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Modeling of Last Recent Tropical Storms in the Arabian Sea

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Abstract: The Gulf of Oman and the Makran coastline as a part of the Arabian Sea are subjected to tropical cyclones influence on an infrequent basis; however, these cyclones can generate relatively large sea states. In this paper, recent tropical cyclones in the Arabian Sea were studied employing a third-generation spectral wave model and a 2D hydrodynamic model. The wind field of all cyclones is produced through an empirical wind generation model. The results of wave and hydrodynamic models are compared with data measured at different stations on the Gulf of Oman. The significant wave height, the peak wave period, the mean wave direction, and the water level changes are the four key features taken into consideration.

Based on the results, it could be concluded that the Young and Sobey parametric model is an appropriate technique to regenerate cyclonic wind fields over the Arabian Sea. In addition, the significant wave height, peak wave period, and the mean wave direction were reasonably predicted, despite the fact that the water level changes of the model were to some extent underestimated. The distribution of the wave fields and water level changes are presented to investigate the critical wave and surge in the study area.

Keywords: Tropical Cyclone; Numerical Model; Cyclone Phet; Cyclone Gonu, Cyclone Nilofar.

1. Introduction

One of the most important types of natural disasters over the coastal areas is tropical cyclones (TC). Based on the recorded data, the total yearly contribution of the North Indian Ocean (the Bay of Bengal and the Arabian Sea) is around 6.5% of all formed TCs (Neumann, 1993).

Tropical Cyclones in the Arabian Sea develop during the spring and fall between summer and winter monsoons over the area. The average sea surface temperature (SST) in the Arabian Sea is warm enough to support the development of tropical cyclones (Evan and Camargo, 2011). Nevertheless, strong vertical wind shear and also the atmospheric monsoon circulation restrict the development of cyclones and strengthening of TC which lead to only permitting a pre- and post-monsoon period for cyclogenesis (Gray et.al, 1968; Krishna, 2009; Rao et al., 2008; Evan and Camargo, 2011). Most of the North Indian Ocean cyclones are formed in an area between latitudes 8°N and 15°N, except June through September, when the little activity that does occur is confined to the north of about 15°N (Dibajnia et al., 2010). These storms are usually short-lived and weak; however, winds of 130 knots have been encountered (Krishna, 2009]. They often develop as disturbances along the Inter-tropical Convergence Zone (ITCZ); this inhibits summertime development since the ITCZ is usually over land during this monsoon season (Mashhadi et al., 2015; Emanuel, 2005; Webster et al., 2005).

The Gulf of Oman and its coastal area (the Makran coastline), as a part of the Arabian Sea, are also subject to tropical cyclones which can generate extremely significant sea states. This coastline which is also termed the Makran Coasts is about 350 km stretching from Gwadar Bay at the border with Pakistan to Rapch Estuary at the border with Hormozgan Province (Figure 1). In general, cyclones generated in the Arabian Sea tend to travel toward Omani coastline or they are redirected to the shores of Indian/Pakistani coastline. However, recently, some of these cyclones, such as Gonu and Phet entered the Gulf of Oman and large waves were produced along the Iranian and Omani coastlines (Dibajnia, et al., 2010). This cyclone had an unusual path, traveling much further west and north than the typical cyclone. The maximum wave height exceeded 4 m along the Iranian coastline, recorded at Chabahar located on the south coast of Iran bordering the Oman Sea (Mashhadi et al., 2015).

The atmospheric aspects and oceanographic results of the Cyclone Gonu were evaluated by different studies (Fritz et al. (2010); Krishna and Rao (2009); Dibajnia et al. (2010); Wang et al. (2012); Mashhadi et al. (2015)). Dibajnia et al. (2010) implemented the WAVEWATCH-III wave model and studied the wave field of the cyclone along the Iranian coastline of the Gulf of Oman. They evaluated their results by comparing the modeled wave height and wave period in contrast to the measured data in the Chabahar Bay. The simulated wave field was used to modify the database for

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extreme wave height over the area. Golshani and Taebi (2008) also discussed the process of numerically simulating the cyclone Gonu and its resulting waves in the Gulf of Oman. The Gonu wind field was simulated using forecasted cyclone data for different scenarios based on varying cyclone radii. Thereupon, they were applied to a wave model which was previously set up and calibrated. Mashhadi et al. (2015) investigated the waves over the Arabian Sea by the Gonu tropical cyclone. In their study, the SWAN third-generation spectral wave model was used. They considered the significant wave height, the peak wave period, and the mean wave direction as the three key features of the wave model. Their results revealed that the significant wave height and the mean wave direction could be reasonably predicted. However, the simulated peak wave period was underestimated with regard to the measured data. In a separate study, Allahdadi et al. (2017) used the wave data from the same station outside of the Chabahar Bay for evaluating both parametric and spectral outputs of the MIKE21 SW model.

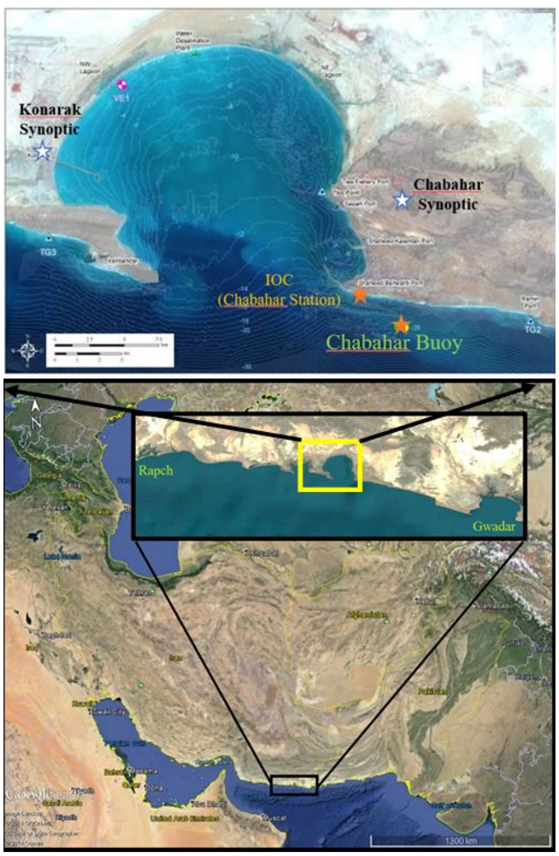


Figure 1. Study area

Previous researchers showed that a better understanding of tropical cyclones and hurricane hazards in this area will help to make a more informed decision on risks and relevant actions to take. There is a pressing need in the operational scenario to provide hindcasts in a meaningful and quantitative way of these events with a greater accuracy. Therefore, in this study, as a part of the sixth phase of Monitoring and Modeling Study of Iranian Coasts, the assessment of tropical cyclone risks along the Iranian coastline of the Arabian Sea and the Gulf of Oman was investigated.

The research aims to improve the understanding of hazards posed by tropical cyclones to ports and harbors of the Makran coastline. The resulting risk information will allow beneficiaries and the government to better integrate risk considerations into infrastructure development and ex-ante disaster planning.

2. Model Implementation

2.1. Numerical Models Description

The results described in this paper were obtained using the well-known MIKE21 modeling system from the Danish Hydraulic Institute to simulate both the storm surge and the wave conditions (DHI, 2007a and b). The system consists of several modules of which two were used in this study. Wind-generated waves were calculated using the Spectral Waves Module (MIKE 21 SW). It is a fully spectral wind-wave model that calculates the growth, decay, and transformation of wind-generated waves and swell in offshore and coastal areas. The MIKE 21 Flow Model-FM is a generally two-dimensional (2D) hydrodynamic modeling system which uses a flexible mesh system in the horizontal direction. MIKE 21 simulates unsteady two-dimensional flows in one layer (vertically homogeneous) fluids. The Hydrodynamic module (HD) and the Spectral Wave module (SW) are two main computational components of this study. The model makes it possible to consider the mutual interactions between waves and currents. This is provided by coupling between the HD and the SW module. The HD modules simulate water level variations and flow in response to a variety of forcing functions (DHI, 2007a). The spatial discretization of the primitive equations is performed using a cell-centered finite volume method. The spatial domain is discretized by subdivision of the continuum into non-overlapping elements/cells. In the horizontal plane, an unstructured grid is employed. More descriptions for the governing equations and numerical formulation in the hydrodynamic and wave models can be found in (DHI, 2007a) and (DHI, 2007b).

2.2. Numerical Models Description

2.2.1. Bathymetry. The bathymetry file for the present study was compiled using a vast hydrographic effort along the Makran coastline. In addition, a number of hydrographic data contributed to the generation of bathymetry, comprising local hydrographic data, minute gridded data of ETPO, Iranian National Cartographic Center (NCC) nautical, vector shoreline data of the Iranian coast from Iranian ICZM database, ESRI 2006 vector shoreline data, global Landsat Imagery, and Admiralty Charts (see Figure 3). The NGDC ETOPO2 data was downloaded from the NGDC website using a custom extent to include data only relevant to the Arabian Sea. This data was published in 2006 and contains bathymetry data at intervals of 2 latitudinal and longitudinal minutes (Smith et al., 1997). The data was used only in areas where there was no data coverage from the NCC nautical charts. No boundary condition data was used at the open ocean boundary in the forecast modeling.

2.2.2. Wind and Pressure. In general, several parametric methods were included in the tropical storms' studies to regenerate the wind field (Young and Sobey, 1981; Holland, 1980, Phadke, 2003). Moreover, different mathematical wind models such as WRF wind model could be applied to regenerate the cyclonic wind structure. In this study, computations of the wind and the pressure field due to a tropical cyclone were done using the parametric wind models.

In other words, wind and pressure data were regenerated by methods which could be described by simple parametric models such as Holland (1980), Young and Sobey (1981), and Rankine (Phadke et al. 2003) methods based on few parameters such as the position of the cyclone's eye, radius of the maximum winds, etc. Most of these parameters are generally available from meteorological publications as the Best Track (BT) and Indian Meteorology Department (IMD) data table for each cyclone (Krishna, 2009; Knapp et al, 2010). Wind and pressure data are then computed for different formats of output files allowing the user to easily investigate the cyclonic forcing.

In this study, the Joint Typhoon Warning Center (JTWC) maintains the "Best Track" database for cyclones in the Indian Ocean with a time span of 1945–2007. Prior to 1975, only track information was available. From 1975 to 1979, maximum wind velocity was not available for all cyclones or was only available for partial cyclone tracks. Since 1979, maximum wind velocity has been available for all storms. Therefore, the International BT Archive for Climate Stewardship (IBTrACS) global tropical cyclone database has been used to represent historical TC activity (Knapp et al., 2010). The IBTrACS database (from here onwards BT in brief) collates information on TC tracks and intensity from reporting agencies around the globe and provides a single authoritative database that can be used for climate analysis.

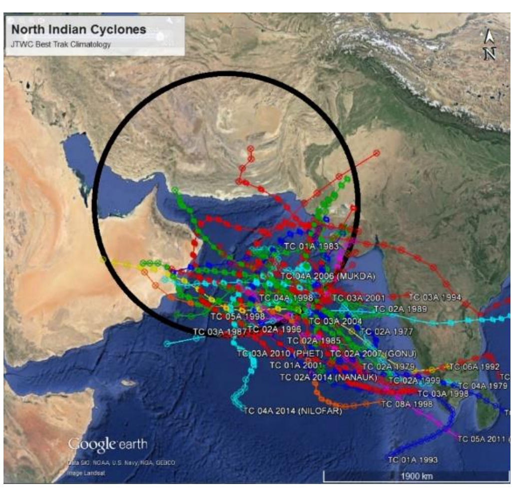


Figure 2. TC Tracks within 100 km of the Eastern End of the Oman Sea Coastline

2.3. Model Calibration

The current study will provide a hindcast estimation of the wave characteristics and storm surge along the southern coast of Iran (Makran Coastline) and the Arabian Sea induced by TCs which are shown in Table 1. For this purpose, applying various domains shows that obtaining reasonable results requires adopting a domain from 10Nº.

Table 1. Major Cyclones in the Arabian Sea during 1977-2014

No.	Year	Vmax (m/s)	Start	End	Name
1	1977	30.84	9-Jun	13-Jun	bio021977
2	1977	20.56	27-Oct	4-Nov	bio041977
3	1978	41.12	3-Nov	13-Nov	bio031978
4	1979	25.70	16-Jun	20-Jun	bio021979
5	1979	28.27	16-Sep	25-Sep	bio041979
6	1980	17.99	12-Nov	19-Nov	bio031980
7	1981	30.84	25-Oct	2-Nov	bio011981
8	1983	23.13	9-Aug	10-Aug	bio011983
9	1985	25.7	28-May	1-Jun	bio021985
10	1987	25.7	4-Jun	12-Jun	bio031987
11	1989	17.99	7-Jun	13-Jun	bio021989
12	1992	28.27	29-Sep	4-Oct	bio061992
13	1993	41.12	5-Nov	16-Nov	bio011993
14	1994	23.13	5-Jun	9-Jun	bio031994
15	1995	25.7	11-Oct	18-Oct	bio021995
16	1996	20.56	9-Jun	12-Jun	bio021996
17	1998	51.4	1-Jun	9-Jun	bio031998
18	1998	17.99	28-Sep	1-Oct	bio041998
19	1998	17.99	15-Oct	18-Oct	bio051998
20	1998	33.41	11-Dec	17-Dec	bio081998
21	1999	56.54	15-May	21-May	bio021999
22	2001	56.54	21-May	29-May	bio012001
23	2001	17.99	24-Sep	28-Sep	bio022001
24	2001	17.99	8-Oct	13-Oct	bio032001
25	2004	17.99	30-Sep	10-Oct	bio032004
26	2006	28.27	19-Sep	26-Sep	bio042006
27	2007	74.53	31-May	8-Jun	Gonu
28	2007	25.7	20-Jun	27-Jun	bio032007
29	2010	64.25	30-May	7-Jun	Phet
30	2011	17.99	25-Nov	1-Dec	bio052011
31	2014	28.27	8-Jun	14-Jun	Nanauk
32	2014	59.11	23-Oct	1-Nov	Nilofar

Figure 3 shows the computational domain and the corresponding bathymetry. The considered area extended from 10º N which reasonably covered the Arabian Sea. The hydrodynamic and wave forcing data used in the models were meteorological data, such as wind speed and direction, and atmospheric pressure.

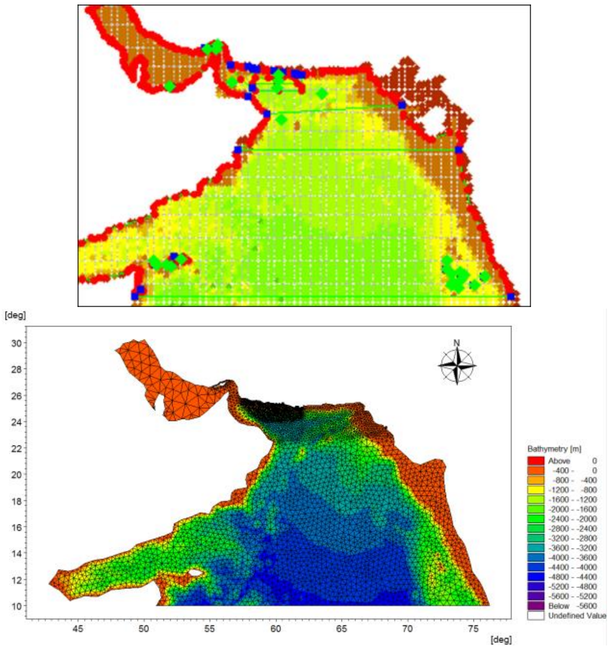


Figure 3. Computational domain and implemented bathymetric data

To calibrate all the implemented models, an intense set of measured data were used. An invaluable data set recorded during the first phase of Monitoring and Modeling Study of Iranian Coasts sponsored by Port and Maritime Organization (PMO) includes wave characteristics measurements in 30 m depth at a location outside the Chabahar Bay (JWERC, 2008). Measurements at this location cover the period from September 2006 until early June 2007 immediately after the Cyclone Gonu event. In addition, wind and wave measurements were carried out offshore of the Chabahar Bay in 20 m water depth from 1998, and the effects of cyclones that occurred from this were detected. A synoptic wind station in Chabahar area also recorded winds characteristics. Furthermore, Intergovernmental Oceanographic Commission (IOC) data were implemented for calibration and verification purpose. Table 2 summarizes the characteristics of the aforementioned data sources.

Table 2. Properties of Measured data

No.	Station		Depth (m)	location	
				Long. (Eº)	Lat. (Nº)
1	Chabahar Buoy (PMO)		30	60.6	25.3
2	Chabahar Buoy (IRIMO)		17	60.65	25.26
3	Phase I stations	AW1	10	60.594	25.289
		AW2	30	60.65	25.26
		AW3	11	60.474	25.291
4	Konarak Synaptic station		land	60.37	25.43
5	Chabahr Synaptic station		land	60.26	25.28
6	Chabahar IOC station		tide gauge	60.62	25.28

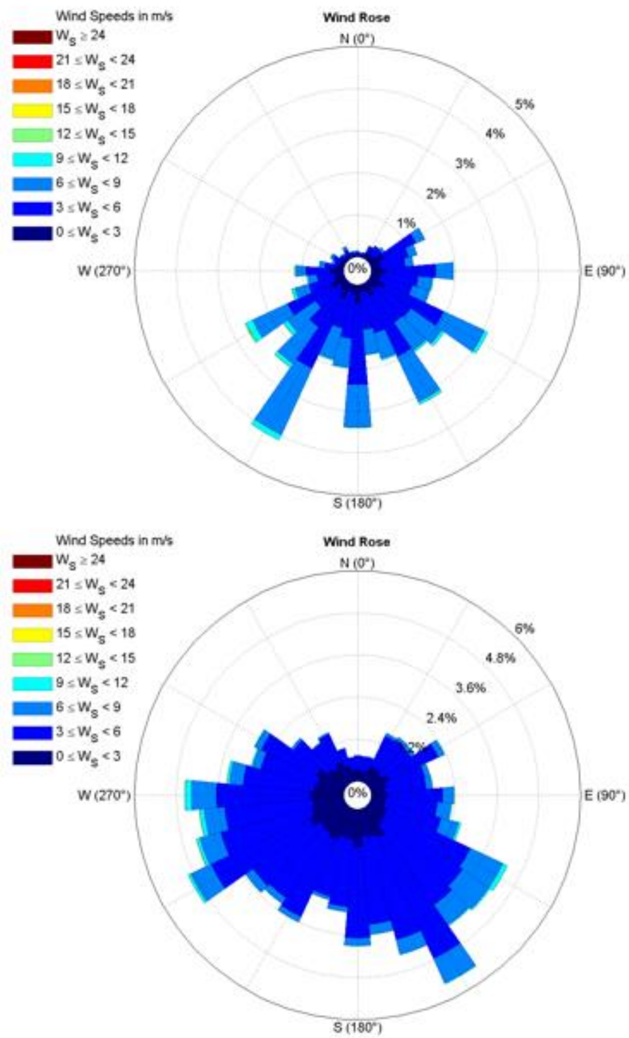


Figure 4. Wind rose of the Konarak (up) and Chabahar (down) synoptic stations.

It worth mentioning that IOC aims at the establishment of high quality global and regional sea level data for application in climate, oceanographic and coastal sea level research (Bekiashev et al. 1981). Original data of the Chabahar IOC station spanned from January 1996-November 2006. The station is part of the Iranian tide gauges project and a new gauge started operation in November 2007 up to now.

All the imperial wind models including Young and Sobey (1981), Holland (1980), and Rankine (Phadke et al., 2003) were considered for the calibration examination of the modeling activities. For the wind regime, time series of wind speeds/pressures measured at 3-h time intervals in Konarak and Chabahar synoptic wind stations were used. Figures 5 and 6 illustrate the model calibration results against the measured data near the Chabahar Bay (Table 2 ad Figure 5). It worth mentioning that all the six input parameters which are required by the Young and Sobey model (i.e. time, track, the radius of maximum wind speed, maximum wind speed, central pressure and neutral pressure) were collected from the BT database.

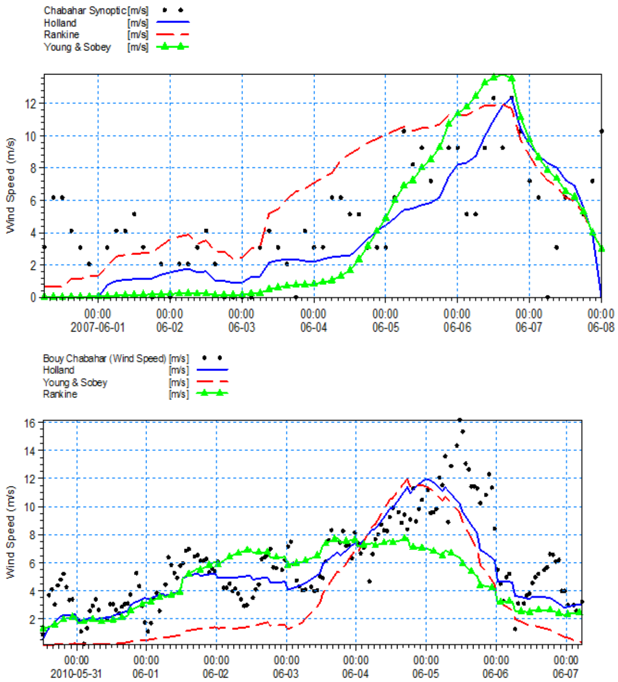


Figure 5. Comparisons between wind speed of Chabahr Buoy data and WGC results during cyclones Phet (below) and Gonu (above).

Table 3. Statistical parameters for wind speed calibration versus measured data.

Model	Root-Mean-Squared Error	Standard Deviation of Residuals	Correlation Coefficient
	RMSE	SDR	R
Holland	2.84	2.83	0.68
Rankine	3.35	3.03	0.62
Young& Sobey	3.26	3.14	0.72

Table 4. Main model parameters for the cyclonic model

Parameter		Value
Mesh characteristics		an unstructured mesh with 8129 nodes and 15470 elements
Time step		120s
White capping	C_{dis}	4.5
	$DELTA_{dis}$	0.5

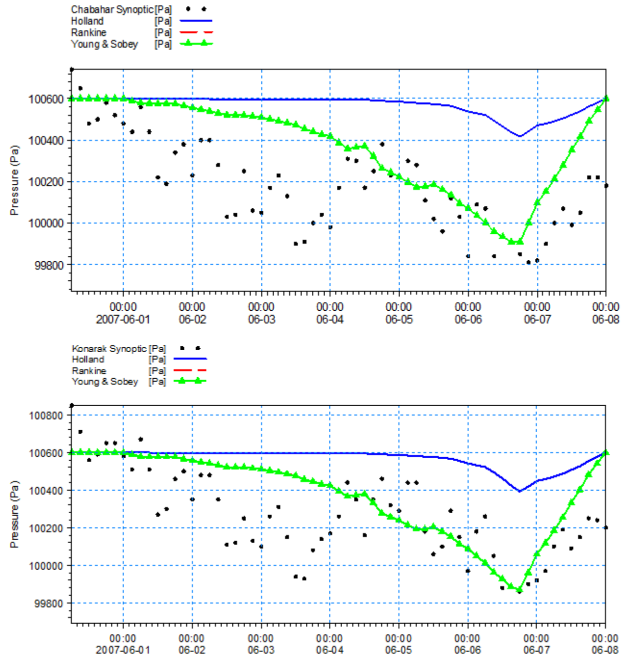


Figure 6. Comparisons between the measured atmospheric pressure of Chabahr Synoptic data (above) and Konarak Synaptic data WGC results during Cyclone Gonu (below).

Table 3 summarizes the results of all calibration activities. Regarding these results, the Young and Sobey method was found to be very consistent with the cyclonic wind data over the Makran Coastline both for wind speed and atmospheric pressure. Holland method also had the same statistical situation for the wind speed, but the atmospheric pressures in this method are less accurate rather than the others. It is more pronounced in the surge calculation part. It should be noted that the Holland method was to some extent underestimated rather than the Young and Sobey method.

2.4. Model Validation

Model parameters were estimated in two main steps. Firstly, in a series of sensitivity analyses, the parameters that had the significant influence on the model output were identified and were calibrated. Recommended values from the literature were extracted for the less sensitive parameters. In the second step, the SW and HD results were verified against the pre-described measurements. In this section, the last step will be described.

Validating simulations for the modeling activities were performed for the HD and SW models results. These validations covered the period of well-known cyclones including cyclones Guno, Phet and Nilofar, where a series of simultaneous measurements of the wave characteristics and water level fluctuations taken at several locations around the study area are available. Figures 7 and 8 display a typical output from the wave model validation and Figure 9 presents the comparison of calculated water level fluctuations (storm surge) due to the cyclone Phet and the cyclone Gonu versus measured data.

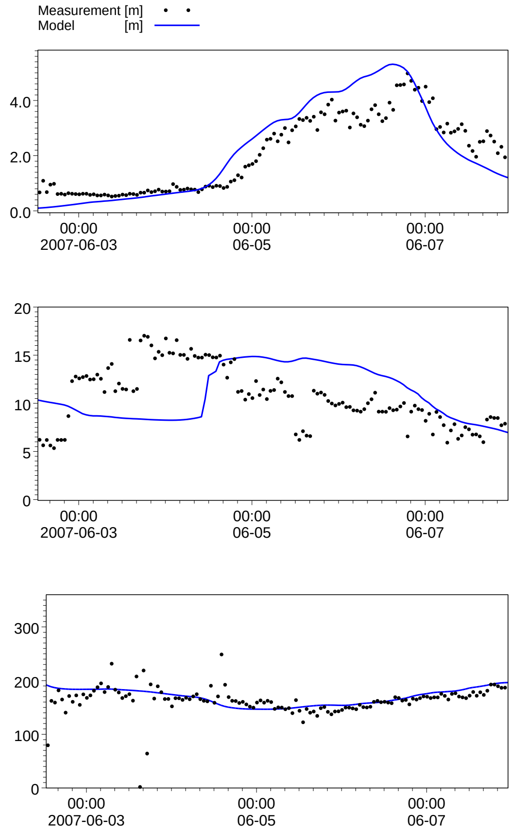


Figure 7. Comparisons between measured AW2 data versus wave model results during the Cyclone Gonu).

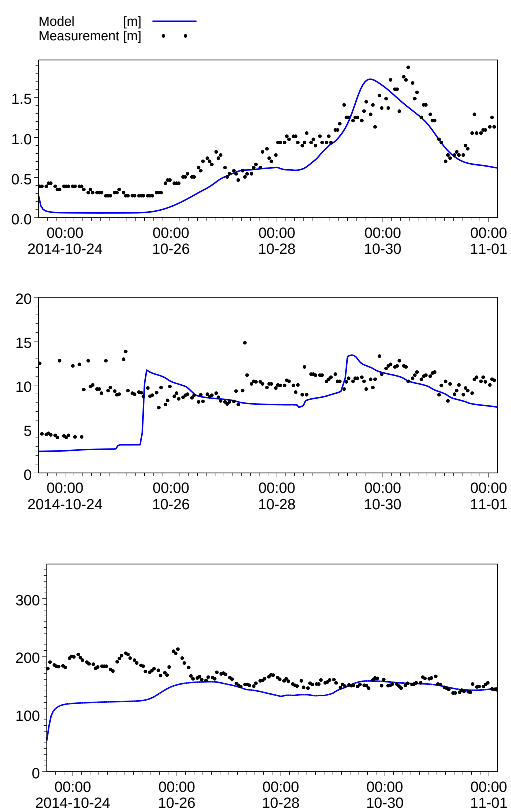


Figure 8. Comparisons between measured Chabahr Buoy data versus wave model results during the Cyclone Nilofar.

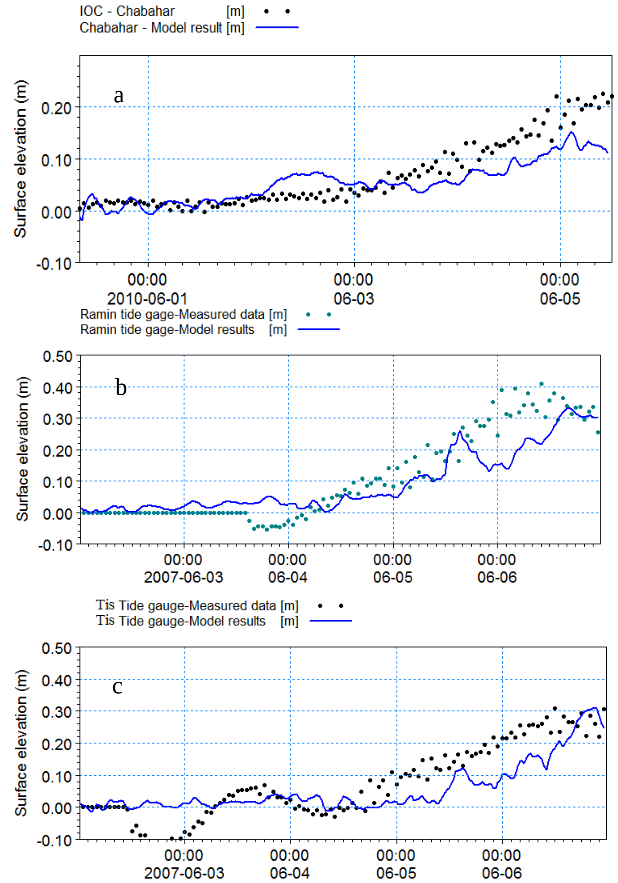


Figure 9. Comparisons between measured data and model results at (a) Chabahr IOC data during the Cyclone Phet (b,c) Ramin and Tiss tide gages during the Cyclone Gonu.

Comparisons of model results with measurements of the Cyclone Gonu for wave height, mean period and mean wave direction are presented in Figure 7. The figure proved that using the simulated wind field and the SW model based on the data at AW2, the model could appropriately simulate variations of wave height when the Cyclone was translating the northern Gulf of Oman Sea. The model resulted in an approximately the same maximum wave height of about 4.5 m measured at AW2. In addition, the values of the peak wave period and the mean wave direction led to reasonable values. With the Nilofar Cyclone, the wave parameters simulated were quite compatible with the Chabahar Buoy data (Figure 8). As illustrated in Figure 9, the water level changes were compared with measured data at the Chabahar IOC station with measured values during the cyclone Phet (Figure 7). For both wave and water level models, the model was able to represent satisfactory results.

Table 4 presents the final selected value of the cyclonic model.

3. Results and Discussion

Figure 10 depicts the maximum value of significant wave height regarding the cyclones Gonu, Phet, and Nilofar tracks during the entire duration of each cyclone. As shown in Figure 10, only the cyclones Gonu and Phet striked the mainland. The cyclone Nilofar started to weaken before it could reach the coast. The maximum significant wave height of the cyclone Gonu was about 15 m along the cyclone track near the Omani coastline which is a higher value rather than some previous results (about 13 m). The cyclone Phet maximum wave height recorded near the south-western part of Omani coastline is around 14 m. However, the significant wave height maxima for the cyclone Nilofar did not exceed more than 10 m.

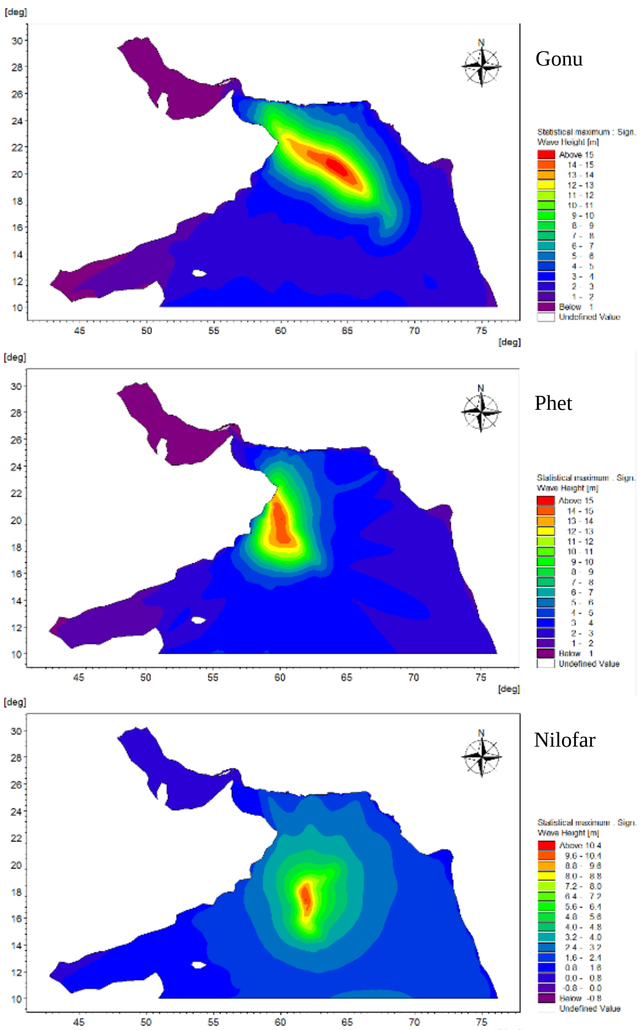


Figure 10. The significant wave heights (m) on the Arabian Sea during cyclones Gonu, Phet, and Nilofar. (Plots represent the maximum significant wave height occurred in each location during a cyclone)

Figure 11 illustrates the cyclones Phet and Gonu wave height along the Makran coastline. As could be seen from the figure, along with the Iranian coasts of the Gulf of Oman, the maximum significant wave height was obtained as about 8 m which occurred near the western part (point 8 on the figure) of the Makran coastline. Toward the east (points 1 and 2 on the figure), the significant wave height was increasing. With cyclone Phet, there was a partly homogeneous distribution of wave height along the coastline.

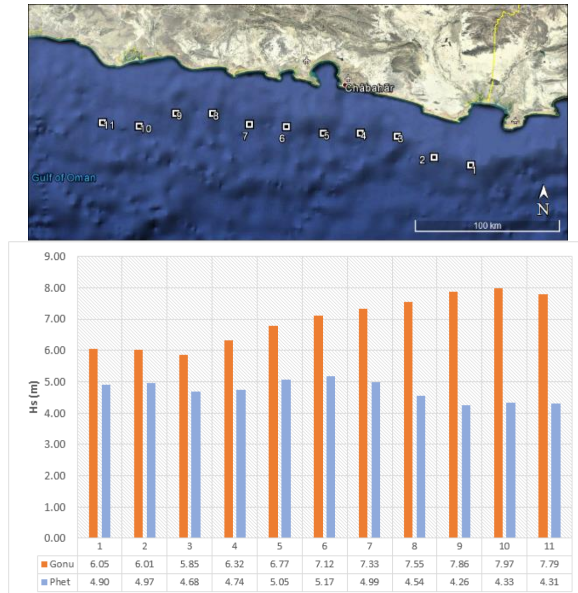


Figure 11. The maximum significant wave height along the Makran coastline (selected points) during the entire duration of cyclones Gonu and Phet

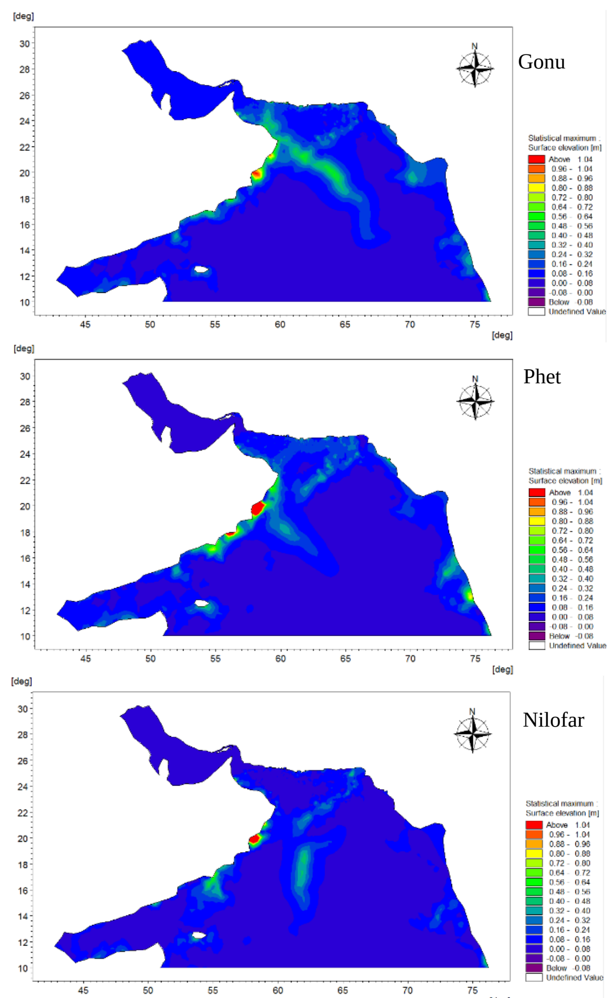
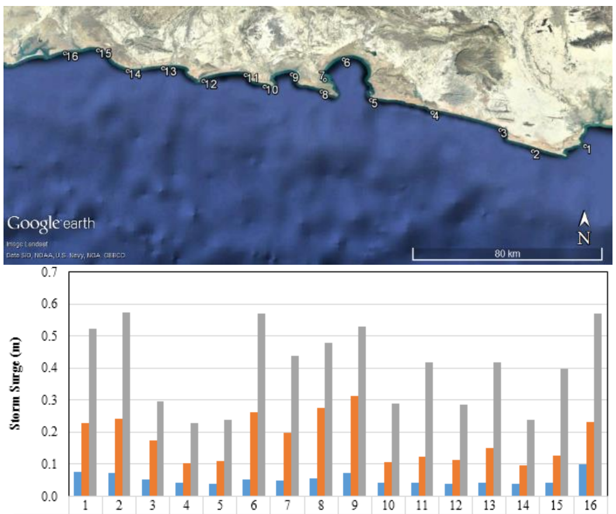


Figure 12. HD storm surge (m) over the Arabian Sea during cyclones Gonu, Phet, and Nilofar. (Plots represent the maximum surge in each location during a cyclone)

The maximum water level due to cyclones Gonu, Phet, and Nilofar are shown in Figure 12. From this figure, it could be concluded that, over the Arabian Sea, the maximum predicted water levels regarding all the Cyclones took place near the Omani coastline. However, the maximum reported water level, along with the Iranian coasts generated by the Cyclone Gonu which was about 0.65 m (Figure 13) near the Chabahar Bay.

Figure 13 presented the maximum water level during the simulated cyclones along the Makran Coastline at a depth of 1.0 m. Based on these results, the Cyclone Nilofar generated water levels less than 0.1 m which are quite negligible. Although the Cyclone Phet derived water level that reached 0.3 m near the Pozm Bay (Point 9), it was also not a severe value.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Nilofar	0.078	0.073	0.053	0.042	0.038	0.052	0.048	0.057	0.073	0.041	0.041	0.040	0.042	0.040	0.043	0.099
Phet	0.229	0.244	0.174	0.104	0.109	0.262	0.197	0.277	0.312	0.108	0.123	0.113	0.151	0.096	0.127	0.231
Gonu	0.522	0.574	0.297	0.228	0.238	0.572	0.438	0.478	0.529	0.290	0.419	0.285	0.417	0.239	0.399	0.569

Figure 13. Maximum surge along the Makran coastline (selected points) during the entire duration of cyclones Gonu, Phet, and Nilofar

However, due to the Cyclone Guno's large wind field and its track across the Gulf of Oman, easterly winds persisted over the Makran coastline for over 72 h. While the winds over these coasts never exceeded 20 ms^{-1}, the long duration and steady direction allowed for effective penetration of surge generated over these waters and into the bays and estuaries around the Makran coastline.

4. Conclusion

A detailed investigation of wind, waves and water level changes generated by tropical cyclones has been carried out for the Gulf of Oman and its Iranian coastline. Model setup and model parameters for the wind regeneration model were selected by evaluating three major tropical storms which occurred in the Gulf of Oman and the Arabian Sea, since 1977 including cyclones Gonu, Phet, and Niloufar. Predicted wind and pressure data were calibrated against recorded data. Eventually, Young and Sobey's parametric model provided the best results both for wind speeds and sea surface pressure. Thereupon, the model's validation demonstrated their capabilities and approved the selected wind field which is exerted on the water level and wave models.

Finally, the following conclusions are summarized and represented based on the analyses and modeling performed in this study.

- The Young and Sobey parametric model was the most appropriate method for regenerating the winds field of recorded TCs over the Arabian Sea.
- Calculated storm surges regarding the selected period are in good agreement with the measured data.
- Wave characteristics and water level variations were reasonably compatible with measured data in the area of interest in this study.
- The maximum storm surge over the Makran Coastline occurred approximately to the Chabahar Bay during cyclone Gonu which is about 0.6 m.
- The maximum significant wave heights along the Makran Coastline take place during cyclone Gonu which ranged from 6 to 8 m, decreasing toward the east.

5. Acknowledgments

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