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Modeling of wind driven waves and estimation of wave energy in Chabahar Bay

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ABSTRACT

Sea waves are one of the main characteristics of water areas in the world, which are mainly produced by wind. Waves are the main boundary condition in the dynamic loading and hydraulic calculations of coastal structures. Numerical models are being developed to bring the sea and ocean conditions closer to the real conditions. In this research, the SW model from MIKE21 software is used to simulate wind waves in the Chabahar Bay and the energy extracted from these waves is estimated. The SW model simulates the growth, transmission and decay of wind waves in offshore and coastal areas. Chabahar Bay is a semi-closed and subtropical bay with an average depth of 7.5 m, which is located in the southeast of Iran. The model was implemented for a period of one year (2017) with a spatial resolution of maximum 5 km for offshore regions and less than 500 m in the interior parts of Chabahar Bay. ECMWF model wind data with a time step of 6 hours and a spatial resolution of 0.125 minutes were used. Comparison of model results for hourly averages with measured data shows a correlation coefficient of 0.84 for significant wave height. The annually average and maximum of wave height due to wind in the entrance of Chabahar Bay is 0.82 m and 2.19 m, respectively. The direction of the dominant waves is from south and the largest share of energy is related to waves with a period of around 11. The average of annual extractable power related to wind waves in the southern parts of Chabahar Bay was calculated from the order of 3 kW/m.

1. Introduction

Coastal areas are one of the most important national areas of Iran; A significant volume of various activities in various fields such as commercial, fisheries, oil, industrial, environmental, tourism, etc. activities are performed in these areas. Unfortunately, due to the lack of sufficient information and field data, achieving long-term goals has not been possible. In some cases, negative interactions in the hydrodynamic and geomorphological process of the region reduce the useful life of structures and ports. Waves are the most important factor in determining the geometric position and composition of beaches and also have a major impact on the design of ports, waterways and other coastal activities (Akbarifard et al., 2017). Sea waves are one of the main characteristics of water zones in the world, which are mainly produced by wind. Waves are the main boundary condition in the dynamic loading and hydraulic calculations of coastal structures (Nayebi et al., 2014). In coastal engineering applications and construction of coastal and offshore structures, wave height is the most important parameter in design (Esmaili and Kohnepushi, 2013). Over the past few decades, various methods and models, including experimental relationships and numerical models, have been developed to establish a direct or indirect relationship between wind speed and wave parameters. The use of mathematical formulas in numerical models increase the impact of wind to achieve more accurate results in wave modeling. Therefore, the impact of numerical models on wind is very important and also the study of the impact of models on wind is very important (Mohamad-Mehdizadeh and Hassan Tabar, 2017). Numerical models are being developed to bring sea and ocean conditions closer to real conditions. Among the various methods, numerical-spectral models can be named as the most complex and, of course, the most accurate methods for estimating the characteristics of wind waves. In this regard, various third generation numerical models such as SWAN (Boij et al., 2009), WAM (Group, 1988) and WaveWatch-III (Tolman, 2014), which are based on solving the equilibrium equation of the wave density spectrum, are presented (Dezvare Rasani et al., 2019). MIKE21 software is one of the most applied and accurate software in hydrodynamic studies. The MIKE21 software package is a third-generation model for simulating hydrodynamic processes. The solution of wave energy equations is based on the finite volume method on irregular triangular networking (Salehpour and Haji Valiei, 2015). This model considers phenomena such as wave breaking, refraction, energy loss in the breaking zone and the effects of bed depth changes (Tavakoli Oskooi and Hakimzadeh, 2016). The Sea of Oman and its shores, due to their connection to the open waters of the world, have been considered in the past and present, and its proximity to the Persian Gulf has increased its importance. Chabahar is one of the southeastern cities of Sistan and Baluchestan province and the only ocean port in the country, which is located on the coast of the Oman Sea and the Indian Ocean, and its berth is capable of mooring ocean-going ships. Chabahar Bay is the largest bay on the shores of the Oman Sea. This Bay is classified as omega bays in geology due to its omega (Ω) shape (Afsharian et al., 2010). Chabahar Bay is a semi-enclosed, subtropical bay (Fazeli and Zare, 2011). The average depth, area and volume of the Bay compared to the chart datum are 7.5 m, 290 km^2 and 2162×10^6 m^3, respectively. Its width at the entrance (east-west) is 13.5 km and its length (south-north) is 17.5 km (Biglari et al., 2015). The Bay is affected by monsoon conditions (Soltanpour and Dibajnia, 2015). Monsoon, meaning season, is a system of winds that blow over the ocean. Summer monsoon winds are much stronger than winter monsoon (Dehbandi et al., 2013). In the northern parts of the Indian Ocean, the prevailing winds are southwest during the months of May to September (summer monsoon) and during November to February, the winds often blow from the northeast (winter monsoon), March to April. And October winds are weak and are transitional months (Shankar et al., 2002).

The potential of the oceans has led many scientists and inventors to build devices that can convert wave, current, and tidal energy into other energies. Shirinmanesh and Chegini (2011) estimated the power extractable from the waves in Chabahar 3.9 kW using the Chabahar Buoy data and the Fourier analysis method. In another study, Saket et al. (2012) Used the SWAN model to model the wave in the Chabahar region and calculated the average annual wave power of just under 3 kW/m. The Ports and Maritime Organization, in line with its governance duty and in order to complete the maritime database and provide a way to solve many existing problems from the perspective of coastal engineering, including sedimentation and erosion in the coastal parts of the country, has defined a monitoring and modeling studies of iran coasts. In the first phase of this project, which covers the area of Chabahar Bay and about 100 km of coastline of Sistan and Baluchestan province, marine parameters during one year (2006-2007) by 7 waveguides and flowmeters and suspended sediment concentrations by 3 devices Turbidity was measured. Abbasi (2012) Using the wave modeling results, related to the Ports and Maritime Organization, the average annual wave height and power extractable from the waves at a point with a depth of 50 meters near Chabahar Bay has been calculated 0.88 m and 8.7 kW/m, respectively. In this research, using the MIKE21 numerical model, wind waves related to 2017 in the Chabahar Bay are estimated and after comparing the modeling results with field data, the energy extracted from the waves is calculated.

2. Materials and methods

2.1 Study area

Chabahar Bay is located in the south of Sistan and Baluchestan province and is considered a part of the Oman Sea. The Sea of Oman, or Gulf of Oman, connects the Arabian Sea in the northern Indian Ocean to the Persian Gulf via the Strait of Hormuz. The study area includes Chabahar and Pozm Bays (latitude 25.00-25.45 °N and longitude 60.00-61.00°E). The location of the study area, water depth in the model area, the position of the Chabahar buoy, the wave measuring device (ADCP) as well as the sampling stations are shown in Figure 1.

2.2 Model MIKE21-SW

The SW model from the MIKE21 simulates the growth, transmission and decay of wind waves in offshore and coastal zone. The basis of the SW model is the wave equilibrium equation in which the wave field is represented using the spectral density of the

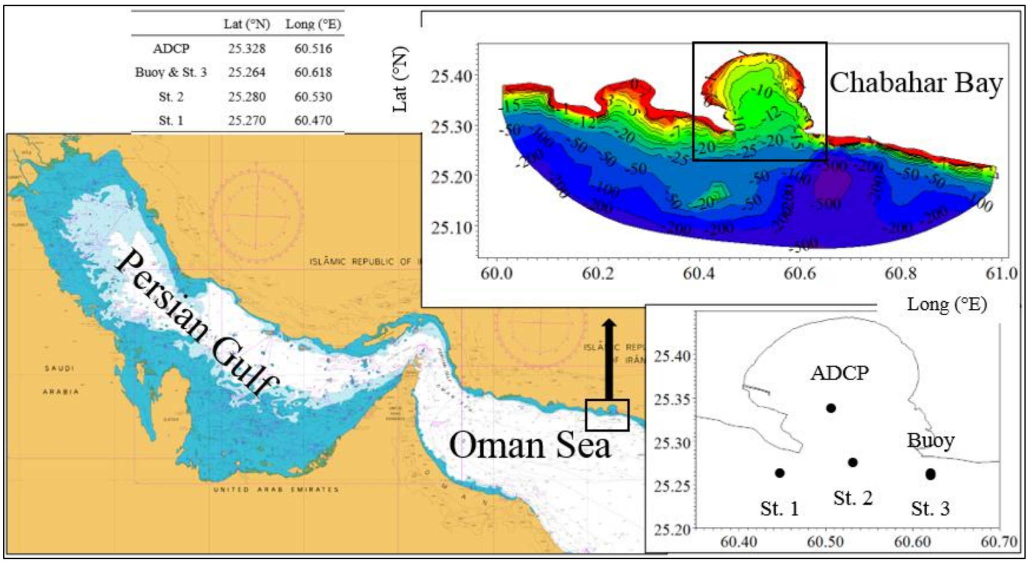


Figure 1. Location of Chabahar Bay, modeling area, hydrography and studied stations

wave, $N = (\sigma, \theta)$ in which the angular frequency σ is a function of the frequency (f) and is defined as $\sigma=2\pi f$ and θ is direction for wave propagation. Also, the relationship between energy spectral density E and wave spectral density N is defined using the relationship $N=E/\sigma$ (DHI, 2009). In the SW model, there are two different types of formulations: 1- Parametric formulation with directional separation and 2- Full spectrum formulation. In cases where there is a need to simulate the growth, transmission and decay of wind waves in coastal and offshore areas, full spectrum formulation is used. In cases where only wave transmission is concerned and the spatial dimensions are less than 10-50 km, or in cases where the sea is fully developed in terms of wave growth rate, or in cases where swell waves or the combination of sea waves and swell waves are not important; Parametric formulation with directional separation can be used. The full spectrum formulation is based on the wave equilibrium equation proposed by Kamen et al. (1994) and Young (1999) (DHI, 2009). In the Mike 21 wave model, the evolution of the wave spectrum at position (x, y) and time t at the Cartesian coordinates is expressed by the spectral equilibrium equation (Abdollahzadeh et al., 2014):

$$\frac{\partial}{\partial t}N+\frac{\partial}{\partial x}C_xN+\frac{\partial}{\partial y}C_yN+\frac{\partial}{\partial \sigma}C_\sigma N+\frac{\partial}{\partial \theta}C_\theta N=\frac{S}{\sigma} \quad (1)$$

The first expression to the left of the equation represents the local variation in the change in spectral density of the wave (N) over time; The second and third expressions show the propagation of N with velocities C_x and C_y in the direction x and y, respectively. The fourth expression shows the relative frequency transfer (with the propagation rate C_σ in the σ space) due to the change in depth and current. The fifth indicator represents the refraction due to depth and flow with velocity C_θ in the θ direction. The expression S on the right side of the equation, which represents energy sources; It includes various physical phenomena:

$$S=S_{in}+S_{wc}+S_{nl}+S_{bf}+S_{br} \quad (2)$$

S_{in} represents wind energy, S_{wc} energy dissipation due to wave whitening, S_{nl} energy transfer due to nonlinear wave-wave interactions, S_{bf} is the loss due to bed friction and S_{br} is the loss due to wave failure due to depth change.

2.3 WAFO Toolbox

The definition of the wave energy spectrum $S(\omega)$ is:

$$\sigma^2 = \int_0^\infty S(\omega).d\omega \quad (3)$$

Where σ^2 is variance of surface elevation and ω is angular frequency (Journee and Massie, 2001). In order to calculate the spectral density, WAFO software package was used. WAFO (Wave Analysis for Fatigue and oceanography) is a toolbox of MATLAB routines for statistical analysis and simulation of random waves and random loads (WAFO, 2011).

2.4 Used data

In order to determine the water depth, ETOPO1 data with a spatial resolution of 1 minute for the entire model range and hydrographic data of the Ports and Maritime Organization with a spatial accuracy of 100 meters for the interior parts of the Bay were used. ECMWF wind data for 2007, 2011 and 2017 with a spatial accuracy of 0.125 degrees and a time step of 6 hours were extracted for the model range and used as a surface force in the SW model. In order to validate the results of the model, Chabahar wave buoy data (2011 and 2017), ADCP measurement data (2007) belonging to the Ports and Maritime Organization were used. Also, the wind data of Chabahar synoptic station belonging to the Meteorological Organization were used to evaluate the wind speed; This data is collected in 3-hour time steps and is related to the years 2009 to 2017.

2.5 Model set up

First, a triangular grid with 3397 points and 6290 triangular elements was created in Mike software environment. In order to model the wind waves, full spectrum formulation was used; Also, ECMWF model wind data were extracted with a time step of 6 hours. The model was implemented for a period of one year (2017) with a spatial resolution of maximum 5 km for offshore areas and less than 500 m in the interior of Chabahar Bay. The refractive index $\gamma = 0.8$ and the bed hardness coefficient $k_n = 0.04$ were selected. In order to validate the model results, three data sets with the following specifications were used (Figure 2); It should be noted that all data used for validation is belong to the Ports and Maritime Organization which include: 1- ADCP data, these data are in the form of hourly averages of the significant wave height, which have been measured in the first phase of the monitoring and simulation studies of Iranian coasts; 2- Chabahar Buoy data for year 2007 and 3- Chabahar Buoy data for year 2011. The average of daily wave height for Chabahar Buoy extracted from the website of the Ports and Maritime Organization.

2.6 Error and accuracy of the model

In order to evaluate the results of the model, the statistical parameters of bias (BIAS), correlation coefficient (R), mean square error (RMSE) and scattering index (SI) according to the definitions of Shanas et al. (2014) were used; In these relationships, the values A_i are related to the model and the values B_i are related to ADCP or buoy.

$$\text{BIAS}=\frac{1}{N}\sum_{l=1}^{N}(A_i-B_i) \tag{4}$$

$$R=\frac{\sum_{l=1}^{N}[(A_i-\bar{A})(B_i-\bar{B})]}{\sqrt{\sum_{l=1}^{N}[(A_i-\bar{A})^2(B_i-\bar{B})^2]}} \tag{5}$$

$$\text{RMSE}=\sqrt{\frac{1}{N}\sum_{l=1}^{N}(A_i-B_i)^2} \tag{6}$$

$$\text{SI}=\frac{\sqrt{\sum_{l=1}^{N}[(A_i-\bar{A})-(B_i-\bar{B})]^2}}{\bar{B}} \tag{7}$$

3. Results and discussion

The monthly average and maximum values of wind speed related to Chabahar synoptic station are presented in Table 1. The annual average of wind speed is 3.1 m/s. The maximum of observed wind speed is in November and February, which were 15 m/s and 14 m/s, respectively. The average monthly wind speed varies in the range of 2.7 m/s (in October) and 3.5 m/s (in July). Figure 2 (a) compares the hourly averages of the measured index wave height data for 2007 with the results of the SW model. The large correlation coefficient (0.84) and the small BIAS error (0.15) indicate that the model prediction for the significant wave height is within an acceptable range. On the other hand, it can be seen that the significant wave height for model usually has predicted the lower hand. In Figure 2 (b and c), the daily averages of the model results are compared with the Chabahar buoy data. The statistical parameters are within an acceptable range. BIAS and correlation coefficient have both decreased; The correlation coefficient of the model results with Buoy Chabahar data is slightly less than 0.70 (0.68 and 0.69). The square of the mean error did not change much in all three cases and ranged from 0.14 to 0.19. Dispersion index related to hourly data (0.12) was better than daily data (0.19 and 0.26).

Table 1. Mean and maximum monthly values of wind speed (m/s), Chabahar Synoptic Station (2009-2017)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ave.	2.9	3.2	3.2	3.1	3.0	3.2	3.5	3.4	3.1	2.7	2.8	2.8
Max.	10.0	10.0	14.0	13.0	9.0	12.0	12.0	8.0	9.0	7.0	15.0	12.0

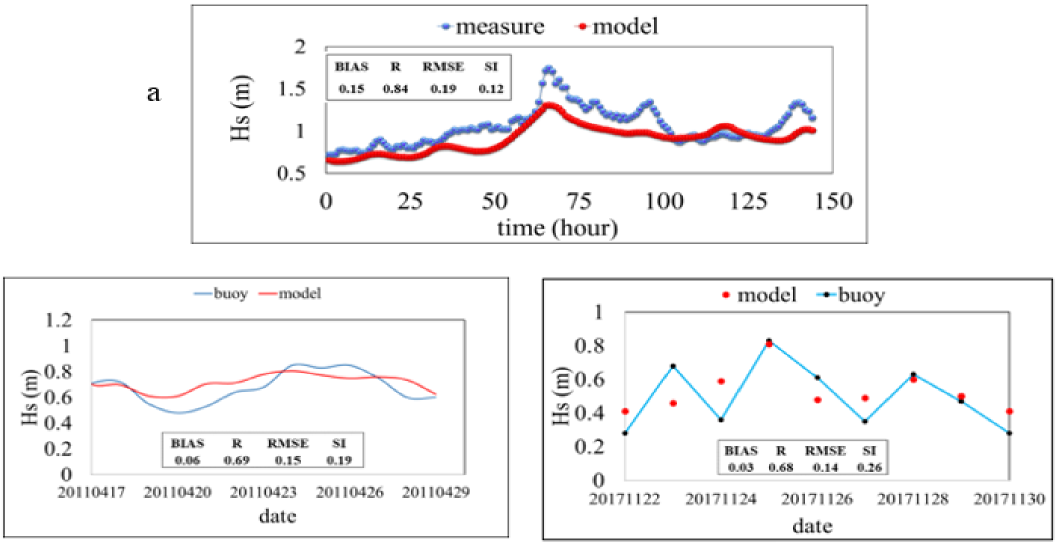


Figure 2. Validation of model results with data a) ADCP, related to 2007 and Chabahar wave buoy related to b) 2011 and c) 2017

The Chabahar wave buoy was active between 2012 and 2017, although there is a lot of missing data during this period; however, a considerable amount of data has been collected. The results related to the monthly averages of the wave height of the Chabahar Buoy in comparison with the monthly averages of Station No. 3 are shown in Figure 3. The results of the model and measured have almost the same annual trend. Thus, in spring, from April to June, the wave height increases and the maximum average wave height is seen in early summer (July). From July to November and December, the wave height decreased and at the beginning of winter, despite small changes, the wave height increased relatively. The highest values of model and buoy wave height occurred in July and are 1.32 and 1.57 meters, respectively. The results of the model are more different from the measured data related to buoy in spring and summer.

The monthly average of the significant wave height in the Chabahar Bay area is shown in Figure 4. In January and February, the significant wave height is often low (less than 0.5 m) and from January to February, slight changes are seen throughout the Bay. In March, the wave height at the entrance and in the middle of the Bay increased relatively. From March to July, the wave height increases in all parts of the Bay, and in July, all parts of the Bay experience maximum wave height. In May to August, the wave height at the mouth of the Bay is often more than 1 meter. From August to December, the trend of wave height changes is decreasing and in December, the lowest wave height is seen. The maximum wave height is related to the entrance of the Bay and the wave height decreases as it progresses into the Bay. The western parts of the Bay usually have lower wave heights than the eastern parts; the wave height in the western regions was usually less than 0.2 meters.

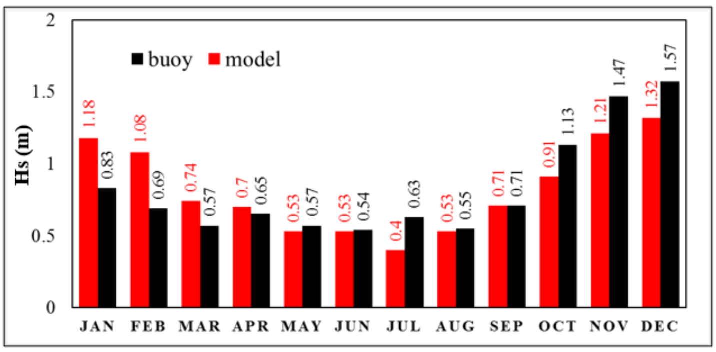


Figure 3. Comparison of monthly mean of significant wave height (m), Chabahar buoy data (black) (2014-2017) with model results (red) (2017)

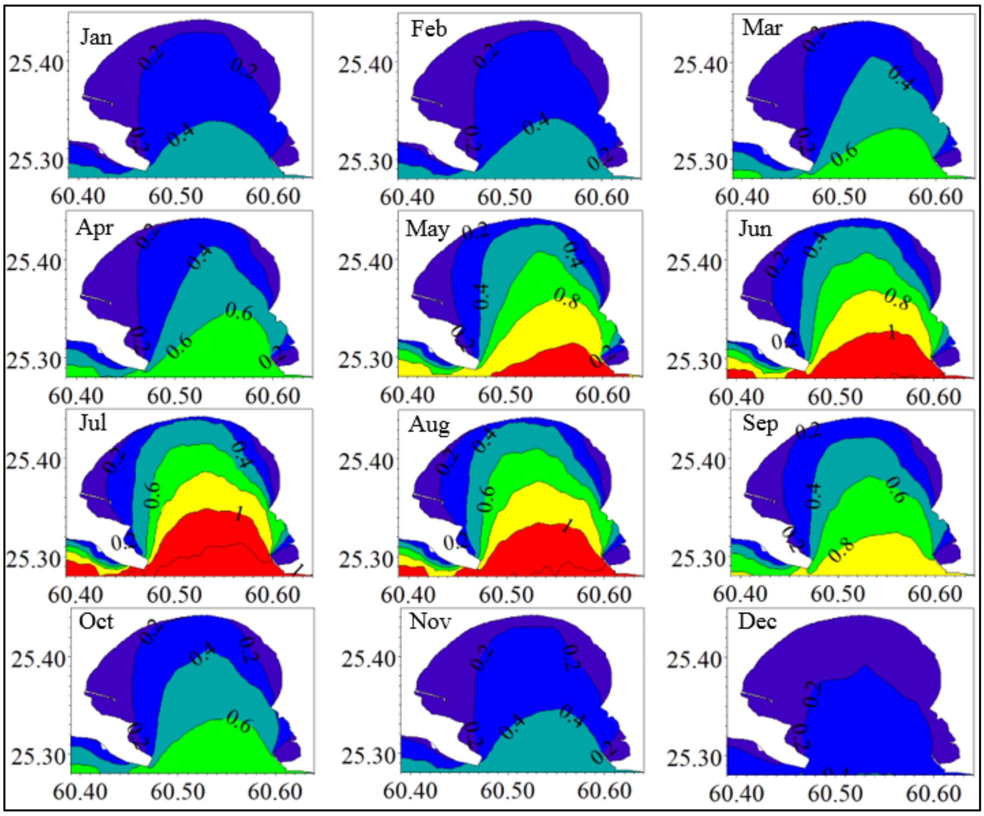


Figure 4. Monthly average pattern of significant wave height (m), MIKE21 model results, 2017

Wave rose corresponds to St. 2 with monthly average and maximum values at this station is shown in Figure 5. In all months except February, March and December there is the dominant southern wave. The predominant wave direction is southwest in February and March and southeast in December.

The frequency of waves with a wave height of more than 1.5 meters (yellow areas of wave rose) in February, May and July is higher than other months. Wave changes in autumn and winter are greater than in spring and summer, although the average of wave height in summer is higher than in other seasons; But the maximum wave height is seen in spring (April) (2.19 meters). Annual trend of wave height changes in three different stations St.1, St. 2 and St. 3 is shown in Figure 6.

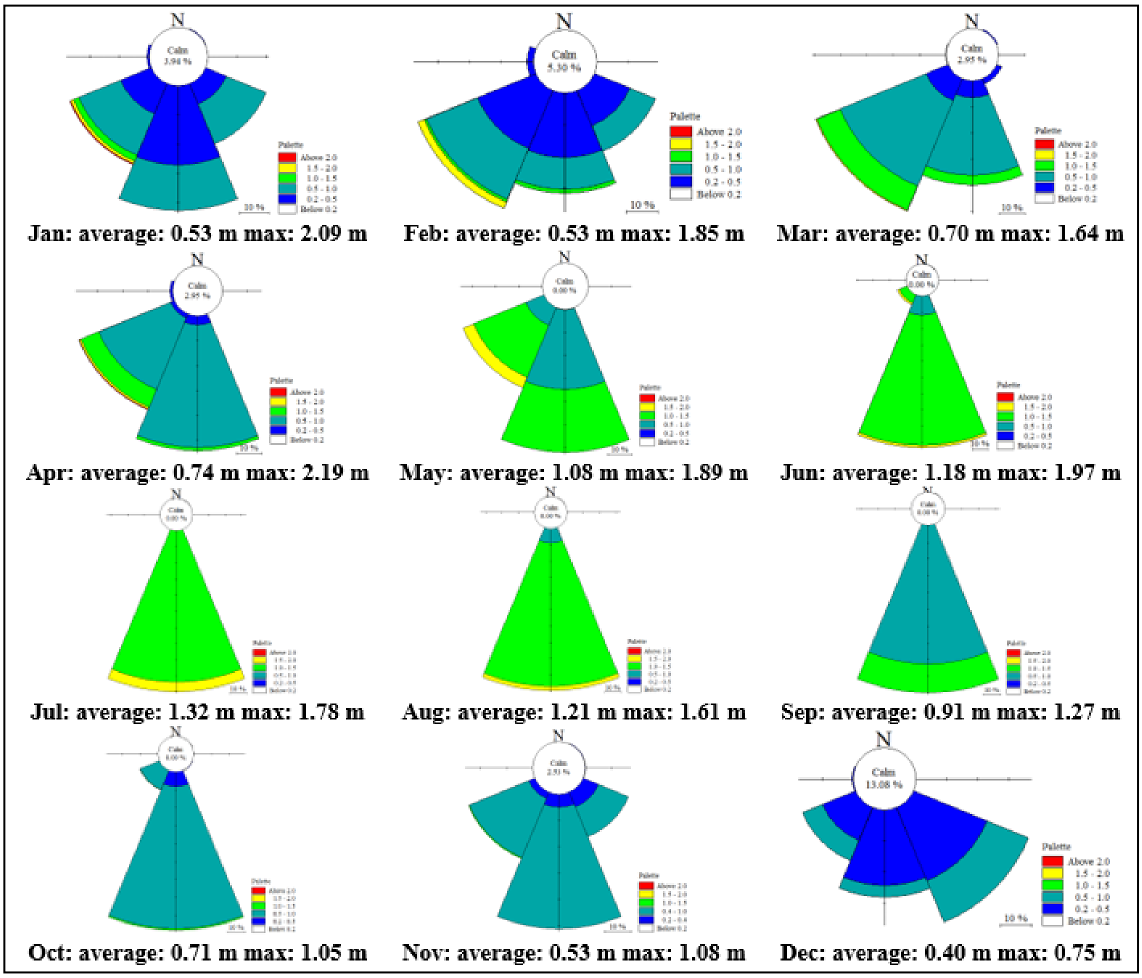


Figure 5. Monthly wave rose related to St. 2 (2017)

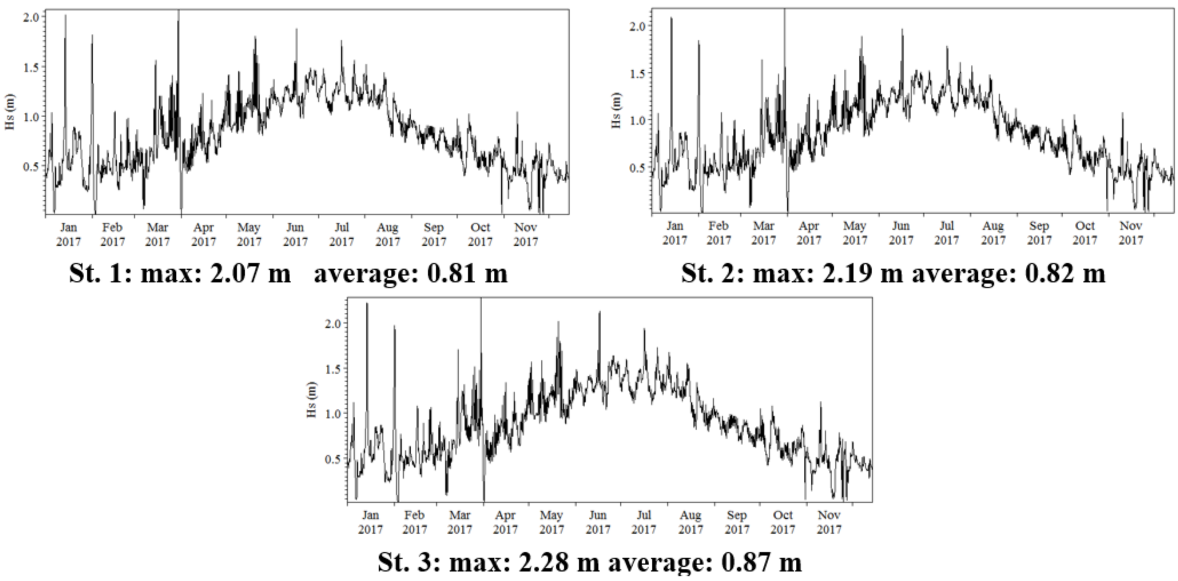


Figure 6. Annual changes in the significant wave height at three stations St. 1, St. 2 and St. 3

The maximum wave height usually occurs in winter and the first three months of the year, in other words, in winter, despite the fact that the monthly and seasonal average of wave height is lower, but we see the maximum wave height in this season. The maximum wave height of the East Station (St. 3) is 2.28 meters. The average of annual wave height increases from west to east; In general, the wave height in the eastern regions is higher than the western regions. As we expect from the wave height results, the wave power increases from west to east (Figure 7). The maximum of wave energy is related to the eastern station (St. 3) and is equal to 18.5 kW/m. The average wave energy at this station is 3.1 kW/m. The annual direction of the dominant wave is from south (Figure 8) and the dominant waves have a wave period between 4 to 8 seconds and often have a wave height of more than 0.5 meters. The maximum power extractable from the waves is also from south and in 90% of cases the extractable energy is more than 0.5 kW/m. Monthly spectral density (Figure 9) shows that in most months of the year, the highest energy is related to waves with a period of less than 30 seconds (often around 10 seconds). In March and September, the highest share of energy is related to storm waves (long period waves). In some months (April, May, June and December), the energy spectrum shows two peaks with different intensities. One of these peaks is related to ordinary winds, which usually produce waves with a period of less than 30 seconds (smaller peak), and the other is related to storm waves, which often produce waves with a period of more than 30 seconds.

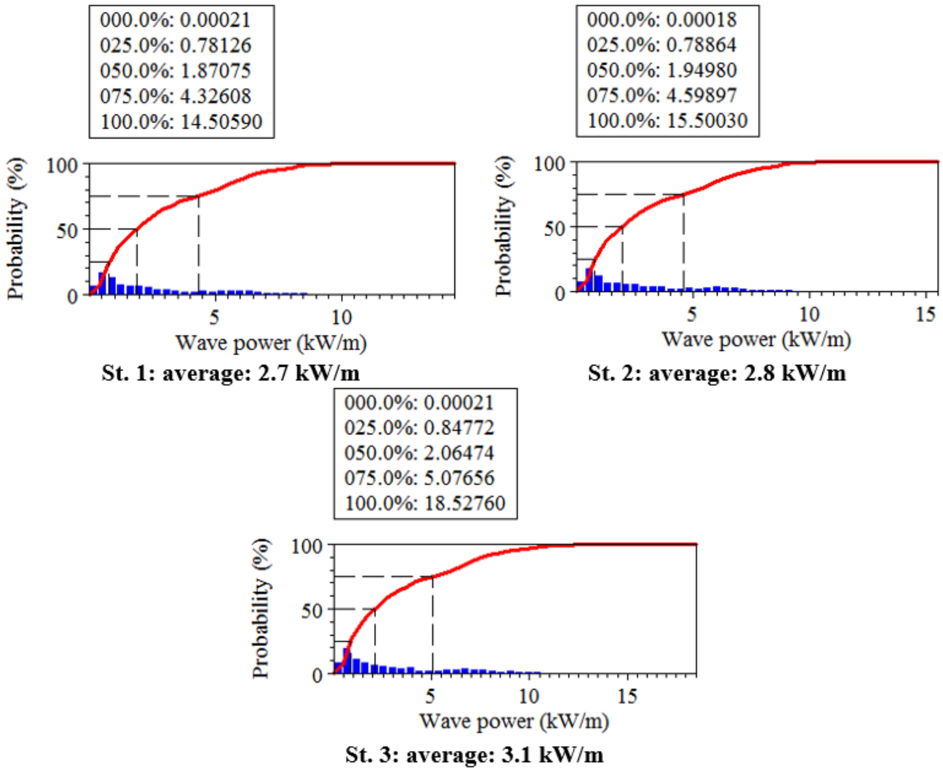


Figure 7. Distribution of wave power probability in different parts of the inlet of the Chabahar Gulf, with mean values (P50%), average and maximum (P100%)

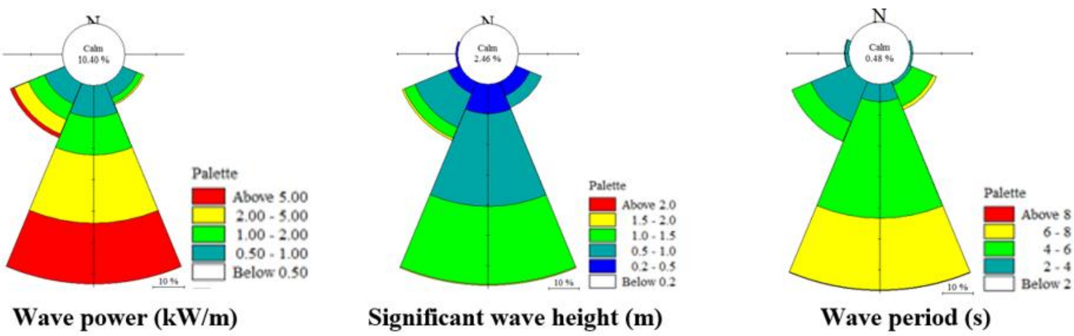
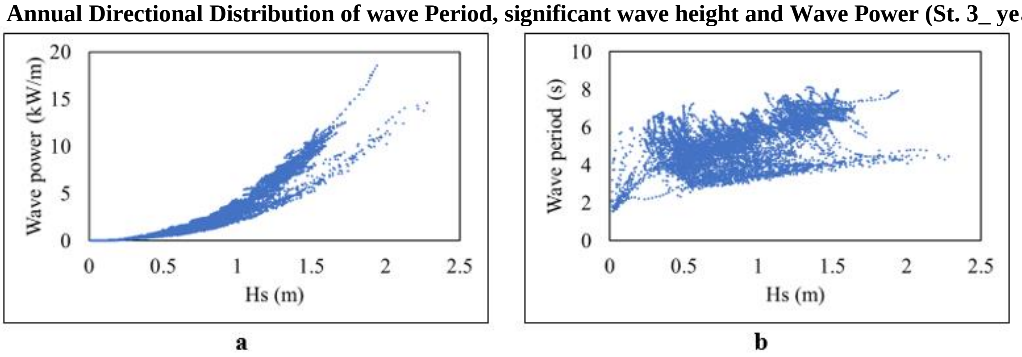


Figure 8. Annual Directional Distribution of wave Period, significant wave height and Wave Power (St. 3_ year 2017)



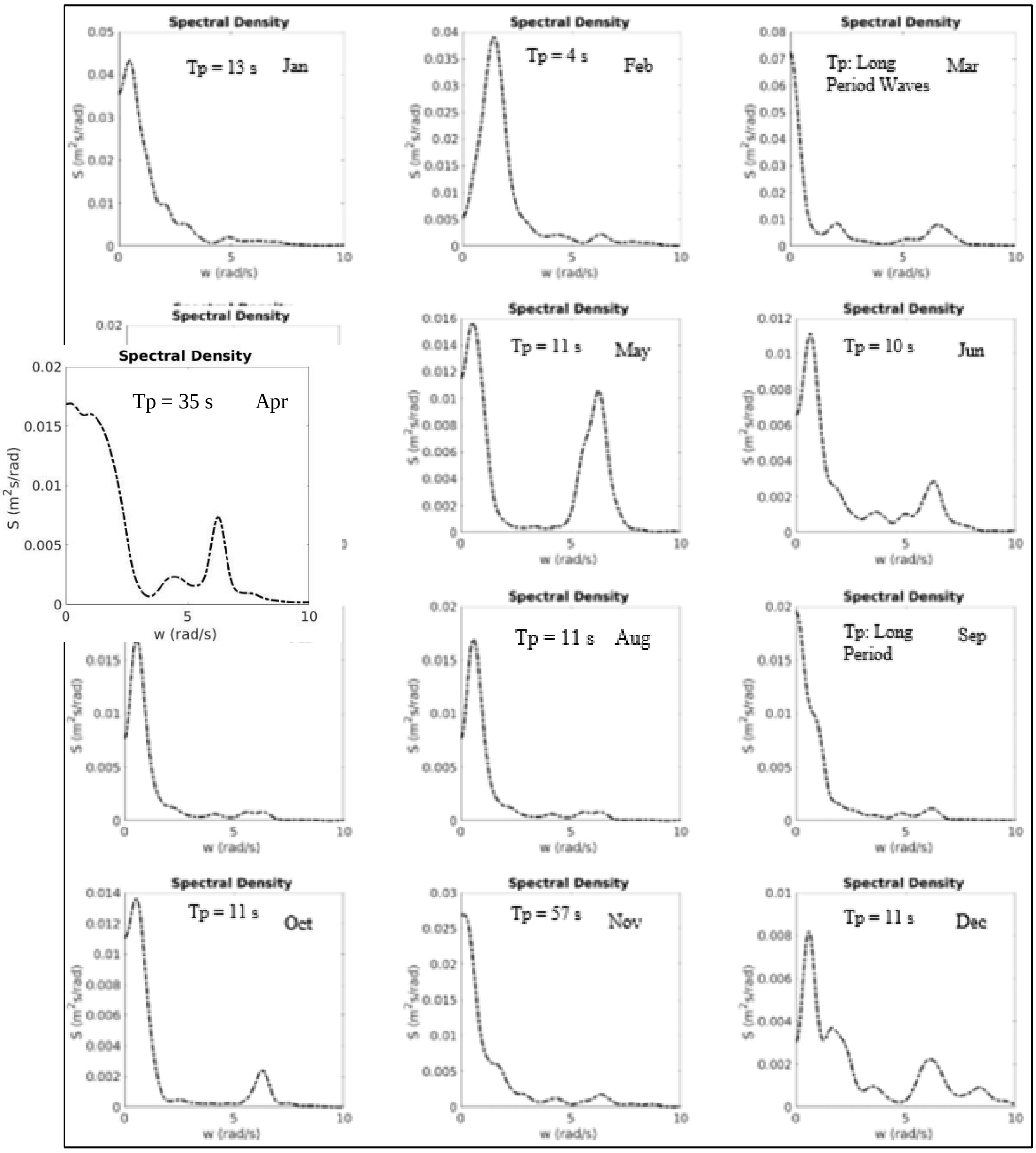


Figure 9. Monthly spectral density (m^2s/rad) versus angular frequency (rad/s), related to St. 2

4. Conclusion

The prediction of the wave height resulting from the SW model was acceptable in comparison with the measured data and the correlation coefficient was calculated between 0.69 (for daily averages) to 0.84 (for hourly averages). Chabahar Synoptic Station recorded an average wind speed of 3.1 m/s in the period 2009-2017. Examination of monthly average values of model results and Chabahar Buoy data shows that the wave height has an annual trend, so that during the spring months and with the arrival of summer, the wave height increases and the maximum wave height at the beginning of summer is observed with the intensification of summer monsoon winds. From mid-summer and with the decrease of monsoon winds, the wave height decreases and the lowest values of wave height are related to the end of autumn. In winter, the wave height was relatively low, but in late winter, we see an increase in wave height. The highest wave height occurs at the entrance of the Bay and decreases as it advances to the interior of the Bay. The annual average and maximum of wave height due to wind in the entrance of Chabahar Bay is 0.82 m and 2.19 m, respectively. From west to east the significant wave height increases. The direction of the dominant wave is from south and the period of the dominant waves changes in the range of 4-8 seconds. The average of annual extractable power in the southern parts of Chabahar Bay was calculated from the order of 3 kW/m. Compared to the data of Chabahar buoy which belongs to the Ports and Maritime Organization and on the one hand covers a limited time-space period and on the other hand has a lot of missing data as well as other statistical methods (dependent on Field data, such as Shirinmanesh and Chegini, 2011); Using the MIKE21 numerical model and applying the minimum wind and wave data at the borders, acceptable results were obtained for a full one-year period (2017) in the entire Chabahar Bay area.

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