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

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ABSTRACT

The extremely severe Cyclone Tauktae (14-19 May 2021) was a powerful, deadly and damaging tropical cyclone in the Arabian Sea that became the strongest tropical cyclone to make landfall in the Indian state of Gujarat since the 1998 Gujarat cyclone. It was one of the strongest tropical cyclones to ever affect the west coast of India. Due to the immense strength of the storm, the west coast of India was affected by strong winds, high storm surges and heavy rainfalls 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 Tauktae, Royal HaskoningDHV.

1. INTRODUCTION

1.1 Formation and intensity of Cyclone Tauktae

The extremely severe Cyclone Tauktae (14-19 May 2021) was a powerful, deadly and damaging tropical cyclone in the Arabian Sea that became the strongest tropical cyclone to make landfall in the Indian state of Gujarat since the 1998 Gujarat cyclone. It was one of the strongest tropical cyclones to ever affect the west coast of India.

Cyclone Tauktae originated from an area of low pressure in the Arabian Sea which was first monitored by the India Meteorological Department (IMD) [1] on 13 May 2021. It became a severe cyclonic storm on 15 May. Tauktae began to parallel the coast of the Indian states of Kerala, Karnataka, Goa and Maharashtra, before rapidly intensifying into a very severe cyclonic storm early on 16 May. Early on 17 May, Tauktae intensified into an extremely severe cyclonic storm (Category 4 in SSHWS) reaching its highest 1-minute sustained wind speed of 220 km/h and lowest pressure of 931 mbar. After making landfall, Tauktae gradually weakened as it slowly turned north-eastward, moving further inland. On 19 May, Tauktae weakened into a well-marked low-pressure area. The above information was obtained from [2].

1.2 Damages from Cyclone Tauktae

Cyclone Tauktae brought heavy rainfall and flash floods to areas along the coast of Kerala and on Lakshadweep. There were reports of heavy rain in the states of Goa, Karnataka and Maharashtra as well. Tauktae resulted in at least 169 deaths in India and left another 81 people missing. There were also 5 deaths reported in Pakistan. The storm displaced over 200,000 people in Gujarat. The cyclone also caused widespread infrastructure and agricultural damage to the western coast of India. Upwards of 40 fishermen were lost at sea when their boats were caught in the cyclone. Mumbai also experienced impact from the cyclone, with airports being closed for safety reasons. Total estimated financial losses from Cyclone Tauktae were $1.57 billion. The above information was obtained from [2].

1.3 The present study

This paper has concentrated on Cyclone Tauktae 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. CYCLONE TAUKTAE TRACK AND DATA

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

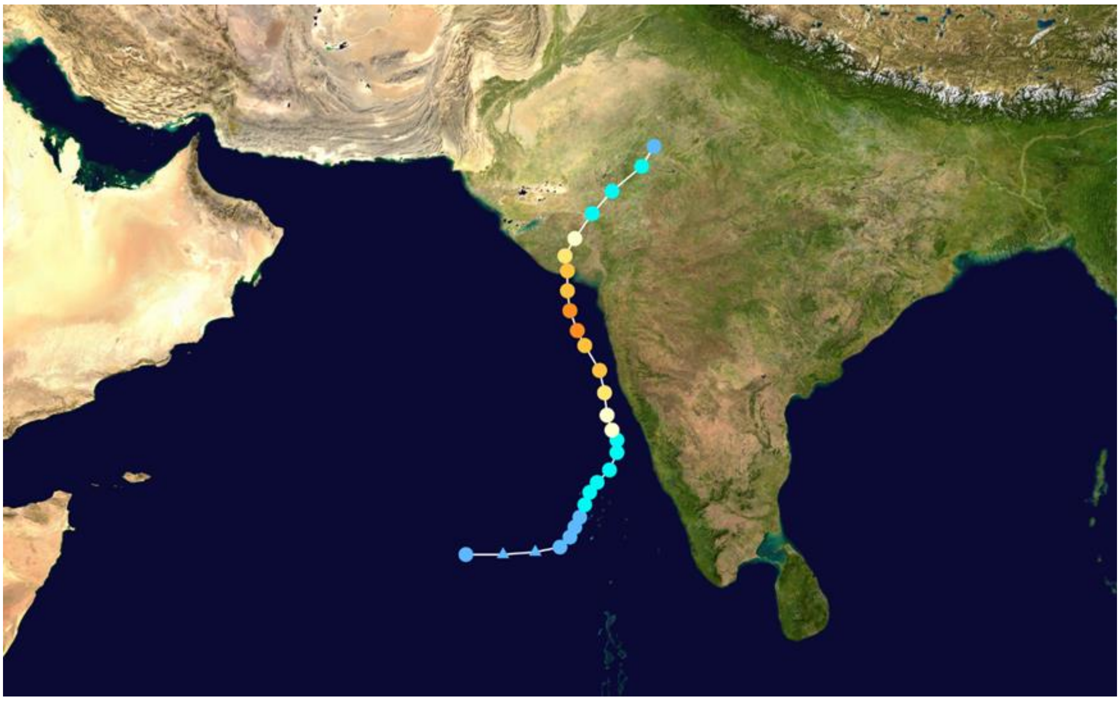

Fig. 1 Track and intensity of Cyclone Tauktae [3]

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 Tauktae 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 Tauktae 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]
14/05/2021 12:00	72.10	11.50	35	998	45
14/05/2021 15:00	71.98	11.71	39	995	42
14/05/2021 18:00	71.97	11.96	43	993	40
14/05/2021 21:00	72.16	12.27	47	991	35
15/05/2021 00:00	72.40	12.60	51	989	30
15/05/2021 03:00	72.55	12.87	*54*	*987*	30
15/05/2021 06:00	72.66	13.12	*57*	*985*	30
15/05/2021 09:00	72.77	13.39	*60*	*983*	27
15/05/2021 12:00	72.86	13.67	*64*	*981*	25
15/05/2021 15:00	72.93	13.97	*67*	*979*	19
15/05/2021 18:00	72.96	14.29	*69*	*977*	14

15/05/2021 21:00	72.95	14.62	*72*	*975*	12
16/05/2021 00:00	72.90	15.00	74	972	10
16/05/2021 03:00	72.86	15.44	81	967	15
16/05/2021 06:00	72.80	15.90	89	962	20
16/05/2021 09:00	72.73	16.34	94	957	25
16/05/2021 12:00	72.60	16.80	99	952	30
16/05/2021 15:00	72.38	17.32	104	946	17
16/05/2021 18:00	72.10	17.80	109	941	5
16/05/2021 21:00	71.78	18.17	114	938	5
17/05/2021 00:00	71.50	18.50	119	935	5
17/05/2021 03:00	71.36	18.84	117	937	8
17/05/2021 06:00	71.30	19.20	115	939	12
17/05/2021 09:00	71.23	19.59	107	944	8
17/05/2021 12:00	71.20	20.00	99	949	5
17/05/2021 15:00	71.25	20.42	104	945	9
17/05/2021 18:00	71.30	20.80	109	942	14
17/05/2021 21:00	71.23	21.11	102	948	12
18/05/2021 00:00	71.20	21.40	95	955	10
18/05/2021 03:00	71.34	21.72	85	961	12
18/05/2021 06:00	71.60	22.10	75	967	15
18/05/2021 09:00	71.92	22.59	67	974	15
18/05/2021 12:00	72.30	23.10	60	981	15
18/05/2021 15:00	72.66	23.55	52	985	15
18/05/2021 18:00	73.10	24.00	45	989	15
18/05/2021 21:00	73.66	24.49	40	992	15
19/05/2021 00:00	74.30	25.00	35	996	15

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 Taukate. 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 Tauktae on 17/05/2021 06:00 when it generated the maximum wave heights. These wind and pressure fields were used to drive the cyclone wave and surge models described later.

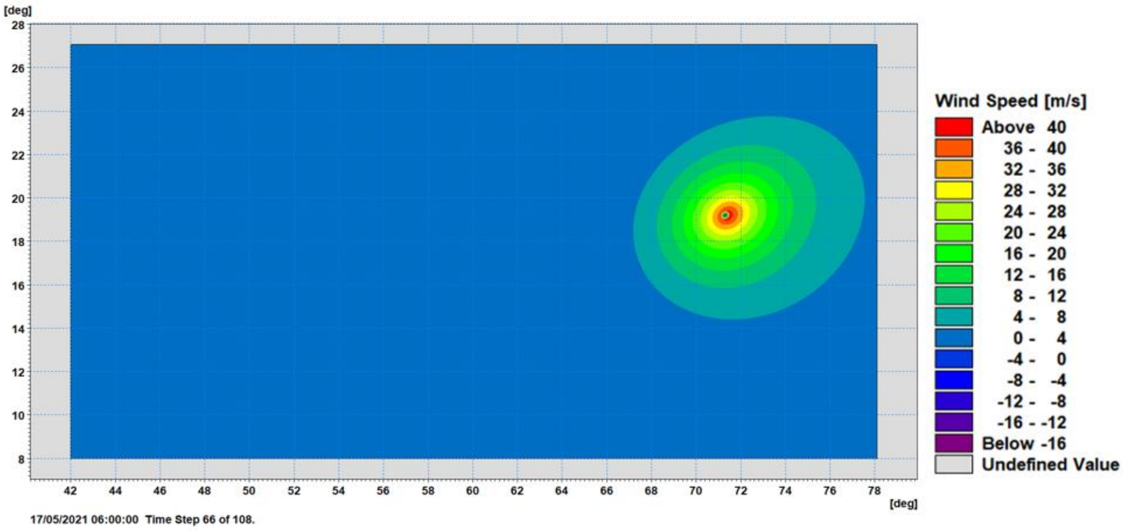

Fig. 2(a) Wind fields of Cyclone Tauktae

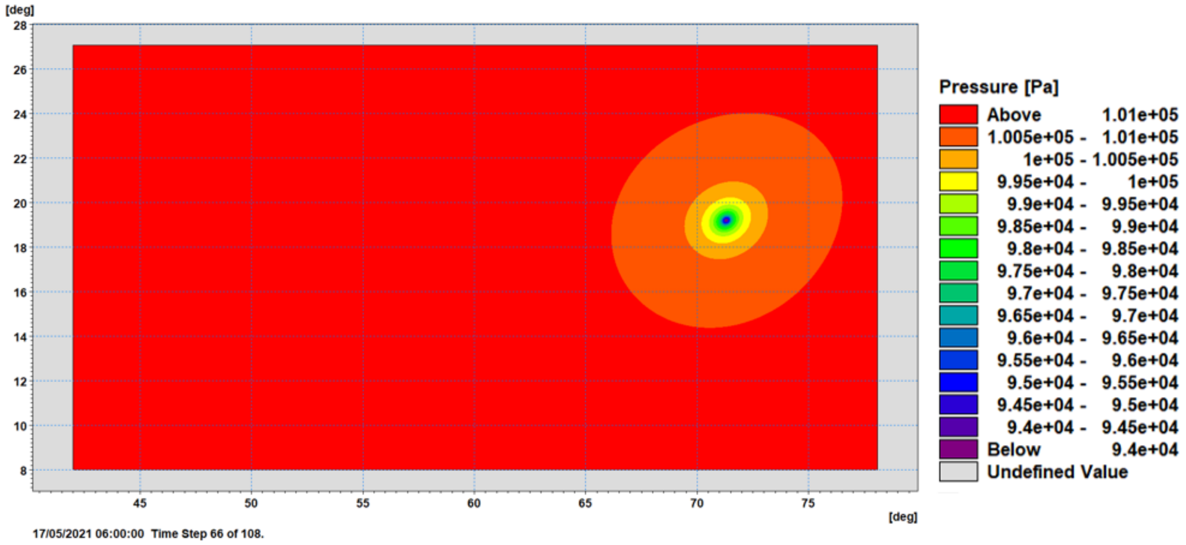

Fig. 2(b) Pressure fields of Cyclone Tauktae

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].

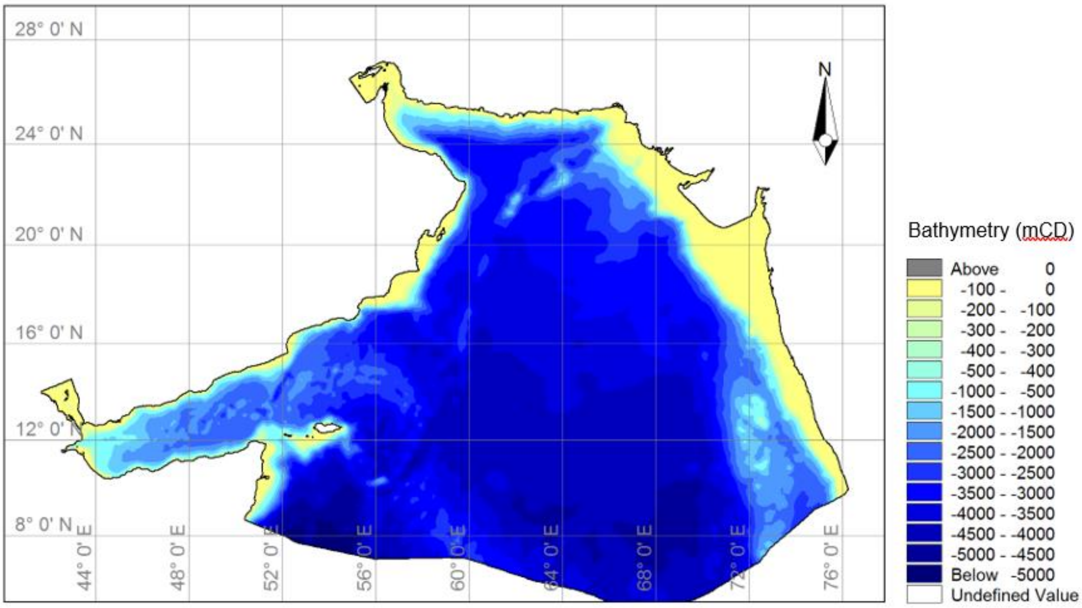

Fig. 3 Model extent and bathymetry (mCD)

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 Tauktae 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 Tauktae 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 TAUKTAE 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 Model Results and Discussions

The maximum significant wave height (Hm0) of approximately 11.3m (with associated peak wave period, Tp of 11.8s) was found at the location of 19.4°N, 71.6°E, 66m depth on 17 May 2021 06:15. The two-dimensional distribution of wave height contours superimposed by wave directional vectors is shown in Figure 4 for this time-step.

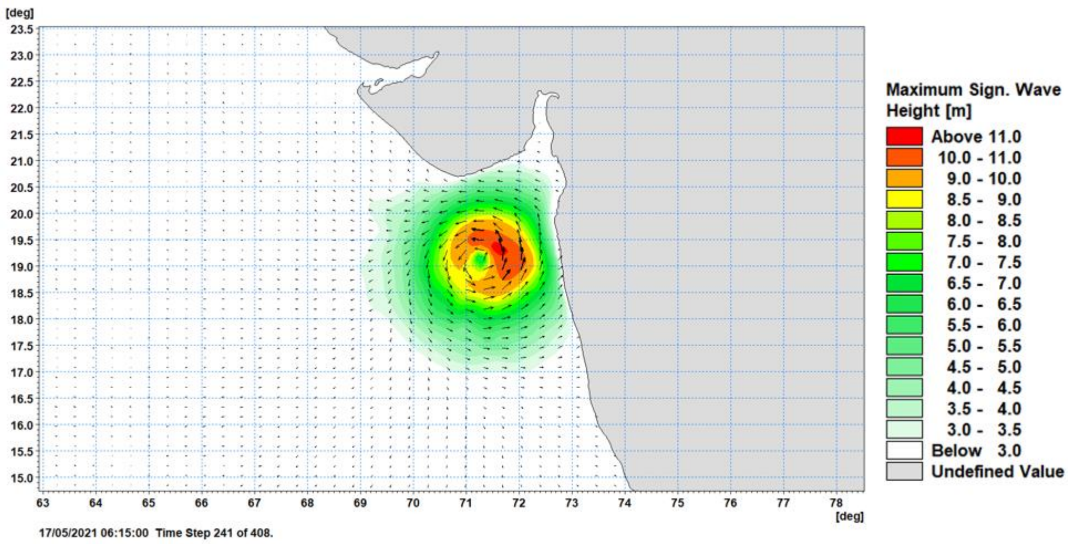

Fig. 4 Significant wave heights (Hm0) of Cyclone Tauktae on 17/05/2021 06:15

The figure indicates that the maximum wave height was found in 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.

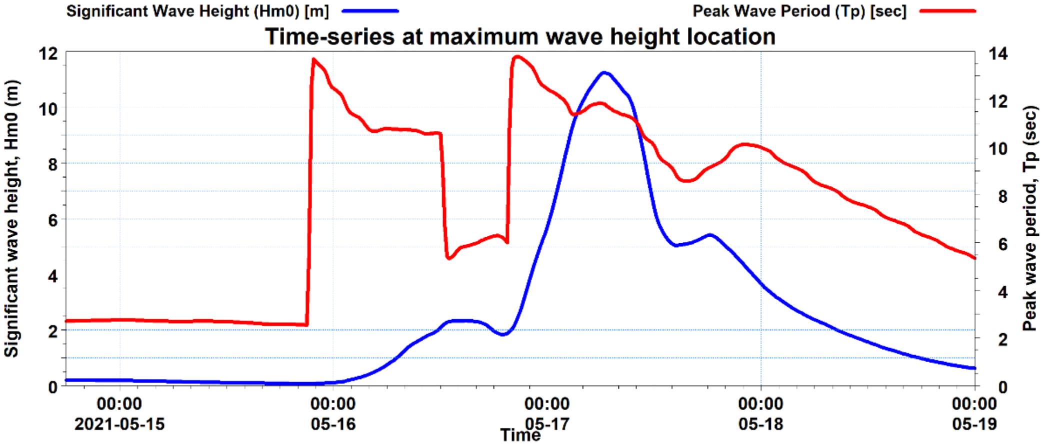

Fig. 5 Time-series of waves during Cyclone Tauktae at maximum wave height location (19.4°N, 71.6°E)

The figure indicates that significant wave heights higher than 10m were sustained for a duration of about 6 hours and wave heights higher than 5m were sustained for a duration of about 21 hours.

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 Tauktae. 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 Indian states of Gujarat and Maharashtra where the cyclone intensity was the highest.

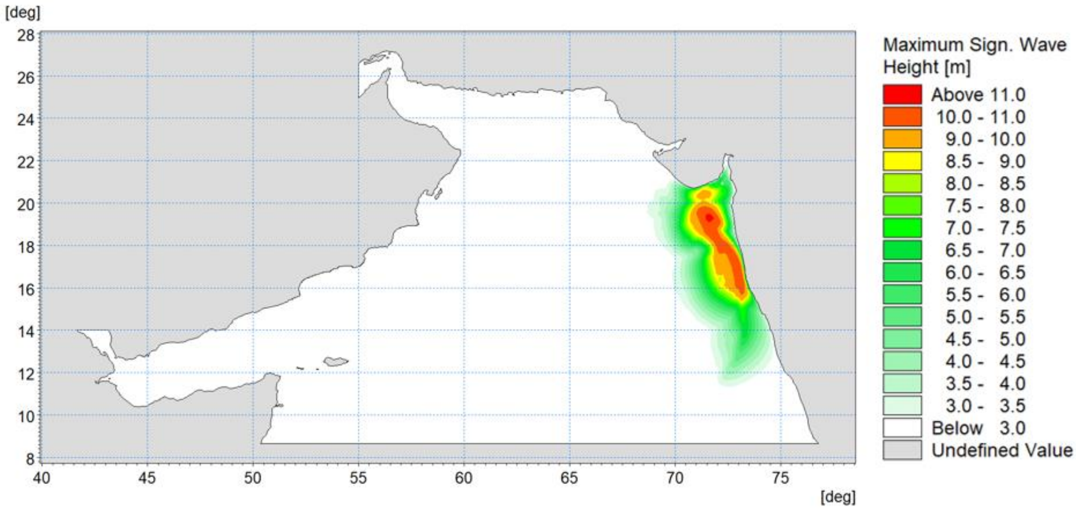

Fig. 6 Maximum significant wave height (Hm0) during the entire duration of Cyclone Tauktae

6. CYCLONE TAUKTAE 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.

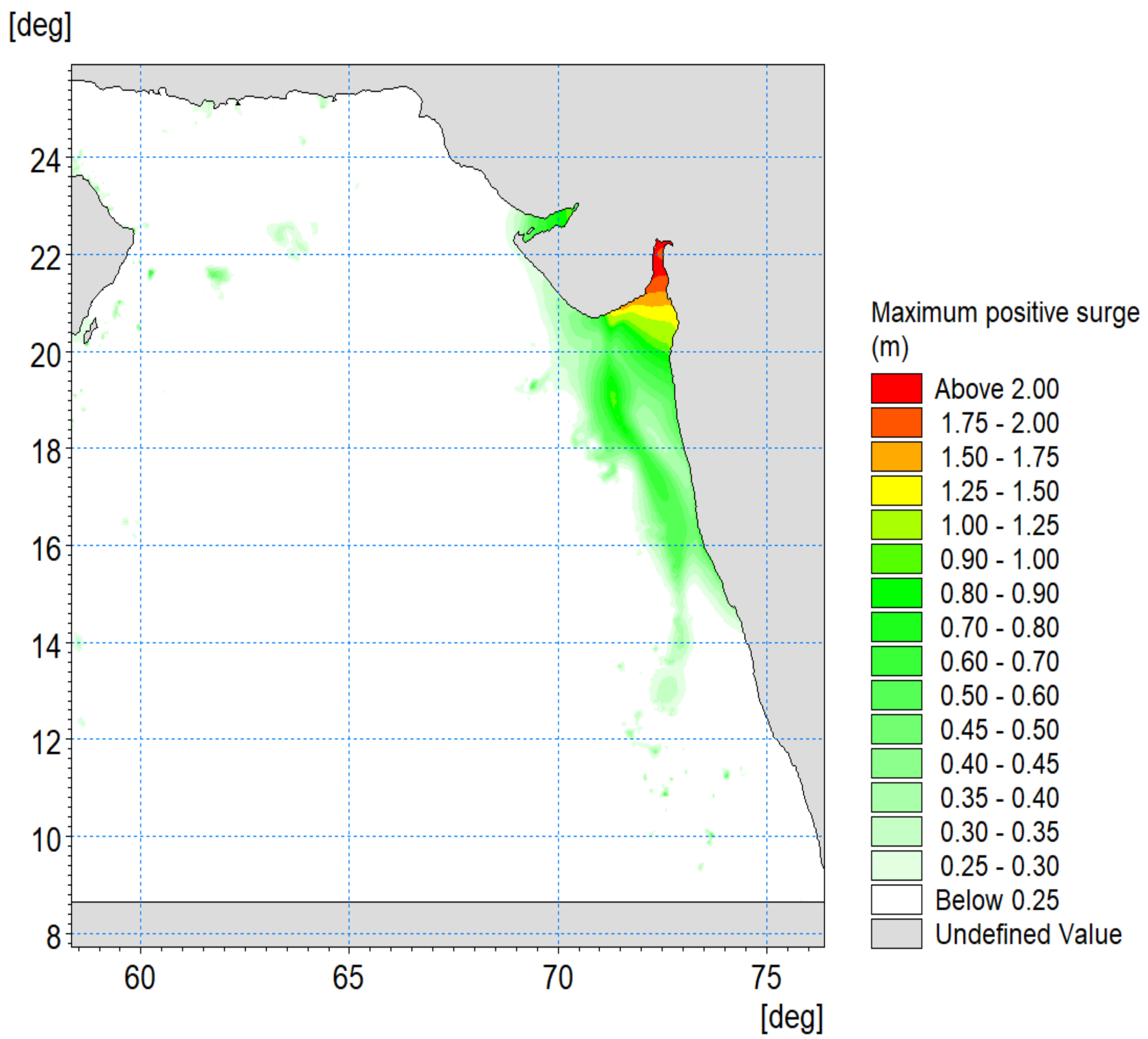

Fig. 7 Maximum positive surge during the entire duration of Cyclone Tauktae

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 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 Tauktae. 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 Indian states of Gujarat and Maharashtra where the cyclone intensity was the highest. Higher positive surges were also occurred in the Gulf of Kutch (about 1.0m) and Gulf of Khambhat (about 2.3m) both in Indian state of Gujarat. Higher positive surge (about 0.6m) was also found in the Gulf of Aden. Highest positive surge was 2.3m at 22.32°N, 72.36°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 Tauktae as shown in Figure 8. Higher negative surge was found in the Gulf of Kutch (up to 1.0m), Gulf of Khambhat (up to 1.0m) and Gulf Aden (up to 1.0m).

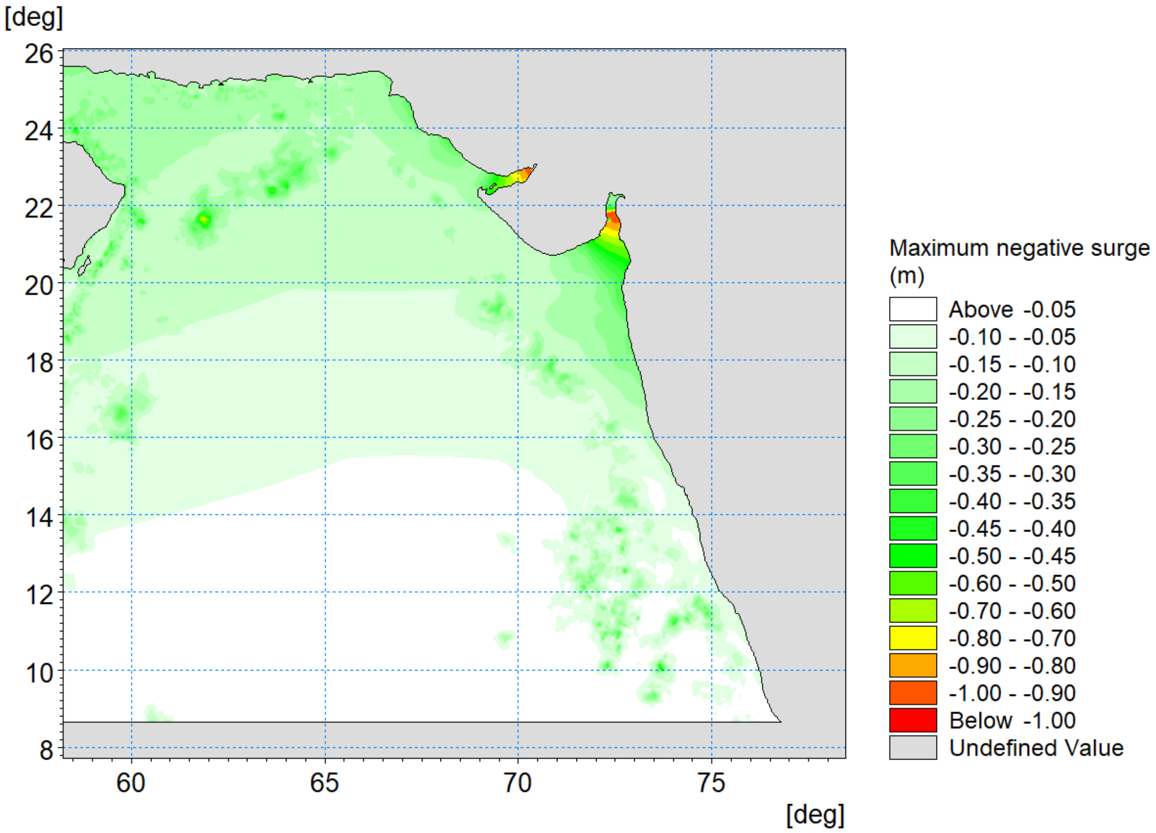

Fig. 8 Maximum negative surge during the entire duration of Cyclone Tauktae

The temporal variation of surge at the location of the highest surge during the entire duration of the cyclone is shown in Figure 9.

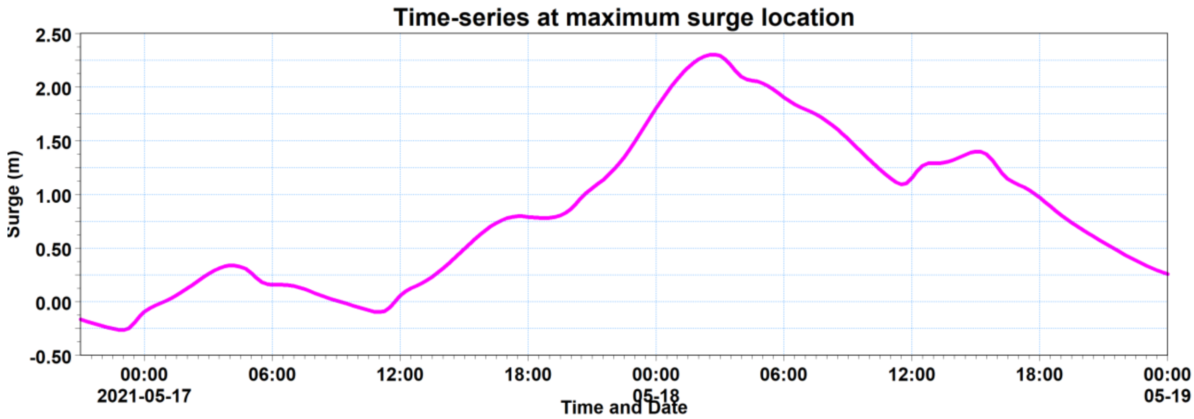

Fig. 9 Time-series of surge during Cyclone Tauktae at maximum surge location (22.32°N, 72.36°E)

The maximum surge of approximately 2.3m was found on 18 May 2021 02:30. Therefore, the highest surge and the maximum significant wave height occurred 20 hours apart albeit at separate locations. The figure indicates that surges higher than 1m were sustained for a duration of about 21 hours and surges higher than 2m were sustained for a duration of about 5 hours.

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 and Gulf 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.

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 11.3m (with associated peak wave period of 11.8s) was found on the track in the Indian states of Gujarat and Maharashtra.

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, 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 20 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

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