Applied Ocean Research 73 (2018) 17–26

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

A new combination of conditional environmental distributions

Jan-Tore Horn[a,b,*], Elzbieta Bitner-Gregersen[c], Jørgen R. Krokstad[b], Bernt J. Leira[b], Jørgen Amdahl[a,b]

[a] Centre for Autonomous Marine Operations and systems (NTNU AMOS), NTNU, Trondheim, Norway
[b] Department of Marine Technology, NTNU, Trondheim, Norway
[c] DNV GL, Veritasveien 1, Høvik, Norway

ARTICLE INFO

Article history:
Received 4 December 2017
Received in revised form 10 January 2018
Accepted 22 January 2018

Keywords:
Joint distribution
Environmental parameters
Directional effects
Design
Offshore wind turbines

ABSTRACT

In this paper, a joint distribution of all relevant environmental parameters used in design of offshore structures including directional components is presented, along with a novel procedure for dependency modelling between wind and wind sea. Probabilistic directional models are rarely used for response calculation and reliability assessments of stationary offshore structures. However, very few locations have the same environment from all compass directions in combination with a rotationally symmetric structure. The scope of this work is to present a general environmental joint distribution with directional descriptions for long term design of stationary offshore structures such as offshore wind turbines. Wind, wind sea and swell parameters will be investigated for a chosen location in the central North Sea.

1. Introduction

The present work presents a general multi-dimensional joint distribution which is fitted to data from the site of a future offshore wind farm in the central North Sea. The aim is to obtain a statistical representation of combinations of all relevant environmental variables for design of offshore wind turbines where absolute and relative load directions are important for response analyses. The proposed model is useful for full long term analyses to calibrate simplified design methods, and finding probable combinations of environmental parameters for extreme sea states and simplified ULS design [1]. Environmental variables include wind, wind sea, swell and tide, as well as their respective directions. A conditional modelling approach [2] will be utilized, due to its robustness for description of simultaneous information in data. Copula-based methods may be an alternative, but still need further exploration [3–5].

Depending on the desired accuracy of the structural response and reliability estimations, the joint environmental distributions can be extended to high dimensions corresponding to the available site-specific data. Accounting for environmental variable correlations has shown to reduce design conservatism [6] for structures related to oil and gas extraction on the Norwegian continental shelf.

Joint modelling of offshore environmental processes has evolved over the years to facilitate probabilistic analysis of structures. Early adoptions include a bottom-fixed structure accounting for wave height and current [7]. A comprehensive omni-directional model including wind, wave, current and tidal elevation can be found in, e.g. [8], and it is often referred to by standards for joint modelling of environmental processes [9]. A similar model is used in, e.g. [10], adopted for the northern North Sea and more recently in [11] for several locations. In [12], an extension is added to model the mean and standard deviation of the wind and wave direction. Later, a model for description of combined sea (wind sea and swell) and relative directions was presented in, e.g. [13]. It is still a challenge to model directional processes. For instance, consistency with regard to combining omni-directional and multi-directional data must be considered in probabilistic design [14].

For offshore wind turbines, the structural dynamics with a power-producing rotor will introduce directionally dependent response characteristics [15–17]. Hence, a statistical description of both absolute and relative directions of the load processes is of importance. A continuous wave directional distribution can be found in, e.g. [18] and combined with a structural resistance in [19] as a function of the absolute direction. Further, a model for relative wind–wave direction was proposed in [20], but lacks relation to the earth-fixed coordinate system, which will be introduced in the present work.

In [21,22], the absolute wind direction was modelled using the von Mises distribution [23,24], which has proven suitable for cir-

---

[*] Corresponding author at: Centre for Autonomous Marine Operations and Systems (NTNU AMOS), NTNU, Trondheim, Norway.
E-mail address: jan-tore.horn@ntnu.no (J.-T. Horn).

https://doi.org/10.1016/j.apor.2018.01.010

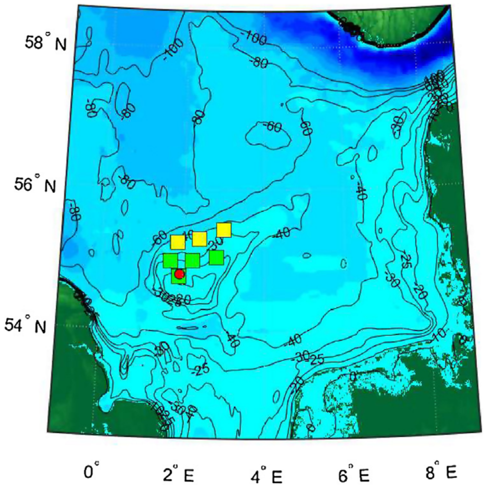


Fig. 1. Planned (green) and possible (yellow) offshore wind farms at Dogger Bank with location for hindcast data (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

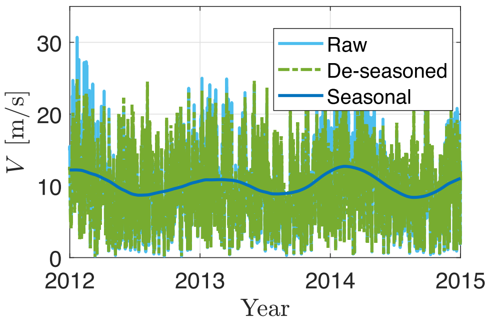
cular distributions. Furthermore, a relation between wind speed and direction was presented in [25]. This dependency will be also explored in this paper, with a slightly more pragmatic approach and in combination with other relevant offshore environmental processes.

The present study proposes a new combination of conditional environmental distributions which can be found in the literature and verifies it by environmental data from the North Sea. The paper is organized as follows: First, the example offshore site is presented along with the data characteristics before and after pre-processing. Secondly, the full environmental join distribution is constructed along with evaluation of the goodness of the conditional fittings. Finally, an error test of the complete distribution is performed.

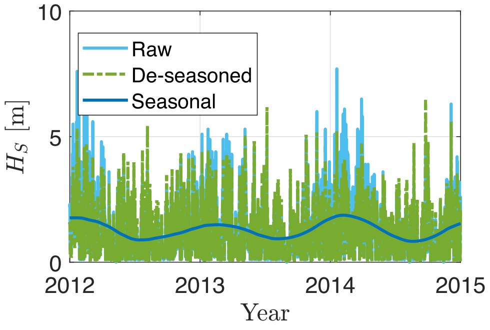
2. Offshore site

Hindcast data for description of the wind and wave environment used in the study is provided by the Norwegian Meteorological Institute [26] for the location shown in Fig. 1. The data contains information about the wind speed, wind direction and significant wave height, peak period, and direction for both wind sea and swell. The data are sampled every third hour and cover the historical period of approximately 60 years.

The hindcast data are pre-processed in order to remove ties due to discrete frequencies in the hindcast model, and to make the data independent and identically distributed (iid). This is done by de-seasonalizing the raw data with a moving average algorithm. De-seasoning is one of the suggested pre-processing methods when using data from measurements [27]. Note that directional data is not pre-processed. The effects of pre-processing can be seen in Figs. 2 and 3 . It is clear that the de-seasonalizing algorithm reduces the tail-distribution of the wind speed and significant wave height, yielding smaller extreme values. The average conditional exceedance rate (ACER) approach as described in [28] is plotted in Fig. 3 for two values of the conditioning parameter k. In the ACER method, k consecutive peaks over a given exceedance level will be considered dependent and only the first peak will be counted. It is seen that de-seasonalizing has a large effect on the high-percentile values, but the ACER method varies from the wind speed to the wave height, indicating a higher inter-dependency in the wave height hindcast data. This is reflected in Tab. 1 where the ACER method has a much larger impact on the extreme values for wave height.

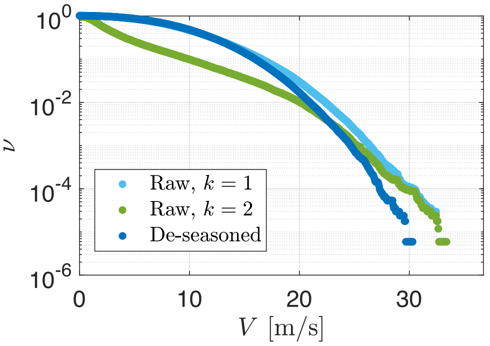


(a) Wind speed

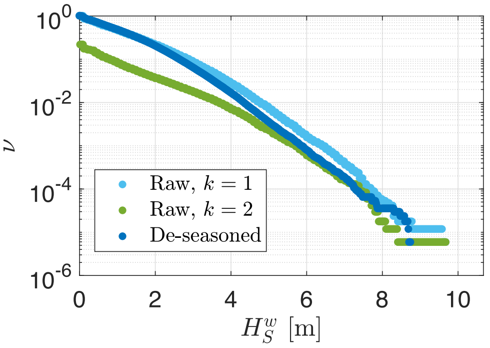


(b) Wind sea significant wave height

Fig. 2. De-seasonalizing of wind and wind sea.



(a) Wind speed



(b) Wind sea significant wave height

Fig. 3. Upcrossing rates by ACER method and de-seasonalizing.