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Analyzing of Wave Energy Resources in Gulf of Cadiz - Spain

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Abstract: Wave energy appears to be one of the most promising sources of the renewable energy. The research on wave energy resource assessment is particularly advanced in countries which have seashores, where access to the wave energy potential is possible. For this reason, this paper presents an assessment of wave resource characterization and wave energy potential in Gulf of Cadiz in Spain, using two different data namely, the measured data of buoy and numerical modeling data of ocean wave model (WAM). The available used data are gathered from the Spanish Port Authority for a period of twelve years (2005-2016). The annual average wave power (AAWP) was found 4.948 kW/m for the buoy, which is equivalent of 43.35 MWh/m. For the modeling data the AAWP was found 4.665 kW/m, which is equivalent to 40.87 MWh/m. These results confirming the slight under-prediction of (5.7%). The numerical simulations data were compared with those measured at the buoy for each month, during the twelve year to test their accuracy, based on common statistical indicators for performance for both the average significant wave height and average wave energy period. Their results showed a fairly good match results with them and the numerical modeling found can be an alternative model which provides more accurate and efficient wave characteristics for evaluation the wave energy conversion in this area.

Keywords: Wave Resource Characterization, Wave Power, Wave Energy, Numerical Modeling

1. Introduction

Ocean waves are the most powerful forces of the renewable energy which generate a clean energy and appear to be one of the most promising alternatives to fossil fuels. Even though almost 75% of the Earth's surface is covered with water, waves are a largely unexplored energy source and hold a lot of energy within their movement, also are able to harness an important energy to generate electricity. Therefore, harvesting wave energy seems very promising because of the very large potential resource located near many coastlines [1]. In recent years, many researches haves been focused on assessing the potential of wave energy resource. Gleizon et al [2] realized a study about wave energy resources along the European Atlantic coast, which presents a joint effort by several European countries, including Spain, France, UK, Portugal and Ireland, to estimate the potential of wave energy resource along the European Atlantic coast. Wave parameters are generally either directly measured, through established in situ measurement devices, or through backscatter and Doppler shifts by radar and satellites. While, the most common direct measurement of wave parameters is achieved by the deployment of in situ wave measurement devices such as the moored wave buoys and seafloor-mounted acoustic measurement [3]. In this study, the wave energy resource in Gulf of Cadiz is characterized based on a long-term numerical modeling data set computed by the WAM ocean wave model [4]. The assessment of wave energy resources is critical for a given site before deploying wave energy converters (WECs). From the obtained results, the averaged wave energy has been found 43.34 MWh/m. Considering the potential of Gulf of Cadiz, wave energy could be a good alternative factor to reduce the dependence of Spain on fossil fuels, especially in the area of Andalusia, and to contribute to reduce greenhouse gas emissions.

This paper focuses on the assessment of wave power resource around Gulf of Cadiz, Spain. The rest of this article is structured as follows: The study area, the available data and the methodology used are presented in Section 2. Section 3 shows monthly, seasonal and yearly assessment of wave energy resource during the period of measurement. Finally, the conclusions are drawn in Section 4.

2. Data and Methods

2.1. Study area

The studied area Gulf of Cádiz is located in the north-eastern Atlantic Ocean between Latitude 36.49°N and Longitude 6.96°W. It is enclosed by the southern Iberian and northern Moroccan margins, west of Gibraltar Strait (Figure 1). The Gulf of Cádiz is the arm of the Atlantic Ocean between Cabo de Santa Maria, the southernmost point of Mainland Portugal and Cape Trafalgar at the western end of the Strait of Gibraltar.

Figure 1. *Location of used buoy and its numerical modeling at Gulf of Cadiz.*

2.2. Available wave data

This paper is based about two sources of data available for Golf of Cadiz at twelve years covering the period (2005-2016) generated by the Spanish Port Authority. The first wave data set was obtained from the buoys (REDEXT) using by Seawatch placed at 200m of depth. Its data set is made up of the measurements from the deep water. The second wave data set was obtained using the WAM numerical model in order to generate the wave fields [4]. This application is a third-generation spectral model that solves the energy balance equation without establishing any a priori hypotheses about the shape of the wave spectrum [5]. The data has been generated with an hourly rate (1h) with a spatial resolution of 1 'longitude x 1' latitude. There has been decomposition of sea of wind and sea bottom. In order to describe situations with cross-bottomed seas, consideration has been given to two bottom-sea contributions. Figure 2 gives the hourly average significant wave height variation (H_s) using the numerical modeling data at Gulf of Cadiz during period of (2005-2016) [6]. The two databases are in the same location and also in the same period of measurement. Further that, the data of buoy is used in this paper to validate the numerical wave data used by the WAM model.

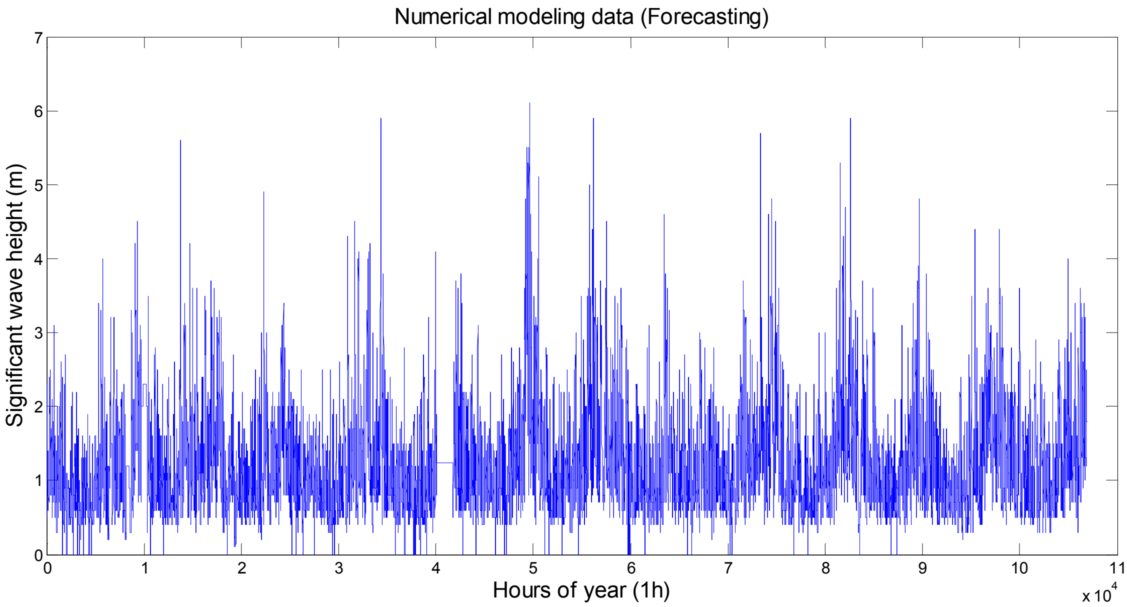

Figure 2. *Hourly average significant wave height variation at Gulf of Cadiz during period (2005-2016).*

2.3. Methodology

The main aim of this study is the analysis of wave resource characterization and assessment using field measurements and data obtained from the numerical modeling. The most important statistical measure of random waves is the significant wave height (H_s), traditionally defined as the average height of the highest third of waves. Therefore, the wave power P, expressed the number of kilowatts per meter of wave front, can be obtained as follow:

$$P = \frac{\rho . g^2}{64\pi} H_s T_e = 0.49 H_s{}^2 T_e \quad (1)$$

The power depends on 4 parameters: density of seawater ρ (1025 kg/m^3), gravitation acceleration (g), significant wave height (Hs) and its energy period (Te), where Te is computed as a function of spectral moments:

$$T_e = \frac{m_{-1}}{m_0} \quad (2)$$

The gathered dataset used in this study does not provide information on spectral moments or spectral shape, and sea states are specified in terms of significant wave height H_s and peak period Tp Therefore, when Tp is known, the energy period Te can be estimated from the following variable approach [7]:

$$T_e = \alpha . \mathrm{T}_p \quad (3)$$

Where α is a coefficient whose value depends on the shape of the wave spectrum (0.86 for a Pierson & Moskowitz spectrum and increasing towards unity with decreasing spectral width) [8]. Taking into account that wave spectra in this area, the predominance of the wind-sea waves together with mixed sea states [9]. A conservative value of $T_e = 0.9\mathrm{T}_p$ was used to evaluate the wave energy resource in a given area.

The wave energy resource at a point (average power wave) can be assessed by using Eqs. (1) and (3). As mentioned above, this assessment of wave energy resources uses available numerical simulations data (forecast), from a period of twelve years. Therefore, in order to assess the performance of wave resource characteristic and to know the accuracy of the forecasting data, we have been compared these data (forecasting) with the data measured at the buoy. Different statistical approaches including three reliable statistical indicators have been used in this study, consisting the relative mean absolute error (RMAE), determination coefficient (R^2) and root mean square error (RMSE) have been applied to offer an appropriate comparative assessment, were computed for both significant wave height (SWH) and wave energy period (WEP). The formulae of the mentioned performance selection criteria are summarized in the following sections. The relative mean absolute error (RMAE) is used to examine the goodness of fit of an observed and a forecasted data. It is expressed as follows:

$$RMSE_{SWH} = \left\langle \frac{|H_m - H_b|}{H_b} \right\rangle \quad (4)$$

$$RMSE_{WEP} = \left\langle \frac{|T_m - T_b|}{T_b} \right\rangle \quad (5)$$

Where H_m and H_b are, respectively the significant wave height of the numerical model and of measured at the buoy. T_m and T_b are, respectively, the energy period given by the numerical model and measured at the buoy.

The determination coefficient (R^2) indicates the accuracy of the obtained regression fit. This parameter which shows how much the model is able to describe data should be close to 1. Its expression is given by [10]:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (X_i - Y_i)^2}{\sum_{i=1}^{n} (Y_i - \overline{Y})^2} \quad (6)$$

Where n is the size of the sample corresponding to the total number of observations, Yi is the buoy data (measured), X_i the value of numerical modeling data (forecast), while Y designates the mean value.

The RMSE gives a measure of the error existing between the measured values and forecasted data. Small values of the RMSE indicate that the regression fit is acceptable. This parameter is expressed as [11]:

$$RMSE = \sqrt{\sum_{i=1}^{n} (Y_i - X_i)^2 / n} \quad (7)$$

The RMAE value obtained is 0.1030 for the significant wave height and 0.1579 for the wave period. While, the determination coefficient (R^2) value has been found such as, 0.9127 of significant wave height and 0.8018 the wave period. The RMSE values obtained for the significant wave height and wave period are 0.1014 and 0.1456 respectively. Consequently, according the obtained results all values found are good.

The temporal variability at different time scales (monthly, seasonal and yearly) is an important factor must taking into account in order to select a site for wave energy converter (WEC). For this reason, two parameters have been proposed to describe the temporal variability in wave power at Gulf of Cadiz namely, the seasonal variability index (SV) and the monthly variability index (MV) which are expressed as follows [12]:

$$SV = \frac{P_{S1} - P_{S2}}{P_{Year}} \quad (8)$$

Where P_{S1} is the average wave power for the highest season of power energy (usually winter) and P_{S2} is the average wave power for the lowest season of power energy (usually summer), and P_{Year} is the annual average wave power. The greater the value of SV the larger the seasonal variability, with values lower than 1 indicating moderate seasonal variability.

$$MV = \frac{P_{M1} - P_{M2}}{P_{Year}} \tag{9}$$

Where P_{M1} is the average wave power for the highest month of power energy and P_{M2} is the average wave power for the lowest month of power energy.

3. Results and Discussion

3.1. Monthly, Seasonal and Yearly Analysis of Wave Energy Resource

This subsection provides the results of wave energy resource characterization for each temporal variability period (month, season and year). Figure 3 shows the average monthly wave power computed for the both data, at the buoy and by the numerical model (WAM). According the graph, we observed that the wave power starts to increase in end of August, reaching its peak in February, decreasing from the end of February and hitting its minimum in August. Also, we see that the average wave power given by the numerical model is lower than that measured at the buoy for all months. Moreover, the forecasted data by WAM model yield very close results with data of buoy. Table 1 and 2 show the characteristics of wave resources analysis at Gulf of Cadiz area such as, the average significant wave height, mean wave energy period and the average wave power, respectively for monthly, seasonal and yearly temporal variability period. About 40% of the averaged significant wave height (H_s) is concentrated between 0.75 and 1 m. Figure 4 illustrates the frequency distribution of the significant wave height at the numerical modeling data of (WAM) model.

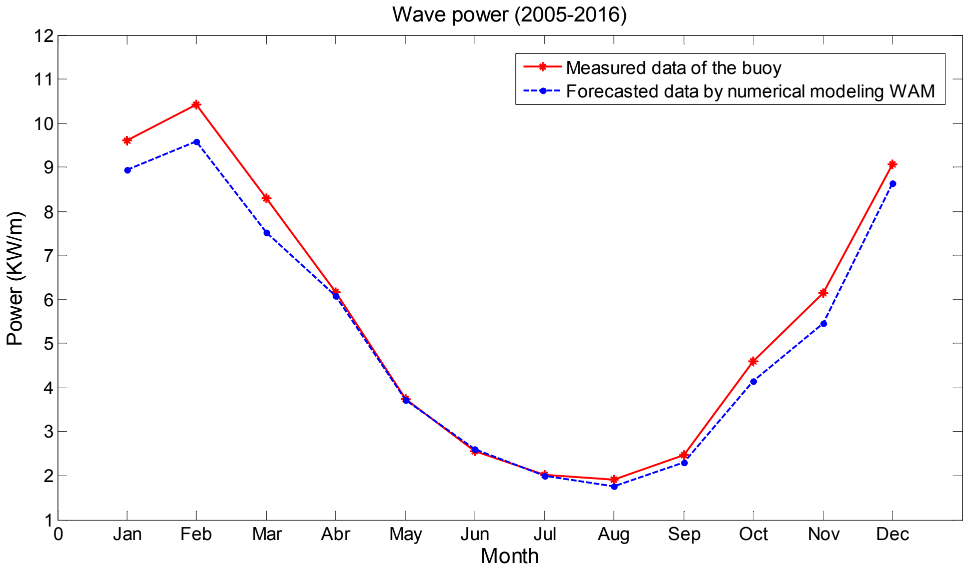

Figure 3. *Monthly average wave power for both given data (Buoy & Model).*

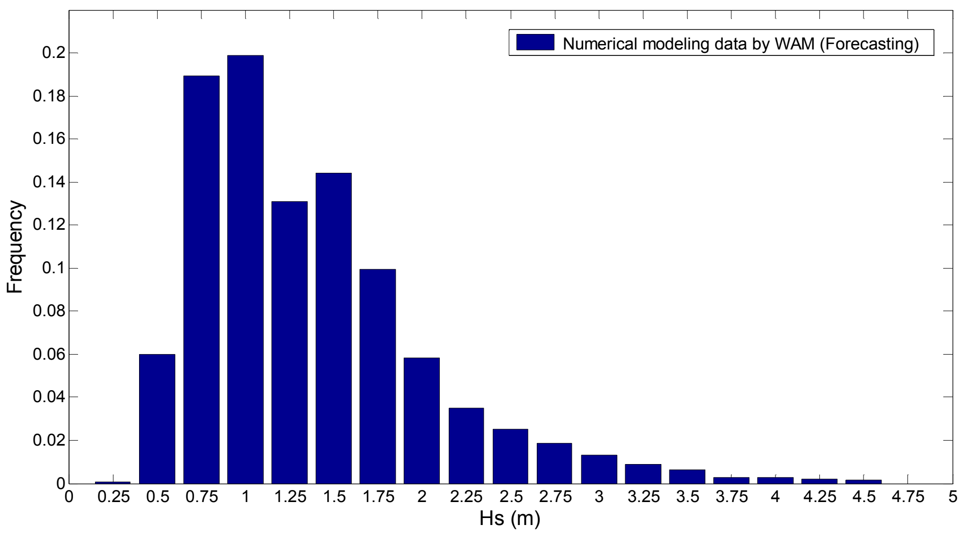

Figure 4. *Frequency distribution of the wave height for all modeling data (Forecasting).*

As results, the highest average wave power value for all forecasting period was found to be in February, while the lowest value was encountered in August. Which is equivalent on average between wave powers in February is 5.42 times of wave power that of August. Moreover, the average wave power reached its maximum values in the winter season, whereas wave power arrives to its lowest values in the summer season. Which is equivalent on average between wave powers in winter is 4.28 times of wave power that of summer. In addition of that, the highest average wave power value was found to be in 2010, while the lowest value was encountered in 2008. On average, average wave power in 2010 is 1.71 times that of 2008.

Table 1. *Monthly and seasonal characteristics of wave power resources (it significant wave height and it wave period) during the period (2005-2016).*

	Measured data (Buoy)			Forecasted data (Model)		
Month	**Hs (m)**	**Te (s)**	**P (KW/m)**	**Hs (m)**	**Te (s)**	**P (KW/m)**
January	1.541	8.245	9.614	1.526	7.808	8.928
February	1.599	8.308	10.43	1.578	7.842	9.589
March	1.467	7.849	8.294	1.444	7.342	7.517
April	1.363	6.756	6.163	1.389	6.42	6.082
May	1.149	5.775	3.744	1.175	5.496	3.726
June	0.959	5.661	2.557	0.994	5.348	2.6
July	0.908	4.985	2.019	0.922	4.792	2.001
August	0.871	5.133	1.913	0.86	4.865	1.767
September	0.912	6.067	2.478	0.911	5.66	2.307
October	1.166	6.882	4.595	1.144	6.45	4.145
November	1.355	6.82	6.149	1.313	6.455	5.465
December	1.556	7.631	9.072	1.556	7.272	8.646
Spring	1.312	6.701	5.664	1.324	6.34	5.458
Summer	0.915	5.252	2.16	0.931	5.011	2.133
Autumn	1.153	6.612	4.317	1.13	6.207	3.892
Winter	1.573	8.032	9.759	1.562	7.624	9.134

Table 2. *Yearly characteristics of wave power resources (it significant wave height and it wave period) during the period (2005-2016).*

	Measured data (Buoy)			Forecasted data (Model)		
Years	**Hs (m)**	**Te (s)**	**P (KW/m)**	**Hs (m)**	**Te (s)**	**P (KW/m)**
2005	1.328	6.193	5.363	1.296	5.91	4.874
2006	1.196	6.745	4.738	1.207	6.45	4.614
2007	1.08	6.714	3.846	1.079	6.33	3.621
2008	1.184	5.933	4.084	1.133	5.55	3.499
2009	1.305	6.225	5.206	1.3	5.99	4.968
2010	1.379	6.743	6.297	1.378	6.4	5.968
2011	1.254	6.795	5.247	1.268	6.46	5.1
2012	1.114	6.986	4.257	1.189	6.57	4.562
2013	1.287	6.65	5.409	1.272	6.26	4.975
2014	1.269	6.844	5.412	1.265	6.4	5.026
2015	1.118	6.609	4.057	1.106	6.22	3.737
2016	1.32	7.253	6.206	1.326	6.85	5.91
Whole	1.234	6.617	4.948	1.232	6.26	4.665

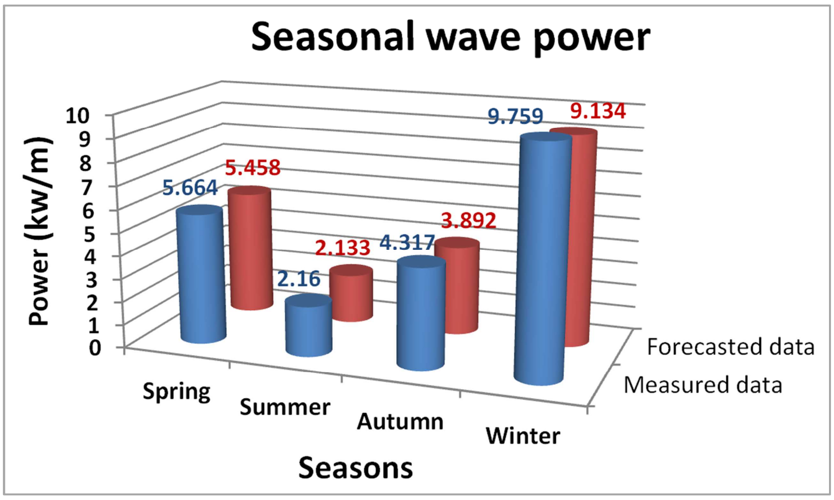

Figure 5. *Seasonal average wave power at Gulf of Cadiz.*

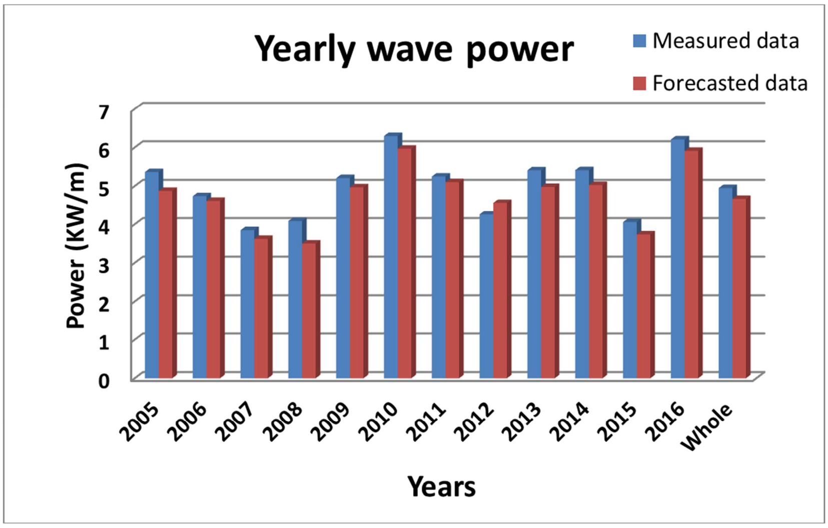

Figure 6. *Annual average wave power at Gulf of Cadiz.*

Figures 5 and 6 show respectively the seasonal and annual average wave power, which is representative of the power energy level in Gulf of Cadiz. From the obtained results we had found that the winter is the highest season for both data in term of the wave power with the values of 9.759 KW/m and 9.134 KW/m for measured and forecasted data respectively. While, the lowest season was found in summer for both using data, with the values of 2.16 KW/m and 2.133 KW/m respectively for measured and forecasted data. From the yearly results, the highest values of wave power were found in 2010 for both data (measured and forecasted), which are respectively 6.297 KW/m and 5.968 KW/m. Whereas, the lowest values were found in 2007 for the measured data with the averaged value is 3.846 KW/m, and for the forecasted data the lowest values were shown in 200, with the averaged value is 3.499 KW/m.

3.2. Statistical Indicators Used for Performance Evaluation of Numerical Modeling Data

After applying equations (6) to (10), the wave energy resource at Gulf of Cadiz can be assessed. Table 3 gives the obtained performance indicator values for the monthly regressions for numerical modeling data using by WAM model. Moreover, it indicates that the coefficient of determination R^2 is sufficiently high. The value of this coefficient for the whole year forecasting data is 0.91270 for the significant wave height and 0.80185 for average wave period. The obtained RMAE and RMSE are 0.10309 and 0.10141, respectively, for significant wave height (H_s). While those obtained for average wave period (T_e) are 0.14799 and 0.14568, respectively.

Table 3. *Performance selection criteria of wave power resource at Gulf of Cadiz.*

Parameters	Hs (m)			Te (s)		
Indicators	**RMAE**	**R²**	**RMSE**	**RMAE**	**R²**	**RMSE**
January	0.07583	0.97671	0.07582	0.14111	0.87479	0.14109
February	0.09890	0.93393	0.09890	0.15376	0.75099	0.15376
March	0.10729	0.83435	0.10729	0.15497	0.81945	0.15497
April	0.09430	0.84250	0.09430	0.15557	0.80838	0.15557
May	0.12432	0.93703	0.12432	0.15578	0.88049	0.15578
June	0.10897	0.92588	0.10007	0.15733	0.74418	0.10723
July	0.10468	0.82670	0.10468	0.15047	0.79119	0.16047
August	0.10756	0.90643	0.10756	0.16473	0.77799	0.16473
September	0.08449	0.97582	0.08449	0.15107	0.80395	0.15107
October	0.11072	0.87120	0.11072	0.15884	0.79683	0.15884
November	0.13056	0.79056	0.11675	0.17622	0.77622	0.14699
December	0.07631	0.96840	0.07631	0.14569	0.82314	0.14568
Whole	0.10309	0.91270	0.10141	0.14799	0.80185	0.14568

These results show the high reliability between the two data used in this study (measurement data of the boy and forecasted data by numerical WAM model). The adjustments as given by RMAE and RMSE indicators are small and remain also acceptable.

4. Conclusion

This study provides a statistical analysis to assess the wave resource characteristics and wave energy potential in Gulf of

Cadiz, using two different available data, one of the buoy data and the other from the numerical modeling data of WAM model. These data are extracted from the Spanish Port Authority for a period of twelve years (2005-2016). The Monthly, seasonal and yearly analysis of wave power resource were calculated. The main results of this study are presented as follows:

a. The wave energy in the Gulf of Cadiz area has an average power up to 4.948 kW/m for the buoy data, which is equivalent on total annual energy about 43.35 MWh/m. Moreover, for the numerical modeling data was found to be 4.665 kW/m, which is equivalent to 40.87 MWh/m on total annual energy.
b. The temporal variability in term of wave energy resource shows great variability and a clear seasonal pattern. Because, about 44.56% of Gulf of Cadiz's annual wave power corresponds to winter, 9.86% to summer, 19.71% to autumn, and 25.86% to spring. So we can say that almost half of the wave potential is found in winter season. There is also significant monthly variability, with February being the highest energy month and August the mildest one for both used data (Measured and forecasted).
c. The average wave power obtained from the numerical modeling data are considerably lower than the values obtained by buoy data for the whole measurement period (2005-2016). In addition of that, their shown a fairly good much reliability with them.
d. The values of the variability temporal coefficients in wave power at Gulf of Cadiz at different time scales are carried out, the seasonal variability index (SV) were found as 1.53 and 1.50 respectively for buoy and model data. Whereas, the monthly variability index (MV) were found as 1.72 and 1.67 for buoy and model data, respectively.
e. Statistical error values of numerical modeling data (forecasting) show satisfactory good values and are achieved for each wave characteristics namely, significant wave height (H_s), wave period (T_e) and wave power (P).
f. Finally, all those results confirming the slight under-prediction of (5.7%) between measurement and forecasting data. Therefore, these small differences support the assumption that the numerical modeling data (forecasting) are suitable for assessing wave energy in Gulf of Cadiz.

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