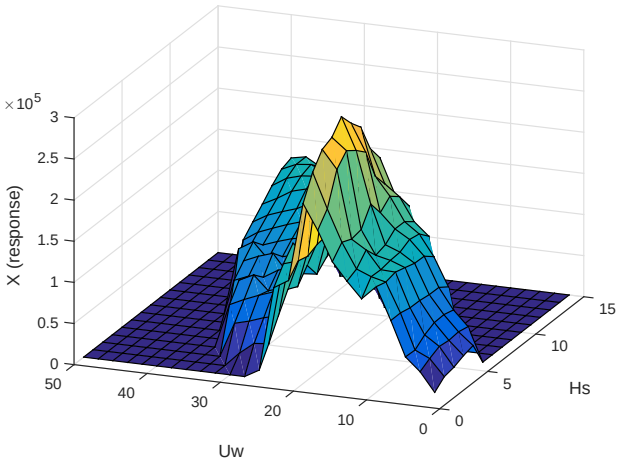

Fig. 3. The upper half of the transformed 50-year contour in the X-space for the IFORM. The response is the 1-hour extreme shear force at the bottom of the wind turbine tower. T_P is set to be the median value.

$$
\begin{aligned}
U &= \Phi^{-1}(1-1/(N*365.25*24)) \\
U_X &= \sqrt{U^2 - U_{u_{IFORM}}^2 - U_{h_{IFORM}}^2 - U_{t_{IFORM}}^2} \\
\xi &= F_X^{LT^{-1}}(1-1/(N*365.25*24)) \approx F_X^{ST^{-1}}(\Phi(U_X)|u_{IFORM},h_{IFORM},t_{IFORM})
\end{aligned}
\tag{5}
$$

By using IFORM, only the environmental condition within the contour of the corresponding return period needs to be considered, which is much fewer as compared to the full long-term analysis. IFORM is especially good when the number of environmental parameters is small, e.g. when only one parameters such as wind speed is considered, because the required environmental conditions are less when there are less parameters. The effectiveness of IFORM has been studied for wind turbine applications [7, 17]. It is also described in both IEC 61400-1 [18] and IEC 61400-3 [19] for land-based and offshore wind turbines respectively. However, the IFORM in IEC 61400-3 for offshore wind turbines is in fact ECM which is explained in Section 3.2 as the ECM only considers the environmental condition parameters as variables in the U-space and X-space contours and does not include the responses.

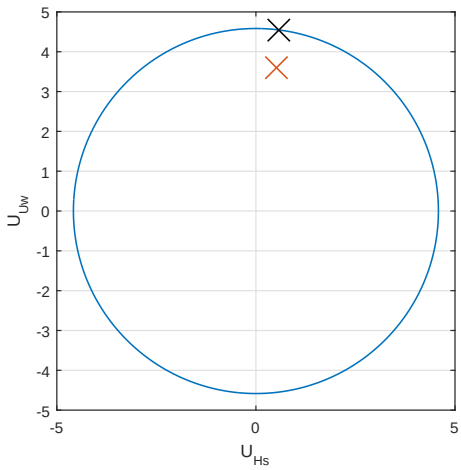

Fig. 4. The 50-year environmental contour of U_W and H_S and the cases used by IFORM and ECM. The red cross is the case used by the IFORM (Figure 4) projected to the 2-D plane. The black cross is the case used by the ECM. The response is the tension of mooring line 1. T_P is set to be the median value.

3.2 ECM

The ECM has been widely used in the offshore industry to determine long-term extreme responses. In theory, it is a further simplified method based on the IFORM. It ignores the variability of the extreme response, i.e. the vertical axis of the response in U-space in Figure 1 to 3. Thus, one dimension is reduced (e.g. 3-D for IFORM reduces to 2-D for ECM) compared to IFORM. This new contour without the response can be defined as the environmental contour since it only includes environmental parameters. Then only the cases located on the environmental contour are checked and the largest extreme response among them is the long-term result.

To compensate for the omission of the variability, empirical fractiles higher than 50% are often used instead. The value is usually between 70% to 90% [3, 20]. ECM further reduces the number of environmental conditions compared to IFORM since only the ones on the contour are to be checked. The idea of ECM can be summarized by Equation 6, where p is an empirical value greater than 50%.

$$\xi = F^{LT^{-1}}(1 - 1/(N * 365.25 * 24)) \approx F^{ST^{-1}}(\Phi(U_X)|u_{IFORM}, h_{IFORM}, t_{IFORM}) \approx F^{ST^{-1}}(p|u_{ECM}, h_{ECM}, t_{ECM}) \quad (6)$$

The method works well if the case found by IFORM is close to the environmental contour. A good example is shown in Figure 4, which compares the environmental condition used by IFORM and ECM. In this case, the two environmental conditions are very close. By using a slightly higher fracitle level, the ECM predicts the same long-term extreme. For the true design point to be close to the environmental contour, it generally requires that the response to be monotonically related to the important environmental parameters. In the example shown by Figure 4, the response is increasing with the increase of wind speed and significant wave height as shown by Figures 5 and 6.

However, for some responses that have design points not close to the environmental contour, the ECM does not perform well. This circumstance is often caused by the responses not being monotonically related to the important environmental parameters or have discontinuity between environmental parameters and response. The wind turbine is either operating or parked depending whether the wind speed is within or outside the operational range. Some responses are higher when wind turbine is operating and may have the most important environmental condition (found by IFORM) located within the operational region and far away from the 50-year contour. An example is shown in Figure 7. It can be observed that extreme response is higher within the operational range and decrease abruptly when wind speed exceeds the cut-out value. Similar behavior can be seen in the relationship between response and significant wave height as shown in Figure 8 because the significant wave height is positively correlated with wind speed. Figure 9 demonstrates how the ECM perform for this example. The environmental condition selected by ECM is located near the edge of the operational range (dashed line) because the response is higher when wind turbine is operating. It is thus far away from the one found by IFORM. For this response, the ECM will not provide a good long-term extreme prediction.

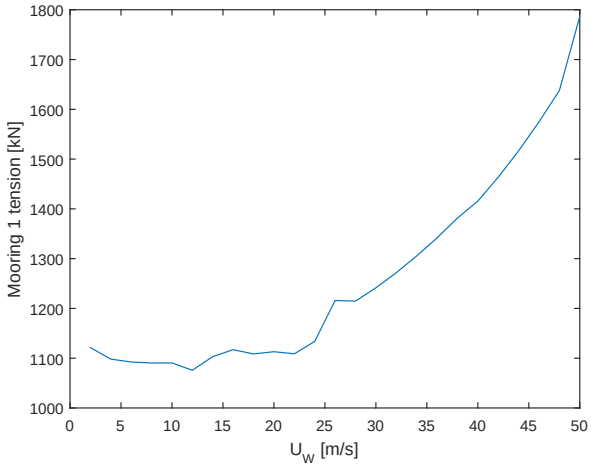

Fig. 5. Expected 1-hour extreme tension of mooring line 1 vs. hub-height mean wind speed. The extreme response corresponds to the labeled wind speed and its corresponding most probable sea state.

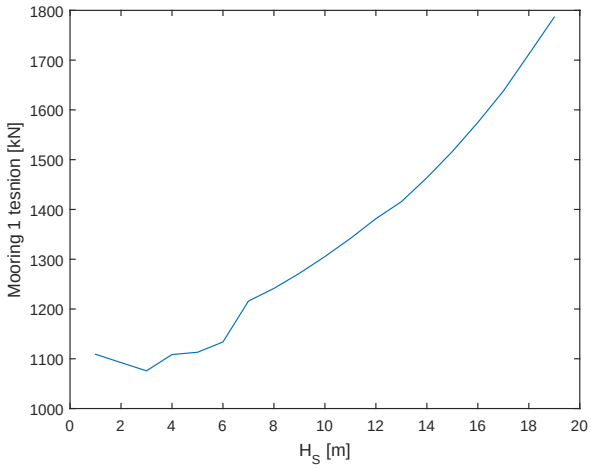

Fig. 6. Expected 1-hour extreme tension of mooring line 1 vs. significant wave height. The extreme response corresponds to the labeled significant wave height and its corresponding most probable wind speed and spectral peak period.

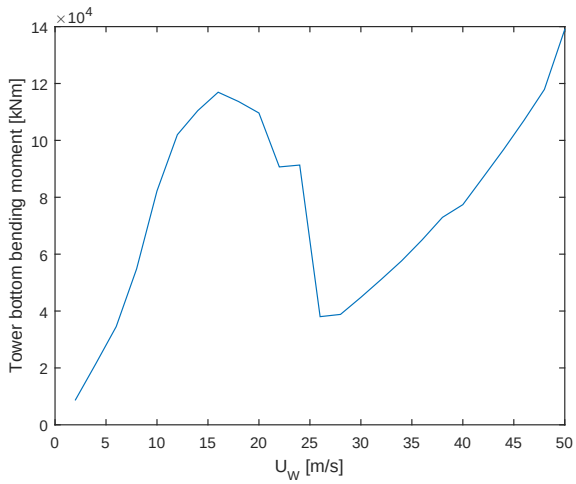

Fig. 7. Expected 1-hour extreme bending moment at tower bottom vs. hub-height mean wind speed. The extreme response corresponds to the labeled wind speed and its corresponding most probable sea state.

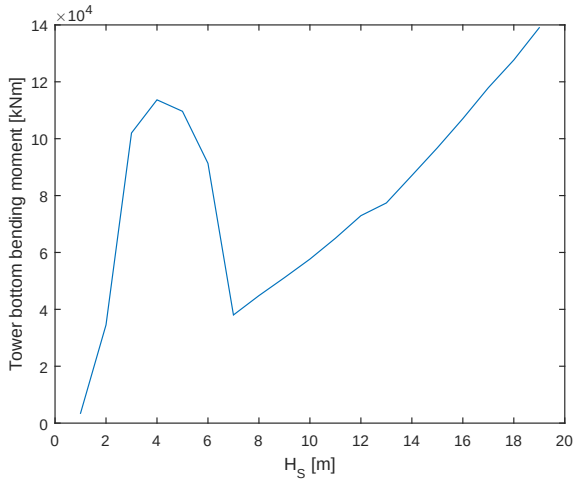

Fig. 8. Expected 1-hour extreme bending moment at tower bottom vs. significant wave height. The extreme response corresponds to the labeled significant wave height and its corresponding most probable wind speed and spectral peak period.

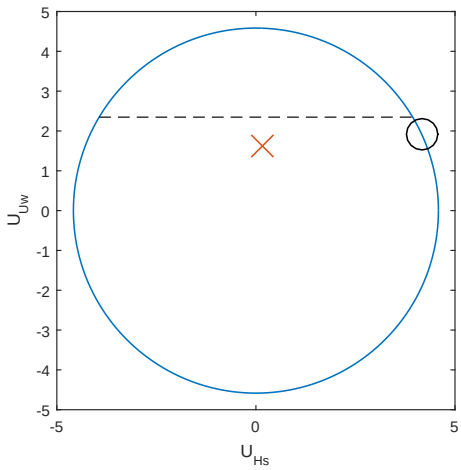

Fig. 9. The 50-year environmental contour of U_W and H_S and the cases used by IFORM and ECM. The red cross is the case used by the IFORM (Figure 4) projected to the 2-D plane. The black circle is the case used by the ECM. The dashed line separates the operational region and parking region, above which the wind turbine is parked. The response is the bending moment at the bottom of the wind turbine tower.

3.3 Modified environmental contour method (MECM)

In Section 3.2, it is shown that ECM does not work well in all situations. However, with a modification, the method can still be used with good accuracy. For the same example of Figure 3 and 9, instead of using the environmental contour of 50-year return period, a new contour with its maximum wind speed within the cut-out wind speed can be used, as shown in Figure 10. The environmental condition found on the new contour is very close to the IFORM one.

The reason for adding another contour at the cut-out wind speed is to avoid the discontinuity of the response. The wind turbine is operational below cut-out wind speed and is parked above it. Thus, the response is continuous within the new contour. By adding additional environmental contour within each system status region (e.g. operational/parking for wind turbines), the ECM can still be applied. We can define the ECM that considers additional contours as the MECM. While MECM is more complicated than the original ECM. Compared to the complete IFORM, the MECM is a simplification as it considers environmental conditions on multiple contours rather than the entire area/space within the return period.

In most cases, the location of the true important environmental condition is unknown. Thus it is necessary to check different contours for each region (e.g. operational and parking) to ensure at least one of them is close to the true design point. If enough contours are tested that cover the whole area within the 50-year contour, the fractile level will be 0.5 and the MECM will be equivalent to IFORM. For the inner contours, their prediction need extrapolation to achieve the same return period as shown in Equation 7, where $p_1, p_2, \cdots, p$ are empirical fractile that are larger than 0.5. The short-term extreme CDF corresponding to a 50-year return period used in Equation 7 is calculated as shown by Equation 8, where M is the return

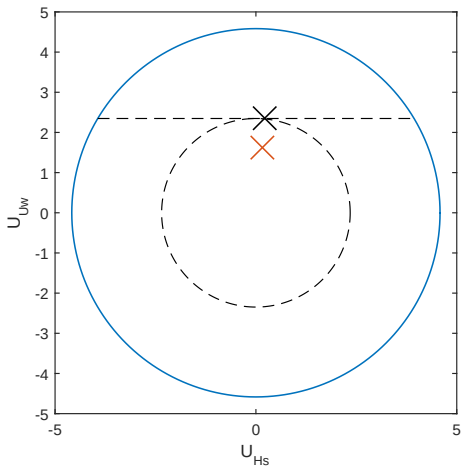

Fig. 10. Two environmental contours and environmental condition found by IFORM and MECM. The MECM uses the inner contour instead of the 50-year one. The two environmental conditions found by IFORM and ECM are close. The response is the bending moment at the bottom of the wind turbine tower.

period of the environmental condition $(U_w = u_M, H_s = h_M, T_p = t_M)$. The new CDF is still Gubmel distribution. Figure 11 shows an example of the short-term PDF of tower bottom bending moment and its 50-year PDF.

$$\begin{aligned}
\xi_1 &= F^{ST(50-yr)^{-1}}_{X|U_w,H_s,T_p}(p_1|u_{contour1},h_{contour1},t_{contour1}) \\
\xi_2 &= F^{ST(50-yr)^{-1}}_{X|U_w,H_s,T_p}(p_2|u_{contour2},h_{contour2},t_{contour2}) \\
&\vdots \\
\xi_{ECM} &= F^{ST(ECM)^{-1}}_{X|U_w,H_s,T_p}(p|u_{ECM},h_{ECM},t_{ECM}) \\
\xi &\approx max[\xi_1,\xi_2,\ldots,\xi_{ECM}]
\end{aligned} \tag{7}$$

$$F^{ST(50-yr)}_{X|U_w,H_s,T_p}(\xi) = F^{ST}_{X|U_w,H_s,T_p}(\xi|u_M,h_M,t_M)^{50/M} \tag{8}$$

The largest predicted value of all the environmental contours is the final result of MECM for the long-term extreme. If the contours are appropriately selected, the results should be close to the one found by the full long-term analysis. Although MECM is more complicated than ECM by introducing more environmental contours, its results will be more reliable, especially for wind turbines with two modes of operation. Compared to the FLTA or IFORM, the MECM is still a much simpler alternative.

3.4 Fractile and multiplication factor for ECM and MECM

For the ECM and MECM, higher fractile are often used to compensate for the omission of the response variability. However, using fractile will require effort of fitting the extreme distribution. When fractile level is high, more simulations are required to ensure good fit of the data. This is especially true for MECM as the equivalent fractile after extrapolation from 0.5 could be as large as 0.9998 for site 14 in this study. Thus, it was suggested to use a multiplication factor on the expected maximums instead of the fractiles because the expected maximum value is easy to calculate and require much fewer simulations. In ref. [21], it was suggested that 1.2 time of the expected extreme value gives good prediction for long-term extreme for a wave energy converter. Multiplication factor is also used in the long-term extreme study of a combined wind and wave energy concept called the SparTorus-Combination (STC) system where a spar wind turbine is combined with a torus-type wave energy converter [22].

The probability distribution used for short-term extreme responses is Gumbel distribution in this study. It is commonly used for fitting maximum values/extreme data. Gumbel distribution is defined by two parameters, μ and β. A fractile level of p corresponds to the extreme value shown in Equation 9.

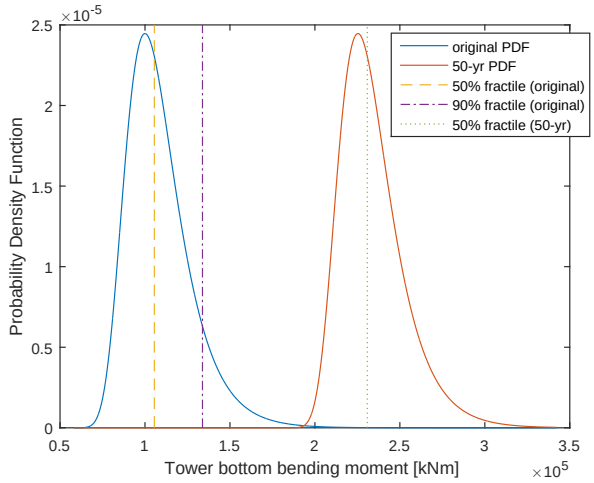

Fig. 11. Original and 50-year short-term probability density functions of tower bottom bending moment. Dashed lines corresponds to different fractile levels.

$$X_p = \mu - \beta * \ln(-\ln(p)) \tag{9}$$

The expected value for Gumbel distribution is shown in Equation 10. The value of γ is the Euler-Mascheroni constant, which is approximately 0.5772.

$$\bar{X} = \mu + \beta * \gamma \tag{10}$$

If a multiplication factor K is used, to achieve $K * \bar{X} = X_p$, the K can be described in Equation 11. Hence, K depends on μ/β in addition to the fractile level. Figure shows how value of K varies with different combinations of F and μ/β.

$$K = \frac{\mu/\beta - \ln(-\ln(p))}{\mu/\beta + \gamma} \tag{11}$$

A commonly used fractile level is 90%, which can be substituted to p in Equation 11. The value of μ/β is different for each response. In this study, it is found that μ/β is generally larger than 10 for most cases. From Figure 12, it can be seen that 1.2 should be convertive for fractile value of 90% assuming μ/β is larger than 10.

For MECM, due to the extrapolation, the multiplication factor will be based on the new probability function that is corresponding to the 50-year return period. The new probability distribution is still Gumbel but with a different value of $\mu_{ext.}$ as shown in Equation 12, where μ and β are the parameters of the original short-term extreme response distribution and N is the return period of the inner environmental contour. Thus, the expected value of the extrapolated distribution is as Equation 13. For a 50% fractile, the multiplication factor only needs to be 1 with the new extrapolated expected value as the expected value is already greater than the median for the Gumbel distribution. However, the extrapolated expected value is dependent on the environmental condition of different sites because the return period N corresponding to the cut-out wind speed is different for each site. If assuming μ/β equals 10, then the extrapolated 50-year expected extreme is approximately 1.8 times and 1.65 times the original expected extreme value for site 14 and 15 respectively.

$$\mu_{ext.} = \mu + \beta * \ln(50/N) \tag{12}$$

$$\bar{X}_{ext.} = \mu_{ext.} + \beta * \gamma = \mu + \beta(\ln(50/N) + \gamma) \tag{13}$$

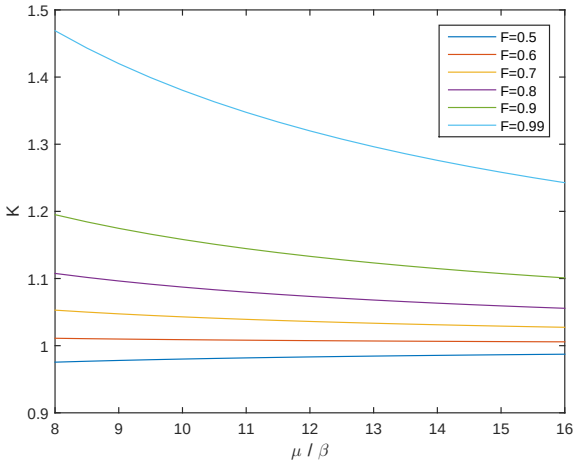

Fig. 12. The multiplication factor K vs μ/β for different fractile level for ECM.

Table 1. The environmental conditions simulated for the FLTA

		min.	max.	bin
U_w	$[m/s]$	2	60	2
H_s	$[m]$	1	20	1
T_p	$[s]$	2	24	2

4 Application of ECM/MECM to the OC4 semi-submersible wind turbine

In previous study, ECM/MECM has been applied to a bottom fixed wind turbine [10]. It is found that ECM can perform well for wave-load dominated responses while MECM is necessary for wind-load dominated responses. In this study, the goal is to evaluate the performance of ECM/MECM for floating wind turbine concepts. Thus, the aero-hydro-servo-elastic model used is based on the OC4 DeepCwind semi-submersible [23, 24] with the NREL 5-MW wind turbine [25]. The DeepCwind semi-submersible consists of a main column in the middle and three offsets columns. The columns are connected by braces and pontoons. The tower of the wind turbine is mounted on the middle column. The wind turbine has hub-height of 90 meter above still water level and has draft of 20 meter. An illustration of the model is shown in Figure 13. Figures 14 and 15 show the top and side view of the semi-submersible, respectively, with labels for each member of the structure (column, braces, pontoons, etc.).

The system is modeled by SIMO/RIFLEX+Aerodyn (SRA) [26–28] developed by MARINTEK and Centre for Ships and Ocean Structures (CeSOS) in Trondheim, Norway. SIMO is used to model the hydrodynamic loads on rigid-body floating structures in the time-domain. The time-domain hydrodynamic loads is based on frequency-domain loads that are calculated using the panel method (potential theory). AeroDyn [28] reads a turbulent wind field generated by TurbSim and calculates the aerodynamic loads on the blades based on Blade Element Momentum theory. RIFLEX is a finite element solver modeling the braces mooring lines, tower, shaft and blades of the wind turbine by beam elements. SRA has been verified with different type of wind turbines [29].

In this study, the hydrodynamic load includes first-order wave loads for large columns with potential theory and viscous drag and hydrodynamic loads on the braces and mooring lines based on Morison formula. The aerodynamic loads on the wind turbine is modeled by Aerodyn. The model is fully coupled. The irregular wave are modelled by a three-parameter JONSWAP spectrum with a peakedness parameter of 3.3. Due to the lack of statistical information, the turbulence intensity is assumed to be constant (0.15) for all wind speeds.

The environmental parameters included are mean wind speed at hub height, significant wave height and spectral peak period. Their ranges and bin sizes are shown in Table 1.

The environmental data used are based on sites 14 and 15 described by Li et al. [14]. Site 14 is located close to the shore of Norway with distance of 30 km. Site 15 is located at central North Sea. The basic information of the two sites are listed in Table 2. The 50-year and cut-out wind speed environmental contour of site 14 and 15 are shown in Figure 16 to 19. Site 14 is better suited for the OC4 DeepCwind wind turbine due to its water depth being close to the design value. The environmental condition of site 15 is still included for comparison purposes because environmental conditions also have a large effect on the extreme response prediction. By including two different sites, it can be checked whether ECM/MECM is site specific

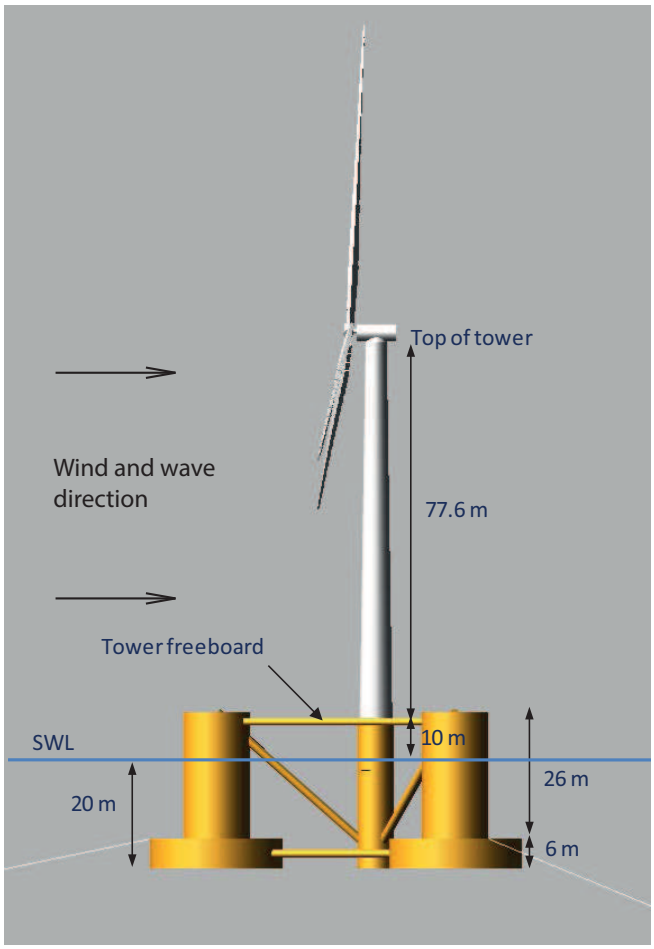

Fig. 13. OC4 DeepCwind semi-submersible wind turbine. [23, 24]

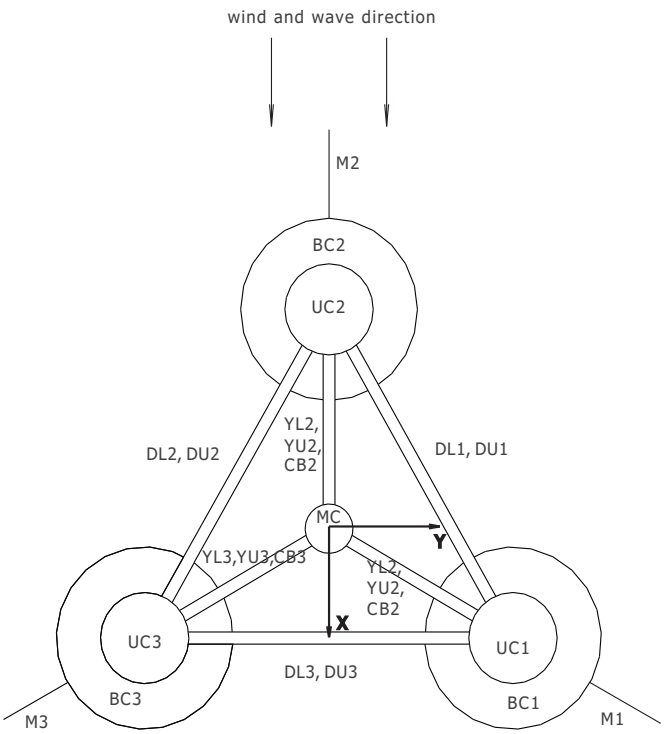

Fig. 14. OC4 DeepCwind semi-submersible wind turbine (top view).

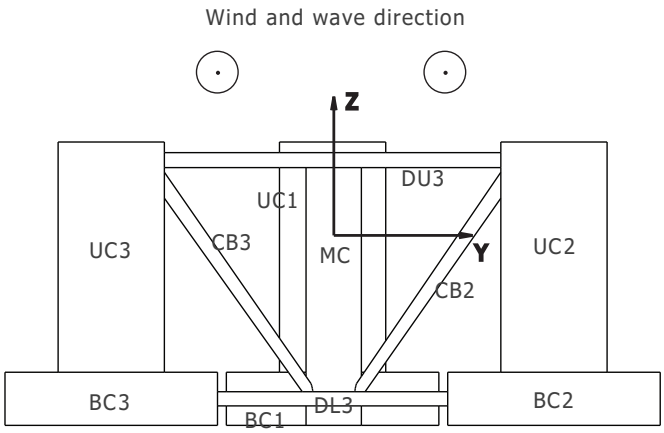

Fig. 15. OC4 DeepCwind semi-submersible wind turbine (side view).

Table 2. Basic information about the environmental condition of site 14 and 15. The water depth is assumed to be 200 meter for both site to be consistent with the design value of the wind turbine. The mean wind speed corresponds to hub-height.

site	50-year U_W [m/s]	50-year H_S [m]	Mean T_P [s]	Location
14	41.4	15.6	11.06	Northern North Sea
15	33.9	9.5	6.93	Central North Sea

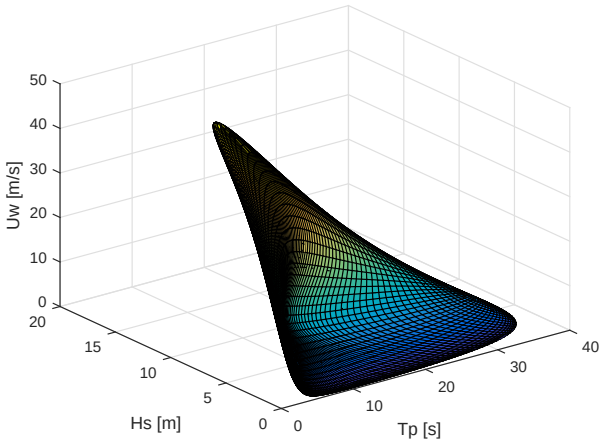

Fig. 16. The 50-year environmental contour surface for site 14. It should be noted that the hub-height wind speed is used here.

or universal. It should be noted that the water depth used in this study is 200 meter, and only the statistics of the wind and wave parameters of the two sites are used. The direction of wind and wave is assumed to be aligned. Due to the lack of site specific information, the turbulence intensity of the wind is assumed to be 0.15 and is the same for all the wind speeds.

The responses considered are the tension of mooring lines (M1 and M2), axial loads of the braces of the semi-submersible (CB1, CB2, DL1, DL3, DU1, DU3, YL1, YL2, YU1 and YU2) as well as the shear force and bending moment at the bottom of the tower. The shear force of the tower is in the direction of the x-axis, which is aligned with wind and wave direction. The bending moment is in the direction of the y-axis, which is perpendicular to wind and wave direction. Figures 14 and 15 show the top and side view of the semi-submersible and illustrate the coordinate system as well as the designation of each member.

For each environmental condition, fifteen 1-hour simulations are performed for short-term analysis and the maximum responses of each simulation are used to fit the short-term extreme distributions.

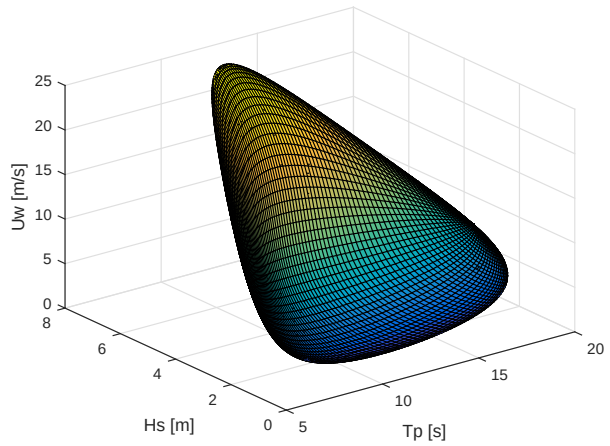

Fig. 17. The environmental contour surface with maximum wind speed of $25m/s$ (cut-out wind speed) for site 14. It should be noted that the hub-height wind speed is used here.

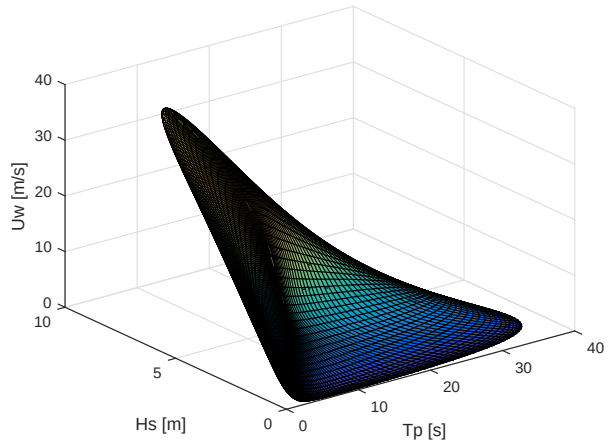

Fig. 18. The 50-year environmental contour surface for site 15. It should be noted that the hub-height wind speed is used here.

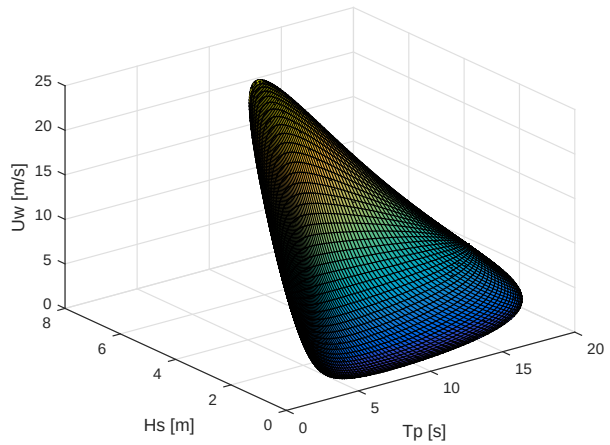

Fig. 19. The environmental contour surface corresponding to the maximum wind speed of $25m/s$ (cut-out wind speed) for site 15. It should be noted that the hub-height wind speed is used here.

5 Results and discussion

The results of ECM, MECM are compared to that of the FLTA. It should be noted that three environmental parameters U_W, H_S and T_P are used instead of just the first two as in Section 3. Thus, the environmental contour is 3-D surface instead of 2-D line as in Section 3.

5.1 Full long-term analysis (FLTA)

The results of full long-term analysis are used as references in determining the effectiveness of the environmental contour method and its modification. Based on Table 1, there are 7200 environmental conditions to be considered, each requiring multiple simulations with different random seeds as well. It will be impractical and inefficient to include every environmental conditions. So only environmental conditions with a joint probability density function greater than $8*10^{-11}$ will be considered. This criteria is conservative and ensures that all the important conditions are still preserved.

The probability criteria $8*10^{-11}$ is based on the average exceedance probability contribution described in Equation 2 of each environmental condition in Table 1. Discretizing Equation 2, it becomes Equation 14.

$$Q_X^{LT}(\xi) \approx \sum Q_X^{ST}(\xi) f_{U_w,H_s,T_p}(u,h,t)\Delta u \Delta h \Delta t = 1/(N*365.25*24) \tag{14}$$

The important environmental conditions are those with high value of contribution of exceedance probability, which is the integrand in Equation 14 as shown in Equation 15.

$$Q_X^{int}(\xi,u,h,t) = Q_{X|U_w,H_s,T_p}^{ST}(\xi|u,h,t) f_{U_w,H_s,T_p}(u,h,t) \tag{15}$$

Since $Q_{X|U_w,H_s,T_p}^{ST} < 1$, the integrand $Q_X^{int}(\xi,u,h,t) < f_{U_w,H_s,T_p}(u,h,t)$. So a conservative value of C can be set such that if $Q_X^{int}(\xi,u,h,t) < f_{U_w,H_s,T_p}(u,h,t) < C$, the environmental condition (u,h,t) can be ignored.

Deriving from Equation 14, the average value for the integrand can be calculated as

$$\bar{Q}_X^{int}(\xi,u,h,t) = 1/(N*365.25*24*S) \tag{16}$$

where S is the range of the environmental parameters calculated as $S = \sum \Delta u \Delta h \Delta t$. The value of the integrand of the important environmental conditions are generally much larger than the average value as the long-term extreme is usually determined only by a few environmental conditions. If S is sufficiently large, the average integrand value in Equation 16 is a conservative value that can be used as a threshold to eliminate the unimportant environmental conditions. Only conditions that satisfy Equation 17 are preserved.

$$f_{U_w,H_s,T_p}(u,h,t) > 1/(N*365.25*24*S) \tag{17}$$

Here $N = 50$ and S is calculated based on Tabel 1. The calculated value of the threshold is around $8*10^{-11}$, which is then used in this study. The number of environmental conditions to be considered is reduced from 7200 to 1530 for site 14 and 728 for site 15. The environmental conditions selected for site 14 and 15 are shown in Figure 20 and 21 respectively. For each environmental condition, 15 simulations are performed to provide 15 sets of one-hour extreme responses.

The results of the full long-term analysis are included in Section 5.2 for comparisons with the results for the ECM and MECM.

5.2 Results of ECM and MECM compared with FLTA

In this section, the results of the ECM and MECM are compared with those of FLTA. The goal of ECM and MECM is to find the long-term extreme to be as close as the FLTA as possible. The results of site 14 and 15 are both included. For MECM, in addition to the contour corresponding to the cut-out wind speed, another contour corresponding to the rated wind speed of the wind turbine is also tested because thrust is largest at rated wind speed and decreases when wind speed exceeding it. The environmental conditions for ECM/MECM are selected on environmental contours of 50-year return period, maximum wind speed of cut-out and rated wind speed as shown in Table 3. For example, Figures 22 and 23 show environmental conditions on the 50-year and cut-out wind speed environmental contours of site 14 respectively.

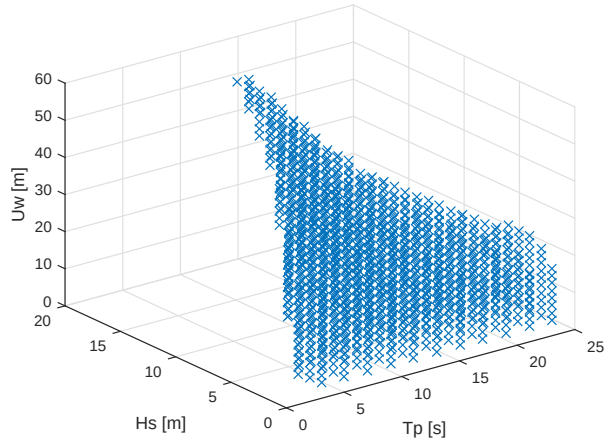

Fig. 20. Environmental conditions for FLTA for site 14.

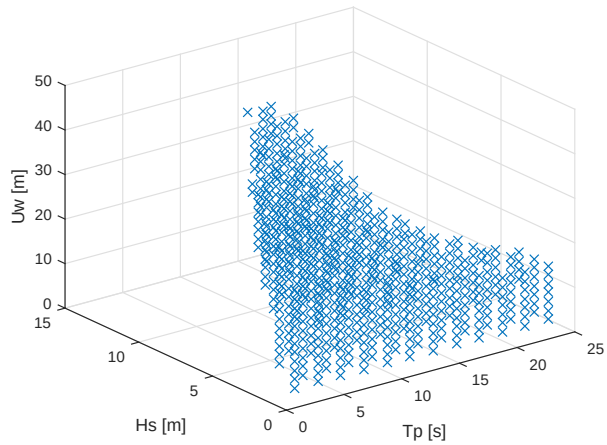

Fig. 21. Environmental conditions for FLTA for site 15.

Table 3. The environmental contours considered by ECM and MECM. “50-yr”, “cut-out”, and “rated” represents the contours corresponding to 50-year, cut-out wind speed and rated wind speed respectively.

ECM	50-year		
MECM	50-year	cut-out	rated

5.2.1 ECM and MECM referred to fractile

Figures 24 to 27 show the difference of ECM, MECM and FLTA with 90% and 50% fractile levels being used for 50-year and cut-out wind speed environmental contour, respectively. The response examined are the tension of mooring line 1 and 2, the tension (+) and compression (-) axial force of the braces, as well as the shear and bending moment of the wind turbine tower at its bottom. The name and location of the braces are illustrated in Figure 14 and 15.

For site 14, based on Figure 24, ECM (with 90% fractile) works well for some of the responses including mooring line 1 axial force (M1) and most of the responses for braces because the fractile levels for these responses are below 90%. However, ECM under-predicts the responses of tower (bending moment/shearing force), CB1 (tension), YU1 (compression), YU2 (tension) and mooring line 2 (tension). The reason is that these responses are more affected by operation/parking of the wind turbine which is shown in Figure 28. As discussed in Section 3, the ECM cannot perform well because these responses have peaks in the operational wind speeds. Especially, the expected extreme responses of YU2 tension and tower are higher in operational range than at the 50-yr level. Thus, MECM using the extreme responses on the environmental contour corresponding the cut-out wind speed is much better than ECM for YU2 tension and tower responses and its fractile levels are

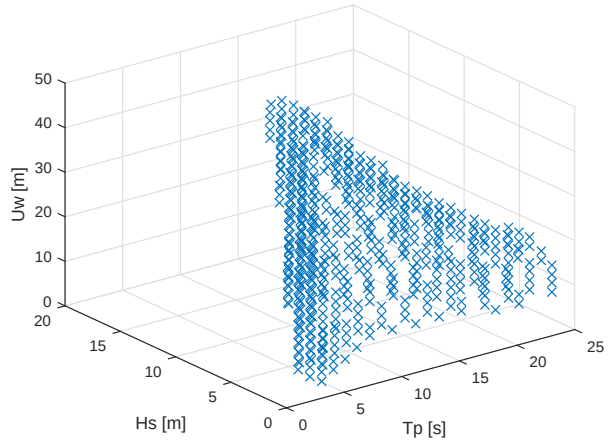

Fig. 22. Environmental conditions selected on the 50-year contour (Figure 1) for ECM/MECM for site 14.

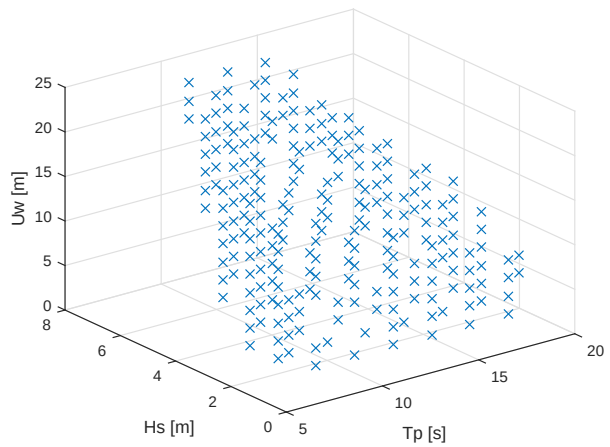

Fig. 23. Environmental conditions selected on environmental contour corresponding to a maximum wind speed of $25m/s$ (cut-out wind speed) for MECM for site 14.

much lower. By implementing the MECM (50% with cut-out wind speed contour), the predicted long-term extreme is greatly improved for these responses that ECM under-estimates. Figure 24 shows the percentage difference between the results of ECM (90% fractile of 50-year contour only) and FLTA. It can be seen that ECM with 90% fractile level underestimates for YU2 (tension) for over 15% and tower responses by over 40% compared to FLTA results. Figure 26 shows the difference between MECM (90% fractile of 50-year contour and 50% fractile of cut-out-wind-speed contour) and FLTA. It can be found that any under-estimated extreme response is within 10% range of difference compared to FLTA. It can also be noted that ECM and MECM over-estimate the extreme response for DU1 (compression), DU3 (tension) and YU1 (tension). This is because these responses is already very close to the FLTA results because the true "design point"s of these responses are located on the 50-year environmental contour. Thus the 90% fractile from ECM causes the over-estimation.

For the site 15, the performance of ECM and MECM is also similar. From the results shown in Table 5, ECM and MECM provides similar results for most of the extreme responses of the braces. However, MECM improves the prediction for tower (bending moment/shearing force), CB1 (tension), YU1 (compression), YU2 (tension) and mooring line 2 (tension). In addition, MECM also improves the compression axial force of CB2. From Figures 24 and 26, it can be seen that the MECM (90% fractile of 50-year contour and 50% fractile of cut-out-wind-speed contour) greatly improves for the responses that ECM (90% fractile of 50-year contour only) performed poorly (i.e. with differences over 20% compared to FLTA results).

Tables 4 and 5 list the fractile levels for ECM and MECM to achieve the exact same results as FLTAof site 14 and 15 respectively. The starred items are the responses with prediction improved by MECM. It can also be seen in Tables 4 and 5 that the rated-wind-speed-contour is not improving the MECM prediction as their fractile level is close to 100%. The design point (U_w,H_s,T_p) of each response is also listed in the last column.

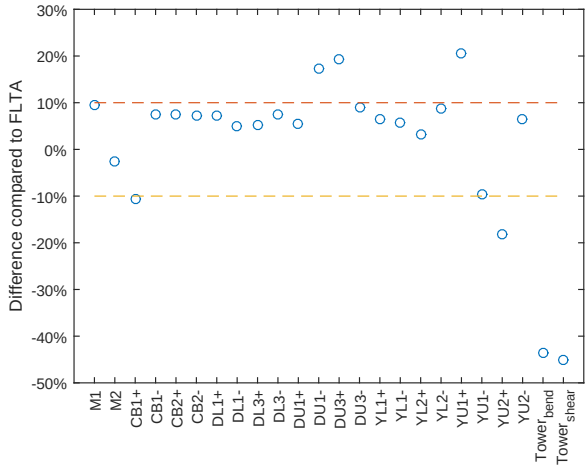

Fig. 24. The percentage difference between ECM (using 90% fractile level of 50-year environmental contour) and FLTA results for site 14.

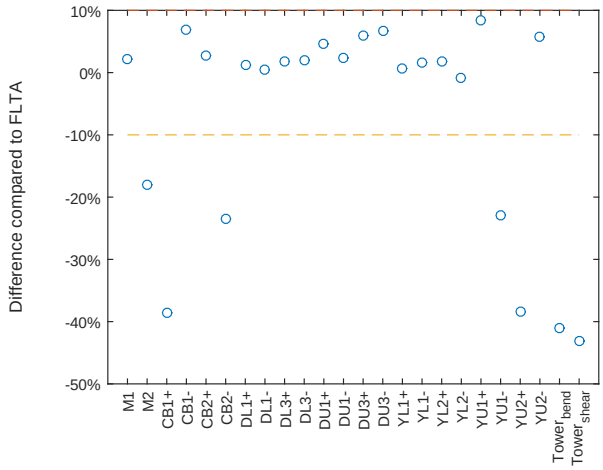

Fig. 25. The percentage difference between ECM (using 90% fractile level of 50-year environmental contour) and FLTA results for site 15.

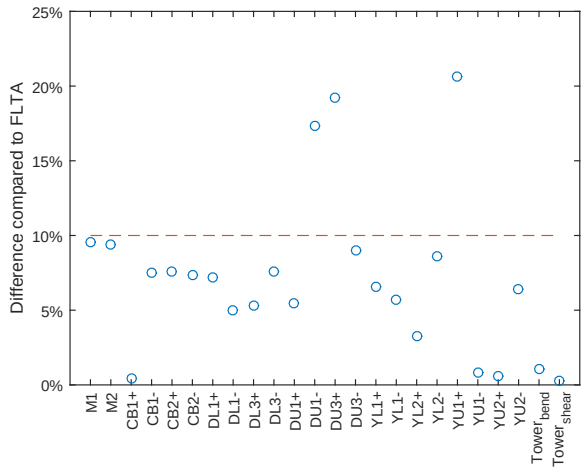

Fig. 26. The percentage difference between MECM (using both 90% fractile level of 50-year and 50% of cut-out wind speed environmental contour) and FLTA results for site 14.

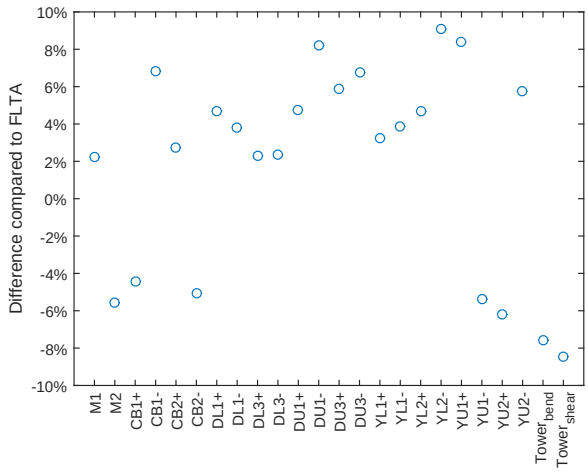

Fig. 27. The percentage difference between MECM (using both 90% fractile level of 50-year and 50% of cut-out wind speed environmental contour) and FLTA results for site 15.

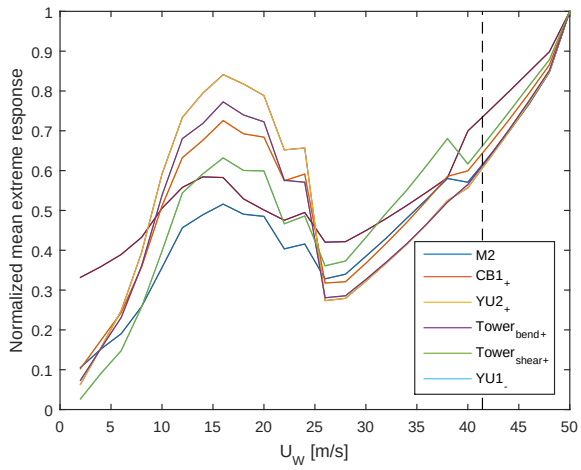

Fig. 28. Normalized expected extreme responses vs. hub-height mean wind speed. The extreme response corresponds to the labeled wind speed and its most probable sea state. The dashed line represents the 50-year wind speed of site 14.

Overall, the MECM provides improved prediction for the long-term extremes compared to the original ECM. Since the MECM compare the short-term extreme of the environmental condition selected both on the 50-year contour and the cut-out wind speed contour, it is suitable for all responses regardless whether its design point is near the 50-year contour or within the operational range. It can also be seen that including the environmental contour at rated wind speed does not improve the overall performance of the MECM as its predictions are much lower than that of the other two contours. Thus, for MECM only the cut-out wind speed and 50-year environmental contours are necessary for this wind turbine model. It is also found that 90% is an acceptable fractile level for ECM (50-year contour). A low fractile level of the cut-out wind speed contour for MECM is sufficient as it is found that 50% is already giving predictions very close to the FLTA.

Compared to previous studies on a bottom-fixed offshore wind turbine [9, 10], the responses of the semi-submersible cannot be easily determined if they are affected by mainly wave or wind loads. Still, the results show that the MECM is very good for long-term extreme prediction for this semi-submersible wind turbine overall. The method should also be applicable to other offshore wind turbine concepts (spar, TLP, or bottom-fixed) as the MECM can cope with the discontinuity in the responses caused by the operational/parking state of the wind turbines.

5.2.2 ECM and MECM referred to multiplication factors

Based on Section 3.4, the results of ECM and MECM using multiplication factor instead of fractile level is discussed in this section. Table 6 and 7 shows the required multiplication factors for each response to achieve the same long-term extreme calculated by FLTA of site 14 and 15, respectively. It can be seen that for responses that are suitable for the ECM,

Table 4. A comparison between 50-year long-term extreme responses predicted by ECM, MECM and FLTA for site 14. The units of the FLTA results are kN or kNm. The shown results are the fractile level for each contour to achieve same results as the FLTA. M1 and M2 are the tension forces of mooring lines 1 and 2, Tower_{bend} and Tower_{shear} are bending moment and shear force at the base of the tower. Other responses are the tension ("+") and compression ("-") axial forces of the braces. "50-yr", "cut-out", and "rated" represents the contours corresponding to 50-year, cut-out wind speed and rated wind speed respectively. The labels for the names of the members in first column are given in Figure 14 and 15. The circled numbers indicate which contour the MECM uses. The starred responses are the ones that are improved by MECM.

Response	FLTA	50-year ① (ECM)	cut-out ②	rated ③	MECM	Design Point
M1	1.62E+03	63.25%	100.00%	100.00%	63.25% ①	(34,15,16)
*M2	3.45E+03	92.75%	1.16%	99.99%	1.16% ②	(14,6,16)
*$CB1_+$	3.67E+03	97.00%	47.89%	100.00%	47.89% ②	(20,4,14)
$CB1_-$	2.15E+03	77.26%	96.22%	100.00%	77.26% ①	(40,14,12)
$CB2_+$	4.33E+03	77.67%	90.98%	100.00%	77.67% ①	(38,14,12)
$CB2_-$	7.12E+03	81.74%	73.95%	100.00%	81.74% ①	(40,16,14)
$DL1_+$	8.51E+03	72.75%	69.64%	100.00%	72.75% ①	(40,11,10)
$DL1_-$	8.71E+03	80.75%	72.74%	100.00%	80.75% ①	(42,14,12)
$DL3_+$	7.61E+03	78.78%	77.17%	100.00%	78.78% ①	(36,14,12)
$DL3_-$	7.03E+03	74.01%	70.10%	100.00%	74.01% ①	(30,11,10)
$DU1_+$	3.09E+03	80.97%	99.47%	100.00%	80.97% ①	(42,14,12)
$DU1_-$	2.26E+03	51.43%	45.87%	100.00%	51.43% ①	(34,9,8)
$DU3_+$	2.52E+03	20.24%	59.13%	100.00%	20.24% ①	(34,9,8)
$DU3_-$	2.90E+03	80.36%	99.46%	100.00%	80.36% ①	(36,14,12)
$YL1_+$	3.58E+03	76.59%	66.21%	100.00%	76.59% ①	(38,11,10)
$YL1_-$	3.27E+03	76.95%	56.58%	100.00%	76.95% ①	(36,14,12)
$YL2_+$	5.73E+03	86.12%	93.14%	100.00%	86.12% ①	(36,14,12)
$YL2_-$	5.07E+03	78.50%	23.92%	100.00%	78.50% ①	(30,9,8)
$YU1_+$	2.31E+03	35.31%	97.61%	100.00%	35.31% ①	(34,9,8)
*$YU1_-$	3.01E+03	97.91%	43.05%	100.00%	43.05% ②	(14,5,6)
*$YU2_+$	6.52E+03	99.82%	46.59%	100.00%	46.59% ②	(20,2,6)
$YU2_-$	3.50E+03	83.95%	99.24%	99.99%	83.95% ①	(42,14,12)
*Tower_{bend}	2.28E+05	99.98%	44.10%	100.00%	44.10% ②	(20,3,6)
*Tower_{shear}	3.07E+03	99.98%	48.66%	100.00%	48.66% ②	(20,3,6)

using the multiplication factor of 1.2 can achieve estimations of extreme responses that are close to the FLTA results. For responses such as tower (bending moment/shearing force), CB1 (tension), YU1 (compression), YU2 (tension) and mooring line 2 (tension), the 1.2 multiplication factor with ECM (50-year contour) is not sufficient as also shown in Figures 29 and 30.

It can be seen that using MECM (contour corresponding to cut-out wind speed in addition to the 50-year contour) in this case can improve the results by using the extrapolated expected extreme response with multiplication factor of 1. It can achieve the long-extreme estimation close to FLTA as shown in Figure 31 and 32, with differences less than 10% for most responses. However, using multiplication factor with MECM still requires data fitting to find the new extrapolated expected extreme. It defeats the purpose of using multiplication factor since it requires same amount of effort of data fitting as using fractile levels for MECM.

In conclusion, the multiplication factor can substitute fractile levels when using ECM when appropriate value (e.g. 1.2)

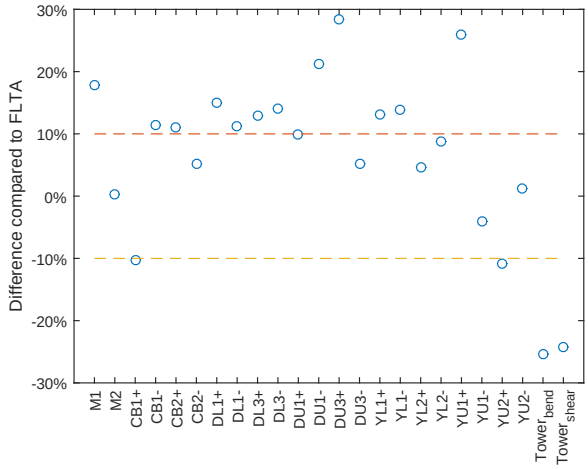

Fig. 29. The percentage difference between ECM (using 1.2 multiplication factor of the expected extreme of 50-year environmental contour) and FLTA results for site 14.

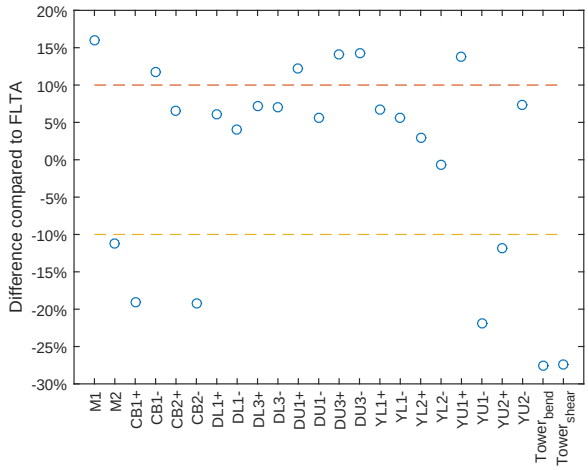

Fig. 30. The percentage difference between ECM (using 1.2 multiplication factor of the expected extreme of 50-year environmental contour) and FLTA results for site 15.

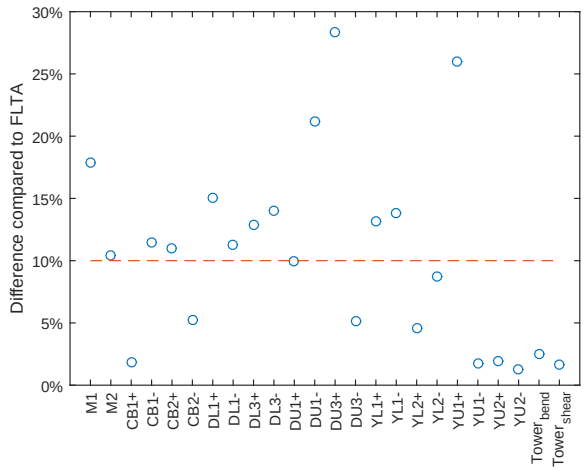

Fig. 31. The percentage difference between MECM (using 1.2 multiplication factor of the expected extreme of 50-year environmental contour and 1.8 multiplication factor of the expected extreme of cut-out wind speed contour) and FLTA results for site 14.

Table 5. A comparison between 50-year long-term extreme responses predicted by ECM, MECM and FLTA for site 15. The units of the FLTA results are kN or kNm. The shown results are the fractile level for each contour to achieve same results as the FLTA. M1 and M2 are the tension forces of mooring lines 1 and 2, Tower_{bend} and Tower_{shear} are bending moment and shear force at the base of the tower. Other responses are the tension ("+") and compression ("-") axial forces of the braces. "50-yr", "cut-out", and "rated" represents the contours corresponding to 50-year, cut-out wind speed and rated wind speed respectively. The labels for the names of the members in first column are given in Figure 14 and 15. The circled numbers indicate which contour the MECM uses. The starred responses are the ones that are improved by MECM.

Response	FLTA	50-year ① (ECM)	cut-out ②	rated ③	MECM	Design Point
M1	1.35E+03	80.83%	96.87%	98.07%	80.83% ①	(32,10,12)
*M2	3.02E+03	99.77%	84.75%	99.65%	84.75% ②	(16,4,6)
*$CB1_+$	3.39E+03	99.95%	69.99%	100.00%	69.99% ②	(20,5,12)
$CB1_-$	1.73E+03	77.85%	48.07%	100.00%	77.85% ①	(26,8,8)
$CB2_+$	3.71E+03	86.34%	53.56%	100.00%	86.34% ①	(28,8,8)
*$CB2_-$	6.36E+03	99.87%	73.67%	100.00%	73.67% ②	(20,5,12)
$DL1_+$	7.86E+03	88.21%	21.95%	100.00%	88.21% ①	(34,8,8)
$DL1_-$	7.80E+03	89.51%	27.96%	100.00%	89.51% ①	(34,8,8)
$DL3_+$	6.76E+03	87.39%	34.92%	100.00%	87.39% ①	(26,8,8)
$DL3_-$	6.32E+03	86.94%	34.35%	100.00%	86.94% ①	(26,8,8)
$DU1_+$	2.47E+03	80.37%	18.42%	100.00%	80.37% ①	(34,8,8)
$DU1_-$	2.28E+03	86.81%	9.62%	100.00%	86.81% ①	(34,8,8)
$DU3_+$	2.54E+03	76.29%	13.73%	100.00%	76.29% ①	(34,8,8)
$DU3_-$	2.12E+03	74.79%	23.44%	100.00%	74.79% ①	(34,8,8)
$YL1_+$	3.20E+03	88.93%	27.46%	100.00%	88.93% ①	(34,8,8)
$YL1_-$	2.89E+03	87.83%	26.78%	100.00%	87.83% ①	(26,8,8)
$YL2_+$	5.13E+03	88.09%	25.14%	100.00%	88.09% ①	(28,8,8)
*$YL2_-$	4.89E+03	92.39%	14.29%	100.00%	14.29% ②	(28,8,8)
$YU1_+$	2.31E+03	73.44%	97.18%	100.00%	73.44% ①	(34,8,8)
*$YU1_-$	2.94E+03	99.62%	77.48%	100.00%	77.48% ②	(20,5,6)
*$YU2_+$	6.22E+03	99.96%	76.29%	100.00%	76.29% ②	(20,2,6)
$YU2_-$	2.80E+03	82.32%	81.63%	99.23%	82.32% ①	(26,8,8)
*Tower_{bend}	2.21E+05	99.98%	78.96%	100.00%	78.96% ②	(20,3,6)
*Tower_{shear}	2.97E+03	99.97%	81.79%	100.00%	81.79% ②	(20,3,6)

is chosen. Choosing the multiplication factors will be empirical if no information is known beforehand, because the value of μ/β is very important to the multiplication factor. For ECM, its value (1.2) is the same regardless of the site environment statistics. Using multiplication factor for MECM requires data fitting to find the extrapolated expected extreme to achieve satisfactory estimation. Thus, it offers no advantages over using fractile levels for MECM.

6 Conclusions

In this study, the MECM is found to be an efficient method for predicting long-term extreme responses for the Deep-Cwind semi-submersible wind turbine operating under two sets of environmental conditions sites in the North Sea. The MECM can cope with the discontinuity between extreme responses relative to wind speed due to the modes of operation and parking of the wind turbine. When the both environmental contours corresponding to 50-year return period and cut-out wind

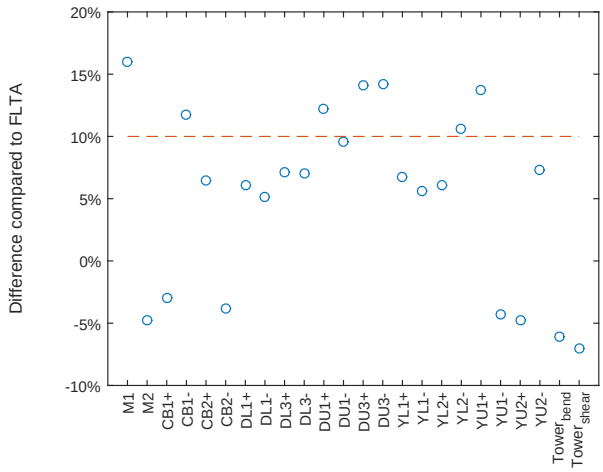

Fig. 32. The percentage difference between MECM (using 1.2 multiplication factor of the expected extreme of 50-year environmental contour and 1.8 multiplication factor of the expected extreme of cut-out wind speed contour) and FLTA results for site 15.

speed are considered, the prediction of MECM is close to that of the FLTA and greatly improves the predictions obtained by the original ECM. The accuracy of prediction is greatly improved by applying MECM instead of ECM for responses such as tower bottom extreme bending and shear that are heavily influenced by the operation/parking status of the wind turbine. In this study, it is found that a combination of 90% and 50% fractile levels for environmental contour corresponding to 50-year return period and cut-out wind speed respectively for MECM can achieve close long-term extreme estimations compared to FLTA.

It is also found that multiplication factors (1.2) can be used to substitute the 90% fractile levels for ECM to give conservative estimates when the appropriate assumptions are made. Multiplication factors are better suited for original ECM since it is not site-dependent. For MECM, using multiplication factors still requires fitting of extreme data to achieve satisfactory estimation, which means it offers no advantages over using fractile levels.

Overall, MECM provides a great improvement over the original ECM for long-term extreme response estimation for offshore wind turbines. In addition, MECM may also be tested for predicting long-term extreme responses for other systems that features similar on/off or change of operational state based on environmental parameters such as wind speed or wave height. Further research can be the study of the probability of failure of the system under the extreme loads predicted by MECM and check whether they are consistent with the required return period.

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Table 6. The FLTA results and multiplication factors for extreme responses using expected extreme values instead of fractile level of worst case on 50-year and cut-out wind speed contours for site 14. The units of the FLTA results are kN or kNm. "50-yr", "cut-out", and "cut-out" indicates that the expected values are on environmental contour corresponding to 50-year return period, cut-out wind speed. "(ext.)" means the values in the column are based on extrapolated expected extreme responses.

Response	FLTA	50-yr	cut-out	cut-out (ext.)
M1	1.35E+03	1.02	1.40	1.21
M2	3.02E+03	1.20	1.47	0.91
$CB1_+$	3.39E+03	1.34	1.64	0.98
$CB1_-$	1.73E+03	1.08	2.70	1.18
$CB2_+$	3.71E+03	1.08	3.67	1.13
$CB2_-$	6.36E+03	1.14	1.75	1.03
$DL1_+$	7.86E+03	1.04	1.89	1.02
$DL1_-$	7.80E+03	1.08	1.81	1.03
$DL3_+$	6.76E+03	1.06	2.00	1.04
$DL3_-$	6.32E+03	1.05	1.67	1.02
$DU1_+$	2.47E+03	1.09	2.11	1.19
$DU1_-$	2.28E+03	0.99	1.87	0.98
$DU3_+$	2.54E+03	0.94	1.53	1.00
$DU3_-$	2.12E+03	1.14	2.16	1.24
$YL1_+$	3.20E+03	1.06	1.76	1.01
$YL1_-$	2.89E+03	1.05	1.78	1.00
$YL2_+$	5.13E+03	1.15	2.26	1.11
$YL2_-$	4.89E+03	1.10	1.70	0.95
$YU1_+$	2.31E+03	0.95	2.39	1.15
$YU1_-$	2.94E+03	1.25	1.51	0.98
$YU2_+$	6.22E+03	1.35	1.56	0.98
$YU2_-$	2.80E+03	1.19	3.73	1.33
$Tower_{bend}$	2.21E+05	1.61	1.79	0.98
$Tower_{shear}$	2.97E+03	1.58	1.78	0.98

Table 7. The FLTA results and multiplication factors for extreme responses using expected extreme values instead of fractile level of worst case on 50-year and cut-out wind speed contours for site 15. The units of the FLTA results are kN or kNm. "50-yr", "cut-out", and "cut-out" indicates that the expected values are on environmental contour corresponding to 50-year return period, cut-out wind speed. "(ext.)" means the values in the column are based on extrapolated expected extreme responses.

Response	FLTA	50-yr	cut-out	cut-out (ext.)
M1	1.35E+03	1.03	1.17	1.05
M2	3.02E+03	1.35	1.43	1.05
$CB1_+$	3.39E+03	1.48	1.52	1.03
$CB1_-$	1.73E+03	1.07	1.75	0.98
$CB2_+$	3.71E+03	1.13	2.02	0.99
$CB2_-$	6.36E+03	1.49	1.82	1.04
$DL1_+$	7.86E+03	1.13	1.51	0.94
$DL1_-$	7.80E+03	1.15	1.57	0.95
$DL3_+$	6.76E+03	1.12	1.49	0.97
$DL3_-$	6.32E+03	1.12	1.51	0.97
$DU1_+$	2.47E+03	1.07	1.42	0.94
$DU1_-$	2.28E+03	1.14	1.54	0.91
$DU3_+$	2.54E+03	1.05	1.34	0.94
$DU3_-$	2.12E+03	1.05	1.45	0.95
$YL1_+$	3.20E+03	1.12	1.42	0.96
$YL1_-$	2.89E+03	1.14	1.54	0.95
$YL2_+$	5.13E+03	1.17	1.64	0.94
$YL2_-$	4.89E+03	1.21	1.57	0.90
$YU1_+$	2.31E+03	1.06	1.59	1.15
$YU1_-$	2.94E+03	1.54	1.67	1.04
$YU2_+$	6.22E+03	1.36	1.48	1.05
$YU2_-$	2.80E+03	1.12	2.42	1.08
$Tower_{bend}$	2.21E+05	1.66	1.73	1.07
$Tower_{shear}$	2.97E+03	1.65	1.72	1.08

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