13th EWTEC 2019 Proceedings of the 13th European Wave and Tidal Energy Conference 1-6 Sept 2019, Naples, Italy

Wave energy assessment and spectral analysis: a case study in the Ionian Sea (South Italy)

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Abstract—**The paper reports the estimation of the offshore wave power offshore Apulian coasts (South Italy), with particular reference to the Ionian Sea. Half-hourly significant wave bulk parameters (e.g. height, period and mean wave direction) measured by a buoy are firstly used for the scope. Both zero-crossing and peak periods are here used for power calculation. The influence of the period is relatively low, and the highest differences can be observed in correspondence of autumn and winter seasons (about 15%). Monthly wave energy calculated over the period 2006-2015 is reported, showing that, compared to the Italian coasts, the energy potential in the Ionian Sea is relatively low, highly influenced by season variability and mean wave direction. Wave power temporal variation over the observation period is here quantified by means of standard statistics (e.g. mean, minimum and maximum values), together with the Monthly Variation Index and the Coefficient of Variation of Power.**

Moreover, in order to perform a further investigation on the influence of spectral parameters on the offshore wave energy assessment, a preliminary analysis of the wave spectra and spectral shape parameters estimated offshore Taranto and their temporal evolution during the recorded period is reported. The spectral narrowness and width parameters are used in order to measure the width of the spectral band. Looking at the monthly variation, it can be noted that the monthly averaged 1D spectrum tends to flatten going from the winter to the summer season evolving from an almost unimodal shape to spectra with very low energy density and multiple peaks from July to August.

Keywords—**Ionian Sea, Buoy data, Wave power, Wave spectra.**

I. Introduction

THE sea represents an immense energy reservoir, which can be considered the highest amongst the available renewable sources [1]. According to [2], the economic contribution of wave energy on the present technology could be higher than 2000 TWh/year with a capital investment of GBP 500 billion (about EUR 740 billion).

Several areas around the world and along the European coastline have been considered during the last two decades till nowadays, aiming these objectives [3]-[4]-[5]-[6]-[7]-[8]-[9]-[10]-[11]-[12]-[13]. In such a context, the assessment of the wave energy resource in both local and regional scales is a basic prerequisite for the strategic planning of its utilization and for the design of the energy devices in order to reach the optimal design criteria. Different authors perform analysis over the European coastline, in higher energy areas as well in intermediate/less energetic basins, by means of both buoy data and numerical models.

The range of variability in the available wave energy resource along European Coast is high. To date, the challenge is to adapt the commonly used wave energy converters systems and technologies to the Mediterranean Seas characteristics. The western area of the Mediterranean Sea, between Sardinia and Balearic Islands, results to be the highest energetic zone due to the strong winds coming from west and north Europe [7]-[8]-[9].

Along Italian coasts, [14] firstly produced a wave Atlas of Italian seas, where yearly, monthly and seasonal mean wave power were reported on the basis of about 20-years buoy data. The analyses were based on the three- hourly wave data set collected by the Italian Wave Network (IWN) since 1989. With respect to other European countries, the analysis shows relatively low values of mean wave power. Western Sardinia and the Southern and Western Sicily seems to be the most promising Italian areas for wave energy production, with average wave energy flux of 6÷7 kW/m and about 5 kW/m, respectively [8]-[9].

For the Apulian region (South Italy, Fig. 1), the wave power assessment derived from the analysis of the IWN buoys placed offshore Monopoli (Adriatic Sea). In 2015 [14], the estimation of wave power offshore Apulian costs was integrated with the analysis of wave data recorded by two buoys placed offshore Tremiti Islands (Adriatic Sea) and Taranto (Ionian Sea), belonging to a broader monitoring network designed and installed with European funds [15].

In the present work the estimation of the offshore wave power offshore Apulian coasts (South Italy), with

Paper ref. 1811-02-06 WRC

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particular reference to the Ionian Sea is reported. The Taranto buoy has been chosen for the analysis since wave spectra at this location are available. Half-hourly significant wave height, spectrum mean period and mean wave direction measured by the buoys are firstly used for the scope. The influence of the wave period (e.g., mean, peak and energy periods) used for power calculation is also investigated, since buoy measurements offshore Italian coasts misses direct measurements of wave spectra. On the contrary, at Taranto buoy wave spectra are available. For this reason, in order to perform a further investigation on the influence of spectral parameters on offshore wave energy assessment, a preliminary analysis of the wave spectra and spectral shape parameters estimated offshore Taranto and their temporal evolution during the recorded period is here reported.

II. STUDY AREA

From 2004 several wide coastal monitoring programmes supported by the European Union (POR 2000-2006 and FESR 2007-2013 funds) have been carried out in Apulia region, allowing to obtain a detailed picture of the coastal trends and a huge database for scientific research. Those programmes included many actions: bathymetric, topographic and sedimentologic field campaigns, aerial and LIDAR surveys, real-time shoreline monitoring using webcams [16]-[17]-[18] and a deployment of a meteomarine network [19]-[20]-21].

Since 2006, the Ionian Sea has been constantly monitored by Apulia Region Meteomarine Network (hereinafter referred to as "SIMOP") including a wave buoy moored installed offshore in the Gulf of Taranto. The wave buoy installation and data management were carried out by a group that included a research unit of the LIC (Laboratory of Coastal Engineering) of the Politecnico di Bari (Bari, Italy).

A Datawell Directional Waverider MKIII buoy was moored offshore the Port of Taranto (Fig. 1) from January 2006 to December 2015 at a local depth (d) of 72 m, in order to record states of sea not yet altered from the interaction with bottom (considering a mean peak period of about 6.9 s, the non-dimensional depth parameter $2\pi d/L$ is equal to 6). The buoy measures wave height for wave periods of 1.6 to 30 seconds with an accuracy equal to 0.5% of measured value.

The wave climate in the gulf is characterized by a rather constant South-South East direction. The waves come from a quite limited approaching sector and the wave field direction of 175°N - 180°N is quite constant all over the year. The only remarkable change happens during the summer season when there is a greater occurrence of low height waves generated from local winds blowing from North-West directions. The longest fetches are found in the South-South East sector (about 1400 km) and great number of severe sea storms from this direction have been observed. In the observation period the most severe sea storm was recorded in February 2014, characterized by a maximum significant wave height H_s = 5.11 m and a peak period T_p equal to 10.5 s.

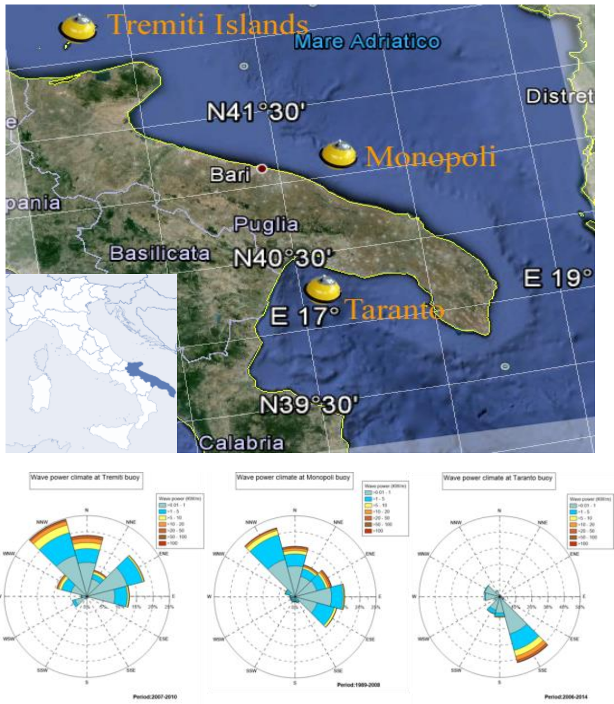

Fig. 1. Upper panel: Apulian Monitoring network (South Italy). location of the offshore wave buoy moored offshore Taranto in the Ionian Sea; Lower panel: wave power climate derived from the buoy-measurements.

III. METHODOLOGY

A. Wave data analysis

Wave data measurements have been firstly filtered, in order to remove unexpected and erroneous data, thus defining the efficiency for each buoy (η_B) as (1):

$$\eta_b = \frac{n_F}{n_T} \cdot 100 \tag{1}$$

Where n_F and n_T are the number of filtered and raw data, respectively.

The half-hourly wave records, before proceeding to the analysis, have been subjected to a quality control for the identification of anomalous data, spikes and timing errors, following the recommendations reported in [22].

A time continuity and consistency check has been performed estimating the maximum deviation σ_T between two successive records [22]:

$$\sigma_T = 0.58 \times \sigma\sqrt{\tau} \tag{2}$$

where σ is the standard deviation calculated for the wave station and τ is the time lag (in hours). Fig. 2 reports the yearly efficiency of the buoy (η_b). Figure 2 shows that on average the percentage of missing data is of about 25% (not including 2012 during which no data were available).

The distribution of missing data is not constant over the year, since it is higher in winter season, when the buoy yield reaches an average value overall the observation period of about 50%, thus the seasonal variability assessment.

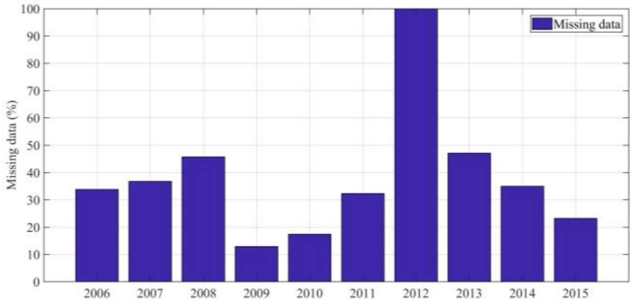

Fig. 2. Missing data in the observed period 2006-2015.

B. Wave power calculation

Wave power is here rated in terms of energy flux in deep water per unit crest and expressed in kW/m. For a general sea state, the total energy density Et per unit area is the sum of kinetic and potential energy given by (3):

$$E_t = \frac{1}{8}\rho g H_s^2 \tag{3}$$

where ρ is the water density equal to 1025 Kg/m^3, g is the gravity acceleration and H_s represents the significant wave height (m). The energy flux P across a vertical section of unit width in the direction perpendicular to wave propagation is equal to (4):

$$P = E_t C_g \tag{4}$$

in which C_g is the wave group celerity equal to $g/2\omega$ in deep water, ω is the wave angular frequency equal to $2\pi/T_e$, where T_e represents the wave energy period (s). For a real sea state, the wave power can be expressed as follow (5):

$$P = \rho g^2 H_s^2 T_e / 64\pi \tag{5}$$

In most cases, the sea states measured by the buoy are specified in terms of either peak period T_p or mean zero-crossing period T_z. In the present work, the influence of wave period in wave power calculation is investigated by assuming $T_e = 1.14T_z$ [23] and $T_e = \alpha T_P$, where α=0.9 [24], corresponding to a standard JONSWAP spectrum with a peak enhancement factor γ =3.3.

C. Wave spectra analysis

Raw elevation data (heave, pitch and roll) have been analyzed by means of the WAFO Matlab Toolbox [25]. Directional and frequency spectra have been obtained for each recording. Frequency spectra have been obtained applying Fourier Transform (FFT) to heave time series. Significant wave height (H_{m0}) and mean wave period (T_m) have been computed from 1D spectral moments and peak period (T_P) as the inverse of the spectral peak frequency. Directional wave spectra have been computed through Maximum Likelihood Method (MLM) [26] with a resolution of 0.005 Hz in frequency and 3.6° in direction.

The spectral narrowness parameter ν [27] and the spectral width parameter ε [28] have been estimated in order to measure the width of the spectral band. The dimensionless parameters ν and ε can vary between 0 (narrow band) and 1 (broadband). The spectral peakedness parameter Q_p was proposed by [29] to describe the peakedness of the spectral peak and the wave groupiness. Since ν and ε depend on the cut-off frequency, Q_P has proved to be a more appropriate parameter to describe spectral distribution [30].

Directional spectra provide additional information about different wave systems that compose an irregular sea state allowing sea and swell detection [31].

IV. RESULTS

Sometimes, it would be useful to carry out a preliminary evaluation of the wave power from Eq. 5, since information about wave energy spectra are not always available. For example, wave spectra measured by buoy offshore Italian coasts belonging to the IWN are not accessible.

In the following a preliminary discussion is reported on the calculation of wave energy power with respect to the choice of the wave period. Fig. 3 shows the monthly wave power over the period 2006-2015, with the energy period T_e calculated as a function of T_z (left panel) and T_P (right panel). It can be observed that with the peak period T_P the monthly wave power averages are higher than those calculated by considering the zero-crossing period T_z, except in July and August.

It is well known that the assumption of JONSWAP spectra shape induces some uncertainties into wave power calculation, especially when the sea-states are composed of multiple wave systems, i.e. more swells approaching from different directions. However, as expected, the influence is relatively low, considering the low values of wave power, even if it could be further investigated in view of optimizing wave energy converters in an area with such limited wave energy resource. Higher differences can be observed in correspondence of autumn and winter seasons. The mean monthly difference D (%) = ($P(T_P)$-$P(T_z)/P(T_P)$) is more than 15% in winter months and decreases in summer reaching values lower than 10%.

Results showed that, compared with the Italian coasts, the Apulian seas are characterized by low values of average wave power which is, furthermore, highly influenced by seasonal variability of waves characteristics. In the Ionian Sea the summer months are characterized by the lowest mean energy fluxes, approximately lower than 1 kW/m. During autumn and winter, storms are more frequent and intense and, consequently, an increase of the wave power can be observed. In the examined period about 90 sea storms, as defined in [32], have been recorded in the winter season. Those winter sea storms alone have generated more than 50% of the total wave power.

At Taranto buoy, the wave measurements allowed to estimate a monthly wave power of about 3 kW/m.

In order to correctly design a system able to produce energy from a wave energy converter, the knowledge of the main characteristics of both wave climate and wave power climate are of primary importance. In Fig. 4 the wave power climate evaluated from buoy measurements, derived from the zero-crossing period is represented, allowing to analyze the propagating direction of the highest energetic waves.

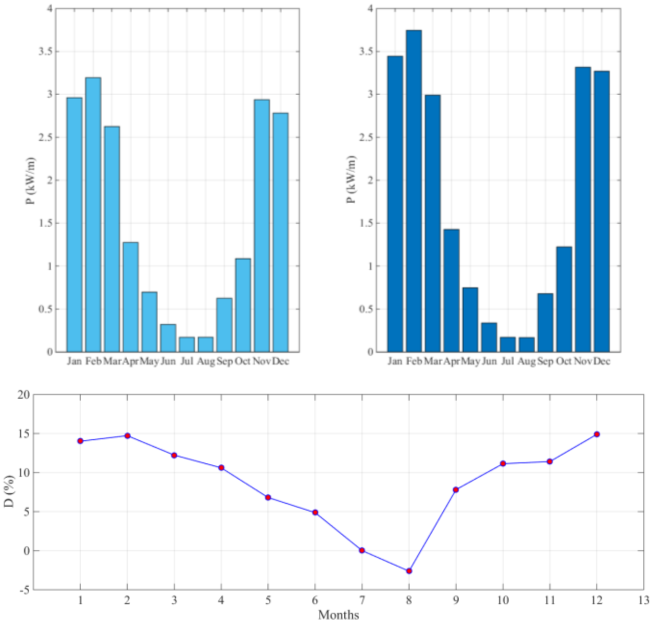

Fig. 3. Monthly average wave power offshore Ionian Sea over the period 2006-2015 by means of zero-crossing period, T_z (left upper panel) and peak period, T_P (right upper panel); the monthly percentage differences (*D*) between the two calculations are reported in the lower panel.

The Ionian Sea is characterized by non-uniform spatial distribution of wave power. Higher and more frequent values especially occur for waves propagating from South-South East direction. Fig. 5 reports the scatter diagrams of significant wave height and zero-crossing period (upper panel) and the wave power (P) related to significant wave height (middle panel) and zero-crossing period (lower panel) occurrences. The graphs show that the wave climate is mostly characterized by wave heights ranging from 0.5 to 1 m and wave periods of 2- 4 s. The wave power is mostly lower over the observation period, reaching values lower than 1kW/m for most of the observations.

Fig. 6 reports the main statistics calculated as reported in e.g. [33]. The mean (Pa-mean), minimum (Pa-min) and maximum (Pa-max) annual wave power are calculated from the monthly wave power for each year. The Monthly Variation Index (MVI) is defined as the ratio of the differences between the maximum and minimum values of the monthly average wave power in each year by the corresponding annual average wave power (Pa-mean), whereas the Coefficient of Variation of Power (COVP) is defined by the ratio between the annual standard deviation of the wave power and the relative annual average wave power in each year.

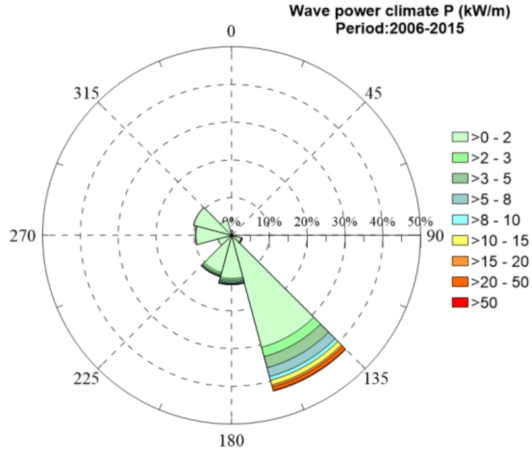

Fig. 4. Wave power climate at Taranto buoy over the period 2006-2015.

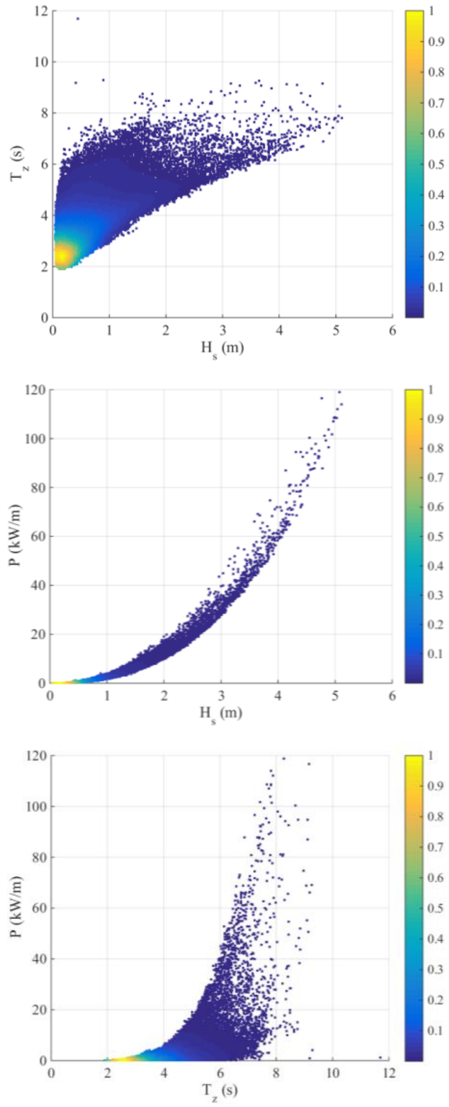

Fig. 5. Scatter diagrams of significant wave height and zero-crossing period (upper panel) and the wave power (P) related to significant wave height (middle panel) and zero-crossing period (lower panel) occurrences.

Wave spectra and spectral shape parameters have been estimated and their monthly pattern has been examined during the observation period.

Figure 7 shows temporal variations of normalized spectral energy density during 2009. To obtain the normalized spectral energy value, energy density corresponding to a given frequency has been compared to the peak energy density.

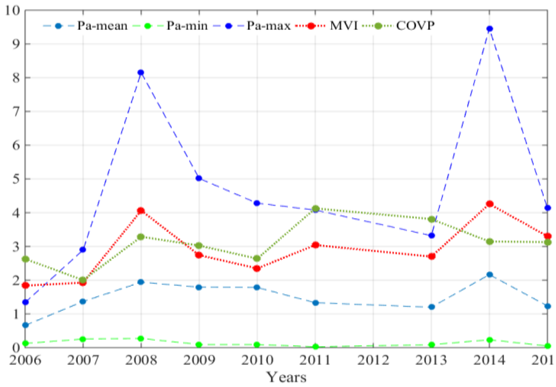

Fig. 6. Main statistics of wave power (kW/m) over the period 2006-2015.

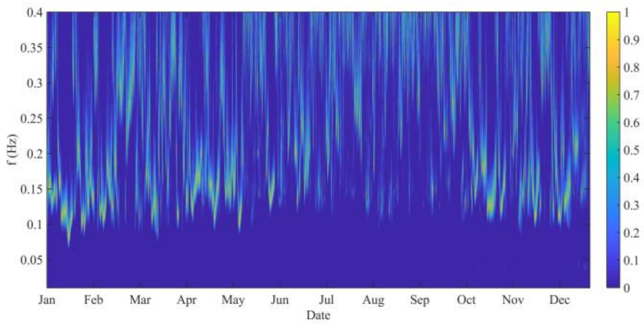

Fig. 7. Temporal variations of normalized spectral energy density during 2009.

The peak frequency of normalized energy density in winter season are higher than f_p values in summer season, when sea wave heights are very low.

The average monthly 1D and 2D spectra have been obtained by averaging semi-hourly recorded spectra (Figs. 8 and 9). Looking at the monthly variation, it can be noted that the monthly averaged 1D spectrum tends to flatten going from the winter season to the summer season evolving from an almost unimodal shape to spectra with very low energy density and multiple peaks from July to August.

In January the average monthly directional spectra have the highest spectral density with a peak frequency at 0.1 Hz and a wave direction of about 150°. In August, frequency bandwidth is significantly wider. A double-peak spectrum can be observed, as the superposition of two main wave systems coming from South-South East and North-North West with a peak frequencies of 0.25 Hz and 0.4 Hz, respectively.

Several spectral parameters have been defined to describe the shape and the type of recorded spectra.

The values of ν and ε for narrow-banded spectra in the winter season are higher than the values found in broad-band spectra in the summer season, indicating that these parameters cannot be used as an indicator for spectral width in the examined site (Fig. 9). It has to be underlined that in the summer months, wave spectra have a significant high frequency component that cannot be measured by the Datawell wave buoy, giving some uncertainties in spectral parameters calculation. However, the influence on wave energy calculation is low, since high frequency component contributes little to the wave energy.

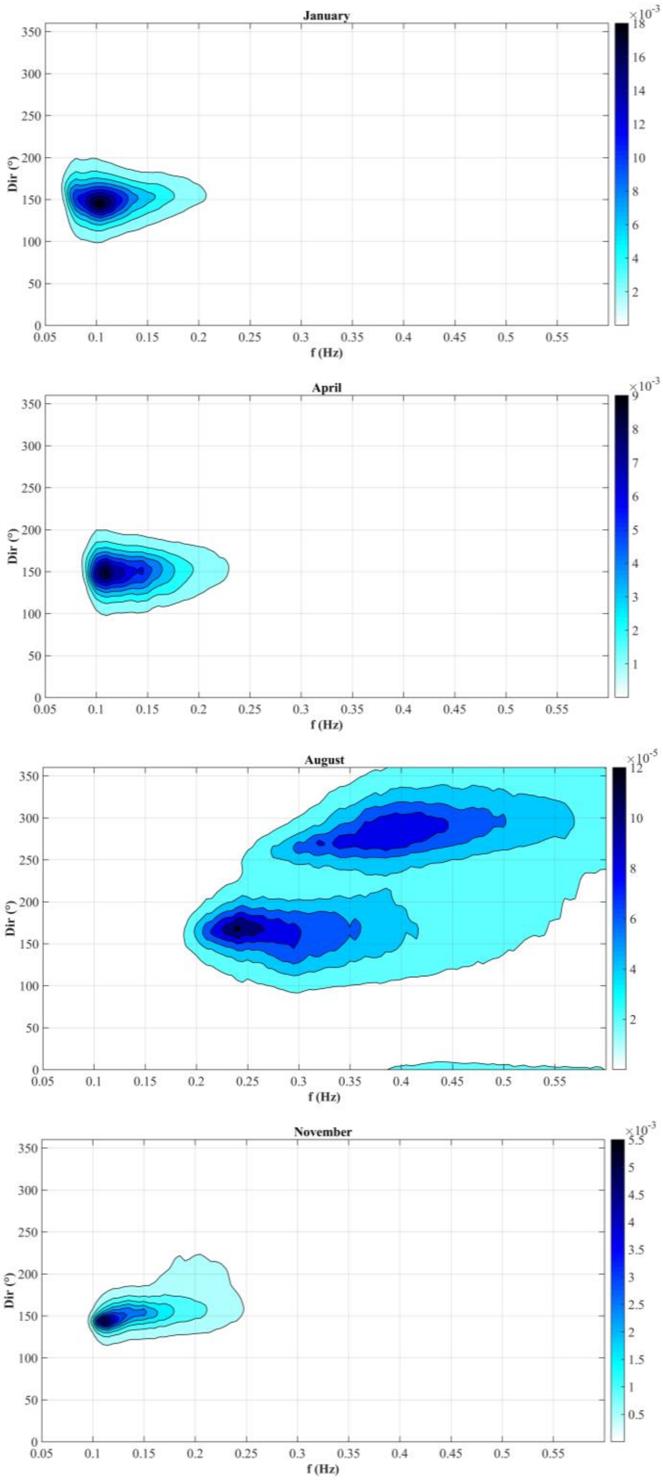

Fig. 8. Example of monthly average 2D wave spectra during 2009 (selected months).

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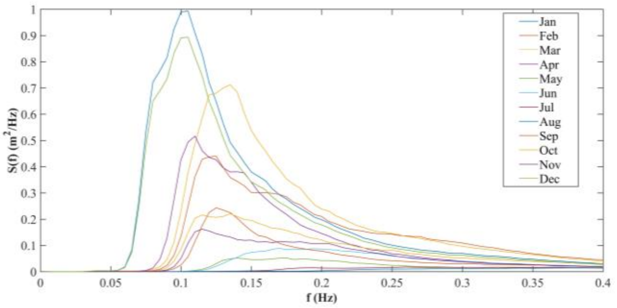

Fig. 9. Monthly average 1D wave spectra during 2009.

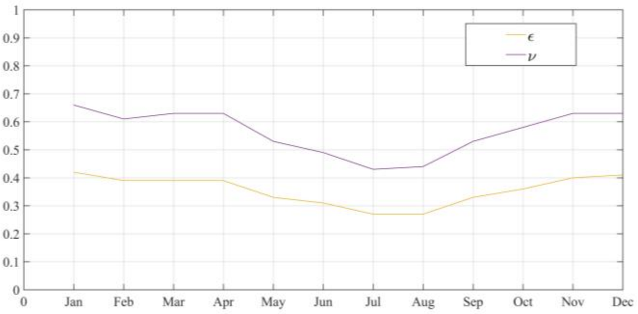

Fig. 10. Monthly average spectral narrowness parameter ν and spectral width parameter ε.

V. CONCLUDING REMARKS

The present work constitutes a first step in estimating the wave energy potential offshore the Ionian Sea with the aim of investigating the influence of spectra characteristics on wave energy assessment. The offshore mean wave power computed by using wave data measured by a buoy placed offshore Taranto (South Italy) over the period 2006-2015 is reported. Both zero-crossing and peak period are used to calculate the wave power, showing that the period has low influence on results, even if higher differences (more than 15%) are observed during winter seasons

Compared to other Italian sites, the wave energy prospective offshore Apulian region, specifically in the Ionian Sea, are relatively low and highly influenced by seasonal variability and wave direction. The site is characterized by higher values of mean wave power when waves propagate from South-South East direction, with a consequent limit in the choice of converter system technology. Wave power temporal variation over the observation period is here quantified by means of standard statistics (e.g. mean, minimum and maximum values), together with the Monthly Variation Index and the Coefficient of Variation of Power.

Wave spectra and spectral shape parameters have been estimated and their monthly pattern over the observation period is reported. Both 1D and 2D average monthly spectra have been obtained by averaging semi-hourly spectra recorded during field measurements. The monthly averaged 1D spectrum tends to flatten going from the winter season to the summer season evolving from an almost unimodal shape to spectra with very low energy density and multiple peaks from July to August. The values of ν and ε for narrow-banded spectra in the winter season are higher than the values found in broad-band spectra in the summer season, indicating that these parameters cannot be used as an indicator for spectral width in the examined site.

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