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Numerical Modelling of Waves and Surge from Cyclone Gulab (2021) in the Bay of Bengal

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ABSTRACT

Cyclonic Storm Gulab (24-28 September 2021) formed in the Bay of Bengal impacting eastern India 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 Bay of Bengal. The methodology described in this paper for modelling cyclone waves and surge in the Bay of Bengal 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, Bay of Bengal, Cyclone Gulab, Royal HaskoningDHV.

1. INTRODUCTION

1.1 Formation and intensity of Cyclone Gulab

Cyclone Gulab can be traced back to a low-pressure area situated over the Bay of Bengal on 24 September 2021. The JTWC [1] noted a cyclone on 24 September that was producing tropical storm-force winds located over the east-central Bay of Bengal some 391 km south of Chittagong (Bangladesh) and designated the system as 03B. The IMD [2] noted the system as a low-pressure area. The IMD upgraded it to a depression on 25 September and the system was upgraded to a deep depression on 26 September and further upgraded it to a cyclonic storm later that day. As it continued westward, the outer rainbands of Cyclone Gulab reached the coastal regions of northern Andhra Pradesh and southern Odisha, which indicated that it had started making landfall, at about 18:00 IST (12:30 UTC) on September 26. The above information was obtained from [3].

1.2 Damages from Cyclone Gulab

Trees were uprooted causing disruption of communication and electricity. Houses were damaged. Flooding and landslides occurred due to heavy rains. Crops were destroyed. There were at least 20 deaths as well as US$271 million in damages. The above information was obtained from [3].

1.3 The present study

This paper has concentrated on Cyclone Gulab 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 Bay of Bengal 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 Bay of Bengal. The methodology described in this paper for modelling cyclone waves and surge in the Bay of Bengal could also be applied to simulate cyclones at other sites around the world.

2. CYCLONE GULAB TRACK AND DATA

The track (route) of Cyclone Gulab was obtained from [4] as shown in Figure 1.

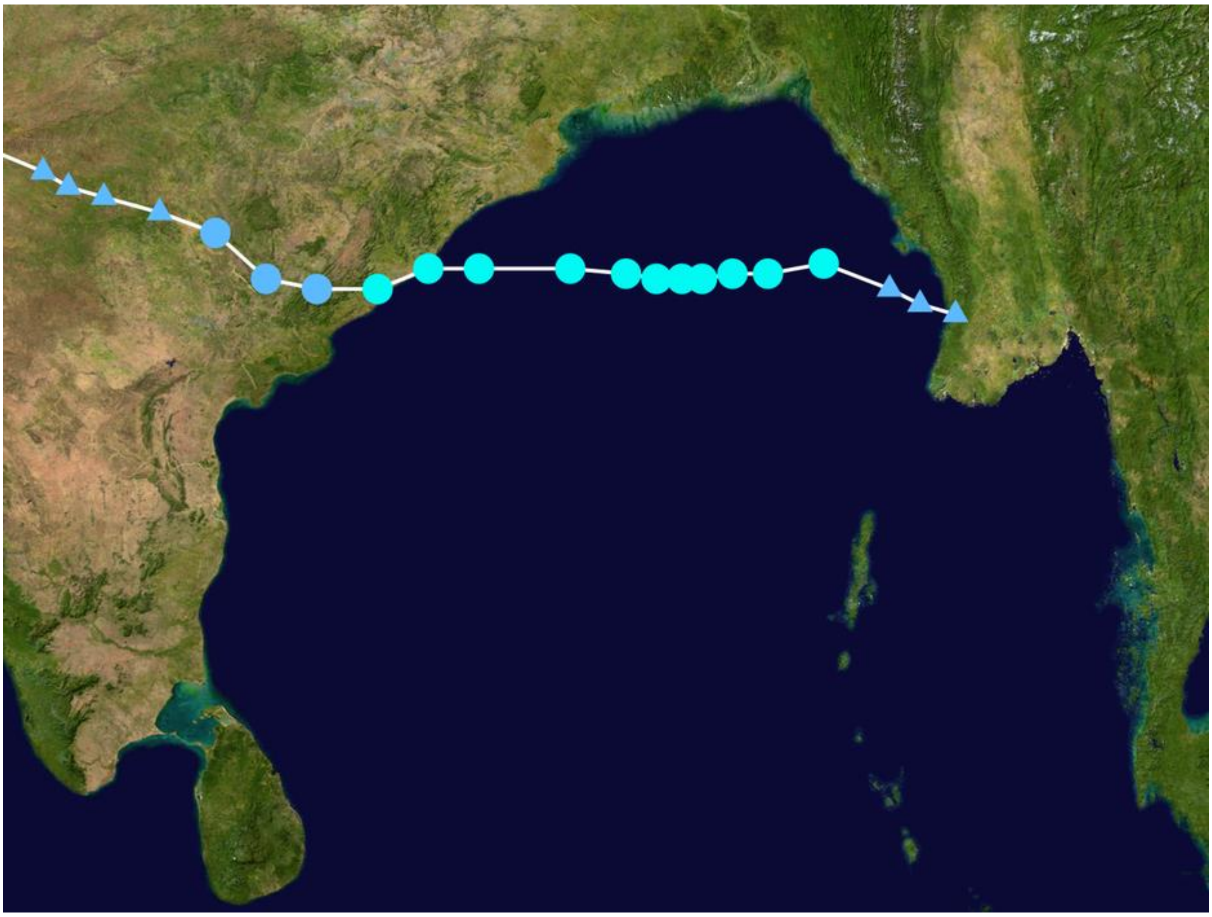

Fig. 1 Track and intensity of Cyclone Gulab [3]

The cyclone data was obtained from the International Best Track Archive for Climate Stewardship (IBTrACS) [5]. 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 Gulab is provided in Table 1.

Table 1: Cyclone Shaheen Track and Data from IBTrACS [5]

Date and Time [UTC]	Longitude [°E]	Latitude [°N]	Max 1-minute wind speeds [knots]	Central pressure [hPa]	Radius of maximum winds [nm]
22/09/2021 12:00	113.3000	12.8000	25	1004	40
22/09/2021 15:00	112.8850	12.8775	25	1004	40
22/09/2021 18:00	112.4000	13.0000	25	1004	40
22/09/2021 21:00	111.8070	13.2051	27	1003	37
23/09/2021 00:00	111.2000	13.5000	29	1003	35
23/09/2021 03:00	110.7070	13.8697	32	1003	35
23/09/2021 06:00	110.2000	14.3000	35	1003	35
23/09/2021 09:00	109.5650	14.7950	35	1002	32
23/09/2021 12:00	108.9000	15.2000	35	1001	30
23/09/2021 15:00	108.3000	15.3597	30	1004	35
23/09/2021 18:00	107.7000	15.4000	25	1008	40
23/09/2021 21:00	107.0200	15.4127	22	1008	40
24/09/2021 00:00	106.4000	15.5000	20	1009	40

24/09/2021 03:00	106.0230	15.8717	20	1008	40
24/09/2021 06:00	105.6000	16.2000	20	1007	40
24/09/2021 09:00	104.8920	16.2063	20	1007	40
24/09/2021 12:00	104.0000	16.0000	20	1007	40
24/09/2021 06:00	92.1000	18.8000	35	1005	40
24/09/2021 09:00	91.4526	18.6579	35	1003	37
24/09/2021 12:00	90.9000	18.5000	35	1002	35
24/09/2021 15:00	90.5042	18.3280	35	1002	35
24/09/2021 18:00	90.2000	18.2000	35	1003	35
24/09/2021 21:00	89.8913	18.1712	35	1002	27
25/09/2021 00:00	89.6108	18.1892	35	1002	20
25/09/2021 03:00	89.3637	18.1861	35	1001	20
25/09/2021 06:00	89.1000	18.2000	35	1001	20
25/09/2021 09:00	88.7395	18.2525	37	998	20
25/09/2021 12:00	88.4000	18.3000	39	996	20
25/09/2021 15:00	88.2101	18.2956	39	996	20
25/09/2021 18:00	88.0306	18.2796	39	996	20
25/09/2021 21:00	87.7925	18.2729	39	996	22
26/09/2021 00:00	87.4000	18.3000	39	996	25
26/09/2021 03:00	86.7501	18.4057	39	996	25
26/09/2021 06:00	86.0000	18.5000	39	996	25
26/09/2021 09:00	85.3383	18.5006	36	997	25
26/09/2021 12:00	84.7059	18.4492	34	998	25
26/09/2021 15:00	84.0967	18.3669	31	999	25
26/09/2021 18:00	83.5000	18.3000	29	1000	25

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 [6].

3. WIND AND PRESSURE FIELDS GENERATION

The MIKE21 Cyclone Wind Generation Tool of DHI [7] was used to generate the cyclonic wind and pressure fields of Cyclone Gulab. 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 Gulab on 24/09/2021 17:00 when it generated the maximum wave heights. These wind and pressure fields were used to drive the cyclone wave and surge models described later.

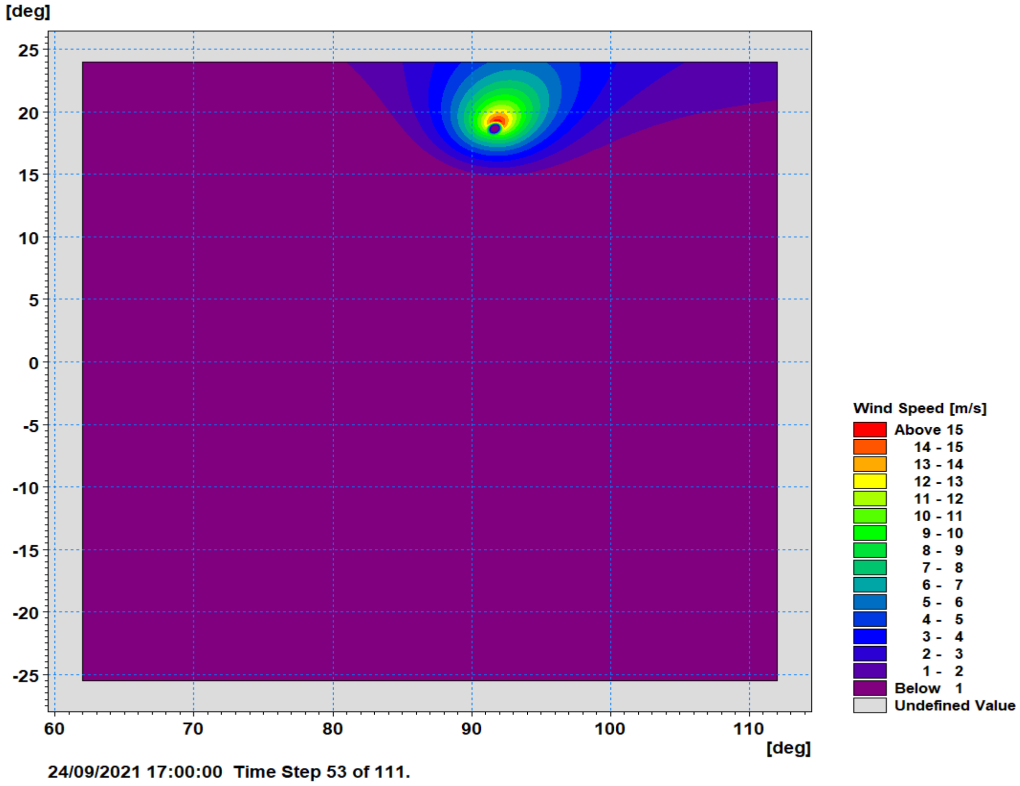

Fig. 2(a) Wind fields of Cyclone Gulab

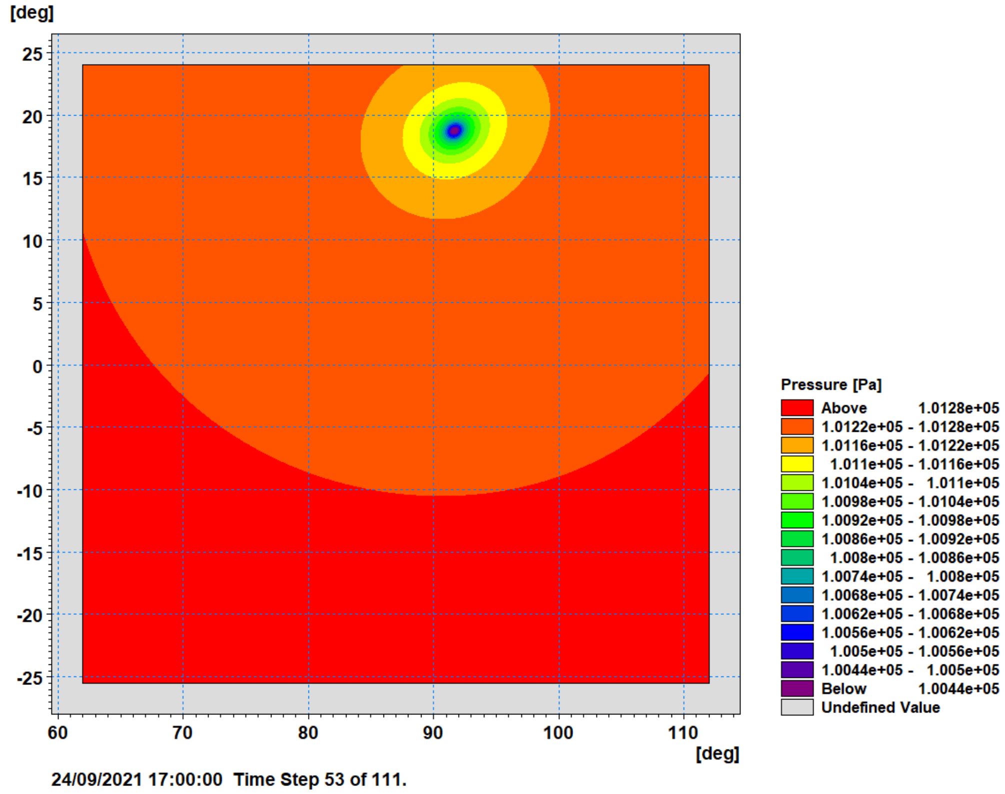

Fig. 2(b) Pressure fields of Cyclone Gulab

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 Bay of Bengal using the MIKE21/3 Flow Model FM software of DHI [8]. 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 six countries – India, Sri Lanka, Bangladesh, Myanmar, Indonesia and Malaysia (see Figure 3).

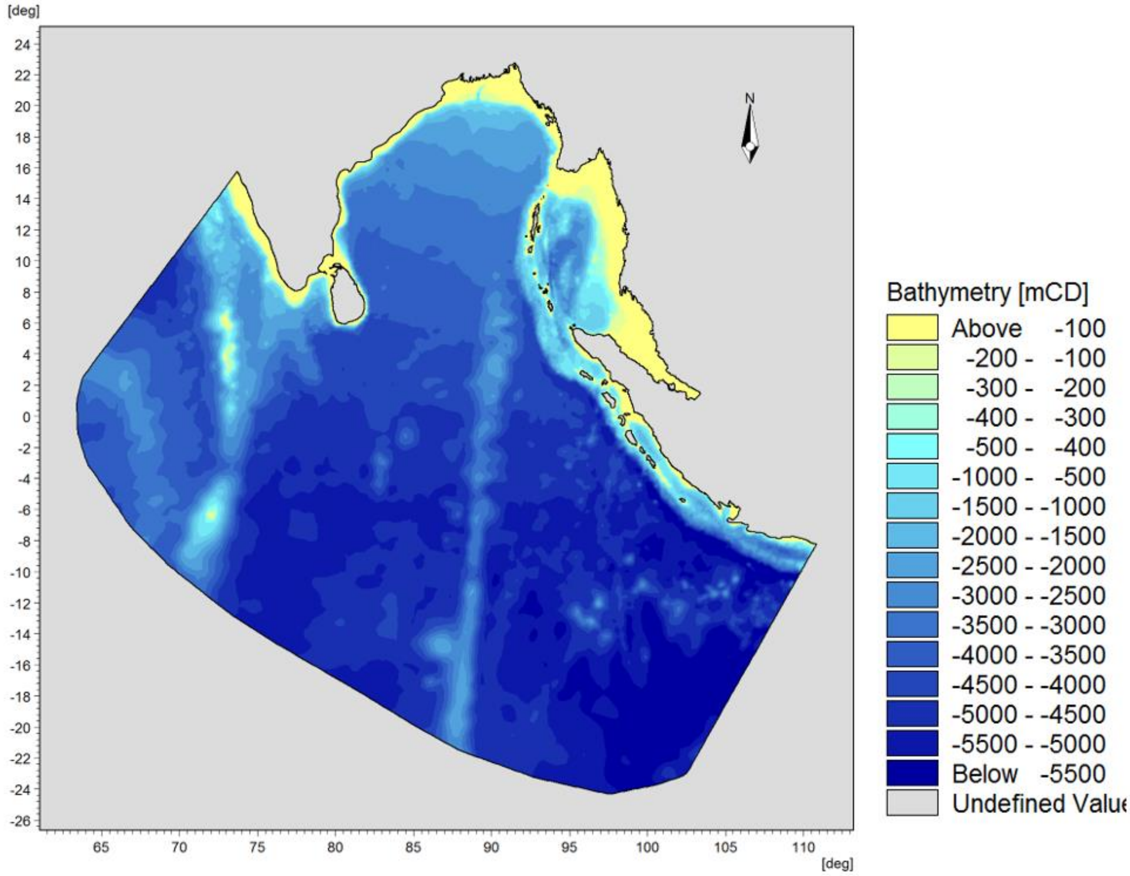

Fig. 3 Regional model extent and bathymetry

The model has four open boundaries – one to the south (Indian Ocean), one to the north-west (Arabian Sea), one to south-east (Indian Ocean) and one to south-east (Malacca Strait). 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 [9].

The regional tidal model was used to drive the cyclone surge model to derive 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 Gulab 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 Bay of Bengal using the MIKE21 Spectral Wave (SW) software of DHI [10]. 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 Gulab 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 GULAB 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 2.6m above the chart datum was used in the model. The model simulations covered the entire passage of the cyclone across the Bay of Bengal.

5.3 Wave Model Results and Discussions

The maximum significant wave height (Hm0) of approximately 4.9m (with associated peak wave period, Tp of 7.2s) was found at the location of 19.60°N, 92.515°E, 165m depth on 24 September 2021 16:30. The two-dimensional distribution of wave height contours superimposed by wave directional vectors is shown in Figure 4(a) for this time-step. The figure indicates that the maximum wave height was found in the eastern Bay of Bengal along the coastlines of Bangladesh and Myanmar where the cyclone intensity was the highest.

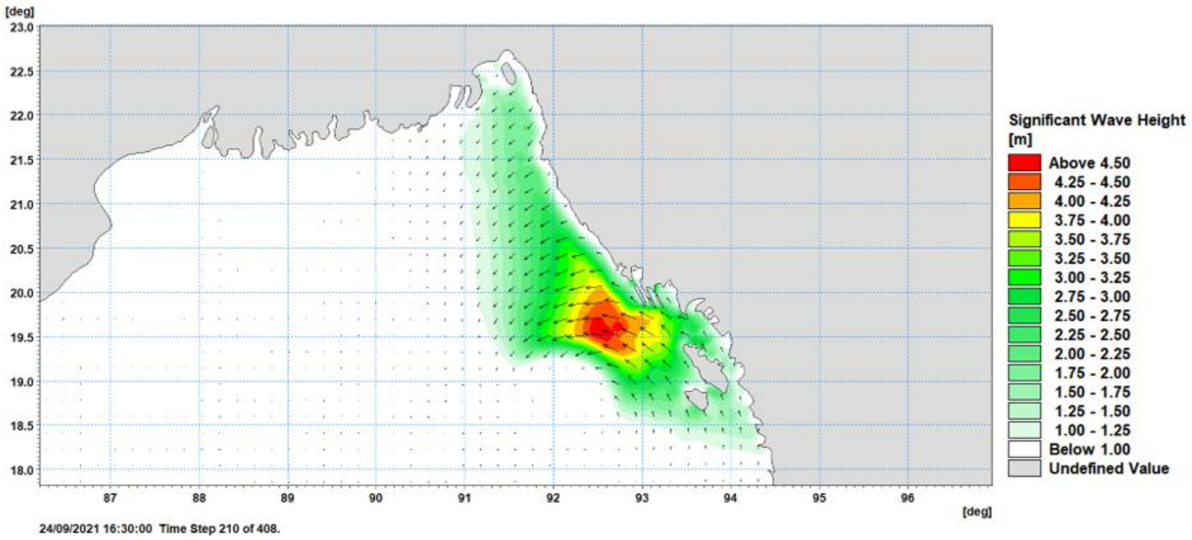

Fig. 4a Significant wave heights (H_{m0}) of Cyclone Gulab on 24/09/2021 16:30

Figure 4(b) shows the two-dimensional distribution of wave height contours superimposed by wave directional vectors at a time when the cyclone was somewhere in the middle of the Bay of Bengal.

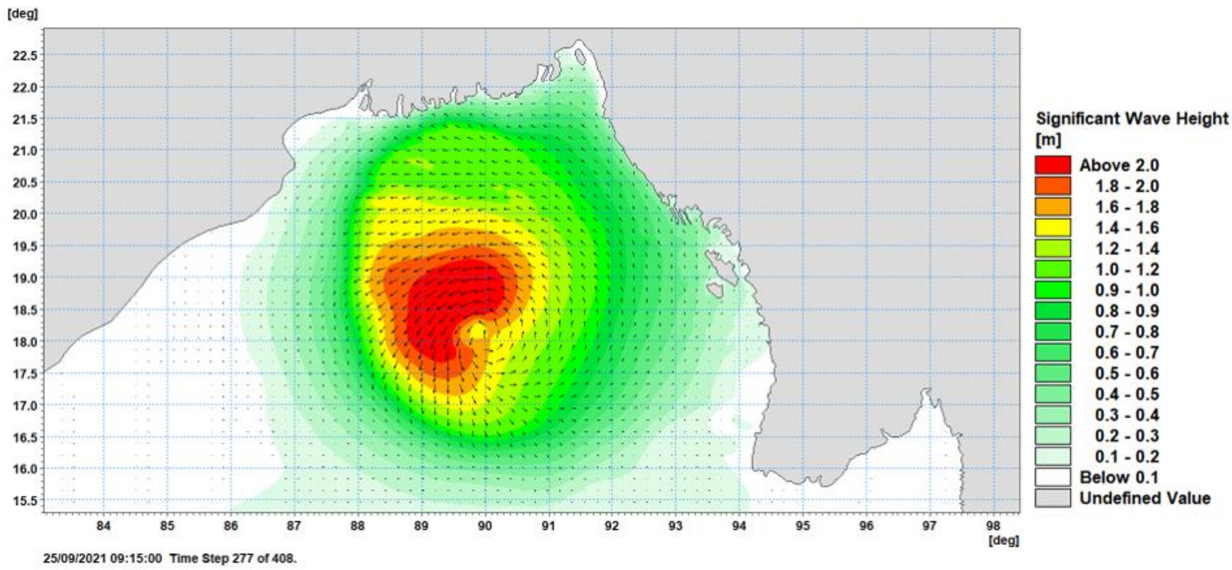

Fig. 4b Significant wave heights (H_{m0}) of Cyclone Gulab on 25/09/2021 09:15

The temporal variation in significant wave height and peak wave period at the location of the highest wave height is shown in Figure 5. The figure indicates that significant wave heights higher than 4m were sustained for a duration of about 2 hours and wave heights higher than 2m were sustained for a duration of about 6 hours. Statistical analyses of model results were carried out using the MIKE21 Tool [7] to derive mean and maximum wave conditions over the whole model domain during the entire duration of Cyclone Gulab.

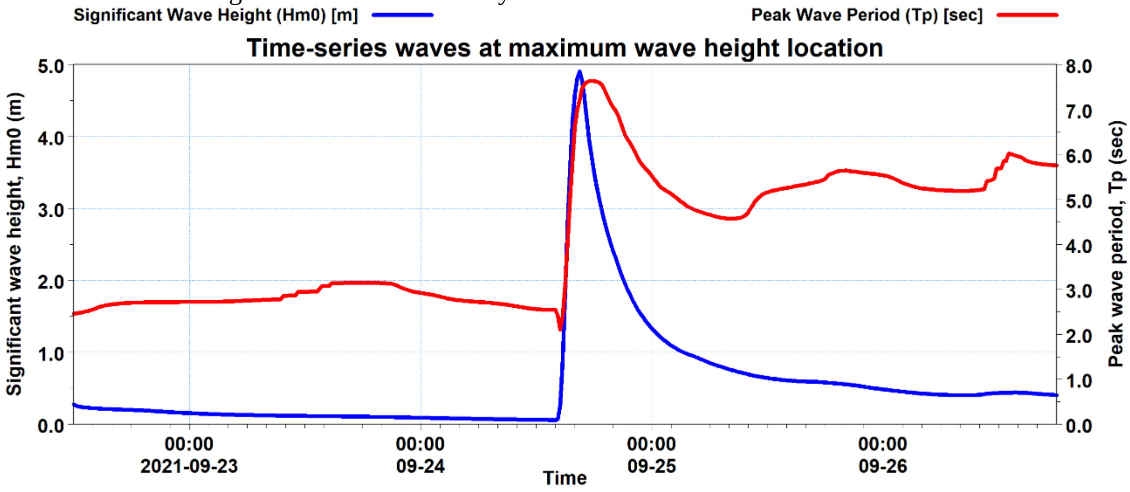

Fig. 5 Time-series of waves during Cyclone Gulab at maximum wave height location (19.6°N, 92.515°E)

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 where the cyclone intensity was the highest. The highest maximum significant wave heights were found along the Myanmar coastline.

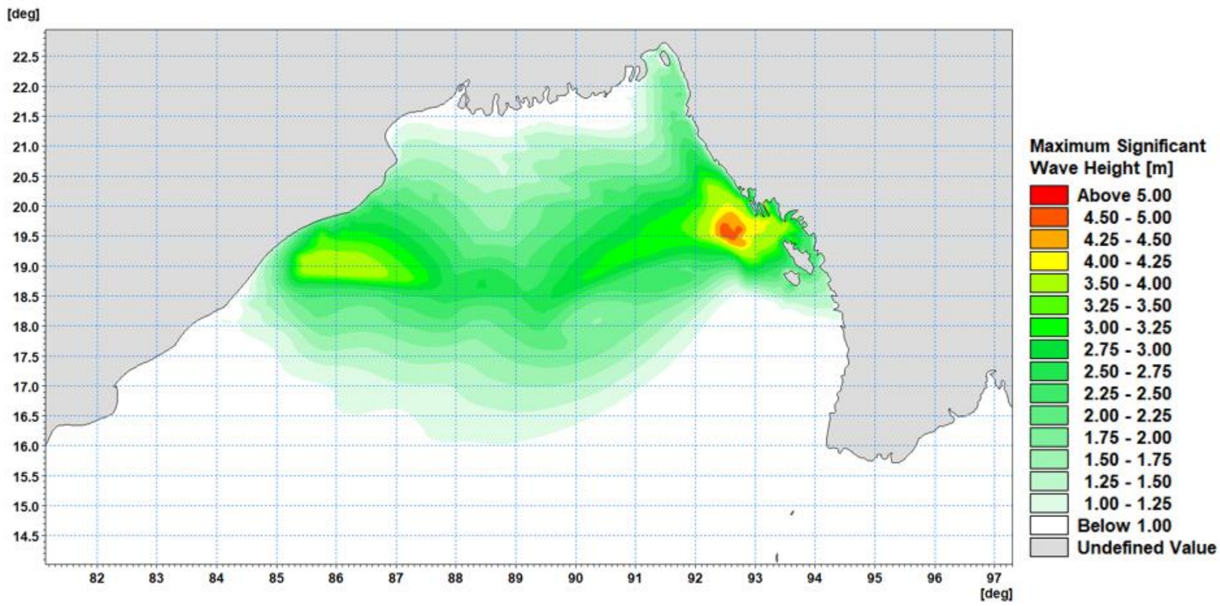

Fig. 6 Maximum significant wave height (Hm0) during the entire duration of Cyclone Gulab

6. CYCLONE GULAB 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 m1/3/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 2.6m above the chart datum was imposed at all the four open boundaries. An initial water level of 2.6m 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 [7] to derive mean and maximum surge values over the whole model domain during the entire duration of Cyclone Gulab. 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 along the Myanmar coastline where the cyclone intensity was the highest. Highest positive surge of about 4.4m was found at the location of 19.8°N, 93.765°E.

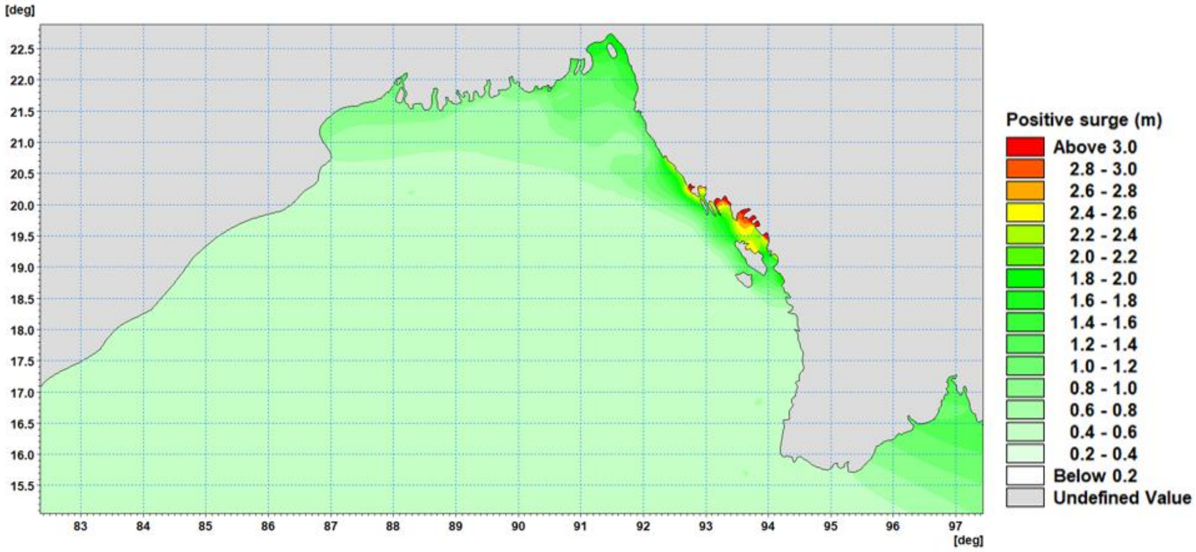

Fig. 7 Maximum positive surge during the entire duration of Cyclone Gulab

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 [7] to derive the maximum negative surges over the whole model domain during the entire duration of Cyclone Gulab as shown in Figure 8. Higher negative surge was found along the coastlines of the northern Bay of Bengal (up to 1.5m), eastern Bay of Bengal (up to 2.3m) and in the Gulf of Martaban (up to 1.7m).

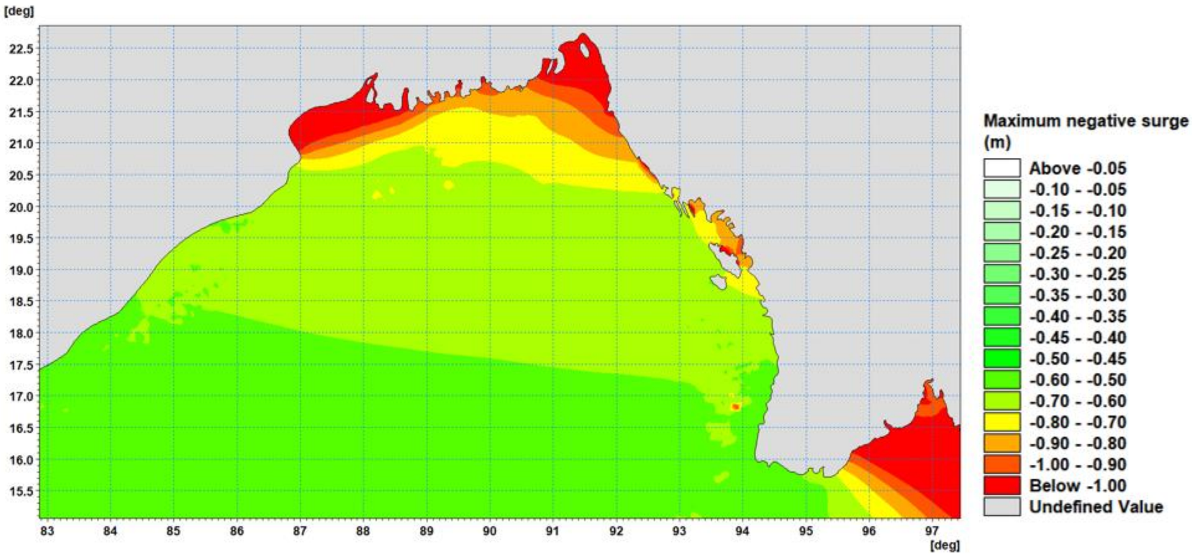

Fig. 8 Maximum negative surge during the entire duration of Cyclone Gulab

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 4.4m was found on 24 September 2021 15:45. Therefore, the highest surge and the maximum significant wave height occurred 0.75 hour apart albeit at separate locations. The figure indicates that surges higher than 3m were sustained for a duration of about 1 hour and surges higher than 2m were sustained for a duration of about 3 hours.
Higher positive surge was found along the cyclone track where the intensity of the cyclone was the highest. Higher positive surges were found in the gulf areas along the Myanmar coastline due to funneling effects resulting from narrowing down of the water body. Higher negative surges were found in the gulf areas along the northern and eastern Bay of Bengal coastlines as the cyclone sucked water away from these areas.

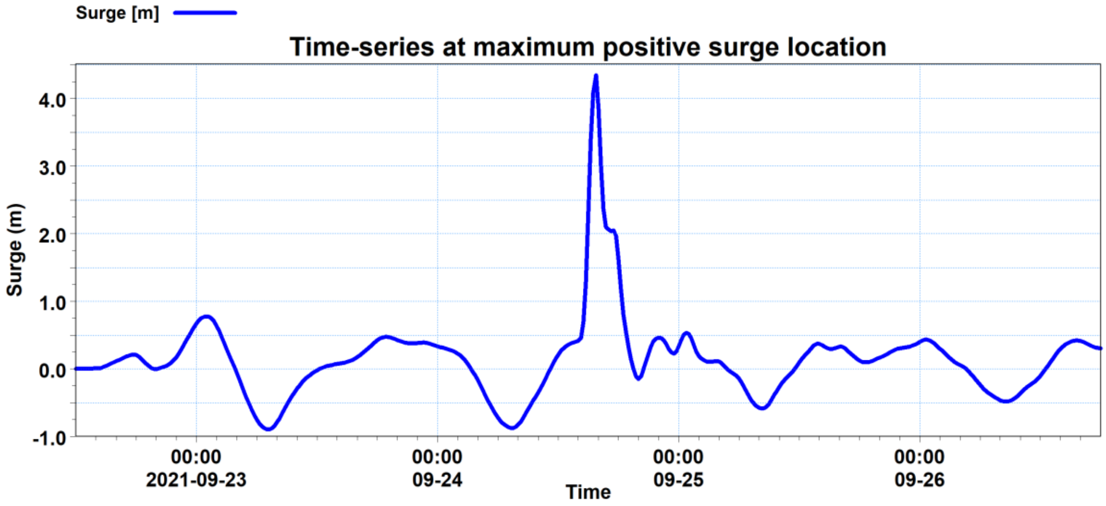

Fig. 9 Time-series of surge during Cyclone Gulab at maximum surge location (19.81°N, 93.78°E)

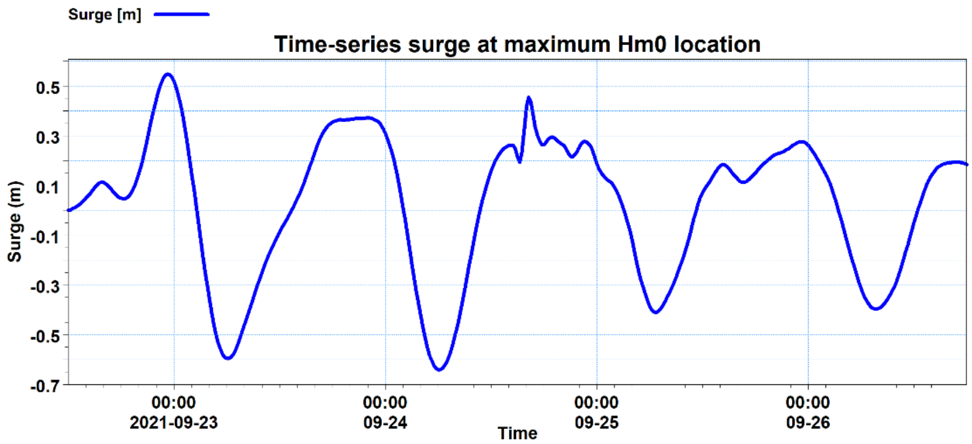

Fig. 10 Time-series of surge during Cyclone Gulab at maximum wave height location (19.6°N, 92.515°E)

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 4.9m (with associated peak wave period of 7.2s) was found on the track in the Myanmar coastline along the eastern Bay of Bengal.
Higher positive surge was found along the cyclone track where the intensity of the cyclone was the highest. Higher positive surges were found in the gulf areas along the Myanmar coastline due to funneling effects resulting from narrowing down of the water body. Higher negative surges were found in the gulf areas along the northern and eastern Bay of Bengal coastlines as the cyclone sucked water away from these areas.
The maximum surge and the maximum significant wave height occurred 0.75 hour apart albeit at separate locations.
The methodology described in this paper for modelling cyclone waves and surges in the Bay of Bengal could also be applied to other sites around the world that are affected by cyclones.

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REFERENCES

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