

# Environmental Contour Methods for Long-Term Extreme Response Prediction of Offshore Wind Turbines

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## Abstract

The long-term responses of offshore wind turbines (OWTs) are critical in the design phase, where precise assessments ensure structural reliability and operational efficiency. The environmental contour method (ECM) enables efficient analysis of design responses by focusing on a selected set of critical environmental conditions that predominantly drive long-term extreme responses. Despite its extensive use in offshore engineering, ECM's application in the structural design and strength assessment of OWTs remains underexplored. This study offers a comprehensive overview of the utilization of ECM in the context of OWT design, incorporating a bibliometric analysis of publications from the Web of Science to identify research trends and key topics. The analysis highlights diverse approaches for estimating long-term extreme responses and constructing environmental contours using statistical distributions. Additionally, the study explores the application of ECM and its modified versions in the design and strength assessment of OWTs. Challenges and opportunities associated with ECM implementation in OWTs are critically analyzed, providing insights into ECM's potential for enhancing the efficiency and reliability of OWT structural design.

**Keywords** Environmental contour method; Offshore wind turbine; Long-term extreme response; Reliability

## 1 Introduction

Offshore structures, including oceangoing ships (Vanem

### Article Highlights

- Bibliometric analysis identifies prominent research trends and hot-spots in the study of long-term extreme responses of OWTs, with an emphasis on the strong connection between environmental contour methods (ECMs) and extreme response estimation.
- The review assesses the theoretical foundations, performance, and advancements of various ECMs, highlighting the critical role of accurately constructing limit state equations and joint distributions of sea state parameters.
- The Modified ECM significantly improves long-term extreme response estimation of OWTs and demonstrates the potential for broader application in systems with state changes driven by environmental conditions.

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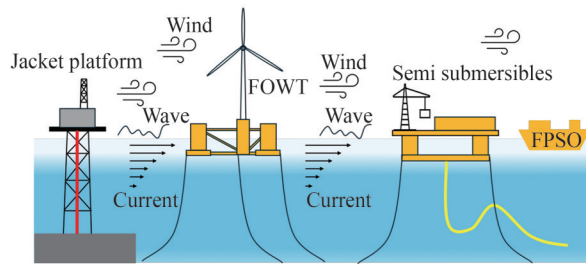
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et al., 2020), deep-sea platforms for oil and gas development (He et al., 2024), wave energy converters (WEC) (Coe et al., 2018; Li et al., 2019; Manuel et al., 2018; Wang and Moan, 2024; Xu et al., 2019, 2024), and offshore wind turbines (OWT) (Thomas et al., 2016; Li and Guedes Soares, 2022; Dong et al., 2024; Katsikogiannis et al., 2024; Amiri et al., 2024a), are continuously exposed to environmental loads caused by wind, current, and waves, as depicted in Figure 1. In designing offshore structures, long-term analysis is essential for estimating extreme structural responses and lifetime fatigue damage (Xi et al., 2024). This analysis integrates short-term responses with a specified environmental distribution model to derive lifetime values, forming the foundation of the full long-term analysis (FLTA). FLTA involves directly integrating the probability distribution of short-term extremes and environmental conditions, providing high accuracy but at the expense of computational efficiency (Naess et al., 2013).

The environmental contour (EC) defines a set of extreme sea state conditions and can be used to approximate the extreme values of long-term structural responses by considering only a limited number of short-term metocean conditions. Design guidelines and standards widely recommend it (DNV GL, 2014, 2019; IEC, 2019) because it offers a pragmatic balance between computational efficiency and statistical as well as dynamical rigor (Haselsteiner et al., 2019a). The ECs provide a simplified and approximate

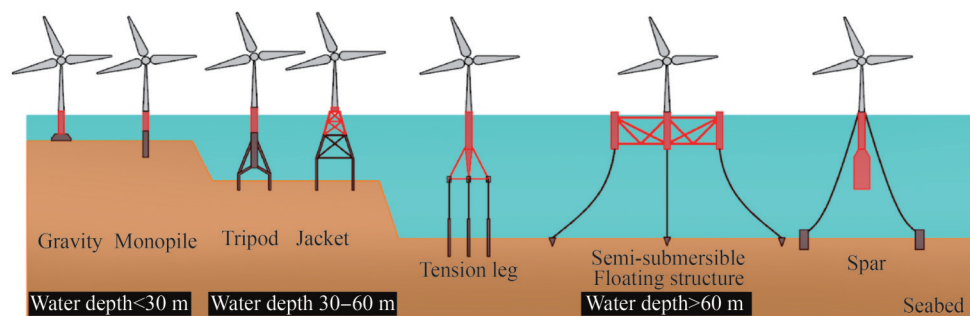


**Figure 1** Offshore structures exposed to environmental loads

alternative to full long-term response analysis to define contours in the metocean space at a specific deployment site (e.g., significant wave height and peak period) along which extreme responses with a given return period (Haselsteiner et al., 2021), requiring significantly less computational effort (Haver and Winterstein, 2008; Winterstein et al., 1993). The environmental contour method (ECM), which Haver (1980) initially used to define design curves relating to extreme wave height and wave period in the Northern North Sea, is a well-respected technique for extrapolating metocean characteristics. The objective of ECM is to identify a region within the environmental parameter space, known as the “design region” where a structure capable of withstanding all conditions in this region has a probability of failure less than or equal to a specified value (Mackay and Haselsteiner, 2021). The method applies several conditions to the environmental contour and determines the relevant extreme response by selecting the largest short-term maxima corresponding to a high fractile (e.g., 70% to 90%) (Haselsteiner et al., 2019a; Mackay et al., 2021).

### 1.1 Motivation

Developing renewable energy resources, such as offshore wind power, is crucial for the energy transition and the achievement of carbon neutrality (Corrêa et al., 2024; De Almeida et al., 2024; Amiri et al., 2024a; Shadman et al., 2023). As an essential engineering infrastructure, the safety of offshore wind turbines is a critical concern (Chen et al., 2021). In the offshore wind turbine market, a variety of supporting structures are available for wind turbines, depending on water depth (Chujutalli et al., 2024), the several solutions are presented in Figure 2.



**Figure 2** Types of offshore wind turbine supports (Chirosca et al., 2022)

Long-term analysis is crucial for assessing extreme structural responses in offshore wind turbine designs. However, performing a comprehensive long-term analysis is often inefficient and uneconomical due to the extensive range of environmental conditions that must be considered. Therefore, various simplification methods have been employed to improve extreme response predictions (Vanem et al., 2015; Wang, 2020). These simplified methods either enhance simulation efficiency or reduce the number of environmental conditions required for integration (Li et al., 2016).

The ECM is employed to analyze and describe patterns of environmental change. Over the past few decades, this method has been widely applied across various fields, including geology, meteorology, hydrology, and environmental engineering (Clarindo and Guedes Soares, 2024; Li et al., 2024; Su et al., 2024). By statistically analyzing and modeling environmental parameters, the method simplifies complex environmental conditions into a series of contours, thereby quantitatively describing patterns of environmental change. Compared to the FLTA technique, the environmental contour’s primary benefit is its capacity to identify the essential environmental loads independently of the structural response (Li et al., 2018), which shortens the time required to predict the long-term extreme. However, a comprehensive review is lacking on a) the relationship between environmental contours for specific return periods and the corresponding long-term extreme structural response of OWTs, b) advancements in ECM development for OWTs, particularly regarding its application in the design and evaluation of systems operating in challenging marine environments, and c) an in-depth discussion of the modified environmental contour methods (MECMs) and its potential for application to OWTs. Consequently, there remains significant uncertainty regarding the best practices for employing ECMs/MECMs in long-term response predictions of OWTs, particularly in complex marine environments.

### 1.2 Objective and outline

This review specifically focuses on the application of the ECM to OWTs. In addition to summarizing the current state of ECM applications, it addresses key technical challenges

and identifies future research directions to advance the method's utilization in offshore wind energy. These future research directions include incorporating multivariate environmental variables, expanding the applicability of the MECM to OWTs, and developing open-source computational tools to enhance its practical implementation in long-term extreme response prediction and validation through experimental data. To achieve these goals, this review 1) highlights the applications of ECM on offshore structures, 2) describes various ECMs and MECMs for modeling the joint distribution of environmental variables, 3) explains the relationship between OWT structural design, long-term extreme response, and environmental contours, and 4) provides basic recommendations on the application of environmental contour approaches in OWT design.

The review is organized as follows: Section 2 presents a bibliometric analysis of relevant publications and research progress in long-term extreme conditions. Section 3 outlines the foundational approaches and statistical concepts for predicting long-term extreme responses in offshore wind turbines. Section 4 introduces the inverse first-order reliability method (IFORM), followed by Section 5, which covers the widely adopted ECMs, such as the inverse second-order reliability method (ISORM), highest density contour (HDC), and direct sampling method (DS). Section 6 reviews recent advancements in applying the ECM and its modified versions to the structural design and strength analysis of OWTs. Section 7 discusses future trends and research challenges, offering a summary and concluding remarks.

## 2 Bibliometric analyses

This section presents a bibliometric analysis, identifying, evaluating, and defining relevant research and acquiring perspectives for the long-term extreme response of OWT. This method is treated as an effective quantitative way to analyze the interdisciplinary science of all knowledge carriers according to mathematical and statistical methods (Donthu et al., 2021). It is a comprehensive knowledge system integrating mathematics, statistics, and philology. The measurement objects are mainly: the number of documents (various publications, especially journal articles and citations), the number of authors (individual, collectives or groups), and keywords (various document identifiers) (Khurshid et al., 2024).

The present study employs VOSviewer to map and analyze the structure of scientific research, identify emerging

trends, and explore relationships among various research entities. To acquire relevant publications from the Web of Science (WoS), the topic-based search string "Long-term extreme" was the primary controlled criterion. The results of 156 articles were identified as a data source in a time window from 2001 to 2024. A complete record was obtained from the database, including titles, keywords, and cited references and saved in text format. To further investigate long-term extreme assessment methods for OWTs, relevant publications were acquired from the WoS using the topic-based search string "Long-term & offshore wind turbine" as the primary criterion. A total of 411 articles, spanning a time window from 2001 to 2024, were identified as the data source, as shown in Table 1.

Figure 3 illustrates the growth in publications from 2015 to 2024, based on WoS data. The number of publications increased steadily from 2015 to 2019, followed by a sharp rise that peaked in 2023. However, a slight decline to 54 occurred in 2024. These data underscore a decade of growing research productivity, with a notable acceleration after 2019.

Nonetheless, more than one-third of the articles have been published in the field of Ocean Engineering or Marine Engineering (as depicted in Figure 4), which supports the high relevance of this research to ongoing advancements in offshore energy technologies. This publication record underscores the critical role of these studies in shaping discourse and guiding research agendas in Ocean Engineering.

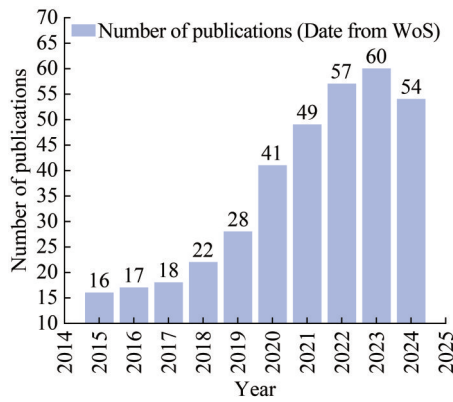
The networks of authors and keywords are created among the articles studied, as shown in Figure 5. The network was formed by nodes and links of different colours, where the colours reflect the clusters and the size of the nodes indicates the publication number of each author or keyword occurrence. A shorter distance between the two nodes on the network shows a stronger relation. Nodes and links of the same colour will form a cluster.

Figure 5(a) presents a network map of co-authorship analysis. Prof. Øiseth (Department of Structural Engineering, NTNU), Prof. Naess (Department of Mathematical Sciences, NTNU), and Prof. Guedes Soares (Centre for Marine Technology and Ocean Engineering) have made significant contributions to the field. The authors' co-occurrence map illustrates the degree of collaboration and partnership within the research community. Authors shown in the same color are interconnected, indicating relationships such as co-authorship on multiple papers, shared research projects, or institutional affiliations.

Figure 5(b) presents a network map based on keyword co-occurrence analysis. Keywords with similar meanings

**Table 1** A Survey of the literature on long-term extreme

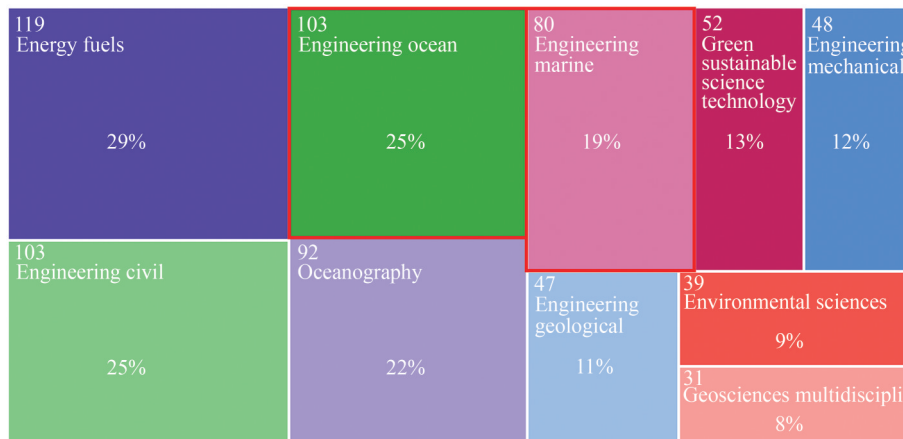
Database	Search method	Search terms	Time duration	No. of results
Web of science core collection	Topic	"Long-term extreme"	2001–2024	156
		"Long-term" & "offshore wind turbine"	2001–2024	411



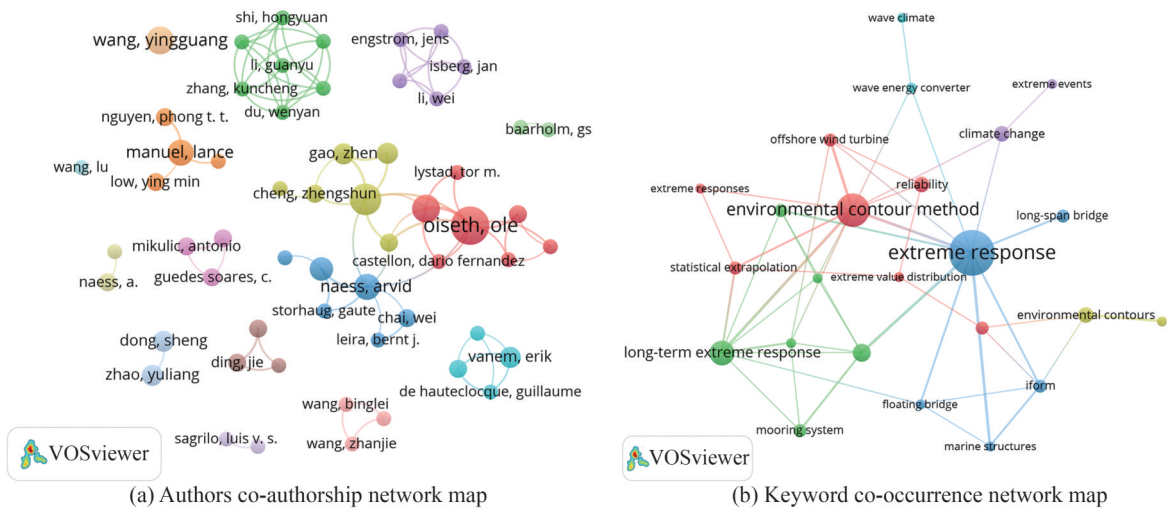
**Figure 3** Trends in the number of publications (Search terms: “Long-term” & “offshore wind turbine”)

are integrated and sorted by frequency. These keywords are grouped into six distinct clusters according to their associations and are represented by different colors in VOSviewer. For instance, keywords related to ECM and OWT are shown in red, indicating a strong relationship between these items. The color-coding facilitates distinc-

tion among various research areas. The bibliometric map reveals three primary research focuses corresponding to distinct clusters. The first focus involves integrating mooring systems with long-term extreme response prediction, emphasizing the development of robust designs for FOWTs operating under multivariate environmental conditions. The second focuses on the advancement of the ECM and its application to OWTs, particularly through reliability-based frameworks and improvements in the ECM to address challenges in floating wind turbines and complex environments. The third explores ECM applications in wave energy converters (WECs), highlighting the method’s adaptability to alternative marine energy systems and its potential for broader use in renewable energy technologies. Together, these research focuses provide valuable insights into current trends and opportunities to address challenges such as incorporating multivariate dependencies, extending ECM’s applicability to diverse offshore systems, and enhancing its practical implementation. This analysis provides insights into emerging trends and gaps in research, where keywords with smaller nodes or fewer connections may suggest less

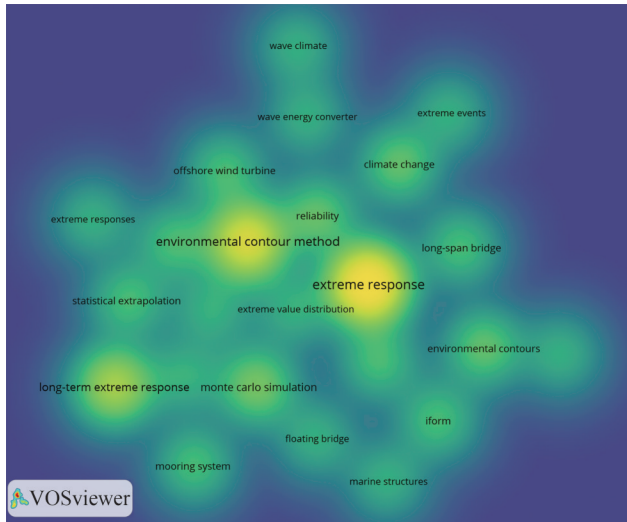


**Figure 4** Distribution of journal publication by subject area (Search terms: “Long-term” & “offshore wind turbine”)



**Figure 5** Authors co-authorship network map and keyword co-occurrence network map

explored or emerging areas of study. Figure 6 illustrates the keyword co-occurrence density network. The darker shades indicate areas of heightened attention within the field, highlighting regions with high keyword co-occurrence, such as “extreme response”, “environmental contour method” as well as “long-term extreme response”. These “hotspots” represent areas in the network where significant research activity is concentrated.



**Figure 6** Keywords co-occurrence density network

The bibliometric analysis highlights emerging research trends in long-term extreme responses for OWTs. A growing body of literature, primarily within the field of Ocean and Marine Engineering, underscores the increasing focus on addressing extreme environmental challenges. Keyword analysis revealed strong associations between ECMs and extreme response studies, identifying key research hotspots such as “extreme response” and “environmental contour method”. These findings provide valuable insights and serve as a foundation for guiding future efforts to enhance the resilience of OWTs.

### 3 Long-term response assessment of offshore wind turbine

#### 3.1 Full long-term analysis by short-term extremes

Long-term analysis is essential in the design of OWTs for accurately estimating extreme structural responses (Zhang et al., 2015; Chen et al., 2023; de N Santos et al., 2023). We briefly discuss the most accurate approaches for this task, particularly methods known as FLTA (Lott and Cheng, 2016; Lystad et al., 2023; Sagrilo et al., 2011). Short-term response statistics can be utilized for foreseeing the long-term response, assuming that the short-term loading process and long-term response in environmental

parameters are ergodic. The FLTA can calculate the long-term cumulative distribution function (CDF) by integrating short-term probability functions as well as the corresponding environmental condition parameters.

$$F_X^{LT}(x) = \int F_{X|s}^{ST}(x|s) f_s(s) ds \tag{1}$$

where  $x$  represents the response variable, and  $s$  denotes the environmental condition parameter.  $F_X^{LT}$  is the long-term CDF of the response, while  $F_{X|s}^{ST}$  is the short-term CDF at a given environmental conditions.  $f_s$  is the probability density function (PDF) that describes the environmental condition. However, calculating the multivariate cumulative distribution of long-term extreme responses is computationally expensive in practical situations. This is because FLTA must account for all possible environmental conditions, and time-domain simulations are required for each sea state to capture the nonlinear and non-Gaussian properties of the dynamic system (Zhao and Dong, 2022; Zhao et al., 2023).

To address the problem of FLTA, the ECM is commonly used to forecast design structural loads for a given target exceedance probability or return period. The idea of ECM can be described by Equation (2), where  $p$  is an empirical value greater than 50%.

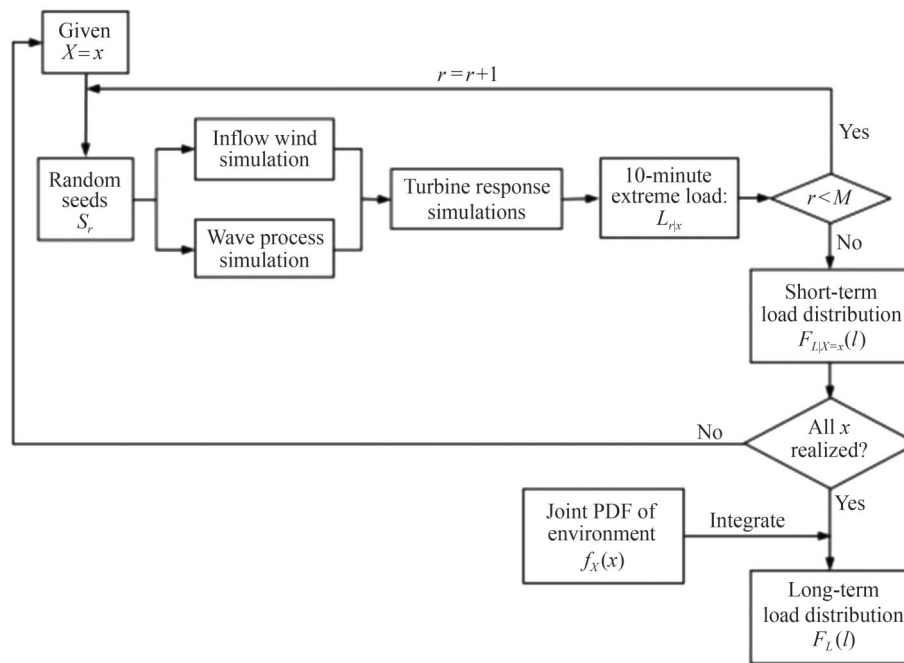
$$F^{LT}(X_{max}) \approx F(X_{max}|s) \tag{2}$$

$$X_{max} \approx F^{ST^{-1}}(p|s)$$

The applicability of the ECM relies heavily on the assumption that the true design point (environmental condition) is close to the selected environmental contour. To compensate for the omission of short-term variability of  $X_{max}$ , empirical fractiles between 70% and 90% are often used (Lee et al., 2023; Winterstein et al., 1993). Estimating the long-term extreme response of a structure to environmental loading requires three components: 1) an environmental dataset, 2) a description of the short-term response as a function of environmental conditions, and 3) a method to combine the short-term response with the environmental data to estimate the long-term extreme response (Haselsteiner et al., 2022a).

Many recent studies have implemented ECM in predicting the long-term extreme response of wind turbines, e.g., (Karmakar et al., 2016; Li et al., 2015, 2019; Ross et al., 2020). Agarwal and Manuel (2009) applied the ECM to derive long-term extreme loads for OWT, as depicted in Figure 7. By varying a set of random seeds, they generated different realizations of stochastic wind and wave processes under the same environmental conditions, and a distinct turbine response was produced each time.

This approach allows for the estimation of the desired  $M$  load extremes. Once the short-term load distributions for all  $X$  (i.e., for all combinations of mean wind speed and significant wave height in this case) are established, they



**Figure 7** Flowchart describing the steps involved in establishing short-term and long-term load distributions based on turbine response simulations (Agarwal and Manuel, 2009)

can be integrated with the joint probability distribution function of the environmental random variables,  $f_x(x)$ , to obtain the long-term load distribution.

Leong et al. (2020) applied Monte Carlo simulation (MCS) to perform the integration over the long-term variables, which include the significant wave height, average period, and the speed/direction of wind and current. The method is effective for conventional offshore structures where wave-induced responses increase monotonically with significant wave height. For these systems, environmental conditions on the outer contour are likely to approximate the true critical conditions. However, for systems such as wind turbines or other structures that may alter their operational modes to limit responses under extreme conditions, the ECM performs poorly and often underestimates the long-term extreme values.

### 3.2 Description of the environmental conditions

A key prerequisite for structural response analysis is accurately representing environmental loads. The design of extreme waves and wind typically follows several key steps. It begins with using hindcast simulations or buoy observations of one location over a sufficiently long period. The extreme value theory and models are then applied to extrapolate the data beyond the observed events recorded over a shorter period. Subsequently, environmental contours are generated that induce extreme structural responses for a specific return period. The process concludes with identifying one or more extreme sea states, which enable the reconstruction of a single extreme wave or wave group to be used

as input for numerical or physical model simulations.

Hindcast data are now available for various locations, encompassing environmental variables such as wind, waves, and currents. In addition, the data was utilized by a wide range of engineering applications, such as marine structural design, where the joint extremes of environmental variables like wave height and wind speed are crucial for defining load cases. Li et al. (2013) used a database of simultaneous hourly wind and wave hindcast data from 2001 to 2010 to present long-term joint distributions of wind speed at a height of 10 meters, significant wave height, and peak wave period. The offshore site selected is located in the northern North Sea, with a water depth of 202 meters, and data were obtained from the National and Kapodistrian University of Athens.

### 3.3 Statistical modeling of environmental conditions

The responses of offshore structures cannot be predicted using a single metocean parameter; instead, they require at least a joint distribution of wave height and wave period. It is crucial to describe marine environmental conditions and establish corresponding probabilistic models accurately. The study on the joint distribution of wave height and period can be traced back to the 1970s (Longuet-Higgins, 1975). In 1983, Longuet-Higgins revised the model he proposed in 1975, introducing a normalization factor pair and proposing an asymmetric joint distribution function for wave height and period (Longuet-Higgins, 1983). Methods for modeling joint distributions include hierarchical condition-

al models (Haselsteiner et al., 2020; Li et al., 2013), copula models (Fazeres-Ferradosa et al., 2018; Heredia-Zavoni and Montes-Iturrizaga, 2019; Montes-Iturrizaga and Heredia-Zavoni, 2015), kernel density estimations (Haselsteiner et al., 2017a), Nataf model (Silva-González et al., 2013), and asymptotic extreme value models (Mackay and Jonathan, 2020).

The studies mentioned above concentrated on the zero up-crossing period and the significant wave height, and they ended up using the 3-parameters Weibull distribution for  $H_s$  and the conditional log-normal distribution for  $T_z$  especially in the northern North Sea area, as suggested by the Det Norske Veritas (DNV GL, 2014; Raed et al., 2020). Bitner-Gregersen suggested that the wave height probability follows a Rayleigh distribution or Weibull distribution. In contrast, the conditional probability density function of the period follows a Gaussian distribution or log-normal distribution (Bitner-Gregersen, 2005). A statistical joint distribution can be fitted to the available data to predict the long-term description of environmental conditions. The review by Jonathan and Ewans (2013) provides a thorough analysis of the statistical modeling of environmental conditions and emphasizes the need for more agreement in multivariate modeling among the metocean community.

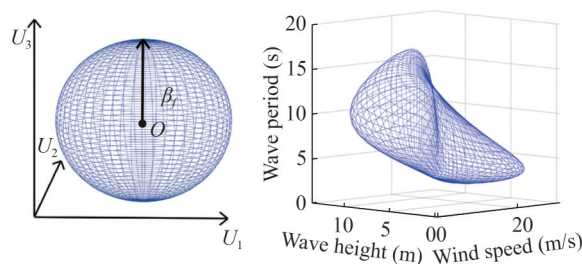
#### 4 Inverse first-order reliability method (IFORM)

The long-term response associated with different return periods can be estimated using statistical extrapolation based on loads derived from the short-term simulations for OWT. As discussed in Section 3, FLTA is a time-consuming and inefficient method, as it requires simulating numerous environmental conditions. However, most of these conditions do not significantly contribute to predicting extreme responses, only a small subset is generally relevant. Therefore, simpler alternative methods, such as the IFORM and the ECM, are often preferred.

The IFORM is derived from the First-Order Reliability Method (FORM) and is employed to estimate the probability of structural failure. Liu et al. (2019) employed IFORM procedures to find appropriate response quantile levels, the proposed adaptive procedure in the 3D IFORM approach helps determine the number of simulations required to ensure accuracy in long-term response estimation. Raed et al. (2020) assessed the uncertainty on the extreme response for the DeepCwind semi-submersible using the inverse first-order reliability method and the direct Monte Carlo simulation approach to estimate the environmental contour for 1-year, 25-year, and 50-year return periods. Liao et al. (2022) constructed environmental contour lines for bivariate random variables using the IFORM, which were subsequently employed to determine design loads corresponding to the target return period. The extreme tensions in the

mooring system of the semisubmersible platform were analyzed using the peaks over threshold (POT) method, and a Gumbel distribution was found to fit the POT-based extremes accurately. Lutes and Winterstein (2014) develop alternative elliptical contours in U-space based on FORM principles, again defining the contour as a locus of all possible FORM design points and studying a load combination problem involving the midspan vertical bending moment of a ship. Lin et al. (2020) studied the joint distribution of wave height and mean zero-crossing period based on the copula mixture, and then used the IFORM to define the met-ocean contours in the North Atlantic Ocean.

The method involves transforming environmental variables into standard normal variables using the Rosenblatt transformation and identifying a circle in the transformed space with a radius equal to the reliability index  $\beta_f$ , as indicated in Figure 8.



**Figure 8** Transformation of environmental conditions from the uncorrelated standard normal space to the original space (Zhao et al., 2023)

The Rosenblatt transformation (Rosenblatt, 1952) is a method for converting the joint probability model of environmental variables into a multidimensional independent standard normal distribution using conditional distributions, as follows:

$$\begin{aligned}
 u_1 &= \Phi^{-1}\left(F_{s_1}(s_1)\right) \\
 u_2 &= \Phi^{-1}\left(F_{s_2|s_1}(s_2|s_1)\right) \\
 &\dots \\
 u_{n+1} &= \Phi^{-1}\left(F_{\tilde{y}|s_1, s_2, \dots, s_n}(y|s_1, s_2, \dots, s_n)\right) = \Phi^{-1}\left(F_{\tilde{y}|s}(y|s)\right)
 \end{aligned}
 \tag{3}$$

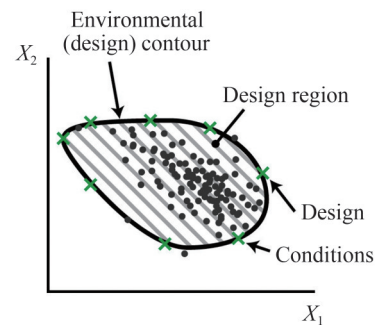
where  $s$  represent the  $n$ -dimensional environmental variables in the real physical parameter space, where  $Y$  denotes the structural response variable. Additionally,  $u$  refers to the  $(n+1)$ -dimensional independent standard normal distribution variable obtained through transformation. Although the Rosenblatt transformation is one of the earliest and most fundamental methods for handling correlated variables, it has notable shortcomings, particularly because it requires inverting conditional distributions during the transformation process. This increases the complexity of the joint distribution, especially in high-dimensional settings.

Additional explicit assumptions regarding the nature of structural failure surfaces concerning environmental variables are introduced by the IFORM and can be stated on transformed marginal scales. More logical inferences concerning the relationship between the probability of structural failure of  $T$ -year and the probability of exceedance of the environmental contour for  $T$ -year when these assumptions are met. However, it is not always clear whether these assumptions are satisfied for a given application (Ross et al., 2020). In general, it is impossible to directly relate exceedance probability to the parameters required for contour definition. Therefore, an iterative approach is typically used to identify contour parameters that result in the desired exceedance probability. However, IFORM offers a contouring method that allows for a direct relationship between exceedance probability and the parameters defining the contour.

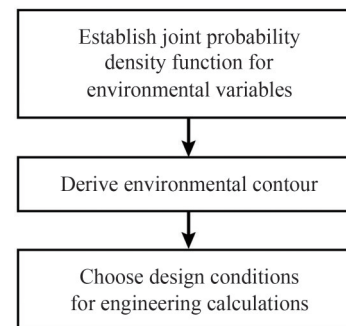
## 5 Environmental contour method

The ECM has been extensively employed in the offshore industry to assess long-term extreme responses. Theoretically, it is a simplified extension of the IFORM, where the return period of an extreme response is determined by its exceedance probability. Compared to IFORM, the ECM reduces one dimension (e.g., from 3D in IFORM to 2D in ECM) (Li et al., 2017). Since it only incorporates environmental data and excludes the response information, the contour can be fully defined within the environmental space. The environmental contour is defined by enclosing a region within the variable space corresponding to a specified return period. The conceptual diagram of the environmental profiling method is shown in Figure 9. As previously discussed, the ECM assumes that the extreme response occurs along a surface constructed within this space, corresponding to the desired return period.

Many methods have been proposed to generate environmental contours of extreme sea states. These methods vary in the approach used to define the joint distribution of sea state parameters and the technique employed to construct the environmental contour from this distribution (Eckert et al., 2020). Winterstein and Haver pioneered the ECM, using the IFORM to evaluate the joint distribution characteristics of extreme variables, including wind, waves, and currents. Eckert-Gallup et al. (2014) proposed using the principal component analysis (PCA) method to improve the contour of the wave environment. Kernel density estimation (KDE) was introduced by Eckert-Gallup and Martin (2016) as a method for generating environmental contours and has been further explored in subsequent studies (Haselsteiner et al., 2017a). Given the importance of the ECM in practical engineering applications, it has already been incorporated into the DNV standards (DNV GL, 2014).



(a) The environmental contour represents the boundary encompassing all variable combinations that must be considered within the design process, defining the design region



(b) A flowchart illustrating the design process that incorporates the environmental contour

**Figure 9** Concept of an environmental contour (Haselsteiner et al., 2017b)

Different methods for constructing environmental contours make varying assumptions about the shape of the failure region—defined as the portion of the environmental parameter space where the structure fails—and, consequently, differ in how they define an exceedance of the environmental contour. Mackay and Haselsteiner (2021) analyzed the relationship between the marginal exceedance probability of the maximum environmental variable and the cumulative probability outside the contour using the ECM. They concluded that selecting an appropriate ECM requires the proper construction of the limit state equation. The probability that an environmental contour is exceeded (exceedance probability  $\alpha$ ) corresponds to a specific recurrence or return period, representing the average time interval between two consecutive environmental states that exceed the contour. In the following formula, the return period  $T_r$  is expressed in years, while  $T_s$ , the state duration of independent events, is given in hours.

$$\alpha = \frac{T_s}{T_r \cdot 365.25 \times 24} \quad (4)$$

The performance of various ECMs has been investigated in several studies. Given the fundamental mathematical differences between these methods, it is generally unreasonable to expect consistent trends in comparisons across different applications. The characteristics of each ECM must

be evaluated on an application-by-application basis. To establish a common framework for comparing proposed methods, two benchmarking exercises were introduced at the International Conference on Ocean, Offshore & Arctic Engineering (OMAЕ) (Haselsteiner et al., 2019a; Mackay and Haselsteiner, 2021). The benchmark experiment comprised two parts: “Exercise 1” assessed the contour methods’ robustness at various sites, while “Exercise 2” dealt with sampling uncertainty characterization. Six datasets with two environmental variables were available. Three datasets featured time series of significant wave height and zero-up-crossing period, whereas the other three had wind speed and significant wave height data. Computing environmental contours with return periods of 1, 20, and 50 years was a task given to the participants. These two-dimensional wave and wind variable contours were compared because they show typical situations needed in practical design applications (Haselsteiner et al., 2021).

Haselsteiner et al. (2019b, 2022b) introduce a software called ViroCon, which enables users to define extreme environmental conditions with a specified return period using the ECM, including the IFORM, the ISORM, DS method, and HDC method. ViroCon can assist in designing marine structures that must withstand load combinations from waves, wind, and currents. Figure 10 presents a flowchart illustrating the overall functionality of ViroCon. A statistical model of the offshore environment is created by fitting a model structure to measurement data. This statistical model is then used to construct an environmental contour.

The ECM generally involves three steps: 1) developing a statistical model to characterize the environment based on a sample of environmental states (statistical modeling), 2) computing the environmental contour using that statistical model (contour construction), and 3) selecting discrete points along the contour for subsequent use in the design phase (design condition selection) (Haselsteiner et al., 2019a). The statistical model structures range from full joint distribution models based on the conditional modeling approach to copula models (Manuel et al., 2018), models derived from applying principal component analysis and joint distributions derived from multivariate kernel

density estimation. The desired contour construction can be carried out based on a variety of definitions, such as the IFORM, ISORM (Chai and Leira, 2018), DS, and HDC (Haselsteiner et al., 2017b).

As shown in Figure 11, Mackay et al. studied the relationship between the total probability outside the contour and the marginal exceedance probability of the maximum value of each variable along an environmental contour, and compared the definitions of different ECMs.

Since each approach makes various environmental assumptions, the contours predicted using multiple methods will typically differ. Thus, the extreme response distribution estimation depends on the selected ECM. Unlike in the univariate case, there is no single definition of multivariate exceedance. Consequently, there are multiple approaches to define an environmental contour. The final step, selecting individual environmental states (design conditions) along the contour, is crucial and is typically guided by best practices for the specific system under consideration.

### 5.1 Inverse second-order reliability method (ISORM)

The IFORM approximation is conservative when the failure region is convex but becomes non-conservative when the failure region is concave. Chai and Leira (2018) extended IFORM by proposing ISORM, which generates environmental contours using a second-order surface to approximate the failure surface at the design point. Compared to IFORM, the ISORM contour imposes more conservative constraints on environmental parameters, based on the assumption that the actual failure surface lies within the environmental parameter space in U-space. This results in an overestimation of the failure domain regardless of the true shape of the failure surface. Consequently, the ISORM contour consistently provides conservative estimates for design purposes.

### 5.2 HDC

Haselsteiner et al. (2017b) expand on the concept introduced by Jonathan et al. (2014) by presenting a novel

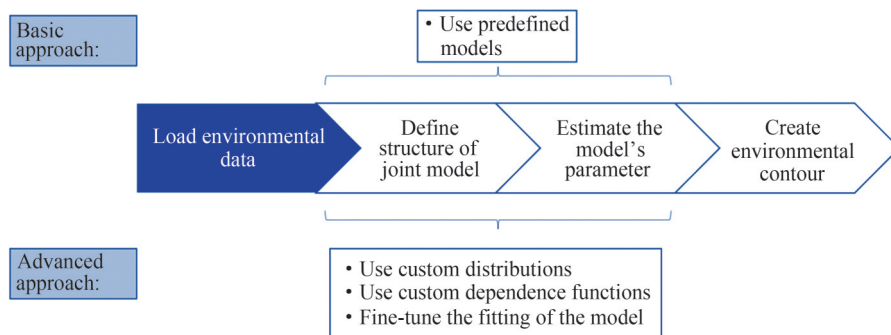
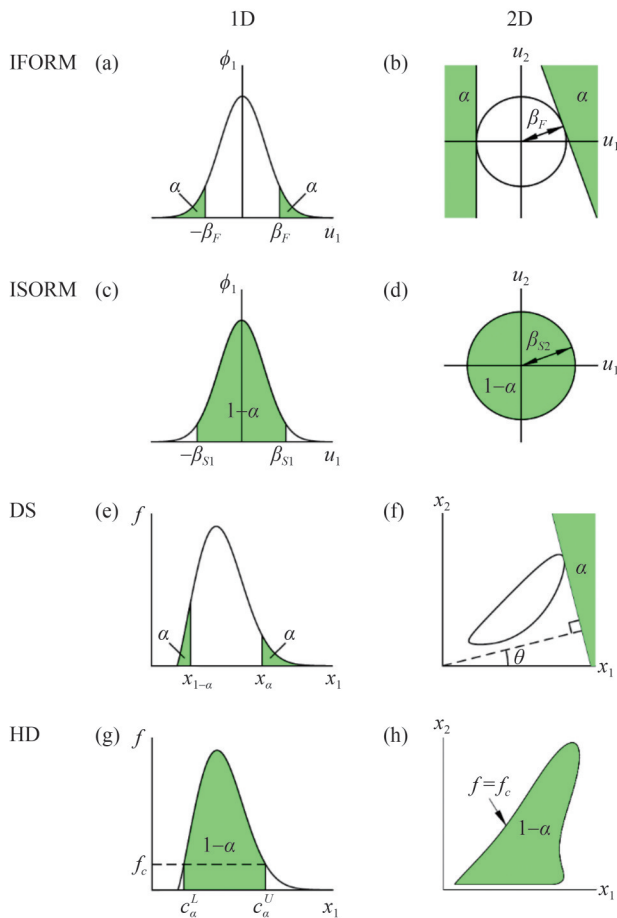


Figure 10 Overall functionality of ViroCon



**Figure 11** Illustration of definitions of IFORM, ISORM, direct sampling (DS) and highest density (HD) contours in 1D and 2D (Mackay and Haselsteiner, 2021)

approach called the HDC, which defines an environmental contour that encloses the highest density region (HDR) of a given probability density. Due to its computational simplicity, this method offers an appealing alternative to the established IFORM. Unlike IFORM, which relies on predefined boundary assumptions and often involves complex calculations, the HDC approach leverages the HDR to estimate extreme environmental conditions based on observed data distributions. The method starts by estimating the PDF nonparametrically, often using kernel density estimation (KDE) to accurately capture the data’s underlying distribution. The HDC then identifies a density threshold corresponding to a specified confidence level, defining an HDR representing the high-probability region of interest. By contouring this high-density region, the HDC provides an intuitive yet robust method for estimating environmental extremes, capturing key data characteristics without the limitations of traditional boundary constraints. Current research shows that the HDC method is not only computationally simpler but also better suited to handling irregular, non-linear, or multi-modal distributions, making it particularly effective in applications such as offshore engineer-

ing, where environmental variables exhibit complex dependencies and non-standard distributions. Due to these advantages, HDC has garnered significant attention, with recent studies focused on enhancing computational efficiency, integrating uncertainty analysis, and expanding its applications to fields like structural safety, renewable energy, and environmental risk assessment.

**5.3 DS method**

Another widely applied method is the DS approach, an alternative model for creating environmental contours directly in the original environmental space based on MCS (Huseby et al., 2013; Sinsabvarodom et al., 2020). The initial inaccuracies caused by an insufficient number of Monte Carlo samples were addressed by Huseby et al. (2014), where various sample sizes were tested. This approach was later extended to three dimensions by Vanem (2019). Based on direct MCS, the proposed method offers several advantages, including more precise interpretations and greater flexibility in modeling environmental parameters. Additionally, it minimizes the risk of both overestimating and underestimating failure probabilities, a common issue in traditional approaches that rely on the Rosenblatt transformation. This new approach has been adopted in several publications, such as for comparisons with the traditional IFORM method (Vanem et al., 2015), evaluations of different statistical models (Vanem, 2016), and reductions in process time (Huseby et al., 2014). Although the MCS addresses the issues associated with the Rosenblatt transformation, it necessitates the simulation of environmental states, which is computationally more demanding than the simpler IFORM calculations. Moreover, the method cannot produce concave contours due to its inherent limitations. It could provide more conservative environmental conditions compared to ISORM and HDC. The Direct MCS method offers a good approximation to the IFORM approach. However, the efficiency of direct sampling depends on the exceedance probability; smaller exceedance probabilities require larger sample sizes, making the Direct Monte Carlo method inefficient. This limitation can be addressed by generating samples closer to the environmental contour line using an alternative probability density function (Clarindo et al., 2021).

**5.4 Modified environmental contour method (MECM)**

The environmental contour approach was primarily developed for structures whose response is dominated by wave height and period. Nonetheless, wave and wind loads are equally significant for offshore wind turbines. Consequently, it could have a greater impact than other structures by simplifying the wind turbine design problem to a 2D contour. Some responses differ significantly between

operational and parked conditions, indicating a discontinuity in the relationship between extreme responses and environmental parameters (e.g., wind speed). Consequently, the ECM may not perform well for wind turbines.

Similarly, for other structures with varying modes of operation and survival mechanisms that alter responses based on environmental conditions, ECM may also be inadequate (Aggarwal et al., 2017). For DLC 1.6, the IEC specification (IEC, 2019) recommends using IFORM contours. As discussed earlier, the IFORM approach assumes a structure's failure surface can be linearized at the design point. Control methods in modern wind turbines aim to minimize loads while optimizing power output. Up to the rated wind speed, the controller is designed to extract as much energy from the wind as possible, until the power output exceeds the specified capacity. Thus, researchers have highlighted that the IFORM contour should not be directly applied in offshore wind turbine design (Li et al., 2016; Velarde et al., 2019).

In a previous study by Li et al. (2016), the ECM and MECM were applied to a bottom-fixed wind turbine. The results indicated that while the ECM performs well for wave-load-dominated responses, the MECM is necessary for wind-load-dominated responses. Choi et al. (2019) propose a modified hybrid marginal distribution model for  $H_s$  and improve the fitting accuracy of the distribution parameters for  $T_p$  by employing an outlier detection technique. Their results demonstrate that the proposed procedure effectively generates environmental contour lines based on observed sea states. Compared to the IFORM method, the MECM offers an alternative approach by focusing on environmental conditions along multiple contours, rather than analyzing the entire area within the specified return period. Although the MECM is more complex than the ECM due to the inclusion of additional environmental contours, it provides more reliable results, particularly for wind turbines with dual modes of operation (e.g. operational and parking).

Although the MECM is more complex than the original ECM, it remains a simplification compared to the full IFORM, as it considers environmental conditions along multiple contours rather than the entire space within the return period. The MECM can address the discontinuity in extreme responses relative to wind speed caused by the wind turbine's different operational and parking modes.

## 6 Advances in ECM/MECM development for OWTs

### 6.1 Application of MECM to the OWT

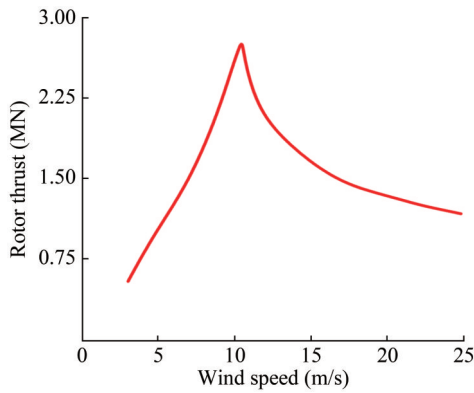
The ECM approach has been widely used in the design of offshore structures subjected to wave loading with good accuracy. It is therefore also applied in the analysis of off-

shore wind turbines (Chai et al., 2024; Lee et al., 2023; Li et al., 2017, 2024; Zhong et al., 2024). When wind effects are disregarded, or only the parked condition is of interest, the wind turbine behaves similarly to an offshore structure. The original ECM is applicable in such cases, as its assumptions hold for responses driven by wave loads. Velarde et al. (2019) use the ECM to establish relevant design conditions for the assessment of offshore wind turbines under extreme resonant response during parked situations based on in-situ metocean observations on the North Sea.

Zhao et al. (2023) analyzed the system reliability of the mooring system for floating offshore wind turbines (FOWT), the extreme design loads are estimated using the environmental contour approach, and a logarithmic function is proposed to describe the relationship between the extreme response and the target return period, simplifying the full long-term analysis. Li and Zhang (2020) developed a joint distribution model for wind and waves using the C-Vine copula approach. They predicted the long-term extreme response of Spar-type offshore wind turbine structures through the ECM combined with the Rosenblatt transformation. Their results indicated that the prediction accuracy of long-term extreme responses improved significantly when using an environmental contour corresponding to a 50-year return period. Liu and Manuel (2018) estimated the impact of wind-waves on offshore wind turbines by studying the system response under different environmental conditions of wind-waves (wind speed and wave height). As previously discussed, the ECM is not a reliable method for predicting the extreme long-term response of structures with complex dynamics, such as FOWTs, due to the non-monotonic behavior of wind loads (Dong et al., 2024; Haselsteiner et al., 2022a; Velarde et al., 2019; Zhao et al., 2023).

The wind load typically reaches its maximum at the rated wind speed, decreases as wind speed increases, and drops sharply at the cut-out wind speed (Allen et al., 2020). The turbine's controller actively minimizes loading, leading to non-monotonic responses in various design variables, such as bending moments on the tower and blades. As shown in Figure 12, the wind force does not vary monotonically with wind speed, particularly around the cut-out wind speed.

A modified ECM was proposed for offshore wind turbines, capable of addressing the discontinuity between extreme responses and environmental parameters (Li et al., 2016, 2017). MECM evaluates extreme responses across different operation modes individually by selecting additional environmental contours associated with these modes, ensuring response continuity. This method is considered more suitable for estimating offshore wind turbines' extreme responses due to turbines' inherently non-monotonic load responses to environmental parameters (Saha et al., 2014). A diagram illustrating the MECM workflow is presented in Figure 13.



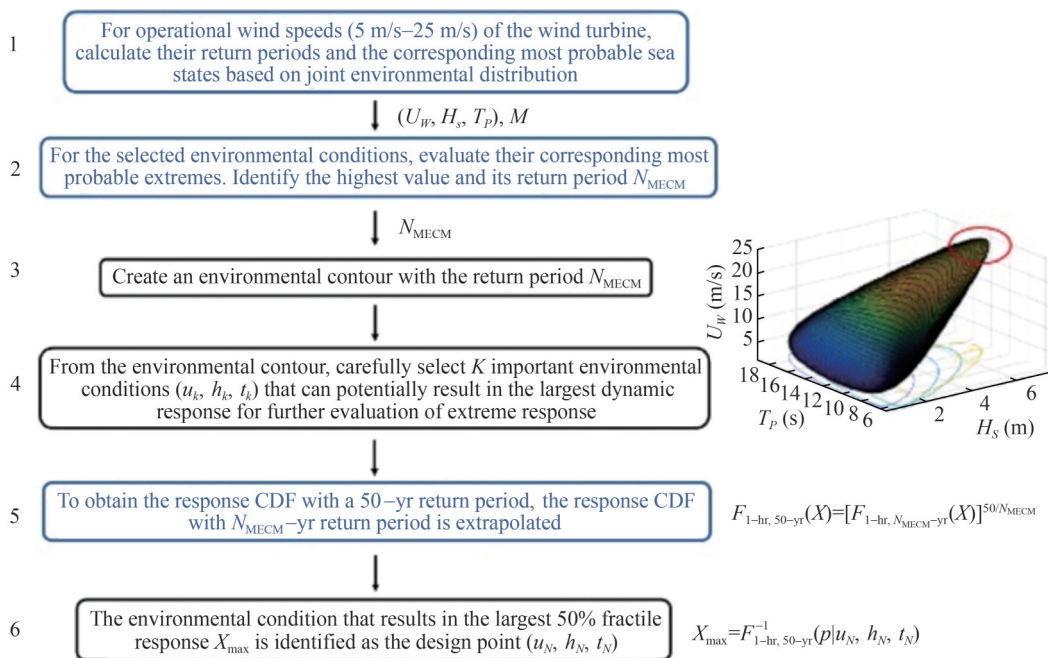
**Figure 12** Trust force curve of the 15 MW IEA offshore wind turbine (Allen et al., 2020)

The methodologies for ECM and MECM proposed for OWT analysis are systematically categorized in Table 2. The table organizes these studies based on their sources, target systems, contour variables, and the types of contours applied.

It illustrates the evolution of ECM and MECM applications from fixed-bottom OWTs to more complex FOWTs and hybrid systems. Recent studies have increasingly focused on incorporating multivariate environmental variables, such as wave direction, turbulence intensity, and directional spreading at the mean wave direction, to address the coupled dynamic responses of floating systems. The MECM has been adapted to account for more complex operational scenarios, including the use of multiple contour surfaces, as demonstrated in studies such as Lee et al. (2023) and Li et al. (2017). The table also highlights emerging applications of MECM in hybrid renewable energy plat-

forms, such as the Hywind-Wavebob-NACA system (Li et al., 2019), showcasing its adaptability to novel offshore renewable systems. Furthermore, recent advancements, such as the integration of copula models (Li and Zhang, 2020), underscore the growing sophistication of contour construction techniques aimed at improving reliability and precision.

To address the complex demands of offshore renewable energy systems, particularly OWT systems, the MECM has emerged as a prominent research focus in recent years. Li et al. (2019) proposed a MECM to estimate the long-term extreme response of offshore renewable energy hybrid systems, which is based on combining a floating wind turbine, a WEC and two tidal turbines. The modified method accounts for response variability by examining multiple environmental contours corresponding to different return periods. This approach ensures that the non-monotonic behavior of the wind turbine is adequately addressed, which is also stated by Saranyasoontorn and Manuel (2004, 2005). A MECM for bottom-fixed offshore wind turbine applications was presented by Li et al. (2016). The most important environmental conditions influencing long-term extremes can be found using the MECM. The NREL 5MW wind turbine, supported by a simplified jacket-type structure, is used to test the approach. Compared to the FLTA, MECM is an effective and reliable technique for forecasting the extreme responses of bottom-fixed offshore wind turbines. Chen et al. (2020) proposed a method that incorporates turbulence intensity as a stochastic variable in the extreme response analysis of a monopile wind turbine based on the ECM. The analysis considers four environmental variables: mean wind speed, significant wave height, spectral peak period, and turbulence intensity. An example is provided



**Figure 13** Illustration of the MECM workflow (Lee et al., 2023)

**Table 2** ECM/MECM proposed for analyzing offshore wind turbines

Source and year	Study subjects	Contour variables	Contour type
Wang et al. (2024)	DTU 10 MW wind turbine	$V, H_s, T_p$	3D IFORM
Horn and Winterstein (2018)	10 MW DTU reference wind turbine	$V - H_s, H_s - T_p$	2D IFORM
Liu et al. (2019)	Semi-submersible platform FOWT	$V, H_s$	2D IFORM, 3D IFORM
Li et al. (2016)	Bottom-fixed OWTs	$V, H_s, T_p$	Modified IFORM
Li et al. (2017)	DeepCwind semisubmersible wind turbine	$V - H_s - T_p$	MECM-including an additional contour within the operational region of the wind turbine
Li et al. (2019)	Hywind-Wavebob-NACA 638xx Combination (HWNC)	$H_s - T_p$	MECM-Including multiple important contour surfaces rather than the 50-year one alone
Li and Zhang (2020)	OC3-Hywind spar type platform	WNDDIR, $V, H_s, T_p$ , WAVD, SPRD	Improved ECM using the C-vine copula model and the Rosenblatt transformation
Chen et al. (2020)	Monopile-based offshore wind turbine	$V, H_s, T_p, TI$	IFORM and Modified IFORM
Lee et al. (2023)	Floating vertical axis wind turbine (FVAWT)	$V - H_s - T_p$	MECM-including additional environment contours to cover different operation modes

Note:  $V$ —wind speed,  $TI$ —turbulence intensity,  $H_s$ —significant wave height,  $T_p$ —spectral peak period, WNDDIR—Wind direction, WAVD—mean wave direction, SPRD—directional spread at the mean wave direction

to evaluate the 50-year extreme dynamic responses, including turbulence intensity as an additional variable. The results obtained using the ECM and MECM methods are compared with those from the FLTA method, which serves as a benchmark. Raed et al. (2020) applied the inverse first-order reliability method (IFORM) and a Monte Carlo simulation algorithm, to assess the uncertainty of long-term extreme responses in offshore floating wind turbines. They fitted the Gumbel and generalized extreme value distributions to the maximum extreme response values under different offshore conditions, enabling the prediction of the overall system response.

Although the MECM is more complex than the ECM due to the inclusion of additional environmental contours, its results are more reliable, particularly for wind turbines with two modes of operation. Compared to the FLTA or IFORM, the MECM remains a significantly simpler alternative.

### 6.2 Strength assessment for substructural design of OWT

In many structural analysis projects, the ECM is needed as a prerequisite and a well-accepted approach to define extreme environmental loads (Coe et al., 2018; Liu et al., 2019; Raed et al., 2020). OWT safety regulations and construction standards aim to ensure structural reliability against extreme loads (Chen et al., 2024; Shittu et al., 2020a, b). Nonlinear time-domain numerical models are now utilized to predict structural responses to extreme waves or wave groups occurring over short time periods, which supports the design of OWT structures capable of withstanding prolonged, harsh sea conditions (Amiri et al., 2024b; Sun et al., 2024).

Li et al. (2024) investigated the response extremes of an FOWT based on ISORM and IFORM, it was found that

the sea state predicted by ISORM is more extreme, potentially leading to a more conservative design compared to IFORM. Wang et al. (2024) focus on the floater column design of FOWT, and employ the ECM to initially choose cases for ultimate limit state (ULS) design based on important wind speed conditions and critical wave periods. The environmental conditions are selected from an offshore site in the Northern North Sea, known for its severe conditions, specifically Site 14 in the study by Li et al. (2015). Response amplitude operators (RAOs) for the cross-sectional forces and moments of the columns and the ECMs are employed to identify representative wind and wave conditions for stress analysis.

## 7 Discussion and conclusions

### 7.1 Challenges and future directions

The ECM, primarily grounded in reliability theory, is commonly applied to bivariate and trivariate random variables. However, its application to multivariate random variables remains underexplored, limiting its broader use in practical engineering contexts. Furthermore, structural design should comprehensively account for external loads and other variables, particularly their stochastic characteristics. Current studies predominantly focus on variables such as wind speed, significant wave height, and spectral peak period, often assuming wind and wave directions are always aligned and other factors, such as sea level, current, turbulence structure, spectrum type, and additional variables, remain constant. The implications of this assumption remain unclear. Incorporating additional variables in ECM and FLTA calculations is possible; however, as the number of variables increases, challenges arise in estimat-

ing joint distributions and conducting sufficient response simulations.

In the calculation of long-term extreme responses for OWTs, the ECM reduces the need for exhaustive simulations, enabling the definition of optimized design load envelopes and improving computational efficiency. It is widely used in the design and analysis of OWTs to predict extreme environmental loads, particularly for the strength design, verification, and structural reliability assessment of platform substructures. During the preliminary design phase, the ECM helps define the maximum expected structural responses of monopile or jacket substructures, allowing for efficient and targeted simulations without evaluating every possible environmental scenario. Beyond platform substructure design, the ECM is also applied to the design and analysis of mooring systems for OWTs, where it helps identify critical load combinations and predict extreme responses, such as mooring line tensions and platform motions, under complex environmental conditions. These applications are especially valuable in deepwater installations, where mooring systems must withstand highly variable environmental conditions and significant structural demands. Additionally, the ECM shows significant potential for application in the design and analysis of integrated systems combining WECs with OWTs. These hybrid systems, which aim to maximize energy extraction by leveraging complementary resources, represent a growing area of research in marine renewable energy.

The difficulties in accurately estimating and applying environmental contours highlight the need for further methodological advancements, encouraging both academic and industrial researchers to address these challenges. Ross et al. (2020) provided a helpful checklist to guide practitioners in identifying when the ECM is most appropriate, recommending its use in the following scenarios: 1) the nature of responses and environmental variables are well understood; 2) response-based analysis is infeasible, and 3) the analysis is at the outline design stage. To fully unlock the potential of the ECM/MECM in offshore wind applications, the following key directions are proposed:

- Addressing non-monotonic responses and the multivariate challenges. The MECM shows potential for use in systems with structural responses that are non-monotonic with respect to environmental parameters. Since ECM/MECM relies on joint distribution models of environmental data, further research is necessary to deepen the understanding of non-monotonic responses in FOWT platforms and consider combining environmental loads to account for varying wind, wave, and current incident directions.

- Developing open-source computational tools. To make the MECM more accessible to the research community, creating open-source computational tools is essential. These tools could include publicly available software packages that implement MECM frameworks for different offshore

systems, providing a standardized and user-friendly interface for practitioners.

- Validation of MECM through experimental data could involve model-scale testing or utilizing full-scale field measurements of OWTs and FOWTs. Comparing MECM-predicted extreme responses with observed data would not only verify its accuracy but also highlight areas for refinement, particularly for systems exposed to complex, non-stationary environmental conditions.

- Extending MECM applications to other regions and complex systems. The MECM can be adapted to other sea regions by identifying the probability distribution characteristics of environmental parameters specific to those areas. Broadening its scope requires examining additional response variables and exploring diverse geographic locations to ensure wider applicability and precision. The MECM can also be extended to other offshore systems, WECs, ocean thermal energy conversion (OTEC) systems, and hybrid renewable energy platforms.

By incorporating these steps, including incorporating multivariate variables, tool development and validation, and expanding MECM applicability, future research can better address the challenges associated with MECM and enable its effective application in both academic and industrial contexts.

## 7.2 Summary

An environmental contour is estimated without considering structural details. Since environmental contours are independent of structural specifics, they can, in principle, be applied to study various structures within a given environment, provided the underlying assumptions linking the environment and the structure are not violated. OWTs differ fundamentally from conventional offshore structures, as designers must account for the non-monotonic behavior of wind turbine responses and incorporate this effect when predicting extreme responses. This paper reviews the efficient determination of long-term extreme responses for OWTs and summarizes the following conclusions:

- 1) Bibliometric analyses reveal significant research trends related to long-term extreme responses in OWTs. Contributions from various research institutions and authors have identified key research hotspots. Additionally, keyword analysis underscores the strong relationship between ECM and extreme responses, providing valuable insights and guidance for the literature review.

- 2) The review compares the performances, theoretical foundations, research limitations, and advancements associated with various ECMs. Selecting an appropriate ECM requires careful construction of the limit state equation and the joint distribution of sea state parameters.

- 3) For long-term extreme response estimation of OWTs, the MECM offers significant improvements over the original ECM. The MECM could also be tested for predicting

long-term extreme responses in other systems with on/off or operational state changes driven by environmental parameters such as wind speed or wave height. Further research could focus on evaluating the probability of system failure under extreme loads predicted by the MECM to ensure consistency with the required return period.

While this review provides a comprehensive overview, it does not cover every aspect of long-term extreme prediction for OWTs. Future research should address specific limitations and explore new directions to advance this rapidly evolving field.

## Nomenclature

CDF	Cumulative distribution function
CWTS	Centre for science and technology studies
DS	Direct sampling
EC	Environment contour
ECM	Environment contour method
FLTA	Full long-term analysis
FVAWT	Floating vertical axis wind turbine
HDC	Highest density contour
HDR	Highest density region
$H_s$	Significant wave height
ISORM	Inverse second-order reliability method
IFORM	Inverse first-order reliability method
KDE	Kernel density estimation
MCS	Monte Carlo simulation
MECM	Modified environmental contour method
OWT	Offshore wind turbine
PDF	Probability density function
POT	Peak-over-threshold
RAOs	Response amplitude operators
TI	Turbulence intensity
$T_p$	Wave spectral period
ULS	Ultimate limit state
$U_w$	Mean wind speed
WEC	Wave energy converter
WoS	Web of Science

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