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Numerical Modelling of Waves and Surge from Cyclone Kyarr (2019) in the Arabian Sea

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ABSTRACT

The Super Cyclonic Storm Kyarr (during 24 October to 3 November 2019) was an extremely powerful tropical cyclone that became the first super cyclonic storm in the North Indian Ocean since the Super Cyclone Gonu in 2007. Kyarr was also the second strongest tropical cyclone in the Arabian Sea and one of the most intense tropical cyclones in the history of the North Indian Ocean. Due to the immense strength of the storm, countries surrounding the Arabian Sea were affected by high tides and storm surges causing loss of life 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 Kyarr

1. INTRODUCTION

The Super Cyclonic Storm Kyarr (during 24 October to 3 November 2019) was an extremely powerful tropical cyclone that became the first super cyclonic storm in the North Indian Ocean since the Super Cyclone Gonu in 2007 [1]. Kyarr was also the second strongest tropical cyclone in the Arabian Sea and one of the most intense tropical cyclones in the history of the North Indian Ocean. The highest 3-minute sustained wind speed was 240 km/h (150 mph). The lowest pressure was 922 hPa (mbar). The cyclone affected Western India, Oman, United Arab Emirates, Socotra, and Somalia. Due to the immense strength of the storm, countries surrounding the Arabian Sea were affected by high tides and storm surges causing loss of life and damage to properties. The above information was obtained from [1].

This paper has concentrated on this event 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 only. 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. CYCLONE KYARR TRACK AND DATA

The track (route) of Cyclone Kyarr was obtained from [1] as shown in Figure 1. The cyclone data was obtained from the Joint Typhoon Warning Center (JTWC) [2]. The JTWC archived cyclone data contains six 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 Kyarr is provided in Table 1. It should be noted that the

JTWC provides 10-minutes mean maximum wind speeds which was converted to 1-hourly mean for the present study using the method in [3].

Table -1 Cyclone Kyarr Track and Data [2]

Date	Time [UTC]	Time [hour]	Longitude [°E]	Latitude [°N]	Radius of maximum winds [km]	Maximum 1-hourly wind speeds [m/s]	Central pressure [hPa]	Constant neutral pressure [hPa]
22/10/2019	18:00	0	66.40	14.70	120.4	8.8	1004	1013
23/10/2019	00:00	6	67.20	15.10	120.4	8.8	1003	1013
23/10/2019	06:00	12	68.10	15.30	120.4	8.8	1005	1013
23/10/2019	12:00	18	69.00	15.50	148.2	8.8	1002	1013
23/10/2019	18:00	24	70.10	15.60	111.1	11.0	1004	1013
24/10/2019	00:00	30	70.50	15.50	111.1	11.0	999	1013
24/10/2019	06:00	36	70.80	15.10	74.1	13.2	1001	1013
24/10/2019	12:00	42	71.10	15.40	101.9	13.2	1001	1013
24/10/2019	18:00	48	71.30	15.40	74.1	15.4	1001	1013
25/10/2019	00:00	54	71.60	15.60	55.6	19.8	994	1013
25/10/2019	06:00	60	71.80	15.90	64.8	22.0	992	1013
25/10/2019	12:00	66	71.90	16.20	37.0	24.2	987	1013
25/10/2019	18:00	72	71.40	16.50	37.0	28.6	984	1013
26/10/2019	00:00	78	70.70	16.60	37.0	30.8	979	1013
26/10/2019	06:00	84	70.00	16.60	37.0	35.1	976	1013
26/10/2019	12:00	90	69.40	16.70	37.0	41.7	961	1013
26/10/2019	18:00	96	68.90	16.80	18.5	52.7	939	1013
27/10/2019	00:00	102	68.20	17.00	18.5	59.3	924	1013
27/10/2019	06:00	108	67.50	17.30	22.2	59.3	926	1013
27/10/2019	12:00	114	66.90	17.50	27.8	57.1	928	1013
27/10/2019	18:00	120	66.20	17.90	27.8	54.9	933	1013
28/10/2019	00:00	126	65.50	18.20	27.8	57.1	929	1013
28/10/2019	06:00	132	64.80	18.30	31.5	57.1	931	1013
28/10/2019	12:00	138	64.40	18.50	31.5	54.9	933	1013
28/10/2019	18:00	144	64.00	18.80	31.5	52.7	937	1013
29/10/2019	00:00	150	63.60	19.10	27.8	50.5	942	1013
29/10/2019	06:00	156	63.30	19.40	27.8	48.3	947	1013
29/10/2019	12:00	162	63.00	19.60	27.8	43.9	955	1013
29/10/2019	18:00	168	62.70	19.60	55.6	41.7	961	1013
30/10/2019	00:00	174	62.20	19.50	9.3	37.3	968	1013
30/10/2019	06:00	180	61.80	19.20	92.6	30.8	979	1013
30/10/2019	12:00	186	61.30	18.90	83.3	26.4	986	1013
30/10/2019	18:00	192	60.60	18.70	83.3	22.0	994	1013
31/10/2019	00:00	198	60.20	18.20	129.6	17.6	999	1013
31/10/2019	06:00	204	59.90	17.70	138.9	15.4	1003	1013
31/10/2019	12:00	210	59.80	17.40	92.6	15.4	999	1013
31/10/2019	18:00	216	59.60	17.00	166.7	11.0	1005	1013
01/11/2019	00:00	222	59.30	16.40	64.8	11.0	1005	1013
01/11/2019	06:00	228	58.50	15.90	148.2	11.0	1006	1013
01/11/2019	12:00	234	57.70	15.30	148.2	11.0	1004	1013
01/11/2019	18:00	240	57.20	14.30	148.2	11.0	1005	1013

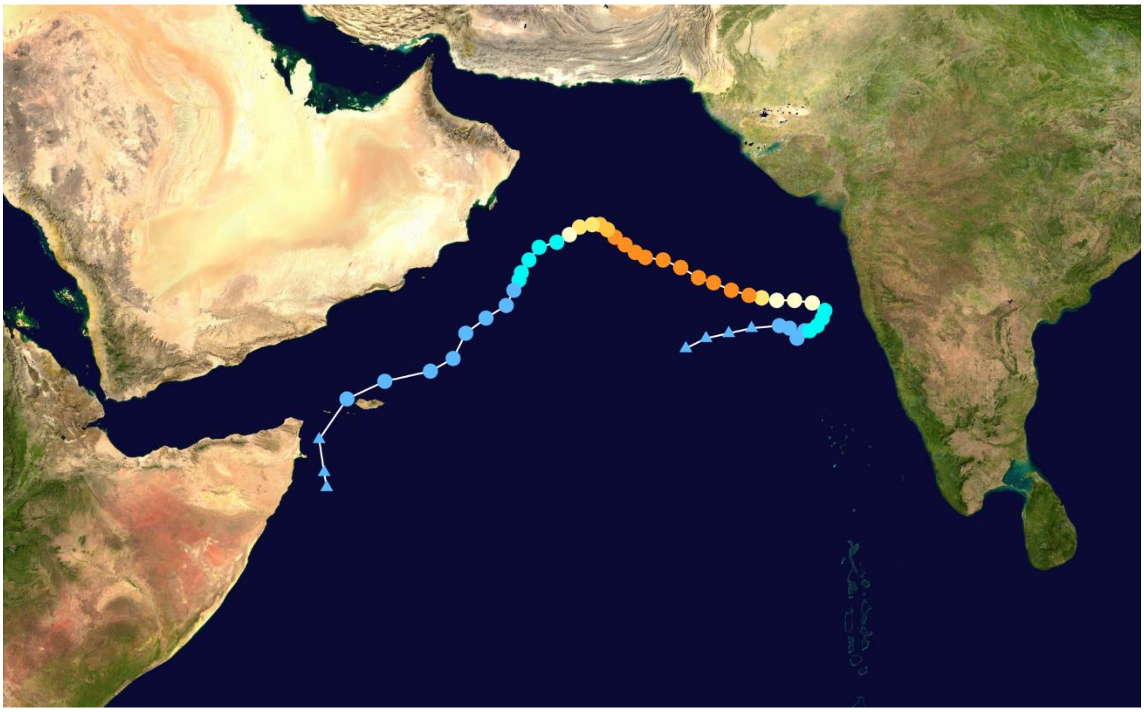

Fig. 1 Track and intensity of Cyclone Kyarr [1]

3. WIND AND PRESSURE FIELDS GENERATION

The MIKE21 Cyclone Wind Generation Tool of DHI [4] was used to generate the cyclonic wind and pressure fields of Cyclone Kyarr. 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 Kyarr on 27/10/2019 17:30 when it generated the maximum wave heights. These wind and pressure fields were used to drive the cyclone wave and surge models described later.

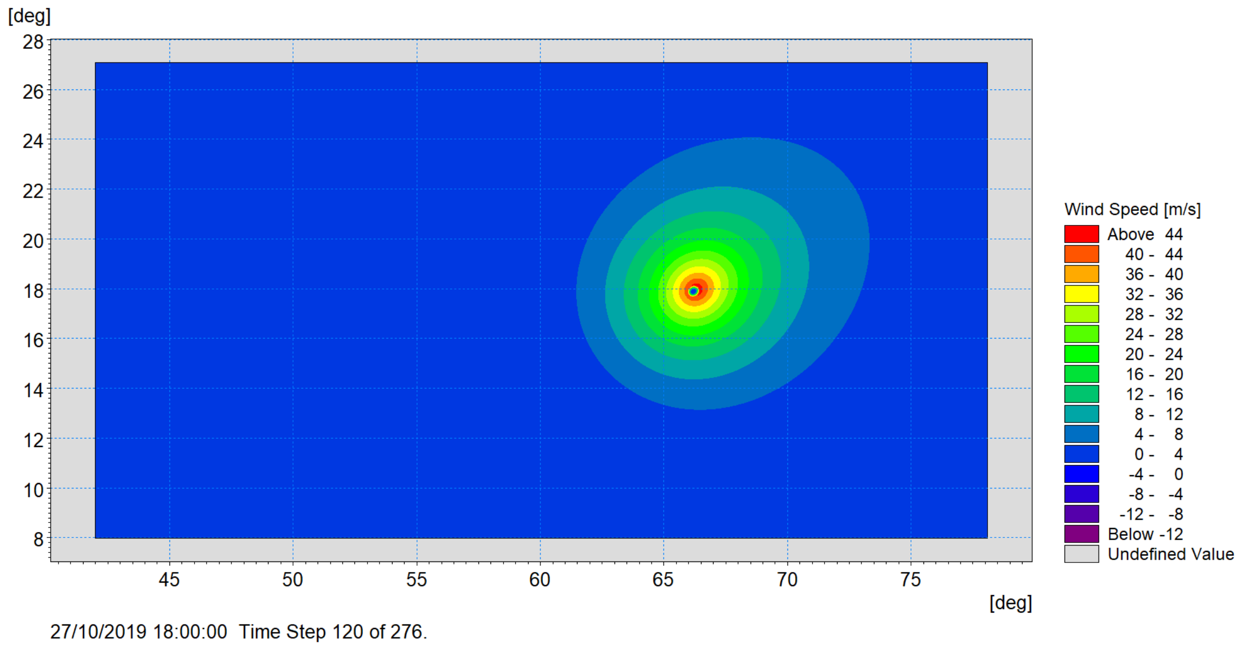

Fig. 2(a) Wind fields of Cyclone Kyarr

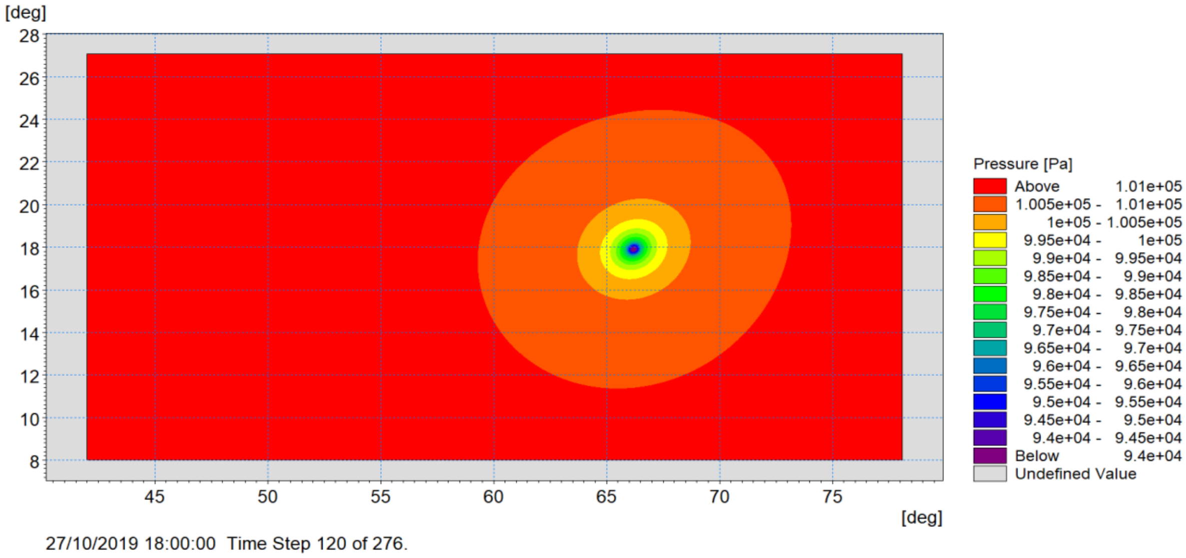

Fig. 2(b) Pressure fields of Cyclone Kyarr

Fig. 2 Wind and pressure fields of Cyclone Kyarr on 27/10/2019 18:00

4. BAY OF BENGAL 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 [5]. 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 is shown in Figure 3 was obtained from the C-Map Global Database [6].

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 Kyarr was not possible due to lack of data.

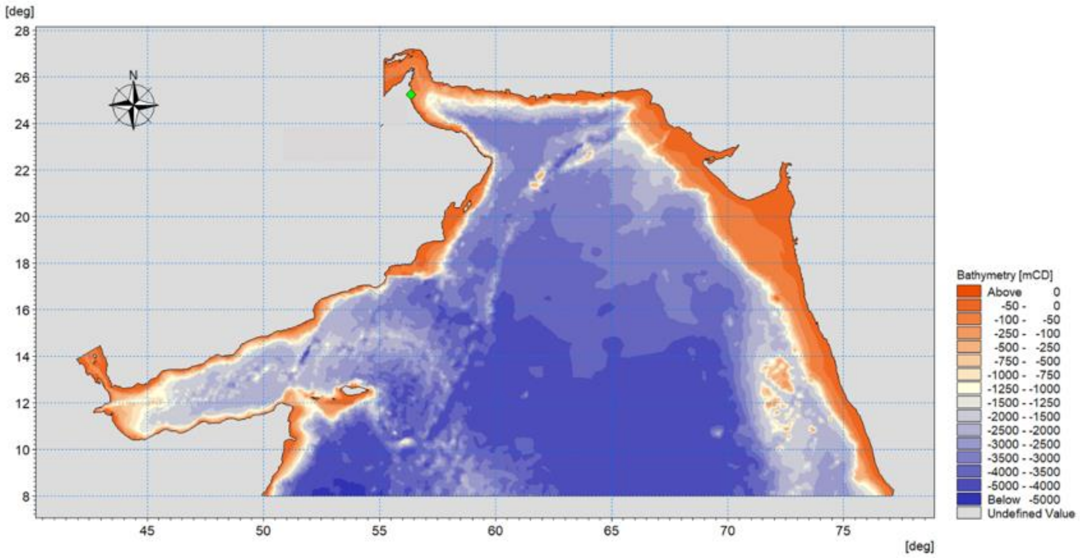

Fig. 3 Model extent and bathymetry

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 [7]. 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 Kyarr was not possible due to lack of 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 KYARR 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 3.15m above datum was used in the model. The model simulations covered the entire passage of the cyclone across the Arabian Sea.

5.3 Model Results and Discussions

The maximum significant wave height (Hm0) of approximately 14.7m (with associated peak wave period of 13.7s) was found at the location of 18.365°N, 66.271°E, 3181m depth on 27 October 2019 17:30. 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 middle of the Arabian Sea closer to the Indian states of Gujarat and Maharashtra. 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 10m were sustained for a duration of about 24 hours and wave heights higher than 5m were sustained for a duration of about 48 hours.

Statistical analyses of model results were carried out using the MIKE21 Tool [4] to derive mean and maximum wave conditions over the whole model domain during the entire duration of Cyclone Kyarr. 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 middle of the Arabian Sea where the cyclone intensity was the highest.

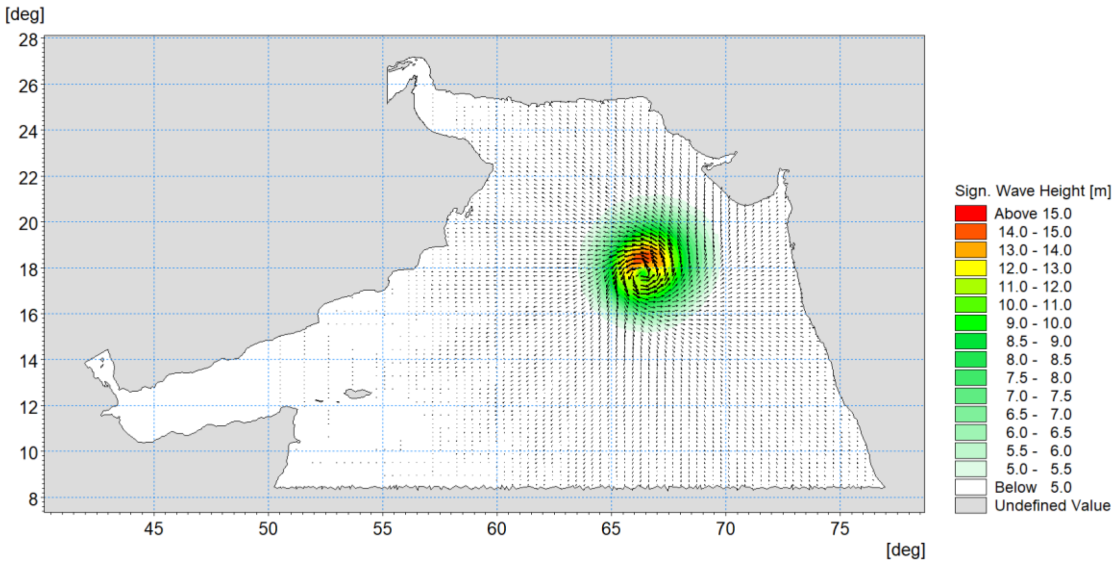

Fig. 4 Significant wave heights (Hm0) of Cyclone Kyarr on 27/10/2019 17:30

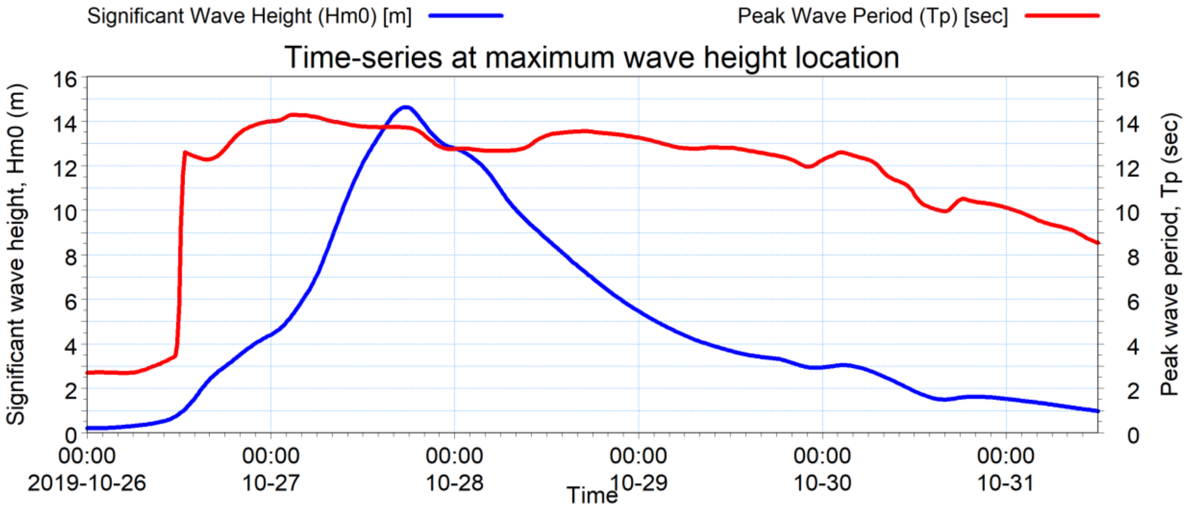

Fig. 5 Time-series of waves during Cyclone Kyarr at maximum wave height location (18.365°N, 66.271°E, 3181m depth)

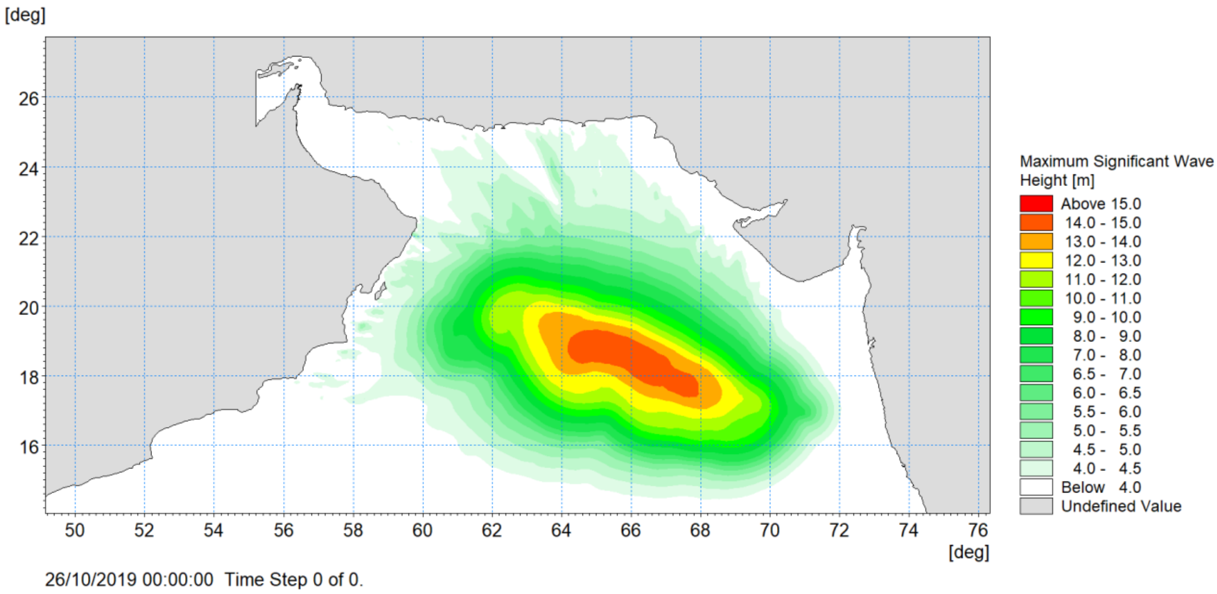

Fig. 6 Maximum significant wave height (Hm0) during the entire duration of Cyclone Kyarr

6. CYCLONE KYARR 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 3.15m above datum was imposed at the three open boundaries at the south, north-west and south-west. An initial water level of 3.15m above datum was maintained over the entire model domain.

6.3 Model Results and Discussions

Statistical analyses of model results were carried out using the MIKE21 Tool [4] to derive mean and maximum surge values over the whole model domain during the entire duration of Cyclone Kyarr. Figure 7 shows the maximum positive surge (rise in water level) during the entire duration of the cyclone. The figure indicates that the highest positive surges occurred close to the cyclone track in the middle of the Arabian Sea where the cyclone intensity was the highest. Higher positive surges were also occurred in the Gulf of Kutch and Gulf of Khambhat both in Indian state of Gujarat. Higher positive surge was also found in the Gulf of Aden. Highest positive surge in the middle of the Arabian sea was 0.91m at 17.261°N, 67.550°E, 3063m depth.

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 [4] to derive the maximum negative surges over the whole model domain during the entire duration of Cyclone Kyarr as shown in Figure 8. Higher negative surge was found in the Gulf of Kutch (up to 1.05m), Gulf of Khambhat (up to 1.06m) and Gulf Aden (up to 0.93m).

The temporal variation of surge at the location of the highest surge along the track in the middle of the Arabian Sea during the entire duration of the cyclone is shown in Figure 9. The maximum surge of approximately 0.91m was found on 27 October 2019 05:30. Therefore, the highest surge and the maximum significant wave height occurred 12 hours apart albeit at separate locations along the track in the middle of the Arabian Sea. The figure indicates that surges higher than 0.5m were sustained for a duration of about 4.5 hours and surges higher than 0.8m were sustained for a duration of about 1.5 hours.

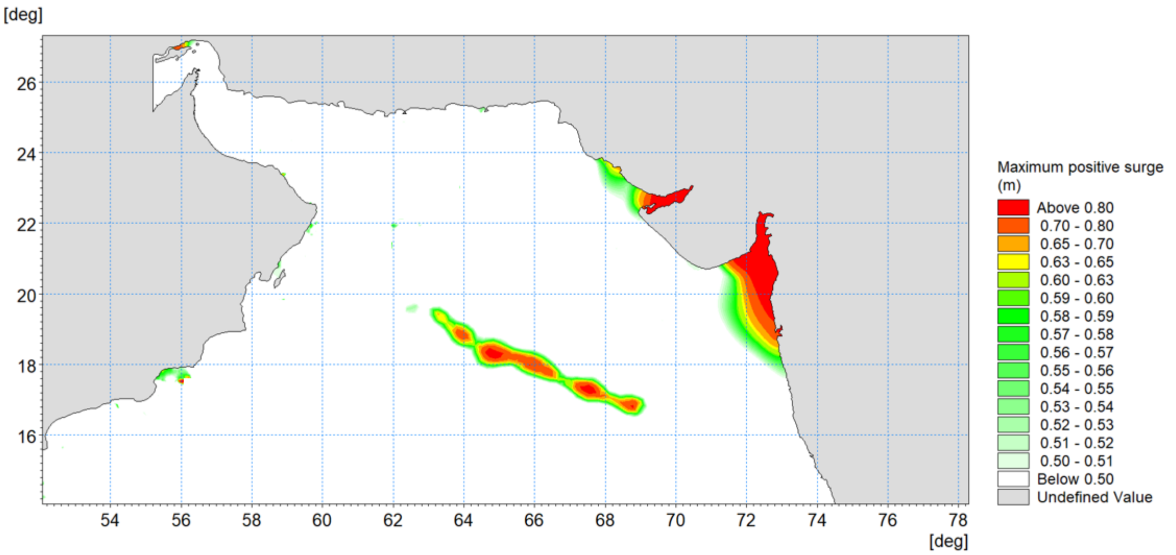

Fig. 7 Maximum positive surge during the entire duration of Cyclone Kyarr

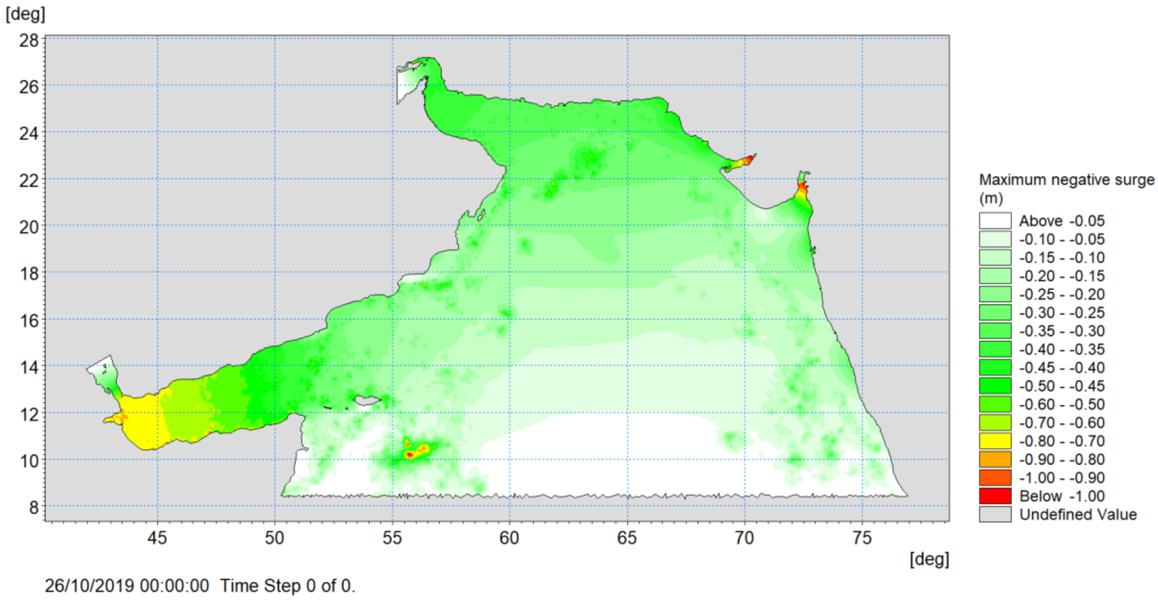

Fig. 8 Maximum negative surge during the entire duration of Cyclone Kyarr

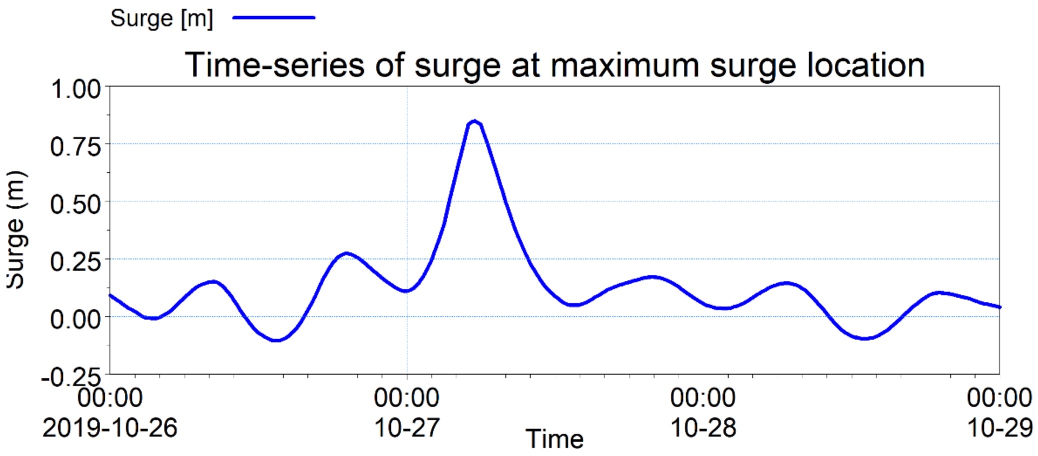

Fig. 9 Time-series of surge during Cyclone Kyarr at maximum surge location (17.261°N, 67.550°E, 3063m depth)

Higher positive surge was found along the cyclone track where the intensity of the cyclone was the highest (with the maximum surge of 0.91m in the middle of the Arabian Sea). Higher positive surges were also found in the Gulf of Kutch (up to 1.21m), Gulf of Khambhat (up to 1.81m) and Gulf Aden (up to 0.91m) 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 14.7m was found on the track in the middle of the Arabian Sea.

Higher positive surge was found along the cyclone track where the intensity of the cyclone was the highest (with the maximum surge of 0.91m in the middle of the Arabian Sea). Higher surges were also found in the Gulf of Kutch, Gulf of Martaban, and Gulf of Aden 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 12 hours apart albeit at separate locations on the track in the middle of the Arabian Sea.

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.

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