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Wave climate analysis for the design of wave energy harvesters in the Mediterranean Sea

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ABSTRACT

The objective of this paper is to provide a synthetic tool for determining expeditiously the wave climate conditions in several areas of the Mediterranean Sea. In the open literature, several authors have already conducted this specific analysis also for the area under examination in this paper. However, the need of discussing aspects strictly related to the design of wave energy harvesters is still relevant. Therefore, considering the variety of devices and the amount of information needed for conducting both an energy-wise optimization and a structural reliability assessment, a holistic view on the topic is provided. Specifically, the paper elucidates the theoretical aspects involved in the estimation of wave energy statistics and in the calculation of relevant return values. Next, it provides synthetic data representing the mean wave power and the return value of extreme events in several coastal areas of the Mediterranean Sea. In this regard, the paper complements information available in the open literature by discussing the influence of the directional pattern of the sea states in the determination of sea state statistics as well as in the design of a wave energy harvester.

1. Introduction

The optimized design of any wave energy harvester is based on the quantitative description of the wave climate at a certain location. Indeed, structural safety, as well as energy production, relies on the calculation of relevant statistical parameters, such as wave height of given return period, average annual wave power, etc. Thus, the remarkable number of contributions given in the field of wave resource assessment, with the construction of wave atlases, is not surprising.

From a methodological perspective, wave atlases are constructed by utilizing either recorded or artificially generated wave data. The first category involves the utilization of buoy or of satellite data. The second one uses numerical codes, such as WAM models [1], for simulating the wave field generation and evolution by using wind field information as input. Depending on data quality and on numerical code peculiarities, wave atlases were developed at different spatial scales. Global estimates were proposed, for instance, by Cornett [2], Barstow, et al. [3], Mørk, et al. [4] and Arinaga and Cheung [5]. The key characteristic of these analyses is the possibility of identifying wide areas of interest for the realization of a wave energy harvester. Obviously, the coarse scale used in these global analyses does not allow the complete design of a wave energy harvester. Nevertheless, it is useful for defining locations where fostering the realization of wave energy devices.

Detailed investigations are restricted to well defined areas and involve the use of high-resolution numerical codes. This aspect is quite relevant in closed areas, such as the Mediterranean Sea, where the spatial variability is not compatible with the resolution associated with classical measurement techniques [6]. Several authors proposed a holistic view on the wave energy status by focussing on certain areas. For instance, Liberti, et al. [6] investigated wave energy availability in the Mediterranean Sea with an emphasis on the Italian area; Ayat [7] developed a wave power atlas for the Eastern Mediterranean Sea and the Aegean Sea; a similar analysis was proposed by Aydoğan et al. [8] for the Black Sea and by Sierra et al. [9] in Spain.

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The mentioned analyses are necessary for an energy-wise optimization of the device. However, an extreme value analysis must be pursued in parallel for predicting extreme actions on the device. So that, a reliability assessment can be conducted by considering certain extreme events. In this regard, the process invokes concepts developed in the context of classical coastal and marine engineering. The common procedure involves an analysis at short time scale (~hours) and at long time scale (~years). This distinction accommodates convenient representations of the wave motion. Specifically, the short-term analysis is pursued by invoking a spectral representation of the free surface displacement, which is connected to a stationary representation of the process [10]. The long-term statistics involves the non-stationary character of the free surface displacement, which is treated by accumulating the statistical information of the process in a few synthetic parameters (commonly, significant wave height, peak spectral period, mean wave direction) described via simplified models [11]. In this context, recently proposed models for extreme value analysis are the Equivalent Triangular Storm (ETS) model and the Equivalent Power Storm (EPS) model [12,13]. These models found on a theoretical representation of real sea storms, which accommodates the derivation of closed form solutions of relevant return values.

To conduct a joint analysis of extreme waves and of wave climate along the coasts of the Mediterranean Sea is the objective of this paper. Specifically, the paper presents a holistic view on the preliminary wave related steps involved in the design of a wave energy harvester. The findings of this article are useful for designing a device as it provides the crucial information for optimizing the energetic performance as well as for conducting a reliability assessment of a device. In this regard, it is worth mentioning that the variety of devices developed in the last decades requires a more detailed quantification of the wave climate. Indeed, some devices can be designed by considering only the energetic characteristics of the sea states, but several are highly influenced by the mean wave direction (see Falcão [14] for a review of the available technologies). Therefore, the paper considers, in addition, the directional features of the recorded sea states, as it is relevant in the design of several wave energy devices. The analysis utilizes data generated by a WAM numerical model. Thus, a reliability assessment of this model is conducted by restricting the attention to the directional pattern of the sea states. Then, the paper elucidates the key characteristics of the theoretical model used in the successive analysis. Next, the results of the analysis are disseminated by investigating both the mean wave power (in conjunction with its "directional" distribution) and the return period of significant wave height (with its "directional" distribution, as well).

2. Wave data: reliability assessment of the used WAM model with emphasis on mean wave directions

Wave simulations have been performed using a parallel version of WAM wave model Cycle 4.5.3 [15]. WAM is a third generation spectral wave model, largely used in wave forecasting systems, that solves the spectral energy balance equation without any a priori assumption on the spectral shape. The model domain used in this work covers the entire Mediterranean Sea from 5.50°W to 36.126°E of longitude and has been discretized with a regular grid in spherical coordinates at the uniform resolution of 1/16° in each direction. The resulting grid cell has a size of about 5–7 Km. Model bathymetry has been derived from the General Bathymetric Chart of the Oceans (GEBCO) 30 arc-second gridded data set [16] by averaging the depths of data points falling in each computational cell. The directional wave energy spectrum has been discretized using 36 directional bins and 32 frequencies starting from 0.06 Hz and increasing with relative size increment of 0.1 to a final frequency of 1.15. A ten year climatology has been produced for the period 2001–2010 using as surface forcing for the model six-hourly wind analysis fields produced operatively by ECMWF at ¼° spatial resolution. The main wave parameters, including significant wave height (H_s), wave direction (θ_m) and mean period (T_m) have been estimated every 3 h for all points in the domain.

An extensive validation of the model both against buoys of the Italian Buoy Network (Rete Ondametrica Nazionale, RON) and against satellite data has been already presented in Ref. [6]. Statistics derived from the comparison with five different satellites over the entire Mediterranean basin show a quite good agreement with a bias for the significant wave heights less than 0.14 m and a slope going from 0.91 to 1.01.

Here model results are compared with buoy data in two of the most energetic sites in the coasts of Central Mediterranean Sea (from Italian Buoy Network): Alghero (West coast of Sardinia Island - buoy coordinates: 40.548°N, 8.107°E) and Mazara del Vallo (Sicily Channel - buoy coordinates: 37.525°N, 12.533°E). Buoy data have been compared with values extracted from the nearest computational model point. Only simultaneous data have been considered, buoy records where the peak spectral period T_p fell in the infra-gravity waves range, above 20 s, have been excluded from the analysis.

Tables 1 and 2 show the principal statistics computed between buoys and model results for significant wave heights and circular statistics for mean wave directions, computed as described by Mardia and Jupp [17]. In particular, Table 1 includes values of the bias between model and measures, root mean square error (rmse), slope of the best fit line passing through the origin and scatter index (si), and Table 2 the directional bias (bias°) and the directional variance (var). The statistics in these two sites give quite good results, with the slope close to the unity and the bias of the order of 1 cm.

Figs. 1 and 2 show histograms with the relative frequency of occurrence of H_s divided in bins of 0.2 m for buoy and model data. In both sites the measured distribution is well reproduced and the main difference observed is the overestimation of the number of events with H_s in the lowest range (0–0.2 m).

A further validation focussing on the sea state directional characteristics is accomplished, as this aspect is relevant for near-shore and on-shore devices.

Figs. 3 and 4 show polar plots associated with buoy and model data at Alghero and Mazara del Vallo, respectively. Data are divided in classes of significant wave heights with intervals of 1 m; calms are identified as significant heights less than 0.5 m. In both sites the prevailing propagation is toward ESE as both places are influenced by the north–westerly winds blowing over most of the western Mediterranean. The wave direction of propagation at Alghero is very well reproduced as shown also by values in Table 2. At Mazara del Vallo the most frequent class in model results appears to be slightly rotated northward respect to observations, the circular bias (see Ref. [4]) is 11° as shown in the table.

3. Theoretical background

The analysis proposed in this paper invokes three different, but connected, elements: a synthetic formula for the calculation of the incident wave power per unit width; a short-term probability distribution accounting for the directional variability of the sea

Table 1
Main statistics of the significant wave height between buoy and model.

Buoys	Bias (m)	Rmse (m)	Slope	si
Alghero	−0.005	0.311	0.985	0.278
Mazara del Vallo	0.013	0.257	1.022	0.253