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Offshore wave potential of the Mediterranean Sea

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Abstract. Among the most promising ocean renewable energy sources, offshore wave energy stands out. In Europe, intensive research and development of offshore wave energy technologies has been carried out with the aim of contributing to the growing demand for clean energy. In order to assess the feasibility of the development of a wave energy device in a specific region, the reliable estimation of the local wave energy potential is crucial. In this work, the offshore wave energy potential for the Mediterranean Sea is presented in an annual and seasonal basis. The assessment is based on wave data from numerical wave simulation models obtained by ECMWF. These hindcast data are in the form of time series and cover a 35-year period (1979 – 2013). In addition, in the same time scales the mean wave direction is estimated, a variable that is often omitted from similar analyses.

Key words

Offshore wave potential, wave direction, ERA-Interim, Mediterranean Sea.

1. Introduction

The oceans and the seas are enormous renewable energy sources with various origins (e.g., tides, marine currents, waves, etc.). The wave energy resource alone has the potential to satisfy a substantial part of the electricity demand of several European countries. Particularly, some of the major advantages of wave energy are: i) the great extent of power concentrated in the motion of waves, ii) the independence from occupying large land masses and the relative independence of the operation of wave energy converters from local weather conditions, iii) the mild impacts on the marine flora and fauna [1]; to this respect, many EU and national programs encourage the R&D of such technologies and it is expected that this exploitation will have a significant growth in the next decades, see for example [2]-[4]. Albeit the up-to-date wave energy technology exhibits a wide variety of systems at different stages of development, even near the commercial stage, the progress and exploitation of wave energy has been hindered up to now due to the high costs for each development stage (i.e., testing, construction, deployment, maintenance) of relevant devices. Except for the economic factor, other main difficulties are the high structural loading in extreme weather conditions and the randomness of sea waves, regarding their size, phase and direction that restricts the maximum efficiency of a device over the range of ocean waves' excitation frequencies [5].

The assessment of the wave energy potential can be based on the wave climate analysis by providing long-term wave statistics. Apart from existing buoy records and remote-sensed data, numerical models can also provide realistic estimations of the wave conditions in coastal and offshore regions, where wave energy technologies are considered to be developed. Some recent studies regarding estimation of wave energy in specific European areas using numerical modeling results can be found, for example, in [6]-[10].

The purpose of this work is to present a preliminary assessment of the offshore wave potential on an annual and seasonal basis for the Mediterranean Sea, using the available time series of the wave spectral parameters from the ERA-Interim database, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The hindcast data are of the highest available spatial and temporal resolution and cover a period of 35 years (1979 – 2013). Nevertheless, in many near-shore areas of the basin there is lack of ocean wave data due to the erratic or non-existent data input from altimeter observations; see [11]. For uniformity reasons, these areas were covered by using an in-filling procedure based on the inverse squared distance weighting interpolation scheme. In this respect, the numerical results of the study should be confined to water depth more than 50 m and addressed to the installation of forthcoming floating structures, such as wave attenuators (e.g., Pelamis), point absorbers (e.g., AquaBuoy), where the presence of energetic waves offers great structural economy.

An additional aspect of this work is the concurrent evaluation of wave direction, an important vector variable for the relevant applications; see for example, [12].

Specifically, in Section 2, the mathematical background of wave power for linear waves and sea waves, as well as the basic statistical computations for estimating mean wave direction are presented. The wave data used in assessing the offshore wave power are described in Section 3 and the relevant results are presented in Section 4. Finally, in the last Section, some general conclusions are provided.

2. Wave power

Wave power (or wave energy flux) is the rate of wave energy transmission in the direction of wave propagation; the capture of that energy can be successfully used to generate electricity. The wave potential is dependent on the amplitude of wave heights and wave periods, propagating across the sea surface. In real applications, the wave resource is difficult to be predicted due to the stochastic behaviour of the meteorological driving conditions and of the sea states; however, most relevant studies are based on the linear theory.

A. Energy of linear waves

According to the linear wave theory (Airy wave theory), for a progressive monochromatic wave front of amplitude α, wave height $H = 2\alpha$ and radian (or angular) frequency ω, propagating over an infinitely deep bottom, the total wave energy (or simply energy density, expressed in $\mathrm{Jm^{-2}}$) is the sum of the potential and the kinetic energy per unit area and is defined as follows:

$$E = \frac{1}{2}\rho g a^2 = \frac{1}{8}\rho g H^2, \quad (1)$$

where ρ is the water density (1025 $\mathrm{kgm^{-3}}$), g is the acceleration of gravity (9.8067 $\mathrm{ms^{-1}}$) and H (m) is the wave height. A wave resource is typically described in terms of power transported per unit of wave-front length. This quantity can be calculated by multiplying the energy density by the wave group velocity c_g ($\mathrm{ms^{-1}}$), i.e.,

$$P_{wave-front} = c_g E = \frac{1}{8} n c \rho g H^2, \quad (2)$$

where

$$n = \frac{1}{2}\left(1 + \frac{2kd}{\sinh(2kd)}\right) \quad (3)$$

and c ($\mathrm{ms^{-1}}$) is the phase velocity (or wave celerity) defined as follows:

$$c = \frac{\lambda}{\mathrm{T}} = \frac{\omega}{k} = \sqrt{\frac{g}{k}\tanh(kd)}, \quad (4)$$

where d (m) is the water depth, $k = 2\pi/\lambda$ ($\mathrm{m^{-1}}$) is the wave number, ω ($\mathrm{s^{-1}}$) is the radian frequency, λ (m) is the wave-front length and $P_{wave-front}$ is expressed in $\mathrm{Wm^{-1}}$. For deep water, $d \to \infty, n \to 1/2$ and $c \to \sqrt{g/k}$, Eq. (2) can be rearranged as follows:

$$P_{wave-front} = nc\frac{1}{8}\rho g H^2 = \frac{1}{16}\rho g H^2\sqrt{\frac{g}{k}} = \frac{1}{16}\rho g H^2\sqrt{\frac{g^2}{\omega^2}}$$

$$= \frac{1}{16}\rho g^2 H^2 \frac{T}{2\pi} = \frac{1}{32\pi}\rho g^2 H^2 T, \quad (5)$$

where T (s) is the wave period. In this case, the wave energy is transported at half of the phase velocity.

B. Energy of sea waves

In a real sea-state, i.e., for irregular sea conditions and for deep water ($d \ge L/2$, $L = \text{wave length}$), the wave power for a given sea state is provided by the following relation:

$$P = \frac{\rho g^2}{64\pi} H_{m_0}^2 T_e \approx \left(0.490\frac{kW}{m^3 s}\right) H_{m_0}^2 T_e, \quad (6)$$

where P ($\mathrm{kWm^{-1}}$) is the wave energy flux per unit of wave-front length, $H_S = H_{m_0}$ is the significant wave height (m), and T_e (s) is the mean wave (energy) period. The significant wave height and energy period are defined as functions of the spectral moments. The significant wave height is defined as follows:

$$H_{m_0} = H_S = 4\sqrt{m_0}, \quad (7)$$

where m_0 is the zeroth-order moment (the variance) of the wave spectrum. The $n-$th order spectral moments are defined by

$$m_n = \int_0^{2\pi}\int_0^{\infty} f^n E(f,\theta)\mathrm{d}f\,\mathrm{d}\theta,\ n = \ldots,-2,-1,0,1,2,\ldots, \quad (8)$$

where $E(f,\theta)$ is the frequency-direction spectrum and f is the spectral frequency.

The energy period, in terms of spectral moments, is given by

$$T_e = \frac{m_{-1}}{m_0}. \tag{9}$$

The offshore wave power P_i for each sea state $(H_{s,i}, T_{e,i})$ of the 35-year time series, was estimated by Eq. (6), where $H_{s,i}$ is the significant wave height and $T_{e,i}$ is the energy period of the $i-$th sea state.

The (overall) mean seasonal and annual wave power $\bar{P}$ can be obtained as follows:

$$\bar{P} = \frac{\sum_{i=1}^{N} \tilde{P}_i}{N}, \tag{10}$$

where $\tilde{P}_i$ denotes the mean annual or seasonal values of wave power (for each examined year or season of the time series), and N is the total number of years or seasons in the examined reference time period.

C. Estimation of mean wave direction

Along with the offshore wave power, the mean wave direction $\bar{\theta}$ was also estimated by the following equation:

$$\bar{\theta} = \begin{cases} \tan^{-1}(S/C), & \text{if } C>0,\, S>0 \\ \tan^{-1}(S/C)+\pi, & \text{if } C<0 \\ \tan^{-1}(S/C)+2\pi, & \text{if } C>0,\, S<0, \end{cases} \tag{11}$$

where $S=\sum_{n=1}^{N}\sin(\theta_n)$ and $C=\sum_{n=1}^{N}\cos(\theta_n)$ with θ_n, $n=1,2,\ldots,N$ denoting the realizations of the angular random variable, i.e., the wave direction.

3. Wave data

The analyzed wave data consist of time series of sea-state parameters (significant wave height, mean wave period and mean wave direction) obtained from the ERA-Interim product, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). These data are provided at a 6-hour time step with a spatial resolution of 0.125°×0.125° (~14 km×14 km) latitude/longitude. The time series length is 35 years extending from 01/01/1979 to 31/12/2013, which is an adequate period to be statistically representative. The results of ERA-Interim are directly implemented in the present work.

ERA-Interim uses a four-dimensional variational analysis system (4D-Var), which outperforms 3D-Var assimilation techniques of the currently available reanalyses [13]. Moreover, according to [11], both the increased resolution and model physics (e.g., the physical phenomenon of wave growth and dissipation), the use of additional observations (e.g., data from polar orbiting satellite) and the updated data assimilation system (e.g., variational bias correction) improved the performance compared to its predecessor, ERA-40. Another main advantage compared to previous reanalysis products of ECMWF is the up-to-date dissemination of the ERA-Interim data. ERA-Interim utilizes the WAve Model, known as WAM model, which is a third-generation spectral model. The wave spectra are discretised using 24 directions and 30 frequencies.

The ERA-Interim reanalysis data, both for meteorological and wave parameters, have been extensively validated and verified in other works, see for example, [14]-[16], proving the high quality of the model. Detailed information about the ERA-Interim reanalysis can be found in [17], [11]. Let us note that data obtained from numerical models should be calibrated and verified by in-situ measurements (e.g., see [18]). However, in this case, the spatial extent of the simulated data was too restrictive for such analysis, since in-situ wave measurements are not representative for wide areas like the Mediterranean basin.

4. Offshore wave power of the Mediterranean Sea

The study area is defined by a rectangle with coordinates for the bottom left corner (30.00°N, -6.00°W) and for the upper right corner (46.00°N, 37.00°E). The area was divided into a grid with resolution 0.125°x 0.125°. The wave hindcast data are used to derive the spatial distribution of the offshore wave power in the Mediterranean Sea. To this end, the iso-energy contours were produced; each contour represents the loci of points with the same values of wave energy.

The study of spatial distribution of offshore wave power over the Mediterranean Sea was elaborated on seasonal and annual basis. The examined seasons are separated as follows: i) December, January, February represent Winter, ii) March, April, May represent Spring, iii) June, July, August represent Summer, and iv) September, October, November represent Autumn.

Furthermore, the spatial distribution of mean wave direction was also depicted for the same time scales. Finally, one annual and four seasonal maps depicting the offshore wave potential and the corresponding wave direction were developed.

A. Annual and seasonal offshore wave power and wave direction of the Mediterranean Sea

The spatial distributions of the offshore mean wave power and wave direction are presented in annual and seasonal basis in Fig. 1a and Fig. 1b-1e, respectively.

On a mean annual basis, the highest values of annual wave energy are of the order of 8 kWm^{-1} and are located above the Algerian basin, between Sardinia and Balearic Islands. In the extended offshore area between Egypt and Crete (Levantine basin), Libya and Ionian Sea (Ionian basin), Tunisia and Sicily, and in the central and northern Aegean Sea the mean annual offshore wave power value is steady and ranges around 5 kWm^{-1}. In relatively closed sea areas (e.g., Ligurian and Adriatic Seas), the wave energy potential is rather low (less than 2 kWm^{-1}). As regards the wave direction, the main annual patterns are: i) the areas characterized by high mean annual offshore wave power (e.g., between Sardinia and Balearic Islands, and the extended area around Crete) are shaped by waves propagating from northwestern directions, ii) the offshore areas north and east of Cyprus, the Ionian and the Tyrrhenian Seas are shaped by waves propagating from the western directions, and iii) the Adriatic and north Aegean Seas and the area between Tunisia and Libya are shaped by waves propagating from northeastern directions.

On a mean seasonal basis, the mean offshore wave power reaches its maximum values during Winter (Fig. 1b). In this season, the maximum wave power is located in the elongate offshore part between France and Algeria with a peak value at 13 kWm^{-1}, south of the Gulf of Lions. The offshore wave energy is around 10 kWm^{-1} in the offshore region between western Crete and Libya, and southern Ionian basin. In Winter, the dominant mean wave direction is the northwestern. During Spring, the highest values of mean wave energy flux do not exceed 7 kWm^{-1} in the Mediterranean Sea, while the corresponding offshore areas of the maximum values are again between Sardinia and Balearic Islands. The mean wave direction during Spring is variable, with northwestern waves propagating in the Alboran Sea, the Algerian, south Ionian and Levantine basins, western-southwestern waves propagating in the Tyrrhenian and north Ionian Seas, and south of Turkey, while in the Adriatic Sea the mean wave direction is mainly eastern. In Summer, the highest mean offshore wave power values are of the order of 4 kWm^{-1}.

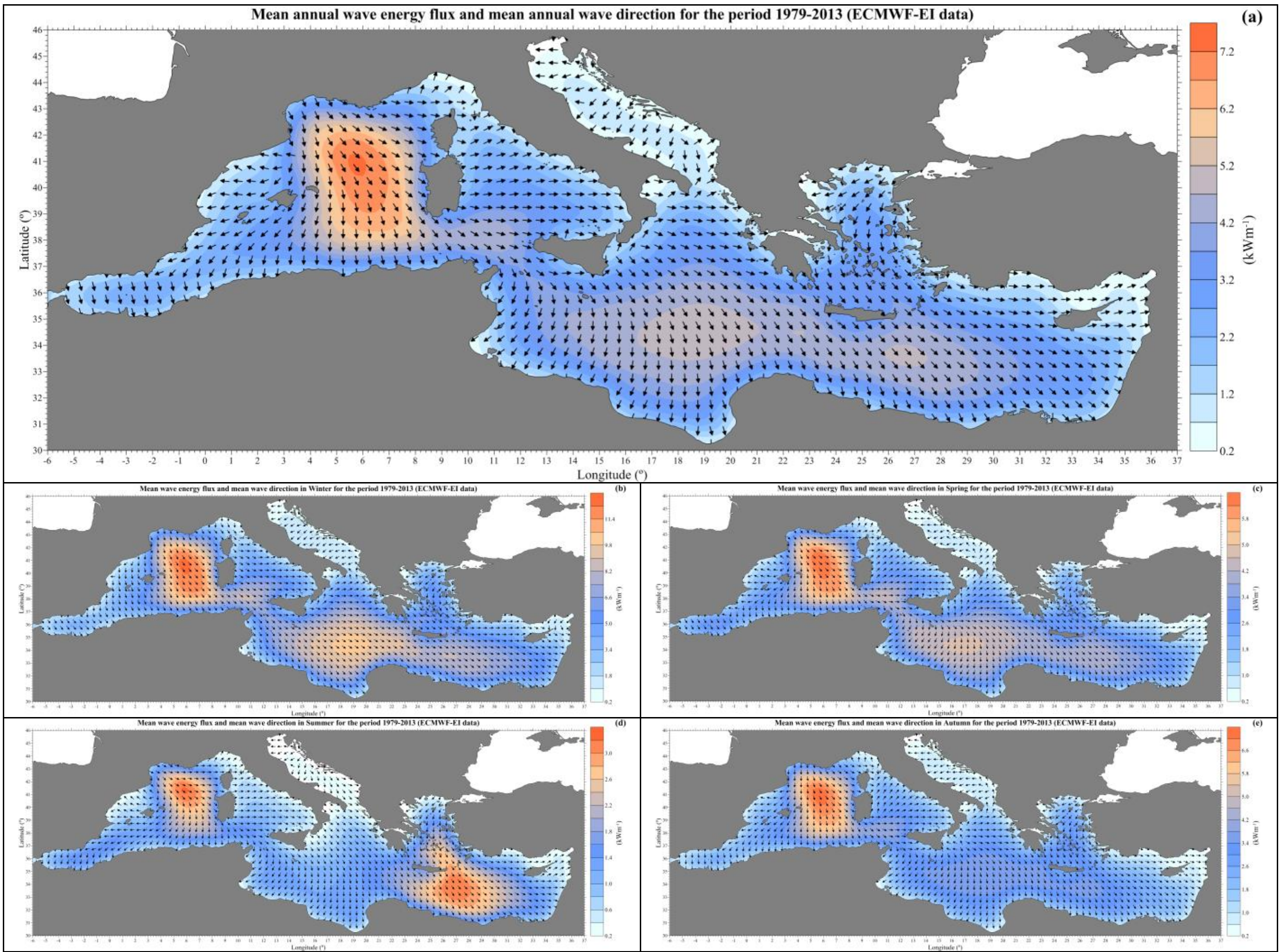

Fig. 1. Spatial distribution of the mean annual (a) and seasonal (b-e) offshore wave power and wave direction for the period 1979 – 2013

The prevailing etesian winds in the Aegean Sea amplify the offshore wave energy, and especially its central and southeast region, close to this value. In this season, the pattern of mean wave direction is similar to the one in Spring except for the north Ionian and south Adriatic Seas (northwestern propagation) and the north Aegean and Alboran Seas (northeastern propagation). During Autumn, the highest value of the wave power is around 8 kWm^{-1} in the eastern Mediterranean Sea. This magnitude decreases approximately 3 units in the central and southeast area of the examined basin, while in the northern and eastern areas the corresponding values are close to 2 kWm^{-1}. In

Autumn, the pattern of mean wave direction resembles Spring apart from the south offshore area of Turkey and south-east of Sicily (northwestern and northeastern propagation, respectively).

In both examined time scales, Mistral and Tramontane, which are intense winds, along with the geomorphological features of the corresponding region contribute to the presence of the highest mean wave potential in the Mediterranean Sea throughout the year.

5. Conclusions

In this work, the offshore wave potential of the Mediterranean Sea is assessed along with the mean wave direction, based on 35-year hindcast data (1979 – 2013) generated by ECMWF.

In the annual scale, the overall offshore wave potential of the basin ranges close to 3-5 kWm^{-1}, while the extended area between Balearic Islands and Sardinia, along with the Ionian and Levantine basins are characterized by the highest values of mean offshore wave potential. In addition, in specific areas, such as the straits of Sicily, the wave energy reaches high values due to channelling effects. In the seasonal scale, the highest offshore wave power values along the examined basin occur during Winter. The offshore wave potential is reduced approximately 3 units during Spring and Autumn compared to Winter, and the lower values correspond to Summer. The area where the maxima occur during the four seasons is the same with the one mentioned in the annual analysis. On the contrary, maxima of offshore wave potential in Summer are observed also in the south Aegean Sea. The behaviour of mean wave direction is similar in offshore areas where intense winds are prevailing, while in relatively enclosed sea areas, like the Adriatic Sea, the behaviour is more variable.

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2) ERA-Interim Reanalysis data provided by the ECMWF can be accessed online at: http://data-portal.ecmwf.int/data/d/interim_full_daily

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