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Developing the Persian Gulf Wave Forecasting System

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Abstract: This paper represents the detailed procedure and outcomes of a research work aiming to develop a wave forecasting system for the Persian Gulf. Considering the high importance of the Persian Gulf for the economy of the region and the world, the need for a reliable forecast data has increased recently and therefore we have developed and calibrated the forecasting model based on all the available wave data in the domain which distinguishingly increased the accuracy and reliability of the system. The obtained Global Forecast System data (GFS) is implemented in Weather Research and Forecast Model (WRF) and the reproduced high resolution wind field is implemented in the third generation WAVEWATCH III (WW3) model. Each forecast covers a 120-hour prediction and provides the users with precise information regarding significant and maximum wave height and peak wave period and direction on any point at the entire Persian Gulf. The forecasts are updated every 12 h and consequently, customized reports are delivered to the users.

1. Introduction

The Persian Gulf is one the most crowded navigation corridors which hosts a significant portion of world's energy and cargo transports. Considering the numerous offshore and onshore constructions, drillings and oil and gas platforms in the region, the demand for a reliable met-ocean forecast system has highly increased in recent years. Thus, Port and Maritime Organization (PMO) of Iran, as the authorized and responsible entity to meet the marine and coastal needs of the country, introduced the Persian Gulf Forecasting System project in 2014. The project, which includes the state of art modeling of wind field, waves and currents in the Persian Gulf, was awarded to K. N. Toosi University of Technology and Institute of Geophysics (University of Tehran) [1].

According to Iranian Sea Wave Modeling (ISWM) Project's reports [2], in the Northern Persian Gulf, the most dominant waves are North-Westerly (NW) which are known as the Shamal. Nevertheless, Shamal wind direction changes from NW in the northwest corner of the Persian Gulf to WNW around Kish Island and then to W at the entrance to the Strait of Hormuz [3]. Between Asalouyeh and Lengeh Port, waves are mostly from the West. The significant wave height (Hs) can reach up to 5.5 m. The northern coastline on the Persian Gulf is also exposed to winds from SE which are strong but not as frequent as Shamal winds [4]. Analytical analysis on a 30-year hindcasting data shows that some areas within the Persian Gulf experience storm events (Hs of more than 2 m) more than 8 times a year (see Figure 1).

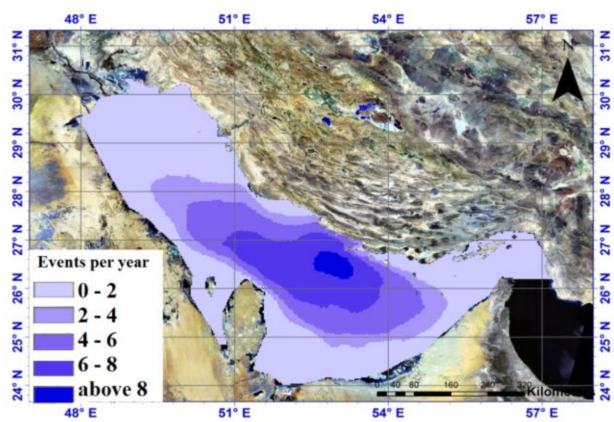

Figure 1. The Persian Gulf Wave Events (Hs>2m)

The Persian Gulf is a nearly 1000 km long water body located in the south of Iran with an average depth of 40 m and a maximum depth of 170 m at its entrance, the Strait of Hormuz [3]. As it is vital, forecasting the wind-wave conditions in the Persian Gulf is of great importance to many entities and so far several attempts have been made in this regard. Iranian public sector entities including, PMO, Iranian National Institute for Oceanography and Atmospheric Science (INIOAS), Iran Meteorological Organization, Ministry of Oil, Isfahan University of Technology and international companies such as DHI of Denmark, NCEP by NOAA (USA), NCOF of UK and Metocean of New Zealand have expended valuable efforts

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in order to develop a forecasting system for the Persian Gulf.

In this research project, we have strived to develop and calibrate the forecasting model based on all the available wave data in the domain which distinguishingly increased the accuracy and reliability of the system.

2. Data Gathering

Figure 2 illustrates the study area and available measured data. As illustrated in Figure 2, the existing data of 10 stations were collected in this study. The waves have been mainly recorded by PMO via different phases of Monitoring and Modeling Projects of Iranian coasts [5]. Moreover, the data of 3 active buoys (BA, BB and BS) are regularly collected and used to improve the accuracy of the model predictions (Figure 3). By this means, a perfect cover all over the Persian Gulf has been achieved which enables the model to be accurate and reliable everywhere within the domain. Table 1 presents the characteristics of the collected data. It should be mentioned that all data stations are located at approximately 25 m depth except for AW4 (Kangan) with a depth of 22 m.

The wind field is provided by Institute of Geophysics, University of Tehran [6]. The obtained Global Forecast System data (GFS) is implemented in Weather Research and Forecast Model (WRF) [7] in order to resolve the meso-scale phenomena. According to Ghader et al. [6], an ensemble forecasting method has been developed for this purpose due to extremely chaotic nature of the weather.

The bathymetry of the Persian Gulf was prepared collecting various data sources of ETOPO1 for deep waters [8] and local data sets of PMO, National Cartographic Center (NCC) of Iran and Iranian Fishery Organization (IFO) for shallow areas (Figure 4). The combined bathymetry data has been proven to be of good quality through several previous research studies [9] [10].

3. Methodology

The waves are simulated by introducing the modeled wind field to the wave generation/propagation model. The wind field generated by WRF model is applied in the third generation WAVEWATCH III (WW3) model [11] to simulate the wave characteristics over the domain of the Persian Gulf. Both wind field and wave forecasting systems are updated every 12 h. The mentioned interval between forecast updates is the minimum required time for downloading the raw GFS wind data, running WRF ensemble model and running WW3 model including all pre and postproductions. Each forecast covers a 120-hour prediction and provides the users with precise information regarding significant and maximum wave height and peak wave period and direction on any point at the entire Persian Gulf.

The wind data is the output of an ensemble prediction system developed for the Weather Research and Forecasting (WRF) model to predict surface wind over the Persian Gulf [6]. To construct the ensemble members, a combination of perturbed initial condition (using Monte Carlo method) and model perturbations (using multi physical parameterization schemes) is used. The ensemble prediction system with 15 members (three physical parameterization schemes and five initial condition perturbations for each one) was used to generate the surface wind and other meteorological field predictions over the Persian Gulf. Assessment of the ensemble mean against the observational *in situ* and satellite (e.g., ASCAT and QuikSCAT) data indicates promising performance of the ensemble prediction system over the deterministic predictions.

Unlike global wind data such as European Centre for Medium-Range Weather Forecasts (ECMWF) or Climate Forecast System Reanalysis (CFSR) which have a coarse resolution of 0.25 degree and a time step of 6 h, the wind field provided [6] for this forecasting system has 0.1 degree spatial resolution and a time step of 1 h. The statistical analysis on wind data results over 26 synoptic wind stations located all around the Persian Gulf show that the correlation coefficient between model and data varies between 0.45 and 0.99 with a mean value around 0.8 and RMSE of less than 1 m/s.

WW3 was selected for numerical modeling, in comparison with other wave generation models such as, SWAN, MIKE-SW, PMO-Dynamics, due to its high performance and accessibility to the source code (using multi-core servers for parallel computation), which enables the implementations of necessary modifications and required developments within a unified automatic system.

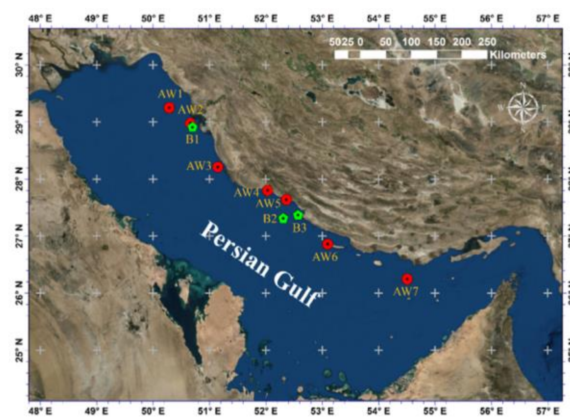

Figure 2. The Persian Gulf and Historical Data Collection stations

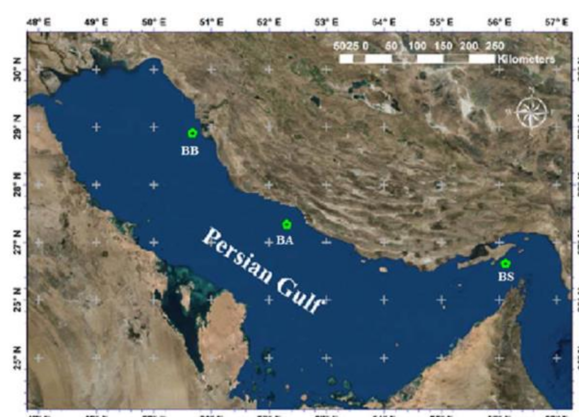

Figure 3. The Persian Gulf and Active Data Collection stations

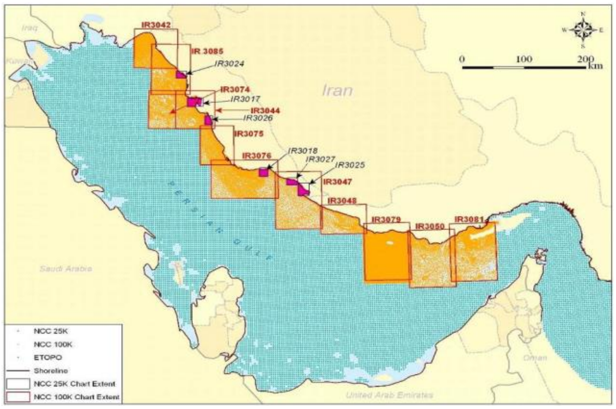

Figure 4. Hydrography data

Table 1. Historical and Active Data Collection stations

Station	Location	Lon.	Lat.	Instrument	Year
B1	Bushehr	50.6	28.91	Buoy	1995
B2	Asaluyeh	52.31	27.32	Buoy	1999
B3	Asaluyeh	52.57	27.37	Buoy	2010
AW1	Khark	50.285	29.29	AWAC	2011
AW2	Bushehr	50.66	28.97	AWAC	2007
AW3	Lavar	51.14	28.21	AWAC	2009
AW4	Kangan	52.03	27.79	AWAC	2010
AW5	Parak	52.36	27.27	AWAC	2010
AW6	Lavan	53.09	26.85	AWAC	2010
AW7	Farur	54.50	26.24	AWAC	2010
BA	Asaluyeh	52.31	27.32	Buoy	2015
BB	Bushehr	50.72	28.85	Buoy	2015
BS	Souza	56.06	26.75	Buoy	2015

4. Numerical Modeling

Version 4.18 of the third generation WW3 model was implemented for the generation and propagation of waves in the Persian Gulf [11].

The source term consists of three parts, i.e. wind-wave interaction, nonlinear wave-wave interactions and dissipation (‘white-capping’) in deep waters; however, additional processes such as the effective wave-bottom interactions need to be considered in shallow waters. In very shallow areas, depth-induced wave breaking and wave-wave interactions become important also.

A structured mesh is developed to resolve the bathymetry within the computational domain (Figure 5). The mesh size is 0.05×0.05° and general time-step of the wave simulation model was set to be 12 min. The main parameters of the model were assigned based on comprehensive sensitivity analyses. Calibration and verification of the model was performed for about 30 individual selected events, based on the available historical and new data. The number of frequencies was set to 20, starting from 0.0714 Hz with a frequency increment factor of 1.108. The directional resolution was set to 10 degree which is recommended for computing the nonlinear interactions.

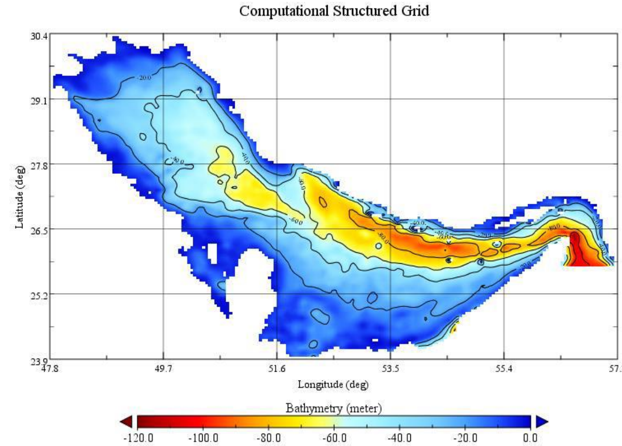

Figure 5. Bathymetry and computational domain of the Persian Gulf

Among available nonlinear schemes for the source terms in the wave model, TC96 and WAM4 represented the best results and the latter was chosen as the operational scheme of the forecasting system because WAM4 showed a better performance on simulation of wave peaks. Figure 6 depicts a comparison between a time series data of significant wave height recorded by Asaluyeh buoy (black dots) in 2010 and simulation results using TC96 (red line) and WAM4 (blue line) nonlinear schemes.

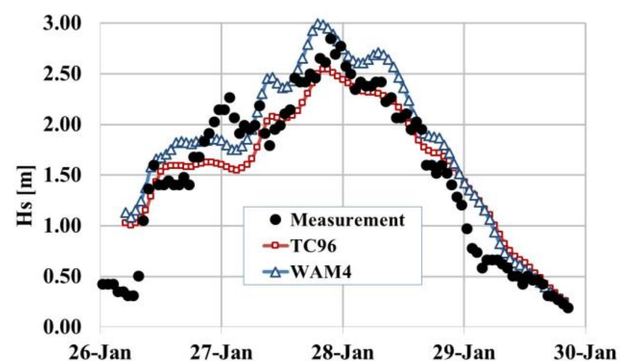

Figure 6. Comparison between B3 (Assaluyeh buoy) data in 2010 and WW3 model results

5. Results and Discussion

Figure 7 illustrates the comparisons between model results and recorded data of AW6 from 18th of March to 7th April, 2010. Given that AW6 was located in the middle of the Persian Gulf (see Figure 2), the recorded waves are generally higher than other parts. Blue dots present the measured data, which include significant wave heights (top panel), peak wave periods (middle panel) and mean wave directions (bottom panel). As shown in this figure, even though significant wave height and mean wave direction are in perfect consistency, wave period seems to be slightly underestimated. It is well known that among wave parameters, peak wave period is more sensitive to the implemented wave spectra. In addition, according to Niroomand et.al. [3], it seems that in spite of acceptable accuracy of conventional wave spectra used in spectral wave models including WW3, with regard to peak wave periods, there is a need to develop a more sophisticated wave spectra for the Iranian Waters including the Persian Gulf.

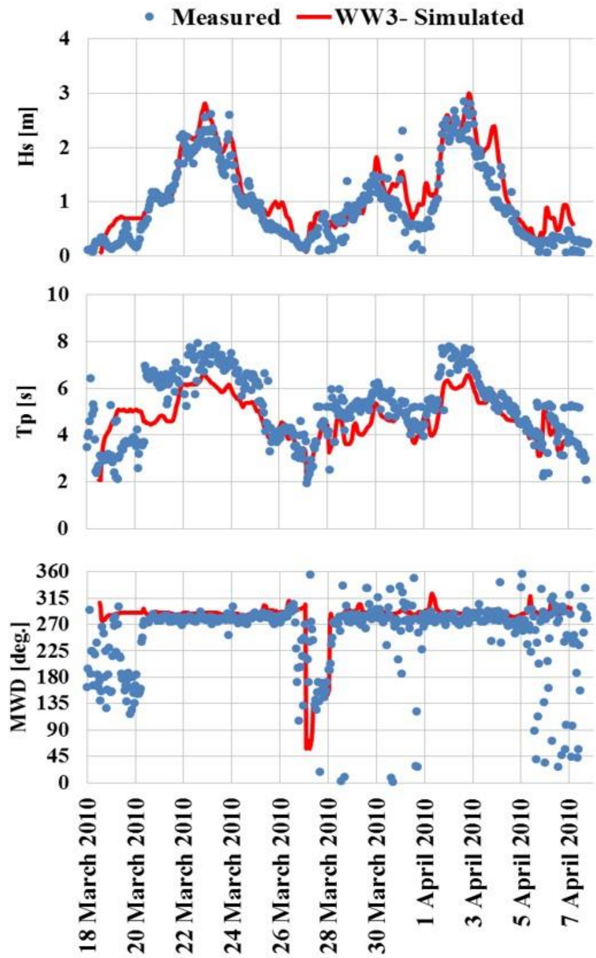

Figure 7. Comparisons between the recorded data of AW6 (Lavan) and WW3 model results

In the Northern part of the Persian Gulf which mostly experiences Shamal winds, similar patterns in the model results can be seen. Figure 8 illustrates comparisons between AW1 data near the Khark Island.

Towards the South East of the Persian Gulf and in the vicinity of the Strait of Hormuz, as shown in Figure 9, the model results are not as highly accurate as rest of the domain. Figure 9 illustrates that, even for a lower wave condition, computed significant wave heights are in slight discrepancy with the observed data. It is worth mentioning that, in this region, global wind models including GFS wind field which is the input data source for WRF model, presented less accurate data compared to the rest of the Persian Gulf. The reanalysis data such as ECMWF and CFSR, are reportedly facing similar deficiencies at this region [2] [4].

Table 2 presents the results of analytical analysis performed on shown comparisons in Figures 7 to 9 for AW6, AW1 and BS data collection stations.

Table 2. Analytical analysis results of presented events

DATA STATION	SIGNIFICANT WAVE HEIGHT		PEAK WAVE PERIOD	
	CC	RMSE (m)	CC	RMSE (s)
AW6 LAVAN FIGURE 7	0.92	0.35	0.85	0.95
AW1 KHARK FIGURE 8	0.86	0.36	0.77	0.87
BS SOUZA FIGURE 9	0.77	0.34	0.50	0.65

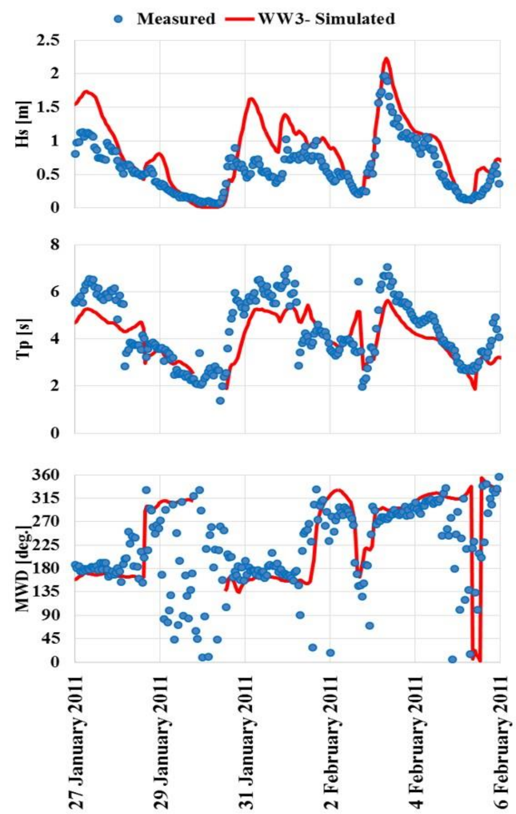

Figure 8. Comparisons between the recorded data of AW1 (Khark) and WW3 model results

An important feature of any forecasting system is the confidence level which in this research has been evaluated by comparing the difference between accuracy of the forecast between 24-h slices of every cast. Figure 10 shows a comparison between measured data and model predictions in less than 24 h and the same comparison when the significant wave heights are predicted between 24 to 48 h before the occurrence. The horizontal axis represents past hours from 1st of February 2015 (12 am) and model prediction results are collected from several consecutive forecast updates. As shown in the figure and represented in Table 3, the accuracy of predictions in the first two slices are almost the same which indicates that the confidence level is at its highest possible level up to 48 h.

Table 3 also presents the correlation coefficients and RMSEs of two proceeding 24-hour slices. Apparently, the ability of the model in prediction of the trends slightly decreases and a slight increase arises in errors.

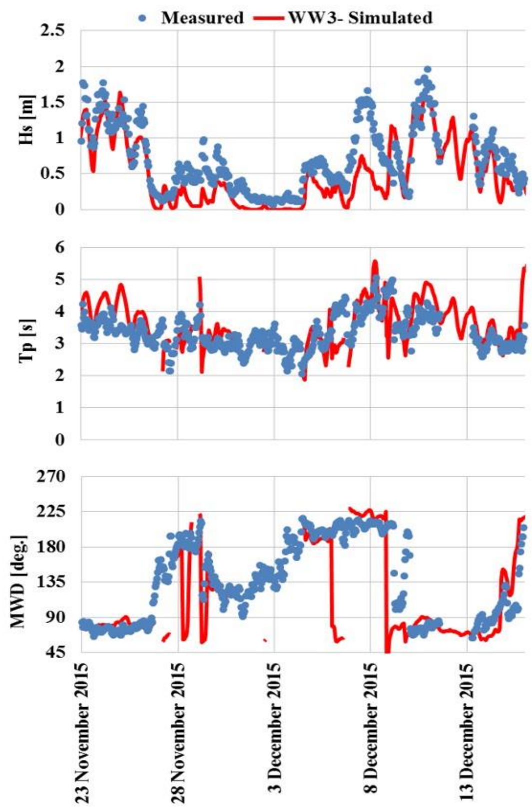

Figure 9. Comparisons between the recorded data of BS (Souza) and WW3 model results

Table 3. Analytical analysis results of forecast 24- hour slices

	24-Hour Slices			
	0 - 24	24 - 48	48 -72	72 -96
CC	0.81	0.81	0.79	0.62
RMSE (m)	0.41	0.43	0.47	0.49

6. Conclusion

The statistical evaluations of model performance show a high rate of consistency with the general correlation coefficient of significant wave heights of more than 80% and the average root mean squared errors being less than 0.35 m. The accuracy of the prediction of wave periods is also reasonable, with the average correlation coefficient of 70% and the root mean squared errors in the order of 0.8 s. The simulation results of mean wave directions also showed no significant issues.

Regarding the peak wave heights, the model showed a very reasonable performance for 65% of the high waves but 23% of the peaks were overestimated (up to 20% of the recorded wave heights) and the remaining 12% of simulated results were about 20% lower than the recorded values. Altogether, it can be concluded that the results of the forecast system for the Persian Gulf are reliable for most practical applications.

As a significant achievement of this research project, a completely automatic, robust and accurate forecasting system has been developed which in addition to providing the forecasting data to the official website of PMO [12], is capable of producing unlimited customized reports for specific locations of concern for clients. Figure 11 illustrates significant wave height and mean wave direction for the entire Persian Gulf. Figure 12 presents a 5-day predicted time series for Abu-Musa Island. Predicted significant and maximum wave heights along with predicted mean wave directions are presented in this figure.

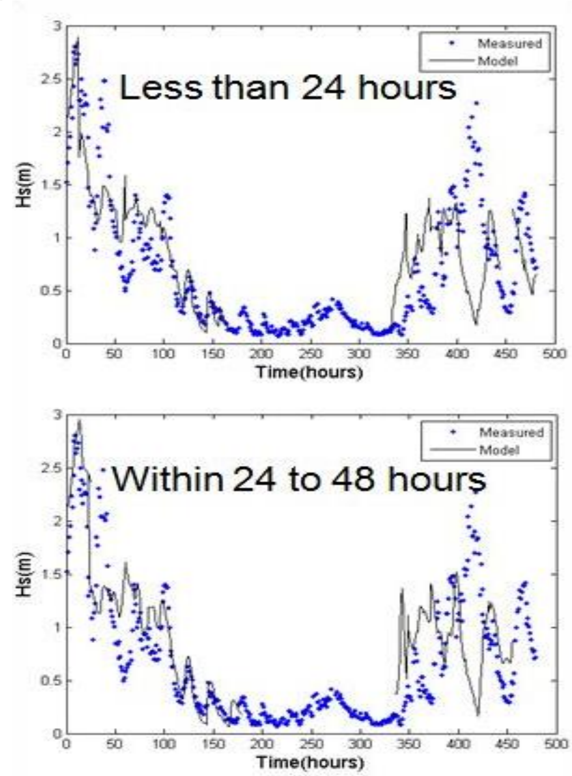

Figure 10. Comparisons between the measured data of BA (Asaluyeh) and forecasting system predictions within less than 24 hours (top panel) and between 24 to 48 hours (bottom panel)

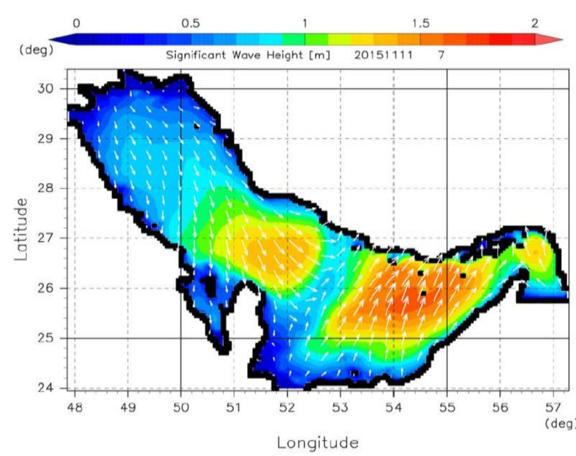

Figure 11. Significant wave height and mean wave direction in the entire domain

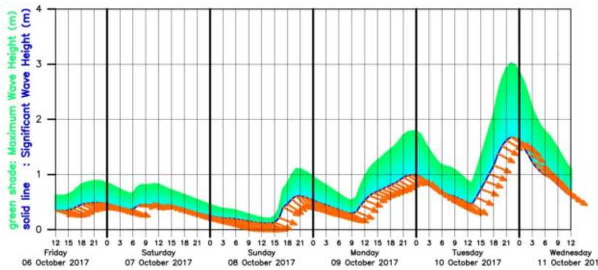

Figure 12. Five days predicted significant and maximum wave height and mean wave direction at AbuMusa Island

7. References

[1] Jedari Attari, M., S.A. Haghshenas, M. Soltanpour, A. Razavi Arab, Z. Hajisalimi, S. J. Ahmadi, A. Zarkani, M.R. Allahyar, A. Bakhtiari and E. Delkhosh (2016) Developing the Persian Gulf wave forecast system:, *Proceedings of 12th ICOPMAS*, Tehran, Iran, pp. 71-72.

[2] National Institute of Oceanography and Atmospheric Science and DHI (2008): Iranian Sea Waves Modeling (ISWM). *Modeling reports,* Ports and Maritime Organization (PMO)

[3] Niroomand, B., R. Kamalian, M. Soltanpour and M.R. Allahyar (2014) Study of the wave spectra in the Persian Gulf:, *Proceedings of 34th ICCE,* Seoul, Korea.

[4] Baird and Associates (2010) Development of a Wave Climate for the Persian Gulf and the Strait of Hormuz, *Modeling report,* Port and Maritime Organization (PMO), 114 p.

[5] Jahad Water Energy Research Co. (JWERC) (2012) Monitoring and Modelling Projects of Iranian coasts, *Phase II & III reports*. Ports and Maritime Organization (PMO).

[6] Ghader, S., D. Yazji, M. Soltanpour and M.H. Nemati (2016) On the use of an ensemble forecasting system for prediction of surface wind over the Persian Gulf:, *Proceedings of 12th ICOPMAS*, Tehran, Iran, pp. 97-98.

[7] Michalakes, J., J. Dudhia, D. Gill, J. Klemp and W. Skamarock (1998) Design of a next-generation regional weather research and forecast model: Towards Teracomputing, *World Scientific*, River Edge, New Jersey, pp. 117-124.

[8] Amante, & Eakins. (2009). ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. *NOAA Technical Memorandum* NESDIS NGDC 24. National Geophysical Data Center, NOAA. doi:10.7289/V5C8276M

[9] Jedari Attari, M., A. Bakhtiari, S.A. Haghshenas, E. Hamidian and J. Sasaki (2015) Long-term suspended sediment transport patterns over the North-Western part of the Persian Gulf, applying a three-dimensional hydrodynamic model. *Proceedings of 13th INTERCOH,* Leuven, Belgium, pp. 3-4.

[10] Haghshenas, S.A., A. Razavi Arab, A. Bakhtiari, M. Jedari Attari and M.J. Risk (2016) Decadal Evolution of Mond River Delta, the Persian Gulf, *Journal of Coastal Research* Special Issue No. 75.

[11] Tolman, H. (1991). A third-generation model for wind waves on slowly varying, unsteady and inhomogeneous depths and currents. *J. Phys. Oceanogr*, 21, 782–797.

[12] http://waveforecast.pmo.ir/