Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2023, 10(6): 17-25

Research Article ISSN: 2394 - 658X

Numerical Modelling of Waves and Surge from Cyclone Shaheen (2021) in the Arabian Sea

M A Sarker (PhD)

Technical Director, Royal HaskoningDHV, Westpoint, Peterborough Business Park, Lynch Wood, Peterborough PE2 6FZ, United Kingdom. E-mail: zaman.sarker@rhdhv.com

ABSTRACT

Severe Cyclonic Storm Shaheen (30 September – 4 October 2021) formed in the Arabian Sea from the remaining part of Cyclone Gulab in the Bay of Bengal. Shaheen impacted Pakistan, Iran, Oman and the United Arab Emirates causing loss of lives and damage to properties. This paper has concentrated on this event to illustrate the use of numerical modelling to simulate waves and surge generated by cyclones. The MIKE21 software developed by DHI was used in the numerical modelling. Sample results of waves and surge from the modelling study are presented in this paper for illustration purposes. The model could be used to simulate any cyclone generated anywhere within the Arabian Sea. The methodology described in this paper for modelling cyclone waves and surge in the Arabian Sea could also be applied to simulate cyclones at other sites around the world.

Key words: Numerical modelling, natural hazards, cyclones, extreme waves, storm surge, port development, Arabian Sea, Cyclone Shaheen, Royal HaskoningDHV.

1. INTRODUCTION

1.1 Formation and intensity of Cyclone Shaheen

Cyclone Shaheen (30 September – 4 October 2021) can be traced back to a low-pressure area situated over the Bay of Bengal on 24 September 2021. It was known as Cyclone Gulab in the Bay of Bengal. On 26 September, Gulab made landfall in India's Andhra Pradesh but weakened overland, before degenerating into a remnant low on 28 September. The system continued moving westward, emerging into the Arabian Sea on 29 September before regenerating into a depression early on 30 September. Early on 1 October, the system restrengthened into a Cyclonic Storm, which the IMD [1] named Shaheen. The system gradually strengthened as it entered the Gulf of Oman. While slowly moving westward, the storm turned southwestward, subsequently making an extremely rare landfall in Oman on 3 October as a Category 1 tropical cyclone with 1-minute mean highest sustained wind speed of 130 km/h and lowest pressure of 976 mbar (SSHWS/JTWC). Shaheen then rapidly weakened before dissipating the next day. The above information was obtained from [2].

1.2 Damages from Cyclone Shaheen

Cyclone Shaheen brought heavy rain and strong winds throughout India and the Middle East killing at least 39 people. Water-related damage was extensive, while communications were disrupted as winds downed many power lines. Hundreds of roads were closed in India. Shaheen delivered extreme rainfall to Oman, causing flooding across a wide area of the country's northeastern governorates. Muscat saw particularly heavy flooding which submerged cars and other low-lying objects. Other neighboring countries in the Arab world also experienced some rain. Total estimated financial losses from Cyclone Shaheen were $791 million. The above information was obtained from [2].

1.3 The present study

This paper has concentrated on Cyclone Shaheen to illustrate the use of numerical modelling to simulate waves and surge generated by cyclones. A large tidal hydrodynamic model is required to simulate cyclone surge on a region whereas a large wave model is required to simulate cyclone waves. Given the above risks, Royal HaskoningDHV (RHDHV) has set up regional tidal hydrodynamic and wave models covering the Arabian Sea to investigate hazards

from cyclones and to support their project work in the region. The models have been used to assess cyclones within this region.
The MIKE21 models developed by DHI were used in the study. Sample results of waves and surge from the modelling study are presented in this paper for illustration purposes. The model could be used to simulate any cyclone generated anywhere within the Arabian Sea. The methodology described in this paper for modelling cyclone waves and surge in the Arabian Sea could also be applied to simulate cyclones at other sites around the world.

2. 2.CYCLONE SHAHEEN TRACK AND DATA

The track (route) of Cyclone Shaheen was obtained from [3] as shown in Figure 1.

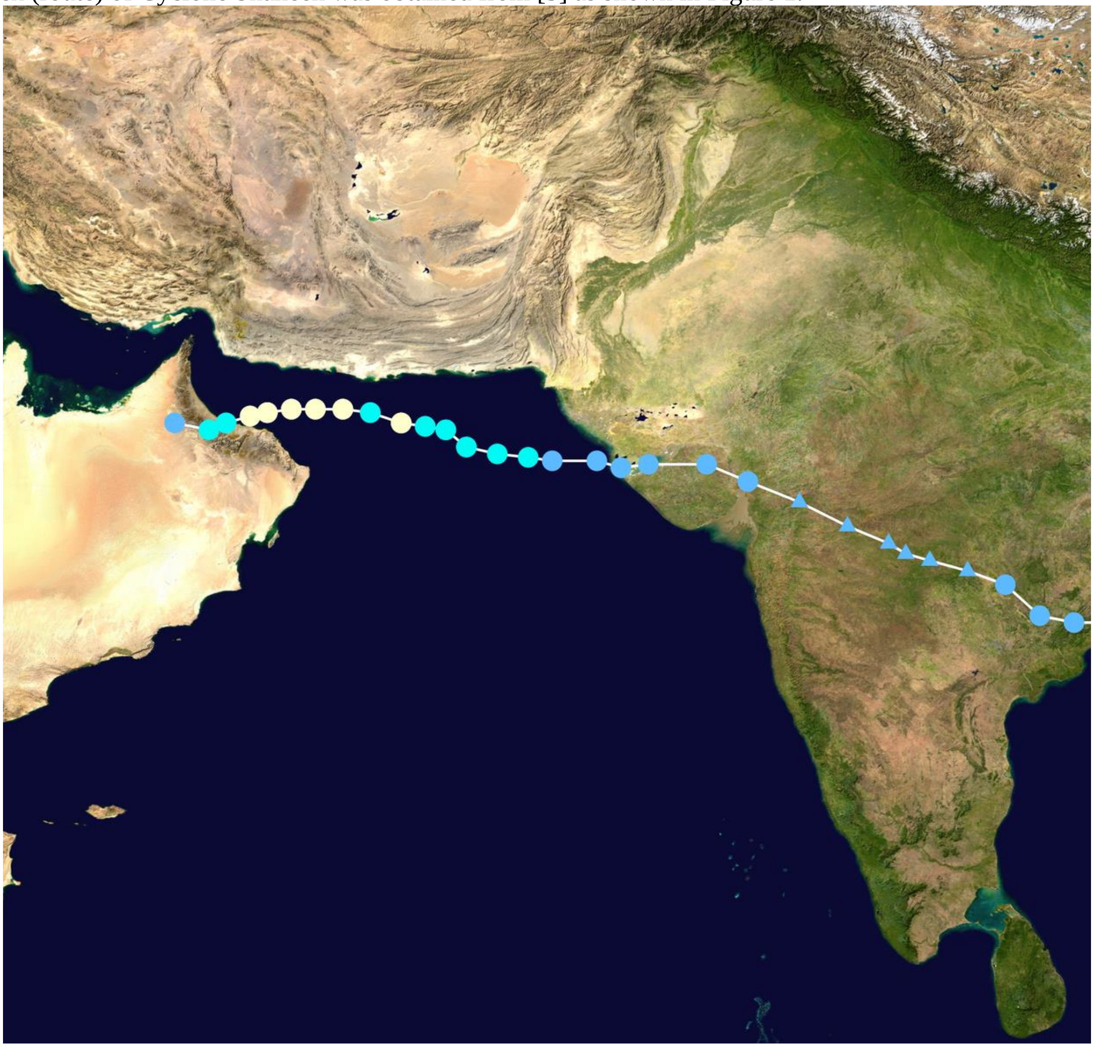

Figure 1: Track and intensity of Cyclone Shaheen [3]

The cyclone data was obtained from the International Best Track Archive for Climate Stewardship (IBTrACS) [4]. The IBTrACS archived cyclone data contains three hourly information including date and time, tracks (path), maximum sustained wind speeds, radius of maximum sustained wind speeds and the minimum central pressures. Such data of Cyclone Shaheen is provided in Table 1. It should be noted that the IBTrACS provides 1-minutes mean maximum wind speeds which was converted to 1-hourly mean for the present study using the method in [5].

Table 1: Cyclone Shaheen Track and Data from IBTrACS [4]

Date and Time [UTC]	Longitude [°E]	Latitude [°N]	Max 1-minute wind speeds [knots]	Central pressure [hPa]	Radius of maximum winds [nm]
29/09/2021 06:00	72.4000	22.1000	25	1001	80
29/09/2021 09:00	71.9220	22.3853	25	1001	80
29/09/2021 12:00	71.4000	22.6000	25	1001	80

29/09/2021 15:00	70.7601	22.6711	25	1001	80
29/09/2021 18:00	70.0919	22.6452	25	1001	80
29/09/2021 21:00	69.4500	22.5610	25	1001	80
30/09/2021 00:00	68.9000	22.5000	25	1001	80
30/09/2021 03:00	68.5583	22.5884	25	1001	80
30/09/2021 06:00	68.2000	22.7000	25	1002	80
30/09/2021 09:00	67.5498	22.7082	27	999	55
30/09/2021 12:00	66.9000	22.7000	30	996	30
30/09/2021 15:00	66.5650	22.7490	35	995	50
30/09/2021 18:00	66.2000	22.8000	40	994	70
30/09/2021 21:00	65.4198	22.7863	42	993	70
01/10/2021 00:00	64.7000	22.8000	45	992	70
01/10/2021 03:00	64.4823	22.9118	47	990	45
01/10/2021 06:00	64.4000	23.1000	50	988	20
01/10/2021 09:00	64.1227	23.3500	55	985	20
01/10/2021 12:00	63.8000	23.6000	60	982	20
01/10/2021 15:00	63.5075	23.7949	57	982	20
01/10/2021 18:00	63.2000	23.9000	54	983	20
01/10/2021 21:00	62.8720	23.8499	59	981	20
02/10/2021 00:00	62.5000	23.8000	65	979	20
02/10/2021 03:00	62.0579	23.9351	62	980	20
02/10/2021 06:00	61.6000	24.1000	60	981	20
02/10/2021 09:00	61.1924	24.1723	62	979	20
02/10/2021 12:00	60.8000	24.2000	65	978	20
02/10/2021 15:00	60.3924	24.2075	65	977	20
02/10/2021 18:00	60.0000	24.2000	65	977	20
02/10/2021 21:00	59.6426	24.2074	67	976	15
03/10/2021 00:00	59.3000	24.2000	70	975	10
03/10/2021 03:00	58.9349	24.1575	70	976	8
03/10/2021 06:00	58.6000	24.1000	70	978	7
03/10/2021 09:00	58.3501	24.0573	67	976	8
03/10/2021 12:00	58.1000	24.0000	65	974	10
03/10/2021 15:00	57.7499	23.9076	60	981	7
03/10/2021 18:00	57.4000	23.8000	55	988	5
03/10/2021 21:00	57.1724	23.6696	45	992	5
04/10/2021 00:00	56.9000	23.6000	35	996	5
04/10/2021 03:00	56.4554	23.6606	30	998	5
04/10/2021 06:00	55.9000	23.8000	25	1001	5

3. WIND AND PRESSURE FIELDS GENERATION

The MIKE21 Cyclone Wind Generation Tool of DHI [6] was used to generate the cyclonic wind and pressure fields of Cyclone Shaheen. The tool allows users to compute wind and pressure data due to tropical cyclone (hurricane or typhoon). Several cyclone parametric models are included in the tool such as Young and Sobey model (1981), Holland – single vortex model (1981), Holland – double vortex model (1980) and Rankine vortex model. All the six input parameters required by the Young and Sobey model (i.e., time, track, radius of maximum wind speed, maximum wind speed, central pressure, and neutral pressure) were available for the study and this was, therefore, used to generate the cyclonic wind and pressure fields. The other models require some additional parameters (such as Holland parameter B and Rankine parameter X) that need to be calculated using empirical relationships which add further uncertainty to the generated wind and pressure fields and were, therefore, not used for the present study. Figure 2 shows an example of wind and pressure fields of Cyclone Shaheen on 03/10/2021 00:00 when it generated the maximum wave heights. These wind and pressure fields were used to drive the cyclone wave and surge models described later.

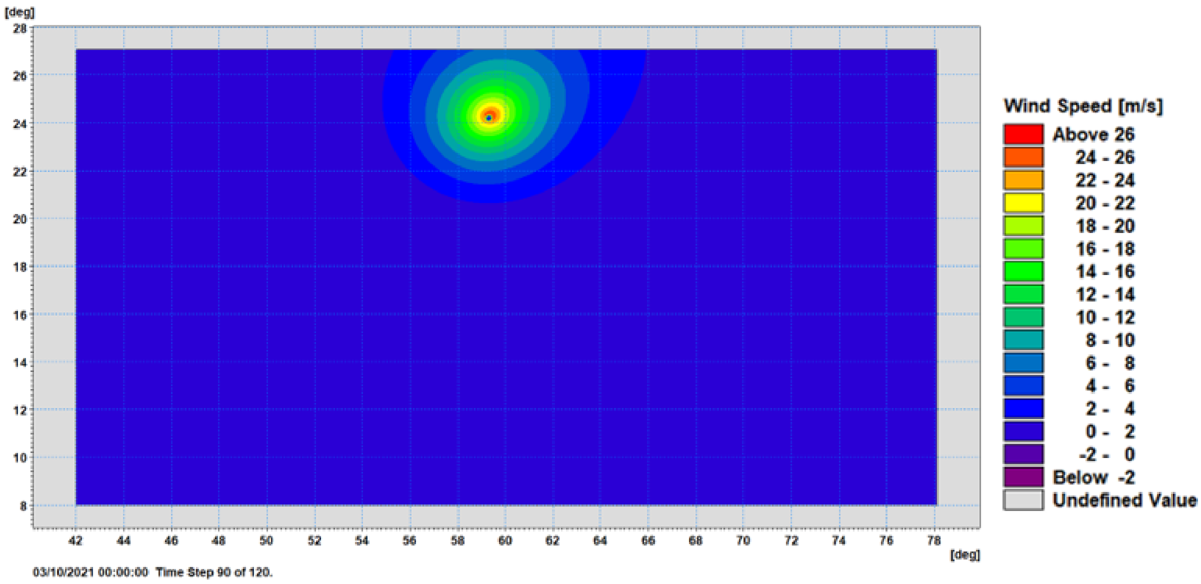

Fig. 2(a) Wind fields of Cyclone Shaheen

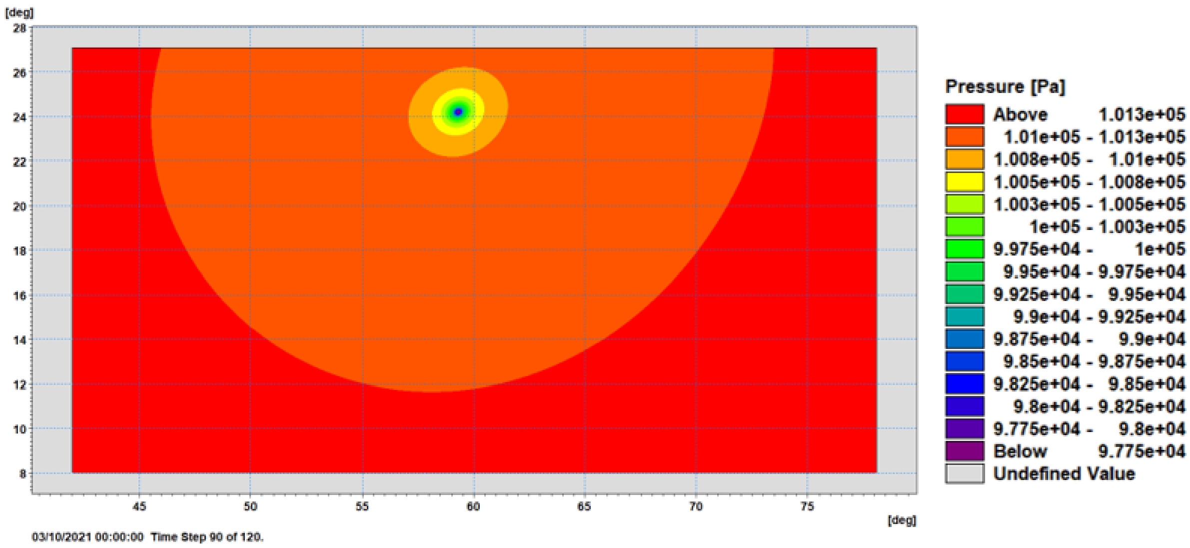

Fig. 2(b) Pressure fields of Cyclone Shaheen

4. ARABIAN SEA REGIONAL MODELS SET UP BY RHDHV

4.1 The Regional Tidal Model

RHDHV has set up a two-dimensional Regional Tidal Hydrodynamic Model for the Arabian Sea using the MIKE21/3 Flow Model FM software of DHI [7]. The model is based on the numerical solution of the two/three-dimensional shallow water incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. Thus, the model consists of continuity, momentum, temperature, salinity, and density equations. The regional model covers the coastlines of eight countries – Somalia, Djibouti, Yemen, Oman, United Arab Emirates, Iran, Pakistan, and India (see Figure 3). The model has three open boundaries – one to the south (Indian Ocean), one to the north-west (Arabian Gulf) and the other to the south-west (Red Sea). The model was set up in such a way that with a finer local mesh and more detailed bathymetry and land boundary data within a specified area, localized water movement can be correctly modelled at a point of interest without the need of introducing nested models. With this unstructured flexible mesh, it is easy to refine the mesh in an area of interest.

For the present study, the regional model was modified by providing a high mesh resolution within the shallow water areas and at the study site where changes in physical processes take place quickly within short distances. The model bathymetry shown in Figure 3 was obtained from the C-Map Global Database [8].

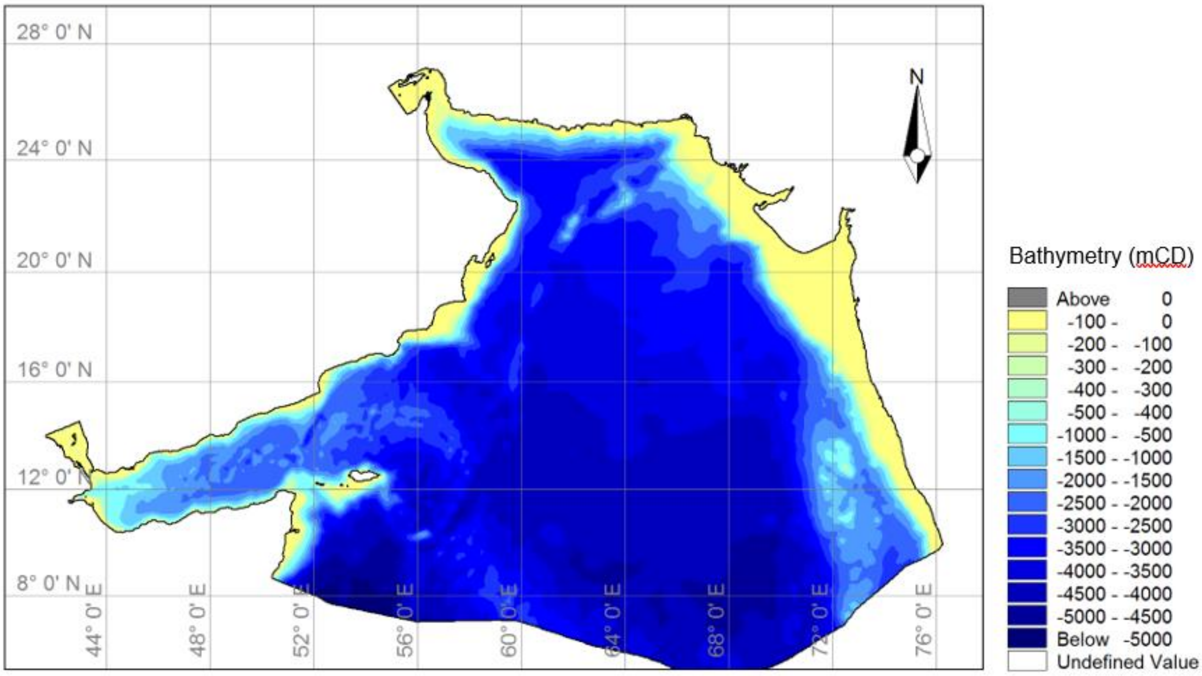

Fig. 3 Model extent and bathymetry (mCD)

The regional tidal model was used to drive the cyclone surge model to assess cyclone surge within the region. The cyclone tidal model was previously validated during multiple consultancy projects in the area carried out by RHDHV and for numerous journal papers published by RHDHV. Re-validation of the model for Cyclone Shaheen was not possible due to lack of measured data.

4.2 The Regional Wave Model

RHDHV has also set up a two-dimensional Regional Wave Model for the Arabian Sea using the MIKE21 Spectral Wave (SW) software of DHI [9]. The model considers various physical phenomena, for example, wave growth by action of wind, non-linear wave-wave interaction, dissipation due to white-capping, dissipation due to bottom friction, dissipation due to depth-induced wave breaking, wave diffraction, wave refraction, wave shoaling and wave-current interaction. The fully spectral formulation of the model is based on the wave action conservation equation, where the directional-frequency wave action spectrum is the dependent variable.

The model extent, mesh system and bathymetry are the same as the regional tidal hydrodynamic model described above. The regional wave model was used to drive the cyclone wave model to assess cyclone wave conditions within the region. The cyclone wave model was previously validated during multiple consultancy projects in the area carried out by RHDHV and for numerous journal papers published by RHDHV. Re-validation of the model for Cyclone Shaheen was not possible due to lack of measured data.

The wave and the tidal models were run simultaneously in a dynamic coupled mode where the models exchanged wave and tidal information automatically as and when required.

5. CYCLONE SHAHEEN WAVE MODELLING

5.1 The Wave Model

The regional wave model set up by RHDHV based on the MIKE21 Spectral Wave (SW) Model was used to simulate the cyclone waves. The model was used to simulate the generation and propagation of cyclone waves. Fully spectral formulation was used with in-stationary time formulation. The higher order numerical scheme was used in the study to improve accuracy in model results. Wave diffraction, wave breaking, bottom friction and white capping were included in the model simulations. Quadruplet wave interaction was also included in the simulations. JONSWAP fetch growth empirical spectral formulation was used. Unstructured flexible mesh was used in the model.

5.2 Methodology

The cyclone wave model was driven by wind and pressure fields as shown in Figure 2. A constant water level of 2.5m above the chart datum was used in the model. The model simulations covered the entire passage of the cyclone across the Arabian Sea.

5.3 Wave Model Results and Discussions

The maximum significant wave height (Hm0) of approximately 7.0m (with associated peak wave period, Tp of 10.0s) was found at the location of 24.4°N, 59.2°E, 2120m depth on 03 October 2021 00:30. The two-dimensional distribution of wave height contours superimposed by wave directional vectors is shown in Figure 4 for this time-step. The figure indicates that the maximum wave height was found in the Gulf of Oman where the cyclone intensity was the highest.

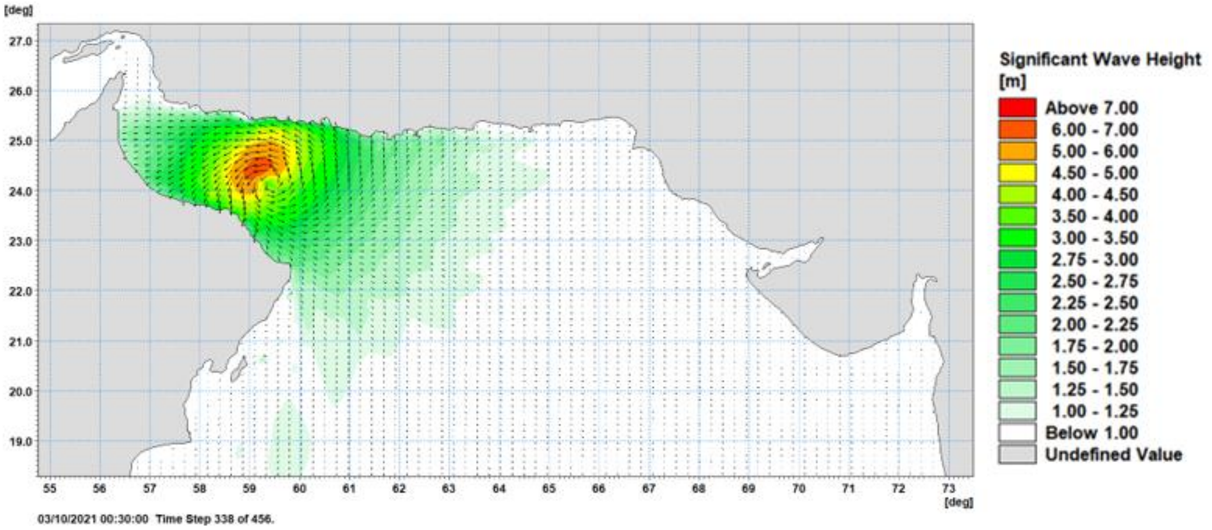

Fig. 4 Significant wave heights (Hm0) of Cyclone Shaheen on 03/10/2021 00:30

The temporal variation in significant wave height and peak wave period at this location is shown in Figure 5. The figure indicates that significant wave heights higher than 5m were sustained for a duration of about 10 hours and wave heights higher than 3m were sustained for a duration of about 20 hours.

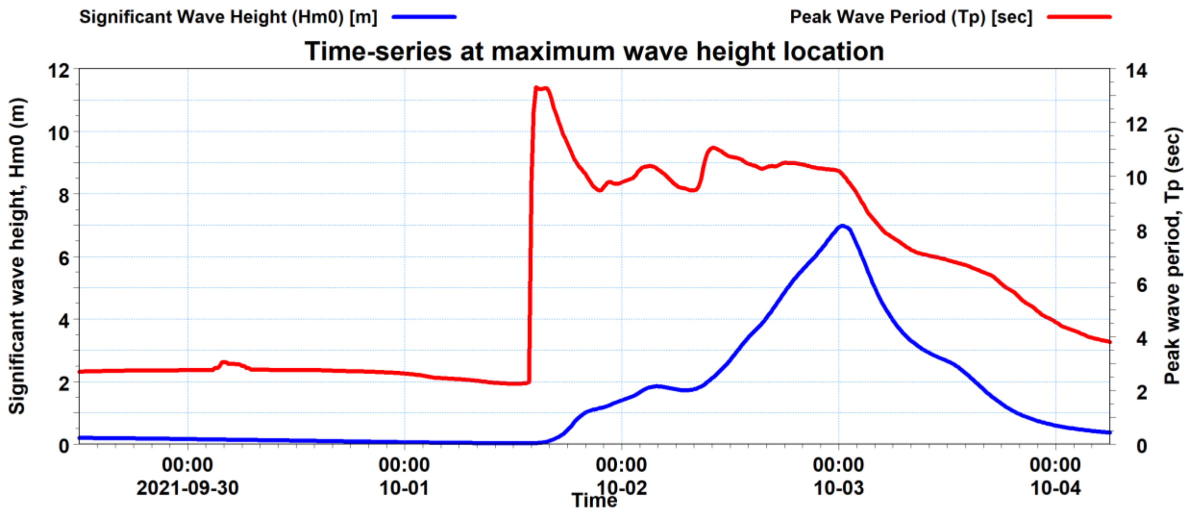

Fig. 5 Time-series of waves during Cyclone Shaheen at maximum wave height location (24.4°N, 59.2°E)

Statistical analyses of model results were carried out using the MIKE21 Tool [6] to derive mean and maximum wave conditions over the whole model domain during the entire duration of Cyclone Shaheen. Figure 6 shows the maximum significant wave heights over the whole model domain during the entire duration of the cyclone. The figure indicates that the maximum significant wave height was found along the track in the Gulf of Oman where the cyclone intensity was the highest.

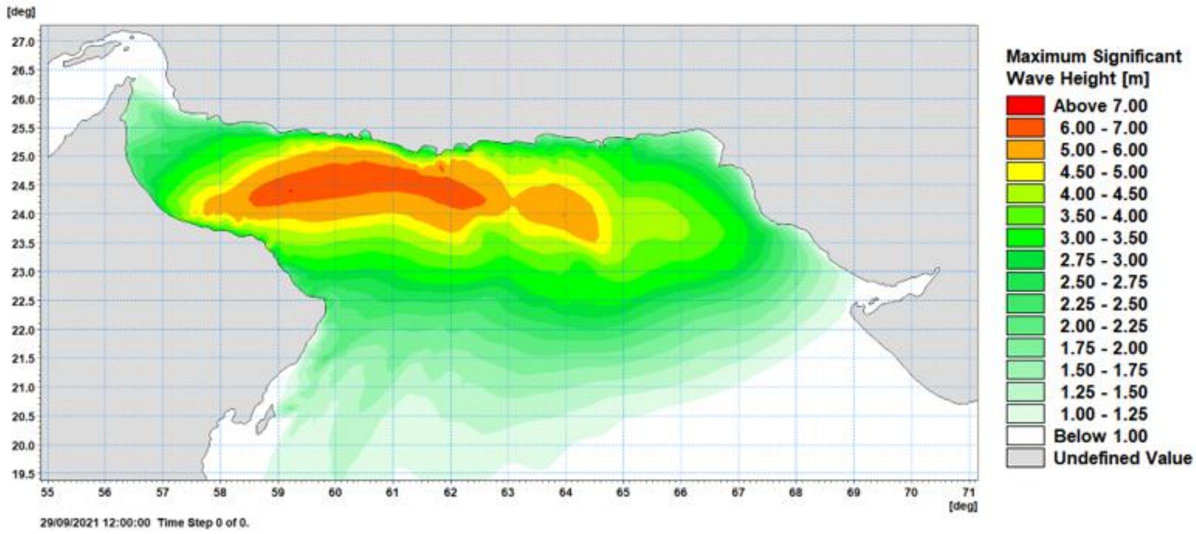

Fig. 6 Maximum significant wave height (Hm0) during the entire duration of Cyclone Shaheen

6. CYCLONE SHAHEEN SURGE MODELLING

A storm surge is an abnormal rise or fall of sea level near the coast caused by a severe tropical cyclone. As a result, sea water inundates low lying areas of coastal regions drowning human beings and livestock, eroding beaches and embankments, destroying vegetation, and reducing soil fertility.

6.1 The Tidal Model

The regional tidal hydrodynamic model set up by RHDHV based on the MIKE21/3 Flow Model FM was used to simulate the cyclone surge. The higher order numerical scheme was used in the study to improve accuracy in model results. Standard "Flood and Dry" were included in the model to consider flooding and drying processes. Barotropic density and Smagorinsky eddy viscosity were used. Coriolis forcing was included in the model as varying in domain. A constant bed resistance as Manning's number ($n = 1/44\ m^{1/3}/s$) was used throughout the model domain. Unstructured flexible mesh was used in the model.

6.2 Methodology

The cyclone surge model was driven by the cyclonic wind and pressure fields as shown in Figure 2. A constant water level of 2.5m above the chart datum was imposed at the three open boundaries at the south, north-west and south-west. An initial water level of 2.5m above the chart datum was maintained over the entire model domain.

6.3 Surge Model Results and Discussions

Statistical analyses of model results were carried out using the MIKE21 Tool [6] to derive mean and maximum surge values over the whole model domain during the entire duration of Cyclone Shaheen. Figure 7 shows the maximum positive surge (rise in water level) during the entire duration of the cyclone.

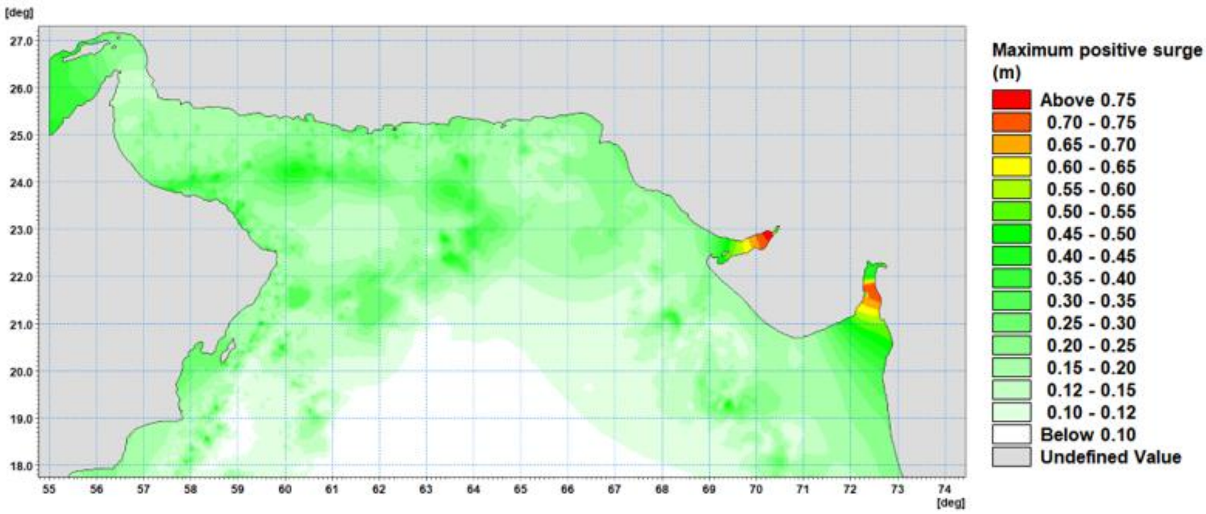

Fig. 7 Maximum positive surge during the entire duration of Cyclone Shaheen

The figure indicates that the highest positive surges occurred close to the cyclone track in the Gulf of Oman where the cyclone intensity was the highest. Higher positive surges were also occurred in the Gulf of Kutch (about 0.80m) and Gulf of Khambhat (about 0.75m) both in Indian state of Gujarat. Higher positive surge (about 0.3m) was also found in the Gulf of Aden with its maximum value of about 0.8m at the entrance of the Red Sea. Highest positive surge was 0.8m at the location of 22.9°N, 70.3°E.

Positive storm surges (rises in sea surface) bring the risk of flooding whereas negative storm surges (drops in sea surface) can damage ships in port and leave them stranded until the water level rises again. Therefore, statistical analyses of model results were also carried out using the MIKE21 Tool [6] to derive the maximum negative surges over the whole model domain during the entire duration of Cyclone Shaheen as shown in Figure 8. Higher negative surge was found in the Gulf of Kutch (up to 0.85m), Gulf of Khambhat (up to 0.50m), Gulf Aden (up to 0.3m) and entrance of the Red Sea (0.95m).

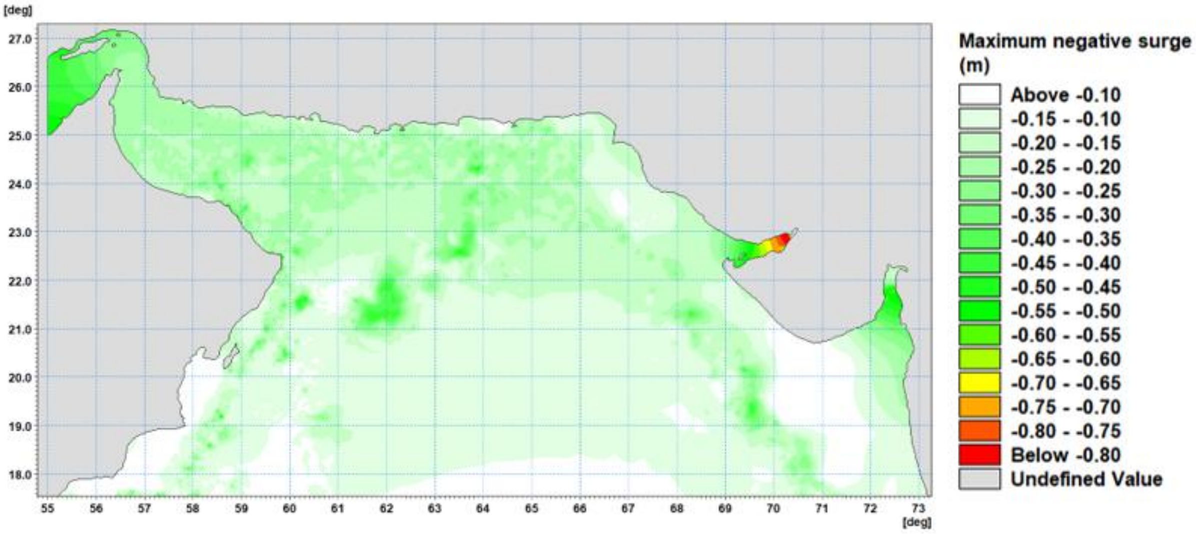

Fig. 8 Maximum negative surge during the entire duration of Cyclone Shaheen

The temporal variation of surge at the location of the highest surge during the entire duration of the cyclone is shown in Figure 9. The maximum surge of approximately 0.8m was found on 03 October 2021 09:45. Therefore, the highest surge and the maximum significant wave height occurred 9 hours apart albeit at separate locations. The figure indicates that surges higher than 0.50m were sustained for a duration of about 4 hours and surges higher than 0.25m were sustained for a duration of about 5 hours.

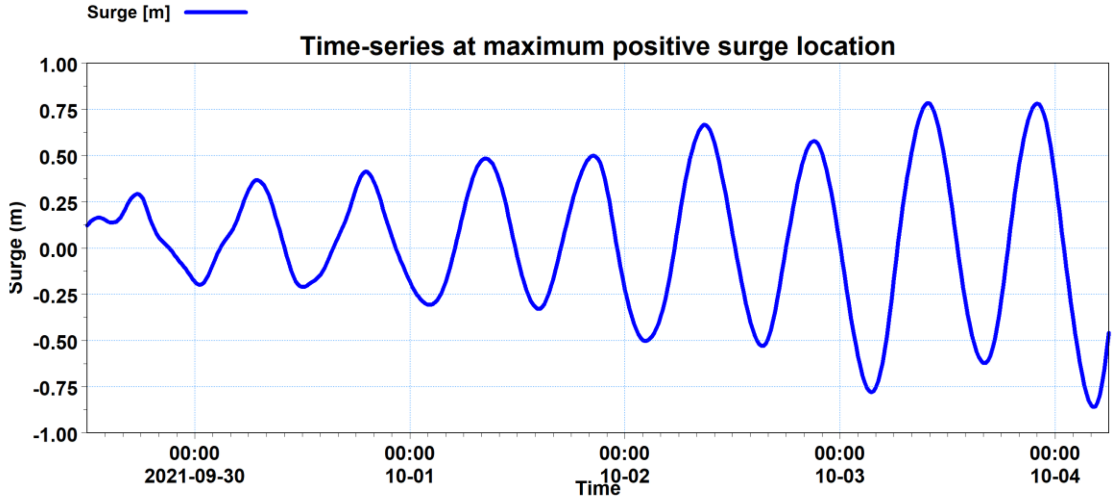

Fig. 9 Time-series of surge during Cyclone Shaheen at maximum surge location (22.9°N, 70.3°E)

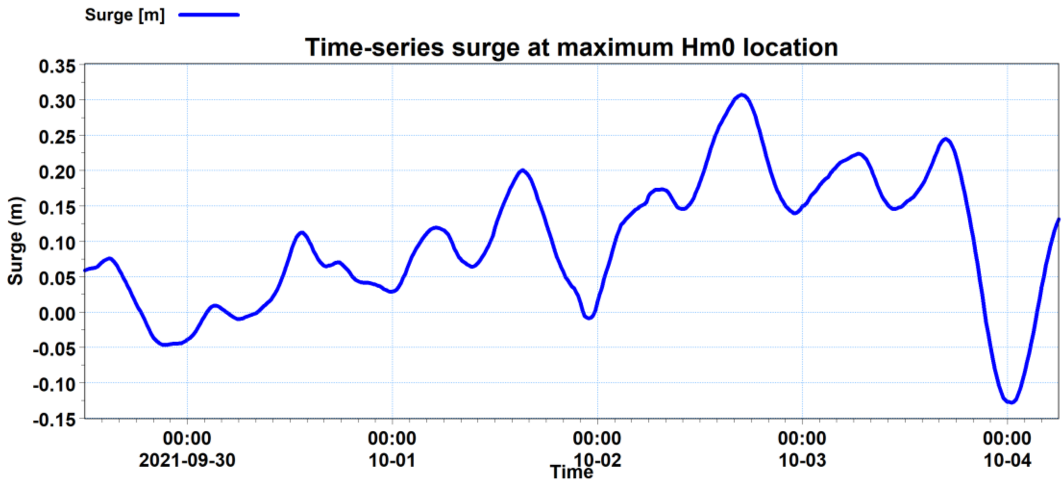

Fig. 10 Time-series of surge during Cyclone Shaheen at maximum wave height location (24.4°N, 59.2°E)

Higher positive surge was found along the cyclone track where the intensity of the cyclone was the highest. Higher positive surges were also found in the Gulf of Kutch, Gulf of Khambhat, Gulf Aden and at the entrance of the Red Sea due to funneling effects resulting from narrowing down of the water body. Higher negative surges were also found in these gulf areas as the cyclone sucked water away from these areas.

7. SUMMARY OF FINDINGS

This article illustrates how tidal hydrodynamic and wave models can be used to simulate the impacts of cyclones on coastal developments, facilities, and communities.

Higher wave heights were found along the track of the cyclone where the cyclone intensity was the highest. Maximum significant wave height of 7.0m (with associated peak wave period of 10.0s) was found on the track in the Gulf of Oman.

Higher positive surge was found along the cyclone track where the intensity of the cyclone was the highest. Higher surges were also found in the Gulf of Kutch, Gulf of Martaban, Gulf of Aden and at the entrance of the Red Sea due to funneling effects resulting from narrowing down of the water body. Higher negative surges were also found in these gulf areas as the cyclone sucked water away from these areas.

The maximum surge and the maximum significant wave height occurred 9 hours apart albeit at separate locations.

The methodology described in this paper for modelling cyclone waves and surges in the Arabian Sea could also be applied to other sites around the world that are affected by cyclones.

Acknowledgement

The author would like to thank Royal HaskoningDHV (an independent, international engineering and project management consultancy company, www.royalhaskoningdhv.com) for giving permission to publish this paper. The author would like to thank his colleague Debra Griffin for carrying out the proof reading of this manuscript. The author would also like to thank the external reviewers who provided valuable comments to improve the paper.

Figure 1 [3] was created by Meow using WikiProject Tropical cyclones/Tracks, the background image is from NASA and tracking data is from NRL.

REFERENCES

[1]. IMD (2023). The India Meteorological Department (IMD), Ministry of Earth Sciences, Government of India.
[2]. Wikipedia (2023a). Cyclones Gulab and Shaheen, https://en.wikipedia.org/wiki/Cyclones_Gulab_and_Shaheen.
[3]. Wikipedia (2023b). https://en.wikipedia.org/wiki/Cyclones_Gulab_and_Shaheen#/media/File:Gulab-Shaheen_2021_track.png
[4]. IBTrACS (2023). The International Best Track Archive for Climate Stewardship (IBTrACS), https://www.ncei.noaa.gov/products/international-best-track-archive.
[5]. WMO (2010). Guidelines for Converting Between Various Wind Averaging Periods in Tropical Cyclone Conditions. World Meteorological Organization, WMO/TD-No. 1555, 27 August 2010.
[6]. DHI (2023a). MIKE21 Toolbox User Guide, DK-2970, Hørsholm, Denmark.
[7]. DHI (2023b). MIKE21 Flow Model FM User Guide, DK-2970, Hørsholm, Denmark.
[8]. C-Map (2014). JEPPESEN Commercial Marine, Hovlandsveien 52, Egersund, Postal Code 4370, Norway, 2014, available online at http://www.jeppesen.com/index.jsp.
[9]. DHI (2023c). MIKE21 Spectral Wave Model User Guide, DK-2970, Hørsholm, Denmark.