Wave energy resource assessment in the Mediterranean Sea on the basis of a 35-year hindcast

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ABSTRACT

A state-of-the-art, in terms of spatio-temporal resolution (about 10 km and on a hourly basis) and temporal span (35 years), wave hindcast is exploited to update existing assessments of wave energy potential in the Mediterranean Sea. The hindcast, covering the period 1979–2013, has been obtained using WavewatchIII with calibrated source-term parameters recently proposed by L. Mentaschi et al. (2015) [1]. The main advantage of such a calibration is that it takes into account the peculiarity of the Mediterranean basin with respect to other calibrations carried out in the oceans. The high resolution allowed to perform a detailed analysis of wave energy potential characteristics providing information on seasonal and longer term variability necessary for reliable and optimal design of wave energy conversion devices. As a result, the identification of areas where the mean wave power reaches values of the order of 10 kW/m clearly emerge. However, these regions are not necessarily optimal in relation to the efficiency of energy extraction, due to possible relevant time variation of the energy availability. The high temporal resolution allows to address issues related to the time variability of the available resource and thus to provide a complete set of statistical information to carry out optimal design of WEC (wave energy converter).

1. Introduction

In the last decades the exploitation of renewable natural resources, such as wind, solar and geothermal, has significantly increased for the sake of energy production. Major attention has been payed to the ocean resources, focusing on the energy harvesting from tidal currents and ocean surface waves.

The conversion of wave energy to common grid has been analyzed in the scientific community following two basic approaches. The first one is dedicated to the development, design and experimentation of devices capable of converting wave energy into electrical power [e.g. [2]]. The second line of research is focused on wave energy assessment along the coast of the different continents, in order to provide detailed figures of the available energy potential and its characteristics to the developers of WEC devices for an optimal design.

Even if the idea of energy conversion from wind waves arises at the beginning of the nineteenth century, a boosting of the research and technology development started in the early seventies due to a dramatic increase of the price of oil products [2]. Wave energy potential has hence been assessed both from field measurement through buoy stations [3] and from numerical model.

A first attempt to assess the wave energy potential along European coasts has been carried out by Ref. [4] on the basis of coarse numerical simulations employed to compile an European Wave Energy Atlas. Hence the employment of wave hindcast has been widely used to assess oceans wave energy potential on global scales [i.e [5–8]].

The availability of extended wave data obtained through numerical simulations opened the possibility to develop a detailed wave energy assessment giving an insight about waver power availability on regional and local scales in order to provide refined and accurate estimates of wave energy flux characteristics for WECs (wave energy converter) design. Different authors developed analysis on the European Atlantic coasts, for example for France [9,10] or over different regions of continental Spain and its islands [11–16], and for Portuguese coasts and islands [17,18]. Assessments

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have been developed for the Northern Atlantic Sea, where even some full scale devices have been tested [19–22]. The analysis has been performed also in different worldwide spread locations [3,23–31].

Generally a major attention has always been payed to higher energy areas such as Pacific, Atlantic and Indian oceans. Despite this tendency, different authors in the last years begun to perform wave energy assessment in less energetic basins which nevertheless could provide interesting information for the harvesting of wave energy. In particular, only recently [32–34], carried out evaluations of Black Sea wave energy potential on the basis of different wave hindcast while [35] gave some insights about wave energy distribution in the Baltic Sea.

The Mediterranean Sea represents, in terms of wave energy power availability, an intermediate level between the open oceans and the enclosed small-fetch basins such as the Black Sea or the Baltic Sea. Hence, wave energy exploitation seems to be promising even if the net quantities are not as significant as in the open ocean. Different authors performed wave potential evaluations on the basis of medium-short term wave datasets obtained through numerical simulations or field observations for restricted areas [36–40] and for the whole basin [41].

The present study follows the line opened by Ref. [41] concerning the use of hindcast for the assessment of wave power distribution in the Mediterranean Sea and it is an extension in greater detail of the previous work. Indeed resolution of the atmospheric forcing has been increased from 1/4° used by Ref. [41] to 1/10° in the present work. Furthermore the range of the numerical simulation has been extended from 10 to 35 years (from 01/01/1979 to 31/12/2013) and the time step for the recording of wave characteristics is equal to 1 h instead of three. Spatial resolution of the wave model is the same of the atmospheric model and is about 10 *km* in both longitude and latitude. The spatial resolution is important in order to resolve and properly describe the wave characteristics on a local scale, but it is not the most important aspect for an assessment on the basin scale, on the contrary a high temporal resolution is strictly necessary to provide detailed information on the variability of the wave energy resource in different parts of the Mediterranean basin. The feasibility of wave energy harvesting projects resides in the correct design of the devices which should be planned to work at the maximum efficiency tuned on the local wave climate. This condition is reached if the temporal variability of the available wave energy potential and its distribution over wave height, peak period and mean direction is known: the optimum design should indeed take into account variations of the resources and not be based on the sole mean value. Variability of the energy resource is indeed expected to be significant thus appreciably reducing the efficiency of a device designed to work under average conditions [22,42–44].

The present manuscript is organized as follows: in section 2 the basic methods of wave energy resource assessment are presented together with the description of the numerical models employed for the wave hindcast. Section 3 presents the results on both the basin scale and on some locations which are promising for energy harvesting projects. Finally, some remarks and conclusions are drawn in section 4.

2. Methods

The assessment of wave energy potential in the Mediterranean basin has been carried out on the basis of a hindcast of sea wave conditions for 35 years, from 01/01/1979 till 31/12/2013. The analysis thus presents a long temporal span, giving insights on long trend variations and reliable seasonal behavior.

2.1. *Atmospheric model*

The wave model is forced by the 10-m wind fields obtained from the non-hydrostatic model WRF-ARW (weather research and forecasting – advanced research WRF) version 3.3.1 [45]. In the present study a Lambert conformal grid covering the whole Mediterranean Sea with a resolution of about 10 *km* has been used (Fig. 1).

Topography, land use and land-water mask dataset have been interpolated from the 2′-resolution USGS (U.S. geological survey) data sets. Initial and boundary conditions for atmospheric simulations were provided from the CFSR (climate forecast system reanalysis) database [46]. Use of CFSR reanalysis data for wave modeling provides reliable results, even if sometimes the simulation of extreme wave conditions is not properly performed [47–51]. For the whole extent of the hindcast, series of 24-hr-long simulations were performed. The analysis (i.e. atmospheric initial conditions) have been updated every 24 h, while conditions on the boundaries of the computational grid were imposed every 3 h. Even if the imposition of boundary and initial conditions can lead to some discontinuities in the numerical simulations, these unbalances are however absorbed quite quickly (because they affect the sole small scales) with characteristic times of the order of the smallest resolved time-scale which is of the order of few time-steps (few minutes). For further details of the set-up and validation of the meteorological model readers can refer to [52].

2.2. *Wave model*

The generation and propagation of sea waves have been modeled using the wave model WavewatchIII®, version 3.14 [53]. A 336 × 180 regular grid (finite differences) covers the whole Mediterranean Sea with a resolution of 0.1273 × 0.09 degrees, corresponding to about 10 *km* at the latitude of $45^\circ N$ (cfr. Fig. 2).

Source terms of growth-dissipation introduced by Ref. [54] have been expoited. These source term are based on [55] for the growth part, and improve the representation of wave dissipation merging the results of recent studies [e.g. [56, 57]] and introducing a new term for the dissipation of long swell, deduced on the basis of the observations of satellite altimeters [58]. During the elaboration of the hindcast the reference parameterization was calibrated in order to reduce a slight tendency to overestimation of moderate seas [1]. Spectral resolution is characterized by 24 bins in direction and 25 frequencies ranging from 0.06 to 0.7 *Hz* with a step factor of 1.1. Wave model has been forced with the wind fields provided by the atmospheric model described in section 2.1 with an hourly time step. The time step chosen for spatial propagation in the wave model is of 100*s* for the fastest spectral component, which guarantees a Courant number close to zero for spatial propagation. The spectral propagation time step was chosen in 900*s*, which is satisfactory for simulations where slopes are averaged over 10 *km* wide cells. The main time step, i.e. the time step relative to the application of the source terms, has been set to half an hour, which is in the order of magnitude of the crossing time of the cell by the fastest spectral components. This is a satisfactory time step, considering that the wind data have a time step of 1 h, and that WWIII has a limiter which automatically reduces the main time step for strong variations. The output has been recorded hourly in all points of the computation grid for integrated quantities (i.e. significant wave height H_s, mean period T_m and mean direction θ_m). The validation of the 35-years wave hindcast has been carried out through extensive comparison of simulated quantities and wave buoy data [cfr. [1,59]].

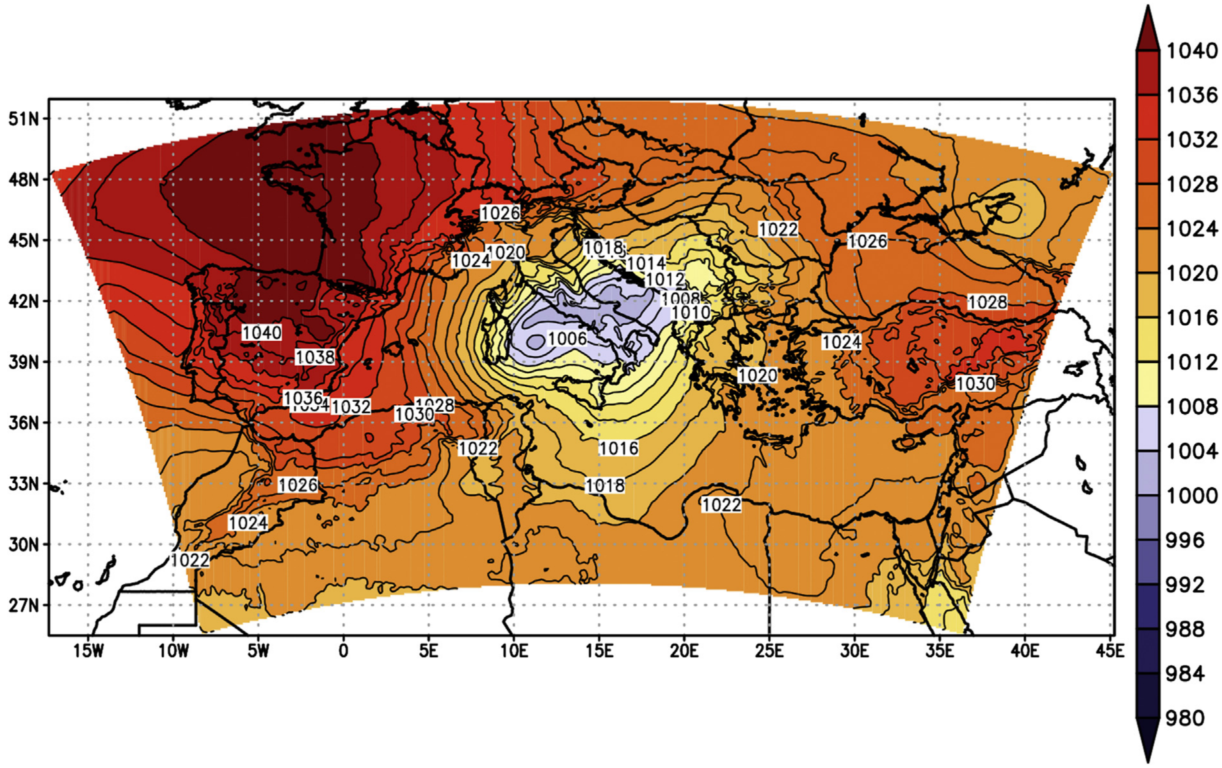

Fig. 1. Integration domain for the meteorological model WRF.

2.3. Wave energy resource

The available wave power per unit length (energy flux per unit of the wave crest length, P), measured in kilowatt (kW) per meter, can be evaluated using the spectral output of the wave model through

$$P = \rho g \int_{0}^{2\pi} \int_{0}^{\infty} S(f,\theta) c_g(f,h) \mathrm{d}f \;\; \mathrm{d}\theta \quad [kW/m] \tag{1}$$

where $S(f,\theta)$ is the directional wave energy spectrum, f is the frequency, θ is the direction of propagation of the spectral component, ρ is the water density, g the gravitational acceleration, c_g is the group velocity and h is the water depth. Taking into account the integrated parameters evaluated from the calculated spectrum (the integral is performed numerically over the spectral bins for frequencies, 25, and directions, 24), an approximation of eq. (1) can be easily derived in the form

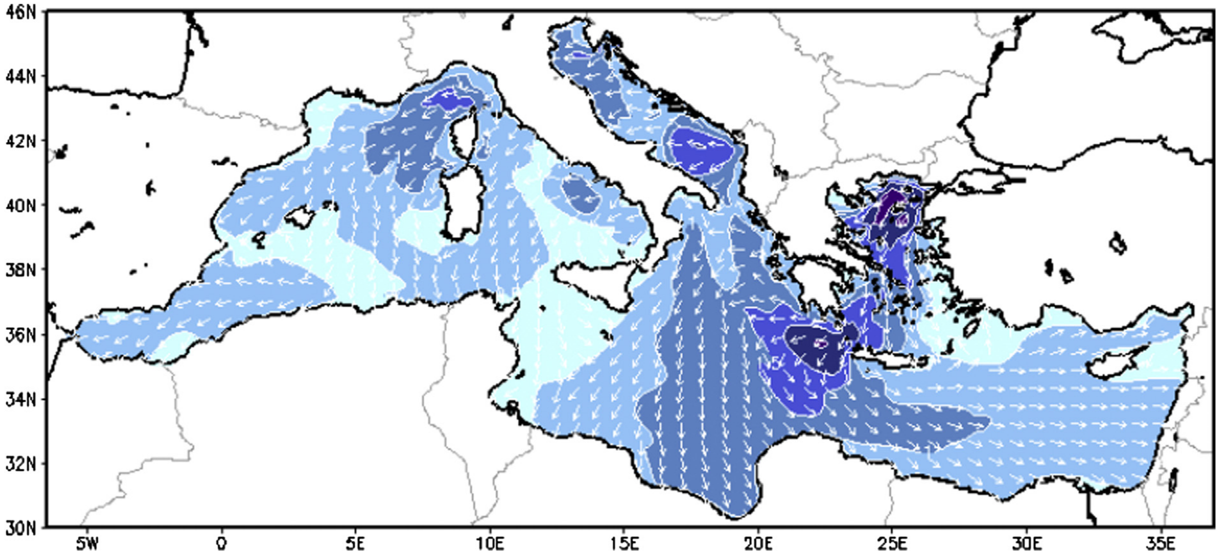

Fig. 2. Integration domain for the wave model WavewatchIII®.

$$P=\frac{1}{16}\rho g H_{m0}^{2} c_g \quad [kW/m] \tag{2}$$

where H_{m0} is the spectral wave height evaluated from the wave energy spectrum $(H_{m0}=4\sqrt{m_0})$, the spectral period $T_{m_{-1,0}}=m_{-1}/m_0$ has been used to calculate the wave length which is needed to evaluate the group velocity c_g. In H_{m0} and $T_{m_{-1,0}}$ m_{-1} and m_0 represent respectively the spectral moments of order -1 and 0 of the wave spectrum computed using the relationship

$$m_i=\int_0^{2\pi}\int_0^{\infty} S(f,\theta)f^i \mathrm{d}f \ \ \mathrm{d}\theta. \tag{3}$$

In the literature concerning wave energy resource assessment and wave energy harvesting the spectral period $T_{m_{-1,0}}$ is known as the energy period T_e [e.g. [4, 5]].

Because the analysis has been carried out mainly in deep water conditions ($h/L>0.5$, where L is the wavelength) the following approximate relationship holds

$$P=\frac{\rho g^2}{64\pi}H_{m0}^{2}T_e \quad [kW/m]\ . \tag{4}$$

The total annual energy flux per unit width, measured in kWh/m or MWh/m, potentially produced during a defined temporal interval $\Delta T=\sum_i \delta t_i$, can be expressed as

$$E_{tot}=\sum_i P_i\delta t_i \quad [kWh/m]. \tag{5}$$

where δt_i is the temporal sampling interval (1 h in the present study). Relationships (4) and (5) are commonly used in literature for wave energy resource assessment even if the deep water condition is not strictly complied (for the four locations analyzed the maximum period could be taken equal to 14 s corresponding to deep water limit equal to almost 150 m).

3. Results

Wave energy resource assessment has been carried out in the whole Mediterranean basin and a detailed analysis has been carried out for four selected sites, where the amount of available wave energy is interesting for possible exploitation. We considered two sites along the Italian coast (Alghero and Mazara del Vallo) whose location coincide with those of the RON (Rete Ondametrica Nazionale) and represent the most promising location for energy conversion along the Italian coast, and two locations on the coast of Northern Africa where the average value of wave energy flux is significant: one in front of the Algerian coast (Annaba) and a second one in front of the Libyan coast (Bengazi, cfr. Fig. 3, Table 2).

3.1. Assessment on the basin scale

As already shown by Refs. [41], the mean wave energy flux in the Mediterranean Sea takes values in between few kW/m in the less energetic areas (Alboran Sea, Adriatic Sea, Aegean Sea) and above 10 kW/m in the Central Mediterranean, on the West of Sardinia. Some areas, such as the Eastern Mediterranean, can be classified as "intermediately energetic" presenting values of the available energy flux between 6 and 9 kW/m (Fig. 3).

One of the main issues concerning the exploitation of wave energy resource is the temporal variability of the resource. The values of the mean energy flux (per unit crest) reported in Fig. 3 represent a rough indicator of the amount of energy which could be exploited theoretically. Indeed the average does not provide information on the distribution of energy over the temporal span analyzed. In order to gather more insights on the temporal variability of the wave energy resource, in Fig. 4 the mean energy flux per unit crest is reported for different seasons (Winter, Spring, Summer and Autumn).

The main contribution to the annual mean energy is developed mainly during the December–February period, i.e. the Winter season, when the average energy flux can reach up to 23 kW/m in the Western Mediterranean, while during the other seasons the amount of available energy is significantly smaller. During Spring

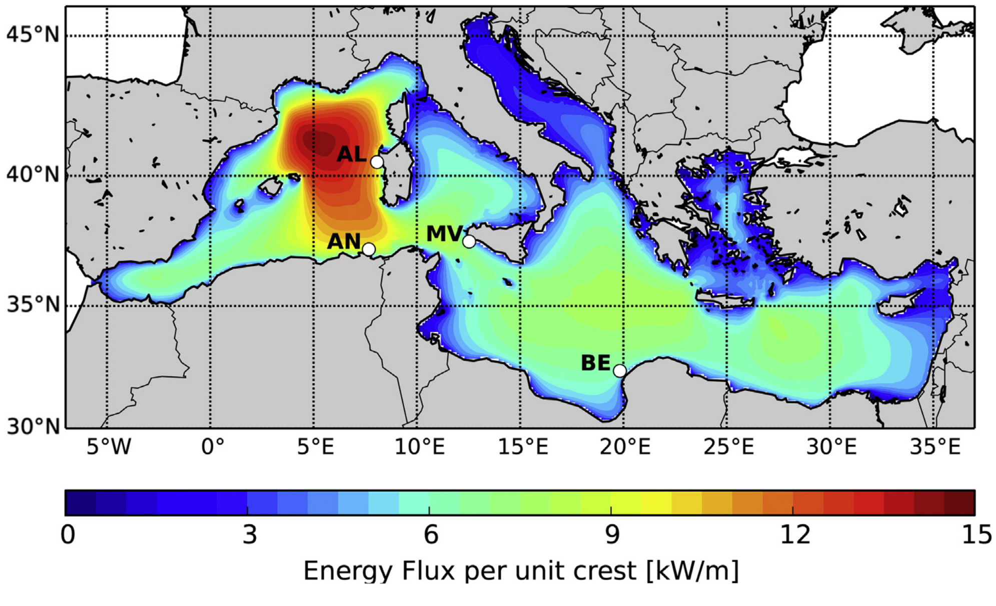

Fig. 3. Mean energy flux per unit crest [kW/m] for the 1979–2013 period.

Table 1
Mean wave power characteristics (Mean yearly energy flux $\overline{P}$, Mean yearly energy E_y, temporal variability *COV*, Seasonality variability index *SV*, Monthly variability index *MV*, for the four analyzed locations.

Site	$\overline{P}$ [kW/m]	E_y [MW h/m]	COV	SV	MV
AL	9.49	83.19	0.18	1.20	1.38
MV	5.58	48.87	0.16	1.35	1.46
AN	9.10	79.73	0.16	1.50	1.68
BE	5.97	52.37	0.19	1.79	1.81

Table 2
Selected site location for the energy assessment analysis. Lon. stands for Longitude, Lat. for Latitude and Dep. for Depth.

Location	Lon.	Lat.	Dep. [M]
Alghero (AL)	7.950	40.450	~350
Mazara del Vallo (MV)	12.660	37.380	~195
Annaba (AN)	7.675	37.250	~2435
Bengazi (BE)	19.830	32.390	~500

(March–May) and Autumn (September–November) the pattern of the energy flux is similar to the winter one, with maxima located west of Sardinia (about 15 kW/m) and less energetic zones in the eastern Mediterranean (about 7 kW/m). Wave energy availability thus has a clear seasonal dependence that can be reasonably traced back to the well known seasonality of wind climatology in the Gulf of Lion [60].

Seasonal and temporal variability of the wave energy resource is an important matter which should be taken into account in the planning of future exploitation of this resource: it would be much more convenient to develop a project in an area with lower yearly average value of energy flux but with a weak variation over months, rather than in a location with a very high mean value but with strong fluctuation around it. This in order to maximize the efficiency and the performances of the harvesting devices. Different variability indicators have been introduced by Ref. [5] to capture the amount of variations of the resource on different time references. A straightforward measure is represented by the coefficient of variation *COV* which is calculated dividing the standard deviation of the energy flux series by its average value

$$COV = \frac{\sigma_P}{\mu_P} \tag{6}$$

where σ_P denotes the standard deviation, and μ_P is the mean value of the time series. Absence of variability is found if $COV = 0$ while variability grows if *COV* increases: for $COV = 1$, indeed, the standard deviation equals the average. Fig. 5 shows the *COV* evaluated for the whole time series on a yearly basis (i.e. σ_P has been evaluated employing the single year average value and the mean over the whole period, i.e. Fig. 3 values), identifying the southern coasts of Italy, the eastern coast of Libya and the northern area of the Eastern Mediterranean as the areas most affected by inter-annual variability. The latter area (i.e. the Aegean Sea and the southern Turkish coast) presents a significant value of the inter-annual variability coefficient *COV* mainly due to the very low mean values rather than because of actual strong fluctuations of *P*.

In order to have more detailed figures about variability of the resources [5] introduced the monthly and the seasonal variability indexes (*MV* and *SV*, respectively) defined as the differences of the most energetic month/season and the less energetic month/season divided by the yearly average value (evaluated over the whole dataset, i.e. Fig. 3 values):

$$MV = \frac{P_{M_{max}} - P_{M_{min}}}{P_{year}} \tag{7}$$

$$SV = \frac{P_{S_{max}} - P_{S_{min}}}{P_{year}}. \tag{8}$$

Figs. 6 and 7 report the values of *MV* and *SV*, evaluated over the whole hindcast. From the results it is possible to observe that, as already stated above, the rate of variation on a monthly basis results

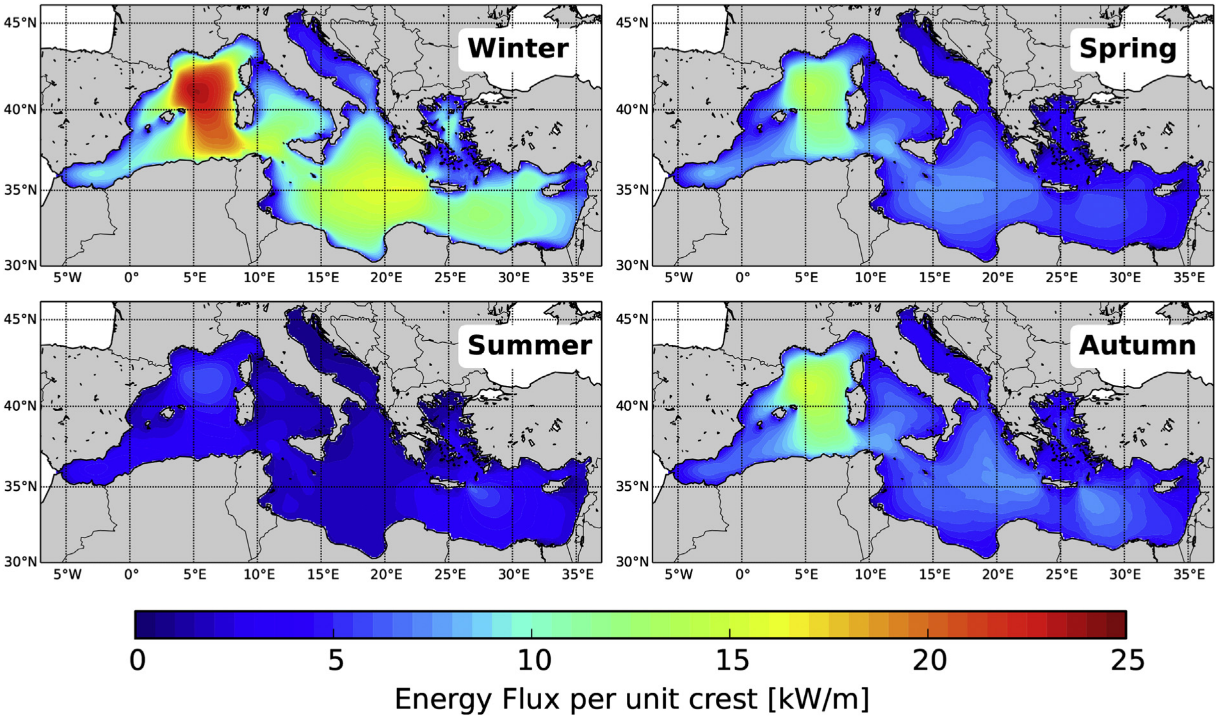

Fig. 4. Seasonal mean energy flux per unit crest [kW/m] for the 1979–2013 period. Winter: Dec–Jan–Feb; Spring: Mar–Apr–May; Summer: Jun-Jul-Aug; Autumn: Sep–Oct–Nov.

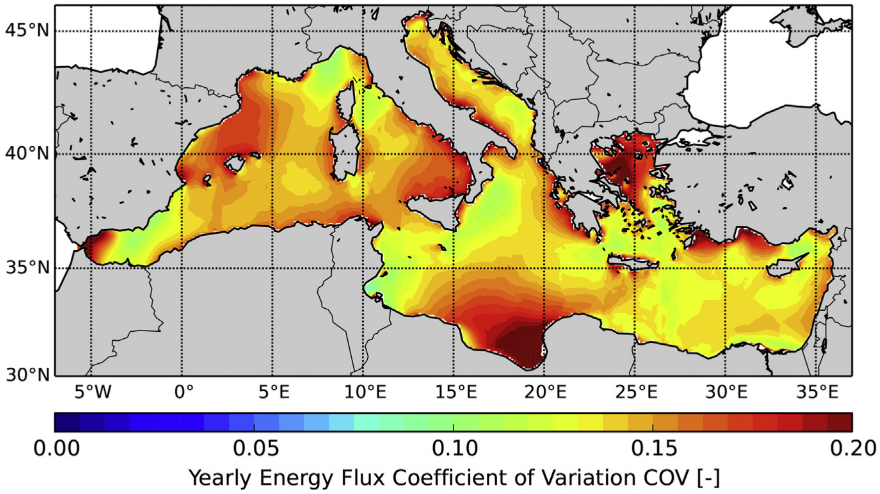

Fig. 5. Coefficient of variation COV on yearly basis for the 1979–2013 period.

to be more significant than the seasonal one, i.e. the variations from one month to another one are stronger than those occurring among seasons. In particular the Central Mediterranean results to be quite variable on a monthly basis while on a seasonal basis the most variable areas are located North of the Libyan coast and in the North–East Mediterranean basin. Results suggest thus that the amount of energy that could be exploited tends to float on an intra-annual basis. Hence, the optimal design of WEC devices still remains a challenging task. On the other hand, the results on seasonal basis should be used carefully for project planning because they do not show a significant variability and hence tend to give a picture of a more stable and constant resource.

3.2. *Assessment on location scale*

Once the characterization of the wave power resources has been addressed on the basin scale identifying which areas are the most promising for a possible resource exploitation, attention has been focused on a detailed analysis of wave power availability on four sites located in the most energetic areas identified thanks to the results presented in section 3.1. For all the four chosen locations the main wave energy flux characteristics are presented in similar plots corresponding to:

a) the wave power rose;
b) distribution of wave power as a function of significant wave height H_s and energy period T_e;
c) persistence of the wave power in hours;
d) CDF (cumulative distribution function) of the wave energy flux;
e) yearly mean wave power and its trend evaluated through a 5 years moving mean for the whole time window;
f) seasonal mean wave power;
g) seasonal mean level during the whole period;
h) wave power characteristics on a monthly basis;
i) overall monthly trends along the whole period.

These information should represent in detail the wave energy resources characteristics and its fluctuations on an intra- and inter-annual basis and should provide a significant insight for a reliable resource assessment to be used for the planning and the design of wave energy harvesting projects. A brief summary of the value of

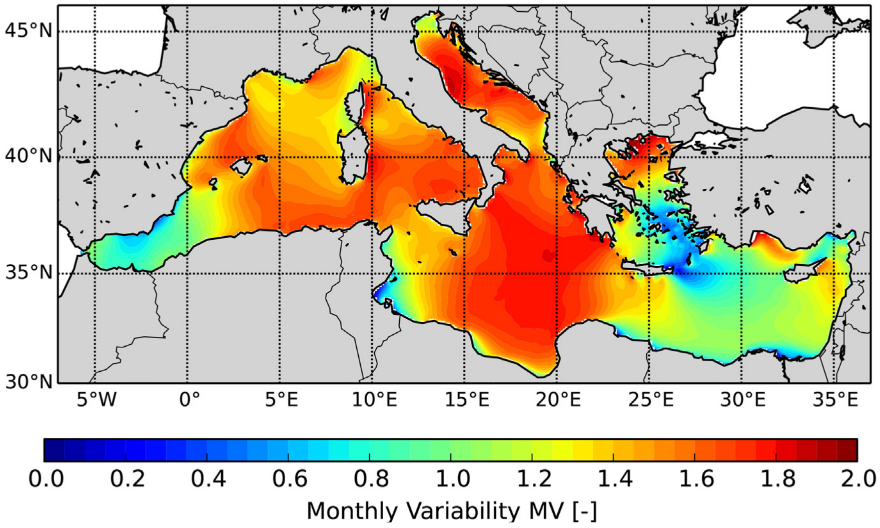

Fig. 6. Monthly variability MV for the 1979–2013 period.

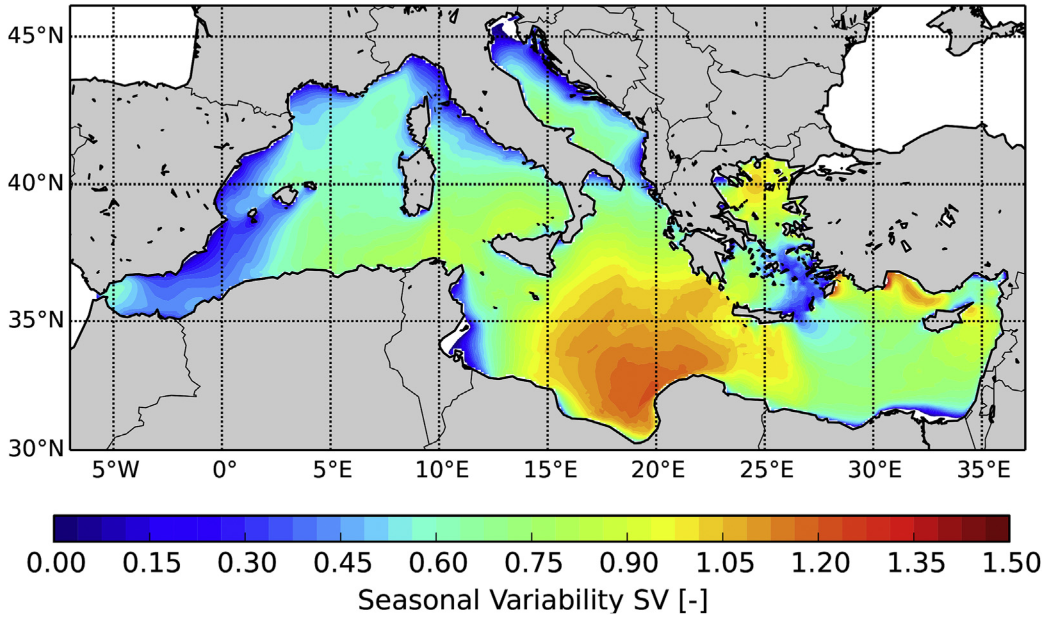

Fig. 7. Seasonal variability SV for the 1979–2013 period.

the mean wave power $\overline{P}$, the mean yearly energy E_y and the coefficient of temporal variation (COV, MV and SV) is reported in Table 1. Results are then illustrated in Figs. 8–11 for Alghero, Mazara del Vallo, Annaba and Bengazi respectively.

The first two sites correspond to two measurement buoys belonging to the Italian buoys network (RON – Rete Ondametrica Nazionale) on the Western coast of Sardinia (Alghero) and on the Western coast of Sicily (Mazara del Vallo). The other two sites are located on the North-African coast, one in the Western Mediterranean (Annaba) and the other in the Eastern Mediterranean (Bengazi). Alghero and Annaba lay on the most energetic area of the Mediterranean basin, i.e. the Western one, while Mazara is slightly peripheral with respect to this zone and Bengazi falls in the Central Mediterranean basin. While Alghero and Annaba should result in higher values of available energy, Mazara and Bengazi should represent a good example of intermediate wave energy potential that could still be exploitable.

As stated before, Alghero and Mazara del Vallo represent the two most promising sites for energy potential in Italian waters. Basically the western part of Sardinia is the most promising area for energy exploitation and values obtained for Alghero site confirm these ideas. In particular, even if the average annual value is not comparable with oceanic ones, it is one of the highest in the Mediterranean Sea, being greater than 9 kW/m. Furthermore the energy is concentrated on the North–West sector, coming mainly from 300° N: the information about the spread of wave energy in direction rose is critical for the choice and installation of the harvesting devices. The distribution of the energy as a function of the significant wave height and the mean period (panel b, Fig. 8) it is necessary in order to estimate the energy converter efficiency on the basis of the power matrices provided by the WEC manufacturers. Maximum efficiency can be reached in the Mediterranean Sea through a downscaling of the devices which have been developed for the Atlantic Ocean wave climate [43]. On the other hand, the information on wave energy persistence (panel c and d, Fig. 8) is needed in order to evaluate the most common conditions and hence to plan the optimal functioning interval for which the devices should be designed for. These information allow one to identify the percentage of sea states (i.e. wave power) that happen to be below a critical level, giving insights of the reliability of operating limits [19,20].

The availability of 35 years wave data allows us to perform some analysis on the inter- and intra-annual variation of the energy resource. In particular panel e) of Fig. 8 gives an insight of the fluctuations of the mean energy flux through the years, revealing that from the 80's up to 2010 the mean wave power first slightly decreased until the mid 90's, while it begun to increase again since 2006 (see red line in panel e) (in web version), Fig. 8). Even if 35 years do not represent a valid basis for a climatological study, it allows to identify a weak trend of increase of the mean yearly energy potential [22]. The marked seasonal character depicted in panel f) presents trends similar to those observed for the mean annual values on an inter-annual basis. The stronger fluctuation occur generally during the winter season, while summer presents a much more constant level of mean energy. (cfr. Fig. 8, panel g). Intra-annual variations are better appreciated if we analyze the mean monthly estimates. Panel h) shows the variability on a monthly basis over the whole time window (average value, 25%–75% percentiles and $\pm$ 2.7σ outliers; red points represent values falling outside the outliers boundaries), revealing how there are strong deviation from a month to another, especially if we consider winter and summer seasons (as already depicted in panels f and g). Moreover panel h) shows the distribution of the wave power values, giving a clue of the excursion rate between the extremes and the mean value, suggesting that in some periods it could be possible to find different extreme events which can represent a hazard for the structural integrity of the devices. Indeed safe structural design of WECs and their mooring system has to be performed on the basis of an extreme values analysis, bearing in mind that during extreme events the devices should not be operational [5,19,20,39]. Finally, in panel i) the overall variability of the mean wave energy flux over the months and over the years is depicted, showing a stronger variability over the years for the autumn and winter months (September–February); furthermore a marked intra-annual variability with respect to the months is revealed.

The same observations and behavior presented for the Alghero location can be recast for the other three sites, where a strongly

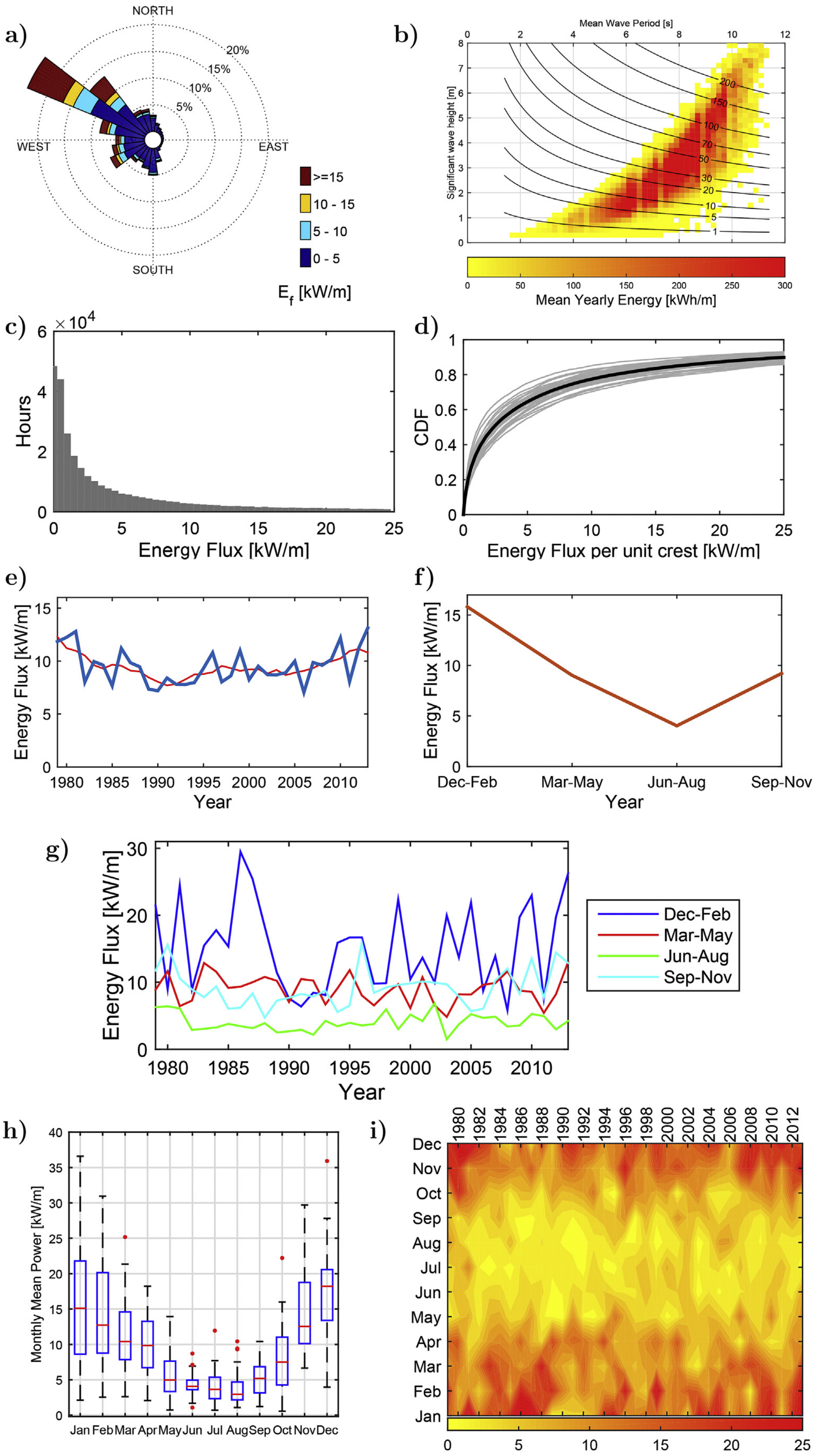

Fig. 8. Wave energy assessment for Alghero (AL) location.

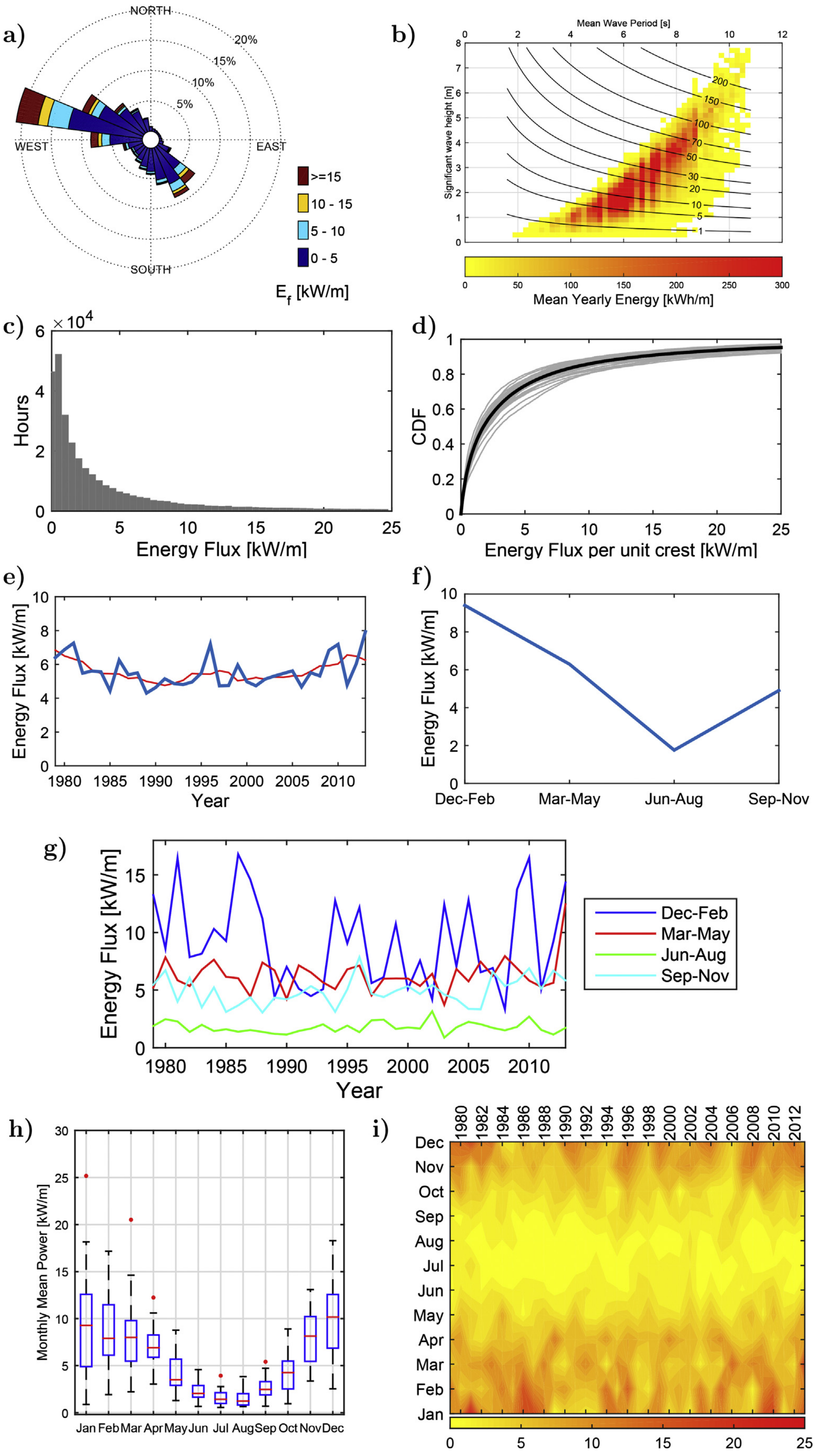

Fig. 9. Wave energy assessment for Mazara del Vallo (MV) location.

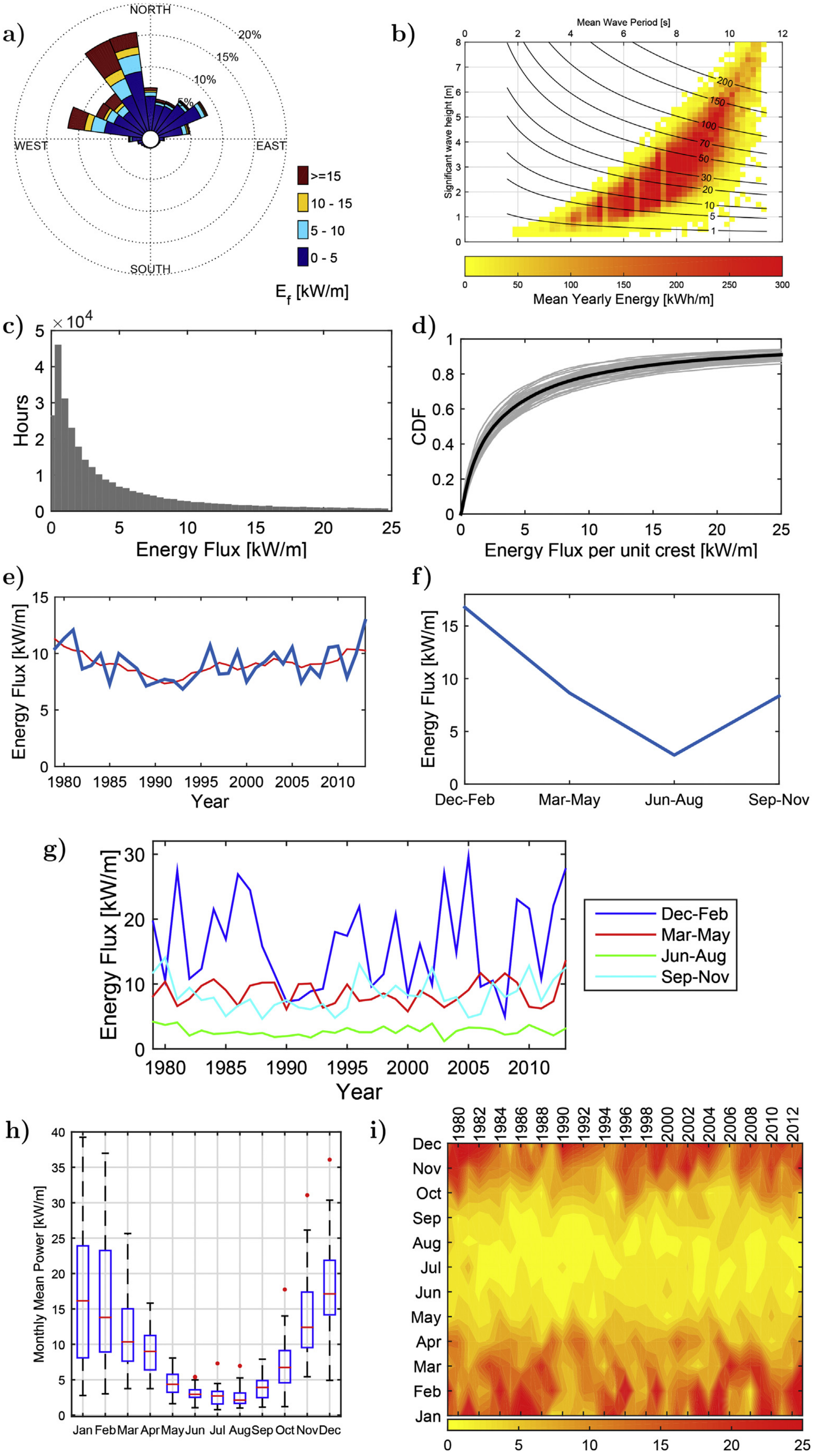

Fig. 10. Wave energy assessment for Annaba (AN) location.

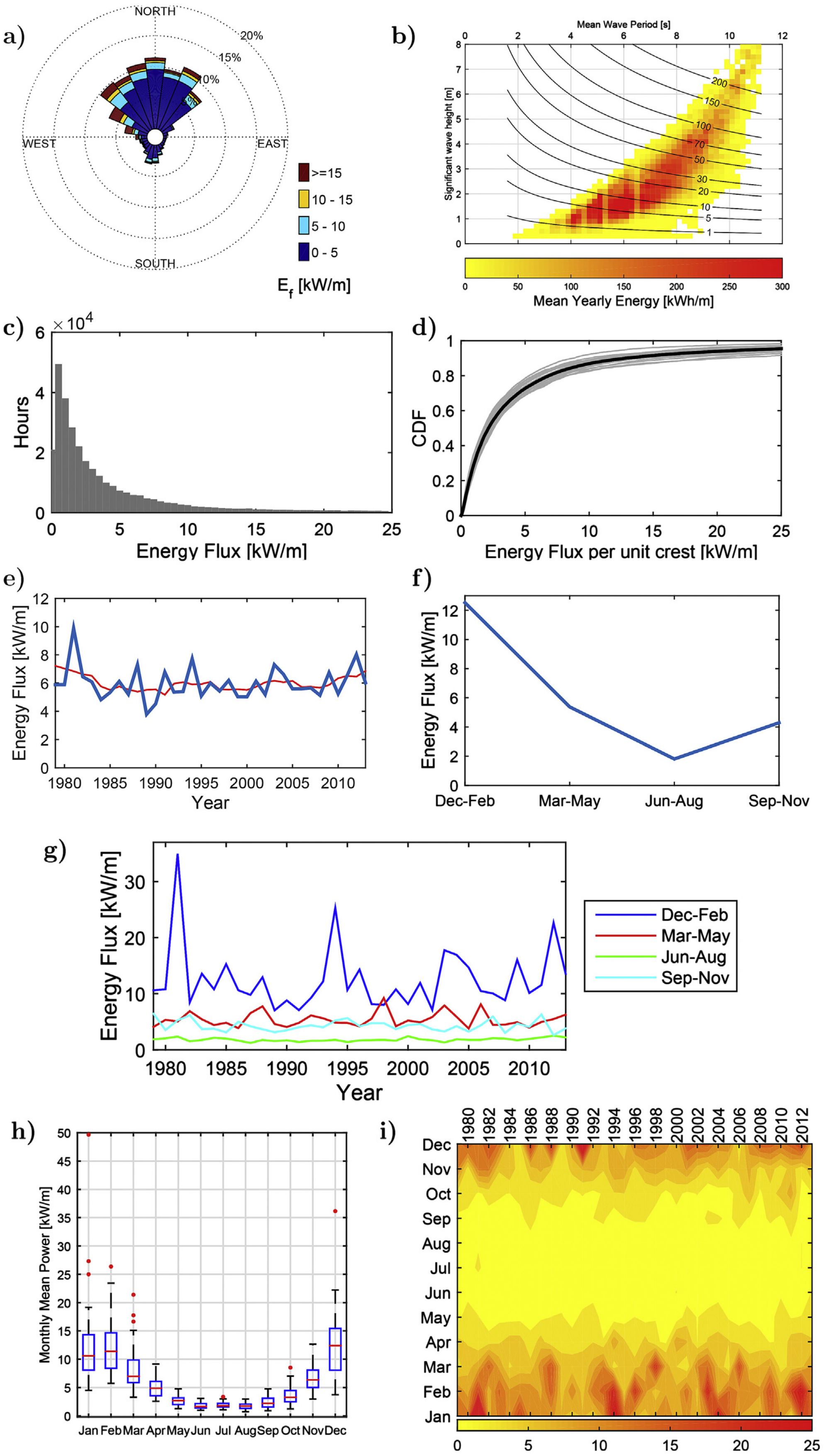

Fig. 11. Wave energy assessment for Bengazi (BE) location.

marked seasonal and monthly behavior is found. The only differences are in the values of the energy which are similar to the Annaba site, while are significantly smaller in Mazara del Vallo and Bengazi sites, in agreement with the results presented by Ref. [41]. Concerning the directional distribution of the wave power, it is interesting to note that while for Alghero the wave energy is concentrated just in a narrow direction sector, for the other three locations the energy is spread on a wider range. In particular, Mazara del Vallo, due to its position halfway between the Western and the Eastern Mediterranean basin, presents two opposite primary direction (W-NW and SE), while for both Annaba and Bengazi the energy power is spread on a 150° angle oriented mainly in the northern direction. Long term trends and seasonality present the same behavior depicted for Alghero location, i.e. strong intra-annual variability and moderate inter-annual variability.

3.3. The role of high/low resolution grid

The estimates provided in the present manuscript have been implemented employing a high resolution either in space (0.1° in longitude and latitude) and in time (wind forcing and output every 1 *hr*). In order to appreciate the effect of the resolution on the results for the wave numerical model we simulated a storm event for Alghero buoy with a different time step for the wind forcing and a looser grid resolution in space. For the sake of brevity and clearness we will here present only one test case representative of the results obtained for all the locations analyzed. In particular we analyzed the storm occurred between 17*th* and 22*nd* of February 2010 employing a wind forcing with a spatial resolution of 0.5° and a temporal resolution of 6 h. Results of the comparison among the two different numerical simulations and the observed buoy data are reported in Fig. 12 for significant wave height H_s, mean period T_m and wave energy flux P.

As it could be observed from the results a looser resolution in space and in time of the wind forcing and a low resolution for the wave numerical model can lead to a significant underestimation of the values of the significant wave height and of the mean period, leading to an important error in the wave energy flux evaluation. Furthermore an output of wave characteristics every 3 or even every 6 h results in a rather coarse description of wave energy flux fluctuation on a small time scale, which is crucial for the evaluation of the persistency of the resource and for the estimate of extreme events for the design of the wave energy converters. More details about the effect of models resolution on the reliability of the results can be found in Ref. [1].

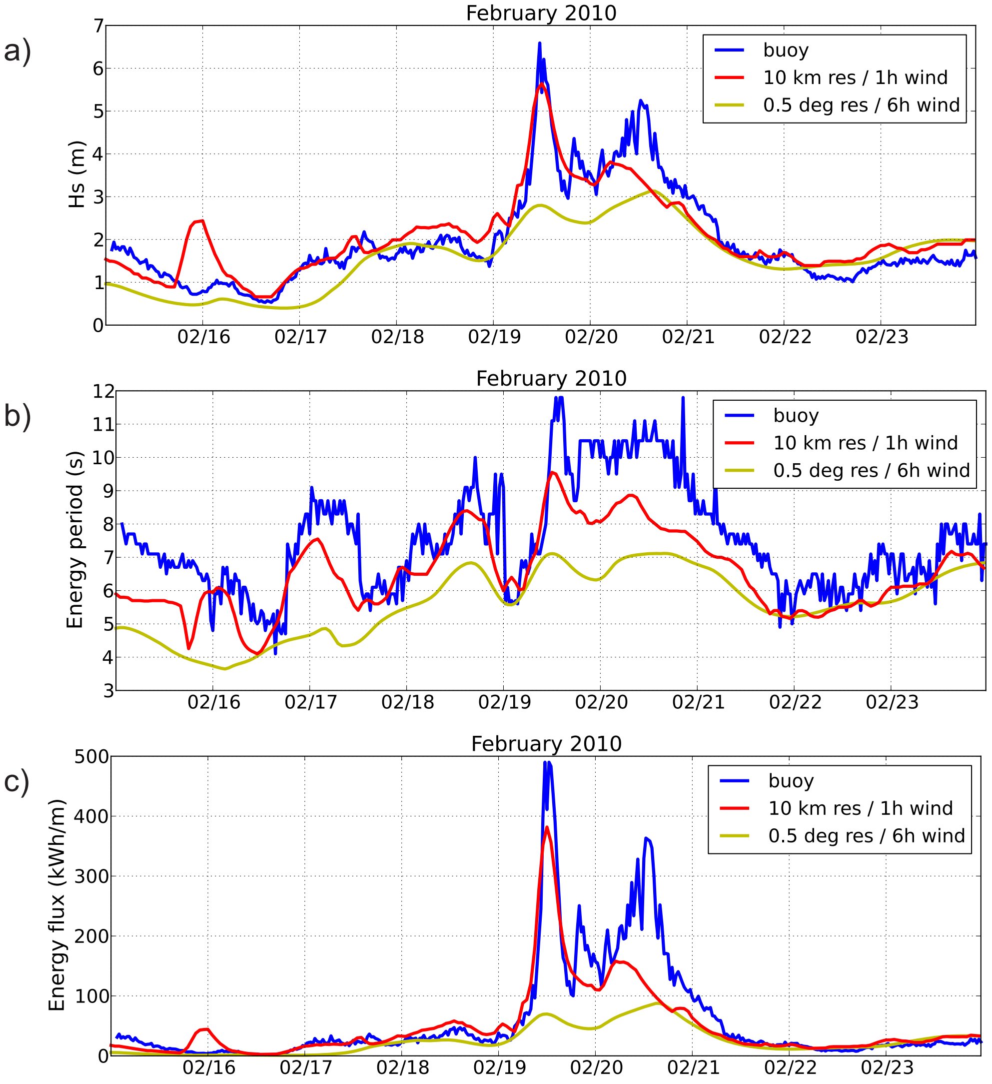

Fig. 12. Comparison among different resolution numerical simulations and observed buoy data. Alghero, February 2010.

Table 3
Energy flux per unit width [kWh/m] integrated over the storm occurred in February 2010 for buoy observations and different numerical simulations.

Location	Buoy	Coarse resolution	Fine resolution
Energy [kWh/m]	~12 490	~5280	~10 490

In Table 3 the value of the available wave energy integrated over the storm is presented for the buoy data and the numerical simulation. Coarse grid can lead up to 50% underestimation of the wave energy resource.

4. Conclusions

Wave energy resource distribution in the Mediterranean basin has been assessed on the basis of numerical simulations for a period of 35 years (1979–2013) with an hourly resolution in time and a resolution in space of about 10 km in longitude and latitude. The hindcast developed by Ref. [1] has been used to develop a detailed assessment of the wave energy resource on the basin scale (the whole Mediterranean Sea) and on a local scale. Significant information on the variability and persistence of wave energy flux have been analyzed thanks to the high temporal resolution. The principal outcomes of the present work can be summarized as follows:

- The most energetic area in the Mediterranean Sea is the Western basin in between the Balearic Islands, Sardinia and Corsica and the Northern coast of Algeria with a yearly available mean wave power of about $10kW/m$ along the coast;
- central and Eastern Mediterranean present moderate wave energy potential with mean figures around $6-7kW/m$;
- as already observed in previous studies, the mean value of wave power over the entire dataset (35 years) is a rough indicator of wave energy potential not taking into account inter- and intra-annual variability and directional distribution of the wave energy resource [42,44];
- in all Mediterranean basin there is a strong variability on monthly base, which results in relevant fluctuations on a seasonal base;
- long-term trends of wave power availability suggest that after a period of general decrease of the mean yearly wave power between the 80's and the 90's, we are experiencing a slightly increase in the last eight years of the temporal series (2005–2013). It would be interesting to extend the temporal series up to nowadays in order to verify if this tendency is confirmed or if it represents a minor fluctuation;
- long term analysis for seasonal energy content shows the same type of trends observed for the annual values. Generally the stronger contributions, and indeed the main component of the trends, are given by the winter values, while the summer ones are much less significant. Different levels of available energy for the four seasons are reported, with differences up to almost $15kW/m$ between the most energetic season and the less energetic one;
- wave power distribution over the hours and the relative Cumulative Density Function should be employed in order to identify good levels of available resource depending on their persistence during the year;
- the choice of grid resolution for both the atmospheric model and the wave model is crucial to obtain reliable estimate of the wave energy resource.

Results presented in this study suggest that the temporal resolution of the wave dataset employed for the assessment of the available energy is crucial in order to have a detailed characterization of the resource trends and variations over different time intervals. It is quite clear indeed that the primary discriminating factor for the development of a wave energy project is basically the intrinsic variability of the available resource: it could be much more problematic to develop a project in a highly energy environment characterized by a strong temporal variability rather than in an environment characterized by a medium energy content but showing a moderate inter- and intra-annual variability. Furthermore the results of the present analysis could be used as boundary conditions to perform detailed analysis for specific location along any stretch of the Mediterranean coast in order to analyze the variation and behavior of the wave energy flux due to the interaction of the sea waves with the bottom bathymetry and the coastline morphology.

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References

[1] Mentaschi L, Besio G, Cassola F, Mazzino A. Performance evaluation of WavewatchIII in the Mediterranean Sea. Ocean Model 2015;90:82–94.
[2] Clément A, McCullen P, Falcão A, Fiorentino A, Gardner F, Hammarlund K, et al. Wave energy in Europe: current status and perspectives. Renew Sustain Energy Rev 2002;6(5):405–31.
[3] Defne Z, Haas KA, Fritz HM. Wave power potential along the Atlantic coast of the southeastern {USA}. Renew Energy 2009;34(10):2197–205.
[4] Pontes M. Assessing the European wave energy resource. J Offshore Mech Arct Eng 1998;120(4):226–31.
[5] Cornett AM, et al. A global wave energy resource assessment. Proc ISOPE 2008. Doc ID ISOPE-I-08-370, 9 pages.
[6] Mork G, Barstow S, Kabuth A, Pontes MT. Assessing the global wave energy potential. In: ASME 2010 29th international conference on ocean, offshore and Arctic engineering, American society of mechanical engineers; 2010. p. 447–54.
[7] Arinaga RA, Cheung KF. Atlas of global wave energy from 10 years of reanalysis and hindcast data. Renew Energy 2012;39(1):49–64.
[8] Gunn K, Stock-Williams C. Quantifying the global wave power resource. Renew Energy 2012;44(0):296–304.
[9] Boudière E, Maisondieu C, Ardhuin F, Accensi M, Pineau-Guillou L, Lepesqueur J. A suitable metocean hindcast database for the design of marine energy converters. 2013.
[10] Guillou N, Chapalain G. Numerical modelling of nearshore wave energy resource in the sea of iroise. Renew Energy 2015;83:942–53.
[11] Iglesias G, Carballo R. Wave energy potential along the death coast (Spain). Energy 2009;34(11):1963–75.
[12] Iglesias G, Carballo R. Offshore and inshore wave energy assessment: Asturias (N spain). Energy 2010;35(5):1964–72.
[13] Iglesias G, Carballo R. Wave energy resource in the Estaca de Bares area (spain). Renew Energy 2010;35(7):1574–84. special section: {IST} national conference 2009.
[14] Iglesias G, Carballo R. Wave power for la isla bonita. Energy 2010;35(12):5013–21. the 3rd international conference on sustainable energy and environmental protection, {SEEP} 2009.
[15] Iglesias G, Carballo R. Wave resource in el hierroan island towards energy self-sufficiency. Renew Energy 2011;36(2):689–98.
[16] Veigas M, Iglesias G. Wave and offshore wind potential for the island of tenerife. Energy Convers Manag 2013;76(0):738–45.
[17] Rusu E, Soares CG. Wave energy pattern around the madeira islands. Energy 2012;45(1):771–85. the 24th international conference on efficiency, cost, optimization, simulation and environmental impact of energy, {ECOS} 2011.
[18] Rusu L, Soares CG. Wave energy assessments in the azores islands. Renew Energy 2012;45(0):183–96.
[19] Smith H, Haverson D, Smith GH. A wave energy resource assessment case study: review, analysis and lessons learnt,. Renew Energy 2013;60:510–21.

[20] van Nieuwkoop JC, Smith H, Smith GH, Johanning L. Wave resource assessment along the cornish coast (uk) from a 23-year hindcast dataset validated against buoy measurements. Renew Energy 2013;58:1−14.

[21] Mackay EB, Bahaj AS, Challenor PG. Uncertainty in wave energy resource assessment. Part 1 Hist Data Renew Energy 2010;35(8):1792−808.

[22] Mackay EB, Bahaj AS, Challenor PG. Uncertainty in wave energy resource assessment. Part 2: variability and predictability. Renew Energy 2010;35(8): 1809−19.

[23] Hughes MG, Heap AD. National-scale wave energy resource assessment for Australia. Renew Energy 2010;35(8):1783−91.

[24] Kim G, Jeong WM, Lee KS, Jun K, Lee ME. Offshore and nearshore wave energy assessment around the korean peninsula. Energy 2011;36(3):1460−9.

[25] Lenee-Bluhm P, Paasch R, zkan Haller HT. Characterizing the wave energy resource of the {US} pacific northwest. Renew Energy 2011;36(8): 2106−19.

[26] Stopa JE, Cheung KF, Chen Y-L. Assessment of wave energy resources in Hawaii. Renew Energy 2011;36(2):554−67.

[27] Kim C-K, Toft JE, Papenfus M, Verutes G, Guerry AD, Ruckelshaus MH, et al. Catching the right wave: evaluating wave energy resources and potential compatibility with existing marine and coastal uses. PloS One 2012;7(11): e47598.

[28] Saket A, Etemad-Shahidi A. Wave energy potential along the northern coasts of the gulf of Oman, Iran. Renew Energy 2012;40(1):90−7.

[29] Chiu F-C, Huang W-Y, Tiao W-C. The spatial and temporal characteristics of the wave energy resources around taiwan,. Renew Energy 2013;52:218−21.

[30] Mirzaei A, Tangang F, Juneng L. Wave energy potential along the east coast of peninsular Malaysia. Energy 2014;68(0):722−34.

[31] López M, Veigas M, Iglesias G. On the wave energy resource of Peru. Energy Convers Manag 2015;90:34−40.

[32] Rusu E. Wave energy assessments in the black sea. J Mar Sci Technol 2009;14(3):359−72.

[33] Akpınar A, Kömürcü Mİ. Assessment of wave energy resource of the black sea based on 15-year numerical hindcast data. Appl Energy 2013;101:502−12.

[34] Aydoan B, Ayat B, Yksel Y. Black sea wave energy atlas from 13years hindcasted wave data. Renew Energy 2013;57(0):436−47.

[35] Soomere T, Eelsalu M. On the wave energy potential along the eastern Baltic sea coast. Renew Energy 2014;71:221−33.

[36] Aoun N, Harajli H, Queffeulou P. Preliminary appraisal of wave power prospects in Lebanon. Renew Energy 2013;53:165−73.

[37] Ayat B. Wave power atlas of eastern Mediterranean and Aegean seas. Energy 2013;54(0):251−62.

[38] Vicinanza D, Contestabile P, Ferrante V. Wave energy potential in the northwest of Sardinia (Italy). Renew Energy 2013;50(0):506−21.

[39] Zodiatis G, Galanis G, Nikolaidis A, Kalogeri C, Hayes D, Georgiou GC, et al. Wave energy potential in the Eastern Mediterranean Levantine Basin. an integrated 10-year study. Renew Energy 2014;69(0):311−23.

[40] Monteforte M, Re CL, Ferreri G. Wave energy assessment in Sicily (Italy). Renew Energy 2015;78:276−87.

[41] Liberti L, Carillo A, Sannino G. Wave energy resource assessment in the mediterranean, the Italian perspective. Renew Energy 2013;50(0):938−49.

[42] Portilla J, Sosa J, Cavaleri L. Wave energy resources: wave climate and exploitation. Renew Energy 2013;57:594−605.

[43] Bozzi S, Archetti R, Passoni G. Wave electricity production in Italian offshore: a preliminary investigation,. Renew Energy 2014;62:407−16.

[44] Carballo R, Sánchez M, Ramos V, Fraguela J, Iglesias G. Intra-annual wave resource characterization for energy exploitation: a new decision-aid tool,. Energy Convers Manag 2015;93:1−8.

[45] Skamarock W, Klemp J, Dudhia J, Gill D, Barker D, Wang W, et al. A description of the advanced research wrf version 3. Technical note tn-468+str. 113 pp, NCAR. 2008.

[46] Saha S, Moorthi S, Pan H-L, Wu X, Wang J, Nadiga S, et al. The NCEP climate forecast system reanalysis. Bull Am Meteorol Soc 2010;91(8):1015−57.

[47] Cavaleri L. Wave modeling – missing the peaks. J Phys Oceanogr 2009;39(11): 2757−78.

[48] Cox AT, Cardone VJ, Swail VR. On the use of climate forecast system reanalysis wind forcing in ocean response modeling. In: Proceedings, 12th int. Workshop wave, hindcasting, forecasting, Hawaii, USA; 2011.

[49] Splinder D, Chawla A, Tolman HL. An initial look at the CFSR reanalysis winds for wave modeling. Technical Note, MMAB Contribution No. 290, NCEP. 2011.

[50] Carvalho D, Rocha A, Gmez-Gesteira M. Ocean surface wind simulation forced by different reanalyses: comparison with observed data along the Iberian Peninsula coast. Ocean Model 2012;56(56):31−42.

[51] Chawla A, Spindler DM, Tolman HL. Validation of a thirty year wave hindcast using the climate forecast system reanalysis winds. Ocean Model 2013;70: 189−206.

[52] Cassola F, Ferrari F, Mazzino A. Numerical simulations of Mediterranean heavy precipitation events with the WRF model: analysis of the sensitivity to resolution and microphysics parameterization schemes. Atmos Res 2015;164−165:210−25.

[53] Tolman HL. User manual and system documentation of WAVEWATCH III version 3.14. Tech. rep., NOAA/NWS/NCEP/MMAB. 2009.

[54] Ardhuin F, Rogers E, Babanin AV, Filipot J, Magne R, Roland A, et al. Semi-empirical dissipation source functions for ocean waves. Part I: definition, calibration, and validation. J Phys Oceanogr 2010;40(9):1917−41.

[55] Bidlot J, Janssen P, Abdalla S. A revised formulation of ocean wave dissipation and its model impact. Tech. Rep. Memorandum 509, ECMWF, Reading, U.K. 2007.

[56] Young IR, Babanin AV. Spectral distribution of energy dissipation of wind-generated waves due to dominant wave breaking. J Phys Oceanogr 2006;36(3):376−94.

[57] Babanin AV, Chalikov D, Young I, Savelyev I. Numerical and laboratory investigation of breaking of steep two-dimensional waves in deep water. J Fluid Mech 2010;644:433−63.

[58] Ardhuin F, Chapron B, Collard F. Observation of swell dissipation across oceans. Geophys Res Lett 2009;36:L06607.

[59] Mentaschi L, Besio G, Cassola F, Mazzino A. Problems in RMSE-based wave model validations. Ocean Model 2013;72:53−8.

[60] Lavagnini A, Sempreviva AM, Transerici C, Accadia C, Casaioli M, Mariani S, et al. Offshore wind climatology over the mediterranean basin. Wind Energy-Bognor Regis 2006;9(3):251−66.