Modified environmental contour method for predicting long-term extreme responses of bottom-fixed offshore wind turbines

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ABSTRACT

Predicting extreme responses is very important in designing a bottom-fixed offshore wind turbines. The commonly used method that account for the variability of the response and the environmental conditions is the full long-term analysis (FLTA), which is accurate but time consuming. It is a direct integration of all the probability distribution of short-term extremes and the environmental conditions. Since the long-term extreme responses are usually governed by very few important environmental conditions, the long-term analysis can be greatly simplified if such conditions are identified. For offshore structures, one simplified method is the environmental contour method (ECM), which uses the short-term extreme probability distribution of important environmental conditions selected on the contour surface with the relevant return periods. However, because of the inherent difference of offshore wind turbines and ordinary offshore structures, especially their non-monotonic behavior of the responses under wind loads, ECM cannot be directly applied because the environmental condition it selects is not close to the actual most important one.

The paper presents a modified environmental contour method (MECM) for bottom-fixed offshore wind turbine applications. It can identify the most important environmental condition that governs the long-term extreme. The method is tested on the NREL 5MW wind turbine supported by a simplified jacket-type support structure. Compared to the results of FLTA, MECM yields accurate results and is shown to be an efficient and reliable method for the prediction of the extreme responses of bottom-fixed offshore wind turbines.

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

1 Introduction

Long-term analysis is very important for determining both life-time fatigue damage and extreme structural responses of offshore wind turbine designs. The full long-term analysis integrates the product of the probability of the environmental

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conditions and the corresponding short-term response probability distribution (extreme probability, fatigue damage, etc.) to calculate the life-time result.

Due to the large number of environmental conditions to be included, the full long-term analysis is not efficient or economical. Thus, many simplification methods are used for the fatigue and extreme prediction. The simplified methods are either improving the efficiency of simulations or reducing the number of environmental conditions for the integration. For fatigue, there are methods for efficient probability integral evaluation such as perturbation approach, asymptotic approximation [1], or univariate dimension-reduction method [2], etc. For fatigue damage, frequency-domain analysis can also be used instead of the more costly time-domain simulations [3]. For extreme analysis, there are simplified methods such as estimating the extreme responses by combining the extremes under each single environmental load, such as [4–6].

The analysis can also be simplified by reducing the environmental cases. This is especially effective for extreme analysis because the long-term extreme is affected by very few environmental conditions. The environmental contour method (ECM) [7] is such an approach based on the Inverse first order reliability method (IFORM) [8], which uses a single short-term environmental condition with the desired return period. It is initially used in offshore structure design and is now also included in the design for land-based and offshore wind turbines. Different from ordinary offshore structures, wind turbines operate or park under varying wind speed. Thus, it has been found by [9–12] that the method is not suitable for many offshore wind turbines. The paper will show that the modified environmental contour method (MECM) can still be applied for bottom-fixed offshore wind turbines and find the long-term extreme response efficiently with accuracy.

The paper introduces MECM and its implementation. A case study on the NREL 5MW wind turbine [13] supported by a simplified 92-meter jacket-type support structure [14] with water depth of 79 meter is conducted. The wind turbine is pitch-regulated with cut-in, rated, and cut-out wind speed of 3 m/s, 11.4 m/s and 25 m/s respectively. The environmental conditions are based on a site located in central North Sea, labeled as site 15 in [15]. The environmental parameters considered are mean wind speed, significant wave height, spectral peak period while the turbulence intensity of the wind speed is assumed to be constant as 0.15.

2 Full long-term analysis (FLTA)

The full long-term analysis (FLTA) is a straight forward method for calculating the long-term extreme response probability distribution. It is an accurate approach because it considers all the environmental conditions, which is also why it is not very economical. The results of the full long-term analysis are used as benchmark to determine the performance of other simpler long-term extreme analysis methods.

The FLTA calculates the long-term result by directly integrating all environmental parameters and the corresponding short-term response probability functions. There are many ways for short-term analysis by using extremes (maxima of each time period), local peaks, or up-crossing rates, etc. [16]. If using the short-term extremes, the long-term extreme can be found by Eq. (1), where F stands for the cumulative distribution function (CDF) and s is the environmental condition that satisfies Eq. (2). $f_S(s)$ is the probability density function (PDF) of s. $F_X^{LT}(\xi)$ and $F_{X|S}^{ST}(\xi|s)$ are the long-term and short-term CDF of the extreme values of the response X, respectively.

$$F_X^{LT}(\xi) = \int F_{X|S}^{ST}(\xi|s) f_S(s) ds \tag{1}$$

$$\int f_S(s) ds = 1 \tag{2}$$

In this study, the 1-hour short-term extremes probability distribution is used. The 1-hour short-term extremes probability distribution is calculated based on the maximum responses of 10-minute periods by assuming each 10-min period is independent. Since mean wind speed, significant wave height and spectral peak period are the variables for the environmental condition, Eq. (1) can be rewritten as Eq. (3), where U_w, H_s, T_p are mean hub-height wind speed, significant wave height, and spectral peak period respectively. $F_{X_{1\text{-}hr}}^{LT}(\xi)$ is the long-term 1-hour extreme CDF of response X and $F_{X_{1\text{-}hr}|U_w,H_s,T_p}^{ST}(\xi|u,h,t)$ is the short-term 1-hour extreme CDF of response X under environmental condition (u,h,t).

$$F_{X_{1\text{-}hr}}^{LT}(\xi) = \iiint F_{X_{1\text{-}hr}|U_w,H_s,T_p}^{ST}(\xi|u,h,t) f_{U_w,H_s,T_p}(u,h,t) du dh dt = \sum F_{X_{1\text{-}hr}|U_w,H_s,T_p}^{ST}(\xi|u,h,t) f_{U_w,H_s,T_p}(u,h,t) \Delta u \Delta h \Delta t \tag{3}$$

For 50-year long-term results, one can either find ξ such that $F_{X_{1\text{-}hr}}^{LT}(\xi) = 1/(50 \cdot 365.25 \cdot 24)$, or find the 50-year 1-hour extreme probability distribution $[F_{X_{1\text{-}hr}}^{LT}(\xi)]^{50 \cdot 365.25 \cdot 24}$ and calculate its most probable value as the result.

The FLTA is used in design of offshore structures and wind turbines, often with some simplification such as reducing the number of environmental parameters. The disadvantage of the method is that it requires a large number of simulations to cover all the environmental conditions. For most requirements, only the high exceedance probability (50-year or 20-year, etc.) is of interest, which means that only the tail part of the long-term extreme CDF is important. This implies that most of the environmental conditions included are not contributing to the result of the long-term extreme. If the most important environmental conditions are preserved while the unimportant ones are ignored, the FLTA will still give the same result.

3 Environmental contour method (ECM)

The environmental contour method aims at using the short-term extreme distribution $F_{X_{1\text{-}hr|U_W,H_S,T_P}}^{ST}(\xi|u,h,t)$ with environmental parameters combination of a "design point" on the contour line or surface of environmental condition with a desired return period (50 year or 20 year, etc.). The basic idea of ECM can be described by Eq. (4), where u_N, h_N, and t_N represent the environmental condition leading to the largest extreme response on the N-year contour.

$$F_{X_{1\text{-}hr,N\text{-}yr}}(\xi) \approx F_{X_{1\text{-}hr|U_W,H_S,T_P}}^{ST}(\xi|u_N,h_N,t_N) \tag{4}$$

ECM is based on the IFORM [8]. The idea of first-order reliability method (FORM) is to transform the known limit-state surface/line to a linear tangent plane/line at the design point in standard normalized random space (U-space) to find out the failure probability more easily. A limit-state surface/line is the collection of all the environmental conditions that have the same value for a response, such as same short-term extreme value, etc. The design point is the point on the limit-state surface that is closest to the origin in U-space. The FORM calculates the failure probability based on the distance of the design point to the origin when the limit-state is known. However, using FORM to calculate the limit state (extreme) requires iterations. IFORM is the inverse process of FORM to calculate the extreme value (limit-state) when the probability is known. IFORM creates a spherical surface with the given probability in U-space and transform it back to the original physical space that include all the variables (X-space) by Rosenblatt transformation [17] and find out the design point on the contour in X-space. Thus, the IFORM also approximates the limit-state surface in U-space as a linear tangent plane at the design point. IFORM is included in both IEC 61400-1 [18] and IEC 61400-3 [19] for land-based and offshore wind turbines respectively. However, the IFORM described in IEC 61400-3 for offshore wind turbines is in fact ECM. ECM is a further simplification of IFORM as the variability of the response is ignored, which means contour consists of only environmental parameters (wind, wave, etc.) and without the response as a variable.

From Eq. (4), it can be seen that the return period of the joint wind and wave condition is N-year. To compensate the omitted variability of the response, an inflated contour surface with higher return period or a higher fractile (typically from 70% to 90% for different types of responses) than median is used as the prediction according to the omission factor [8,20] of the short-term extreme response probability distribution. Multiplication factors have also been used instead of higher fractile in some studies [21].

For ECM, the procedure is straight forward.

1. Construct the 50-year environmental contour surface/line.
2. Select environmental conditions on the contour surface/line.
3. Choose the case with largest extreme response and use a higher fractile or a multiplication factor to achieve the 50-year extreme response.

The method has been used in the extreme response analysis in offshore design considering combined loads such as wave, wind, and current, etc. The advantage of the environmental contour method is that it decouples the response and the environment and requires only simulations of several selected design cases on the contour surface. However, this is also the limitation of the method, as it assumes that the actual important environmental condition to be close to that selected on the contour surface. Because of this, ECM does not perform well for many offshore wind turbines. It is mainly due to the non-monotonic behavior from wind load. The responses due to wind loads are generally higher when the wind turbine is operating. This means that they are higher within the operational wind speed range and lower when it exceeds cut-out wind speed. If wind load dominates a response, it is very likely that larger extreme occurs when environmental condition is not severe. In this case, the omission of the response variability by ECM is not suitable. In earlier studies by [9–11], it was also found that ECM is not applicable and only the complete IFORM without omission of the responses can be applied to wind turbines.

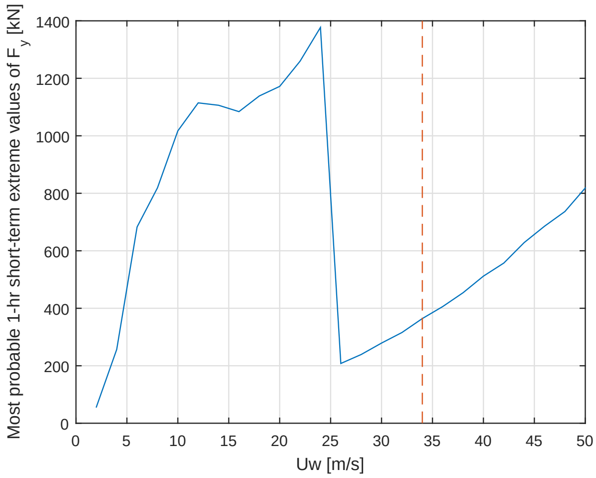

Fig. 1. Most probable 1-hr short-term extreme responses of bottom fore-aft shear force F_y under wind loads only; dashed line corresponds to 50-year hub-height mean wind speed.

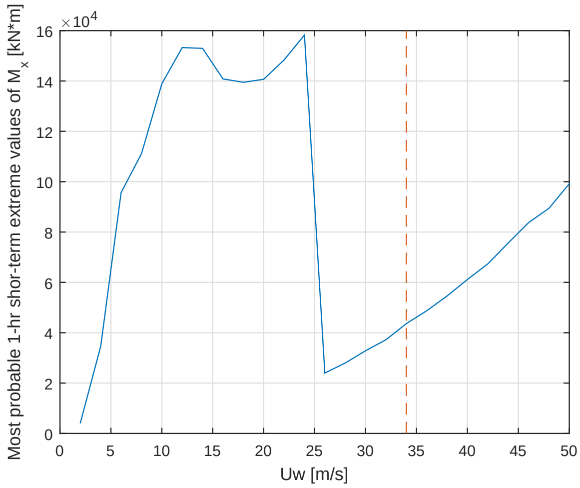

Fig. 2. Most probable 1-hr short-term extreme responses of bottom fore-aft bending moment M_x under wind loads only; dashed line corresponds to 50-year hub-height mean wind speed.

For example, Fig. 1. and Fig. 2. shows the most probable 1-hour extreme responses of bottom fore-aft shear force and bending moment under wind load only against the mean hub-height wind speeds. In this case, the responses are only under wind load and the wind speed is the only environmental parameter, thus the "contour" of ECM reduces to a point, which is the 50-year mean hub-height wind speed.

From Fig. 1. and Fig. 2., it is easy to observe the non-monotonic behavior of the extreme responses with respect to the wind speed. The extreme responses at ECM selected case (dashed line) is much lower than that of the operational wind speeds. On the other hand, the same extreme responses due to wave loads only are shown in Fig. 3 and Fig. 4. The relationship between the response and the wave environmental parameters is monotonic, which is the reason the variability of the response can be ignored and ECM can be applied when only wave is considered.

For a combined wind and wave load, ECM cannot be applied directly either if the response is mainly dominated by wind. The method will generally suggest an environmental condition with an operational wind speed combined with a wave condition so that the joint return period is 50-year, which is essentially a frequent wind speed with a rare wave. However, for a response that is dominated by wind, having a rare wave condition will not increase its extreme value as much. As a result, ECM will under-predict the long-term extreme responses. As an example, Fig. 5. shows the 2-D 50-year environmental contour, the approximation made by ECM and the true limit-state. T_p is omitted in the figure. The results are based on the simulations under the environmental conditions of different U_w-H_s combinations and their corresponding most probable value of T_p , i.e. the one with the highest probability density with given U_w and H_s. The selected case by ECM is the one with the largest extreme response on the 50-year contour. It can be seen that the tangent line cannot approximate the true

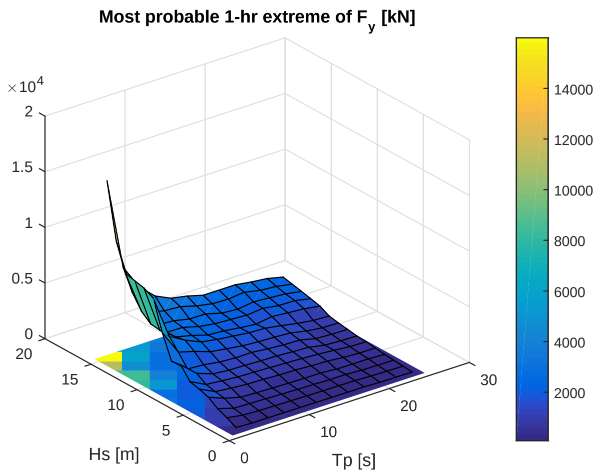

Fig. 3. Most probable 1-hr short-term extreme responses of bottom fore-aft shear force F_y under wave loads only.

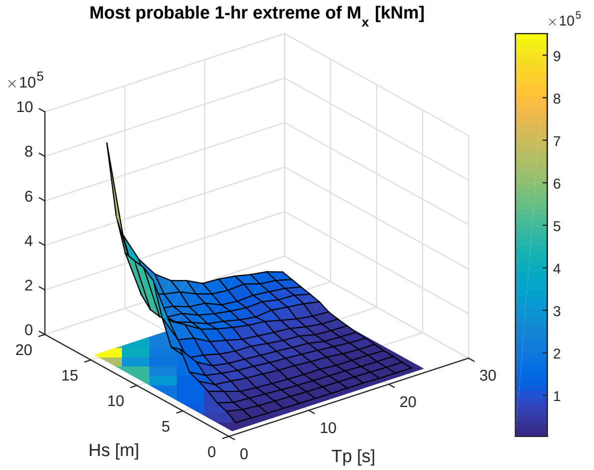

Fig. 4. Most probable 1-hr short-term extreme responses of bottom fore-aft bending moment M_x under wave loads only.

limit-state very well.

The assumption of ECM is that the variability of the extreme response can be ignored, which requires that there should not be large non-monotonic behavior in the responses under the dominating environmental parameter. From the examples shown by Fig. 1 - 5., one can see that the behavior of the responses violates the assumption and ECM cannot be applied directly.

4 Modified environmental contour method (MECM)

Even though the original environmental contour method does not perform well for wind turbines under wind or combined loads, the method can still be useful with appropriate modification. The major problem of ECM is that at 50-year return period, the non-monotonic behavior of the responses causes the environmental case found by ECM to be far away from the true case. However, if such an obstacle can be bypassed, ECM is still applicable.

For an N-year extreme, since there are $(N \cdot 365.25 \cdot 24)$ numbers of 1-hour periods and assuming each 1-hour period is independent, the N-year 1-hour extreme CDF is $F_{X_{1\text{-}hr,N\text{-}yr}}(\xi) = [F^{LT}_{X_{1\text{-}hr}}(\xi)]^{N \cdot 365.25 \cdot 24}$. The 50-year 1-hour extreme CDF can be rewritten as Eq. (5).

$$F_{X_{1\text{-}hr,50\text{-}yr}}(\xi) = \{[F^{LT}_{X_{1\text{-}hr}}(\xi)]^{N \cdot 365.25 \cdot 24}\}^{50/N} = [F_{X_{1\text{-}hr,N\text{-}yr}}(\xi)]^{50/N} \quad (5)$$

Thus, the 50-year extreme can be extrapolated from any N-year extreme as long as the same 1-hour long-term extreme

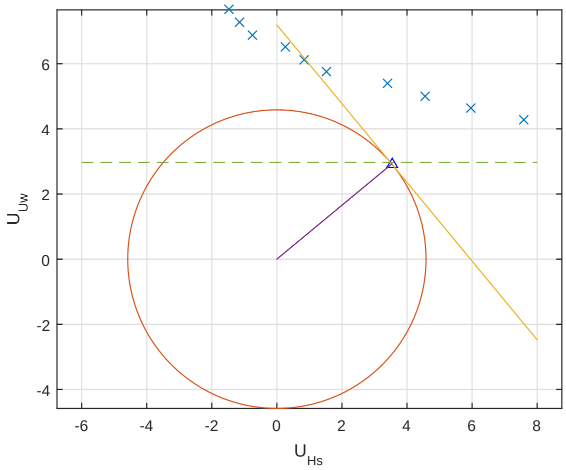

Fig. 5. The 50-year 2-D environmental contour in U-space. The triangular symbol and the straight solid lines represents the case selected by ECM and the approximated limit-state. The “x”s represent the limit-state of the long-term extreme response of F_y with the same return period (50-year). The dashed line represents the cut-out wind speed.

CDF is used. Further more, if the N-year extreme CDF $F_{X_{1\text{-}hr,N\text{-}yr}}(\xi)$ can be well-approximated by ECM, the 50-year extreme CDF $F_{X_{1\text{-}hr,50\text{-}yr}}(\xi)$ can also be extrapolated from the ECM result.

The idea of MECM is to use the $F^{ST}_{X_{1\text{-}hr|U_w,H_s,T_p}}(\xi|u_N,h_N,t_N)$ to approximate the N-year environmental contour to represent $F_{X_{1\text{-}hr,N\text{-}yr}}(\xi)$ and extrapolate it to find $F_{X_{1-hr,50-yr}}(\xi)$, where N is chosen such that ECM can perform well. Eq. (6) shows the idea of MECM, where $F_{X_{1\text{-}hr,50\text{-}yr}}(\xi|u,h,t)$ is the 50-year 1-hour extreme response CDF extrapolated from the short-term environmental condition (u,h,t). Fig. 6 shows the environmental contour with maximum wind speed of 25 m/s. This corresponds to a return period of 0.0766 year or 672 hours. For the extreme response with this return period, ECM is applicable because the tangent line can well approximate the true limit-state curve. It should be noted that the limit-state curve is not a bijective function if the curve passes both the operation and parking region. One can see a discontinuity in the limit-state curve at the cut-out wind speed ($25m/s$) in Fig. 6. This is because in the operational region, the response of the wind turbine is much higher. Given the same wave condition, there will be two environmental conditions in operational (lower wind speed) and parked region (higher wind speed) having the same extreme response. Hence one can observe an overlap of limit-state curve near the cut-out wind speed.

$$F_{X_{1\text{-}hr,50\text{-}yr}}(\xi) = [F_{X_{1\text{-}hr,N\text{-}yr}}(\xi)]^{50/N} \approx F_{X_{1\text{-}hr,50\text{-}yr}}(\xi|u_N,h_N,t_N) := [F^{ST}_{X_{1hr|U_w,H_s,T_p}}(\xi|u_N,h_N,t_N)]^{50/N} \tag{6}$$

The most probable value of the extrapolated probability distribution by MECM can be used to approximate the 50-year long-term extreme. The reason for the modification is to avoid the non-monotonic behavior of the responses due to the wind loads and use a better environmental condition for approximation instead of the 50-year one to represent the 50-year long-term 1-hour extreme response probability distribution. If N is 50, then MECM is the same as ECM. If N is chosen such that the maximum wind speed on the contour is less than the cut-out speed, the discontinuity of the limit-state surface is bypassed and the environmental contour method can be used. Further more, if N is more closely selected to capture the most important environmental condition that contribute to the tail region of the long-term extreme response probability distribution, the result should be very close to that of the FLTA and the correction factor or higher fractile will not be required.

4.1 Procedure of MECM

The procedure of MECM is more complicated compared to ECM but is still a huge simplification compared to the FLTA.

When wind is not considered or when only parked condition is of interest, the wind turbine is similar to an offshore structure. The original ECM is applicable, because the assumptions are valid for responses due to wave load. MECM gives cases that are close to that selected by ECM and will not provide much improvement in accuracy.

When wind is considered and wave is ignored, the original ECM cannot be applied due to the violation of its assumption. To achieve accurate result without correction factor or higher fractiles, multiple cases should be tested between rated and cut-out wind speed to find the largest value. The procedure for wind load alone can be described as follows.

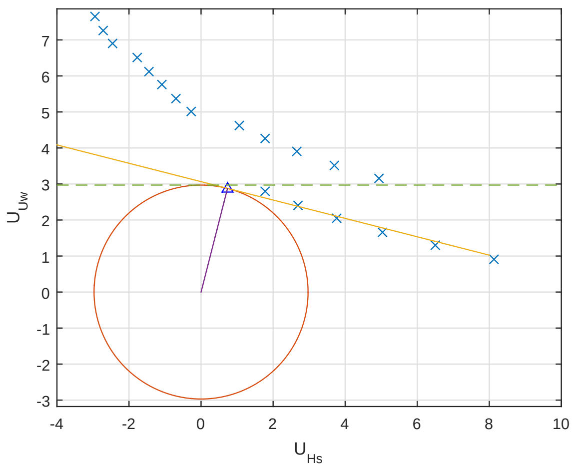

Fig. 6. The 2-D environmental contour with maximum wind speed of 25 m/s (0.077-year) in U-space. The triangular symbol and the straight solid lines represents the case selected by MECM and the approximated limit-state. The "x"s represent the limit-state of the long-term extreme response of F_y with the same return period (0.077-year). The green dashed line represents the cut-out wind speed. A discontinuity can be observed, which is caused by the non-montonic behavior of the response.

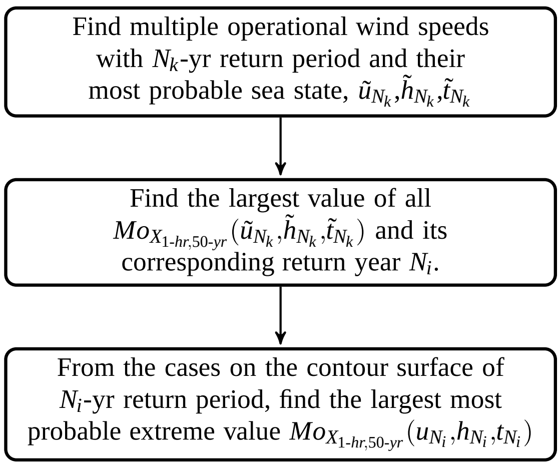

Fig. 7. The procedure of MECM when considering combined wind and wave loads for bottom-fixed offshore wind turbine. $Mo_{X_{1\text{-}hr,50\text{-}yr}}(u,h,t)$ is the most probable value of the 50-year 1-hour extreme extrapolated from the short-term extreme at environmental condition (u,h,t)

1. Select multiple wind speed between rated and cut-out speed and find their extrapolated 50-year extreme response probability distribution.
2. Compare the selected ones, and use the largest extrapolated most probable extreme as the representation for the 50-year extreme.

When combined loads are considered, the procedure for an offshore fixed wind turbine will be to select wind conditions first and pick wave condition for a given return period of the wind condition. The procedure is also illustrated by Fig. 7 and 8.

By following the procedure in Fig. 7, the variability of the responses are included by checking multiple contour surfaces with different return periods.

The results of MECM provides much better predictions compared to the original ECM for bottom-fixed offshore wind turbines because the responses are generally heavily influenced by wind load. By checking multiple contours within the operational wind speed range, the most probable value of the extrapolated extreme response probability distribution matches the result of FLTA.

In addition to offshore wind turbines, MECM may also be applicable to other system whose structural responses are non-monotonically related to environmental parameters such as systems with on-off or active control features according to the external conditions.

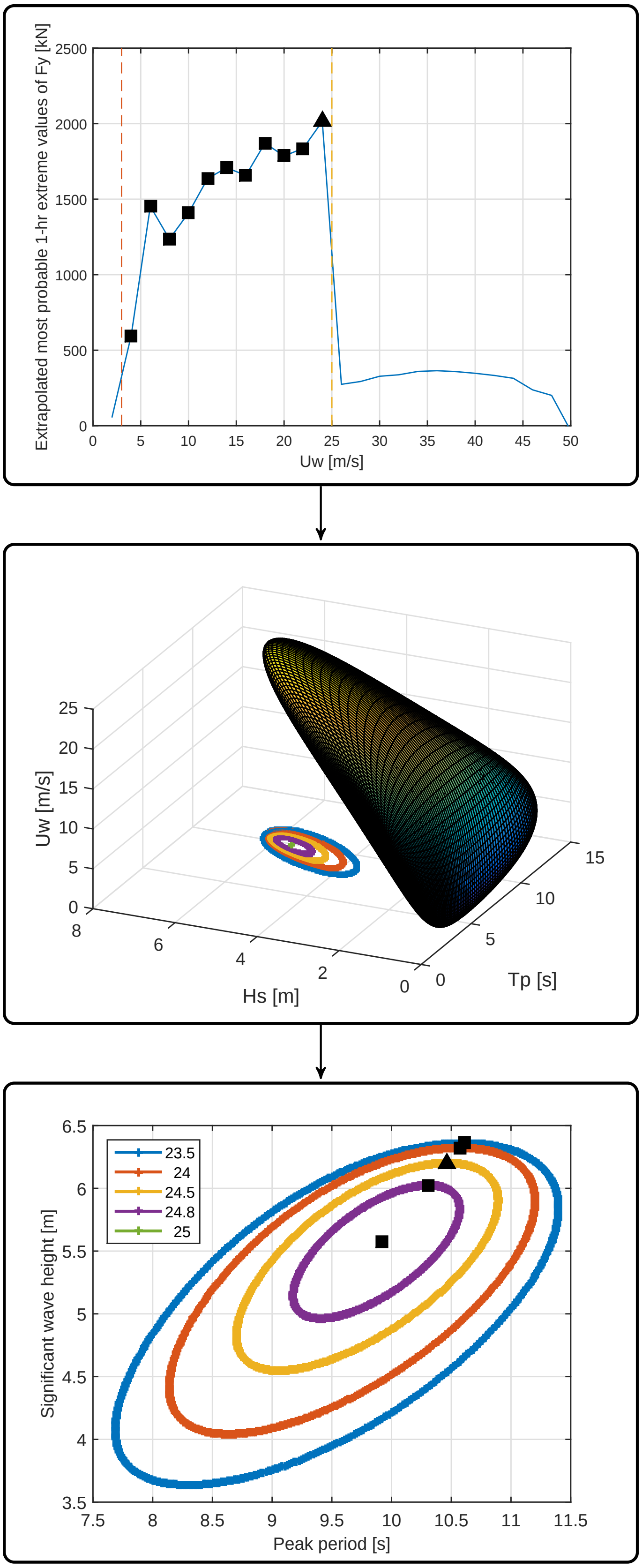

Fig. 8. An example of the procedure of MECM when considering combined wind and wave loads for bottom-fixed offshore wind turbine. Top figure shows that the first step is to find the most important wind speed within the operational range (between dashed lines). Middle figure shows the 3-D environmental contour surface corresponding to the return period of identified most important wind speed, where several cases should be selected and compared to find the most important environmental condition (combination of wind speed, significant wave height and peak spectral period), which should be located near the top tip of the surface where wind speed and significant wave height are highest. For better illustration, the bottom figure shows the projected 2-D contour lines of the top tip of the surface in the middle figure. Points on each contour line have the same wind speed. The triangular markers are the identified most important environmental condition for MECM.

4.2 Number of short-term simulations

Assuming that the correct environmental condition is found, the extrapolated extreme response probability distribution of MECM requires enough number of short-term simulations to achieve a good extreme prediction. Because of the extrapolation in Eq. (6), the number of simulations required is different for each case depending on their return period. The smaller the return period is, the more simulations is required.

In this study, the short-term 1-hour extreme probability distribution is extrapolated from 10-minute extremes. It is assumed that each 10-minute period is independent. Since the maximums of a normal distribution converges to a Gumbel distribution, the probability of 10-minute extremes are assumed to be Gumbel distribution, which can be described by the CDF in Eq. (7). It is defined by two parameters μ and β.

$$F(x) = e^{-e^{-(x-\mu)/\beta}} \tag{7}$$

Since there are six 10-min periods in 1 hour, assuming independence, the 1-hour extreme CDF can be described as the 10-min CDF to the power of six. The extrapolation of 50-year 1-hour CDF is described by Eq. (8).

$$F_{X_{1\text{-}hr,50\text{-}yr}}(\xi|u_N,h_N,t_N) \approx [F^{ST}_{X_{1\text{-}hr|U_w,H_s,T_p}}(\xi|u_N,h_N,t_N)]^{50/N} = [F^{ST}_{X_{10\text{-}min|U_w,H_s,T_p}}(\xi|u_N,h_N,t_N)]^{6\cdot 50/N} \tag{8}$$

The most probable value or mode of a Gumbel distribution is μ. After extrapolation, the new most probable value $Mo_{X_{1\text{-}hr,50\text{-}yr}}(u_N,h_N,t_N)$ is described by Eq. (9).

$$Mo_{X_{1\text{-}hr,50\text{-}yr}}(u_N,h_N,t_N) = \mu + \beta \ln(6 \cdot 50/N) \tag{9}$$

Generally, when N is large or comparable to 50, since also μ is larger than β, μ is more influential on the most probable extreme value. However, after extrapolation, the value of return year N is very small compared to 50. For this study, N is as small as 0.077 for the cut-out wind speed. This means that β is more important to achieve the accuracy of the extrapolated most probable extreme. The error of μ does not influence the result as much as the error of β. So it requires enough number of simulations to ensure the error of β is small.

Eq. (7) can also be rewritten as a linear Eq. (10). For this study, the parameter is fit by the simple linear regression (SLR), which is the least square estimator of a linear model. So the extrapolated most probable value fit is shown by Eq. (11), where $\hat{\mu}(n)$ and $\hat{\beta}(n)$ are the estimation from the SLR with n data points.

$$x = \beta[-\ln(-\ln F)] + \mu \tag{10}$$

$$\hat{Mo}(n) = \hat{\mu}(n) + \hat{\beta}(n)\ln(6 \cdot 50/N) \tag{11}$$

One way to test the parameter fit is to check the 95% confidence interval of the estimation of the extrapolated extreme. If assuming the error of the value is normal distributed, the confidence interval can be calculated assuming that the error is normal as Eq. (12).

$$Mo_{CI^{\pm}}(n) = \hat{Mo} \pm t_{0.975,n-2}\sqrt{var(Mo(n))} \tag{12}$$

where $t_{0.975,n-2}$ is 97.5% fractile value of Student's t-distribution with $(n-2)$ degrees of freedom and n is the number of simulations. Based on Eq. (11) and the variance summation rule of multiple random variables, the variance can be calculated by Eq. (13) with the variances and the covariance of μ and β. They can be found with the calculation of SLR. It can be seen that if N is very small, only the variance of β is most influential.

$$var[Mo(n)] = var[\mu(n)] + [\ln(6\cdot 50/N)]^2 var[\beta(n)] + 2\ln(6\cdot 50/N) cov[\mu(n),\beta(n)] \tag{13}$$

Assuming that it is desirable to achieve a difference between the upper and lower 95% bound of the most probable value to be less than 3% of the estimated most probable extreme of SLR, we can use a test expressed by Eq. (14) to see whether the number of simulations is sufficient.

$$CI\%(n) = \frac{Mo_{CI^+}(n) - Mo_{CI^-}(n)}{\hat{M}o(n)} \leq 3\% \tag{14}$$

It is found that when such requirement is met, the extrapolated most probable value is stable and accurate. For different cases and different responses, the number of simulations required could be different depending on the variance of β.

5 Simplified FLTA

In Section 2, it is mentioned that the FLTA is inefficient mainly because most of the environmental conditions are negligible for the 50-year extreme. The environmental condition with the largest contribution of long-term exceedance probability $Q^{ST}_{X_{1\text{-}hr}|U_w,H_s,T_p}(X_{1\text{-}hr,50\text{-}yr}|u,h,t)\, f_{U_w,H_s,T_p}(u,h,t)$ is the most important one for predicting the 50-year extreme. The short-term exceedance probability $Q^{ST}_{X_{1\text{-}hr}|U_w,H_s,T_p}(X_{1\text{-}hr,50\text{-}yr}|u,h,t)$ is calculated by Eq. (15), where $X_{1\text{-}hr,50\text{-}yr}$ is the 50-year 1-hour extreme predicted by FLTA.

$$Q^{ST}_{X_{1\text{-}hr}|U_w,H_s,T_p}(X_{1\text{-}hr,50\text{-}yr}|u,h,t) = 1 - F^{ST}_{X_{1\text{-}hr}|U_w,H_s,T_p}(X_{1\text{-}hr,50\text{-}yr}|u,h,t) \tag{15}$$

In Section 4, it was shown that the extrapolated most probable extreme value can be used to find the important environmental conditions without the knowledge of the long-term extreme value. Comparing the extrapolated most probable extreme $Mo_{X_{1\text{-}hr,50\text{-}yr}}(u_N,h_N,t_N)$ and exceedance probability contribution $Q^{ST}_{X_{1\text{-}hr}|U_w,H_s,T_p}(X_{1\text{-}hr,50\text{-}yr}|u,h,t)\, f_{U_w,H_s,T_p}(u,h,t)$, one can see that the two methods finds the same most important cases. Fig. 9 and Fig. 10. shows the exceedance probability contribution and the most probable extrapolated 50-yr 1-hr extreme response of the bottom shear force. They both find the same environmental conditions that are the most important.

Fig. 9 shows that most cases are unimportant as their exceedance probability contribution is very low. For these unimportant cases, if value 1 substitutes the CDF value in the FLTA, the 50-year long-term extreme result does not change noticeably. Thus, it means the simulations are not needed for all conditions. Only the extreme probability distribution of the important cases will be useful in long-term analysis. Thus, the full long-term extreme analysis can be simplified as Eq. (16), where $\{u_i,h_i,t_i\}$ represents all the important conditions and $\{u_i,h_i,t_i\}^C$ are the unimportant ones.

$$F^{LT}_{X_{1hr}}(\xi) = \sum_{\{u_i,h_i,t_i\}} F^{ST}_{X_{1\text{-}hr}|U_w,H_s,T_p}(\xi|u,h,t)\, f_{U_w,H_s,T_p}(u,h,t)\Delta u \Delta h \Delta t + \sum_{\{u_i,h_i,t_i\}^C} 1\cdot f_{U_w,H_s,T_p}(u,h,t)\Delta u \Delta h \Delta t \tag{16}$$

This simplification of long-term analysis is also applied for marine structures when only wave conditions are concerned and yield good accuracy [22]. The most important and difficult thing is to select appropriate cases to efficiently approximate the FLTA.

Without the knowledge of the 50-year extreme, the selection of environmental conditions can be similar to that of the modified environmental contour method, which is to find the most important condition based on the the extrapolated most probable extreme $Mo_{X_{1\text{-}hr,50\text{-}yr}}(u,h,t)$ and other environmental conditions around it. Depending on the bin size of the environmental parameters, different numbers of cases should be used.

6 Modeling and simulations

The model used is the NREL 5MW pitch-regulated wind turbine supported by a jacket structure. The jacket structure is 92 meter high located at 79 meter deep water. Here the jacket structure is simplified as a six-section monopile with each

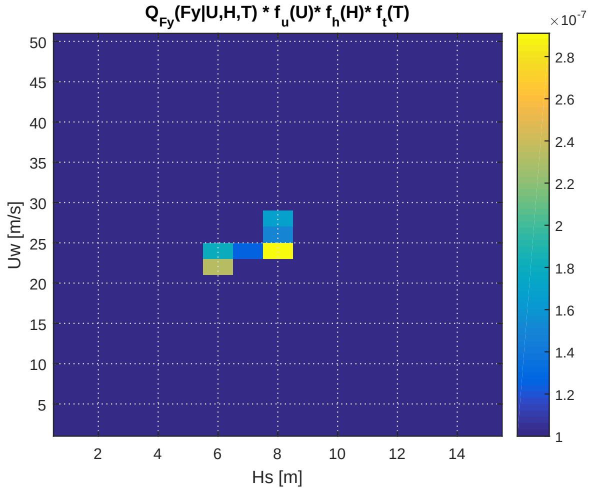

Fig. 9. The exceedance probability contribution of the bottom shear force from each environmental condition (only cases with largest values are included for a more clear comparison).

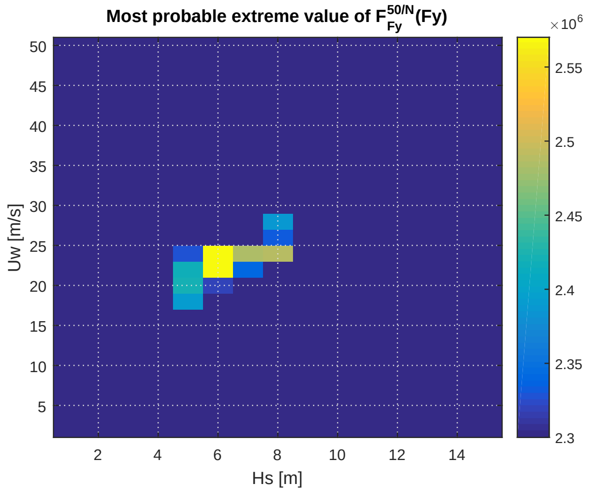

Fig. 10. The most probable extrapolated 50-yr 1-hr extreme response of the bottom shear force under each environmental condition (only cases with largest values are included for a more clear comparison). The found cases covers the ones in Fig. 9.

section shaped as a cylinder. The bending stiffness and hydrodynamic properties are equivalent to that of the original jacket structure. The model is assumed to be quasi-static, so the wind turbine and the support structure are uncoupled and the wind and wave are simulated separately. The response from combined wind and wave loads is found by summation of response time series induced by wind only and wave only. The simplification has been verified by [14], which significantly reduced the number of simulations needed. The coordinate system of the tower, support and the blades are shown in Fig. 11.

It is modeled by HAWC2 [23] for wind loads and USFOS [24] for wave loads. The wind load is calculated by blade element momentum theory and the wave load is calculated by linear Airy wave theory with Wheeler stretching. The JONSWAP wave spectrum is used.

The environmental condition used is from site 15 in central North Sea in study by [15]. Mean wind speed, significant wave height and spectral peak period are the environmental parameters considered. The wind speed is fit to Weibull distribution, and the significant wave height and spectral peak period are both conditional log-normal distribution. The joint probability density function is as Eq. (17). The turbulence intensity is assumed to be constant as 0.15. The misalignment of wind and wave direction is not considered in this study.

$$f_{U_w,H_s,T_p}(u,h,t) = f_{U_w}(u)\, f_{H_s|U_w}(h|u)\, f_{T_p|H_s}(t|h) \tag{17}$$

The 3-D environmental contour surfaces used in ECM and MECM are generated by the Rosenblatt transformation, which transforms the sphere in normal U-space to the contour surfaces in original X-space. There are 90 10-min simulations

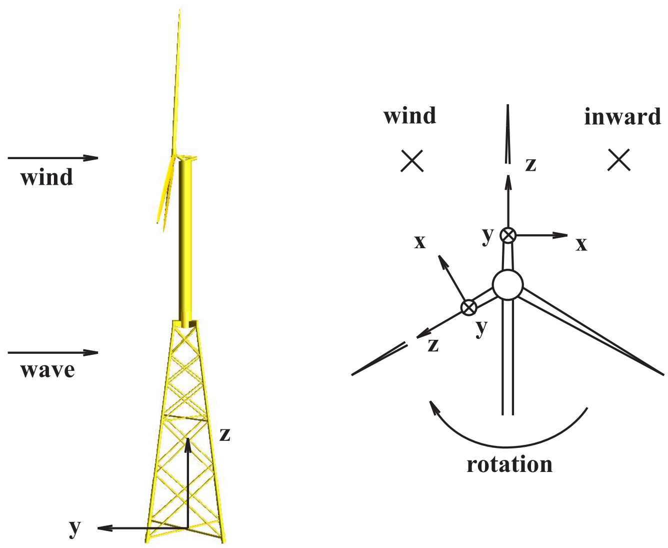

Fig. 11. The global (left) and blade (right) coordinate system. The wind and wave are towards the negative y-direction of the global coordinate. For blades, the z-axis is from root to tip, x-axis is in chordwise direction and y-axis is towards the suction side. [23]

Table 1. The environmental conditions simulated for the FLTA

		min.	max.	bin
U_w	$[m/s]$	2	50	2
H_s	$[m]$	1	15	1
T_p	$[s]$	2	24	2

performed for each environmental condition, which give 90 data points for the extreme responses. This large amount number of simulations is to ensure the probability distribution estimation is accurate and will not affect the result. The 1-hour extreme distribution is calculated based on the 10-min extremes by assuming each 10-min is independent. For the FLTA, the environmental parameters are selected as Table 1.

For ECM, several cases are selected along the 50-year environmental contour. For MECM, the cases are chosen along the contour with different maximum wind speed such as the cut-out wind speed 25 m/s, etc.

The responses considered are the jacket bottom shear force and bending moment, tower bottom shear force and bending moment, and blade root bending moments as shown in Table 2. Since the model is uncoupled, the tower and blade responses are only due to wind loads. The jacket bottom responses are studied under both the wind load only, wave load only as well as combined wind and wave. The responses due to the combined are the summation of the responses induced by wind only and wave only.

7 Results and discussion

The result of ECM, MECM are compared to that of the FLTA. The results of FLTA are shown in Tables 3 and 4.

In Table 3, the combined extreme results is relatively low compared to the sum of the extreme values under wind only or wave only. Especially, the extreme value under combined loads for M_x is very close to that under wind load alone. The reason is that the extreme values of wind and wave do not occur simultaneously. The wave extreme occurs near the 50-year sea state, while the wind extreme occurs within the operational range of the wind turbine. Thus, the low correlation between wind and wave extremes means the combined extreme is much lower than their sum.

7.1 ECM

The original ECM works well with responses that are under wave load only. This is because the responses are monotonically related to the environmental parameters and the assumptions of ECM are valid. ECM prediction for responses under wave loads matches that from FLTA when a higher fractile is used.

Table 2. Types of responses considered in this study

Response	Description
F_y	support bottom fore-aft shear force
M_x	support bottom fore-aft bending moment
$F_{y,Tower}$	tower bottom fore-aft shear force
$M_{x,Tower}$	tower bottom fore-aft bending moment
$M_{x,Blade}$	blade root flapwise bending moment
$M_{y,Blade}$	blade root edgewise bending moment
$M_{z,Blade}$	blade root torsional moment

Table 3. Extreme responses with return period of 50 year obtained by the FLTA.

		Wind	Wave	Combined
F_y	[kN]	2.04E+03	2.58E+03	2.74E+03
M_x	[kNm]	2.39E+05	1.56E+05	2.53E+05

Table 4. Extreme responses with return period of 50 year obtained by the FLTA. These responses are only influenced by wind load, so there is no responses from wave or combined loads.

		Wind
$F_{y,Tower}$	[kN]	1.46E+03
$M_{x,Tower}$	[kNm]	8.37E+04
$M_{x,Blade}$	[kNm]	2.15E+04
$M_{y,Blade}$	[kNm]	1.05E+04
$M_{z,Blade}$	[kNm]	2.65E+02

For the responses under wave loads only, by following ECM procedure, one case on the 50-year contour can be selected, and it predict the 50-year long-term extreme well when a 90% fractile is used as shown in Fig. 12.

However, when wind is included, ECM will under-predict even when a very high fractile is included. This is mainly due to the fact that the environmental condition selected by ECM is far from the true most important one because of the non-montonic behavior of the responses.

When only wind load is considered, the environmental "contour" reduces to a 1-D point with 50-year wind speed 33.7 m/s, at which the wind turbine is parked. Table 5 shows the 99% fractile value. The results from ECM is significantly lower than the FLTA results because the wind turbine is parked at the 50-year wind speed. The responses when parking is generally much lower than that when the turbine is operating.

Due to the problem with the wind loads, when combined loads are considered, ECM cannot perform well either as shown in Fig. 13. ECM prediction of F_y is still conservative and acceptable because F_y is more dependent on the wave condition. However the extreme prediction of M_x is still more than 10% lower than the FLTA result when a high fractile of 90% is used. When even higher fractile such as 99% is used, the M_x extreme can be predicted exactly. But it is not practical because the results of FLTA is not available in reality so the fractile level have to be selected intuitively. The fractile levels are different for each response and are also influenced by the environment of the site. For a typical extreme value probability distribution such as Gumbel distribution, when the fractile level is close to a high value such as 99%, the predicted value is in the tail region of the probability distribution. In this case, a small change of the fractile level will lead to a large difference in the prediction. Fig. 13 shows an example of this problem. One can observe that the change of the value of the percentage differences is much larger when the fractile is higher than 90%. This means that the result based on intuitively selected high fractile level is not consistent.

It should also be noted that the expected or median extreme with a conservative empirical multiplication factor such as

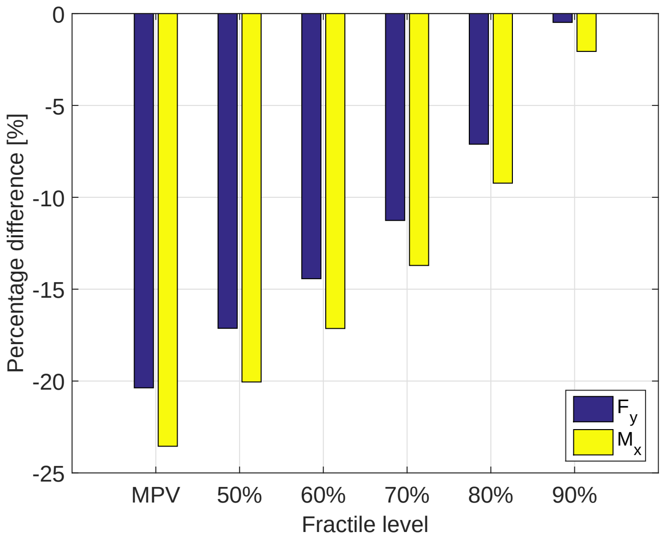

Fig. 12. The percentage difference between ECM prediction at different fractile levels and FLTA results of the extreme response under wave load only. ($\frac{ECM-FLTA}{FLTA} \cdot 100\%$)

Table 5. ECM prediction against FLTA results of the extreme response under wind load only. ECM results are the 99% fractile level extreme at $U_w = 33.7 m/s$.

Method	$F_y[kN]$	$M_x[kNm]$	$F_{y,Tower}[kN]$	$M_{x,Tower}[kNm]$
ECM	4.51E+02	5.61E+04	2.57E+02	1.16E+03
FLTA	**2.04E+03**	**2.39E+05**	**1.46E+03**	**8.37E+04**

Method	$M_{x,Blade}[kNm]$	$M_{y,Blade}[kNm]$	$M_{z,Blade}[kNm]$
ECM	6.08E+03	1.44E+03	9.10E+01
FLTA	**2.15E+04**	**1.05E+04**	**2.65E+02**

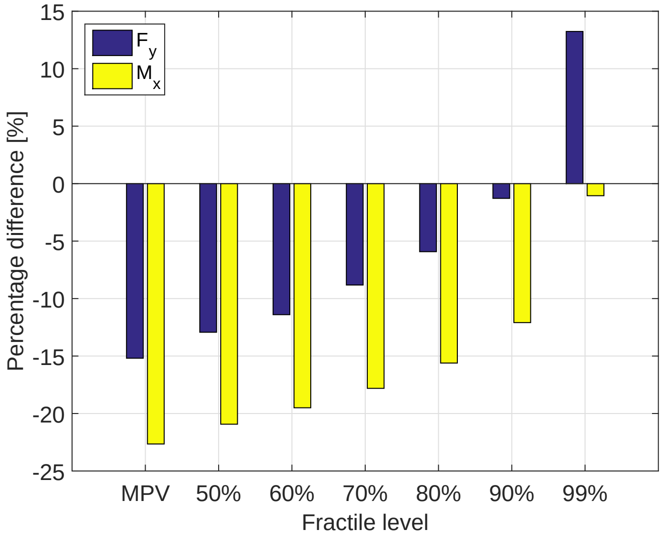

Fig. 13. The percentage difference between ECM prediction at different fractile levels and FLTA results of the extreme response under combined loads. ($\frac{ECM-FLTA}{FLTA} \cdot 100\%$)

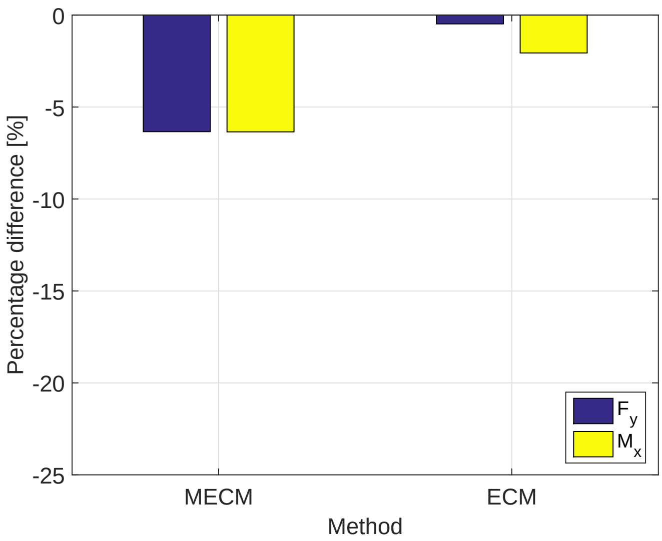

Fig. 14. The percentage difference ($\frac{ECM-FLTA}{FLTA} \cdot 100\%$) between MECM/ECM prediction at different most probable value and 90% fractile level and FLTA results of the extreme response under wave loads. For wave only cases, ECM performs even better than MECM when the appropriate fractile level is chosen, though prediction of MECM is also good (less than 7%).

1.25 was also used for extreme prediction in some study instead of fractile for ECM [21]. Its advantage is that it requires less simulations since only the median is required to be predicted.

7.2 MECM

In this section, the results of MECM are compared to those of the FLTA. The results of MECM shown are all $Mo_{X_{1\text{-}hr,50\text{-}yr}}(u,h,t)$ values.

Compared to ECM, MECM is similar when only wave loads are considered as shown in Fig. 14. Since there is no non-monotonic behavior of the responses, the variability of response can be safely ignored. So the case selected by MECM is close to that selected by ECM as shown also in Table 6. Thus, if a higher fractile such as 90% is applied, ECM can predict the long-term extreme well and have the same prediction as MECM. So when only wave is of interest, the original ECM is the more efficient and effective method.

Table 6. Environmental conditions selected by ECM or MECM.

	$H_s[m]$	$T_p[s]$
ECM	10.8	14.7
MECM	9.3	13.3

However, as explained in Section 4, the advantage of MECM can be seen when wind is included. The environmental conditions tested are listed in Table 7. They range from cut-in to cut-out wind speed evenly with a bin size of 2 m/s, as well as rated speed and more cases near cut-out speed. The MECM predictions are very close to the reference results from FLTA as shown in the Table 8. The results in Table 8 include the most important wind speeds for each response. For most responses, the cut-out wind speed is the most important. However 14 m/s is found to be the most important one for tower responses. Thus additional cases near them are simulated to find more accurate important wind speed for each response.

MECM also have advantage when combined wind and wave are of concern. In Table 9, one can see that MECM predicts the long-term extreme close to that of FLTA. The found cases for the bottom shear force and bending moment are both located on the environmental contour (as shown in Fig. 8) of the cut-out wind speed 25 m/s, which is consistent with the results of the extreme responses under wind load only as shown in Table 8.

The results show that MECM can effectively and efficiently predict long-term extreme response as it does not require a lot of simulations but can provide good prediction. As explained in Section 4.1, when investigating the responses due to combined wind and wave load, the first step is to test environmental conditions with wind speeds between rated and cut-out wind speed and the corresponding most probable sea state to determine the important wind speed for each response. The

Table 7.   Tested wind speeds for responses under wind load only.

$U_w[m/s]$	Description
4 - 24	cut-in to cut-out with bin size of 2 m/s
11.4	rated
13	near 14 m/s (important for tower responses)
15	near 14 m/s (important for tower responses)
25	cut-out
24.8	near cut-out
24.5	near cut-out
23.5	near cut-out
23	near cut-out

second step is to more closely search the environmental conditions located on the contour surface corresponding to the return period of the important wind speed for each response identified in the first step. For this study, seven cases are tested in step 1 (between cut-in and cut-out wind speeds), and four cases are tested in step 2 (on the contour surface corresponding to the return period of the cut-out wind speed) as illustrated in Fig. 8 because the cut-out wind speed is important for both F_y and M_x. So the total number of cases required is eleven. The cases in step 1 need less simulations as they are only used to identify the important wind speeds, while the cases in step 2 may require more simulations to achieve accurate predictions.

7.3 Number of short-term simulations

The results shown in the previous sections are all based on 90 simulations. For efficiency, the simulation number should be as low as possible but still achieve good fits. In section 4.2, a method is described to test if the estimated parameter is accurate enough. Table 10 shows the results of MECM of F_y and M_x under combined wind and wave with different numbers of simulations. It shows that when CI% requirement (3%) is satisfied, MECM result is close to the reference, with less than 5% difference.

7.4 Simplified FLTA

The results of SLTA is compared with the FLTA. In this study, 25 wind speeds, 15 significant wave heights and 12 spectral peak period are used. So the FLTA requires simulations of 25 cases for wind load only, 180 cases for wave load only, and 4500 cases for combined wind and wave. If all the cases are ranked by the value of their extrapolated most probable extreme, the top ranked cases can be included in the long-term analysis while the rest unimportant cases can be discarded. Table 11 shows the comparison of the results of the extreme responses under combined wind and wave loads when different numbers of environmental conditions are included in the simplified long-term analysis.

One can see that for different responses, less than 10% of the cases are required to be simulated to achieve the same result as the FLTA. For both responses, 20 cases gave a reasonably close results to the FLTA.

However, selecting the important cases will be difficult. One possible method is to select the cases the same way as described in MECM. Following MECM, one target case will be selected for each response, and the cases surrounding the target can be included in the SLTA. For wind only response, only one case for the most critical wind speed (4% of total cases) is needed to achieve a good result compared to that from FLTA as shown by Table 12.

For wave only cases, using one case is not enough because it only covers 0.5% of the environmental conditions. When 9 cases (3% of the total cases) around the target case found by MECM are included, the result of the responses are very close to that of the FLTA as shown by Table 13.

For combined wind and wave cases, the procedure is the same. If simulating 18 cases (0.4%) surrounding the target, we have the long-term results as Table 14. Compared to wind only or wave only conditions, the combined load requires fewer cases in terms of its ratio to the number of total cases for FLTA analysis.

The result of the SLTA is close to that of the FLTA, each with a difference of less than 10%. However, compared to MECM, it does not have advantages as it requires more simulations and cases to consider but does not achieve a more accurate prediction.

Table 8. MECM prediction of the extreme response under wind load. The table shows the results of the some of the tested cases. The bold one are the identified most important wind speeds for different responses.

$U_w[m/s]$	$F_y[kN]$	$M_x[kNm]$	$F_{y,Tower}[kN]$	$M_{x,Tower}[kNm]$
4	5.97E+02	8.30E+04	5.11E+02	2.88E+04
11.4 (rated)	1.54E+03	1.98E+05	1.18E+03	7.17E+04
13	1.64E+03	2.11E+05	1.34E+03	7.64E+04
14	1.71E+03	2.34E+05	**1.45E+03**	**8.41E+04**
15	1.70E+03	2.26E+05	1.40E+03	8.02E+04
23	1.84E+03	2.15E+05	1.19E+03	6.84E+04
23.5	1.91E+03	2.19E+05	1.29E+03	7.17E+04
24	2.01E+03	2.27E+05	1.21E+03	7.03E+04
24.5	1.98E+03	2.24E+05	1.23E+03	6.74E+04
24.8	**2.04E+03**	2.28E+05	1.22E+03	6.91E+04
25 (cut-out)	2.03E+03	**2.38E+05**	1.32E+03	7.56E+04
FLTA	**2.04E+03**	**2.39E+05**	**1.46E+03**	**8.37E+04**

$U_w[m/s]$	$M_{x,Blade}[kNm]$	$M_{y,Blade}[kNm]$	$M_{z,Blade}[kNm]$
4	5.40E+03	4.29E+03	3.83E+01
11.4 (rated)	1.94E+04	8.09E+03	1.67E+02
13	1.96E+04	7.79E+03	1.82E+02
14	2.01E+04	7.67E+03	1.72E+02
15	2.03E+04	7.59E+03	1.70E+02
23	1.81E+04	9.31E+03	2.47E+02
23.5	1.90E+04	1.01E+04	2.43E+02
24	**2.10E+04**	**1.04E+04**	**2.63E+02**
24.5	2.03E+04	9.85E+03	2.53E+02
24.8	1.96E+04	9.90E+03	2.51E+02
25 (cut-out)	1.92E+04	9.91E+03	2.46E+02
FLTA	**2.15E+04**	**1.05E+04**	**2.65E+02**

Table 9. MECM prediction of the extreme response under combined wind and wave load. All the cases listed are selected on the environmental contour corresponding to the cut-out wind speed 25 m/s (0.077-year) as shown in Fig. 8.

$U_w[m/s]$	$H_s[m]$	$T_p[s]$	$F_y[kN]$	$M_x[kNm]$
24.5	6.2	10.5	**2.79E+03**	2.40E+05
24	6.3	10.6	2.39E+03	2.27E+05
25	5.6	9.9	2.45E+03	2.36E+05
24.8	6	10.3	2.65E+03	**2.51E+05**
FLTA			**2.74E+03**	**2.53E+05**

Table 10. MECM prediction of the extreme response under combined wind and wave load with different numbers of simulations.

No. of sim	$F_y[kN]$		$M_x[kNm]$	
	$CI\%$	MECM	$CI\%$	MECM
90 (ref)	2.50%	2.79E+03	1.92%	2.51E+05
80	3.00%	2.79E+03	1.96%	2.52E+05
60	3.08%	2.90E+03	2.17%	2.54E+05
40	4.97%	3.02E+03	2.49%	2.55E+05
20	10.96%	2.89E+03	3.10%	2.44E+05

Table 11. The SLTA prediction of the extreme responses with different numbers of simulated environmental condition under combined wind and wave loads.

No. of cases	$F_y[kN]$	$M_x[kNm]$
1	2.48E+03	2.30E+05
2	2.52E+03	2.36E+05
5	2.62E+03	2.39E+05
10	2.65E+03	2.47E+05
20	2.67E+03	2.49E+05
50	2.71E+03	2.52E+05
100	2.72E+03	2.52E+05
200	2.73E+03	2.53E+05
500	2.73E+03	2.53E+05
1000	2.74E+03	2.53E+05
2000	2.74E+03	2.53E+05
4500 (FLTA)	**2.74E+03**	**2.53E+05**

Table 12. SLTA prediction of the extreme responses under wind load only. Numbers of simulated cases are labeled in the parentheses.

	$F_y[kN]$	$M_x[kNm]$	$F_{y,Tower}[kN]$	$M_{x,Tower}[kNm]$
SLTA(1)	2.03E+03	2.35E+05	1.42E+03	8.26E+04
FLTA(25)	**2.04E+03**	**2.39E+05**	**1.46E+03**	**8.37E+04**

	$M_{x,Blade}[kNm]$	$M_{y,Blade}[kNm]$	$M_{z,Blade}[kNm]$
SLTA(1)	2.11E+04	1.05E+04	2.64E+02
FLTA(25)	**2.15E+04**	**1.05E+04**	**2.65E+02**

Table 13. SLTA prediction of the extreme responses under wave load only. Numbers of simulated cases are labeled in the parentheses.

	$F_y[kN]$	$M_x[kNm]$
SLTA(9)	2.54E+03	1.53E+05
FLTA(180)	**2.58E+03**	**1.56E+05**

Table 14. SLTA prediction of the extreme responses under combined wind and wave load. Numbers of simulated cases are labeled in the parentheses.

	$F_y[kN]$	$M_x[kNm]$
SLTA(18)	2.57E+03	2.39E+05
FLTA(4500)	**2.74E+03**	**2.53E+05**

8 Conclusions

The paper introduces MECM, which is a simplified method for the long-term extreme response predictions for bottom-fixed offshore wind turbines based on ECM. The results from the original ECM, MECM and SLTA are compared. The conclusion is shown as follows:

1. ECM is an efficient method when its assumptions are valid. When under wave loads only or when parking, the variability of the responses can be omitted because the responses are monotonic in relation to the environmental conditions. Thus, for bottom-fixed offshore wind turbines, the method can be applied for responses dominated by wave or when only parking condition is considered.
2. For the responses that are dominated by wind when the wind turbine is operating, ECM is not applicable due to the non-monotonic behavior of the responses in relation to the wind speed. The environmental condition selected by ECM is far from the actual important condition that contributes the most to the long-term extreme.
3. MECM is applicable in any situation because it does not ignore the variability of the responses with respect to the environmental conditions and bypassed the non-monotonic behavior of the response. Thus, it can substitute ECM when wind load is important. It does not require empirically selecting fractile levels. The results show that MECM predictions are close to that of the FLTA.
4. The FLTA can utilize MECM to identify the important environmental condtions and be simplified as SLTA. So less environmental conditions are required while the same prediction can be achieved.

Currently, only ECM and the FLTA are used for offshore wind turbines. As shown here, the first method is not suitable for offshore wind turbines and its results are not conservative. It is not reliable due to the empirical selection of the high fractile level. The FLTA on the other hand is not efficient and requires a lot of simulations. It can be seen that MECM is an efficient and effective method for the long-term extreme prediction for offshore bottom-fixed wind turbines compared to the existing methods. It can be easily implemented in the current design requirements because it only requires statistical extrapolation of the extreme responses from load cases.

The offshore wind turbines are inherently different from ordinary offshore structures. It is important for the designers to not neglect the non-monotonic behavior of the wind turbine responses, and include that effect in the prediction of the extreme responses.

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