Wave Energy Evaluations in Enclosed Seas

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Abstract: - The present work has as main objective to evaluate the wave energy patterns in two enclosed seas. These are the Black and the Caspian seas. A medium term analysis of recent satellite data gives a first perspective of the wave and wind climate in the two sea basins. This allowed the identification of the areas that can be considered as most energetic. Wave prediction systems based on the third generation spectral model SWAN were implemented and validated in the two seas. A general picture on the wave conditions and the wave energy potential, in the basins of the Black and the Caspian seas is provided by the present work. The development of the wave energy devices for small amplitude waves is expected to be very dynamic in the near future. Following these tendencies, the problem of extracting this type of renewable energy in the two sea environments under consideration, most probable coupled in hybrid farms wind-waves, might become of actuality**.**

Key-Words: - enclosed seas, waves, numerical models, renewable energy

1 Introduction

Extraction of wave energy became in the last decade one of the most challenging engineering problems. Wave energy is abundant and using numerical models it can be predicted with a good accuracy in a time window of a few days. On the other hand, wave energy is not only more predictable than wind or solar energy but it has also a higher energetic density allowing extraction of more energy in smaller areas.

Various devices to extract this energy have been designed, but at this moment there is yet no technology that can be considered as being the most effective. A very important inconvenience that is usually encountered in the areas traditionally considered as having high potential in wave energy is that very often these areas are subjected to strong wave conditions that may destroy the devices operating for extracting the wave energy.

From this reason an alternative solution would be to explore the possibility of implementing the energy farms, eventually together with wind farms, in areas with smaller wave amplitudes, but where the extreme wave conditions are usually not so severe, allowing the functionality of the wave extraction systems for considerably longer time intervals.

In this respect the objective of the present work is to evaluate in parallel the wave conditions and the wave energy resources in two enclosed seas using both satellite data and results coming from a wave prediction system based on numerical models.

The Black Sea is an enclosed sea located deeply inside the continent that represents the most isolated part of the World Ocean while the Caspian Sea can be considered the largest inland body of water in the world and accounts for 40% to 44% of the total lake waters of the world.

The maximal length of the Black Sea (along the latitude 42^{o}29’N) is 1148 km, while its minimal width along the meridian from Crimea to the coast of Turkey is only 258 km. The principal characteristics of the Black Sea are: 423000 km^2 for the sea area, 555000 km^3 for its volume, and 1315 and 2258 meters for the mean and maximal depths, respectively. Three principal structures: the shelf, the continental slope, and the deep-water basin, can be clearly distinguished in the bottom topography of the sea.

The Caspian Sea extends approximately 1200 km from north to south, with an average width of 325 km east to west, covering a total area of about 400000 km^2. Most of the northern Caspian is shallow, with water depths averaging only 4 m. The central Caspian approaches depths of 800 m, while the southern Caspian has a maximum depth of slightly over 1000 meters.

The present work points to find out some preliminary answers to the question of the availability of the wave energy resources in these two seas.

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2 Analysis of Remotely Sensed Data

In the last years more accurate satellite data became available on various internet sites (as for example http://las.aviso.oceanobs.com that was the main source considered in the present work). An altimeter node gives for each day at zero hours near real time multi-mission merged non interpolated values of the significant wave height (Hs) and wind speed (Vw). These are time (for the last 48 hours) and space (for 1° squares centered in the node) averaged data sets.

As regards measuring the sea waves, the estimates are obtained using empirical models derived from analyses of the altimeter data. The algorithm used to deduce the significant wave height is based on the initial results provided in [1] with the new parametric fits indicated in [2]. For a typical significant wave height of 2 meters, the error in the sea state bias correction is approximately 1-2 cm, i.e., 0.5% to 1.0% of the effect. For measuring the wind speed, a mathematical relationship that considers the Ku-band backscatter coefficient together with the Vandemark and Chapron algorithm, as in [3]. The wind speed model function is evaluated for 10 meters above the sea surface.

In order to provide a more recent picture of the characteristics and dynamics of the most relevant parameters (Hs and Vw) concerning the wave and wind conditions in the two seas, some synthetic results coming from the analysis of the remotely sensed data, corresponding to the time interval December 2005- June 2010 are presented bellow. The monthly average of the Hs data in eight selected points (denoted with A1, A2,…A8) from the Black Sea where this parameter has greater values is illustrated in Figure 1. The second parameter analyzed is the wind speed (Vw) and its monthly average values are illustrated in Figure 2.

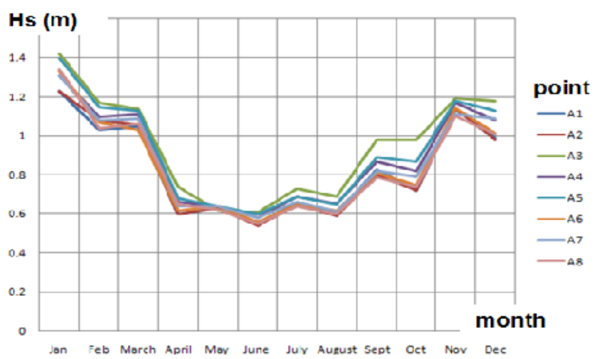

Fig.1. The Black Sea monthly averaged values of Hs in eight reference points

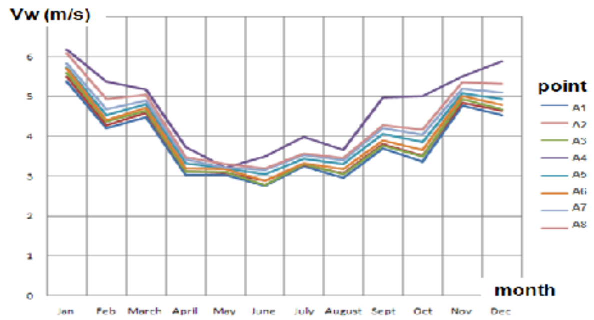

Fig. 2. The Black Sea; monthly averaged values of Vw (m/s) in eight reference points

The main statistical parameters for three most energetic points regarding the characteristics of the wave height and wind speed are presented in Table 1 and Table 2.

Table 1. The Black Sea; overall statistics for the Hs data in the in three most energetic points for the period 2005 to June 2010

Pt	Poz	Mean (m/s)	Max (m/s)	Std	Kurt	Skew
A4	36°E, 42°N	0.91	5.1	0.50	7.25	1.92
A8	38°E, 44°N	0.86	5.1	0.48	7.82	1.95
A7	36°E, 44°N	0.89	5.1	0.48	6.90	1.85

Table 2. The Black Sea; overall statistics for the Vw data in three most energetic points for the period 2005 to June 2010

Pt	Poz	Mean (m/s)	Max (m/s)	Std	Kurt	Skew
A4	36°E, 42°N	4.76	16.3	2.37	1.22	1.03
A8	38°E, 44°N	4.42	16.2	2.11	1.28	1.00
A7	36°E, 44°N	4.28	16.2	2.09	1.42	1.03

For the Caspian Sea, initial 14 reference points covering the entire basin of the sea were defined. They were denoted as P1 to P14 and they are counted from south to north. The results presented in Tables 3 and 4 show that the central part of the Caspian Sea is more energetic, especially the locations corresponding to the reference points P8, P9 and P10. The histograms for these two parameters (*Hs* and *Vw*) related to the same data set (related to the time interval December 2005- June 2010) are presented in Figure 3 and 4, respectively. The data from the histograms was structured in total and winter time respectively, where winter time is considered here the interval between the beginning of October until the end of March.

Table 3. The Caspian Sea; overall statistics for the Hs data in three most energetic reference points

Pt	Poz	Mean (m/s)	Max (m/s)	Std	Kurt	Skew
P8	51ºE, 42ºN	0.95	4.18	0.65	2.75	1.51
P9	50ºE, 42ºN	0.95	4.01	0.64	2.65	1.50
P10	49ºE, 42ºN	0.95	3.90	0.65	2.56	1.49

Table 4. The Caspian Sea; overall statistics for the Vw data in fourteen reference points

Pt	Poz	Mean (m/s)	Max (m/s)	Std	Kurt	Skew
P8	51ºE, 42ºN	5.32	17.77	2.92	0.24	0.73
P9	50ºE, 42ºN	5.31	17.43	2.92	0.23	0.73
P10	49ºE, 42ºN	5.33	17.19	2.93	0.20	0.72

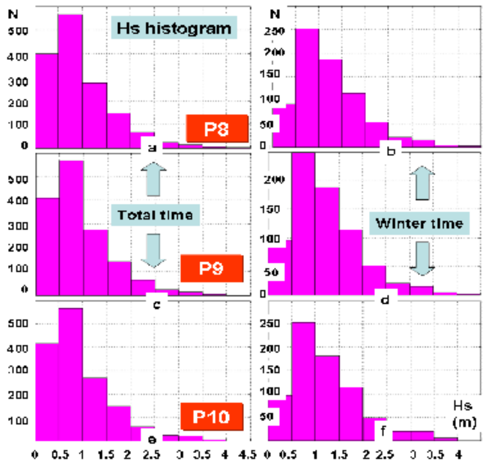

Fig. 3. Satellite data, H_s histograms for the reference points P8, P9 and P10. Daily records for the time interval December 2005 - June 2010; a), c) and e) total time, b), d) and f) winter time.

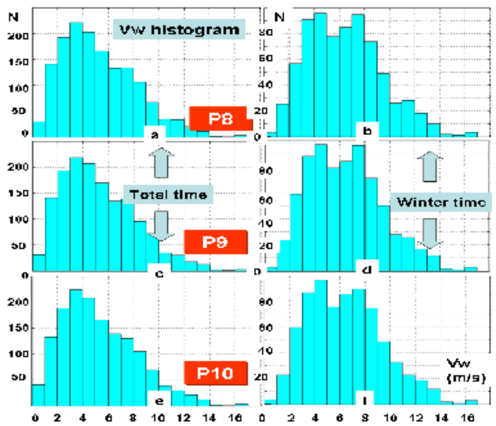

Fig. 4. Satellite data, Vw histograms for the reference points P8, P9 and P10. Daily records for the time interval December 2005 - June 2010; a), c) and e) total time, b), d) and f) winter time

2 Implementation of the Wave Model

A wave prediction system based on the SWAN model was implemented and evaluated separately in each sea. As regards the Black Sea basin, validation tests were previously performed against buoy data as presented in [4, 5]. Further validations of the above modeling system were performed also in [6] and the above system was used to provide the support in the case of the environmental alerts and to assess the wave-current interactions at the mouths of the Danube [7, 8].

Some results concerning the implementation in the Caspian Sea of a wave modeling system SWAN based are presented bellow. The system origin corresponds to the lower left corner point and has the coordinates (46.7°E, 36.2°N), where as the lengths are 8° in x-direction (longitude) and 11.2° in y-direction (latitude). The computations were performed in the non stationary mode with a 5 minutes time step. For the three points that were found as the most energetic in the Caspian Sea (P8, P9 and P10) Figure 5 illustrates direct comparisons for Hs, SWAN results against remotely sensed data, while Figure 6 (a, c and e) presents the Hs scatter plots for the same three locations.

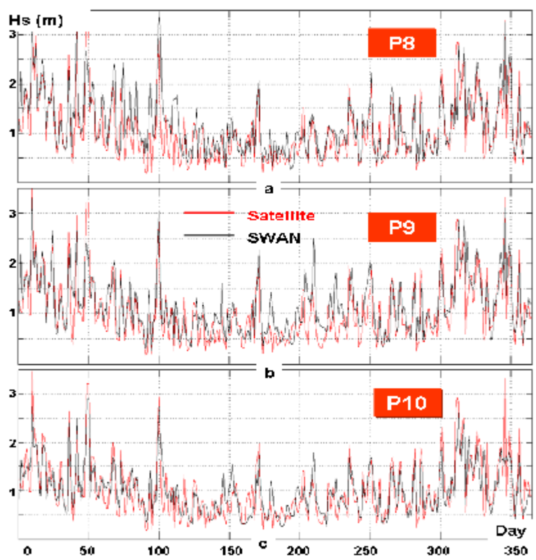

Fig. 5. The Caspian Sea; Hs direct comparisons, SWAN results against satellite data for the entire year 2009. a) Reference point 8; b) Reference point 9; c) Reference point 10.

Since the accuracy of the input wind field represent a fundamental issue in obtaining better results in wave modeling, Table 5 presents also the statistical analysis for Vw (ECWMF model wind against the corresponding remotely sensed data) at the same five locations (for the reference points P4, P8, P9,

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P10 and P12) and Figure 6 (b, d and f) presents the Vw scatter plots for the points P8, P9 and P10.

Table 5. The Caspian Sea; wave and wind statistics, remotely sensed data against SWAN and wind model outputs. Results in five reference points for: a) *Hs* statistics; b) *Vw* statistics.

Pt	X_m	Y_m	bias	rmse	si	r
a) Hs (m)						
P4	0.91	1.04	-0.13	0.37	0.41	0.79
P8	1.03	1.18	-0.14	0.39	0.37	0.83
P9	1.04	1.16	-0.12	0.38	0.37	0.81
P10	1.01	1.02	-0.01	0.34	0.34	0.82
P12	0.60	0.44	0.16	0.33	0.55	0.77
b) Vw (m/s)						
P4	4.49	4.37	0.12	1.26	0.28	0.83
P8	5.33	5.60	-0.27	1.40	0.26	0.86
P9	5.29	5.26	0.03	1.28	0.24	0.88
P10	5.20	4.83	0.37	1.29	0.25	0.89
P12	5.08	5.44	-0.36	1.28	0.25	0.90

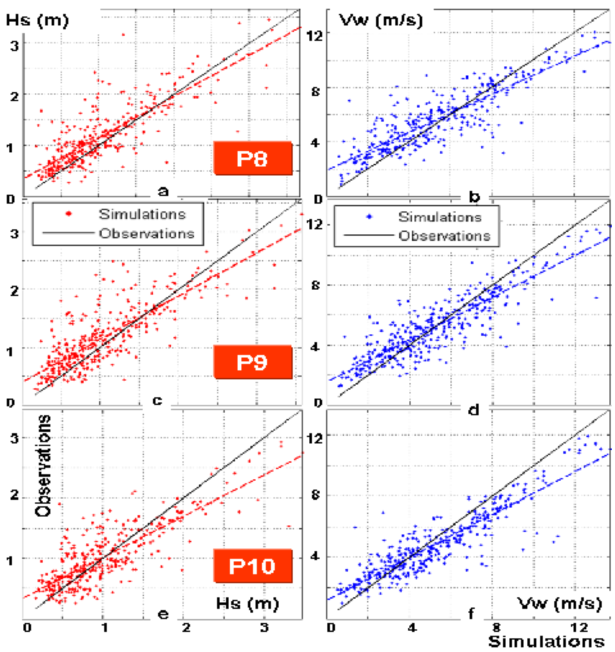

Fig. 6. The Caspian Sea; Scatter plots for the parameters Hs and Vw model (wave and wind) against satellite data for the entire year 2009, coresponding for the points P8, P9 and P10.

4 Evaluation of two Case Studies

Using the wave modeling systems implemented in the two seas, two case studies will be considered for each sea to evaluate and analyze the most relevant patterns concerning the spatial distribution of the wave energy.

In SWAN, the energy transport components (expressed in W/m, i.e., energy transport per unit length of wave front), are computed with the relationships:

$$E_{TR\,x} = \rho g \iint c_x E(\sigma,\theta) d\sigma\, d\theta$$
$$E_{TR\,y} = \rho g \iint c_y E(\sigma,\theta) d\sigma\, d\theta, \qquad (1)$$

where: x, y are the problem coordinate system (for the spherical coordinates x axis corresponds to longitude and y axis to latitude), $E(\sigma,\theta)$ the wave energy spectrum, σ the relative wave frequency, θ the wave direction and c_x, c_y are the propagation velocities of the wave energy in the geographical space defined as:

$$\frac{d\vec{x}}{dt} = (c_x, c_y) = \vec{c}_g + \vec{U}. \qquad (2)$$

Hence the absolute value of the energy transport (denoted also as wave power) will be:

$$E_{TR} = \sqrt{E_{TRx}^2 + E_{TRy}^2}. \qquad (3)$$

The non dimensional normalized wave power is expressed as:

$$E_{TR\,n} = \frac{E_{TR}}{E_{TR\,\max}}. \qquad (4)$$

In the present work E_{TRmax} was defined separately for each individual case study. This is a round off value approximated the maximum value corresponding to the computational domain.

4.1 Black Sea, Case study 1 – 1997/01/12/h12

This case study, denoted as BS1, provides an average energy distribution for the entire Black Sea basin and is illustrated in Figure 7. This figure shows the normalized wave power in background and the energy transport vectors (in kW/m of wave front) in the foreground. The locations, for this computational domain, of the maximum values of

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the wave power are marked with circles. For this case study the value of E_{TRmax} was set at 20 kW/m. Although there is an obvious relationship between significant wave height and wave power, the energetic peak in a computational domain is not necessarily located at the same point as in the present case.

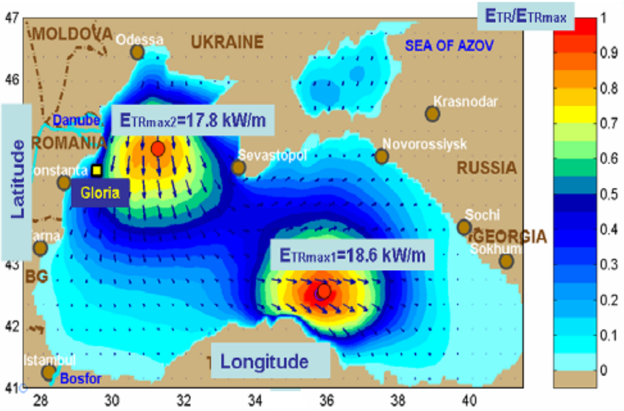

Fig. 7. The Black Sea, Case study 1-1997/01/12/h12, average energetic situation, representation for the entire Black Sea.

4.2 Black Sea, Case study 2 - 1997/01/21/h18

This second case study presents some storm conditions in the Black Sea (BS2) and is illustrated in Figure 8. It should be noted that this is not an extreme event, but a regular storm (a typical storm when the western part of the Black Sea is more energetic due to the dominant wind patterns). For this case the value of $E_{TR\ max}$ was set at 150 kW/m.

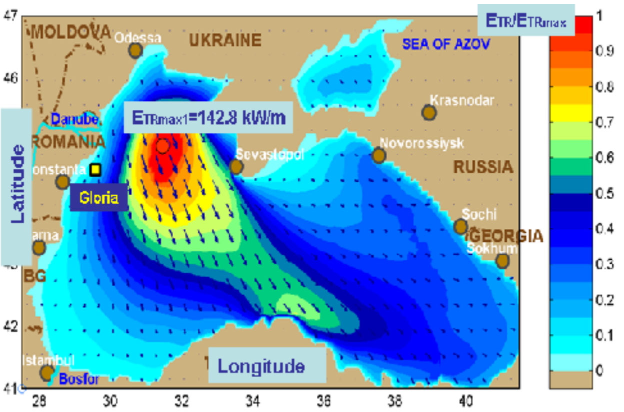

Fig. 8. The Black Sea, Case study 2-1997/01/12/h12, average energetic situation, representation for the entire Black Sea basin

4.3 Caspian Sea, Case study 1-2009/10/02/h18

The first case study in the Caspian Sea, denoted as CS1, reflects wave conditions with average energy (for the winter time period) in the Caspian basin.

The background of Figure 9a shows the normalized wave power (E_{TR}/E_{TRmax}) for CS1 and the foreground shows energy transport vectors (represented with red arrows in kilowatts per meter of wave front). The location in the computational domain of the maximum value for the wave power is marked with a red circle. For the present case study the value of $E_{TR\ max}$ was set to 20 kW/m while the maximum wave energy in the sea was 22.4 kW/m.

4.3 Caspian Sea, Case study 2-2009/11/27/h03

The second case study considered in the Caspian Sea, denoted as CS2, reflects one of the highest energetic conditions that were encountered in the central part of the Caspian Sea for the entire five-year period analyzed (the time interval December 2005 - June 2010). Thus, although it cannot be considered as an extreme event this situation can give a good perspective on the highest energetic conditions that can be expected in the basin of the Caspian Sea.

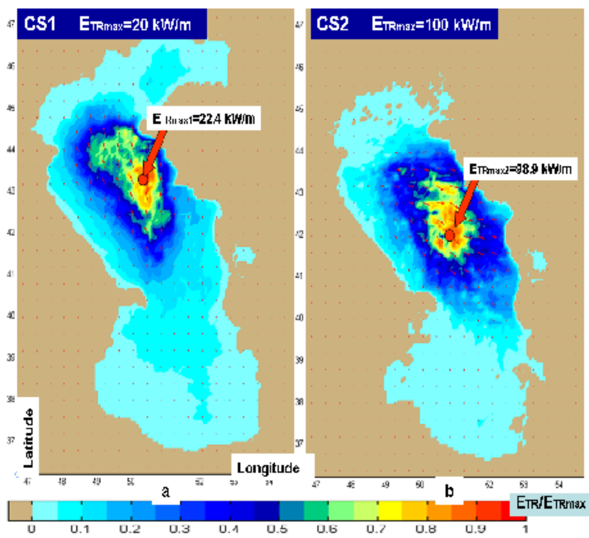

Fig. 9. The Caspian Sea; a) Case study 1-2009/10/02/h18, average energetic situation, b) Case study 2- 2009/11/27/h03, high energy conditions.

Figure 9b shows in background the normalized wave power (E_{TR}/E_{TRmax}) and in foreground the energy transport vectors (represented with red arrows in kilowatts per meter of wave front). The location in the computational domain of the maximum value for the wave power is marked with a red circle. For the present situation the value of $E_{TR\ max}$ was set to100 kW/m while the maximum wave energy in the sea was 98.9 kW/m.

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4 Discussion of the Results

At this point, a discussion will be employed in relationship with the accuracy of the results provided by the wave prediction system that was implemented herewith. A comparison of these wave predictions with some results obtained in similar environments (semi-enclosed or enclosed seas) coming also from SWAN model simulations will be made first.

On reference [9] was evaluated a SWAN based wave forecasting system in the Adriatic Sea forced with ALADIN wind model (acronym from AROME Limited Area Decentralized International Network). For *Hs* nowcast against buoy data *S.I.* was in general between 0.22-0.3 and *r* about 0.9, the accuracy of the results decreasing in the case of the forecast products.

Nevertheless for the case of the wave hindcast against altimeter data the same system provided *Hs* results with lower accuracy (*S.I.* about 0.32-0.34 and *r* about 0.72-78). The accuracy of the wind velocity was also evaluated against satellite measurements and there resulted *S.I.* about 0.34-36 and *r* about 0.78-79.

In the Black Sea using ECMWF wind to force SWAN, given in [5] was performed a hindcast study for *Hs* against buoy data *RMSE* in the interval 0.32-0.36, *S.I.* 0.36-0.42 and *r* 0.78-0.88. Against satellite data the same prediction system provided *RMSE* 0.37-0.4, *S.I.* 0.31- 0.34 and *r* 0.77-0.8, as in [8].

Looking at the results presented in Table 5 and Figure 6 (a, c and e) it can be noticed that from a statistical point of view the estimations provided by the wave prediction system implemented in the Caspian Sea are compatible with those coming from similar systems in the Adriatic Sea or the Black Sea. Thus *RMSE* has values between 0.33-0.39, *S.I.* between 0.34-0.41 and *r* about 0.79-0.83.

An exception is related with the reference point P12 that is located in the north. The lower accuracy concerning *S.I.* (0.55) and *r* (0.77) in the conditions when the wind accuracy is even better in that region than in other parts of the Caspian Sea (*S.I.*=0.25 and *r*=0.90 for *Vw*) are probably related with the fact that the entire northern region of the Caspian Sea is characterized by very shallow water (about 4 m depth). Thus some process as triad wave-wave interactions, bottom friction, diffraction, breaking, etc, that were not accounted in the global simulations may become rather relevant in this area. A solution to improve the model predictions in the north of the Caspian Sea would be to define a higher resolution computational domain, nested in the area that covers the entire basin, which would cover the northern sector of the sea and where the main shallow water processes available in SWAN would be also activated (performing eventually a calibration process).

In relationship with some other factors that may improve the performances of such a wave prediction system based on spectral phase averaged models, on the first place should be probably considered the quality of the wind fields. Many studies have been performed on the effects of the wind fields when modeling waves in enclosed, semi-enclosed or relatively small basins, as for example in [10, 11]. The most obvious conclusion would be that the accuracy of the results provided by the wave models is highly dependent on the accuracy of the meteorological models that were used to force them.

The most obvious conclusion would be that the accuracy of the results provided by the wave models is highly dependent on the accuracy of the meteorological models that were used to force them.

5 Concluding Remarks

The results presented in this work concerning the evaluation of the wave energy potential in the Black and the Caspian seas will be discussed in this final section in parallel with data from another area that is considered among the coastal environments richest in wave energy resources. This is the Iberian coastal environment in relationship with which in depth analyses concerning the spatial distributions of the wave energy were carried out in [12, 13]. Thus for the case of average energetic conditions the maximum values encountered for the wave power were between 50 and 100 kW/m, in the Iberian coastal environment, between 20 and 50 kW/m in the Black Sea while a little over 20 kW/m for the Caspian Sea. As regards the highest energetic conditions in the three environments considered the differences are even more significant. Thus in the Iberian near-shore the maximum wave power was sometimes, even greater than 600 kW/m, in the Black Sea, was around 300 kW/m, while in the Caspian Sea less than 100 kW/m.

Finally, it should be also highlighted that in the perspective of the development of the wave energy devices for small amplitude waves that is expected to be quite dynamic in the near future bringing also some technological breakthroughs, and most probable coupled in mixed farms wind-waves, the problem of extracting this type of renewable energy in the Black and the Caspian Seas might become of actuality.

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