Open Journal of Marine Science, 2017, 7, 22-34
http://www.scirp.org/journal/ojms
ISSN Online: 2161-7392
ISSN Print: 2161-7384

Validation and Coupling of the SWAN Wave Prediction Model by WRF for the Persian Gulf

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How to cite this paper: Zoljoodi, M. (2017) Validation and Coupling of the SWAN Wave Prediction Model by WRF for the Persian Gulf. *Open Journal of Marine Science*, **7**, 22-34.
http://dx.doi.org/10.4236/ojms.2017.71003

Received: November 17, 2015
Accepted: August 15, 2016
Published: November 30, 2016

Abstract

Generation of waves is affected by forces that exerted constantly in the oceans. The most obvious reason for the appearance of surface-waves is a process of interaction between atmosphere and sea surface that results in wind generation. Wave predictions are usually issued for a maximum of a few days for using in different fields such as shipping, fishing, oil industry, tourism, and to increase the safety of seafarers and beach habitants, maintaining economic assets and optimal utilization of natural resources. In this study, SWAN model has been run for this research over the Oman sea and the Persian Gulf. For implementation of SWAN, another dynamic model with prediction ability of 99 hours also has been used. In this example, wind field is obtained from the outputs of the WRF model converted to the required format for SWAN model. The computational network of SWAN model has been set to spatial grid points of 6 minutes with 1-hour temporal scale. Standard validation ways, including experimental verification, Multiplicative Bias, Mean Error and Root Mean Square Error are used in this study by comparing together for evaluation of accuracy of the model outputs. The results show that the prediction of wave heights by the model for 9 to 24-hour prediction could be the most accurate.

Keywords

Wave Prediction, SWAN Model, Validation, WRF Model and Coupling

1. Introduction

Many coastal, offshore and navigation engineering applications rely on a detailed wave climate at specific locations. However, such information is usually incomplete or even not available since *in situ* measurements are expensive. Therefore, an accurate and efficient prediction of wave conditions is crucial for these situations. For example, tropical cyclones out at sea or near coasts can cause high winds and result in large waves, which

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may disrupt international shipping, damage coastal structures and, sometime even cause Shipwrecks [1]. Therefore, models for describing wave generation and forecast are required. Usually, the main focus of wave studies is on near shore regions where a local high-resolution wave model should be applied with its boundary conditions obtained from lower-resolution models of a larger area. For example, Holthuijsen *et al.* (2000) [2] upgraded the SWAN model by providing an option for coupling a low-resolution WAM and a high-resolution SWAN simulation. There are wind wave models using curvilinear or unstructured grids to adapt the resolution to areas of interest. For example, curvilinear grids were adopted in recent versions of the SWAN model [3].

Waves at the surface of the deep ocean can be well predicted with third-generation wave models that are driven by predicted wind fields [4] [5].

These are all based on the energy or action balance equation, sometimes extended to shelf seas by adding the finite-depth effects of shoaling, refraction and bottom friction [6]. These models cannot be realistically applied to coastal regions with horizontal scales less than 20 - 30 km and water depth less than 20 - 30 m (with estuaries, tidal inlets, barrier islands, tidal flats, channels, etc.), because 1) the shallow-water effects of depth-induced wave breaking and triad wave-wave interaction are not included and 2) the numerical techniques that are used are prohibitively expensive when applied to such small-scale, shallow-water regions. Two alternatives seem to be available: a) extend the above (phase averaged) approach of the energy or action balance equation by adding the required physical processes using other numerical techniques or b) exploit the alternative approach of phase-resolving models based on mass and momentum balance equations. Such phase-resolving models are usually based on Hamiltonian equations [7] [8], Boussinesq equations [9] [10] [11], or on the mild-slope equation [12] or its parabolic version [13] [14].

These two problems, of adding depth-induced breaking and triad wave-wave interactions and of using implicit numerical schemes, have been addressed in detail for the development of Simulating Waves Near shore (SWAN) model [3].

SWAN is a wave model that can be run at high resolution in the littoral regions of the ocean and promises to provide output within the practical limits driven by operational constraints. SWAN is a "third-generation" numerical wave model and has no limitations on propagation direction. Input for SWAN typically consists of surface wind, wave spectra boundary conditions, and high-resolution bathymetry. SWAN provides the user a large span of configuration options to fit the needs of varied applications [15].

A third-generation wind driven wave model WAM is used by K. Al-Salem, *et al.* (2005) [16] to model the wind waves in the Persian Gulf. The WAM model is a two dimensional model that uses non-stationary and non-homogeneous wind fields in predicting wind waves. The model was validated using measured waves at several locations in Kuwait and was shown to predict the wave conditions well.

In this study, respectively, the pre-processing, performance and post-processing of the model for the coupling of the WRF regional model and SWAN wave model predictions are discussed. This research is focused on the Persian Gulf and Sea of Oman. Firstly, the 10-meter wind field of WRF model outputs were extracted and then a software package to convert the wind field to a format pairing with SWAN model is developed, tested and has been used, also the water depth in the desired grid format, pairing with SWAN model is tested and converted. At the end, the codes necessary for post-processing of SWAN outputs and converting them to the format needed for plotting model outputs were developed in GrADS software. Then the standard methods including experimental verification, multiplicative Bias, mean roots-square error were applied for comparison.

- *Study area*

Persian Gulf is one of little internal seas and regarding the marine division is recounted a shallow sea. Across the north of Persian Gulf and Sea of Oman, is restricted to the territory of Iran. Persian Gulf in ellipse shape is situated along Iranian southern shorelines between 24˚ to 30˚30' north latitude and 48˚ to 56˚25' east longitude. Sea of Oman is a branch of the Indian Ocean which has an average depth of 3000 m. In Oman the deepest point is measured 3694 meters, whiles in the Persian Gulf as shallow water upon passing the Strait of Hormuz the sea depth rarely exceeds 73 meters. The northern Persian Gulf belonging to Iran has the maximum depth.

- *Computational Network*

As usual, upon obtaining the out puts of global models from a few international centers, this datasets are downloaded as the basic materials to transfer for the regional meteorological model and after implementing the model the needed parameters have been extracted and provided to a wave prediction model to be run. In this study, the global GFS model output is used as initial boundary conditions of WRF regional forecast model and then wind-parameters at a height of 10 meters are extracted from WRF output and so SWAN wave prediction model is run.

The study used the rectangular grids based on longitude and latitude. SWAN model is implemented in an area from 47˚ to 66˚ east longitude and from 18˚ to 31˚ north latitude. This network is that the same computational grids of the SWAN model and the output of the model are made in its accordance. It has been developed by spatial geographic resolution of 6 minutes (11.1 km) and temporal resolution of 1 hour. The reason to extent the implementation area of SWAN model is to reduce the computational effects in wind and temperature boundary over the study area (the Persian Gulf).

The SWAN model has 4 input parameters, including water depth network, stream field, friction field and wind field. This study used only two following input parameters; water depth network and wind field.

Wind field input parameter that is resulted from separating and converting of the WRF regional model format, has a spatial resolution of 12 minutes (22.2 km) with a 3-hour temporal resolution which continues up to 99 hours. It is worth mentioning that the MM-5 Model is adjusted to 102-hour forecast, so that, it has 34 time steps of 3-hour forecasting because of the input data to the SWAN model is resulted from the same model. So the first step of WRF output from the GFS model has been ignored and then 33 time steps of 3-hour are interning to the SWAN model generating a wave prediction of 99-hour. The second input is the water depth network of study area with a spatial resolution of 2 minutes (3.7 km) that has been produced once and then each day it is used.

Finally, given that the SWAN model is not performing any processing on wind field, so the field is no longer used only for some other calculations, it is expected that the output images of SWAN model to be equal of WRF model. Also for more reliability in addition to the image comparison, the values are compared point by point, so the consistent results confirmed the format conversion of the wind field is done correctly by the codes produced.

WRF model settings to use its outputs for implementing the wave model over the Sea of Oman and the Persian Gulf, is adjusted to a central geographic position of 50˚E and 32˚N, number of maximum amplitude is two, number of grid points of the large amplitude in the x and y respectively ranges 90 and 98, the second amplitude ranges 106 and 124, the size of the grid spacing in the x and y coordinates for each domain respectively 45 and 15 km is considered. In this research the spatial resolution for the wind field of 10-meter height is considered 12 minutes. This wind field has been generated by conversion of the WRF model outputs into the needed model of SWAN. Its time lag is considered the same of WRF model outputs which is currently in 3-hour format.

- *Input and output parameters of the SWAN model units and coordinate systems*

SWAN covers all values given by the user in terms of the units of SI system such as meter, kilogram, second, and their compounds such as Newton and Watt. The wave height and water depth in meters, wave period is in seconds. For both wave and wind directions the Descartes and marine conventions can be used. The directions and spherical coordinate systems, both are projected for degree [17].

Figure 1 shows how a model is determined to the regular, integrated and rectangular grid points in different places according to the coordinate system.

If other models such as WRF model be checked, we do find that, all parameters of the model outputs after running are available in a general file to the users, but in the SWAN model it is optional to deliver the outputs and it must be determined by the user before executing the model. The output parameters can optionally specify a point to be extracted on a specified path, a curve or a regular grid. Since this study had to verify the

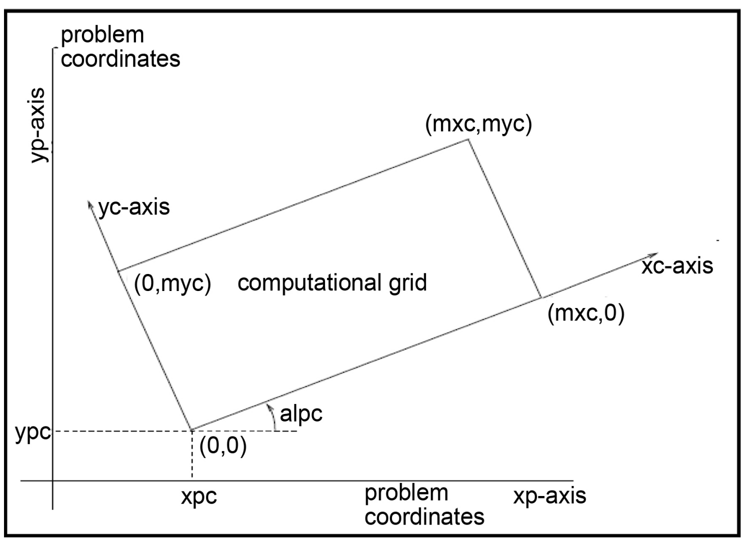

Figure 1. Different places of the grid points according to the executive coordinate system of the model.

results of the SWAN model at certain points, adjustments necessary to extract the parameters of the model output are done on the same points and the parameters considered include wave height and directions.

2. Results

The raw output of the SWAN model for 12:00 UTC at the first day of December 2010, in Table 1 is shown, with a time step of 6 hours to 99 hours for a control point with 52.71 degrees east longitude and latitude of 24.54 degrees of the northern.

- *Description of the observational data series for the study period*

ASALOOYEH buoy is located in a geographic position of 52˚57'E and 27˚37'N, that has been used to verify the data extracted from the model outputs (Table 2).

- *An example of atmospheric-oceanic model outputs*

By conversion of the SWAN model grid output to DAT and CTL files and plotting it by GrADS, the map of prediction of wave height and direction, and prediction of wind

Table 1. Point based raw output of the SWAN implementation model, at 12:00 UTC in the first day of December 2010 for a control point with a time step of 6 hours.

Run: Per	Table: Typical		SWAN	version: 40.72	
Time	X-Windv	Y-Windv	Hsig	Dir	Tm01
unit	[m/s]	[m/s]	[m]	[degr]	[sec]
1012011800	−3.304	−1.355	0.3067	224.333	1.779
1012020000	3.031	−1.4255	0.19451	224.012	1.541
1012020600	1.464	−3.968	0.24314	321.302	1.593
1012021200	−1.132	−2.608	0.26752	317.359	1.723
1012021800	−3.242	−1.025	0.22249	258.461	1.552
1012030000	1.948	−0.098	0.13245	217.321	1.386
1012030600	1.234	−2.599	0.11401	310.198	1.211
1012031200	−0.187	−2.331	0.14229	321.235	1.405
1012031800	−1.830	−1.524	0.17354	313.002	1.552
1012040000	2.061	−0.676	0.12733	329.264	1.601
1012040600	1.154	−4.276	0.20739	322.532	1.512
1012041200	−5.536	−2.906	0.23509	288.688	1.634
1012041800	−6.659	−1.304	0.30467	230.831	1.598
1012050000	−0.317	1.724	0.23195	201.497	1.491
1012050600	0.471	−5.821	0.13273	235.713	1.203
1012051200	−5.761	−3.369	0.20751	234.124	1.422
1012051800	−5.367	−1.021	0.32062	202.458	1.654
1012011800	−3.604	−1.815	0.3067	229.321	1.801
1012020000	3.031	−1.255	0.19451	248.064	1.501
1012020600	1.656	−3.098	0.24314	310.419	1.589
1012021200	−1.027	−1.560	0.26752	329.359	1.687

Table 2. Profile parameters measured by Asalooye buoy.

Row	*Parameter*	*Unit*	*Feature*
1	Wind direction	Deg.	
2	*Wind Speed*	m/s	
3	0Hm	m	Significant wave height
4	*mdir*	Deg.	Mean wave direction
5	*Tp*	s	peak period of spectral estimation

direction and speed can be plotted and made available to users. These images are drawn with a time step of 6 hours and cover 99 hours forecast (**Figure 2**).

- *Result validation*

The validation as a process specifies the quality, skill, and values of a prediction by comparing to the corresponding observations. The main objective of the validation is that the results should be informative to be able to offer new approaches for better prediction. Statistical analysis of validation can be helpful by evaluating the strengths and weaknesses of the predictor or forecasting method.

As there are different forecasting ways, validation also can be performed by various methods. One of the most common methods to consider model functions in the prediction of marine quantities is that, the consideration as a binary quantity is different for each threshold quantity of a $2^\circ \times 2^\circ$ grid point and then the corresponding numerical quantities can be calculated for each grid. Finally, the conclusions are derived based on the analysis of these obtained quantities.

SWAN marine model outputs for the predicted quantities have been verified and compared using corresponding data from the available observational stations in the study field, and applying conventional and well known verification methods. Selection of quantities and methods could be according to the fact that the datasets are of discrete kinds, so the conventional methods for this type of data should be used.

- *Validation of model outputs using human skill*

One of the oldest and best methods of verification is observational based method. In this method, monitored and predicted datasets are watched by an observer and then by using human judgment the errors are estimated. In this study in order to compare the observational and predicted wave height, after collection of the corresponding data, comparative data charts in 24 forecast lags from 3 to 72-hour at three-hour intervals in a 3-month period were plotted for ASALUYEH station. Here only a few examples of which are given (**Figures 3-6**).

The charts above show the comparison between the predicted and observational values of wave height in a given period and area.

Evaluating and comparing the model output and observational values of the wave height in prediction lags of 3 to 72-hour, illustrated the accuracy and consistency between them.

Comparison of 24 charts shows that the predicted values for 9, 12, 15, 18 and 24-hour of the wave height are more consistent to the observational values. As a result, the accuracy of the first 24-hour prediction is more than which of the second 24-hour prediction, so by increasing the prediction lags from 24-hour to 72-hour the accuracy is

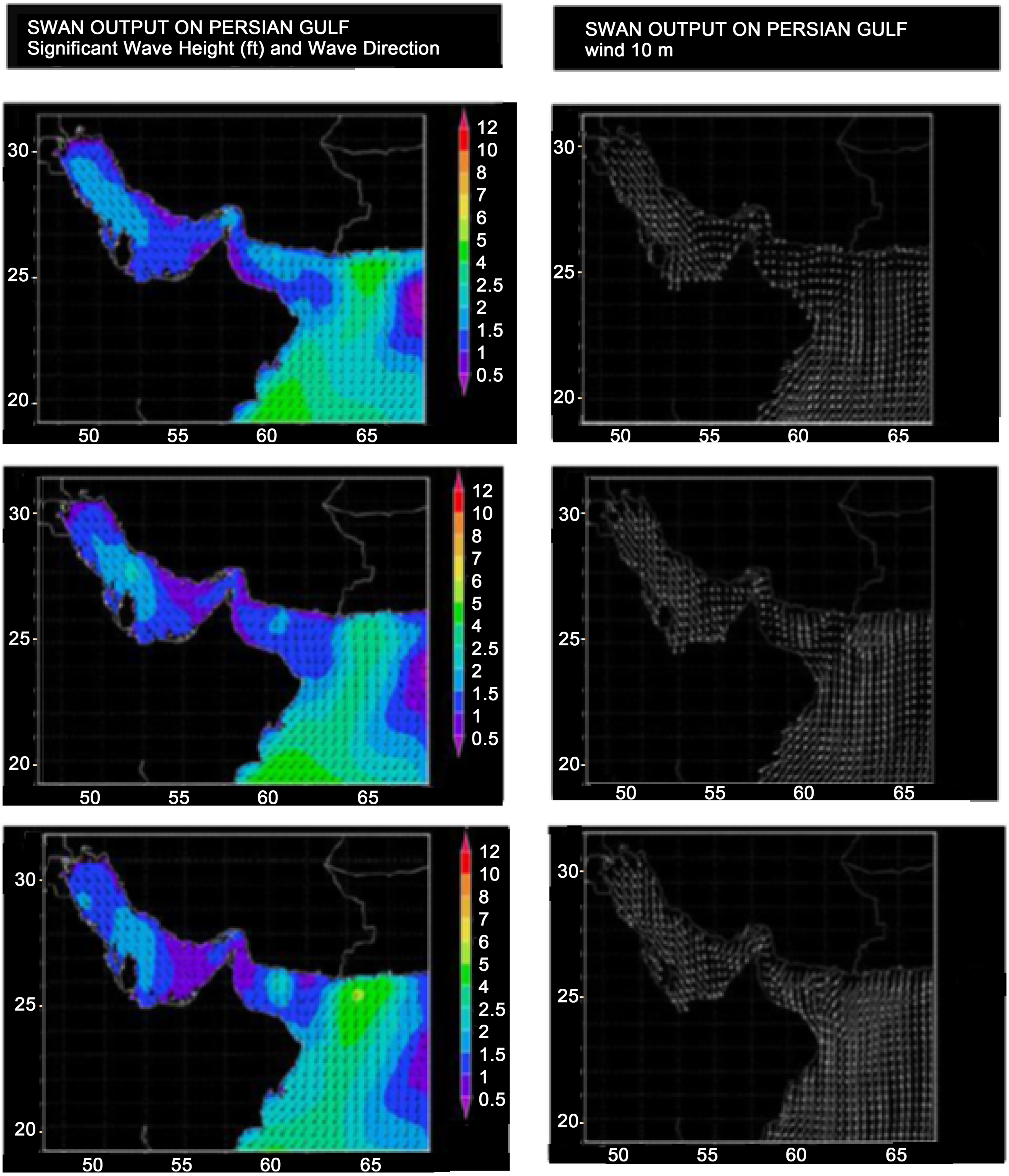

Figure 2. Prediction map of the wave height and direction as well as wind speed and direction, the output of operational network of SWAN model, in the first day of December 2010 at 02:00 UTC.

falling down.

For further evaluation of the SWAN model output, we do not only rely on human skill and it is validated also through the statistical methods as following.

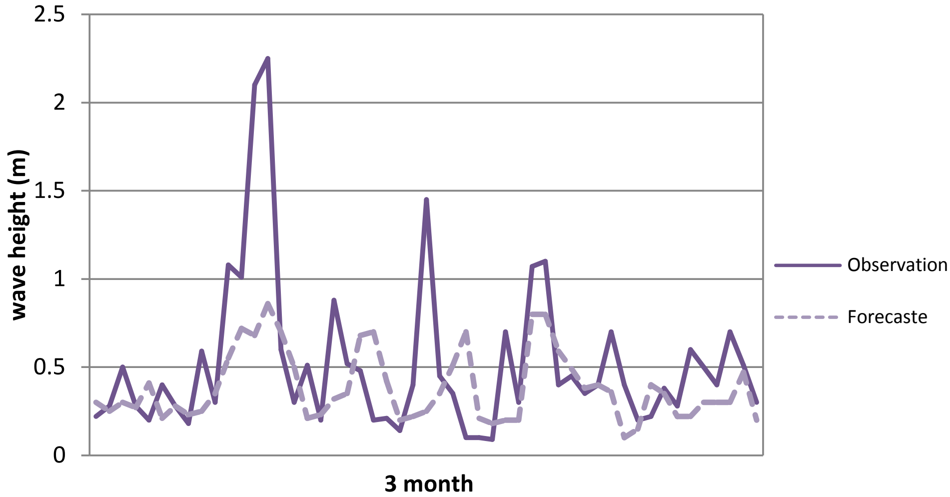

Figure 3. Comparison of the observational wave-height and the SWAN marine model outputs (3-hour forecast) September, October, November 2010).

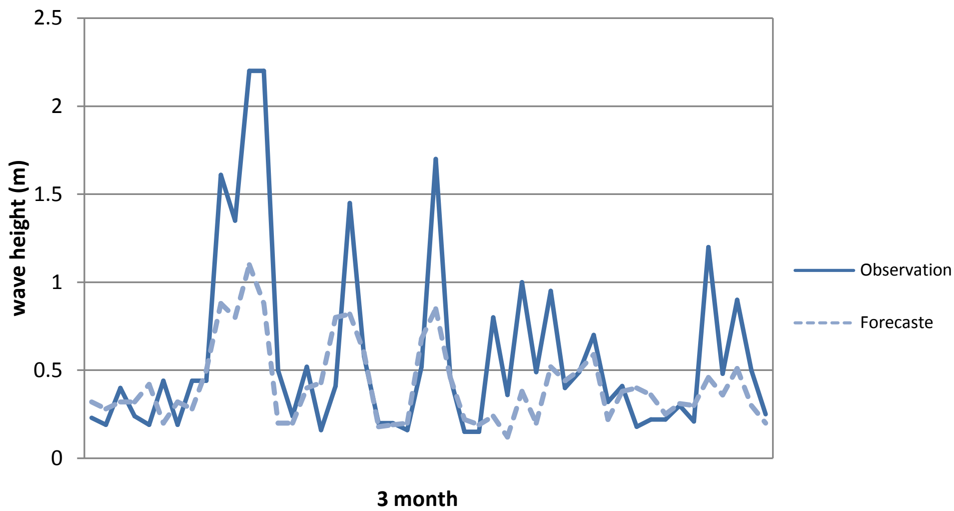

Figure 4. Comparison of the observational wave-height and the SWAN marine model outputs (6-hour forecast) September, October, November 2010).

- *Validation of the model outputs using statistical methods*

The statistical method for assessing the model outputs is applied in this investigation. The statistical methods used, include; Mean Error (ME), Multiplicative Bias and Root Mean Squared Error (RMSE). Moreover, to estimate the model accuracy these functions are compared in the study area.

- *-Mean Error:*

This method is called sometimes Additive Bias and defined as following:

$$\text{mean error} = \frac{1}{N}\sum_{i=1}^{N}\left(F_i - O_i\right).$$

F_i is the predicted value of the given variable, and O_i is the corresponding observational value. Although it seems that only at the optimal point the predicted mean error value is equal to zero but this is not right, sometimes the predicted values have much errors and then, the mean prediction error is zero or near to zero, but this value can be

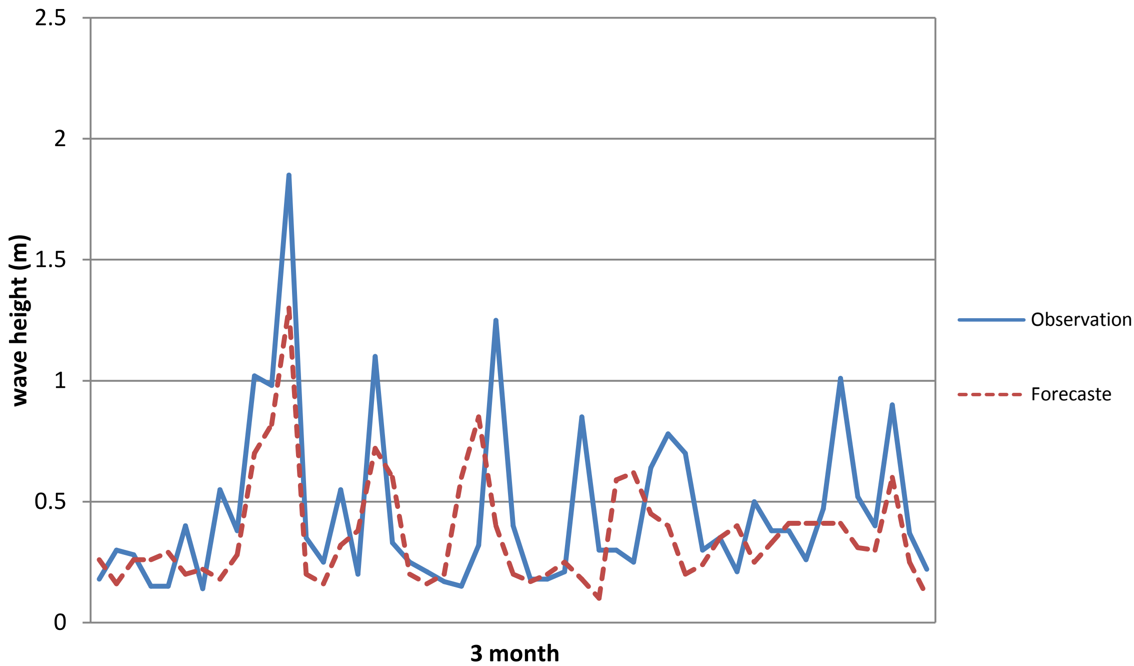

Figure 5. Comparison of the observational wave-height and the SWAN marine model outputs (12-hour forecast) September, October, November 2010).

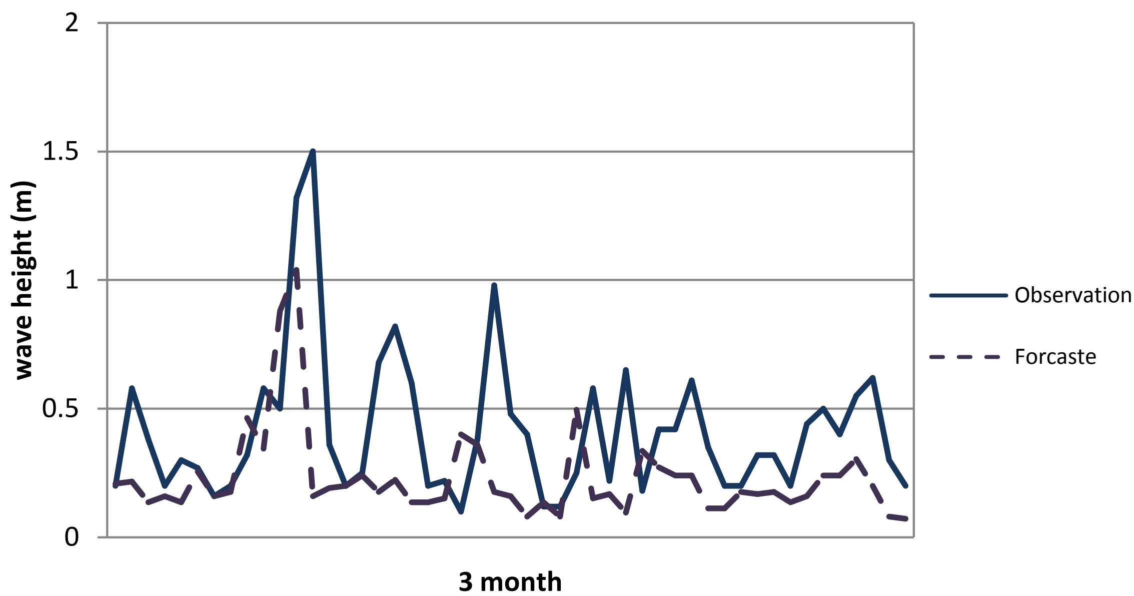

Figure 6. Comparison of the observational wave-height and the SWAN marine model outputs (24-hour forecast) September, October, November 2010).

compared with other statistical values and observational comparison to obtain a proper conclusion.

For the prediction lags of 3 to 72-hour in the study area the mean error values have been calculated and plotted as in Figure 7.

As above chart shows the error rate is very low and for 9 to 24-hour forecast of model, the error rate is near to zero. The mean error is represented the mean difference between predicted and observational values and sometimes it does not give a right number

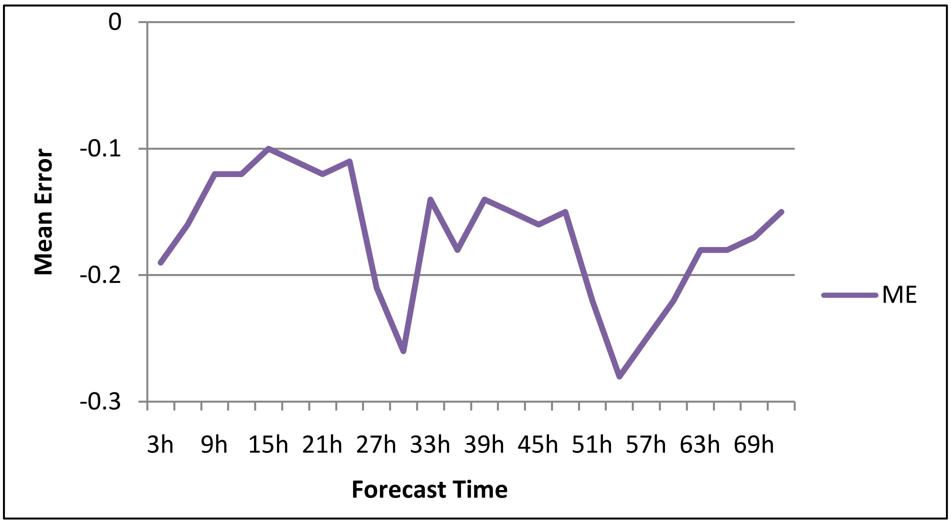

Figure 7. Calculated mean error of the SWAN model outputs for 3 to 72-hour prediction (Sept, Oct and Nov, 2010).

of errors, so for further evaluation of SWAN model we calculated other statistical quantities.

- *Multiplicative Bias*

This index compares the predicted mean values to the corresponding observational values. This index is defined as following equation:

$$\text{multiplicative bias} = \frac{\overline{F}}{\overline{O}} = \frac{\frac{1}{N}\sum_{i=1}^{N}(F_i)}{\frac{1}{N}\sum_{i=1}^{N}(O_i)}.$$

As the equation results 1, it means the best consistency. The using of this index could be very proper, particularly in the quantities which limit to zero. The values bigger than 1 indicate that the predicted rates are higher than observations and in contrary the values lower than 1 explain the predicted rates are smaller than the observations.

In this section, the multiplicative bias values according to the equation for the prediction lags of 3 to 72-hour in a 3-month period on the study area was calculated and then plotted (**Figure 8**).

As indicated in the above figure, multiplicative bias values for 72-hour forecast period, is near to "one", so regarding human judgment graphs, it represents the good forecast of wave height. Since the values of multiplicative bias in 9 to 24-hour prediction of model are almost the complete forecast and also regarding the result of the mean error in this prediction lag, it is concluded that the predicted wave heights could be more reliable in the forecast lag of 9 to 24-hour, comparing to the else lags.

- *Root Mean Square Error*:

RMSE is defined through following equation:

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(F_i - O_i)^2\right]^{1/2}.$$

The best value of this quantity is zero and also can be greater than zero. Note that the

RMSE gives greater penalty for larger errors because the error values are Square. In the other words, this quantity is sensitive to digressive predicts. The results in the 72-hour forecast of wave height over a 3-month period have been calculated and plotted as follows (Figure 9).

3. Conclusions

This study was conducted to verify the SWAN marine model output. Using the real data of wave height, the marine model outputs are evaluated over a 3-month period (Sept, Oct, Nov. 2010) in 72-hour prediction at Asaluyeh marine station.

Initially, verification of the results is done using human-skill method (direct observation).

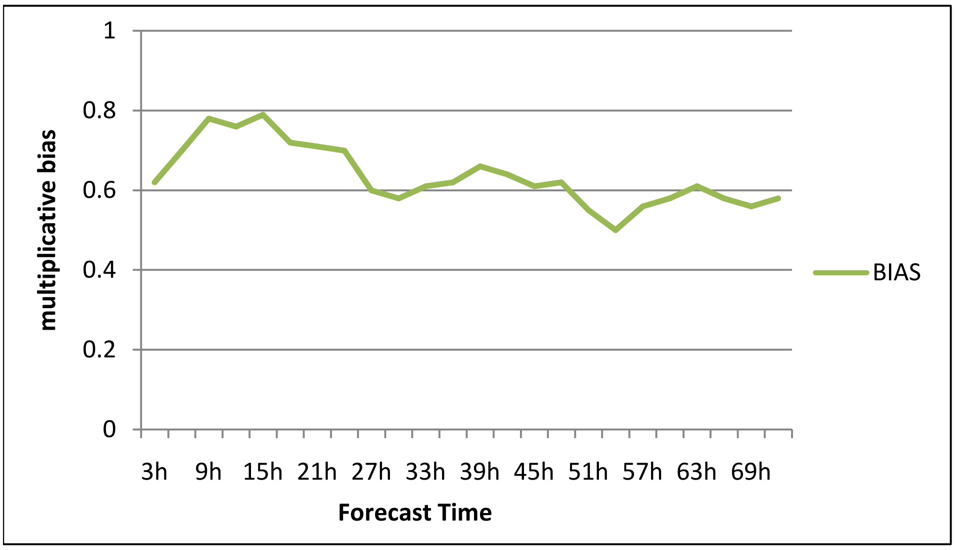

Figure 8. Multiplicative bias values of the SWAN model outputs in prediction of 3 - 72-hour (Sept., Oct., Nov. 2010).

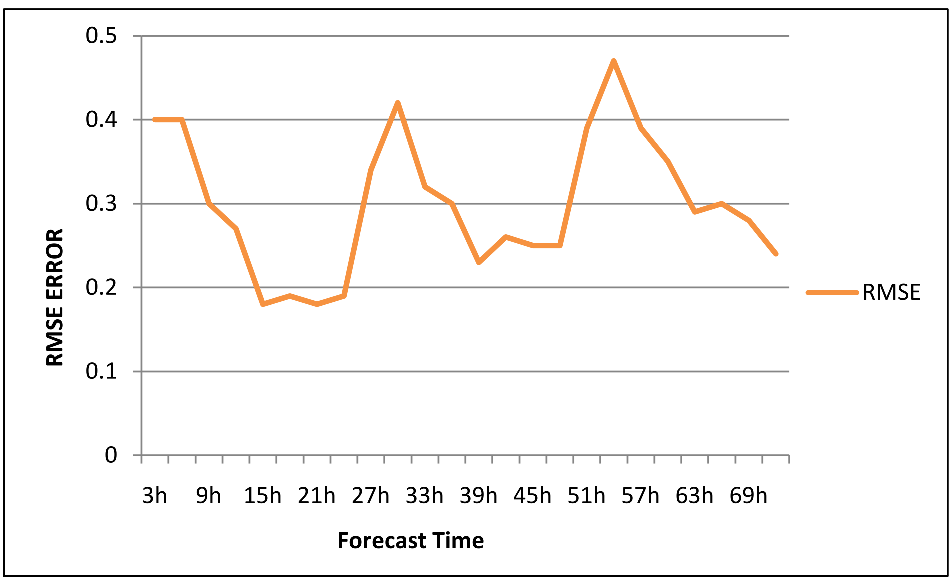

Figure 9. Calculated RMSE of SWAN model outputs in 3 to 72-hour prediction (Sept., Oct., Nov. 2010).

In the next step, we used some statistical methods including: Mean Error, Multiplicative Bias and Root Mean Square Error, in order to validate the model outputs, and then the results obtained through the above-mentioned validation methods were compared.

The results of the statistical methods and the charts of human-expertise often show high accuracy for the wave height predicted by SWAN model during the study period. Furthermore, through the prediction lags of 09, 12, 15, 18, 24-hour, the predicted wave heights are more consistent with the observational values. Thus, with good confidence, the results predicted by SWAN marine model can be used, and according to the results obtained from statistical and observational methods, the prediction of wave heights through the model during 9 to 24-hour prediction is the most accurate.

References

[1] Tsai, C.-C., Hou, T.-H., Popinet, S. and Chao, Y.Y. (2013) Prediction of Waves Generated by Tropical Cyclones with a Quadtree Adaptive Model. *Coastal Engineering*, **77**, 108-119. https://doi.org/10.1016/j.coastaleng.2013.02.011

[2] Holthuijsen, L.H., *et al*. (2000) SWAN Cycle III Version 40.11 User Manual. Delft University of Technology Department of Civil Engineering, The Netherlands.

[3] Booij, N., Ris, R. and Holthuijsen, L. (1999) A Third-Generation Wave Model for Coastal Regions. I—Model Description and Validation. *Journal of Geophysical Research*, **104**, 7649-7666. https://doi.org/10.1029/98JC02622

[4] WAMDI Group (1988) The WAM Model—A Third Generation Ocean Wave Prediction Model. *Journal of Physical Oceanography*, **18**, 1775-1810. https://doi.org/10.1175/1520-0485(1988)018<1775:TWMTGO>2.0.CO;2

[5] Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S. and Janssen, P.A.E.M. (1994) Dynamics and Modelling of Ocean Waves. Cambridge University Press, New York, 532 p. https://doi.org/10.1017/CBO9780511628955

[6] Tolman, H. (1991) A Third-Generation Model for Wind Waves on Slowly Varying, Unsteady, and Inhomogeneous Depths and Currents. *Journal of Physical Oceanography*, **21**, 782-797. https://doi.org/10.1175/1520-0485(1991)021<0782:ATGMFW>2.0.CO;2

[7] Miles, J.W. (1981) Hamiltonian Formulations for Surface Waves. *Applied Scientific Research*, **37**, 103-110. https://doi.org/10.1007/BF00382621

[8] Radder, A.C. (1992) An Explicit Hamiltonian Formulation of Surface Waves in Water of Finite Depth. *Journal of Fluid Mechanics*, **237**, 435-455. https://doi.org/10.1017/S0022112092003483

[9] Peregrine, D.H. (1966) Long Waves on a Beach. *Journal of Fluid Mechanics*, **27**, 815-827. https://doi.org/10.1017/S0022112067002605

[10] Freilich, M.H. and Guza, R.T. (1984) Nonlinear Effects on Shoaling Surface Gravity Waves, Philos. *Philosophical Transactions of the Royal Society A*, **A311**, 1-41.

[11] Madsen, P.A. and Sørensen, O.R. (1992) A New Form of the Boussinesq Equations with Improved Linear Dispersion Characteristics, 2, A Slowly-Varying Bathymetry. Coastal Engineering, **18**, 183-205. https://doi.org/10.1016/0378-3839(92)90019-Q

[12] Berkhoff, J.C.W. (1972) Computation of Combined Refraction-Diffraction. *Proceedings of 13th International Conference on Coastal Engineering*, Vancouver, Canada, 1973, 471-490. https://doi.org/10.1061/9780872620490.027

[13] Radder, A.C. (1979) On the Parabolic Equation Method for WATER-Wave Propagation. *Journal of Fluid Mechanics*, **95**, 159-176. https://doi.org/10.1017/S0022112079001397

[14] Kirby, J.T. (1986) Higher-Order Approximation in the Parabolic Equation Method for Wa-

ter Waves. *Journal of Geophysical Research*, **91**, 933-952.
https://doi.org/10.1029/JC091iC01p00933

[15] Dykes James, D., Larry Hsu, Y. and Erick Rogers, W. (2002) The Development of an Operational SWAN Model for NGLI. *Proceedings of the Oceans* 2002 *MTS/IEEE Conference*, Biloxi, Mississippi, 859-866.

[16] Al-Salem, K., Rakha, K., Sulisz, W. and Al-Nassaar, W. (2005) Verification of a WAM Model for the Arabian Gulf. *Arabian Coast Conference*, Dubai/Kuwait, 15 October 2005.

[17] SWAN Team (2008) Swan User Manual. Delft University of Technology, The Netherlands.