ORIGINAL PAPER

Assessment of wind datasets on the tropical cyclones' event (case study: Gonu tropical cyclone)

Ahmad Rezaee Mazyak[1] · Mehdi Shafieefar[1] 🆔

Abstract

Even though the occurrence rate of tropical cyclones (TCs) is almost steady as reported in earlier studies, however, the intensity of TCs has shown a significant increase due to global warming. Gonu (2007) and Phet (2010) are examples of TCs, which affected the southern coasts of Iran. The first step in evaluating the effects of TC is the accuracy as well as the correctness of the wind field. For this purpose, the WRF and parametric models have been implemented for the wind field simulation, in the Makran coasts during the Gonu TC. QuikSCAT satellite data and coastal synoptic stations data have been used to evaluate the wind field results. The results indicated that the WRF model can successfully forecast the cyclone's path and its outputs can be employed to forecast such weather hazards. Comparing the wind field results with satellite data, highlights the accuracy of the WRF model in the coastal areas. Modeling the wind field asymmetry due to the cyclone confinement and more realistic wind distribution, distinguishes the results of WRF model from other studied counterparts. In addition, a comparison of the wind field results with the synoptic data indicates that the WRF model results meet very good accuracy. Furthermore, the study of cyclone damage potential (CDP) index in the Gulf of Oman northern coasts shows that the WRF outcomes have a very high accuracy. This study highlights the capability of the ARW model in simulating the wind field, especially on the southern and southeastern coasts of Iran, which are affected by TCs.

1 Introduction

Tropical cyclones (TCs) are intense atmospheric vortices, which are generated in the tropical regions and humid oceans. They are in the form of hundreds of kilometers thunderstorms sucking the air around. Severe TCs cause heavy and destructive winds, heavy rains, and strong waves in the coastal areas, which can lead to extensive destructions in these places. Hence, accurate investigation of the effects of TCs may lead to the optimal design of the coastal structures, adoption of optimal strategies for the coastal zone management and reduction of damage caused by this natural phenomenon.

Examining the accuracy as well as correctness of the tropical cyclones' wind field is the first essential step in evaluating the effects of this phenomenon on the coastal area. Since the wind's speed and direction change rapidly in the place and time when this phenomenon occurs, the correct hindcasting of the wind field is a very difficult process.

The common methods of wind field hindcasting can be classified into three groups, including the parametric models based on gradient wind balance, Hurricane Research Division (HRD) surface wind analyses system (H*WIND), and mesoscale meteorological models such as weather research forecasting (WRF) (Alizadeh-Choobari 2015; Das 2018; Dunion et al. 2003; Green and Zhang 2015; Guo and van de Lindt 2019; Lin and Chavas 2012; Powell et al. 1998; Young 2017). In addition to the above hindcasting approaches, the wind field of the reanalysis models such as the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalysis (ERA-Interim) and Climate Forecast System Reanalysis (CFSR) are currently used for hindcasting the waves, ocean circulation, and storm surge due to the TC (Durrant et al. 2014; Mazaheri et al. 2013). Examining the technical literature of this field indicated that the parametric, atmospheric mesoscale models (WRF) and reanalysis databases information have been widely used by many researchers (Cardone and Cox 2009; Krien et al. 2018; Tanemoto and Ishihara 2013).

✉ Mehdi Shafieefar
 shafiee@modares.ac.ir

[1] Faculty of Civil and Environmental Engineering, Tarbiat Modares University, Tehran, Iran

Parametric models are based on the vortex physics. In these models, the wind field pattern is simulated radially like vortices. To hindcast the TC's wind field using the parametric models, the temporal and spatial distributions of parameters such as location of the cyclone center (eye), wind radii, maximum velocity and pressure drop are required. In recent decades, the use of such models has received much attention for hindcasting the influences of the tropical cyclones (Holland et al. 2010; Vickery and Twisdale 1995). The initial wind field hindcasting models have been presented by Holland (Holland 1980; Young and Sobey 1981). The initial models presented by them are based upon the parametric analysis of the angular wind speed gradient. Thompson and Cardone have modeled the simultaneous impacts of the two cyclones by improving the Holland model (Thompson and Cardone 1996). Rankin model is another parametric model of wind field simulation, in which, the considered profiles for the wind field have been developed using the vortex model and radial profile definition (DHI 2017). The ease of using parametric models is one of the important advantages of this method. However, the wind field simplification for the simulation is one of the disadvantages of the parametric models that can lead to the modeling errors in some cases.

Therefore, if the wind field is more carefully considered, the capabilities of mesoscale atmospheric models can be used for its simulation. WRF is one of the most common examples of the mesoscale atmospheric models. The performance of the WRF model to simulate the TC's wind field has been evaluated in numerous studies in terms of its path and intensity. The results indicate that this model is highly dependent on the initial boundary conditions and selection of the used parameterizations (Alimohammadi and Malakooti 2018; Cha and Wang 2013; Dodla et al. 2011; Mohanty et al. 2010; Osuri et al. 2012a; Srinivas et al. 2013; Xue et al. 2017). Dodla et al. have simulated Katrina tropical cyclone near Florida coasts by implementing the three models of HWRF, ARW and NMM (Dodla et al. 2011). Osuri et al. investigated the performance of the advanced research WRF (ARW) model in real-time forecasting of 17 tropical cyclones that occurred in the North Indian Ocean. The results indicate the high capability of operational ARW model in simulating the wind field within the study area (Osuri et al. 2013). Comparison of the three models' outputs illustrated that the HWRF model has better performance in simulating Katrina cyclone. Xue et al. used the WRF model to simulate the tropical cyclone in southern coasts of China (Xue et al. 2017). Nadimpalli et al. assessed the performance of hurricane WRF (HWRF) and WRF models in simulating 10 tropical cyclones occurred Bay of Bengal during the time frame 2013–2017. The results point out to the necessity for using high-resolution initial and boundary conditions to forecast the cyclone in the study area (Nadimpalli et al.

2020). The obtained results showed that the WRF model is capable of simulating this cyclone with high accuracy.

In addition to the above-mentioned wind field simulation methods, one can use the reanalysis wind field data to evaluate the effects of tropical cyclones. The wind field data of the reanalysis models during the tropical cyclones have been evaluated as input data for the ocean flow modeling in many studies (Bell et al. 2013; Rathmann et al. 2014). Murakami investigated the tropical cyclones' characteristics in the reanalysis data (Murakami 2014). The results illustrated the reasonableness of the spatial and temporal distributions of the tropical cyclones via the reanalysis data. Comparison of the different reanalysis data also indicated that higher spatial accuracy of the reanalysis data does not necessarily lead to the accurate evaluation of the tropical cyclone's conditions. Hodges et al. assessed the track and intensity characteristics of the tropical cyclones in the reanalysis data (Hodges et al. 2017). The conducted investigations show that the cyclone track in the reanalysis data is in good agreement with the Best track data. However, the reanalysis data underestimate the wind speed values of the tropical cyclones while overestimate the corresponding pressure much higher than the measured values.

The results of the technical literature review indicates that the wind field examination of the TCs is one of the crucial steps in studying this natural phenomenon. Improving the accuracy of the TC's wind field data yields the improved results of other studies such as hindcasting the waves and ocean circulation formed due to this phenomenon. Less attention is paid to comprehensive study on wind field distribution by different methods (Parametric method, WRF model, and Re-Analysis data) in the literature. Therefore, the aim of this study is to simultaneous evaluation of all methods in the most severe cyclone-affected the Gulf of Oman northern coasts. Since the tropical cyclone Gonu is the most severe one that has occurred in the Arabian Sea, it has been investigated in this paper. The results of present study highlight the need to use an appropriate model for simulating and forecasting the weather risks in the coastal areas. For this purpose, the wind field due to the reanalysis data of ECMWF (ERA-Interim) and CFSR, simulation using WRF models and parametric ones of Young and Sobey (S&Y), Holland and Rankin, have been evaluated during the cyclone Gonu occurrence. To assess the accuracy of the studied wind fields, the data associated with QuikSCAT satellite, and Chabahar and Jask synoptic stations have been used. Therefore, after presenting the research methodology in Sect. 2, the study area will be introduced in Sect. 3. Section 4 is dedicated to the provision of data specifications and undertaken models. Model setup properties are described in detail in Sect. 5. Comparison and interpretation of the models' results with the measurement data as well as examination of the damage potential caused by the storm based on

the simulation results are presented in Sect. 6. Further, the conclusions are presented in the final section.

2 Research methodology

Identifying the dominant wind field in the study area is one of the most basic and important necessary information for conducting the ocean and marine simulation studies. The proposed method in this study can be employed for identifying the wind field in an area. The present method can be summarized in the following three steps (see Fig. 1).

The first step is to determine the characteristics of the tropical cyclone Gonu. At this point, information of the investigated databases is selected after checking the authentic best tracking databases of Joint Typhoon Warning Center (JTWC, https://www.metoc.navy.mil/jtwc) and Indian Meteorological Department (IMD, http://www.rsmcnewdelhi.imd.gov.in), (Step A). In the second step, the wind field in the study area is hindcasted with the aid of different simulation methods. At this stage, the different mesoscale models, parametric as well as reanalysis databases can be used (Step B). The validation and verification of the numerical model has been conducted in Sect. 3 (Step C). To validate the numerical model, the obtained results have been compared with the measurement data and the cyclone potential damage index has been examined as well. To ensure the accuracy of the results obtained via the selected numerical model, another cyclone's wind field was examined in the study area.

3 Study area

The North Indian Ocean, with the two sub-basins in the east (Bay of Bengal) and west (Arabian Sea), is one of the almost active areas in terms of the tropical cyclones occurrence. The position of the Arabian Sea and dominant track of the tropical cyclones formed in this area are depicted in Fig. 2. As shown in this figure, for the tropical cyclones formed in the Arabian Sea, one can imagine three routes including the movement to the north and inclination towards the west (Oman), moving north and inclination towards the east (India and Pakistan) and moving from east to west. Generally, the tropical cyclones moving towards the north of Arabian Sea can affect the southern and southeastern coasts of Iran and cause significant coastal damages in these areas.

Cyclone Gonu is the strongest tropical storm ever occurred in the Arabian Sea. According to the Saffir–Simpson criterion, this storm ranks as one of the most severe tropical cyclones (category 5). The best track of this cyclone
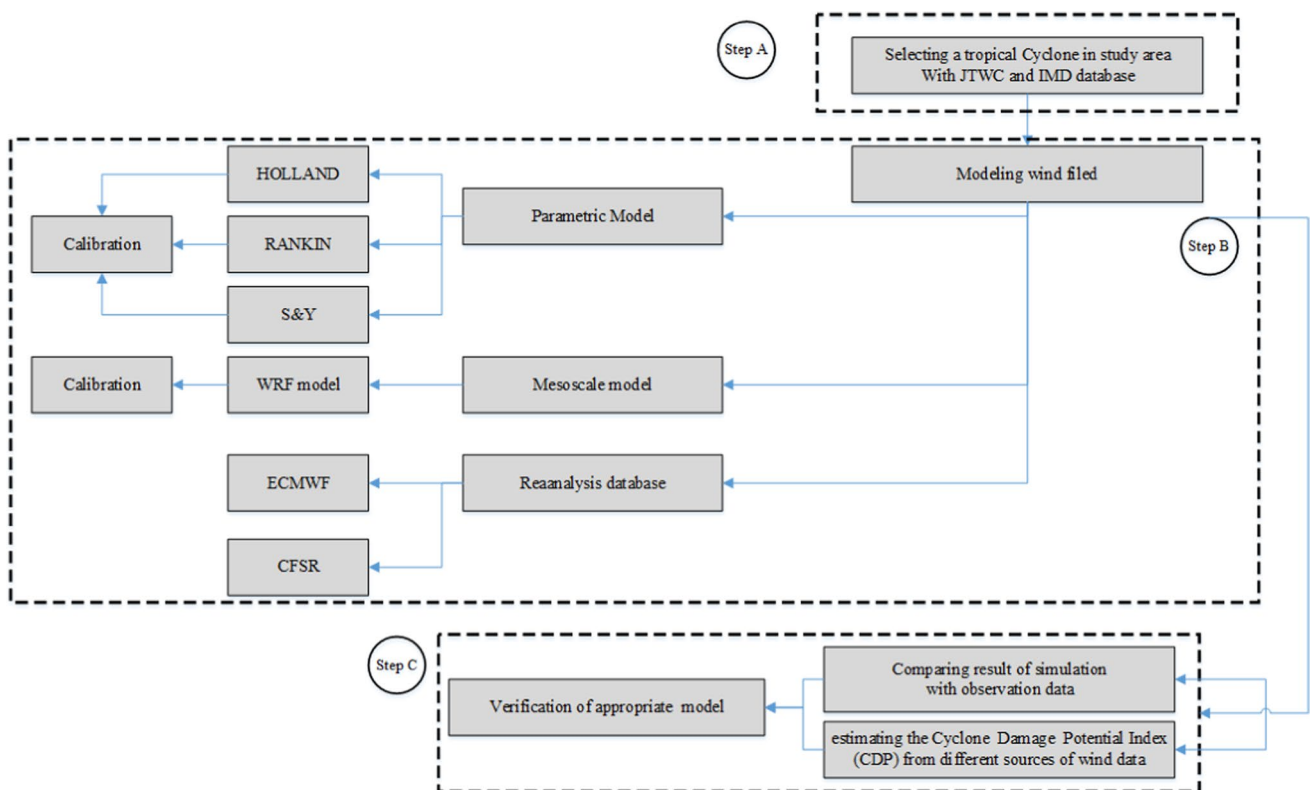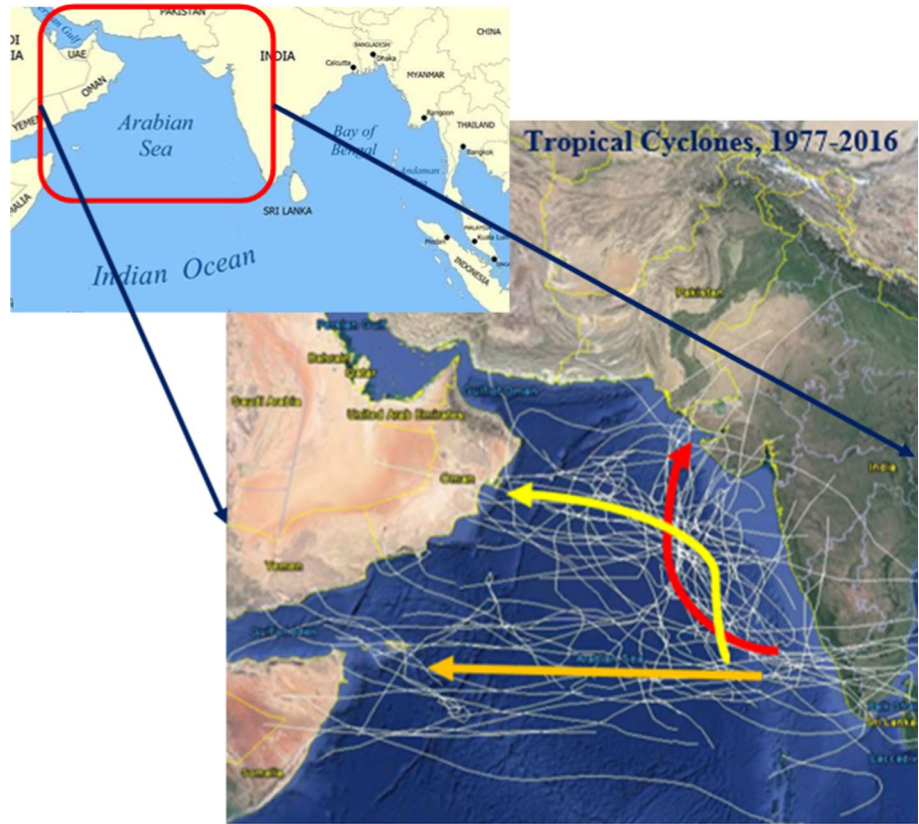

Fig. 1 The methodology and steps of the present research

Fig. 2 The trajectory of tropical cyclones within the range of Arabian Sea and Gulf of Oman based on JTWC data


in the Arabian Sea region are shown in Fig. 3a according to the JTWC data. Figure 3b depicts the pressure variations of the cyclone center and maximum wind speed along its direction according to the two databases of JTWC and IMD. According to the JTWC database, the minimum pressure in the cyclone center is less than 900 hPa while it is estimated about 915 hPa on the basis of the IMD one. The

important point is that according to the JTWC data, there is a fluctuation in the cyclone's center pressure before reaching the minimum pressure, which may indicate the weakening and re-intensification of the tropical cyclone Gonu. The cyclone's maximum speed difference based on the JTWC and IMD data is about 10 m/s. Since the JTWC database information is more specific and has been cited by further
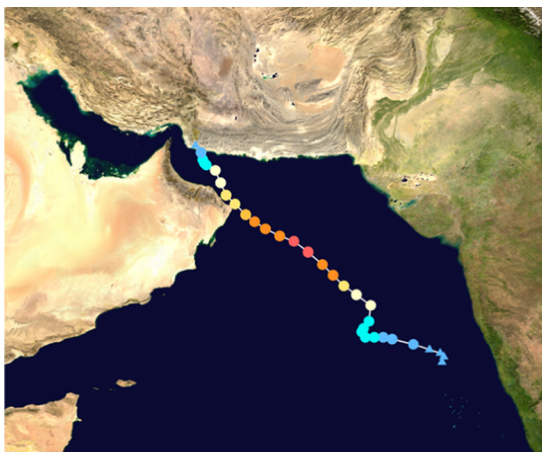
(a)
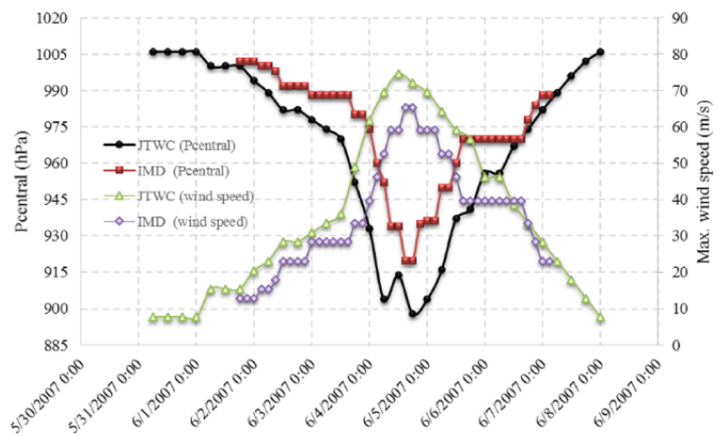
(b)

Fig. 3 **a** The path of cyclone Gonu based on JTWC data. **b** Comparison of the central pressure and maximum wind speed based on JTWC and IMD data

studies, this database have been used in the remaining of the current study for controlling the numerical models and reanalysis data.

According to the available track data of the cyclones occurred in the Arabian Sea during the timeframe 1977–2016 (Fig. 2), the storm Gonu is the only tropical one that has made landfall along the southern and southeastern coasts of Iran. Hence, the present study has focused on this tropical cyclone. However, based on the methodology presented in this study, it is necessary to evaluate the performance of the selected numerical model for another TC to verify the results. The track investigation of various storms, illustrated that the tropical cyclone Phet is the only very severe one within the Arabian Sea region that has approached the southeastern coasts of Iran due to its movement and affected these areas. Therefore, the cyclone Phet has been also considered to verify the numerical model. This cyclone has been formed on May 31, 2010 in the Arabian Sea and dissipated on June 7, 2010. During the activity period of the tropical cyclone Phet, its intensity has reached category 4 according to the Saffir–Simpson scale. The track, maximum wind speed changes and center pressure of this cyclone are shown in Fig. 4 based on the JTWC data.

4 The utilized data

The information used in the present study includes both the measurement and the reanalysis data. The measurement data include the information associated with the satellite and synoptic stations during the cyclone Gonu happening. These data have been used for the results assessment. The second part of the utilized data contains the wind field of the reanalysis data of ECMWF (ERA-Interim) and CFSR when the tropical cyclone Gonu occurred. The collected information includes the wind speed and direction. The

details corresponding to each of the utilized information are summarized below.

4.1 Measurement data
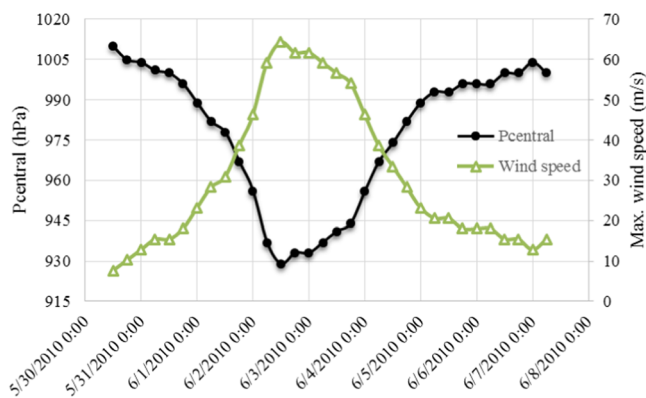
4.1.1 Satellite data

One of the wind field control tools is the use of satellite measurement information. In the present study, the QuikSCAT satellite's information has been used during the tropical cyclone Gonu. Since 1999, this satellite has been collecting the wind field information on the earth with the temporal and spatial resolutions of 12 h and 25 km, respectively. The QuikSCAT observations are available at https://podaac.jpl.nasa.gov. The small temporal and spatial steps of this satellite's harvesting networks are one of the most important reasons for selecting this information. An example of the QuikSCAT satellite data during the Gonu TC is shown in Fig. 5. This figure indicates the spatial variations of wind speeds in the Persian Gulf, Oman Sea and Arabian Sea during the Gonu.

4.1.2 Local databases

To verify the wind field results obtained via the simulation models, the data from Chabahar and Jask synoptic stations have been used in the current research. Table 1 gives the specifications of each of these stations together with their temporal resolution. The position of the utilized measurement stations in relation to the cyclone's path is shown in Fig. 6. As would be observed, the Jask synoptic station is very close to the direction of the cyclone Gonu during the final days.

(a)

(b)

Fig. 4 **a** Track, **b** maximum speed and **c** center pressure changes of the tropical cyclone Phet based on the JTWC data
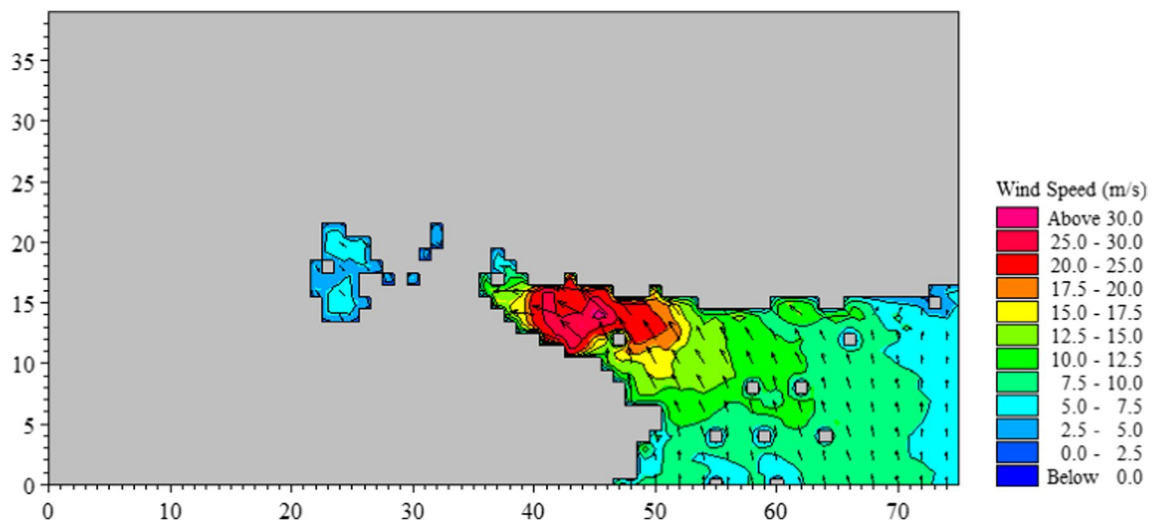
Fig. 5 An example of the QuikSCAT satellite data during the Gonu TC

Table 1 Specifications of the utilized measurements

Name	Source	Position	Temporal resolution (h)
Chabahar synoptic	Synoptic	Lat: 25.283000 Long: 60.617000	3 hourly
Jask synoptic	Synoptic	Lat: 25.633333 Long: 57.766667	3 hourly

4.2 Reanalysis database

The present investigation uses the wind field information obtained through the reanalysis data of ECMWF (ERA-Interim) and CFSR databases. These data can be accessed online on https://apps.ecmwf.int/datasets/data/interim-full-daily and ftp://nomads.ncdc.noaa.gov/CFSR, respectively. The wind field extracted from the reanalysis data is one of the useful tools for meteorological and oceanographic surveys and studies. The information of reanalysis data on the studied parameters faces deficiencies and shortcomings due to the limitations of field observations in the coastal regions. However, the results of the literature review show that the recorded data of these databases provide a reliable source for studies due to the mixing of the modeling results and available measurements (Durrant et al. 2014; Mazaheri et al. 2013; Saket et al. 2013; Wang et al. 2018).

One of the doubts about the reanalysis data is the quality of these information sources when severe weather conditions such as TCs occur. Therefore, the quality of the reanalysis data of ECMWF (ERA-Interim) and CFSR has been examined during the most severe tropical cyclones in the Arabian

Sea. The specifications of the data used are presented in Table 2.

5 Numerical modeling

In the present study, in addition to the reanalysis data, the simulated wind field by the WRF models and parametric ones during the occurrence of Gonu TC has been evaluated. In this section, the specifications of the conducted simulations are presented.

5.1 WRF model

Use of the mesoscale models is one of the tools for improving the wind field of the reanalysis data in the coastal areas. The Weather Research and Forecasting (WRF) model is a new generation of mesoscale atmospheric simulation systems designed for both research and operational applications (Skamarock et al. 2008). The WRF model is considered as an appropriate choice from a variety of perspectives including accuracy, up-to-date numerical and physical schemes, multiple and varying physical parameterization options, and high-resolution information accessibility. Hence, the present study uses this model to improve the wind field accuracy of the reanalysis data during the tropical cyclone Gonu.

Selecting the modeling area is one of the most effective parameters in simulating the mesoscale models. To arrive at the best model configuration, several sensitivity analyses have been performed to select the modeling range. The simulation outputs and multiple sensitivity analysis to the modeling dimensions indicate that selecting an internal range with lower resolution leads to better results. The defined modeling domain with the WRF model is depicted
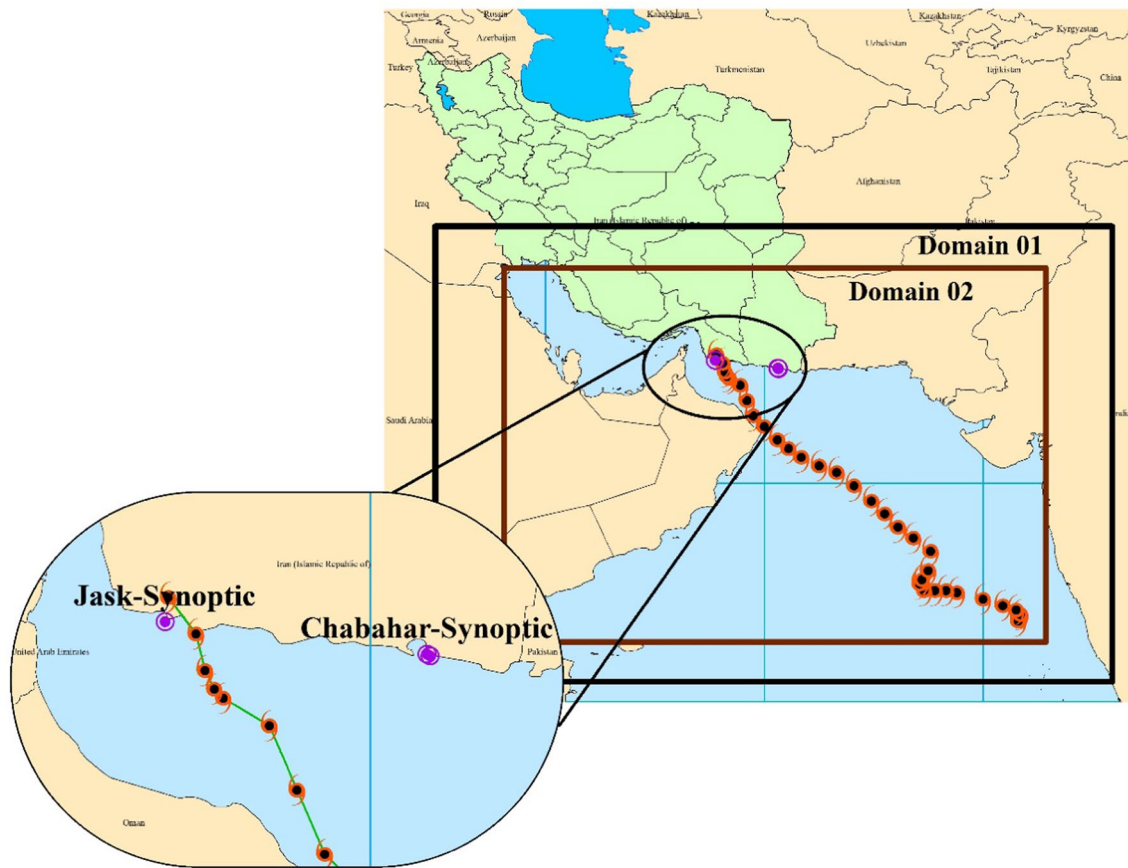
Fig. 6 Location of the measurement stations in relation to the cyclone's track and the computational domain boundary of the WRF model

Table 2 The wind field specifications of the reanalysis data

Temporal resolution	Highest available spatial resolution	Period covered	source	Name
6 hourly	$0.75° \times 0.75°$	1979–present	ECMWF	ECMWF Interim Reanalysis (ERA Interim)
Hourly	$0.3° \times 0.3°$	1979–present	NOAA	Climate Forecast System Reanalysis (CFSR)

in Fig. 6. Four different configurations have been also considered for the wind field modeling with WRF. The characteristics of the configurations have been selected based on the results of previous studies (Osuri et al. 2012a, b; Perlin et al. 2014; Rakesh et al. 2009). The details of the examined configurations are given in Table 3. In addition, 39 vertical grid, two-way integration, and 6-h spin-up time, and 24 h forecasting length have been considered for the modeling. The data of initial and boundary conditions are needed to run the regional-scale meteorological model. Here, the data of ECMWF (ERA-Interim) have

been selected for defining the initial and boundary conditions of WRF.

5.2 Parametric models

In this study, in addition to the implementation of the WRF model for the wind field hindcasting, parametric models have been also used to simulate it. Many parametric models have been reported for the wind field simulation of the TCs from which, the three models of Young and Sobey, Holland and Rankin have been evaluated and compared in the current

Table 3 The configurations of the WRF model

	Scenario 1 (SC1)	Scenario 2 (SC2)	Scenario 3 (SC3)	Scenario 4 (SC4)
Horizontal grid distance				
Domain 01 (degree)	0.3	0.15	0.3	0.15
Domain 02 (degree)	0.1	0.05	0.1	0.05
Longwave radiation	Rapid Radiative Transfer Model (RRTM)		Rapid Radiative Transfer Model (RRTM)	
Shortwave radiation	Goddard		Goddard	
Surface layer	Revised MM5		Eta	
Land surface	Noah		Noah	
Planetary boundary layer	MRF		MYJ	
Cumulus scheme	Kain–Fritsch		Kain–Fritsch	

research (DHI 2017). Specifications of the implemented models are described in this section.

- Young and Sobey (S&Y) model

Young and Sobey (1981) expressed the rotational gradient wind speed (V_g) as:

$$V_g(r) = V_{\max}\left(\frac{r}{R_{mw}}\right)^7 \times \exp\left(7\left(1-\frac{r}{R_{mw}}\right)\right) \text{ for } r < R_{mw},$$
$$V_g(r) = V_{\max} \times \exp\left((0.0025R_{mw}+0.05)\left(1-\frac{r}{R_{mw}}\right)\right) \text{ for } r \geq R_{mw}, \quad (1)$$

where, r, R_{mw} and $V_{\max}$ stand for the distance from the cyclone center, radius of maximum wind speed and maximum wind speed, respectively. The values of R_{mw} and $V_{\max}$ have been extracted from the JTWC data. In addition, the pressure in this model is obtained based on the following equation:

$$P(r) = P_c + (P_n - P_c)\,\exp\left(-\frac{R_{mw}}{r}\right). \quad (2)$$

Here, P_c is the pressure in the cyclone center and P_n defines the natural pressure or cyclone's peripheral one. In the same manner as above, the value of P_c is deduced from the JTWC data.

- Holland model

Holland demonstrated wind speed (V_g) profile as:

$$V_g(r) = \sqrt{(P_n-P_c)\frac{B}{\rho_A}\left(\frac{R_{mw}}{r}\right)^B \exp\left(-\frac{R_{mw}}{r}\right)^B + \left(\frac{r.f}{2}\right)^2} - \frac{r|f|}{2}. \quad (3)$$

In the above relation, ρ_a, f and B define the air density, Coriolis parameter and shape coefficient, respectively. Holland has used a rectangular hyperbolic function

to model the pressure changes at the time of the tropical cyclones formation. The pressure and shape coefficient B are defined as in the following equations:

$$P(r) = P_c + (P_n - P_c)\,\exp\left(-\frac{R_{mw}}{r}\right)^B, \quad (4)$$

$$B = 2.0 - \frac{p_c - 900}{160}. \quad (5)$$

The Coriolis parameter depends on the Earth's rotational frequency (Ω) and latitude (ϕ) of the studied area. This parameter is defined according to the following equation:

$$f = 2\Omega \sin\varphi. \quad (6)$$

- Rankin model

The Rankin vortex model uses the following velocity distribution (DHI 2017):

$$V_g(r) = V_{\max}\left(\frac{r}{R_{mw}}\right) \text{ for } 0 \leq r < R_{mw},$$
$$V_g(r) = V_{\max}\left(\frac{r}{R_{mw}}\right)^X \text{ for } r \geq R_{mw}. \quad (7)$$

Here, X is the shape parameter being proportional to the wind speed distribution in radial directions. The value of this parameter is commonly considered to be within the range of 0.4–0.6. In the Rankin model, the pressure is obtained from Eq. (2).

Table 4 lists all the information needed to simulate the cyclone Gonu wind field. To calculate the superficial winds, the geostrophic correction, motion's asymmetry correction and internal flow angle have been also considered (DHI 2017).

Table 4 Input data needed to simulate the cyclone Gonu field

Time (h)	Longitude (degrees)	Latitude (degrees)	Radius (km)	V_{max} (m/s)	$P_{central}$ (hPa)	$P_{neutral}$ (hPa)	B	X
0	71.60	13.70	0.00	7.7167	1006	1007	1.338	0.45
6	71.70	14.00	0.00	7.7167	1006	1007	1.338	0.45
12	71.50	14.20	0.00	7.7167	1006	1007	1.338	0.45
18	70.90	14.40	0.00	7.7167	1006	1007	1.338	0.45
24	70.00	14.70	74.08	15.433	1000	1004	1.375	0.45
30	68.80	15.00	46.30	15.433	1000	1004	1.375	0.45
36	68.30	15.10	74.08	15.433	1000	1004	1.375	0.45
42	67.80	15.10	64.82	20.578	994	1005	1.413	0.45
48	67.30	15.10	55.56	23.150	989	1005	1.444	0.45
54	67.10	15.40	46.30	28.294	982	1004	1.488	0.45
60	67.20	15.60	46.30	28.294	982	1002	1.488	0.45
66	67.50	16.00	37.04	30.867	978	1002	1.513	0.45
72	67.60	16.90	37.04	33.439	974	1000	1.538	0.45
78	66.80	17.50	37.04	36.011	970	1000	1.563	0.45
84	66.10	18.00	9.26	48.872	952	1001	1.675	0.45
90	65.50	18.60	13.89	61.733	933	1001	1.794	0.45
96	64.90	19.20	18.52	69.450	904	1002	1.975	0.45
102	64.10	19.90	18.52	74.594	914	1002	1.913	0.45
108	63.30	20.50	27.78	72.022	898	1003	2.013	0.45
114	62.50	20.80	18.52	69.450	904	1003	1.975	0.45
120	61.70	21.20	18.52	64.306	916	1001	1.900	0.45
126	61.10	21.60	27.78	59.161	937	1001	1.769	0.45
132	60.60	22.00	27.78	56.589	941	1001	1.744	0.45
138	60.00	22.60	27.78	46.300	956	1001	1.650	0.45
144	59.50	23.10	37.04	46.300	956	1000	1.650	0.45
150	59.20	23.80	46.30	38.583	967	999	1.581	0.45
156	58.90	24.50	55.56	33.439	974	998	1.538	0.45
162	58.40	24.80	64.82	28.294	982	1000	1.488	0.45
168	58.30	24.90	74.08	23.150	989	1001	1.444	0.45
174	58.20	25.10	0.00	18.006	996	1002	1.400	0.45
180	58.10	25.50	0.00	12.861	1002	1002	1.363	0.45
186	57.80	25.90	0.00	7.712	1006	1002	1.338	0.45

6 Results and discussion

The accuracy of the TC's wind field is usually investigated by evaluating the cyclone's path and wind speed. Therefore, in this study, the path of cyclone's motion and then wind field pattern have been evaluated. Furthermore, the wind speed and direction are compared with the coastal stations data. The statistical tests and CDP index are implemented to evaluate the results. The results of the conducted investigations are given as below.

6.1 Cyclone Gonu tracking

Investigating the trajectory of the TCs is one of the tools for evaluating the results of numerical models. Given that the cyclone's track is as input information in the parametric models, it is, therefore, important to evaluate the results of the WRF model. The cyclone Gonu's path based on the WRF simulation results is plotted in Fig. 7 and compared to that of JTWC track. As would be observed, there is a significant difference between the modeling results and JTWC at the beginning of the cyclone's path and there are no sudden variations of the storm direction in the WRF model's results. However, the overall results illustrate that the WRF model is capable of forecasting the tropical cyclones' path.

A comparison of the four scenarios defined in the WRF model showed that the results obtained by WRF (SC2, SC4), corresponding to the higher model resolutions, forecast the first cyclone landfall on the coasts of Oman with higher accuracy. However, the results of WRF (SC1, SC3) models with coarser resolutions were unable to successfully forecast the first cyclone landfall on the Oman's coastlines. Besides, the
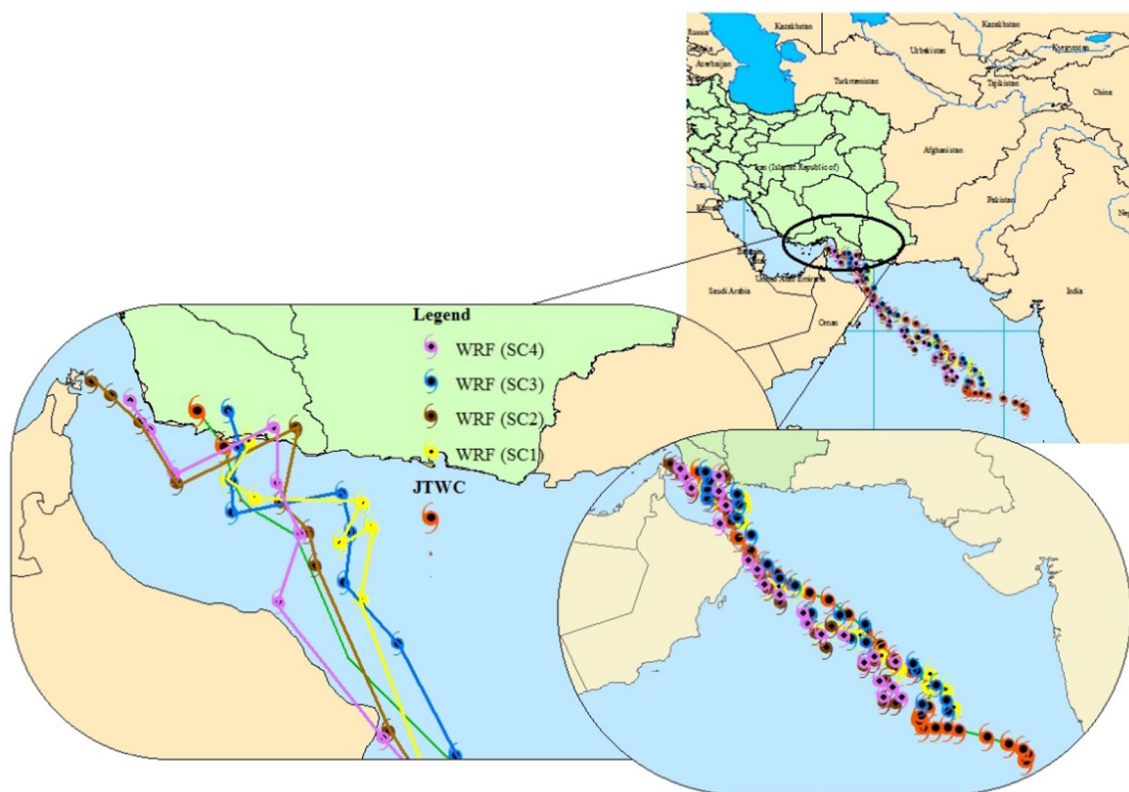
Fig. 7 Comparison of the trajectory of the tropical cyclone Gonu according to the information of JTWC and WRF results

results achieved by WRF (SC2, SC4) models indicate three landfalls. Here, the second cyclone landfall, which affects the coasts of Iran in the Jask area, has been forecasted toward the east of the range. In addition, there is a 1-day difference between JTWC data and results of WRF (SC2, SC4) models. Furthermore, based on simulation results, the third cyclone landfall has occurred in the vicinity of the Strait of Hormuz.

The unusual displacement at the end of the 24 h forecasting length can be observed in the results by all the simulations. For example, the forecasted path by WRF (SC3) model at 18UTC 06 June 2007, has been on the east side of JTWC data, whereas with a sudden change in the direction, the second landfall has been successfully predicted close to them. These large displacements are mainly due to the considered forecasting length. Hence, according to the results of previous studies and the current research, it seems that considering the forecasting length of less than 24 h can lead to an improvement in the cyclone track forecasting results (Nadimpalli et al. 2020).

6.2 Comparison of the simulated information results with the reanalysis models and satellite data

Figure 8a, b depicts the wind speed at two different times of the tropical cyclone Gonu in the reanalysis, WRF and

parametric models along with the QuikSCAT satellite data. Comparison of the results obtained via the reanalysis models with satellite data indicate that outputs of the reanalysis models' do not perform well in the wind speed modeling of Gonu. The cyclone speed is estimated to be more than 20 m/s in the satellite data while its maximum value reaches 15 m/s in the reanalysis models. The asymmetric cyclone's rotational pattern in the reanalysis models is in good agreement with the satellite data. In general, the results show that as the cyclone approaches the coastal areas of Iran, the wind field modeled by ECMWF (ERA-Interim) exhibits a better intensity and pattern.

Comparison of the results associated with the different WRF model configurations with the satellite data in the range of the studied area is presented in Fig. 8a, b. This comparison illustrates that the wind field obtained via WRF model with different configurations is consistent with the satellite data. Improving the time resolution and parameterizing effective physics in the WRF mid-scale model, have improved the results compared to the reanalysis counterparts.

Comparing the results of WRF (SC1, SC3) models with satellite data in Fig. 8a, b illustrates the higher accuracy of the WRF (SC3) one in forecasting the maximum wind speed. However, the overall distribution of wind speed
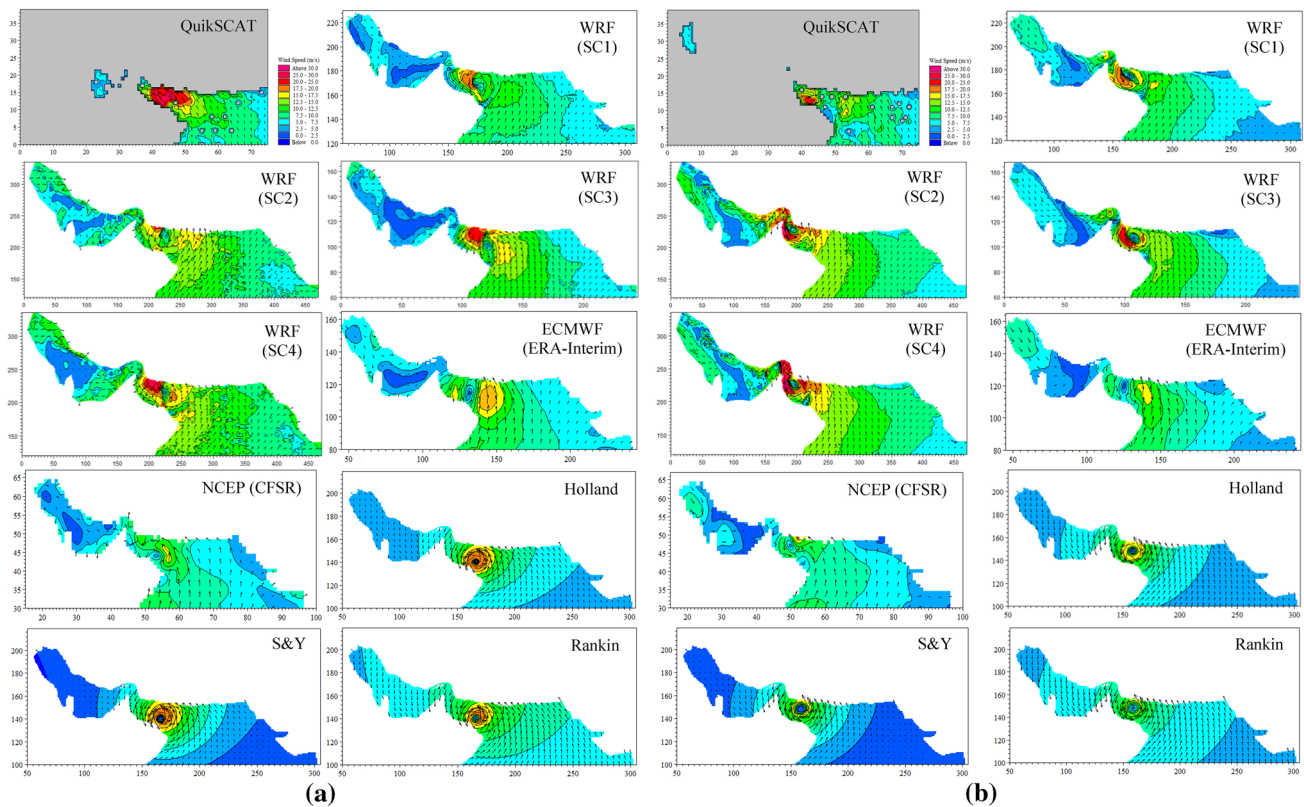
Fig. 8 Comparison of the achievements of various models with the QuikSCAT satellite data on **a** 06.06.2007 at 2:00 PM, **b** 06.07.2007 at 2:00 AM

and direction in both models is almost the same and well matched to the measurement data. Due to the mesh resolution increment in WRF (SC2) and WRF (SC4) models, the accuracy of the numerical model's results has increased in forecasting the maximum wind speed.

Another important point is the asymmetry of tropical cyclone Gonu's wind field due to being trapped between coasts of Oman and Iran. According to Fig. 8a, b, the asymmetry of cyclone Gonu is observable in the results of all WRF model configurations. The results of WRF (SC2, SC4) models in Fig. 8a, b indicate that the accuracy of the model in forecasting the intensity and asymmetry of the wind field's rotational pattern of the TC caused by the coastal impact has improved with an increment in the mesh resolution.

Figure 8a, b shows that the estimated maximum speed in the parametric models is in good agreement with the satellite data. The cyclone confinement between the Iran's and Oman's coasts has led to a decrement in the accuracy of the parametric models' results for hindcasting the wind speeds, which is due to the best track information quality. Unlike the results of the reanalysis models and WRF modeling, no asymmetry is observed in the cyclone's rotational pattern in the parametric models. Given that the cyclone's rotational pattern in the parametric models is considered to be ideal

like Rankin vortex, the asymmetry is not tangible. Although parameterizations have been made to apply asymmetry in the parametric models, they meet significant differences from the actual patterns. As the cyclone approaches the coasts and it is enclosed between the coasts of the Gulf of Oman, the influence of the cyclone's surrounding environment on the wind field is increased and this fact is not observed in the parametric models' results.

The results of Fig. 8a, b show that due to the cyclone Gonu confinement between the coasts of Oman and Iran, the accuracy of the parametric models' results within this area has decreased. This could be due to the inability to modify the wind field of parametric models under the influence of the coasts.

The general comparison of the reanalysis data results, WRF and parametric models with the satellite data, indicated that the WRF model performs better than other investigated ones. All of the configurations examined in the WRF model have been able to successfully forecast the speed and asymmetry of the cyclone's rotational pattern. In addition, the overall distribution of wind speed and direction in this model is well simulated.

6.3 Comparison of the WRF model's outputs and reanalysis data with the measurement

A comparison of the wind field results of the reanalysis data and WRF model configurations with the synoptic stations of Chabahar and Jask are presented in in Figs. 9 and 10, respectively.

In addition, comparing the time history and Q–Q graph of wind speed during the tropical cyclone Gonu at Chabahar synoptic station (Fig. 9) illustrates that the reanalysis data and WRF model's results successfully cover the approaching process of the storm (speed increasing) to the Iran's coasts. Comparison of the observational wind speed results with the reanalysis and simulated values points out to the overestimation of the latter ones. Comparisons among the observational, reanalysis data and the results obtained via WRF (SC3) model illustrate that WRF (SC3) overestimate the wind speed higher than measured values. However, comparison of the wind speed results of WRF (SC1, SC2, and SC3) models indicates that although the results are slightly overestimated for wind speeds less than 9 m/s, the maximum wind speed values are well forecasted by this model.

Further to these, comparison of the wind direction results confirms the convergence of the reanalysis data and WRF model with those via the Chabahar synoptic station.

Examining the direction variation at Chabahar station indicates that the results of the reanalysis data and WRF (SC3) model are almost the same. However, the other simulations (WRF (SC1, SC2, and SC3)) have also forecasted the wind direction variations well. As shown in the Fig. 9, the spatial resolution improvement in WRF (SC2, SC4) models has led to an improvement in the wind direction and speed forecasting within Chabahar synoptic range.

Figure 10 presents the reanalysis data and WRF simulation results in comparison with the information of the Jask synoptic station. The path examination of the cyclone Gonu in Fig. 6 indicates that the Jask synoptic station was directly exposed to this storm. The sudden increases and decreases in the wind speed and significant changes in its direction within the Jask synoptic data indicate the direct impact of the cyclone on this area. Comparison of the wind speed results points out to the weakness of the reanalysis data in estimating the maximum cyclone speed. As shown in Fig. 10, the maximum recorded speed at Jask synoptic station is about 20 m/s while at the same time the maximum speed via the reanalysis ones is reported as 12 m/s.

The improvement in the WRF model's results for forecasting the wind speed and direction are observable in Fig. 10. The distinctive forecasting results of the WRF models with respect to the reanalysis data can be observed
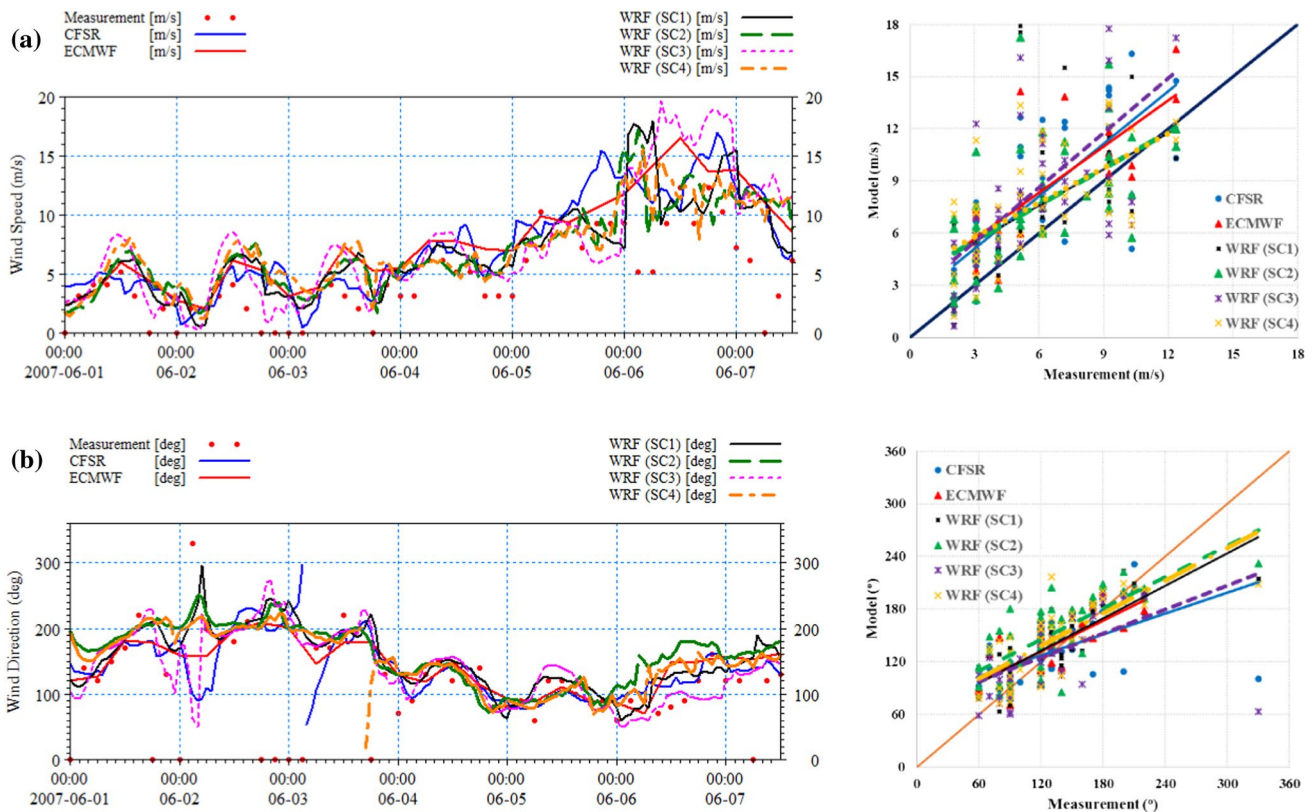

Fig. 9 Comparison of **a** speed and **b** direction of the wind at Chabahar synoptic station
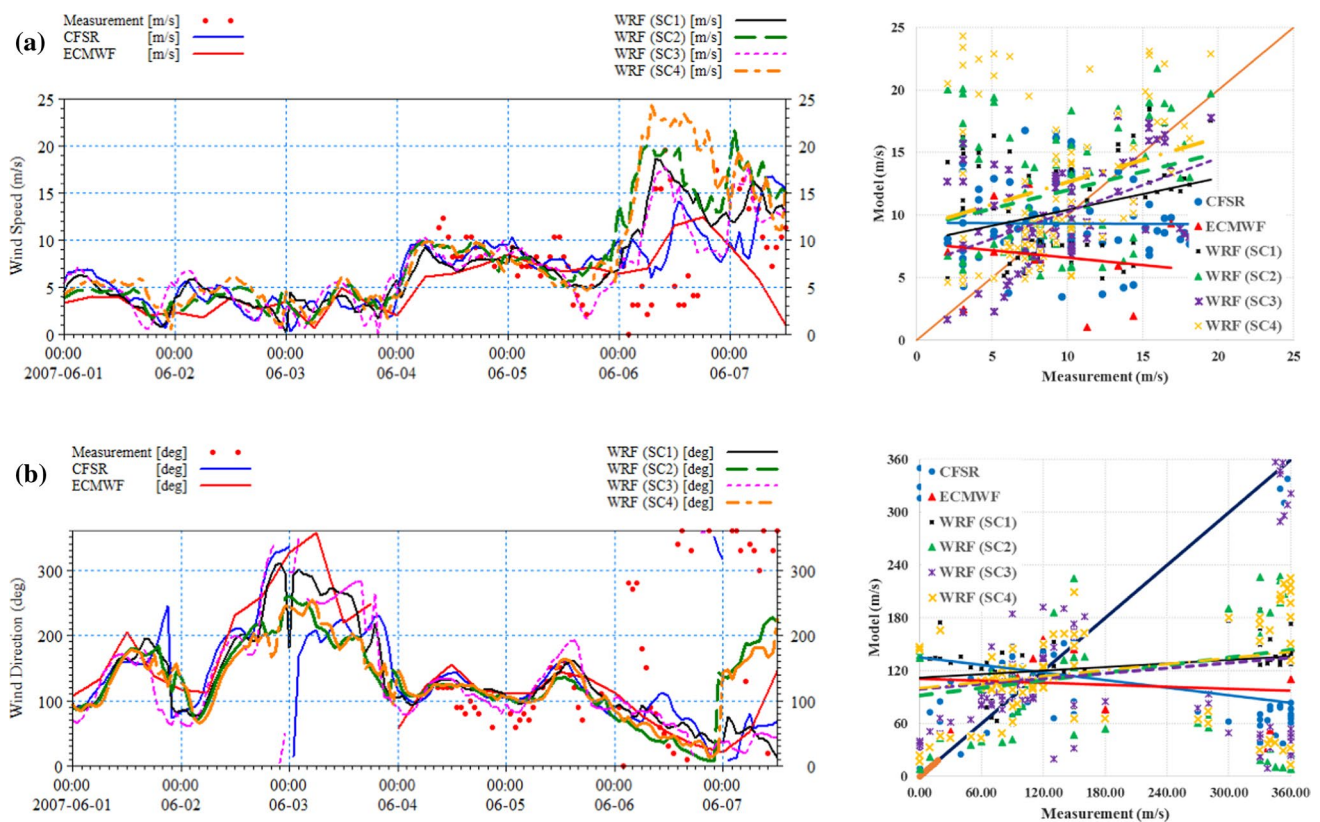
Fig. 10 Comparison of the wind's **a** speed and **b** direction at Jask synoptic station

in Fig. 10. As it is clear, the results of this model are very accurate in forecasting the wind speeds within the Jask station area. It is noteworthy that the maximum wind speed at Jask station is well forecasted by all the studied models (WRF (SC1, SC2, SC3, SC4)). Examination of the results via WRF (SC2, SC4) models also indicated that the simulation results improve with the increasing mesh resolution.

Upon the storm proximity to the synoptic station and simultaneous occurrence of the cyclone's eye and wall speeds (minimum and maximum wind speeds) in the measured data, the weakness of the numerical models in simulating the abrupt changes is identified. For this reason, no suitable correlation is observed between the simulation results and measured data. As for the wind direction, when the cyclone approaches the Iran's coast, a large difference is apparent between the observed and numerical data. However, as shown in Fig. 10, increasing the spatial resolution of WRF models has led to an improvement in the results.

In general, investigating the time history and distribution charts of the speed and direction variations of the reanalysis data and WRF models at the two synoptic stations of Chabahar and Jask, indicate that the WRF model has been able to successfully forecast the maximum speed values in coastal areas. In addition, with the increase in the spatial resolution of the WRF model, the accuracy of the model results in wind speed forecasting has significantly improved. The overall evaluation of the results shows that those obtained via WRF (SC4) model are more consistent with the measurement data.

6.4 Comparison of the parametric models' results with measurements

The comparison of the wind speed and direction results corresponding to the parametric models with measured data at synoptic stations of Chabahar and Jask are presented in Fig. 11a, b. Comparison of the wind speed obtained from parametric models with the measured information in Fig. 11a indicate that the increasing trend of wind speed affected by the cyclone approaching is successfully modeled and wind speed values are well hindcasted. However, as it turns out, the wind direction agrees with the measurement results only when the cyclone approaches Iranian coasts and there is no consistency between the results at other times.

Comparison of the parametric model's results and Jask synoptic data in Fig. 11b indicates the underestimation of the wind speed values. In addition, the wind direction hindcasted by these models is significantly different from the coastal synoptic data and there is no proper agreement between the wind direction of the parametric models and the synoptic data.
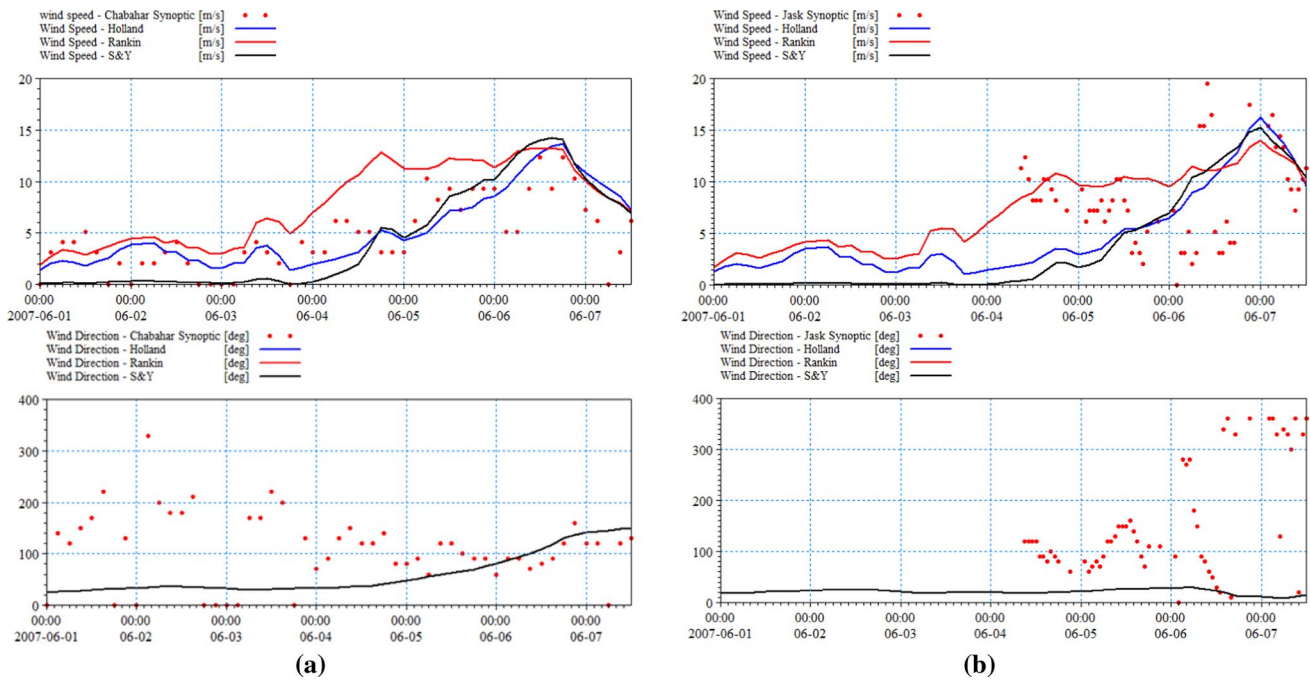
Fig. 11 Comparison of the wind speed and direction via the parametric models at **a** Chabahar synoptic station and **b** Jask synoptic station (points describe the measurement data, dark-blue line: Holland para-

metric model, red line: Rankin parametric model and black line: S&Y parametric model)

The results of parametric models indicate slight underestimation on the wind speed and the wind direction pattern near the coast is not in good agreement with the measured information due to the lack of coastal effects. The overall evaluation of the results shows that among the investigated parametric models, the wind field achieved via the Holland parametric model is more consistent with the measured data.

6.5 Evaluation criteria of the wind field simulation results

Finally, the statistical tests are used for the quantitative evaluation of the reanalysis data and wind field simulate results. The modeling performance index statistics used in this study are the Root Mean Square Error (RMSE), Bias and correlation (R) between the simulated information and observational data. The RMSE is used as an analogy to highlight the difference between the simulated and measured values. This criterion is defined as in Eq. (8) and it is used as the most common error indicator. The Bias is the mean of difference between the simulation results and observations, whose positive and negative values indicate the overestimation and underestimation of the model compared to observational values, respectively. The Bias value in the simulation is given in Eq. (9). The correlation (R) shows the linear relationship between the simulation and observational data which can be defined as in Eq. (10):

$$\text{RMSE} = \frac{\sqrt{\sum_{k=1}^{n}(O-S)^2}}{n}, \tag{8}$$

$$\text{Bias} = \frac{\sum_{k=1}^{n}(\overline{O}-\overline{S})}{n}, \tag{9}$$

$$R = \frac{\sum_{k=1}^{n}(O-\overline{O})(S-\overline{S})}{\sqrt{\sum_{k=1}^{n}(O-\overline{O})\sum_{k=1}^{n}(S-\overline{S})}}. \tag{10}$$

In the above relations, O defines the observational specifications at measurement stations, S is the simulated values, $\overline{O}$ and $\overline{S}$ stand for the observational and simulated mean values, respectively. In addition, n is the number of samples.

The summary of the statistical measurements at each of the four observational stations for each of the modeling methods are listed in Table 5 together with the data from the two reanalysis databases of ECMWF and CFSR. Here, the wind speed is in meters per second while wind direction in degrees.

Investigating the statistical parameters of the WRF models error, parametric models and reanalysis data highlighted the distinctive results forecasted by the WRF model in the study area. This distinction is especially significant in the wind field assessment at Jask synoptic station. The results

of WRF models better forecast the wind speed and direction changes within the coastal areas compared to the parametric ones which are established based on the observations. This can be seen in the wind speed and direction forecasting results at both Chabahar and Jask synoptic stations. Among the various WRF configurations, the evaluation of the results indicated the better performance of WRF (SC4) model. Among the parametric models, the Holland model has a better estimation.

6.6 Cyclone damage potential (CDP)

There is a growing need for the objective and timely information on the damages caused by TCs to conduct planning. Thus, several indicators have been developed capable of estimating the damage potential using the storm characteristics. The Saffir–Simpson scale, hurricane intensity index (HII), and Carvill hurricane index are examples of these indicators (Kantha 2006; Simpson and Riehl 1981; Smith 2010).

The examined indicators show that the rate of damage caused by TCs is proportional to the third power of the maximum wind speed (Emanuel 2005). Conducted studies during the last decade have also shown that in addition to the wind speed, the maximum values of other wind field parameters also affect the damage induced by the cyclone (Czajkowski and Done 2014; Zhai and Jiang 2014). These concepts have led to the development of the CDP index as follows (Holland et al. 2019):

$$CDP = 4 \frac{\left[\left(\frac{v_m}{65} \right)^3 + 5 \left(\frac{R_h}{50} \right) \right]}{v_t}, \tag{11}$$

where v_m is the maximum surface wind speed (knots), R_h defines the cyclone radius (nautical miles) and v_t stands for the cyclone forward speed (knots).

CDP is used to estimate the damages caused by the offshore wind, wave and current damage, onshore wind and cyclone surge. This index can also be used individually, quarterly and globally for a wide range of social purposes. Moreover, the CDP parameter ranges from 0 to 10.

In the present study, to evaluate the wind field results, the damage potential due to the direct impact of the cyclone Gonu on the coasts of Iran has been investigated during the period from June 5 to 7, 2007. Since the wind field derived from parametric models is based upon the JTWC data, the CDP index associated with these models has been calculated in the same way based on these information. In addition, due to the coarser resolution of the reanalysis data, the maximum surface wind speed (v_m) obtained via them did not considerably differ from the average wind speed, so the CDP index has not been calculated for them.

The variations of v_m, R and v_t and cyclone Gonu's damage potential are depicted in Fig. 12 according to various WRF configurations and JTWC data within the corresponding

Table 5 Statistical measurement values for the investigated information

Input data	Bias		R		RMSE	
	Speed (m/s)	Direction (º)	Speed (m/s)	Direction (º)	Speed (m/s)	Direction (º)
Chabahar synoptic						
WRF (SC1)	1.69	7.71	0.55	0.75	3.59	30.07
WRF (SC2)	1.30	19.72	0.60	0.73	3.34	40.30
WRF (SC3)	1.87	6.50	0.70	0.55	4.05	50.63
WRF (SC4)	1.40	19.02	0.62	0.77	3.20	39.79
ECMWF	2.29	9.14	0.77	0.55	3.29	42.86
CFSR	2.11	− 0.49	0.76	0.82	3.27	30.39
Holland	0.11	–	0.74	–	2.41	–
Rankin	2.96	–	0.69	–	3.97	–
S&Y	− 0.57	–	0.79	–	3.21	–
Jask synoptic						
WRF (SC1)	1.06	− 47.99	0.28	0.12	5.03	143.53
WRF (SC2)	2.51	− 51.87	0.26	0.29	6.09	131.11
WRF (SC3)	0.72	− 49.56	0.47	0.14	4.22	148.97
WRF (SC4)	3.16	− 46.59	0.26	0.25	7.05	130.15
ECMWF	1.80	54.70	− 0.15	− 0.10	5.63	145.85
CFSR	0.19	− 53.60	− 0.01	− 0.24	5.15	166.92
Holland	− 1.32	–	0.46	–	4.55	–
Rankin	0.80	–	0.17	–	4.57	–
S&Y	− 2.09	–	0.31	–	5.64	–

time period. According to Fig. 12, the CDP index falls within the range of 0–5 and 0–7 according to the JTWC data and results of WRF forecasting models, respectively. Investigation of the results of various WRF configurations shows that this model has been able to successfully estimate the CDP. In addition, the results of the conducted forecasting are in line with the CDP range obtained on the basis of the JTWC data. The maximum CDP has been obtained with according to the WRF (SC4) model results.

As shown by Fig. 12, the forecasting results of the WRF model can be used to estimate the CDP in the coastal areas of Iran. The obtained CDP can be used to plan and minimize the damages caused by TCs.

6.7 Verification

In general, the results of the previous sections show that the outputs of the WRF model with SC4 configuration have better performance compared to the other models examined in simulating the cyclone Gonu. Therefore, to verify the results of this configuration, the wind field associated with the tropical cyclone Phet has also been modeled.

Figure 13 depicts a comparison of the track simulation results with Best Track data along with the wind speed and direction of the tropical cyclone Phet compared to the measurement data of Chabahar synoptic station. As can be seen in Fig. 13a, the tropical cyclone Phet track has abruptly

changed toward the east and then northeast after the landfall. Thus, the track modeling of cyclone Phet has higher uncertainty than that of Gonu. Comparing the results of cyclone track modeling with JTWC data in Fig. 13a, indicates that the model has been able to well simulate the tropical cyclone landfall to the coasts of Oman and Pakistan. In addition, the overall cyclone Phet track has been successfully modeled. However, there are inconsistencies in the modeling results in the situation where the cyclone direction has changed drastically. Reducing the forecasting length may improve the results.

Due to the cyclone Phet track, the impacts of this storm on the southeastern coasts of Iran and especially the data of Chabahar synoptic station have been significant (Fig. 13a). Therefore, the comparison of wind speed and direction results via WRF (SC4) model with Chabahar synoptic station data is illustrated in Fig. 13b, c. As shown in Fig. 13b, the simulation results have been able to forecast the maximum wind speed as well as cyclone proximity to the study area. However, due to the sharp change in the cyclone direction toward the east of the Arabian Sea as it approaches the coasts of Iran, the time period of its impact on June 5 has been predicted to be about a few hours, while it is about 1 day according to the measurement results. In addition, the decreasing trend of the maximum wind speed, which indicates the cyclone approaching, is more severe in the results of the numerical model.
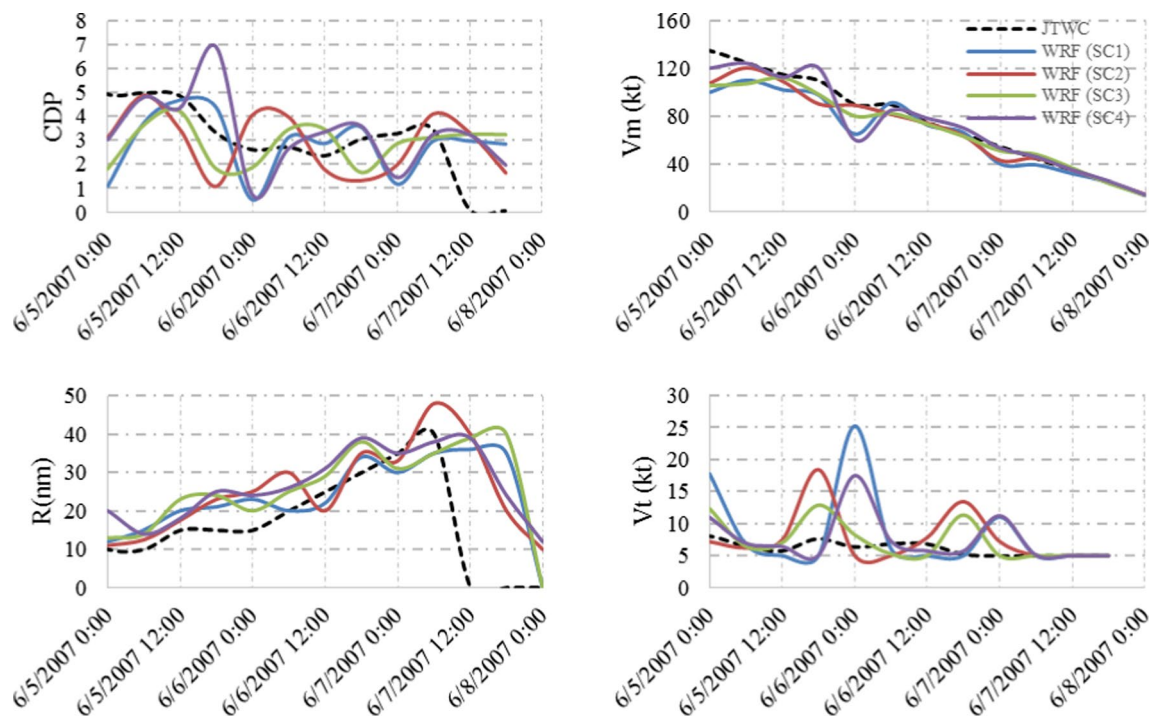

Fig. 12 Time history of the variations in the cyclone damage potential (CDP), maximum surface wind speed (v_m), cyclone radius (R) and forward speed (v_t)
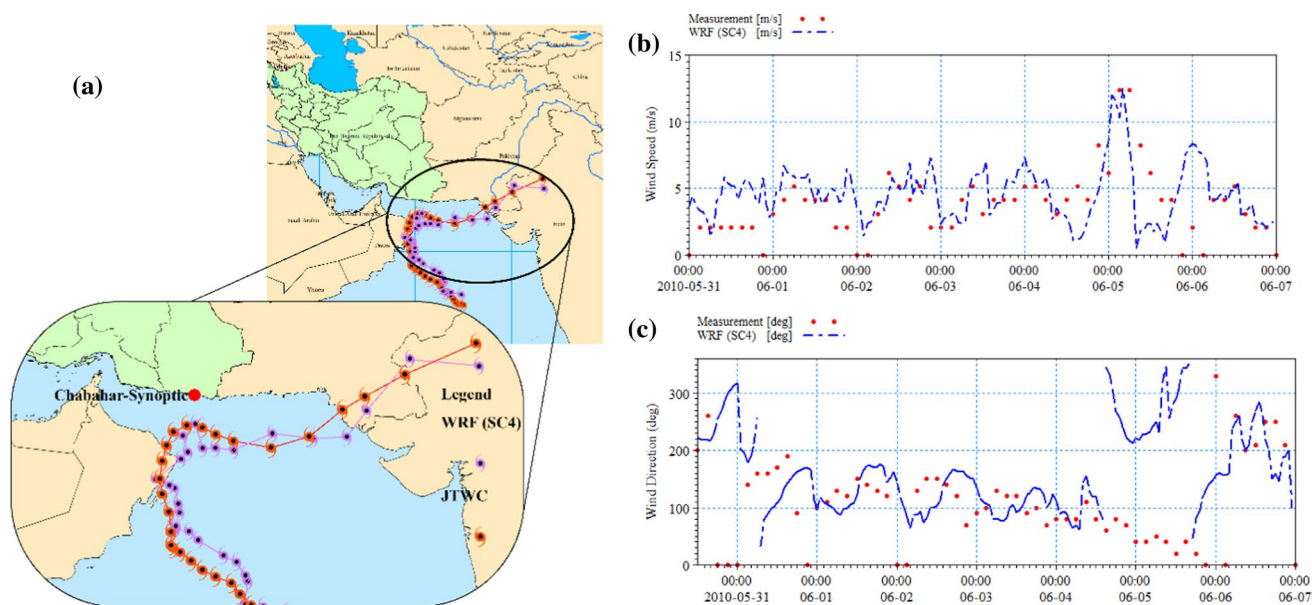
Fig. 13 Comparison of the simulation results of **a** the cyclone track with JTWC data and with Chabahar synoptic station data, **b** wind speed, **c** wind direction in the tropical cyclone Phet

Comparing the wind speed changes in Fig. 13c shows that these variations have been well modeled. The difference between modeling results and measurement data is significant when the cyclone impacts the Iranian coasts. This is mainly due to the cyclone Phet track fluctuations in the numerical model. However, it should be noted that considering the general direction of wind (north–south) when the cyclone approaches the Iranian coasts, the results of numerical modeling meet acceptable accuracy. Due to the drastic change in the tropical cyclone Phet track, the numerical model performance is evaluated as desirable.

In the same manner as the cyclone Gonu, statistical tests have been used for the quantitative assessment and to ensure the accuracy of the numerical modeling results. Figure 14a, b exhibits the scatter plot of wind speed and direction changes and statistical error values in Chabahar station. Figure 14a also shows the accuracy of the WRF (SC4) model results in wind speed simulation. Evaluation of the statistical errors indicates the appropriate correlation coefficient of the modeling achievements and acceptable dispersion rate of the wind speed results. Moreover, the results of numerical modeling have been able to successfully model the maximum wind speed values due to the tropical cyclone Phet.

Examination of the scatter plot in Fig. 14b shows inconsistencies in the wind direction modeling. The inconsistency of the results is significant when the wind direction in Chabahar station is from the north (0–60°). Considering the overall direction of the wind (north–south), it can be stated that the results of the numerical model with a direction of higher than 300° also indicate a direction in compliance with

the measurement data. However, the drastic change in the cyclone Phet track has caused the conditions of Chabahar station in this storm to be similar to that of Jask station in cyclone Gonu. An overview highlights the proper performance of WRF (SC4) numerical model in simulating the tropical cyclone conditions.

7 Conclusions

In present study, wind field of Gonu tropical cyclone has been investigated The wind field has been hindcasted using the WRF model and three parametric ones including S&Y, Holland and Ranking. Four different configurations have been considered to forecast the wind field using WRF model. In addition, the wind field of the ECMWF (ERA-Interim) and CFSR reanalysis databases has also been studied during the tropical cyclone Gonu.

Comparing of the wind field of the reanalysis stations and observational data, one can conclude that both ERA-Interim CFSR datasets have very close performance in the studied area. However, CFSR showed better overall performance.

Comparison of the parametric models' results and satellite images illustrates that these models meet significant differences in the hindcastings of the actual wind patterns. As the cyclone approaches and encloses among the Gulf of Oman coasts, the impact of cyclone's peripheral environment on the wind field increases and this behavior is not observed in the outputs of the parametric models. However, among the parametric models, the Holland model has shown

Fig. 14 The scatter plot corresponding to the results of Chabahar synoptic station data and modeling **a** wind speed, **b** wind direction

(a)

(b)
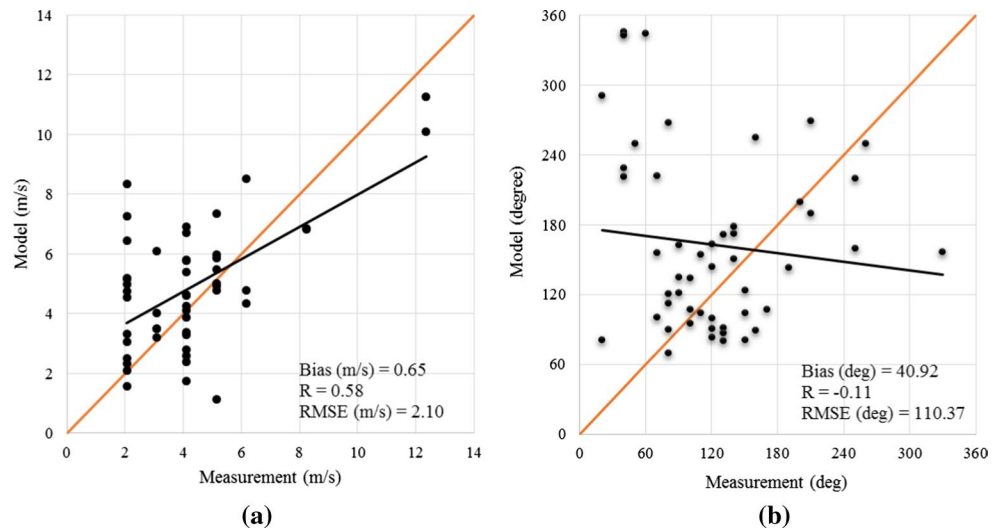
better performance for hindcasting the wind field within the region.

The results from various WRF model's configurations indicate that this model can well forecast the cyclone's path. It is also possible to reduce the model error rate in the cyclone track simulation by reducing the forecasting length. In addition, comparing the wind field results with satellite data illustrates that the WRF model has been able to well simulate the asymmetry of the cyclone's rotational pattern while being trapped between the coasts of Iran and Oman. However, increasing the model's mesh resolution has improved the results of cyclone's asymmetry modeling.

Evaluating the results of WRF models in forecasting the maximum wind speed and direction in the coastal areas of Iran highlights the significant difference between the results of this model and other ones along with the data examined in the current research.

To plan and minimize the amount of damage caused by TCs, the CDP index has been calculated based on the results of WRF models. This investigation indicates that the WRF model's results can be well employed to forecast the potential damage index of tropical cyclones within the coastal areas of Iran.

Based on the assessments made, the SC4 configuration of WRF model has met the best performance in simulating the tropical cyclone Gonu in the coastal areas of Iran rather than other models and data examined.

In addition, the verification of this configuration in the Phet TC shows its suitable in simulating the TC wind field with drastic changes in the path of movement. In addition, verification of the SC4 configuration of WRF model in the Phet TC indicates a suitable performance of the WRF model to simulate the TC's wind field with sever changes in the trajectory of TC.

References

Alimohammadi M, Malakooti H (2018) Sensitivity of simulated cyclone Gonu intensity and track to variety of parameterizations: Advanced hurricane WRF model application. J Earth Syst Sci. https://doi.org/10.1007/s12040-018-0941-4

Alizadeh-Choobari O (2015) RETRACTED: Large-eddy simulation of the hurricane boundary layer: evaluation of the planetary boundary-layer parametrizations. Atmosph Res 154:73–88. https://doi.org/10.1016/j.atmosres.2014.11.004

Bell R, Strachan J, Vidale PL, Hodges K, Roberts M (2013) Response of tropical cyclones to idealized climate change experiments in a global high-resolution coupled general circulation model. J Clim 26:7966–7980

Cardone V, Cox A (2009) Tropical cyclone wind field forcing for surge models: critical issues and sensitivities. Natl Hazards 51:29–47

Cha D-H, Wang Y (2013) A dynamical initialization scheme for real-time forecasts of tropical cyclones using the WRF model. Mon Weather Rev 141:964–986

Czajkowski J, Done J (2014) As the wind blows? Understanding hurricane damages at the local level through a case study analysis. Weather Clim Soc 6:202–217

Das Y (2018) Parametric modeling of tropical cyclone wind fields in India. Nat Hazards 93:1049–1084

DHI (2017) MIKE 21 cyclone wind generation tool (scientific documentation). DHI Water and Environment company web. https://manuals.mikepoweredbydhi.help/2017/Coast_and_Sea/CycloneTool_Scientific_Doc.pdf. Accessed 1 June 2019

Dodla VB, Desamsetti S, Yerramilli A (2011) A comparison of HWRF, ARW and NMM models in Hurricane Katrina (2005) simulation. Int J Environ Res Public Health 8:2447–2469

Dunion JP, Landsea CW, Houston SH, Powell MD (2003) A reanalysis of the surface winds for Hurricane Donna of 1960. Mon Weather Rev 131:1992–2011

Durrant T, Greenslade D, Hemer M, Trenham C (2014) A global wave hindcast focussed on the Central and South Pacific. CAWCR Technical Report No. 070 CAWCR Publications Web. https://www.cawcr.gov.au/publications/CAWCR Technical Reports. Accessed 01 June 2019

Emanuel K (2005) Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436:686–688

Green BW, Zhang F (2015) Numerical simulations of Hurricane Katrina (2005) in the turbulent gray zone. J Adv Model Earth Syst 7:142–161. https://doi.org/10.1002/2014ms000399

Guo Y, van de Lindt J (2019) Simulation of hurricane wind fields for community resilience applications: a data-driven approach using integrated asymmetric Holland models for inner and outer core regions. J Struct Eng 145:04019089

Hodges K, Cobb A, Vidale PL (2017) How well are tropical cyclones represented in reanalysis datasets? J Clim 30:5243–5264

Holland GJ (1980) An analytic model of the wind and pressure profiles in hurricanes. Month Weather Rev 108:1212–1218

Holland GJ, Belanger JI, Fritz A (2010) A revised model for radial profiles of hurricane winds. Mon Weather Rev 138:4393–4401

Holland GJ, Done JM, Douglas R, Saville GR, Ge M (2019) Global tropical cyclone damage potential. Hurricane risk. Springer, Berlin, pp 23–42

Kantha L (2006) Time to replace the Saffir-Simpson hurricane scale? Eos Trans Am Geophys Union 87:3–6

Krien Y et al (2018) Can we improve parametric cyclonic wind fields using recent satellite remote sensing data? Remote Sens 10:1963

Lin N, Chavas D (2012) On hurricane parametric wind and applications in storm surge modeling. J Geophys Res. https://doi.org/10.1029/2011JD017126

Mazaheri S, Kamranzad B, Hajivalie F (2013) Modification of 32 years ECMWF wind field using QuikSCAT data for wave hindcasting in Iranian Seas. J Coast Res 65:344–350

Mohanty U, Osuri KK, Routray A, Mohapatra M, Pattanayak S (2010) Simulation of Bay of Bengal tropical cyclones with WRF model: Impact of initial and boundary conditions. Mar Geodesy 33:294–314

Murakami H (2014) Tropical cyclones in reanalysis data sets. Geophys Res Lett 41:2133–2141

Nadimpalli R, Osuri KK, Mohanty U, Das AK, Kumar A, Sil S, Niyogi D (2020) Forecasting tropical cyclones in the Bay of Bengal using quasi-operational WRF and HWRF modeling systems: an assessment study. Meteorol Atmos Phys 132:1–17

Osuri KK, Mohanty U, Routray A, Kulkarni MA, Mohapatra M (2012a) Customization of WRF-ARW model with physical parameterization schemes for the simulation of tropical cyclones over North Indian Ocean. Nat Hazards 63:1337–1359

Osuri KK, Mohanty U, Routray A, Mohapatra M (2012b) The impact of satellite-derived wind data assimilation on track, intensity and structure of tropical cyclones over the North Indian Ocean International. J Remote Sens 33:1627–1652

Osuri KK, Mohanty U, Routray A, Mohapatra M, Niyogi D (2013) Real-time track prediction of tropical cyclones over the North Indian Ocean using the ARW model. J Appl Meteorol Climatol 52:2476–2492

Perlin N, De Szoeke SP, Chelton DB, Samelson RM, Skyllingstad ED, O'Neill LW (2014) Modeling the atmospheric boundary layer wind response to mesoscale sea surface temperature perturbations. Mon Weather Rev 142:4284–4307

Powell MD, Houston SH, Amat LR, Morisseau-Leroy N (1998) The HRD real-time hurricane wind analysis system. J Wind Eng Ind Aerodyn 77:53–64

Rakesh V, Singh R, Pal P, Joshi P (2009) Impacts of satellite-observed winds and total precipitable water on WRF short-range forecasts over the Indian region during the 2006 summer monsoon. Weather Forecast 24:1706–1731

Rathmann NM, Yang S, Kaas E (2014) Tropical cyclones in enhanced resolution CMIP5 experiments. Clim Dyn 42:665–681

Saket A, Etemad-Shahidi A, Moeini MH (2013) Evaluation of ECMWF wind data for wave hindcast in Chabahar zone. J Coast Res 65:380–386

Simpson RH, Riehl H (1981) The hurricane and its impact. Louisiana State University Press, Baton Rouge

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Wang W, Powers JG (2008) A description of the Advanced Research WRF version 3. NCAR Technical note-475 STR.

Smith S (2010) Managing catastrophic risk: beyond cat bonds. Weather risk management: a guide for corporations, hedge funds and investors. Incisive financial Publishing Ltd, Harcourt, pp 199–213

Srinivas C, Bhaskar DR, Yesubabu V, Baskaran R, Venkatraman B (2013) Tropical cyclone predictions over the Bay of Bengal using the high-resolution Advanced Research Weather Research and Forecasting (ARW) model. Q J R Meteorol Soc 139:1810–1825

Tanemoto J, Ishihara T (2013) Prediction of tropical cyclone induced wind field by using mesoscale model and JMA best track. In: Paper presented at the The Eighth Asia-Pacific Conference on Wind Engineering, Chennai, India, pp 10–14

Thompson EF, Cardone VJ (1996) Practical modeling of hurricane surface wind fields. J Waterwa Port Coast Ocean Eng 122:195–205

Vickery PJ, Twisdale LA (1995) Wind-field and filling models for hurricane wind-speed predictions. J Struct Eng 121:1700–1709

Wang T, Yang Z, Wu W-C, Grear M (2018) A sensitivity analysis of the wind forcing effect on the accuracy of large-wave hindcasting. J Mar Sci Eng 6:139

Xue L, Li Y, Song L, Chen W, Wang B (2017) A WRF-based engineering wind field model for tropical cyclones and its applications. Natl Hazards 87:1735–1750

Young I (2017) A review of parametric descriptions of tropical cyclone wind-wave generation. Atmosphere 8:194. https://doi.org/10.3390/atmos8100194

Young I, Sobey R (1981) The numerical prediction of tropical cyclone wind-waves. Department of Civil and Systems Engineering, James Cook University of North Queensland, Research Bulletin No. CS20.

Zhai AR, Jiang JH (2014) Dependence of US hurricane economic loss on maximum wind speed and storm size. Environ Res Lett 9:064019