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Numerical Modelling of Waves and Surge from Cyclone Amphan (May 2020) in the Bay of Bengal

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ABSTRACT
The Super Cyclonic Storm Amphan (during 16-21 May 2020) was a powerful and catastrophic tropical cyclone that caused extensive damage ($13.7 billion) and loss of life (128 fatalities) in eastern India, Bangladesh, Sri Lanka and Bhutan. This paper concentrates on this event to illustrate the use of numerical models to simulate waves and surge generated by cyclones. The MIKE21 software developed by DHI was used in the numerical modelling of waves and surge in a coupled mode. Sample results of waves and surge from the cyclone 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 Amphan

1. INTRODUCTION

As reported in Wikipedia [1], Super Cyclonic Storm Amphan was a powerful and catastrophic tropical cyclone that caused widespread damage in eastern India (specifically West Bengal and Odisha) and in Bangladesh during 16-21 May 2020. It was the strongest tropical cyclone to strike the Ganges Delta since Sidr in 2007 and the first super cyclonic storm to have formed in the Bay of Bengal since the 1999 Odisha cyclone. It was also the fourth super cyclone to hit West Bengal and Kolkata since 1582 and one of the strongest storms to impact the area [2, 3, 4]. Causing over US$13 billion of damage, Amphan is also the costliest cyclone ever recorded in the Northern Indian Ocean [5].

Amphan originated from a low-pressure area persisting a couple hundred miles (300 km) east of Colombo (Sri Lanka) on 13 May 2020. Tracking north-eastward, the disturbance organised over exceptionally warm sea surface temperatures. The Joint Typhoon Warning Center (JTWC) [6] upgraded the system to a tropical depression on 15 May while the Indian Meteorological Department (IMD) [7] did so on the following day. On 17 May, Amphan underwent rapid intensification and became an extremely severe cyclonic storm within 12 hours.

On 18 May, at approximately 12:00 UTC, Amphan reached its peak intensity with 3-minute sustained wind speeds of 240 km/h, 1-minute sustained wind speeds of 260 km/h, and a minimum central barometric pressure of 920 mbar. The storm gradually weakened as it paralleled the eastern coastline of India and on 20 May, between 10:00 and 11:00 UTC, the cyclone made landfall in West Bengal. At the time, the JTWC estimated Amphan's 1-minute sustained winds to be 155 km/h. Amphan rapidly weakened once inland and dissipated shortly thereafter. Coastal areas in West Bengal were affected by the cyclone. It also caused significant destruction in Bangladesh [8]. The text above was obtained from Wikipedia [1].

This paper has concentrated on Cyclone Amphan to illustrate the use of numerical models 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 and tools developed by DHI [9, 10, 11] were used in the study. Sample results of waves and surge from the cyclone modelling study are presented in this paper for illustration purposes only. 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 AMPHAN TRACK AND DATA

The track (route) of Cyclone Amphan was obtained from [1] as shown in Figure 1. The cyclone data was obtained from the India Meteorological Department (IMD) [7]. IMD provides 3-hourly information including date and time, tracks (path), maximum sustained wind speeds and the minimum central pressures. Such data of Cyclone Amphan is provided in Table 1 [7]. It should be noted that the IMD provides 3-minutes mean maximum wind speeds which was converted to 1-hourly mean for the present study using the method in the World Meteorological Organization [12].

Table -1 Cyclone Amphan Track and Data [7]

Date	Time [UTC]	Longitude [°E]	Latitude [°N]	Max 3-minutes wind speeds [knots]	Central pressure [hPa]
16/05/2020	0000	87.0	10.4	25	1000
16/05/2020	0300	86.5	10.7	25	1000
16/05/2020	0600	86.3	10.9	25	1000
16/05/2020	0900	86.3	10.9	30	998
16/05/2020	1200	86.3	10.9	35	996
16/05/2020	1500	86.2	11.0	40	995
16/05/2020	1800	86.1	11.1	40	995
16/05/2020	2100	86.1	11.3	45	994
17/05/2020	0000	86.0	11.4	45	992
17/05/2020	0300	86.0	11.4	50	990
17/05/2020	0600	86.0	11.5	55	988
17/05/2020	0900	86.0	11.7	65	980
17/05/2020	1200	86.0	12.0	70	978
17/05/2020	1500	86.2	12.8	70	978
17/05/2020	1800	86.1	12.5	80	970
17/05/2020	2100	86.4	12.9	90	962
18/05/2020	0000	86.3	13.2	100	952
18/05/2020	0300	86.2	13.3	115	936
18/05/2020	0600	86.2	13.4	120	930
18/05/2020	0900	86.2	13.7	120	930
18/05/2020	1200	86.3	14.0	125	926
18/05/2020	1500	86.4	14.5	125	926
18/05/2020	1800	86.5	14.9	130	920
18/05/2020	2100	86.6	15.2	130	920
19/05/2020	0000	86.7	15.6	125	926
19/05/2020	0300	86.8	16.0	120	930
19/05/2020	0600	86.9	16.5	115	936
19/05/2020	0900	86.9	17.0	110	942
19/05/2020	1200	87.0	17.4	105	946
19/05/2020	1500	87.1	18.1	100	950
19/05/2020	1800	87.2	18.4	100	950
19/05/2020	2100	87.2	18.7	100	950
20/05/2020	0000	87.5	19.1	95	954
20/05/2020	0300	87.7	19.8	90	958
20/05/2020	0600	88.0	20.6	90	960
20/05/2020	0900	88.1	21.4	90	960
20/05/2020	1200	88.4	21.9	80	968
20/05/2020	1500	88.6	22.7	65	978
20/05/2020	1800	89.0	23.3	50	984
20/05/2020	2100	89.0	24.2	45	986
21/05/2020	0000	89.3	24.2	40	988
21/05/2020	0300	89.5	24.7	35	990
21/05/2020	0600	89.6	25.0	30	992
21/05/2020	0900	89.6	25.4	20	995

3. WIND AND PRESSURE FIELDS GENERATION

The MIKE21 Cyclone Wind Generation Tool of DHI [11] was used to generate the cyclonic wind and pressure fields of Cyclone Amphan. 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. The Young and Sobey model was used in the study to generate the cyclonic wind and pressure fields. Radius of maximum wind speed was not available from IMD and, therefore, was derived from Vmax-Radius relationships of previous cyclones in the Bay of Bengal. Figure 2 shows an example of wind and pressure fields of Cyclone Amphan on 19/05/2020 03:00. These wind and pressure fields were used to drive the cyclone wave and surge models described later.

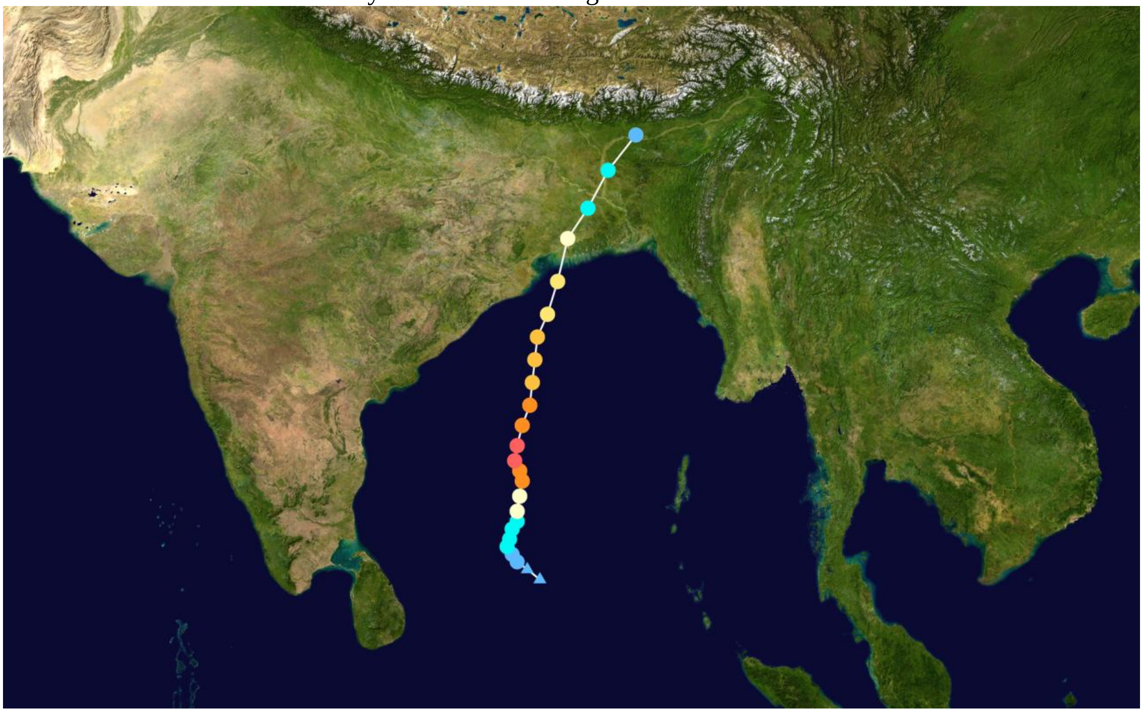

Fig. 1 Track and intensity of Cyclone Amphan [1]

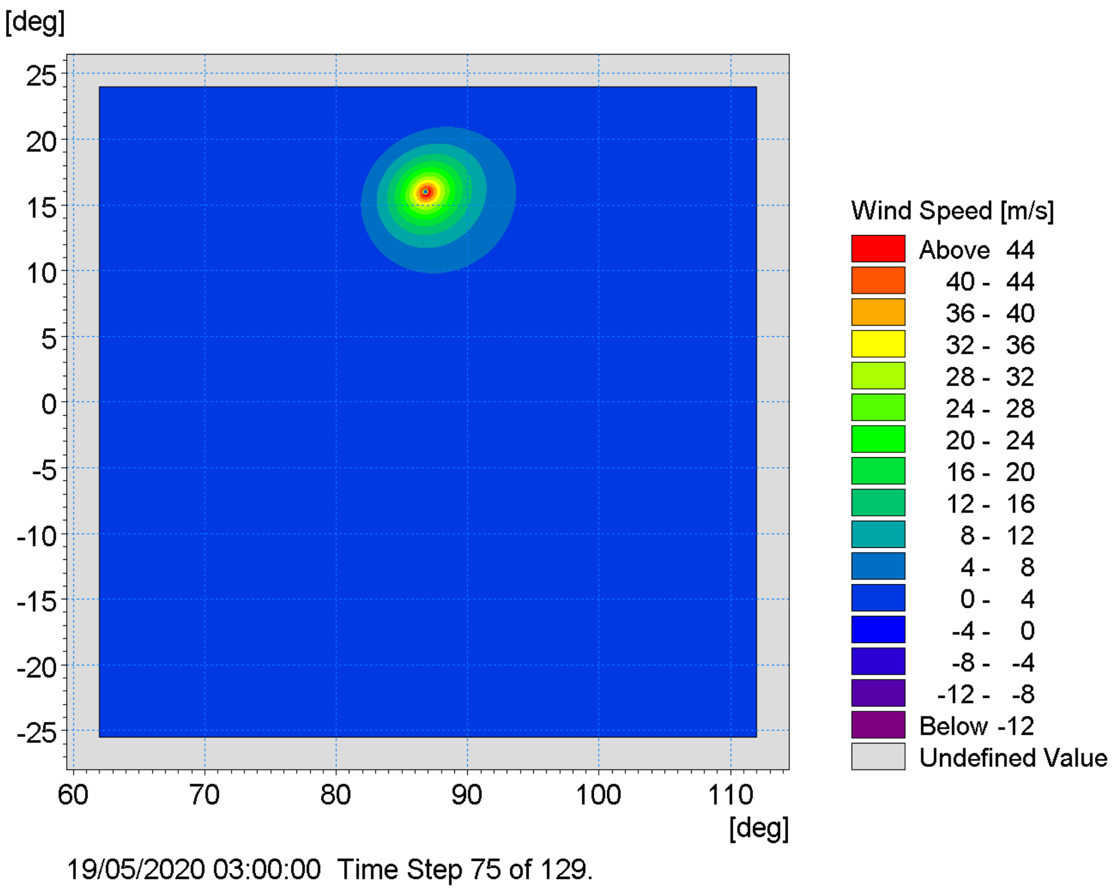

Fig. 2(a) Wind fields of Cyclone Amphan

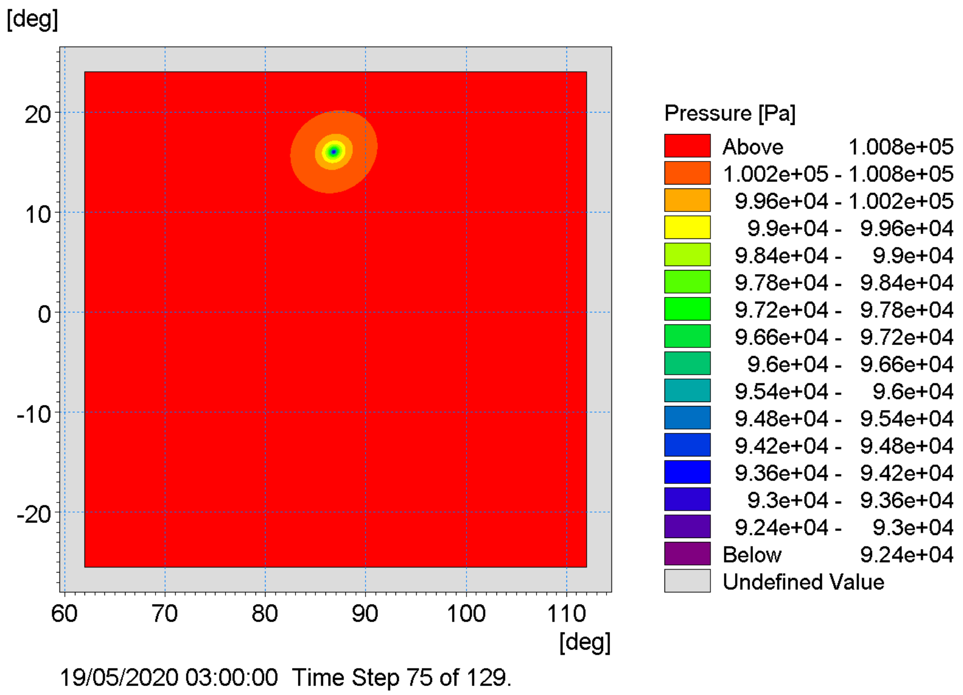

Fig. 2(b) Pressure fields of Cyclone Amphan

Fig. 2 Wind and pressure fields of Cyclone Amphan on 19/05/2020 03:00

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 Bay of Bengal using the MIKE21/3 Flow Model FM software developed by DHI [9]. 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, Malaysia and Indonesia (see Figure 3).

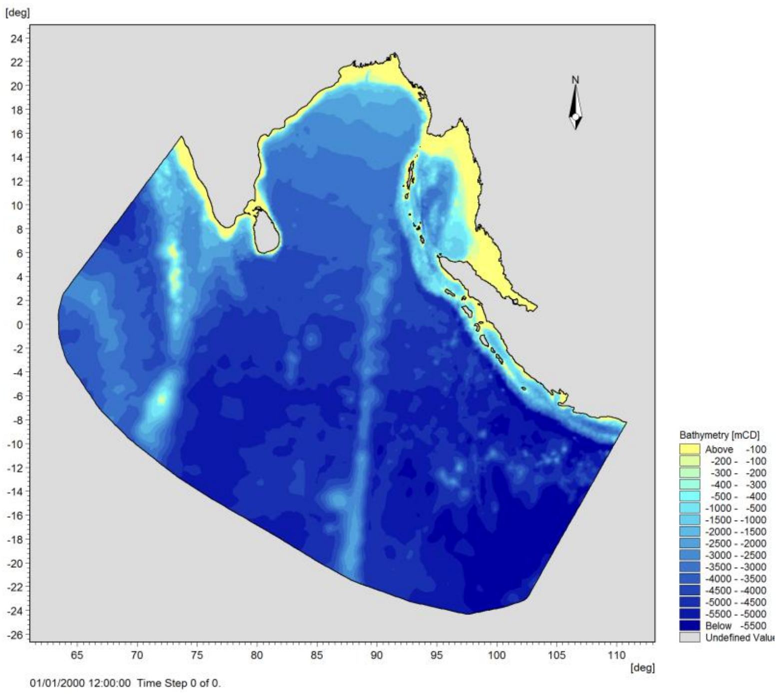

Fig. 3 Regional model extent and bathymetry

The model has three main open boundaries – one to the south, one to the north-west and the other to the south-east. 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 and was obtained from the C-Map Global Database [13].

The regional tidal model was used to drive the cyclone surge model to assess cyclone surge within the region.

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 developed by 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 earlier. The regional wave model was used to drive the cyclone wave model to assess cyclone wave conditions within the region.

5. CYCLONE AMPHAN WAVE MODELLING

5.1 The Wave Model

The regional wave model set up by RHDHV based on the MIKE21 Spectral Wave (SW) software 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 Wave Modelling Methodology

The cyclone wave model was driven by wind and pressure fields shown in Figure 2. A constant water level of +2.6mCD (Chart Datum) was used in the model. The model simulations covered the entire passage of the cyclone across the Bay of Bengal.

The Spectral Wave Model and the Flow Model were run in a dynamic coupled mode where the models exchanged information as necessary.

5.3 Wave Model Validation

Observed significant wave heights at buoys BD08 and BD11 from INCOIS (Indian National Center for Ocean Information Services) were reported by [14] and are provided in Table 2. Wave data at the Gopalpur Buoy was downloaded directly from INCOIS [15]. Modelled wave heights at these locations were also provided in the table. The model underpredicted wave height at BD08. However, the modelled and observed wave heights at BD11 and Gopalpur Buoy were very similar. Overall, a reasonable agreement between the observed and the modelled wave heights was found. Therefore, it was concluded that the wave model can be used to predict wave heights anywhere within the Bay of Bengal with reasonable confidence.

Table 2 – Cyclone Amphan observed and modelled wave heights

Locations	Coordinates	Seabed levels (mCD)	Maximum significant wave height (m)	
			Observed [14]	Modelled
BD08	18.2°N, 89.7°E	-2073	8.5	7.4
BD11	13.5°N, 84.0°E	-3075	6.3	6.5
Gopalpur Buoy	19.28°N, 84.97°E	-13.4	4.2	4.4

5.4 Wave Modelling Results and Discussions

An example of wave heights and directions at a particular time step is shown in Figure 4. Statistical analyses of the model results were carried out using the MIKE21 Toolbox [11] to derive mean and maximum wave conditions over the whole model domain during the entire duration of Cyclone Amphan. Figure 5 shows the maximum significant wave heights over the whole model domain during the entire duration of the cyclone. Maximum wave heights were found in the middle of the Bay of Bengal almost in north-south direction (along the path of the cyclone). Figure 6 shows a time-series of wave height and period at 88.429°E, 20.6°N (120m depth) where the highest wave height was found. The maximum significant wave height H_{m0} of approximately 16.1m (with associated peak wave period T_p of 13.9s) was found

at this location on 20 May 2020 06:15. The figure indicates that significant wave heights higher than 10m were sustained for a duration of about 8 hours and wave heights higher than 14m were sustained for a duration of about 3 hours.
Higher wave heights were found along the path of the cyclone where the cyclone intensity was the highest. Higher significant wave heights were found near the Indian-Bangladeshi coast before the cyclone made the landfall.

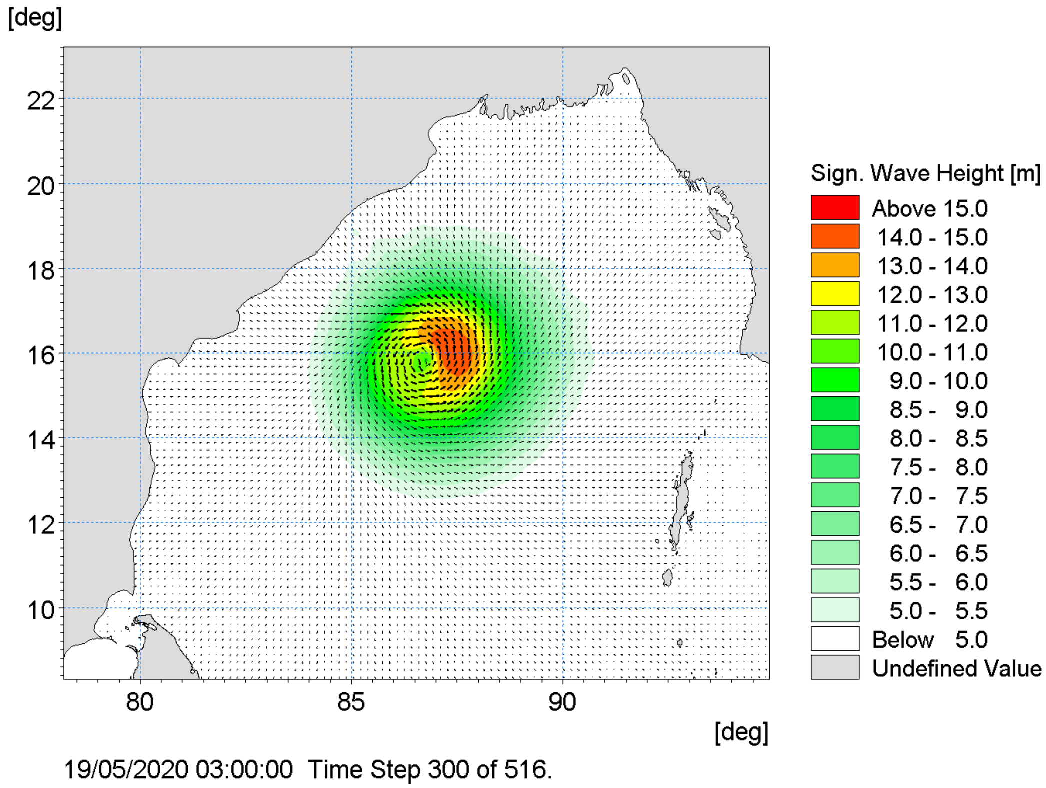

Fig. 4 Significant wave heights and directions of Cyclone Amphan on 19/05/2020 03:00

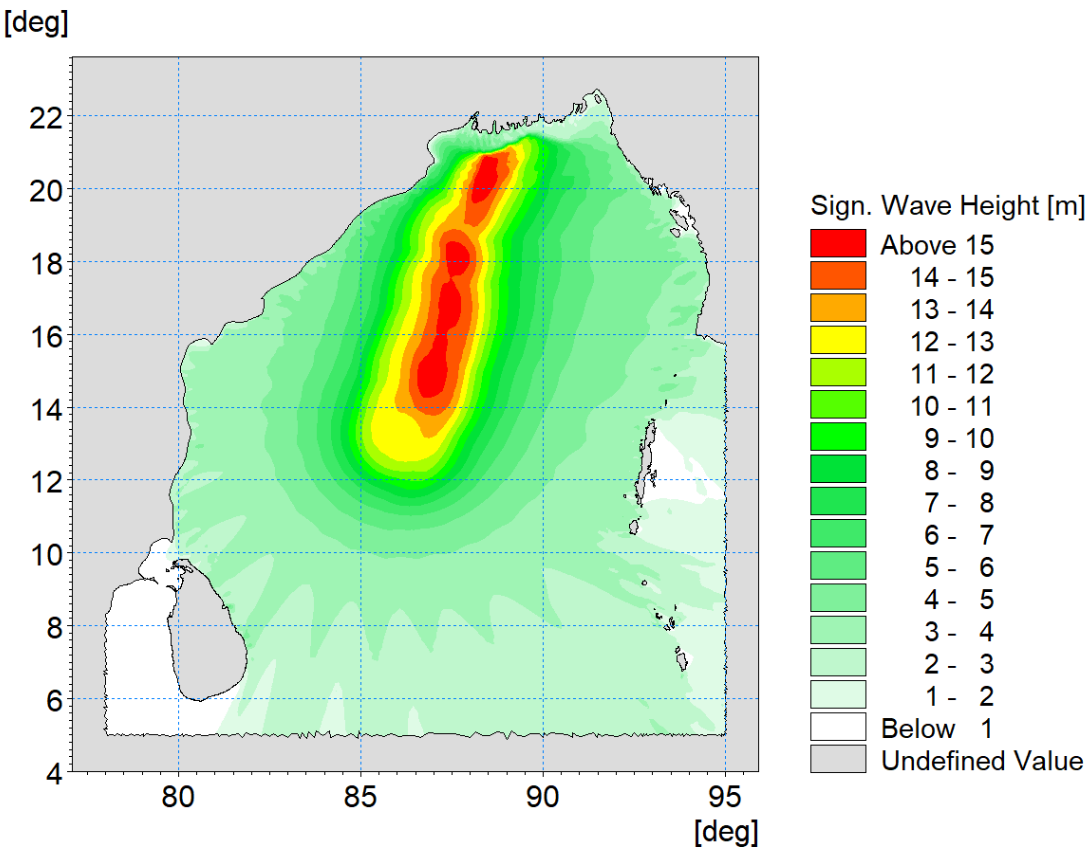

Fig. 5 Maximum significant wave height (H_{m0}) over the entire duration of Cyclone Amphan

6. CYCLONE AMPHAN 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 people and livestock, eroding beaches and embankments, destroying vegetation and reducing soil fertility.

6.1 The Surge 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 in the model. 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 Surge Modelling Methodology

The cyclone surge model was driven by the cyclonic wind and pressure fields shown in Figure 2. A constant water level of +2.6mCD was imposed at the three open boundaries at the south, north-west and south-east. An initial water level of +2.6mCD was maintained over the entire model domain.

As mentioned earlier, the Spectral Wave Model and the Flow Model were run in a dynamic coupled mode where the models exchanged information as necessary.

6.3 Surge Model Validation

Observed surge at various locations along the northern Bay of Bengal coast was reported by [14] and are provided in Table 3. Modelled surge at these locations were also provided in the table. The model underpredicted surge at Angtihara, Galachipa and Tajumuddin. However, the modelled and the observed surge at Visakhapatnam, Kuakata and Chittagong were very similar. Overall, a reasonable agreement between the observed and the modelled surge was found. Therefore, it was concluded that the model can be used to predict surge anywhere within the Bay of Bengal with reasonable confidence.

Table 3 – Cyclone Amphan observed and modelled surge

Locations	Coordinates	Maximum surge (m)	
		Observed [14]	Modelled
Visakhapatnam	17.7°N, 83.25°E	0.4	0.5
Angtihara	22.2°N, 89.3°E	1.4	1.0
Kuakata	21.9°N, 90.1°E	1.4	1.2
Galachipa	22.25°N, 90.45°E	1.5	1.0
Tajumuddin	22.45°N, 90.8°E	1.7	1.2
Chittagong	22.35°N, 91.9°E	1.3	1.2

6.4 Surge Modelling Results and Discussions

Statistical analyses of model results were carried out using the MIKE21 Toolbox [11] to derive mean and maximum surge values over the whole model domain during the entire duration of Cyclone Amphan. Figure 7 (zoomed-in view) shows the maximum positive surge values (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 as well as in the northern part of the Bay of Bengal along the Indian-Bangladeshi coast. The highest positive surge was 3.3m.

Positive storm surges (rises in water level) bring risks of flooding whereas negative storm surges (drops in water level) can damage ships in port and leave them stranded until the water level rises again. Therefore, statistical analyses of the model results were also carried out using the MIKE21 Toolbox [11] to derive the maximum negative surge values over the whole model domain during the entire duration of Cyclone Amphan as shown in Figure 8 (zoomed-in view). Higher negative surge was found in the northern part of the Bay of Bengal along the Indian-Bangladeshi coast with a maximum value of up to 1.3m.

The temporal variation of surge at the location (88.204°E, 22.1°N) where it reached to the highest value is shown in Figure 9. The maximum surge of approximately 3.3m was found on 20 May 2020 14:00. Therefore, the highest surge and the maximum significant wave height occurred 8 hours apart albeit at different locations near the Indian coast. The figure indicates that surges higher than 1.5m were sustained for duration of about 10 hours, surges higher than 2m were sustained for duration of about 8 hours and surges higher than 2.5m were sustained for duration of about 6.5 hours.

Higher positive surge was found along the cyclone path where the intensity of the cyclone was the highest (with the maximum surge of 3.3m near the Indian coast). Higher positive surge was also found in the northern part of the Bay of Bengal (up to 3.3m) due to funneling effects resulting from narrowing down of the water body. Higher negative surge was also found in these areas as the cyclone sucked water away from these areas.

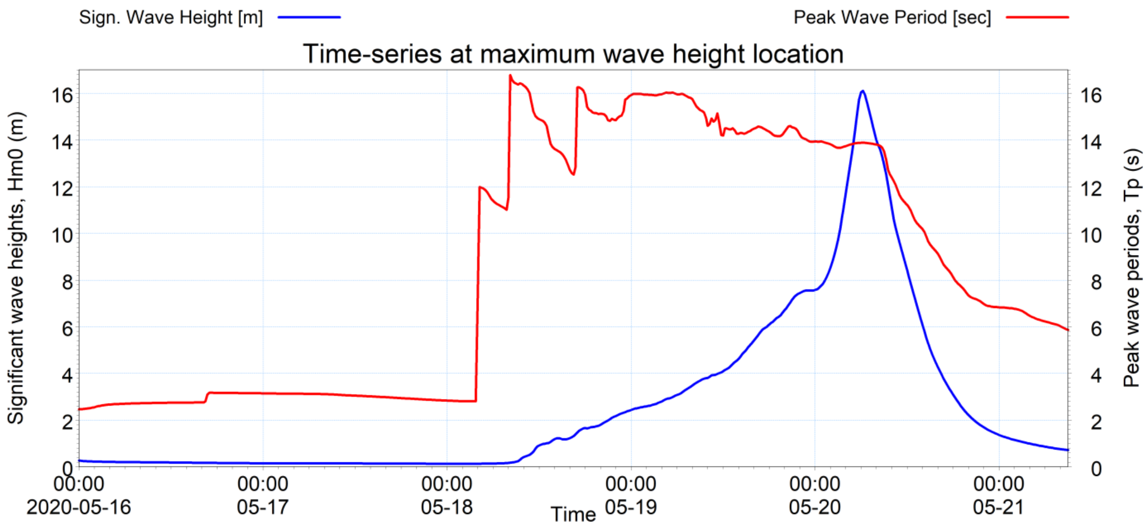

Fig. 6 Time-series of waves over the entire duration of Cyclone Amphan at the location of the maximum wave height [88.429°E, 20.6°N, 120m depth]

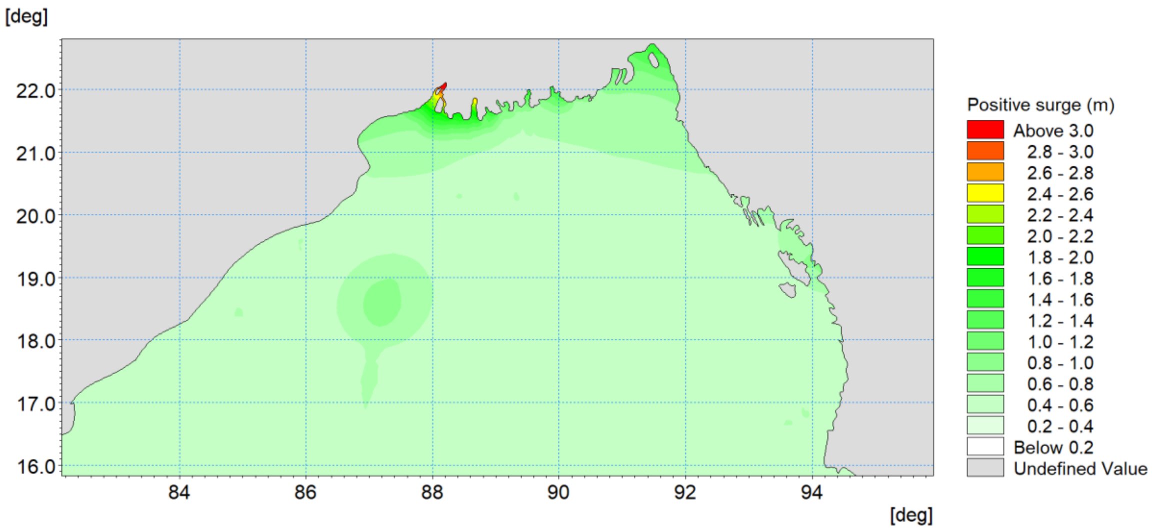

Fig. 7 Maximum positive surge during the entire duration of Cyclone Amphan

7. LIMITATIONS ON THE MODEL RESULTS

Model results presented in this paper are for illustration purposes only. These should not be used for any practical project work for which use of local survey bathymetry data and detailed local calibration are essential.

8. SUMMARY AND FINDINGS

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

Higher wave heights were found along the path of the cyclone where the cyclone intensity was the highest. Maximum significant wave height of 16.1m was found.

Higher positive surge was found along the cyclone path where the intensity of the cyclone was the highest (with the maximum surge of 3.3m near the Indian coast). Higher positive surge was also found in the northern part of the Bay of Bengal due to funneling effects resulting from narrowing down of the water body. Higher negative surge was also found in these areas as the cyclone sucked water away from these areas.

The maximum surge and the maximum significant wave height occurred 8 hours apart albeit at different locations near the Indian coast.

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.

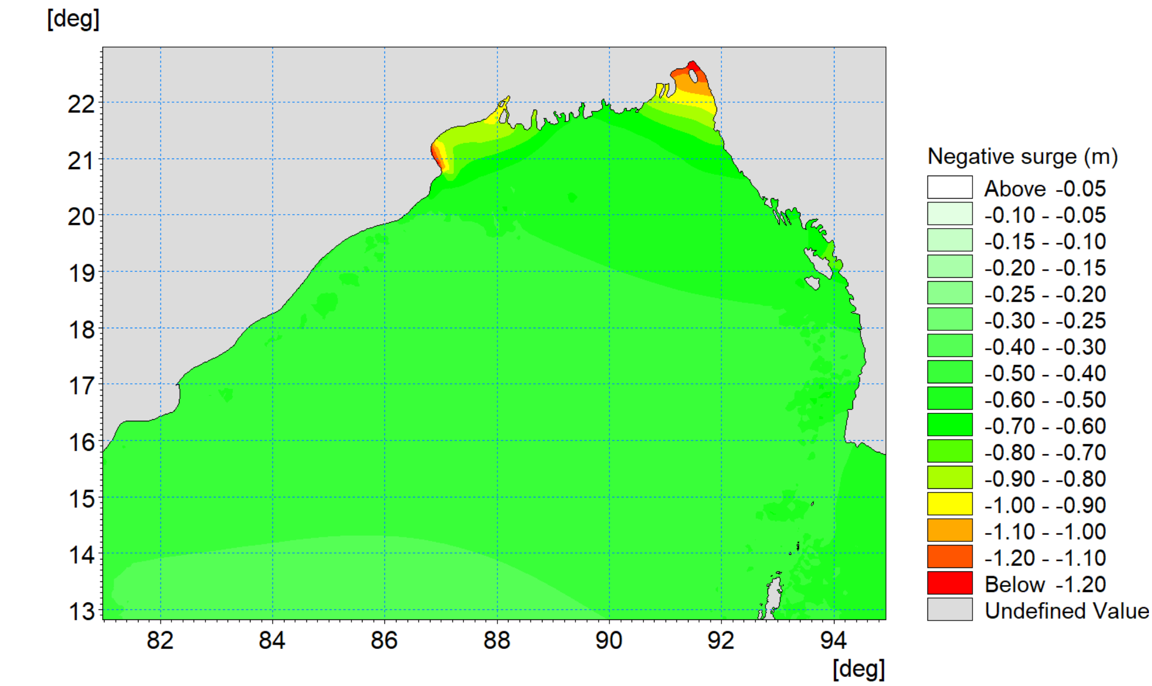

Fig. 8 Maximum negative surge during the entire duration of Cyclone Amphan

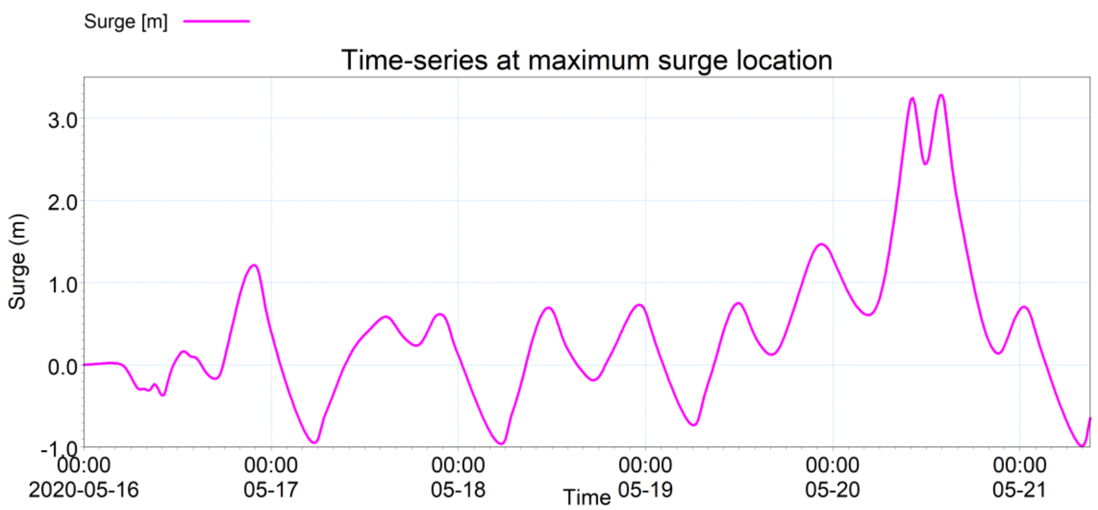

Fig. 9 Time-series of surge over the entire duration of Cyclone Amphan at the location of the maximum surge [88.204°E, 22.1°N, 2.6m depth]

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