Renewable Energy 69 (2014) 311–323

Contents lists available at ScienceDirect

Renewable Energy

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Wave energy potential in the Eastern Mediterranean Levantine Basin. An integrated 10-year study

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ARTICLE INFO

Article history:
Received 30 July 2013
Accepted 25 March 2014
Available online

Keywords:
Wave energy
Numerical atmospheric
Wave modeling

ABSTRACT

The main characteristics of wave energy potential over Eastern Mediterranean Levantine Basin, an area of increased interest for energy resources exploration/exploitation, is presented in this work. In particular, an integrated hindcasting platform consisting of state-of-the-art wind-wave numerical models at a very high resolution mode is utilized to produce a 10-year database for the wave energy potential in the Levantine Basin and the environmental parameters that affect it. The numerical results are analyzed by means of a variety of statistical measures focusing, apart from the conventional statistical information, on the potential impact of extreme values and the probability distribution functions that optimally describe the spatial and temporal distribution of the wave power potential over the Eastern Mediterranean sea area. The regions with increased values of wave energy potential are mainly the western and southern coastlines of Cyprus island, the sea area of Lebanon and Israel, as well as the coastline of Egypt especially around Alexandria. Over these areas, relatively low but also stable, and hence exploitable, wave energy potential is revealed. However, non-trivial impact of infrequent values is also recorded.

1. Introduction

The exploitation of renewable energy resources is nowadays a key issue worldwide under the warnings of the scientific community for global warming, ocean acidification, the open questions relevant to climate change mitigation and adaptation, the shadow of the recent economic crisis that directly affected the oil-dependent energy sources, as well as the concerns raised for the security and robustness to natural disasters of nuclear power infrastructures. The last decades a number of actions have been taken towards the development of new technologies and scientific methodologies in order to support clean forms of energy.

In this framework, wind and solar approaches are keeping the primary roles in Europe and the U.S. Lately, action is taken, especially in European countries, for another renewable source, the wave energy, that is the energy that can be produced by sea waves. There are some critical advantages in this alternative form of energy, the most crucial of which is the low variability, especially when compared with wind energy, a fact that allows the easier adaptation to large power grids. However, there is a serious distance that remains to be covered before wave energy science and technology reach the maturity level of its wind and photovoltaic counterparts, a goal that needs to be succeeded before wave power production becomes a commercially viable resource.

The discussion on converting the energy of sea waves to power goes back to 19th century or even earlier [45]. In the 1940's Yoshio Masuda was testing wave-energy devices [50]. However, a more active development began only after the rapid increase of the prices of oil-dependent fuels in 1970's [11]. The research efforts in the field gained the support of the European Commission the last two decades and a number of national and international projects have been carried out focusing on different regions and using a variety of technical tools and configurations. Ref. [16] studied the wave energy potential along the southeast Atlantic coast of the United States based on the measurements of buoy stations in the area. Ref.

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http://dx.doi.org/10.1016/j.renene.2014.03.051
0960-1481/

Fig. 1. Wave model domains.

[20] focused on wave-energy converters and wave spectrum parameters related to the distribution of wave energy. Ref. [58] presented a European Wave Energy Atlas based on annual and seasonal wave statistics derived from a coarse grid wave modeling simulations. Ref. [27] investigated different possible wave power installations in the Baltic and North Seas. Refs. [29–31] studied the wave energy distribution over different areas of Spain (Death Coast, Galicia and Bares) based on hindcast simulated data and buoy measurements. Ref. [3] published a 10-year hindcast study based on the WaveWatch3 wave model. Energy assessment in the Azores islands is discussed in Ref. [64]. The Black Sea was studied over a 13-year period in Refs. [2,10] were a detailed wave climate analysis was presented utilizing modeled hindcast data. Going back to the Mediterranean Sea, Ref. [71] studied the area of Sardinia, Italy, based on the Italian buoy network and corresponding hindcast data by ECMWF while Ref. [5] focused on the area of Lebanon. Further corresponding studies for the European Atlantic coastline have been published by Refs. [25,38]. Interesting similar approaches for non-European areas are, among others, the works in Ref. [46] where resource analysis for ten locations is presented based on spectral wave data from US-National Data Buoy Center (NDBC) buoys, Ref. [68] performed a hindcast analysis along the Hawaiiwan coastline, Ref. [12] focused on wave energy resources in Taiwan, Ref. [28] presented a study for Australia's shelf waters based on numerical models.

In this work, a systematic study of the wave energy potential and the relevant sea parameters in the Levantine Basin, Eastern Mediterranean is presented. In particular, an integrated very high resolution atmospheric/wave modeling system was developed for simulating the atmospheric circulation and the sea waves evolution in the area over a period of ten years (2001–2010). The system was operated in a hindcasting mode taking advantage of available atmospheric and wave observations in the area under study: satellite records, meteorological station observations and ship reports have been assimilated in the simulation procedure providing, in this way, a complete representation of the environmental parameters and resulting to detailed wave climatology of the area. This fact in conjunction with the very high horizontal resolution ($\sim 0.01^\circ$) both for the atmospheric and wave numerical models and the long temporal horizon adopted, although very expensive in CPU time, makes this study one of the most detailed approaches for the Eastern Mediterranean Sea, an area with increased political and commercial interest in the field of energy resources exploration/exploitation.

Moreover, an extended statistical analysis of the results is presented including not only the classical statistical information for the sea and energy parameters usually obtained, but also measures for the asymmetry of the results and the impact of extreme values, information that could be critical for site assessment. On the other hand, probability distribution functions are proposed for the complete description of the main parameters that affect the wave energy potential, that is, the significant wave height and the energy period, but also the wave energy itself.

The paper has been organized as follows: In Section 2 the numerical wind and wave models, the data sets and the methodology adopted for estimating the wave energy related parameters are described. Section 3 contains the main information and results obtained while the conclusions reached are summarized in Section 4.

Table 1
Summary of the wave model characteristics.

Wave model	WAM, ECMWF version CY33R1
Area covered	30N–41N, 15E–37E
Horizontal Resolution	$1/60 \times 1/60^\circ$ (1.852 km × 1.553 km approximately)
Frequencies	25 (range 0.0417–0.54764 Hz logarithmically spaced)
Directions	24 (equally spaced)
Timestep	45 s
Wind forcing	SKIRON atmospheric model
Wind forcing time step	3 h

2. Models and methodology

In the present work, state-of-the-art numerical models have been utilized for the simulation of the main atmospheric and wave parameters, needed for the detailed monitoring of the wave energy, in conjunction with available observations in the area of interest and a variety of statistical approaches, targeting to a high quality analysis of the obtained results.

2.1. Wave modeling

The main issue for a wave energy study is the simulation or monitoring of the significant wave height H_s and wave energy period T_e that directly affect the wave energy potential [58]:

$$P = \frac{\rho \cdot g^2}{64\pi} H_s^2 T_e \quad (1)$$

where ρ denotes the water density and g the gravity acceleration. Towards this direction, the wave model WAM [7,43,69] was used. WAM is a third generation wave model which solves the wave transport equation explicitly without any presumptions on the shape of the wave spectrum. It represents the physics of the wave evolution in accordance with our current knowledge and uses the full set of degrees of freedom of a 2d wave spectrum. In our case, the ECMWF version, CY33R1 [35,36] has been utilized. This new version contains a number of important updates that increase significantly the potential capabilities of the wave system: A new advection scheme, based on the Corner Transport Upstream scheme, is used by the introduction of contributions from the corner points [7], a new parameterization of shallow water effects is introduced that affects both the time evolution of the wave spectrum and the determination of the kurtosis of the wave field [37]. In addition, two extreme wave parameters have been introduced, namely the average maximum wave height and the corresponding wave period [51]. The same version of the WAM model employed for the present work, is also used in the CYCOFOS-Cyprus coastal ocean forecasting system [73] providing operational 3-hourly wave forecasts for four and half days on a daily basis, in the Mediterranean Sea and the Levantine Basin at a resolution of 10 km and 5 km respectively (www.oceanography.ucy.ac.cy/cycofos).

It is important to note that this new version of the wave model has been already successfully validated in different studies [7,8,19,23,24,49]. Moreover, a short evaluation of the model adapted in the present study against buoy data for the area of Hadera, Israel – a near shore and shallow water site – is presented in Section 3.

The wave model domain covers the eastern part of the Mediterranean Sea: 30N–41N, 15E–37E (Fig. 1) in order to capture all the necessary swell information that affects the region of Levantine: 30N–38N, 27.5E–36.5E (red in web version rectangle in Fig. 1) which is the main area of interest. On the other hand, a very high spatial resolution has been adopted (1/60 × 1/60°). To the author's knowledge, this resolution is the highest used by research or operational models running presently for this area. In this way, the local characteristics are taken into account in a more credible and detailed way in contrast to previous local wave energy studies in which much coarser grids were used. For example, Ref. [58] used a 0.5 × 0.5 degree resolution for the Mediterranean Sea. Ref. [3] employed the WaveWatch3 model with a 1.25 × 1 degree resolution. The wave spectrum was discretized to 25 frequencies (range 0.0417–0.54764 Hz logarithmically spaced) and 24 directions (equally spaced) while the propagation time step has been set to 45 s in order to meet the CFL stability criterion's standards resulting to a system highly demanding in computational power. The main characteristics of the wave model employed are summarized in Table 1.

WAM was operated on a shallow water mode, driven by 3-hourly wind input (10 m wind speed and direction) obtained from the SKIRON regional atmospheric system [40,55]. The horizontal resolution used for the SKIRON model coincides with that of the wave model while 45 vertical levels stretching from surface to 20 km altitude are employed. The atmospheric system uses NCEP/GFS 0.5 × 0.5 degree resolution fields for initial and boundary conditions. The necessary sea surface boundary conditions are interpolated from the 0.5 × 0.5° SST (Sea Surface Temperature) field analysis retrieved from NCEP on a daily basis. Vegetation and topography data are applied at a resolution of 30 s and soil texture data with resolution of 120 s.

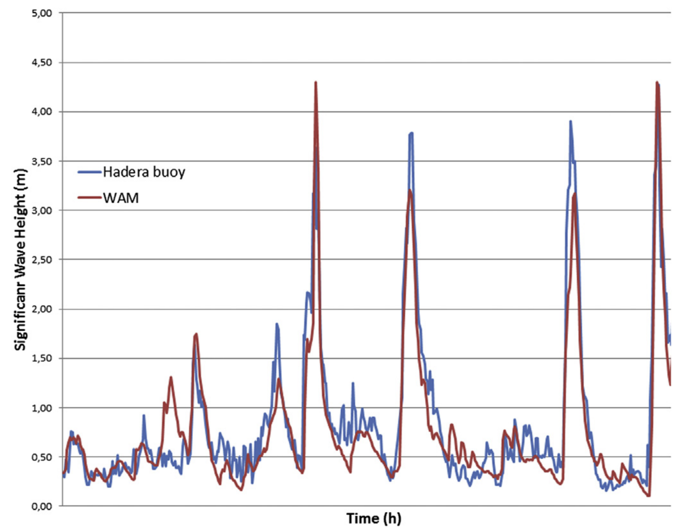

Fig. 2. Significant wave height time series of observed (blue line) and WAM-simulated (red line) for the area of Hadera port, Israel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The quality of the atmospheric forcing is of critical importance for the credible simulation by wave models as different studies and authors have been pointed out (for example Refs. [1,9,21,33,57,59]). In this respect, the use of SKIRON model in a high resolution mode was an advantage for the presented study since SKIRON is a well-established model used and evaluated successfully in the past in various research, technical and operational works. Trying to give a brief overview, we could refer the reader to studies covering the area of Mediterranean Sea with emphasis to wave applications [24,56,57,72,74], over the Atlantic Ocean for oil spill modeling [33], for the Adriatic Sea [17], the Aegean Sea [44] and, additionally, for air-quality applications [4,75], renewable energy [14,32,48,67], photochemical processes [70], and desert dust studies [6,41,53,66].

Moreover, the SKIRON modeling system has been successfully utilized in a number of major European projects: Marine Renewable Integrated Application (MARINA) Platform, MFSTEP, ENVIWAVE, POWWOW, NHREAS, ADIOS and so on (see for details: http://forecast.uoa.gr/oldproj.php). The model is today operationally used by many research and forecasting centers in Europe and the United States: Atmospheric Modeling Group, University of Athens (www.mg.uoa.gr), Oceanography Center, University of Cyprus (http://www.oceanography.ucy.ac.cy/), CENER – National Renewable Energy Centre, Spain (www.cener.com), Israel Oceanographic and Limnological Research (www.ocean.org.il/mainpageeng.asp), Middle East Technical University, Turkey (http://www.metu.edu.tr/), Center of Excellence in Earth Systems

Table 2
Statistical evaluation of the wave model at the area of Hadera Port, Israel.

Bias	−0.09
RMSE	0.32
Nabsbias	0.31

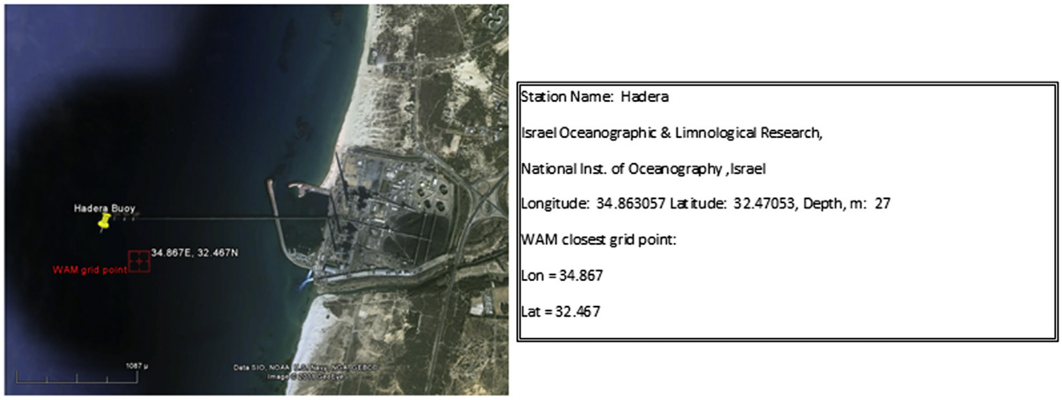

Fig. 3. The area of Hadera port, Israel, the buoy (pointed in yellow) and the corresponding WAM grid point (in red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Modeling & Observations, Chapman University (http://www.chapman.edu/scst/centers-of-excellence/earth-observing/), US-Naval Postgraduate School, Naval Ocean Analysis and Prediction (NOAP) Laboratory (faculty.nps.edu/pcchu/noap_home.htm) and others.

It is also important to underline that any available observations in the area under study obtained by meteorological stations for the atmospheric model and satellite records for wave parameters have been assimilated into the atmospheric and wave models respectively based on the standard assimilation schemes of SKIRON and WAM models (see Refs. [13,18,21,34,42,47,60]), leading in this way, to a fully integrated hindcasting system.

The main output of the wave model is the 2-d wave spectrum $F(f,\vartheta,\phi,\lambda)$ where f stands for frequencies, ϑ for directions, over all latitudes and longitudes (ϕ,λ) of the domain used. The necessary parameters for our study are obtained as integrated byproducts computed based on the moments of the spectrum:

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

More precisely, the significant wave height H_s and the energy period T_e are given by

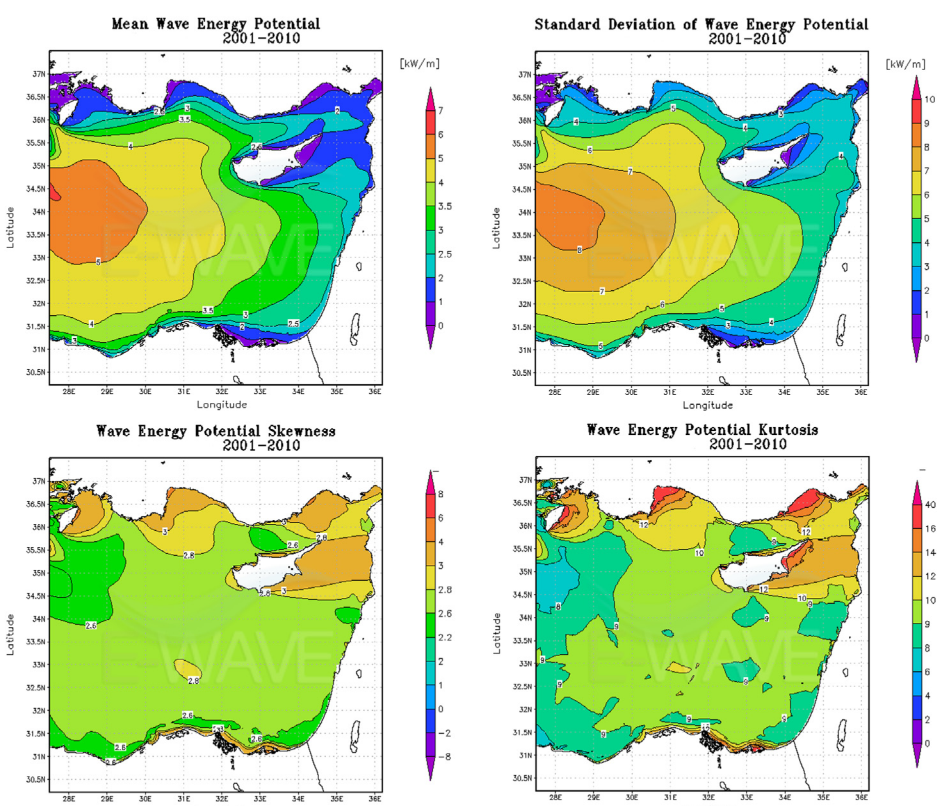

Fig. 4. Main statistical parameters regarding the available wave energy potential (kW/m) for the Eastern Mediterranean. The 10-year a) Mean, b) Standard deviation, c) Skewness, d) Kurtosis values.

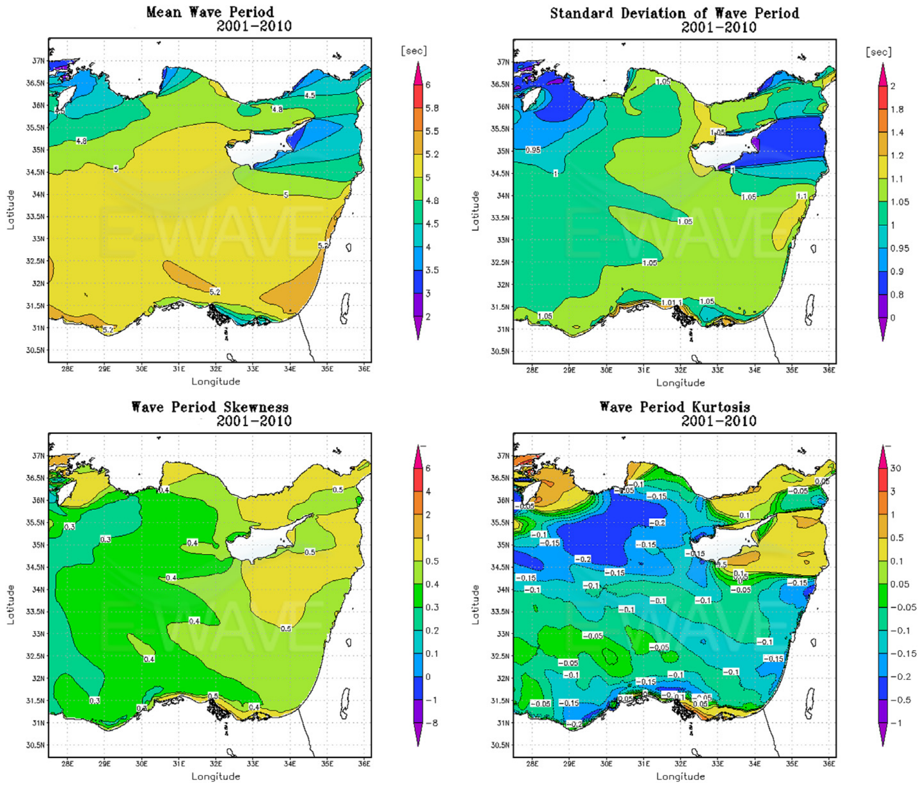

Fig. 5. Main statistical parameters regarding the energy wave period (s) for the Eastern Mediterranean. The 10-year a) Mean, b) Standard deviation, c) Skewness, d) Kurtosis values.

$$H_s = 4\sqrt{m_0}, \quad T_e = \frac{m_{-1}}{m_0} \tag{3}$$

2.2. Statisital analysis/measures

It is one of the main targets of the present work to provide a detailed statistical analysis of the obtained wave-energy information by utilizing statistical measures that provide qualitative information with potential added value for energy applications. Towards this direction, the following statistical indices and measures are used:

The *mean value*:

$$\mu = \frac{1}{N} \cdot \sum_{i=1}^{N} x(i), \tag{4}$$

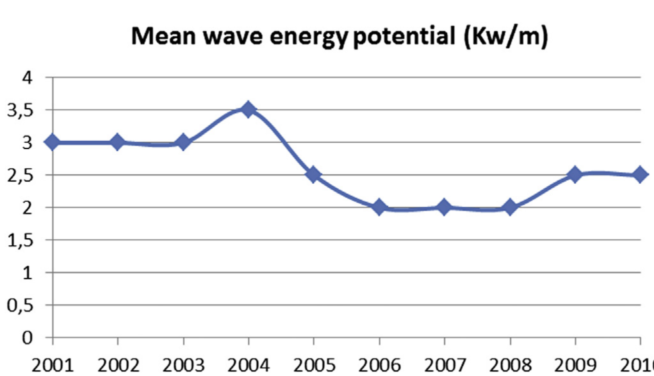

Fig. 6. The yearly evolution of the mean wave energy potential for the western coasts of Cyprus.

where x denotes the parameter in study (significant wave height, mean wave period or wave energy) and N the size of the sample;

The *standard deviation*:

$$\sigma = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (x(i) - \mu)^2}, \tag{5}$$

which is a typical variation index;

The *skewness*:

$$g_1 = \frac{\frac{1}{N} \cdot \sum_{i=1}^{N} (x(i) - \mu)^3}{\sigma^3} \tag{6}$$

a measure of the asymmetry of the probability distribution,

and the *kurtosis*:

$$g_2 = \frac{\frac{1}{N} \cdot \sum_{i=1}^{N} (x(i) - \mu)^4}{\sigma^4} - 3 \tag{7}$$

which measures the “peakedness” of the probability distribution and the impact of possible extreme values. On the other hand, the estimated power data were approached by a distribution fitting point of view as discussed in detail in Section 3.

3. Results and analysis

The 10-year (2001–2010) wave energy resource monitoring for the Levantine Basin in the Eastern Mediterranean is based on the high resolution hindcast data produced by the wave model WAM that was configured to simulate the wave conditions of the entire

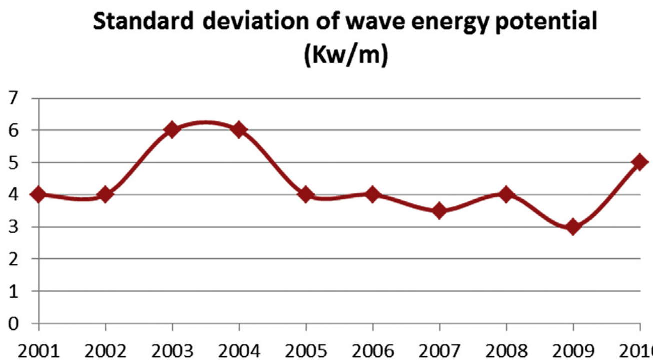

Fig. 7. The yearly evolution of the standard deviation of wave energy potential for the western coasts of Cyprus.

Eastern Mediterranean sea with a resolution of 1 arc minute (about 1.8 km by 1.5 km).

The new version of the wave model adopted for the present study has been already evaluated successfully in a number of previous studies for areas with different wave climate: The developing Center's (ECMWF) wave group in Refs. [7,8,49] provides detailed analysis of the abilities and the performance of the model. Moreover, an application and evaluation in the North Atlantic Ocean can be found in Ref. [19], an evaluation study against remote sensing data for the Mediterranean Sea is presented in Ref. [24] while similar evaluation and analysis for the west coastline of the US (Pacific Ocean) is presented in Ref. [23].

In addition to these previous works, a short, indicative evaluation of the model adapted in the present study against 3-month (December 2006–February 2007) buoy measurements for the

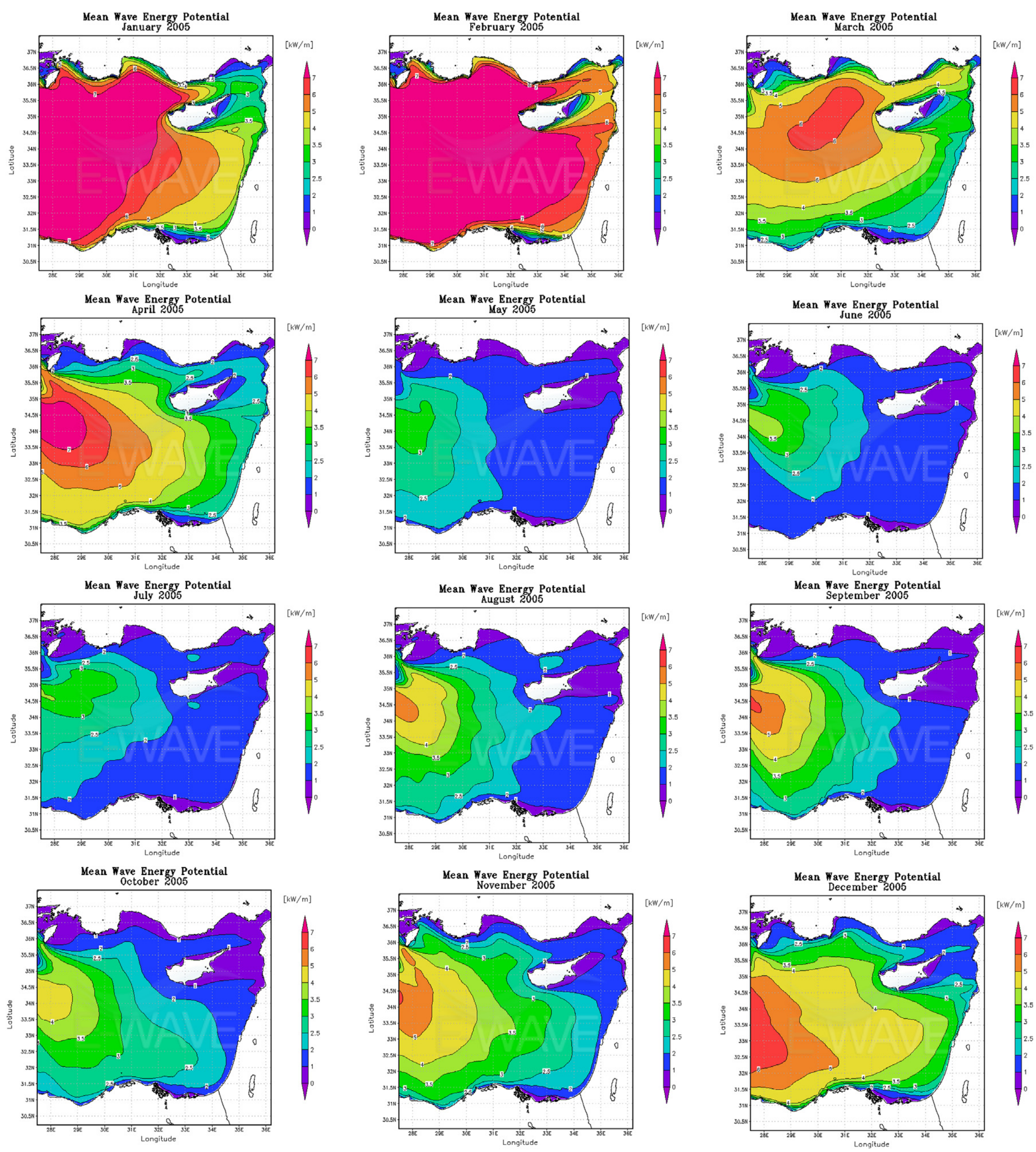

Fig. 8. Mean monthly values of wave energy potential for the year 2005.

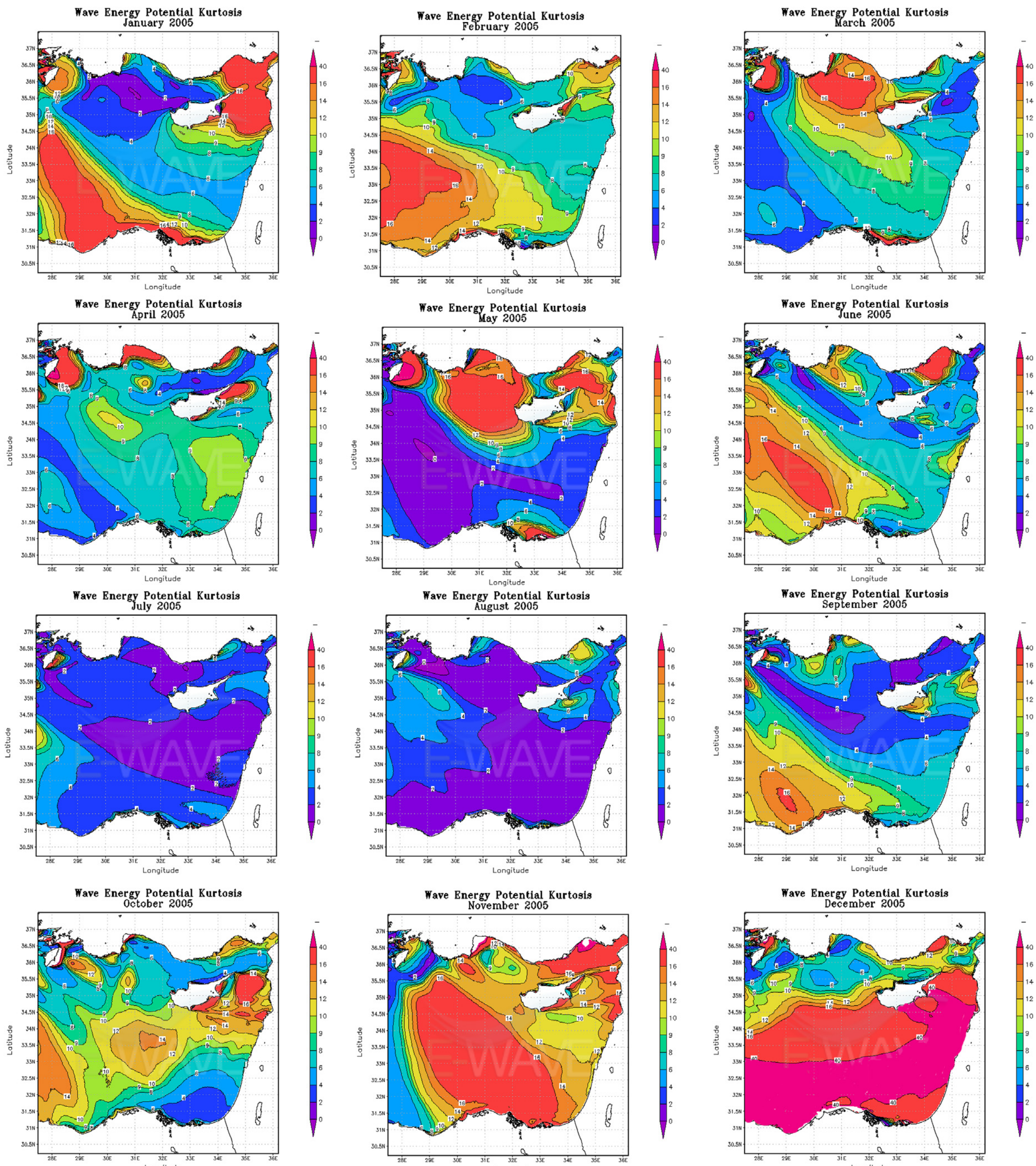

Fig. 9. Kurtosis monthly values of wave energy potential for the year 2005.

port of Hadera, Israel proves a very satisfactory simulation ability at a near shore and shallow water (27 m depth) area: The modeled significant wave height does not only follow the general pattern of the corresponding observations but captures also successfully the picks/maximum values of the wave height (Fig. 2). The corresponding statistics support further the previous assertions giving very low mean (Bias: $1/N \cdot \sum_{i=1}^{N}(\text{obs}(i) - \text{mod}(i))$, Normalized Absolute Bias: $1/N \cdot \sum_{i=1}^{N}\text{abs}(\text{obs}(i) - \text{mod}(i))/\text{obs}(i))$ and variance values (Root Mean Square Error: $\sigma = \sqrt{1/N \cdot \sum_{i=1}^{N}(\text{obs}(i) - \text{mod}(i))^2}$), for the discrepancies between observed (obs) and modeled (mod) data (Table 2).

For this evaluation the closest grid point of the wave system has been used (Fig. 3). It worth noticing that the above mentioned buoy was the only available to us for the area of Levantine Sea.

In order to depict the main wave climatological characteristics of the area, an analysis in different time scales was performed. Decadal, interannual and monthly characteristics of the main parameters concerning this study were analyzed. A detailed yearly presentation of all the statistical parameters utilized for the wave energy potential and the main wave parameters that affect it (significant wave height and mean wave period) is provided in the Supplement.

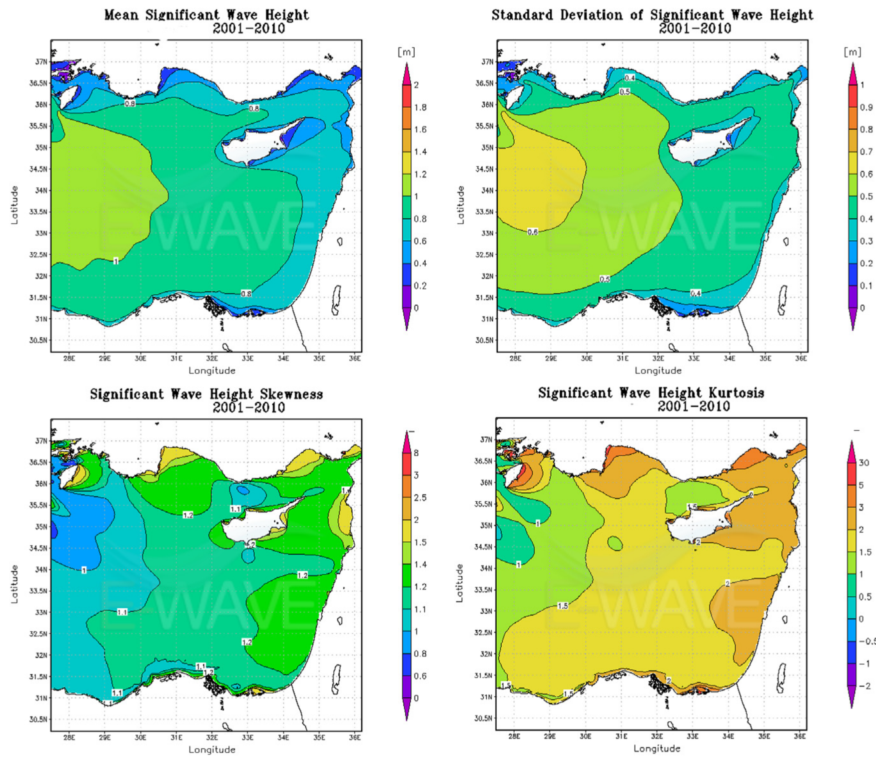

Fig. 10. Main statistical parameters regarding the significant wave height (m) for the Eastern Mediterranean. The 10-year a) Mean, b) Standard deviation, c) Skewness, d) Kurtosis values.

Levantine's coastal areas are characterized in general by low wave energy potential with 10-year mean of about 2 kW/m. An area of increased interest is the western coastline of Cyprus island that experiences the highest mean values (2.5 kW/m) in contrast to the northern, southern and eastern coastal sea areas of the island where the 10-year mean power values are lower than 1 kW/m (Fig. 4). This can be attributed to their exposure to the synoptic scale forcing resulting in prevailing winds from the western sector [39] which, in conjunction with the long fetch, characterizes the western coasts of Cyprus as a swell dominated area with a mean decadal wave period of approximately 5 s (Fig. 5).

A second region worth noticing is the coastal areas of Lebanon and Israel as well as the sea area of Alexandria in Egypt which have comparable available energy potential values to the western coasts of Cyprus with similar behavior regarding the statistical analysis. The wave energy potential during the 10 year period of study in this area is mostly concentrated in values lower than the mean (positive skew) with a relatively high standard deviation of ~5 kW/m and a high positive kurtosis (about 10) revealing an intense influence from infrequent deviations (Fig. 4). The relatively stable behavior of the mean and standard deviation values of wave energy (Figs. S.1 and S.2) along with the elevated decadal and annual standard deviation values reveals increased monthly variability partly attributed to the seasonality of wave energy as depicted in three representative years (Supplement 2002–2007–2009). More precisely for the period May–September a stable behavior with more frequent moderate deviations of wave energy potential is indicated. On the other hand, during the winter months (December–March) increased mean values of wave power are associated with high variability (Figs. 8, 9 and 14). April and November could be characterized as transient months. Moreover, kurtosis seems to vary significantly in an annual and monthly basis taking rather high decadal, annual, monthly values greater than 6 indicating a significant influence by extreme values (Figs. 4 and 9). The high spatial variability of kurtosis in comparison with the rest of statistical measures is also a critical characteristic of the area underlying the importance of high resolution modeling in site selection (Fig. 9).

The wave period is the most stable component of the energy equation with a behavior close to a normal distribution as seen by the small values of the main asymmetry measures under study (skewness and kurtosis values less than 1, Fig. 5). On the other hand, wave height seems to vary significantly inside the study period experiencing relatively high, compared to the mean value, standard deviation (Fig. 10). The stable interannual behavior of the mean significant wave height along with monthly variability through the years reveals a type of seasonality similar to that of wave energy (Figs. S.5 and S.6). Relatively low decadal kurtosis (~3, Fig. 10) along with small annual values (0.5–3, Fig. S.8) and significant monthly variations denote that the impact of extreme values has a seasonal character too. In general, the wave energy potential is primarily affected by the deviation of the significant wave height, a fact which is in accordance with the 2nd order relation with it, and secondary by the energy period which has a stable behavior due to the local wave climatology.

Some statistics for a number of hot spots (Fig. 13) in a power potential point of view are particularly presented in Figs. 14–17. The available power over these areas – along the coastlines of Cyprus, Lebanon and Egypt, is even five times more than the average reaching 10 kW/m during the winter months. Special emphasis should be given to the area of Eratosthenes Sea mountain which outperforms all other sites in a power potential point of view having at the same time critical advantages: is an offshore area with low bathymetry and near to the area of the EEZ of Cyprus where significant activity is taken recently for the exploitation of natural gas resources.

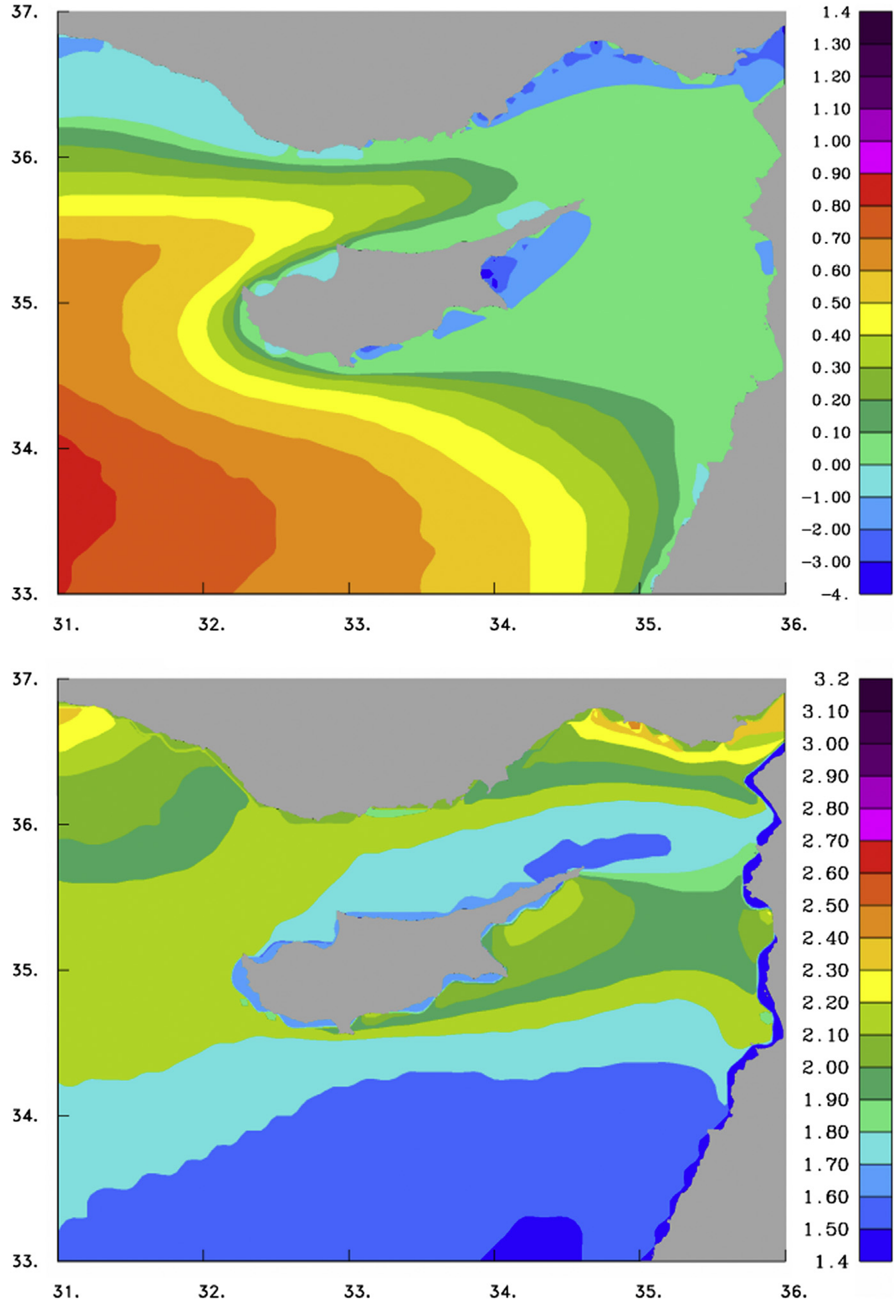

Fig. 11. The spatial distribution of the lognormal pdf parameters during the period October–March.

Similar studies for the Mediterranean Sea have been given in Ref. [61]; where an extended (44 years) atmospheric database produced in the framework of the HIPOCAS project – as described in Ref. [65] – used to perform hindcast simulations at a resolution of 25 km [52]; studied the eastern Mediterranean at a rather high resolution (12.5 × 12.5 km). On the other hand, the west Iberian coastline is studied in Ref. [62]; where the HIPOCAS database is being utilized and extended for studying shallow water regions. The wave region of Madeira Archipelagos is the target area for Ref. [63].

Compared to the above studies, the main advantages of the approach and results discussed in the present paper lie in the significantly higher resolution adopted for both the atmospheric and the wave model used which, in conjunction with the fact that all available atmospheric and remote sensing records have been assimilated into the simulation procedure, guarantying high credibility of the obtained results and analysis. Moreover, the statistical analysis performed does not remain into the standard/conventional tools but approaches the data by different points of view employing statistical indices and methodologies that reveal qualitatively and critical information. The above advantages are of special interest in the light of latest developments and activities in the area of Levantine Basin for natural gas detection and exploitation.

In this framework, the estimated power potential was, further analyzed by a probability density point of view in order to define the statistical distribution that optimally describes the data under study. In this way the full package of the statistical information is

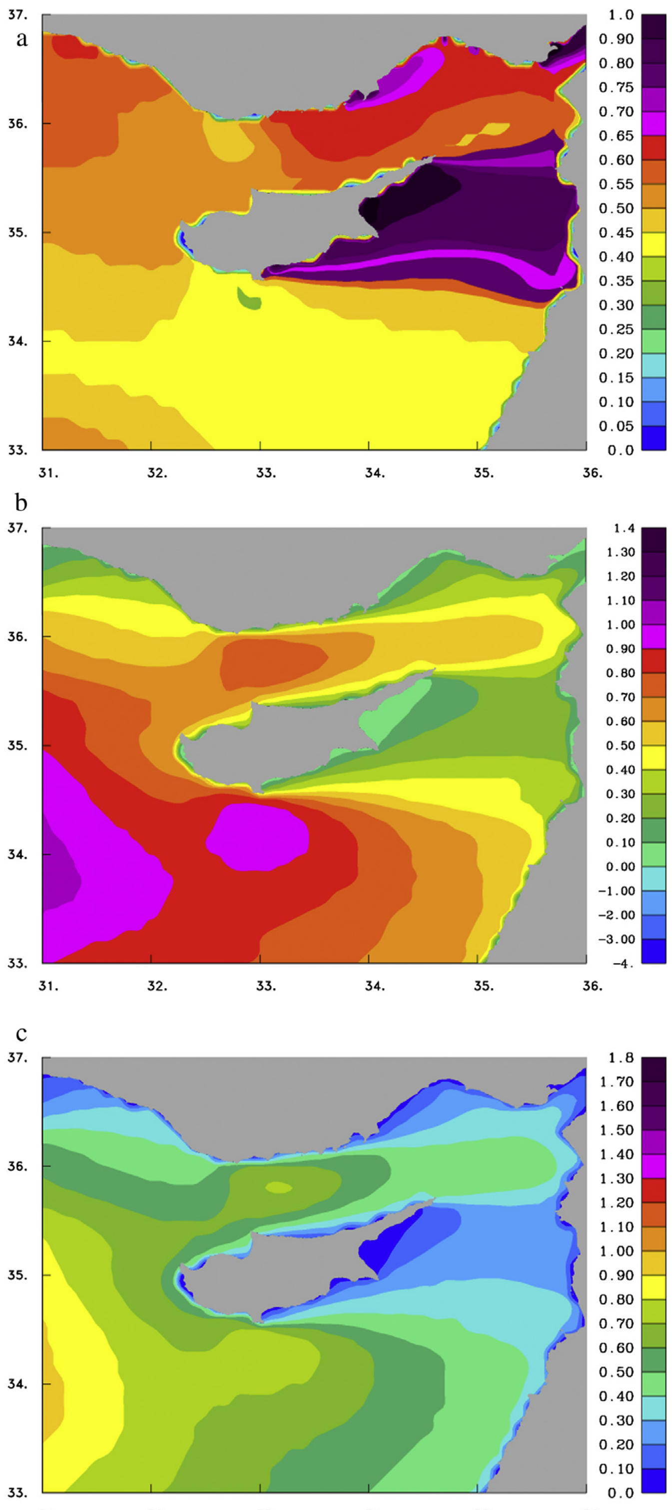

Fig. 12. The spatial distribution of the GEV pdf parameters during the period April–September 2009. (a) k parameter, (b) m parameter, (c) sigma parameter.

provided. More precisely, the following pdfs were tested: Logistic, Normal, Gamma, Log–Gamma, Log–Logistic, Lognormal, Weibull, Generalized Logistic while different statistical fitted tests were used: Kolmogorov–Smirnov, Anderson–Darling [15].

The obtained results for the “cold” period October–March indicate a clear prevalence of the lognormal distribution:

$$f(x;\mu,\sigma) = \frac{e^{-\frac{1}{2}\left(\frac{\ln x-\mu}{\sigma}\right)^2}}{x\sigma\sqrt{2\pi}}, \tag{8}$$

where the parameters μ and σ are defined by the mean value m and the variance v:

$$\mu = \log\left(\frac{m^2}{\sqrt{v+m^2}}\right), \quad \sigma = \sqrt{\log\left(\frac{v}{\sqrt{m^2+1}}\right)} \tag{9}$$

On the other hand, the Generalized Extreme Values (GEV) distribution:

$$f(x;k,\mu,\sigma) = \frac{1}{\sigma}\left(1+k\frac{x-\mu}{\sigma}\right)^{-1-\frac{1}{k}} e^{-\left(1+k\frac{x-\mu}{\sigma}\right)^{-\frac{1}{k}}} \tag{10}$$

where the μ is the location, σ the scale and k the shape parameters, prevails during the “warm” months April–September.

What is important to be underlined, is that the parameters of the optimal distribution for each case vary in space providing critical information for the wave energy potential. In Figs. 11 and 12 this spatial variation is illustrated. The western coastline of Cyprus as the area with increased mean values of wave energy is reconfirmed here. However, non-trivial values are revealed for the variation indices.

The use of the lognormal distribution for statistically modeling the wave height has been also proposed in previous works. For example Ref. [22], discusses the optimal use of a distribution to fit long-term series focusing especially on the lognormal and Weibull pdfs, Ref. [26] presents a case study for the Norwegian continental shelf, while Ref. [54] focuses on extreme wave heights. In this respect, one would expect some relation between wave energy values and lognormal distribution since wave energy is directly depended on the significant wave height. However, the later dependence has a non-linear form and is also affected by the corresponding wave period values. Therefore, the lognormal fitting to wave energy data is not a straight-forward result. The findings presented in the present study provide a more solid support.

On the other hand, the GEV distribution seems to describe well here the complete data set of wave power values and not merely the corresponding extremes. It is not our purpose in this work to study or approach the extreme values of wave heights or wave power. We analyze the total sample of wave power values which seem to be described in a satisfactory way by the GEV distribution as well. Only the potential impact of non-frequent values is studied by means of asymmetry and kurtosis measures of the total data sample again.

Based on the above results, potential end users are able to consider the appropriate version of probability density function that fits to the wave data parameters and to energy potential at the point or area of interest obtaining accurate information on the wave energy mean value, variance and uncertainty.

4. Conclusions

The wave energy potential over the Eastern Mediterranean Sea is the subject of this work focusing on the corresponding spatial and temporal distribution. Two state-of-the-art numerical models for the simulation of the atmospheric and sea state parameters have been used for a time period of 10 years (2001–2010) at a very high spatial resolution (1/60°). Available observational data by satellites and meteorological stations have been assimilated into the models leading to an integrated hindcast system. The obtained results have been analyzed based on a variety of statistical

Fig. 13. Hot-spots in a power potential point of view in the Levantine Basin.

measures monitoring their expected values, variation, asymmetry and potential impact of extreme/non-frequent values while probability density functions have been also employed for the description of wave power leading to the following main outcomes:

- The most energetic offshore areas of the Levantine Basin, in a wave energy potential point of view, are the western coastline of Cyprus, the sea area around Israel and Lebanon and the coastline of Alexandria in Egypt, characterized by relatively low 10 years mean wave energy potential of about 2.5 kW/m.
- For these areas there is a generally stable yearly behavior of wave power values which, however, are exposed to increased non-frequent values as the elevated positive kurtosis indicates.
- The significant spatial variability of kurtosis, which is an important indicator of the impact of possible extreme values, is a critical characteristic of the area revealing the importance of high resolution studies for site selection.
- The wave energy potential is well described by the 2-parameter log-normal distribution during the period October–March while the Generalized Extreme Values distribution fits better to the data during April–September. However, a non-negligible spatial distribution of the corresponding scale and shape pdf parameters is revealed.
- Wave height values over the area have a non-trivial decadal variation with increased – normalized by the mean value – kurtosis and standard deviation.

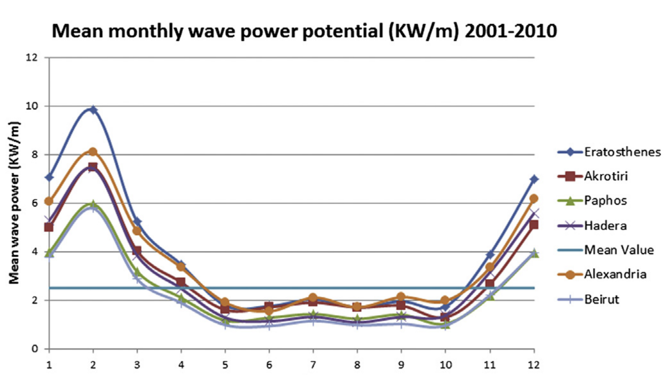

Fig. 14. Mean monthly wave power potential (kW/m) for the period 2001–2010 over different areas of the Levantine.

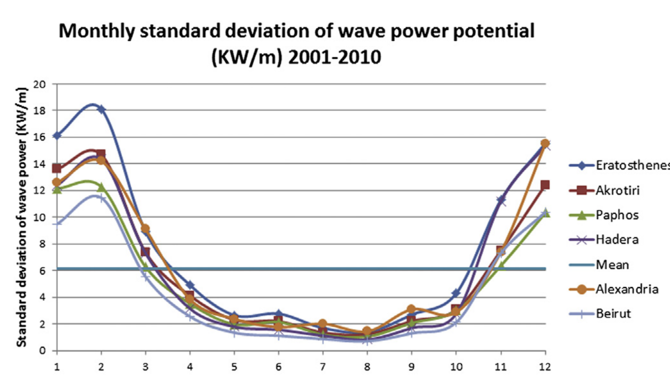

Fig. 15. Monthly standard deviation of the wave power potential (kW/m) for the period 2001–2010 over different areas of the Levantine.

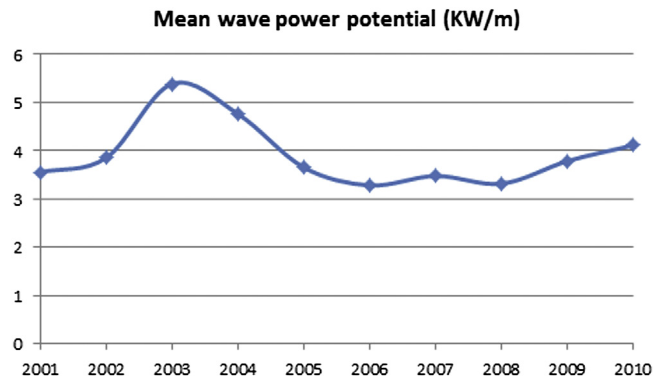

Fig. 16. Yearly mean wave power potential for the area of Eratosthenes Sea mountain.

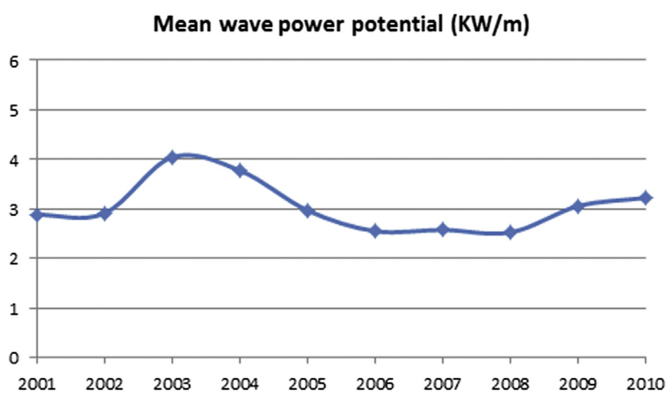

Fig. 17. Yearly mean wave power potential for the area of Paphos.

- The wave period, on the other hand, appears much more stable and normally distributed.
- The area of Eratosthenes sea mountain seems to be a point of exceptional interest with increased power potential even 500% more than the average of the Levantine Basin having at the same time critical geographical advantages.

Acknowledgments

The present work was supported by the E-WAVE project (Project Protocol Number ΤΕΧΝΟΛΟΓΙΑ/ΕΝΕΡΓ/0609(ΒΙΕ)/01) funded by the Research Promotion Foundation of the Republic of Cyprus and the European Regional Development Fund.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.renene.2014.03.051.

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