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A statistical methodology for the estimation of extreme wave conditions for offshore renewable applications

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ABSTRACT

Accurate estimation of extreme wave conditions is critical for offshore renewable energy activities and applications. The use of numerical wind and wave models gives a credible and convenient way of monitoring the general atmospheric and sea state conditions, especially in the absence of sufficient observational networks. However, when focusing on the study of non-frequent cases, in particular over coastal areas, increased uncertainty in the model outputs and accordingly in the reliability of the estimation of extreme waves becomes an important issue. The current study introduces a methodology to validate and post-process outputs from a high resolution numerical wave modeling system for extreme wave estimation based on the significant wave height. This approach is demonstrated through the data analysis at a relatively deep water site, FINO 1, as well as a relatively shallow water area, coastal site Horns Rev, which is located in the North Sea, west of Denmark. The post-processing targets at correcting the modeled time series of the significant wave height, in order to match the statistics of the corresponding measurements, including not only the conventional parameters such as the mean and standard deviation, but also a new parameter, the second-order spectral moment. This second-order spectral moment is essential for extreme value estimation but has so far been neglected in relevant studies. The improved model results are utilized for the estimation of the 50-year values of significant wave height as a characteristic index of extreme wave conditions. The results from the proposed methodology seem to be in a good agreement with the measurements at both the relatively deep, open water and the shallow, coastal water sites, providing a potentially useful tool for offshore renewable energy applications.

1. Introduction

Accurate estimation of the extreme wave height is essential for design of offshore and coastal structures such as wind turbines and platforms. Such an estimate requires long term, good quality measurements, which are seldom available.

To complement the shortage of measurements, long term, climatological outputs from wave models have been used for calculating the extreme wave atlas, e.g. Refs. [1,10,11,14,39,40,47].

However, the outputs from the existing wave models, even the most advanced ones as we will discuss in the following, are sometimes limited for the estimation of the extreme values. It is a common phenomenon and challenge that the smoothing effect as embedded in numerical modeling will lead to flattened variability at relatively high frequencies, resulting in the "missing peaks" as discussed extensively in the review article of [13]. In Ref. [13]; a thorough discussion was given on the challenges for wave modeling of storm conditions. One of the challenges lies in the limitation of existing mesoscale wave models in resolving the response of waves to the fast turbulent atmospheric forcing during strong wind conditions; together with the limitations of the atmospheric models in resolving the gust, this leads to "missing peaks" in the wave modeling. The modeling is even more challenging in the coastal areas.

The wave model (WAM) has been utilized in numerous studies, not only for deep waters but also for coastal areas and sheltered seas [14,39,40]. Note that in these studies, they validated the model through mean wave statistics rather than extreme values [5]. used

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WAM, and through H_s, they showed that the model captured the storm events at several sites in the North Sea with rather deep water, including FINO 1. The shallow water formulations incorporated in the latest WAM version make the model capable of simulating the wave conditions reaching performance comparable to the coastal models like SWAN applied in higher resolution [9]; although both WAM and SWAN need improvement for shallow waters in the coastal zones. It has been observed frequently that for shallow waters, the significant wave height, H_s, is over-predicted for strong wind conditions, both with WAM [14,25,39,40] and coastal models MIKE 21 SW and SWAN [48]. This reflects the challenges in wave modeling for issues of swell decay in the coastal zones.

Whereas forecast of waves has been performed at much higher horizontal resolution, such as 1–2 km in Ref. [41]; the existing extreme wave atlases were often made from data of coarser resolutions, e.g. those from the ERA-40 reanalysis correspond to a horizontal resolution of 1.5° [11]; those in Ref. [10] have a horizontal resolution of 0.125° and those in Ref. [1] 10 km. The data analyzed here, within the framework of the EU MARINA Platform project, are outputs from a new version of WAM run at a resolution of 5 km. The model has been endowed with routines that take into account of shallow water effects, which is expected to improve the simulation for the coastal areas. WAM, as well as the forcing atmospheric system SKIRON, was implanted with assimilation modules for correcting their initial conditions based on available wind and wave in situ and remote sensing records [15,17,23].

By reviewing the difficulties and uncertainties related to the current wave modeling systems, in this study, we aim at developing a statistical approach to implement missing information as in the modeled data through measurements.

In this study, first, it will be shown through the analysis of measurements that even with a high resolution of 5 km and with routines taking into account of shallow water effect, the most up-to-date model is limited in resolving the high frequency variability of H_s. This phenomenon, as examined through the literature, shows to be a general issue with wave modeling, even with SWAN at fine resolution. The impact of the high frequency variability on the extreme value estimation is shown here to be important through spectral moments (Section 4) and should not be neglected. None of the published studies regarding the extreme wave height have taken this into account.

In this study, we define the extreme wave height as the significant wave height, H_s, with a 50-year return period, denoted as H_s^{50}.

The paper is accordingly structured as follows. The measurements, including one open water, rather deep water and one coastal, rather shallow water site, are introduced in section 2. The wave model and the atmospheric model that provides the wind force to the wave model are described in section 3. Section 4 introduces the spectral correction method. In section 5, the use of two statistical methods for the estimation of the T-year return value, the periodic maximum method and the peak-over-threshold method, is described. Data analysis, the post-processing procedure and the results of H_s^{50} are presented in section 6, followed by discussions and conclusions in sections 7 and 8.

2. Measurements

The wave measurements used in this study are recorded at two offshore sites: Horns Rev and FINO 1. The locations of the two sites are shown in Fig. 1.

Horns Rev is a coastal site. The water depth at this site varies from 6 to 12 m. According to the distribution of the ratio of water depth (D) and the peak wave length (L_w), $r = D/L_w$, the site can be considered as intermediate to shallow water (Table 1). The wave measurements were made through a Wave Rider buoy. The details of the measurements can be found in Refs. [43]; the buoy data used in the current study were from “Wave Rider S” as referred to in Ref. [43] (their Figs. 4–14). The waves were measured through the vertical acceleration of the buoy. As the buoy follows the waves, the force of the mooring line will change. The force is produced by the changing immersion of the buoy, resulting in an error of 1.5% maximum [46]. The significant wave height was derived from a 1D wave power spectrum measured by the buoy. The data are available from July 1999 to June 2006, half hourly. Data analysis was done in Ref. [43] for the year 2004 where the data quality was considered to be reliable. Similar data examination was done here for 1999 to 2006 and we did not find any abnormal data distribution behaviors and therefore conclude that the data quality is fine. The data coverage for each month from 2001 to 2006 is listed in Table 2. The information about the monthly data coverage is important when we need the spectrum from measurements for the spectral correction method proposed here in this study, which can only be calculated from continuous time series (see section 6.1).

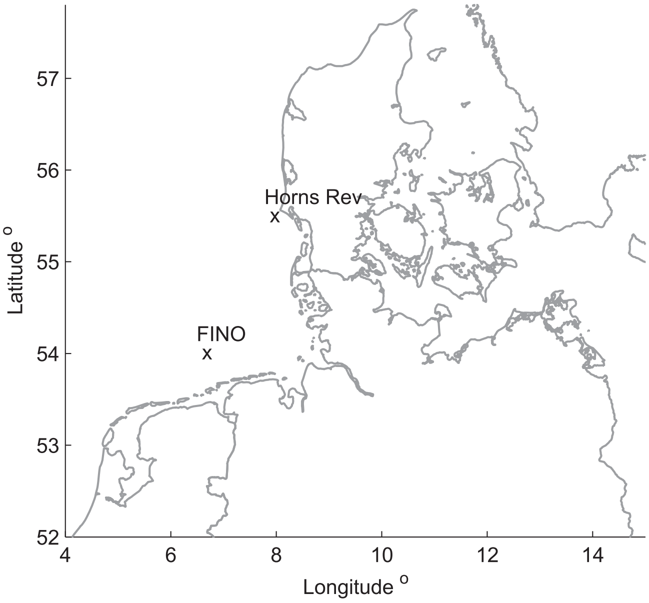

Fig. 1. Locations of the shallow water site Horns Rev and the deep water site FINO 1.

FINO 1 has rather open ocean condition. The water depth is 30 m. According to the distribution of $r = D/L_w$, it can be considered as an intermediate to deep water site (Table 1). The wave measurements at FINO 1 analyzed in this paper were made from a directional waverider DWR (Datawell BV). The data quality was examined in terms of comparison with measurements from four other different instruments in Ref. [44]. The consistent statistics between the various measurements suggest a good data quality. More details about the measurements at FINO 1 can be found in Ref. [44]. The data used here are half hourly and are from 2003 to 2013. The data coverage is on average much less than the Horns Rev site and it is shown in Table 3 for each month.

Table 1
The distribution of the ratio between water depth and the peak wave length $r = D/L_w$ at the coastal site Horns Rev and open water site FINO 1.

Site	$r<\frac{1}{20}$ shallow	$r<\frac{1}{10}$	$r<\frac{1}{5}$	$\frac{1}{20}<r<\frac{1}{2}$ intermediate	$r>\frac{1}{2}$ deep
Horns Rev	0.8%	24.3%	76.4%	98.2%	1%
FINO 1	0%	0.8%	7.6%	57.3%	42.7%