Efficient determination of the long-term extreme responses by the modified environmental contour method for a combined wind turbine and wave energy converter system

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This paper deals with the performance of the Modified Environmental Contour Method (MECM) for determining long-term extreme load effect in a combined wind turbine and wave energy converter system. The wind turbine of the combined system is in the operational or parked mode depending on the wind speed. In addition, the wave energy converter in this study also experiences three modes depending on the significant wave height to reduce structural responses under extreme sea states. These features make the original Environmental Contour Method (ECM) not applicable to the prediction of the long-term extreme of some responses. However, the MECM is suitable for

analysis in such a system as it includes the effect of the changes of operational mode by considering additional environmental contours. It is found that the results of the MECM agree very well with the full long-term analysis (FLTA) which indicates that the MECM is applicable for such a system. In addition, the MECM can also be used to identify important environmental conditions to include in the reduced long-term analysis (RLTA), which is similar to FLTA but only includes selected environmental conditions that contribut to the relevant extreme responses.

Introduction

Recently there is a growing interest of combining wave-energy converter (WEC) and wind turbine concept. The reason for such systems is to utilize the ocean space more efficiently in the wind farm because wave and wind energy are naturally correlated. The MARINA Platform project (*MARINA, 2014*) aimed at developing analysis tools for new multi-purpose floating platforms for marine renewable energy. As a results, several combined floating wind turbine and WEC concepts were investigated, including a oscillating-water-column-type WEC or a point-absorber-type WEC with a semi-submersible type floating wind turbine " WindFloat" (*Peiffer et al., 2011*), a combination of a wind turbine on a semi-circular-shaped barge with a surge-type WEC (*Soulard and Babarit, 2012*), a concept of a 5-MW wind turbine and three point absorber WEC's with a single column tension leg platform (*Bachynski and Moan, 2013*), a combined semi-submersible wind turbine and rotating flap type wave energy converters (SFC) (*Michailides et al., 2014*) and a combination of a spar-type wind turbine (*Karimirad and Moan, 2012*) and a torus-shaped point absorber-type WEC (STC) (*Muliawan et al., 2012, Muliawan et al., 2013, Ren et al., 2015*). The latter concept is investigated in this study. It was found that the STC system has greater responses compared to an ordinary spar wind turbine. Slamming and green water effects were also found in laboratory tests (*Wan et al., 2014*). Thus, several survival strategy was proposed and investigated for this STC system to reduce loads under extreme conditions including reducing PTO damping and submerging the torus (*Ren et al., 2015*). Such strategies of the WEC in addition to the operation behaviour of the wind turbine make the estimation of extreme responses harder because traditional environmental contour method (*Haver and Winterstein, 2009*) that only investigates the environmental conditions on the contour corresponding to a certain return period may not be suitable. However, the modified environmental contour method (MECM) (*Li et al., 2013,Li et al., 2016*) that considers multiple environmental contours to include the difference of different operational mode could still be applicable. The MECM has been tested for a bottom-fixed (*Li et al., 2013,Li et al., 2016*) and a semi-submersible wind turbine, and the results agrees well with the more accurate but time-consuming full long-term analysis (FLTA).

In this study, the applicability of the MECM for the long-term extreme prediction for the wind turbine and WEC (STC) concept is tested. The MECM for wind turbines considers two environmental contours corresponding to 50-year and cut-out wind. For this combined concept, the MECM is extended by adding additional contours corresponding to key significant wave heights where the operational mode of the WEC is changed. The performance of the reduced long-term analysis using only the environmental condition tested by the MECM is also investigated.

1 Brief overview of the methods of the long-term extreme response analysis

1.1 Full long-term analysis

The full long-term analysis is in principle an exact method to account for the long-term variability of environmental conditions and the variability of the short-term extreme responses. It has been applied for extreme load prediction for wind turbines in many studies (*Lott and Cheng, 2016*). The method integrates 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 to find the long-term CDF of the extremes. Other approaches such as peak-over-threshold (POT) or up-crossing rate can also be used. Full long-term analysis for N-year return period is often described by Equation 1 if one-hour extreme is used. $F_X(\xi)$ is either the long-term or short-term CDF, 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. It is stated in (*Naess and Moan, 2012*) that Equation 1 is based on the reliability theory and is an approximation of the "exact" method though the difference is usually very small. Since Equation 1 is straightforward and is the basis of the simplified methods such as ECM and MECM, it is used here as comparison to evaluate the performance of the simplified methods.

$$F_X^{LT}(\xi) = \iiint F_X^{ST}(\xi) f_{U_W,H_S,T_P}(u,h,t)dudhdt = 1 - 1/(N * 365.25 * 24) \tag{1}$$

1.2 Environmental Contour method

The ECM has been widely used in the to determine long-term extreme responses. In theory, the version commonly applied is a simplified method based on the Inverse first-order reliability method (IFORM) (*Winterstein et al., 1993*), but without the variability of the extreme response. The method uses a contour corresponding to a desired return period (e.g. 50 year) consisting of all the environmental parameters. Then only the cases located on the environmental contour are checked and the largest short-term extreme response among them is the long-term result. The environmental condition that has the largest long-term extreme is called the "design point". The short-term extremes used are obtained at an empirical fractile level of the distribution that is higher than 50%. The fractile value is usually between 70% to 90% (*Winterstein et al., 1993, Madsen, 1988*). ECM greatly reduces the number of environmental conditions to be considered since only the ones on the contour are to be checked. Usually, only part of the contour is of interest (e.g. high wind speed or high significant wave height). The idea of ECM can be described by Equation 2, where p is an empirical value greater than 50%.

$$\xi = F^{LT^{-1}}(1 - 1/(N * 365.25 * 24)) \approx F^{ST^{-1}}(p|u_{ECM}, h_{ECM}, t_{ECM}) \tag{2}$$

The method performs well for normal offshore structures that have wave-induced responses monotonically increasing with the significant wave height. For such systems, the environmental conditions located on the outer contour will be close to the true critical conditions. For systems like wind turbines or other structures that may change its operation mode to limit responses in extreme conditions, the ECM performs poorly and often under-estimates the long-term extreme (*Saranyasoontorn and Manuel, 2004, Rendon and Manuel, 2014, Li et al., 2013, Li et al., 2016*). When wind turbine rotor is parked, the responses of blades, tower or mooring lines may be greatly reduced under extreme conditions compared to the conditions when the rotor is operational. The long-term extremes of these responses are often caused by more frequent occuring environmental conditions within the operational range.

1.3 Modified Environmental Contour method

In Section 1.2, it is explained that ECM does not work well in all situations and requires a modification when applying to systems that change mode depending on the environmental condition. The MECM uses multiple contours in addition to the contour corresponding to the return period used by ECM. For example, an environmental contour with a maximum mean wind speed corresponding to the cut-out wind speed is added in previous studies to account for wind turbines extreme responses when operating. In this study, the WEC will have lower PTO damping value or be submerged depending on wave condition. Thus, two more additional contours are added corresponding to significant wave heights of 6 and 12 meter, at which the WEC changes its operational mode. Thus, for the system in this study, there are additional environmental contours corresponding to cut-out wind speed, significant wave heights of 6 and 12 meter inside the original contour of the ECM.

Equation 3 demonstrates the idea of MECM. It should be noted that the CDF of the contours are extrapolated according to Equation 4, where M is the return period in year for the environmental contours. The extrapolation is necessary because the inner contours have a lower return period and requires a much higher fractile level of the short-term extreme responses. p_i are the empirical fractile levels of the extrapolated short-term extreme response distribution for each environmental contour. The largest value of the extreme responses from all the environmental contours is the result of MECM. Though MECM is more complicated than ECM with more environmental contours, it is more reliable, especially for wind turbines or the combined system in this study. Still, the computational effort is much less than the FLTA. More detail of the MECM are given in (*Li et al., 2016*).

$$\begin{aligned}\xi_1 &= {F_{N-yr}^{ST}}^{-1}(p_1|u_{contour1},h_{contour1},t_{contour1})\\ \xi_2 &= {F_{N-yr}^{ST}}^{-1}(p_2|u_{contour2},h_{contour2},t_{contour2})\\ &\vdots\\ \xi_{ECM} &= {F_{ECM}^{ST}}^{-1}(p|u_{ECM},h_{ECM},t_{ECM})\\ \xi &\approx max[\xi_1,\xi_2,\ldots,\xi_{ECM}]\end{aligned} \tag{3}$$

$$F_{N-yr}^{ST}(\xi) = F^{ST}(\xi)^{N/M} \tag{4}$$

1.4 Reduced long-term analysis (RLTA)

Previous studies (*Li et al., 2013, Videiro and Moan, 1999*) have shown that it is possible to perform long-term analysis with reduced number of cases that only covers the important environmental conditions. Thus, by using the exceedance probability $Q = 1 - F$ where F is CDF, Equation 1 becomes 5, where only a part of the environmental conditions are integrated while the others are ignored.

$$Q_X^{LT}(\xi) = \iiint_{reduced} Q_X^{ST}(\xi) f_{U_W,H_S,T_P}(u,h,t) dudhdt = 1/(N * 365.25 * 24) \tag{5}$$

Such a change will always under-estimate the results compared to the full long-term analysis because the calculated exceedance probability value will be lower with the same extreme responses (i.e. ξ in Equation 5). However, if the important cases are included, the difference should be very small. One conservative approach is adding a 10% increase to the results from Reduced long-term analysis. It has been shown in (*Li et al., 2013*) that such method will produce very accurate results even when only less than 20% of the environmental conditions are included. The difficulty of RLTA is to efficiently locate the important conditions. This problem can be solved by applying the same principle of ECM and MECM. When applying the ECM and MECM, a number of environmental condition on certain part of the contours (usually with high wind speed or significant wave height) will be checked. RLTA can be performed by directly using these same environmental conditions as the important cases are generally covered.

One advantage of the RLTA is that the results will be more stable compared to those obtained by ECM/MECM as there will be not be any large over-estimation found in ECM and MECM when the empirical fractiles may be too high for some responses.

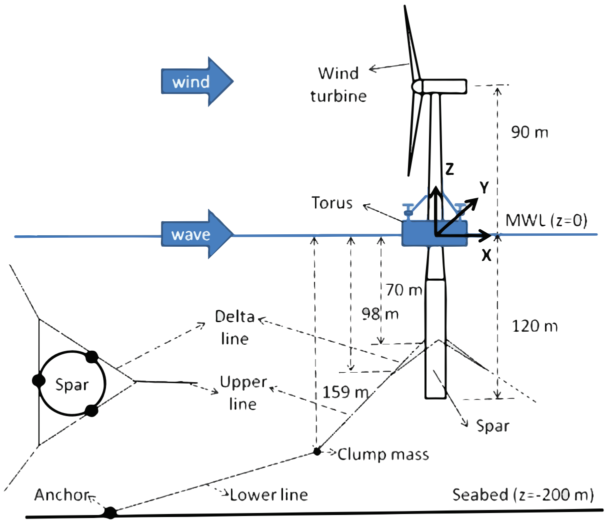

Figure 1: Combined wind turbine and wave energy converter (STC) system.

2 Combined wind turbine and wave energy converter system

The combined STC system in this study is inspired by spar-type wind turbines such as “Hywind” and the two-body axis-symmetric floating WEC, such as “Wavebob”. The system is illustrated in Figure 1. The torus moves along the spar and harness wave energy. The combined concept is based on the NREL 5 MW wind turbine (*Jonkman et al., 2009*) and the torus in (*Muliawan et al., 2012*). The details of the power-take-off (PTO) and connection between the torus and the spar are described in (*Muliawan et al., 2012*). The mooring systems consists of of three mooring lines with clump weight and four segments. The delta lines provide yaw stiffness for the spar.

In the numerical study, the system is modeled as two rigid bodies, the wind turbine and the torus which are connected by mechanical coupling at the interface. The hydrodynamic coupling is also included. The stochastic analysis of the combined system is performed with SIMO-TDHMILL (*Karimirad and Moan, 2012*) in time domain. SIMO models the multi-body system and include the mechanical and hydrodynamic coupling of the bodies. The wave loads are generated according to the frequency domain analysis from WAMIT, including first and second order wave forces. The viscous forces are modeled as the Morison drag. The loads from wind turbine is approximated by TDHMILL as thrust forces on the top of the tower. The drag force of the tower is also included. The torus is able to move in heave direction while constrained in other five DOFs. More detail of the modeling of the connection of the torus and the spar is discussed in (*Muliawan et al., 2012*). The mooring system is modeled as nonlinear springs. The drag forces caused by the mooring line motion is simplified as the inertia forces are ignored. The power take-off (PTO) of the WEC is modeled as a spring-damper combination and the power produced by the WEC is approximated by the product of the PTO damping and the velocity of the torus. In this study, the spring and damper is considered linear. This includes the internal force between the torus and the spar proportional to their relative velocity and position.

In the previous study on the extreme responses of the system (*Ren et al., 2015*), it was found that by implementing a better survival and operation strategy, the extreme responses of the system can be greatly reduced. Three different modes are purposed in (*Ren et al., 2015*). They are the normal operational mode, the low PTO damping mode, and the submerged mode. The wave-energy converter changes its mode based on the significant wave height. The three modes are normal operation (when H_S is less than 6 meter), low PTO (when H_S is between 6 and 12 meter) and submerged mode (when H_S is larger than 12 meter). The PTO damping of the normal mode is 8000 kNs/m while the low value is 1000 kNs/m. The low PTO mode can decrease the responses caused by WEC. The submerged mode aim to fill the locked torrus with sea water and submerged the whole system so that the torus is below sea surface in most cases to reduce wave loads. It also reduces the probability that torus moves above water level and causes slamming when re-entering. All modes are illustrated from Figures 2 to 4. Therefore, the system has three modes of the WEC combined with two modes for the wind turbines (operation/parking) as shown in Table 1, which make the estimation of long-term extreme responses more compli-

Table 1: Different operational mode for the combined wind turbine and WEC system. The units are m/s and m for Uw and Hs respectively. The Uw in this table is the hub-height mean wind speed. The normal and low PTO damping are 8000 and 1000 kNs/m respectively.

	$4 < Uw < 25$	$Uw > 25$
$0 < Hs < 6$	WT: operational; WEC: operational	WT: parked ; WEC: operational
$6 < Hs < 12$	WT: operational; WEC: low PTO	WT: parked; WEC: low PTO
$Hs > 12$	WT: operational; WEC: submerged	WT: parked; WEC: submerged

cated. Thus, it is important to include the effects of these changes of operational modes when estimating the long-term extreme responses. For MECM, four contours corresponding to 50-year return period, cut-out wind speed, wave height of 12 and 6 meters are required. For some sites, the number of contours could be less if some of the contours listed has return period larger than 50 year.

Both motion and structural responses of the system are considered in this study. Table 2 lists all the response variables and the results for the long-term extreme predictions are presented in Section 4. As stated above, a major concern for this concept is the possible slamming when the torus exits and re-enters the water. Due to the limitation of the numerical model, it is not possible to include the structural responses caused by slamming. However, it is possible to use the contact velocity when torus re-enters the water as an indicator for slamming. This velocity can be represented by the relative velocity of torus and wave elevation when torus enters the water. Thus, this velocity is included as shown in Table 2 (response variable 10). Other structural and motion responses are also shown (response variables 1 - 9) in Table 2.

3 Environmental conditions

The information about the environmental conditions used in this study is from (*Li et al., 2015*). Site 3 and site 14 are considered, and the basic information are listed in Table 3. In this study, the water depth of 200 meter is used for both sites because it is the design value for the system.

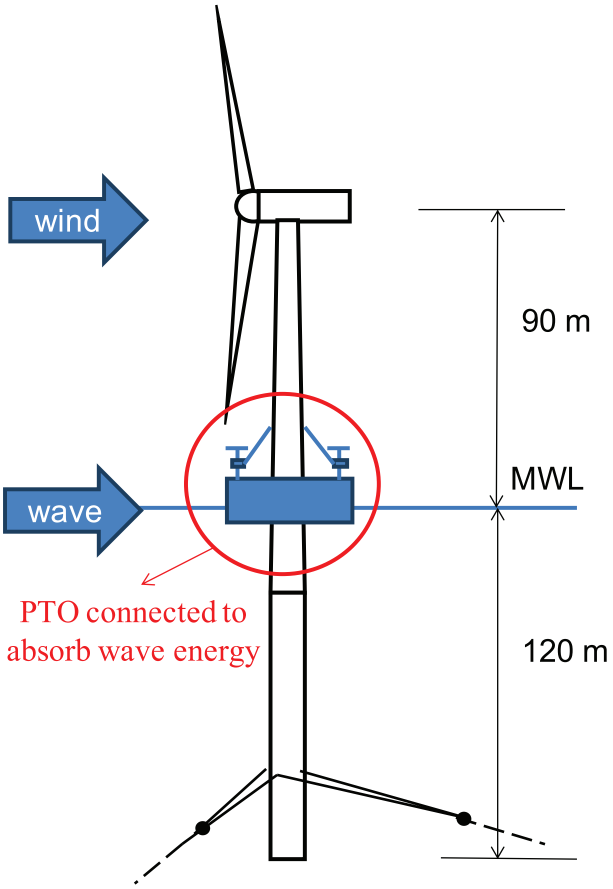

Figure 2: Normal mode of the system. WEC is operating as normal.

Table 2: Responses parameters of the STC.

No.	Response Descriptions
1	Spar-torus horizontal contact force [kN]
2	Spar surge [m]
3	Spar heave [m]
4	Spar pitch [degree]
5	Surge acceleration $[m/s^2]$
6	Pitch acceleration $[degree/s^2]$
7	Relative heave [m]
8	Axial force of upper mooring line 2 [kN]
9	Tower fore-aft bending moment [kN*m]
10	Torus-water contact velocity [m/s]

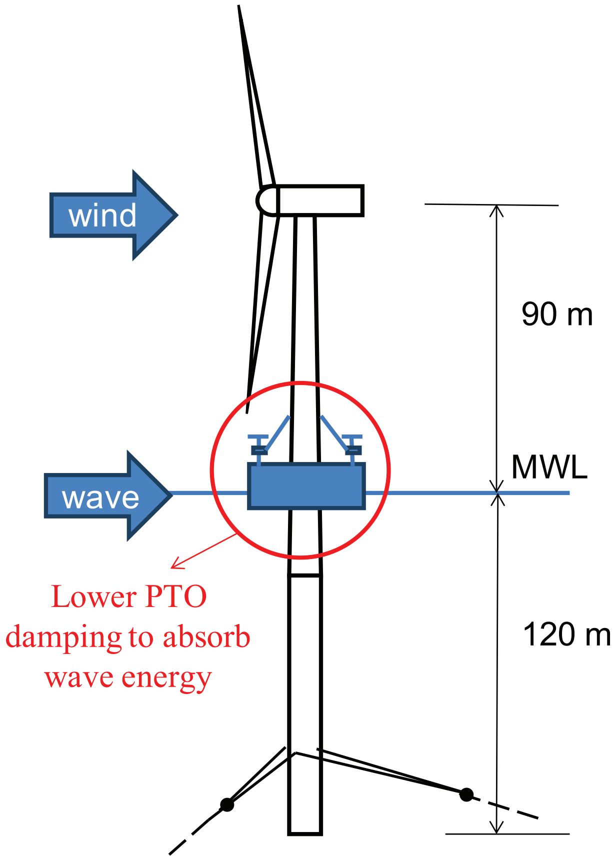

Figure 3: System with normal operation but with reduced PTO damping.

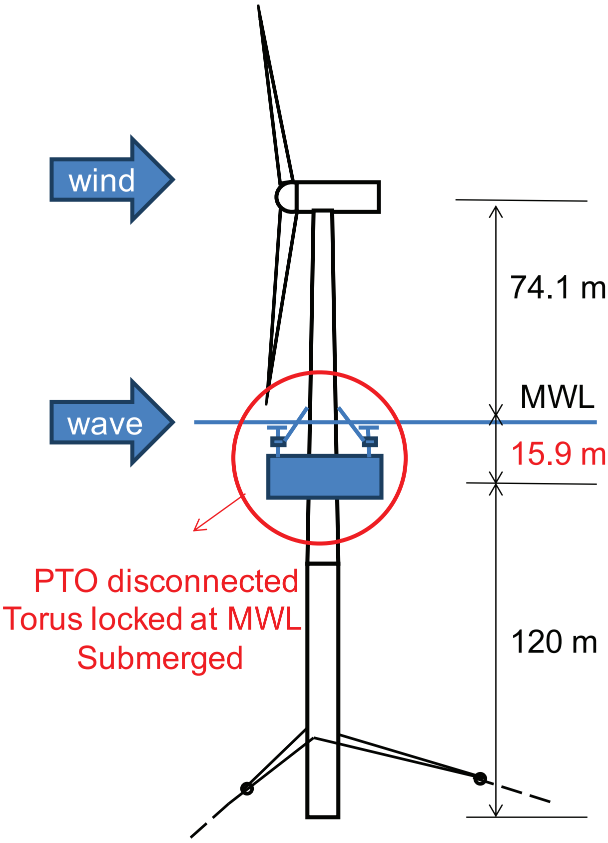

Figure 4: Submerged mode of the system. Torus is fixed, filled with water and submerged. The whole system is lowered.

Table 3: Basic information of the two sites. The 50-year extreme mean wind speed (10 meter) and significant wave height are shown.

	Site 3	Site 14
Location	Atlantic	North Sea
U_{W50-yr} [m/s]	28.37	10.19
H_{S50-yr} [m]	33.49	10.96

Table 4: Envrionmental conditions for full long-term analysis. Total number of cases is 3726. The wind speed is more coarse beyond cut-out wind speed due to responses being lower thus less important when wind turbine is parked.

	Cases
U_W [m/s]	4, 6, ..., 26
	30, 34, ..., 50
H_S [m]	1, 2, ..., 20
T_P [s]	3, 5, ..., 25 (if $H_S < 10$)
	7, 9, ..., 25 (if $H_S \geq 10$)

Only the environmental conditions (i.e. mean wind speed, significant wave height and peak spectral period) of the two sites are used. The turbulence intensity is assumed to be constant at 0.15. For FLTA, the cases considered are listed in Table 4. More detailed information can be found in (*Li et al., 2015*), including the probability distribution of all the environmental parameters.

As mentioned in Section 2, four contours corresponding to the 50-year return period, cut-out wind speed, wave height of 12 and 6 meters (for the changes of operational mode of WEC) need to be studied for MECM. Figures 5 and 6 show the contours for site 3 and 14 respectively. The contours are created using IFORM (*Winterstein et al., 1993*) and Rosenblatt transformation (*Rosenblatt, 1952*) of all the environmental parameters. It can be seen that only three contours are presented for site 3 since the contour corresponding to significant wave height of 12 meter has a return period larger than 50-year.

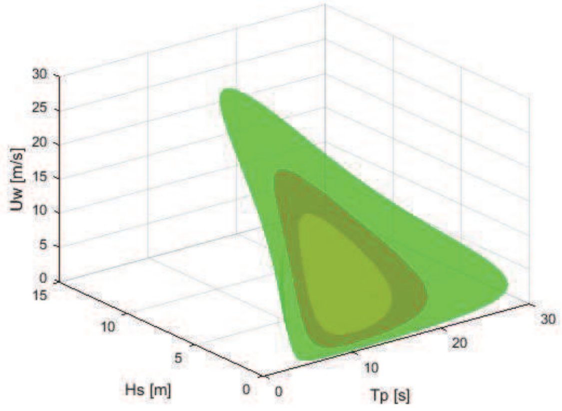

Figure 5: Environmental contours corresponding to the 50-year return period, cut-out wind speed, significant wave height of 6 meters (from outside to inside) for Site 3.

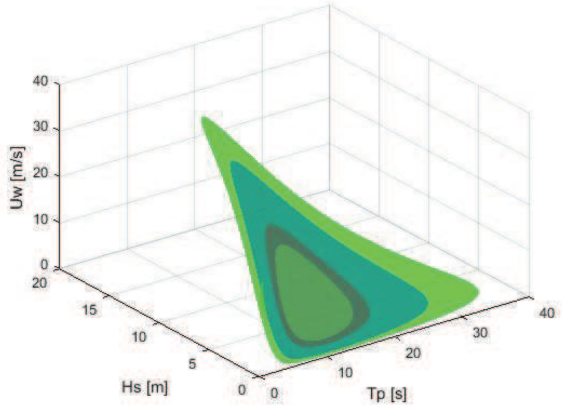

Figure 6: Environmental contour corresponding to the 50-year return period, significant wave height of 12 meters, cut-out wind speed, significant wave height of 6 meters (from outside to inside) for Site 14.

4 Results of long-term extreme responses

4.1 ECM and MECM

As shown in Sections 1.2 and 1.3, ECM considers the environmental contour for 50-year return period while MECM studies all the contours as mentioned in Section 3. The contour surfaces shown in Figures 5 and 6 are discretized as shown in Figures 8 to 14. The black points represent the “design point”s to be used in MECM. The design points are the ones that provide the greatest short-term extreme response of all the points on each contour. The cross points represents the cases to be tested for ECM and MECM as these are the ones with higher wind speed and significant wave heights. It can be seen that these cases included the design points which means that the selected range is sufficiently large for ECM/MECM.

First issue for ECM and MECM is how to efficiently locate the important “design point”s on the contour. In previous studies of a bottom-fixed offshore wind turbine as well as a semi-submersible wind turbine, the “design point”s were found to be located near the maximum wind speed or maximum significant wave heights which should occur near each other. The same trend can be observed in this study as well. It can be seen from Figures 8 to 14 that the important “design point”s for ECM and MECM shown as black dots are near the “tip” where maximum wind speed and significant wave height occur. Thus, it is reasonable to ignore points that are far away from this “tip” on the contour when applying ECM or MECM in future studies for long-term extreme response predictions. One way to select these cases is to create a plane such as the one shown in Figure 7. The plane is created based on the distance to the “origin” and its normal vector, which goes from “origin” to the “tip”. The so called “origin” is the origin point in U-space transformed to X-space, which represents the most probable combination of wind speed and sea state. The part of the environmental contour that is outside of this plane can be selected for ECM or MECM. The cross points in Figures 8 to 14 are selected by this method.

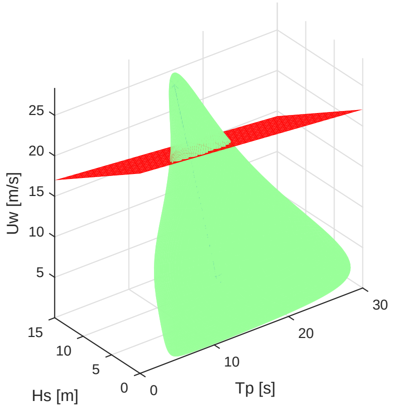

Figure 7: 50-year environmental contour of Site 3 and the separation plane, beyond which the cases are selected for ECM, MECM and RLTA.

The total numbers of environmental conditions for MECM of site 3 and site 14 are 121 and 211, respectively. They are significantly smaller than the number of cases that FLTA uses, which is 3726 in this study.

The responses considered are listed in Table 2. The results of FLTA, ECM and MECM are compared as shown in Tables 5 and 6 as well as Figure 15. Tables 5 and 6 show the fractile levels required for each environmental contour to achieve the same extreme results as the full long-term analysis. With reference to the 90% fractile level for 50-year contour and 50% for the other environmental contours, the percentage differences between FLTA and ECM/MECM are shown by Figure 15. 90% fractile is commonly used for ECM and 50% is used previously for inner environmental contours for MECM for offshore wind turbines.

Alternatively, a multiplication factor on the mean value of the extreme was also used instead of fractile level to achieve the long-term results, and it was discussed in previous studies on wind turbines (*Li et al., 2013*) and WEC (*Muliawan et al., 2012*). Factors of 1.2 for ECM and 1.0 for other contours with extrapolated expected extreme were used. The percentage differences when using multiplication factor are shown in Figure 16. Similar to earlier studies, it can be seen that

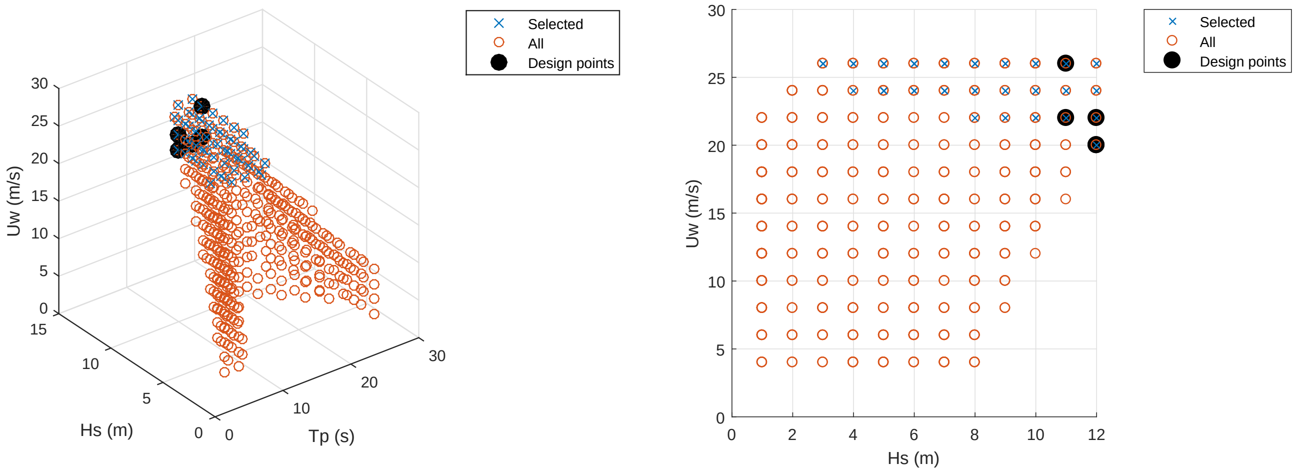

Figure 8: Discrete points of environmental contours corresponding to the 50-year return period for Site 3. The cross dots represents the selected conditions. The black dots represents the design points.

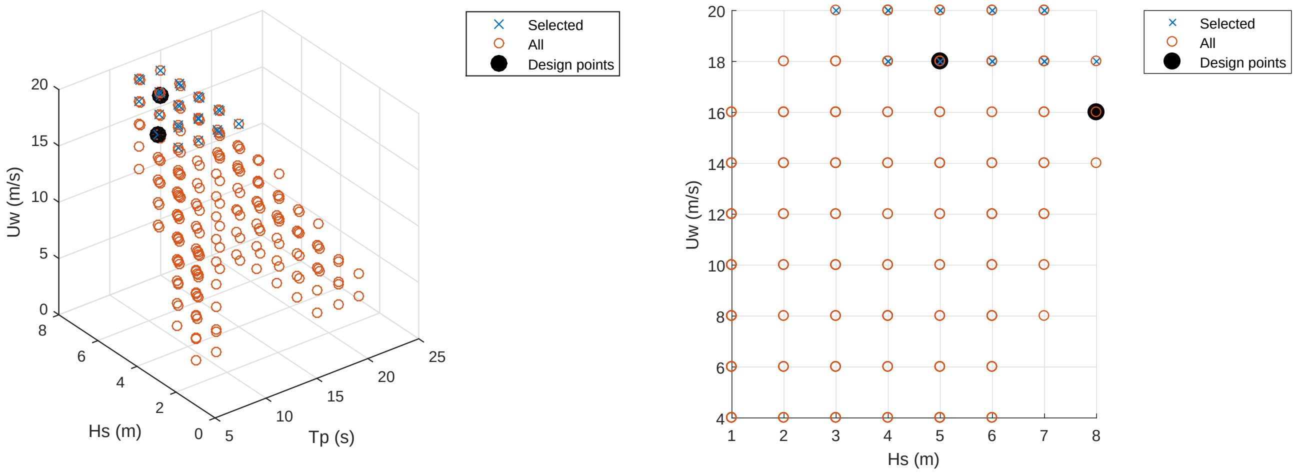

Figure 9: Discrete points of environmental contours corresponding to the cut-out wind speed for Site 3. The cross dots represents the selected conditions. The black dots represents the design points.

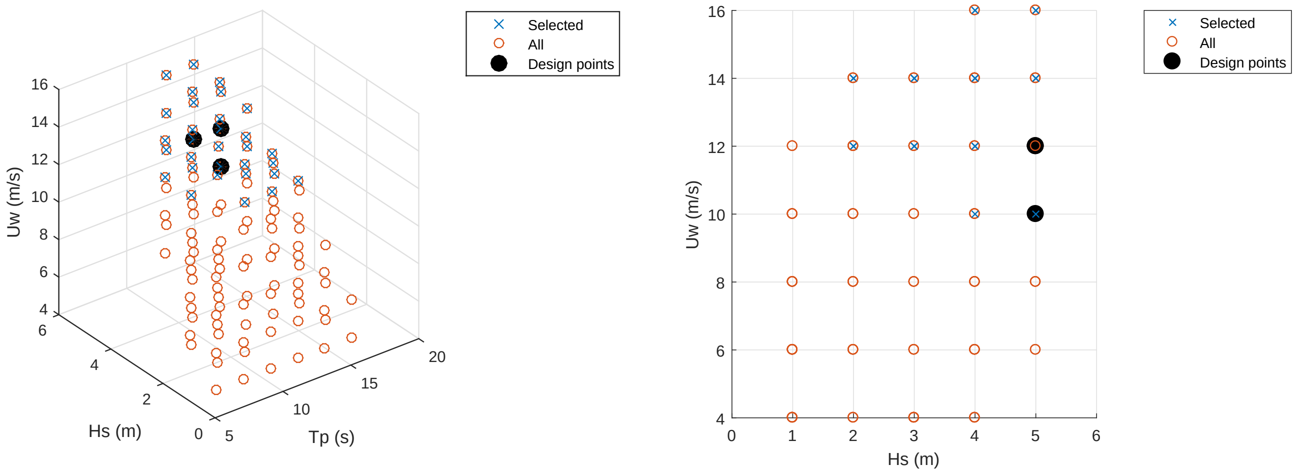

Figure 10: Discrete points of environmental contours corresponding to the maximum significant wave height of 6 m for Site 3. The cross dots represents the selected conditions. The black dots represents the design points.

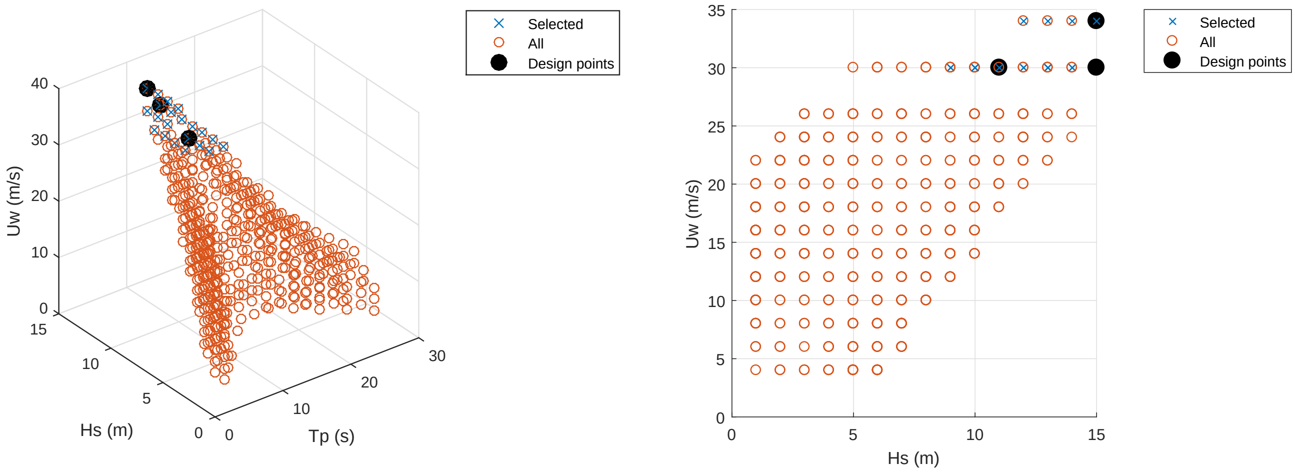

Figure 11: Discrete points of environmental contours corresponding to the 50-year return period for Site 14. The cross dots represents the selected conditions. The black dots represents the design points.

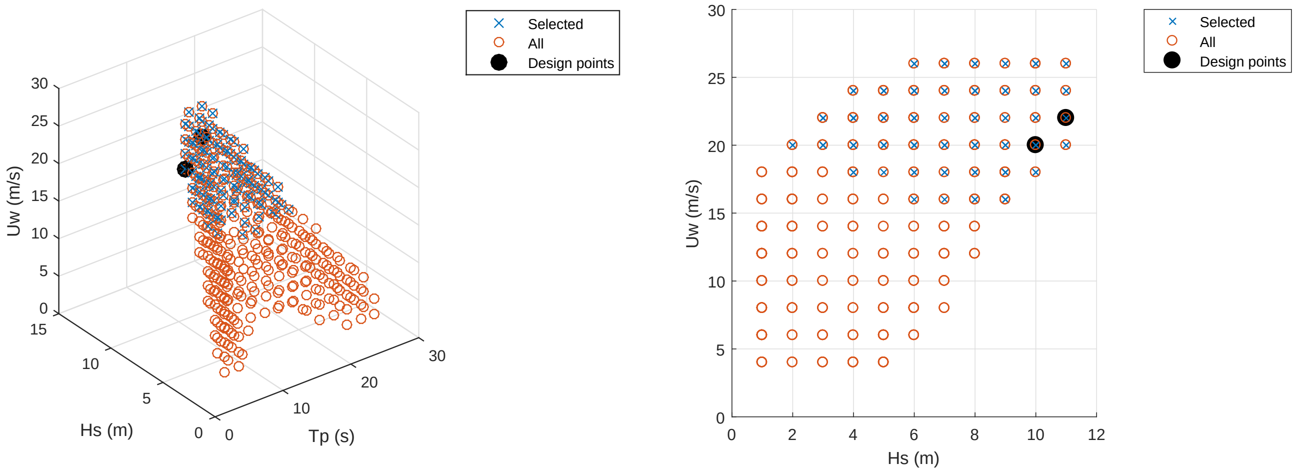

Figure 12: Discrete points of environmental contours corresponding to the significant wave height of 12 m for Site 14. The cross dots represents the selected conditions. The black dots represents the design points.

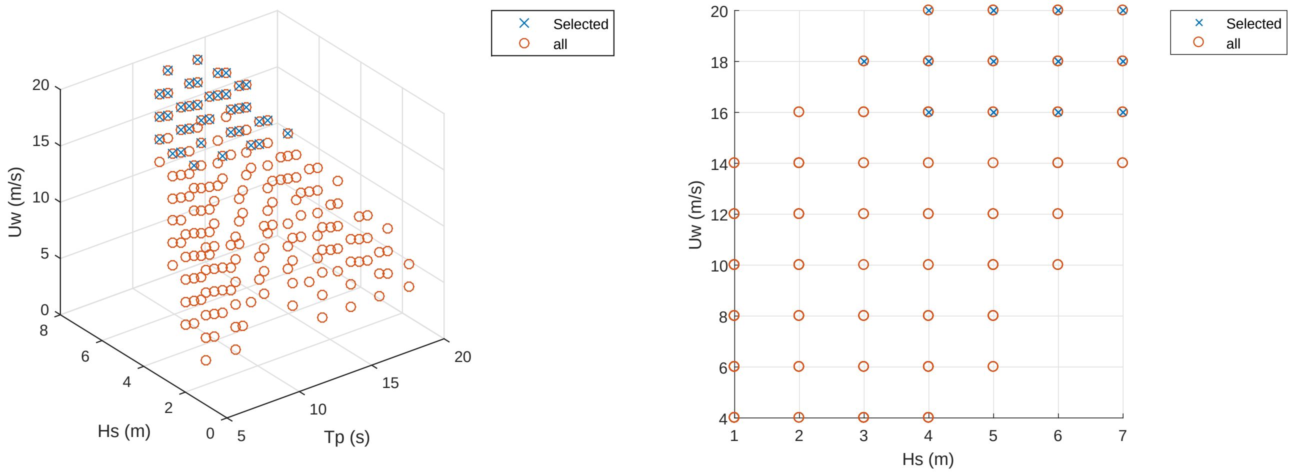

Figure 13: Discrete points of environmental contours corresponding to the cut-out wind speed for Site 14. The cross dots represents the selected conditions. No design points are located on this contour.

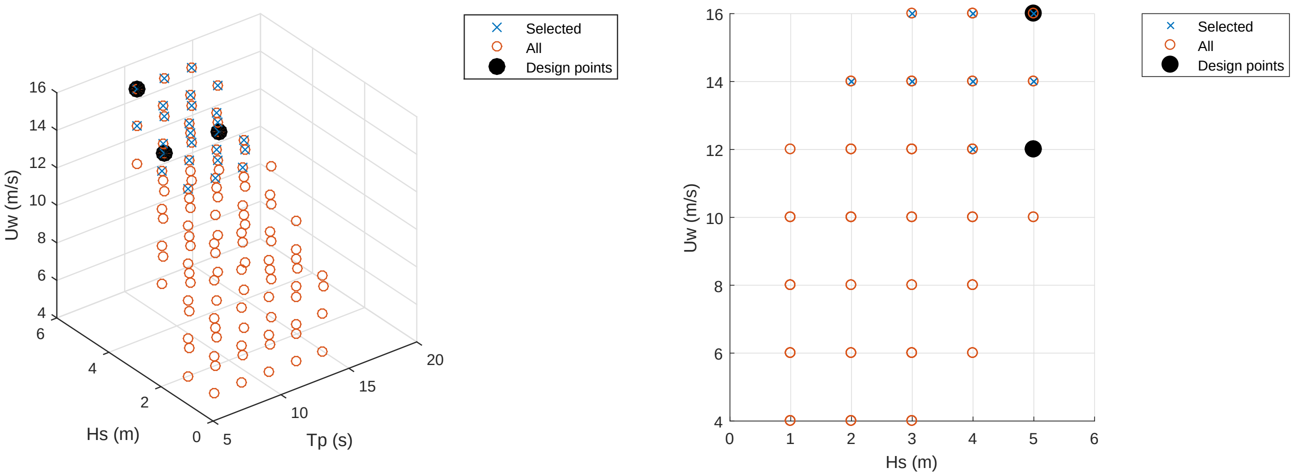

Figure 14: Discrete points of environmental contours corresponding to the maximum significant wave height of 6 m for Site 14. The cross dots represents the selected conditions. The black dots represents the design points.

1.2 is a good alternative for 90% fractile for ECM when it is applicable. 1.0 can also substitute 50% for MECM when extrapolated expected extreme response is used. However, it should be noted that the extrapolated expected extreme value still require data fitting.

ECM performs well for most of the responses as the percentage differences compared to FLTA is mostly within 10%. However, MECM noticeably improves extreme responses of spar heave (3) for both sites, relative heave (7) and torus contact velocity (10) for site 14, and the mooring force (8) for site 3, while the prediction of ECM is much lower than the FLTA results. The under-prediction of ECM here is mainly due to the operational modes of the WEC as well as the different statistics of the environmental condition of the two sites. Figures 17 and 18 shows the relations between the normalized expected short-term extreme responses of spar heave (3), relative heave (7) and mooring force (8) and the significant wave heights, respectively. For spar heave (3) response, it can be seen that there is a peak where the WEC changes from normal operation to low PTO mode ($H_S = 6m$). So MECM with contour corresponding to the significant wave height of 6 meter provides the best prediction for both sites. For relative heave

Table 5: Fractile levels of all the responses at each environmental contour so that the extrapolated short-term extreme is the same as the FLTA results at site 3.

	FLTA	50-yr ① (ECM)	cut-out ②	hs6 ③	MECM
1	2.29E+03	86.25 %	78.88 %	60.88 %	86.25 % ①
2	3.07E+01	92.65 %	96.59 %	85.16 %	92.65 % ①
3	9.93E+00	99.95 %	79.17 %	32.56 %	32.56 % ③
4	1.52E+01	88.96 %	85.44 %	37.28 %	88.96 % ①
5	3.14E+00	32.91 %	86.72 %	99.60 %	32.91 % ①
6	1.84E+00	17.42 %	86.96 %	99.96 %	17.42 % ①
7	9.11E+00	96.05 %	78.39 %	100.00 %	78.39 % ②
8	2.86E+03	99.75 %	87.32 %	27.85 %	27.85 % ③
9	2.66E+05	15.28 %	55.81 %	96.73 %	15.28 % ①
10	5.88E+00	94.06 %	1.86 %	64.92 %	1.855 % ②

Table 6: Fractile levels of all the responses at each environmental contour so that the extrapolated short-term extreme is the same as the FLTA results at site 14.

	FLTA	50yr (ECM) ①	hs12 ②	cut-out ③	hs6 ④	MECM
1	3.05E+03	95.58 %	70.74 %	97.20 %	99.02 %	70.74 % ②
2	3.26E+01	90.75 %	99.69 %	98.16 %	95.50 %	90.75 % ①
3	9.77E+00	99.50 %	97.01 %	14.25 %	5.87 %	5.87 % ④
4	1.61E+01	91.69 %	98.65 %	69.23 %	48.54 %	48.54 % ④
5	4.21E+00	87.47 %	95.27 %	99.00 %	100.00 %	87.47 % ①
6	2.79E+00	57.73 %	99.99 %	99.92 %	100.00 %	57.73 % ①
7	1.05E+01	99.50 %	76.00 %	98.88 %	100.00 %	76.00 % ②
8	2.91E+03	61.54 %	91.25 %	53.70 %	11.14 %	61.54 % ①
9	3.34E+05	69.04 %	99.30 %	92.72 %	99.99 %	69.04 % ①
10	7.02E+00	99.71 %	19.25 %	33.48 %	8.98 %	19.25 % ②

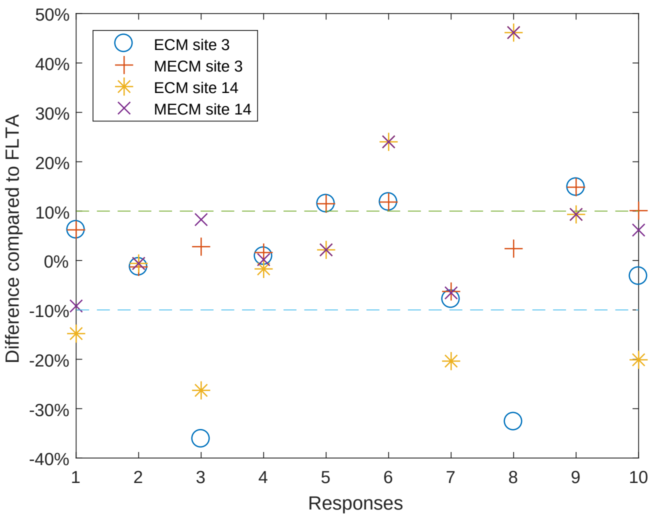

Figure 15: The percentage differences of ECM (90 % fractile with 50-year contour) and MECM (90% with 50-yr and 50% with other contours) when compared to the FLTA results for both site 3 and 14.

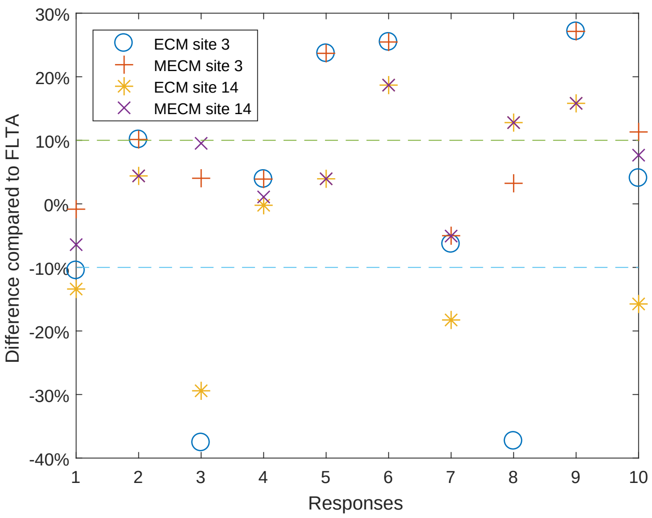

Figure 16: The percentage differences of ECM (1.2 multiplication factor with 50-year contour) and MECM (1.2 multiplication factor with 50-yr and 1.0 with other contours) when compared to the FLTA results for both site 3 and 14.

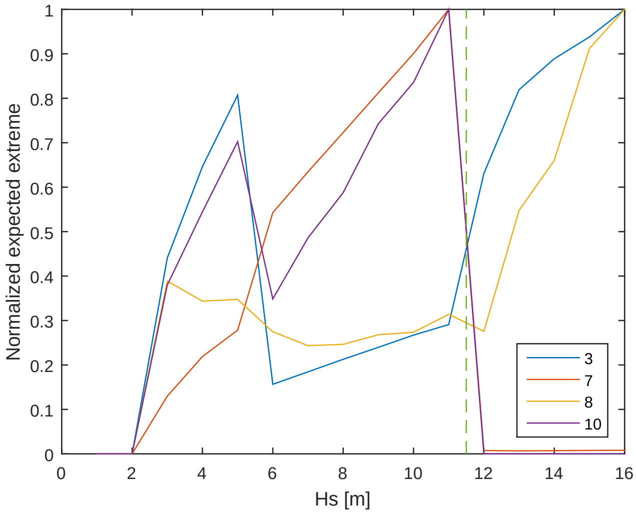

Figure 17: Normalized expected short-term extreme response versus the significant wave heights for site 3. The response values are divided by the maximum. H_S (horizontal axis) represents its most probable environmental condition, i.e. the combination of U_W and T_P that gives the highest probability density with the given H_S.

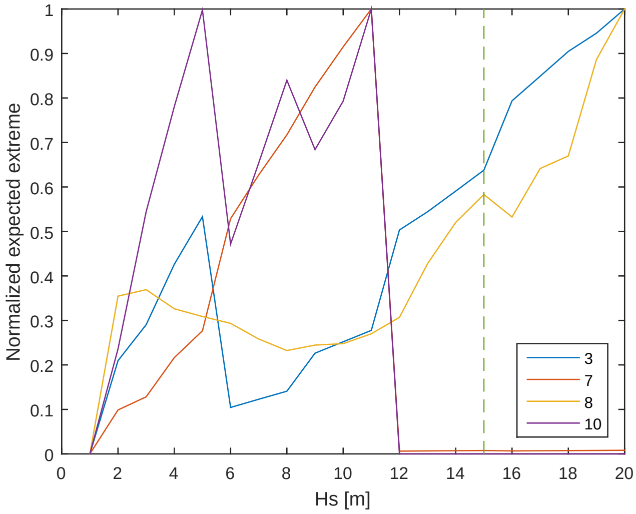

Figure 18: Normalized expected short-term extreme response versus the significant wave heights for site 14. The response values are divided by the maximum. H_S (horizontal axis) represents its most probable environmental condition, i.e. the combination of U_W and T_P that gives the highest probability density with the given H_S.

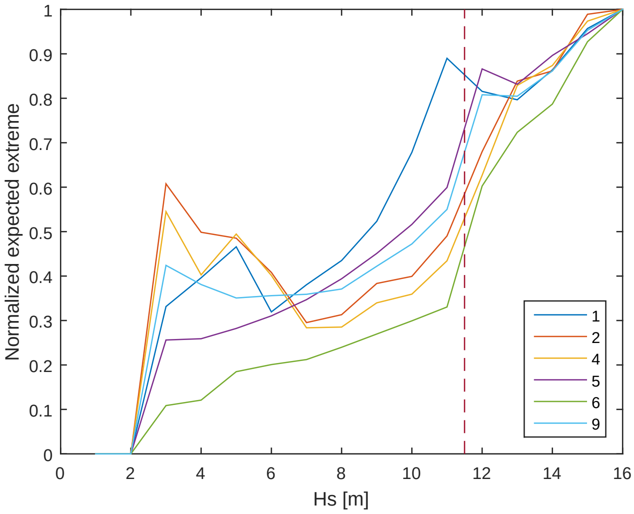

Figure 19: Normalized expected short-term extreme response versus the significant wave heights for site 3. The response values are divided by the maximum. H_S (horizontal axis) represents its most probable environmental condition, i.e. the combination of U_W and T_P that gives the highest probability density with the given H_S.

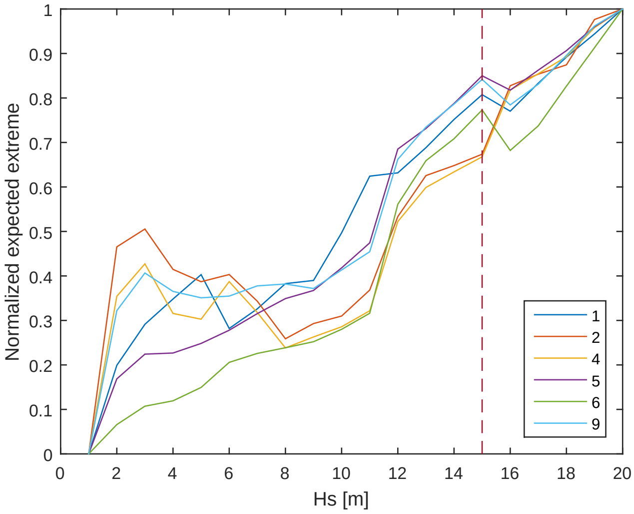

Figure 20: Normalized expected short-term extreme response versus the significant wave heights for site 14. The response values are divided by the maximum. H_S (horizontal axis) represents its most probable environmental condition, i.e. the combination of U_W and T_P that gives the highest probability density with the given H_S.

(7) response, it can be seen the peak of the short-term extreme response is at the $H_S = 12m$ where WEC changes from low PTO to lock-submerge mode, which essentially eliminate any relative heave between the WEC and the spar. The 50-year environmental contour of site 3 has its maximum significant wave height slightly lower than 12 meters. The point selected by ECM on the 50-year contour will provide a good prediction. Therefore, ECM is applicable for the relative heave (7) response for site 3. However, the 50-year H_S for site 14 is around 15 meters and is larger than the wave height where WEC is locked-submerged. So ECM under-predicts the extreme response for relative heave (7) for site 14. MECM includes the environmental contour corresponding to $H_S = 12$ and successfully predicts the long-term extreme for the relative heave (7). For the same reason, and ECM under-predicts torus contact velocity (10) for site 14 but works well for site 3. On the other hand, the expected short-term extreme responses of mooring force (8) rises significantly when H_S is above 12 meters (WEC locked and submerged) and has also a relative smaller peak with H_S lower than 6 meters. For site 14, the long-term extreme is contributed mainly by the environmental conditions with H_S above 12 meters. With 50-year contour at H_S of 15 meter, the ECM can provide a good result. For site 3, since the maximum H_S for the 50-year contour is lower than 12 meter, the ECM under-predicts. In comparison, for responses (shown by Figure 19 and 20 that ECM performs well, a general monotonic increasing relation between the responses and H_S can be observed. The expected extreme responses of Figures 17 to 20 are the responses from the most probable environmental conditions of the corresponding value of the significant wave heights (i.e. the U_W-T_P combination with the highest probability density), and the shown normalized values are divided by the maximum value so that they are between 0 and 1.

From the results, it can be seen that the performance of ECM for this WEC with different operational mode is dependent on the statistic of the environmental condition of each site. Even for the same responses, ECM may or may not predict the correct result depending on whether the 50-year environmental contour matches the most important H_S. The MECM includes four important environmental contour (50-year, cut-out wind speed, $H_S = 12m$ and $H_S = 6m$) to consider all the change of operation mode (i.e. operation/park of the wind turbine and normal/low PTO/lock-submerge modes of the WEC) is a much more robust and reliable method for this combined wind turbine and WEC concept.

While MECM can improve the results, it can also be seen that the ECM/MECM can overestimate of about 25% for some extreme responses, such as surge/pitch acceleration and tower bending moment. The cause is that the true “design point”s are already very close to the 50-year contour, so the ideal fractile level should be around 50%. Thus, with a higher fractile level such as 90% is too conservative.

Compared to bottom-fixed (*Li et al., 2013*) and semi-submersible wind turbines in earlier studies, one notable difference of this STC system is that the tower bending moment has “design point”s that are located near the 50-year environmental contour which implies that it is dominated by wave loads and is thus suitable for ECM as shown in Tables 5 and 6 as well as Figure 15. In previous studies, the tower bending moment is governed by wind loads and requires MECM to achieve good long-term extreme prediction. This difference is caused by larger pitch acceleration of the spar induced by extreme wave conditions, which is greater than the effect of the thrust of the wind turbine when operating. On the contrary, there is no pitch motion for bottom-fixed structure. The semi-submersible wind turbine also has much smaller pitch motion compared to a spar.

Overall, it can be seen that MECM can be used for this application, despite the differences compared to the offshore wind turbines. It improves the long-term extreme performance of ECM by reducing the under-prediction to be within 10%.

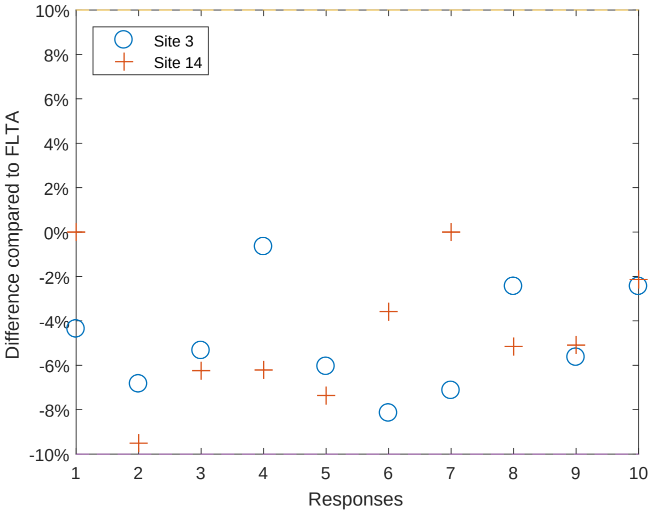

Figure 21: RLTA percentage difference of sites 3 and 14.

4.2 RLTA

When applying the ECM and MECM, a number of cases (i.e. 121 and 211 environmental conditions for site 3 and 14 respectively) are tested as discussed in Section 4.1. Since these tested environmental conditions cover the most important cases for long-term analysis, one can simply use these environmental conditions to perform the RLTA directly as explained in Section 1.4. The difference between FLTA and RLTA are shown in Figures 21. The advantage of the RLTA is also clearly demonstrated by the fact that there is no over-estimation possible for RLTA by definition, unlike ECM/MECM for some responses. Since all the important environmental conditions are included, the under-estimation is also less than 10%. Thus, if an additional 10% increase is applied to the results of RLTA, the final estimation will be conservative and still very close to the FLTA.

5 Conclusion

The paper focuses on the efficient determination of the long-term extreme responses of a combined wind turbine and wave-energy converter system, which changes its operational mode depending on both mean wind speed and significant wave height. The performance of Environmental Contour Method (ECM), Modified Environmental Contour Method (MECM) and Reduced Long-Term Analysis (RLTA) is studied and compared with the Full Long-Term Analysis (FLTA).

ECM is applicable for extreme responses that are caused by extreme wave conditions but performs poorly for some responses that are sensitive to the operational mode of the WEC. In addition, its performance for some responses is found to be dependent on the statistics of the environmental conditions of the site. Thus, the MECM with four environmental contours (50-year, cut-out wind speed, H_S=12 m and $H_S = 6$ m) is required to give more reliable and accurate long-term extreme prediction. The MECM predicts conservative long-term extreme responses and its under-predictions are within only 10% compared to the FLTA results.

The design environmental conditions for ECM and MECM are found to be only on the part of the contour that are near the “tip” region corresponding to maximum wind speed and maximum significant wave height is important. Thus, only this part of needs to environmental contour be checked for each environmental contour.

Alternatively, using the environmental conditions checked by ECM/MECM, RLTA can also be applied. The results of RLTA are very close to the FLTA and the differences of their results are lower than 10%. It is found that RLTA provides more stable results as there will not be any large over-estimations as in ECM/MECM, which is caused by fractiles being too large for some responses. Since RLTA is inherently under-predicting, a 10% increase of the RLTA results can be added to ensure the method to be conservative.

Overall, the MECM and RLTA performs well with the combined wind turbine and wave energy converter system and is a much simpler alternative to FLTA. They can also be applied to other systems that has different operational modes depending on the environmental parameters.

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