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Numerical Modelling of Waves and Surge from Cyclone Hudhud (2014) in the Bay of Bengal

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ABSTRACT
The Extremely Severe Cyclonic Storm Hudhud (during 7-14 October 2014) was a strong tropical cyclone that caused extensive damage and loss of life in eastern India and Nepal. 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 Hudhud

1. INTRODUCTION

Cyclone Hudhud was an Extremely Severe Cyclonic Storm that caused extensive damage and loss of life in the eastern India and Nepal during 7-14 October 2014. The cyclone originated on 6 October from low pressure that formed under the influence of an upper-air cyclonic circulation in the Andaman Sea. It intensified into a cyclonic storm on 8 October and as a Severe Cyclonic Storm on 9 October. Hudhud underwent rapid deepening in the following days and was classified as a Very Severe Cyclonic Storm by the Indian Meteorological Department (IMD) [1]. Shortly before landfall near Visakhapatnam in Andhra Pradesh of India on 12 October, the cyclone reached its peak strength with three-minute wind speeds of 185 km/h (115 mph) and a minimum central pressure of 960 mbar (28.35 inHg). Hudhud then drifted northwards towards Uttar Pradesh of India and Nepal causing widespread rains in both areas and heavy snowfall in the latter. Hudhud caused extensive damage to the City of Visakhapatnam and the neighbouring districts of Vizianagaram and Srikakulam of Andhra Pradesh. Damages were estimated to be US$3.58 billion by the Andhra State Government. At least 124 deaths have been confirmed, a majority of them from Andhra Pradesh and Nepal, with the latter experiencing an avalanche due to the cyclone. The above information was obtained from [2].

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, 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 model developed by DHI [3, 4, 5] was 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 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 HUDHUD TRACK AND DATA

The track (route) of Cyclone Hudhud was obtained from [2] as shown in Figure 1. The cyclone data was obtained from the Joint Typhoon Warning Center (JTWC) [6]. The JTWC archived cyclone data contains 6 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 Hudhud 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 [7].

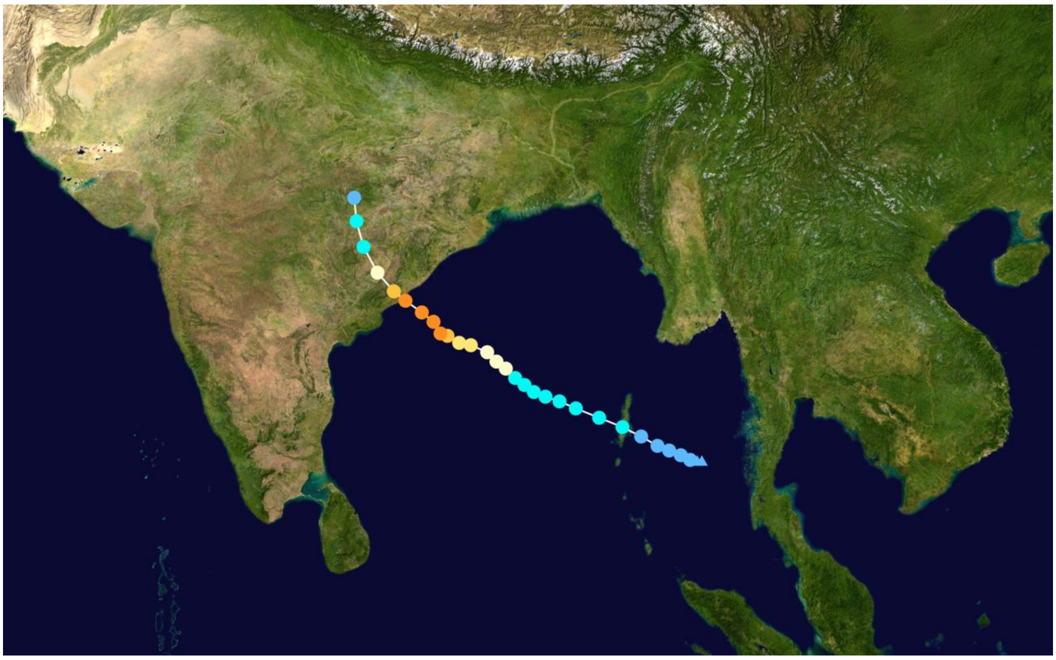

Fig. 1 Track and intensity of Cyclone Hudhud [2]

Table -1 Cyclone Hudhud Track and Data [6]

Date	Time [UTC]	Time [hour]	Longitude [E]	Latitude [N]	Radius of max winds [km]	Max 1-hourly wind speeds [m/s]	Central pressure [hPa]	Constant neutral pressure [hPa]
08-10-14	1200	0	90.7	13.0	64.82	18.65	989	1013
"	1800	6	90.0	13.3	46.30	20.73	985	1013
09-10-14	0000	12	89.4	13.5	46.30	22.80	982	1013
"	0600	18	88.9	13.7	55.56	24.87	978	1013
"	1200	24	88.5	14.0	55.56	24.87	978	1013
"	1800	30	88.1	14.3	55.56	24.87	978	1013
10-10-14	0000	36	87.7	14.7	55.56	26.94	974	1013
"	0600	42	87.3	15.0	55.56	26.94	974	1013
"	1200	48	86.9	15.4	46.30	31.09	967	1013
"	1800	54	86.2	15.7	37.04	35.23	959	1013
11-10-14	0000	60	85.7	15.8	37.04	39.38	952	1013
"	0600	66	85.2	16.1	18.52	43.52	944	1013
"	1200	72	84.9	16.2	18.52	47.67	937	1013
"	1800	78	84.6	16.7	18.52	47.67	937	1013
12-10-14	0000	84	84.1	17.1	18.52	47.67	937	1013
"	0600	90	83.4	17.6	27.78	47.67	937	1013
"	1200	96	82.9	18	27.78	43.52	944	1013
"	1800	102	82.2	18.8	37.04	33.16	963	1013
13-10-14	0000	108	81.6	19.9	55.56	22.80	982	1013
"	0600	114	81.3	21	55.56	16.58	993	1013
"	1200	120	81.2	22	55.56	12.44	1000	1013

3. WIND AND PRESSURE FIELDS GENERATION

The MIKE21 Cyclone Wind Generation Tool of DHI [5] was used to generate the cyclonic wind and pressure fields of Cyclone Hudhud. 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 Hudhud on 12/10/2014 02:00:00 when it generated the maximum wave heights. These wind and pressure fields were used to drive the cyclone wave and surge models described later.

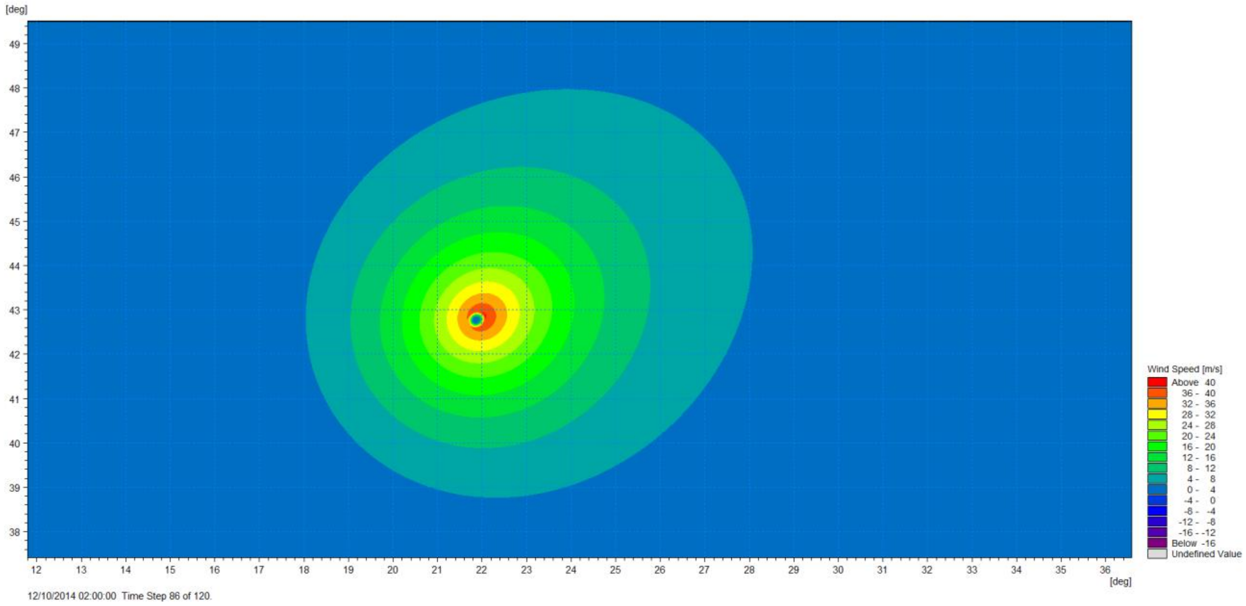

Fig. 2(a) Wind fields of Cyclone Hudhud

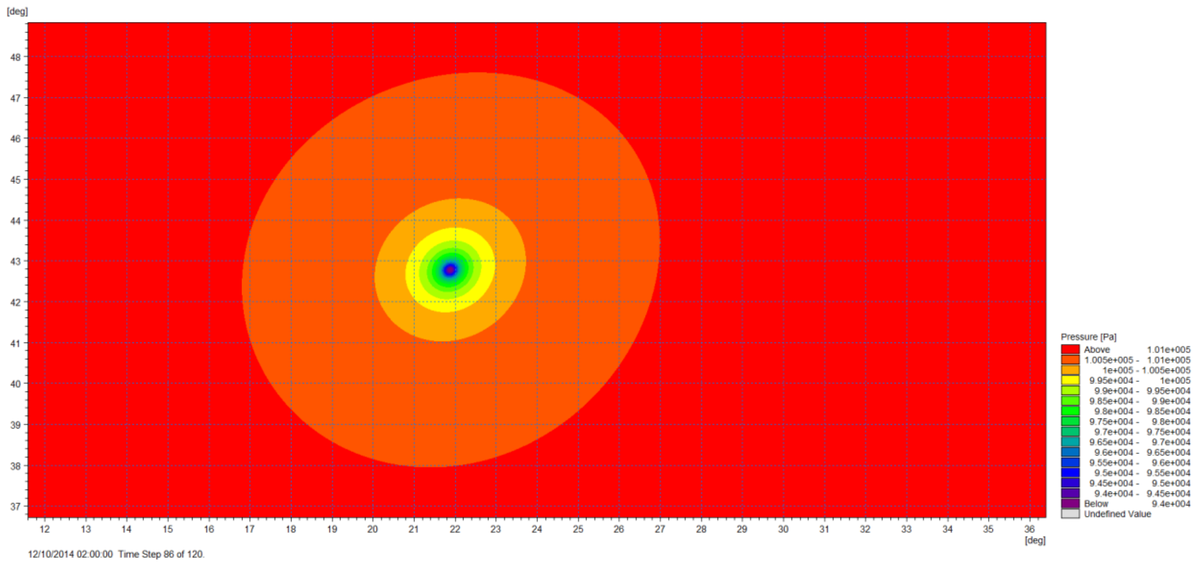

Fig. 2(b) Pressure fields of Cyclone Hudhud

Fig. 2 Wind and pressure fields of Cyclone Hudhud on 12/10/2014 02:00:00

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 of DHI [3]. 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). 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.

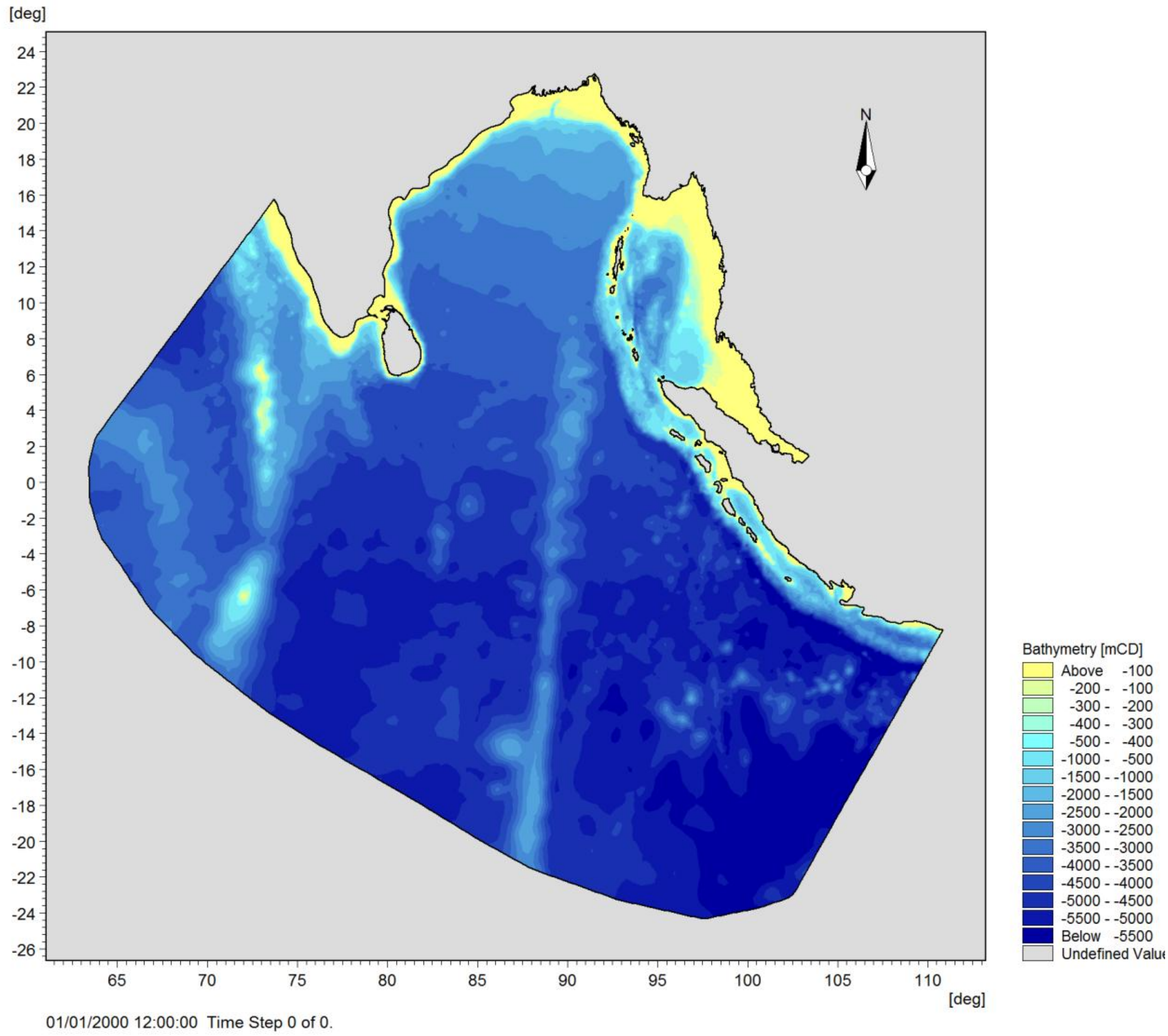

Fig. 3 Model extent and bathymetry

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 [8].

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 of DHI [4]. 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.

5. CYCLONE HUDHUD WAVE MODELLING

5.1. The 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 was used in the model. The model simulations covered the entire passage of the cyclone across the Bay of Bengal.

5.3. Model Validation

Observed and modelled wave heights at various locations from previous studies by [9], [10] and [11] are provided in Table 2. The table also shows the modelled wave height from the present study. A good agreement was found between the previous studies and the present study.

Tp = 11.8s (observed) and 11.8s (modelled) at Gopalpur and Tp = 9.0 (modelled) at Vizag were reported by [10]. Peak wave period of 12.2 (mean period of 9.4s) was found from the present study.

Table -2 Maximum significant wave height (H_{m0}, m) comparison

Sources	Locations		
	Visakhapatnam	**Gopalpur**	**Vizag**
Samiksh et al. (modelled) [9]	6.2	-	-
Samiksh et al. (observed) [9]	7.8	-	-
Remya (modelled) [10]	-	5.6	6.2
Remya (observed) [10]	-	6.0	6.3
E-Book India (observed) [11]	8.1	5.8	-
E-Book India (modelled) [11]	8.6	6.3	-
Present study	8.0	6.0	-

5.4. Model Results and Discussions

The maximum significant wave height (Hm0) of approximately 11.1m (with associated peak wave period of 12.2s) was found at a location of 83.7°E, 17.35°N on 12 October 2014 02:00:00. 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 east coast of India near Visakhapatnam (Andhra Pradesh). 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 duration of about 10 hours and wave heights higher than 5m were sustained for duration of about 1.25 day.

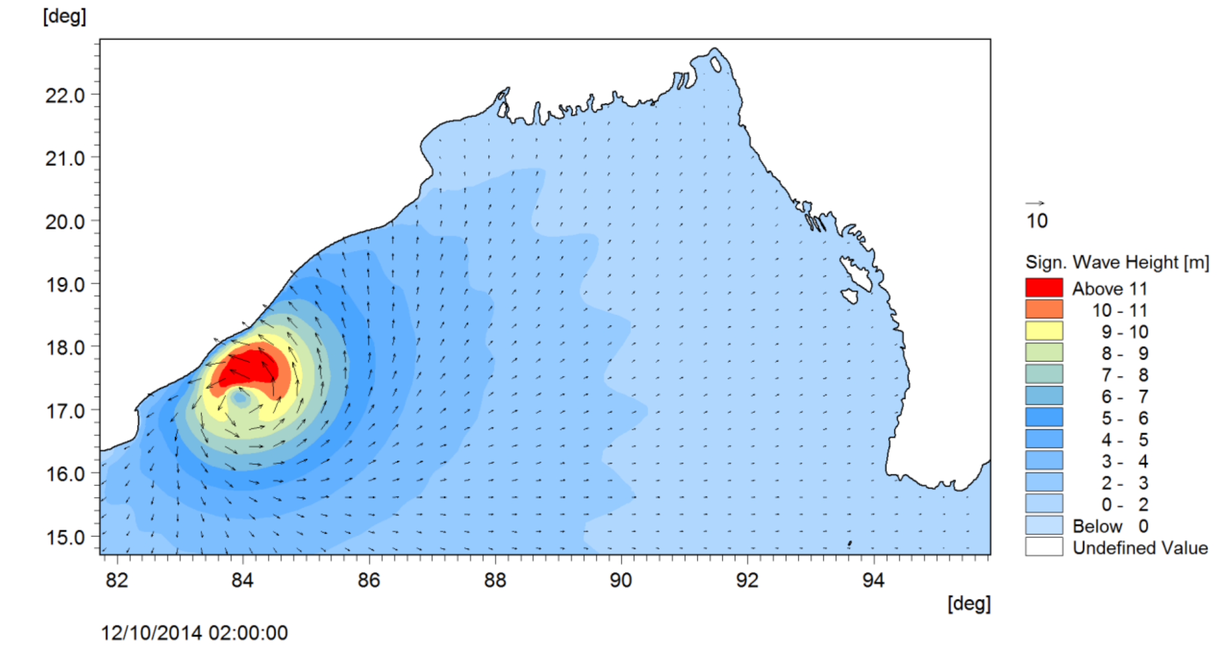

Fig. 4 Significant wave heights (Hm0) of Cyclone Hudhud on 12/10/2014 02:00:00

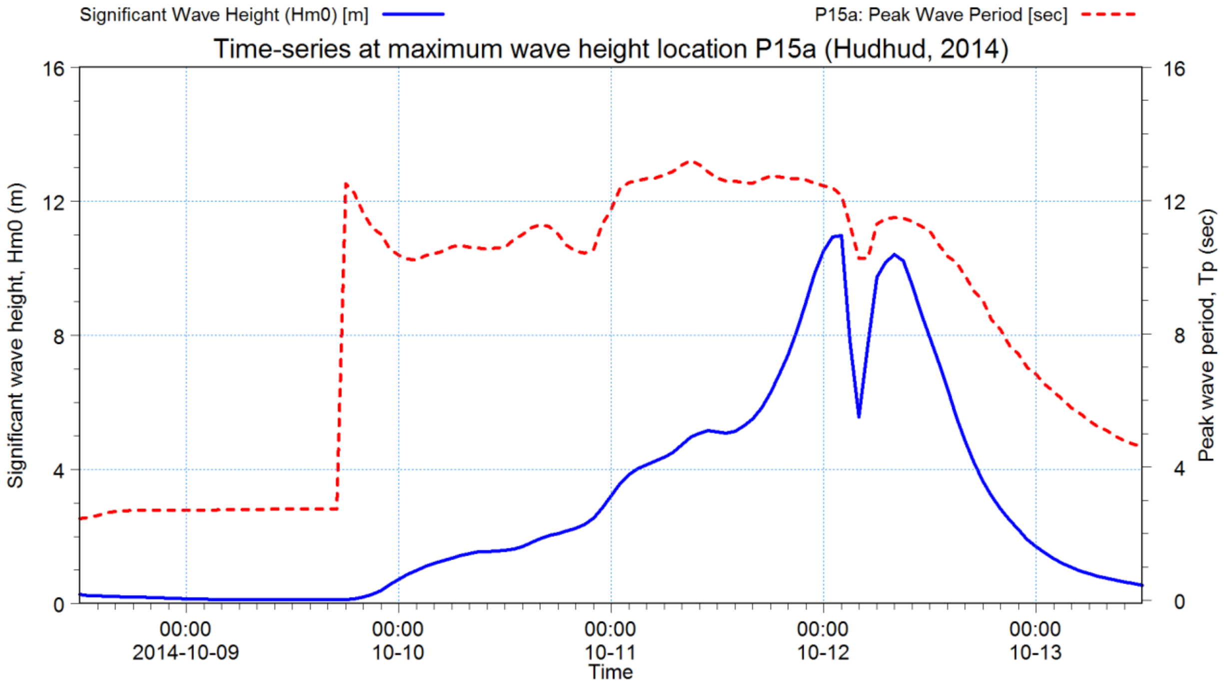

Fig. 5 Time-series of waves over the entire duration Cyclone Hudhud at point P15a [83.7°E, 17.35°N, 1210m depth]

Statistical analyses of model results were carried out using the MIKE21 Tool [5] to derive mean and maximum wave conditions over the whole model domain during the entire duration of Cyclone Hudhud. Figure 6 shows the maximum significant wave heights over the whole model domain during the entire duration of the cyclone. Figure 7 shows the locations and bed levels of some selected points (points 1 to 16) along the cyclone track where model results were extracted. Maximum significant wave heights along the cyclone track during the entire duration of the cyclone were provided in Figure 8. Figures 6 and 8 indicate that the maximum significant wave height was found in the east coast of India.

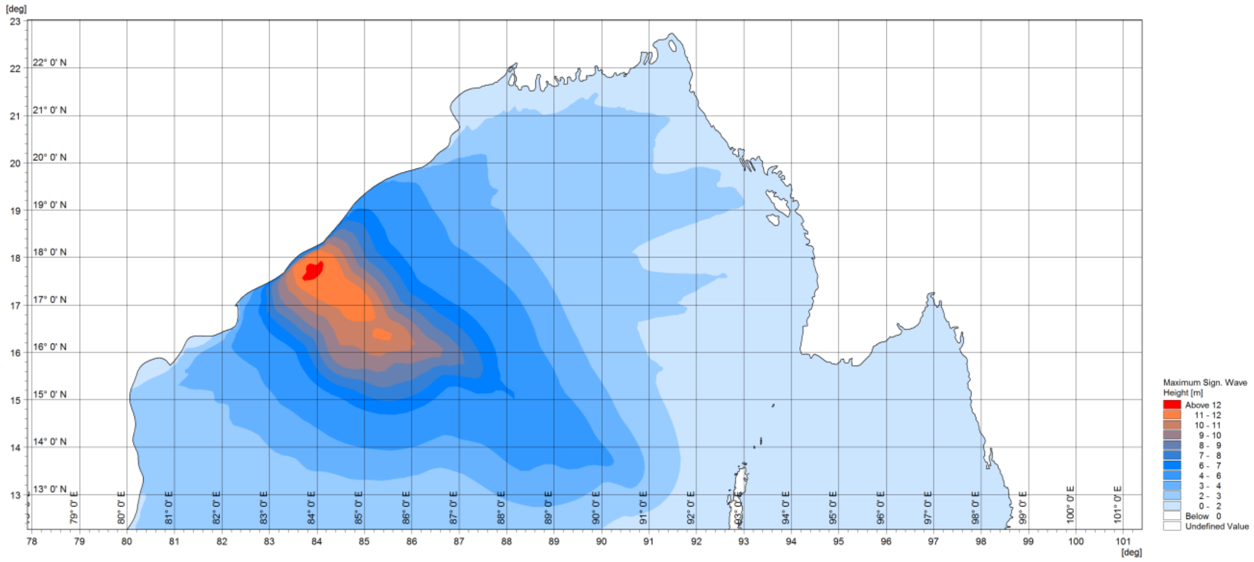

Fig. 6 Maximum significant wave height (Hm0) over the entire duration of Cyclone Hudhud

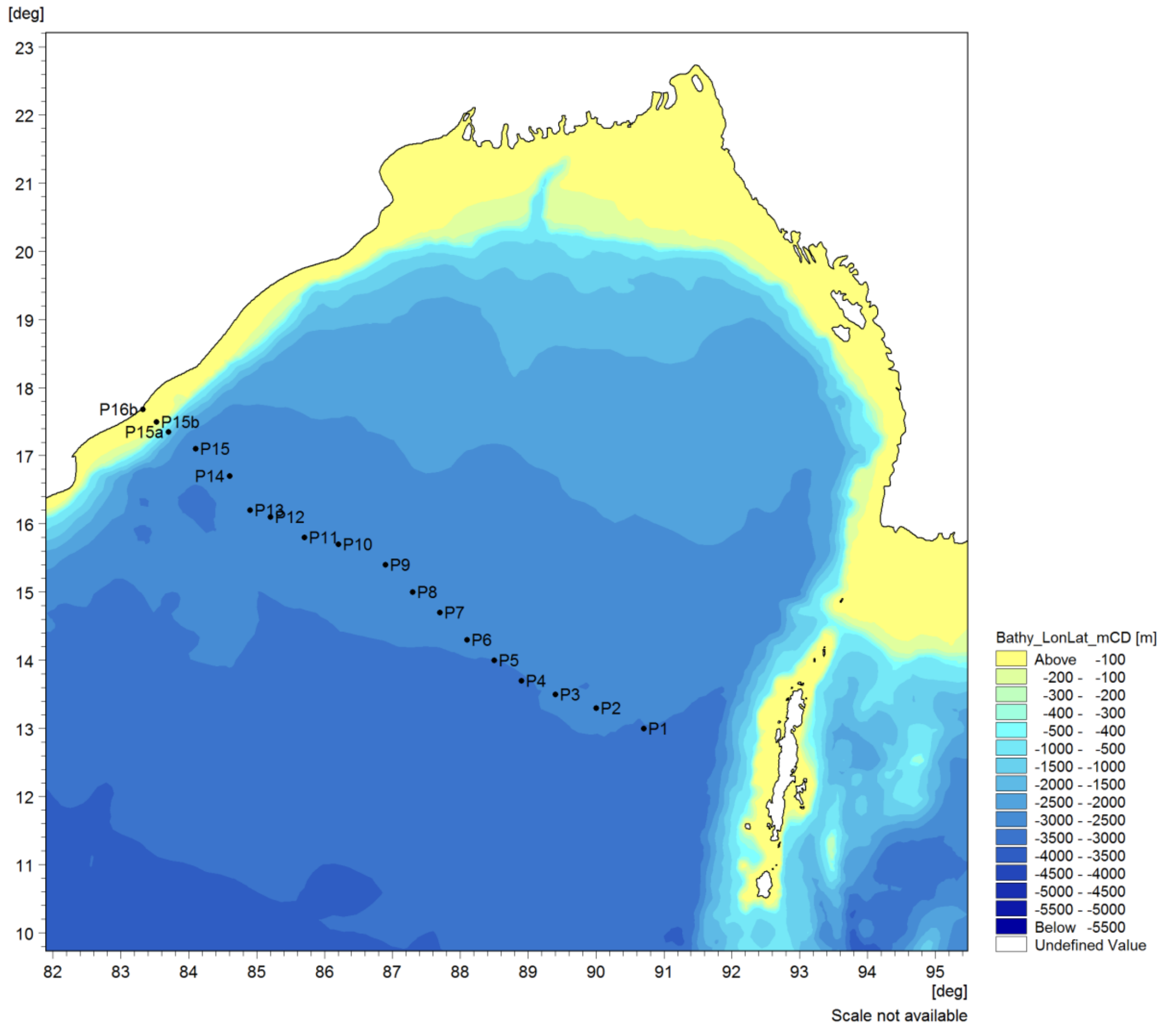

Fig. 7 Output points along the track of Cyclone Hudhud

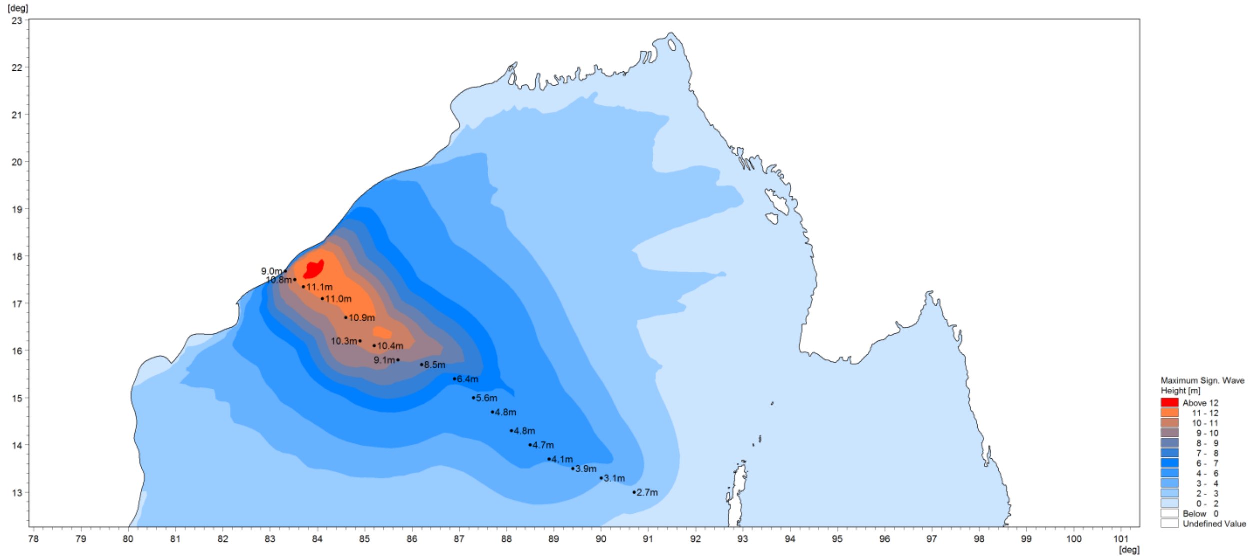

Fig. 8 Maximum significant wave heights (Hm0) at various points along the track of Cyclone Hudhud

The maximum significant wave heights along the cyclone track shown in Figure 8 were reproduced in Figure 9 to provide clearer comparison of wave heights at various points along the cyclone track. The horizontal axis in this figure shows the selected locations along the track (a total of 18 points as illustrated in Figure 7) and the vertical axis shows the maximum significant wave heights (Hm0) at these points. The line in this figure shows the maximum significant wave heights along the cyclone track and the points (and the values) in this figure show the maximum significant wave heights (in meter) at selected 18 points along the cyclone track. The figure shows that the highest significant wave height of 11.1m was found at point P15a [83.7°E, 17.35°N, 1210m depth].

Higher wave heights were found along the path of the cyclone where the cyclone intensity was the highest. Maximum significant wave height was found near the Indian coast before the cyclone made the landfall.

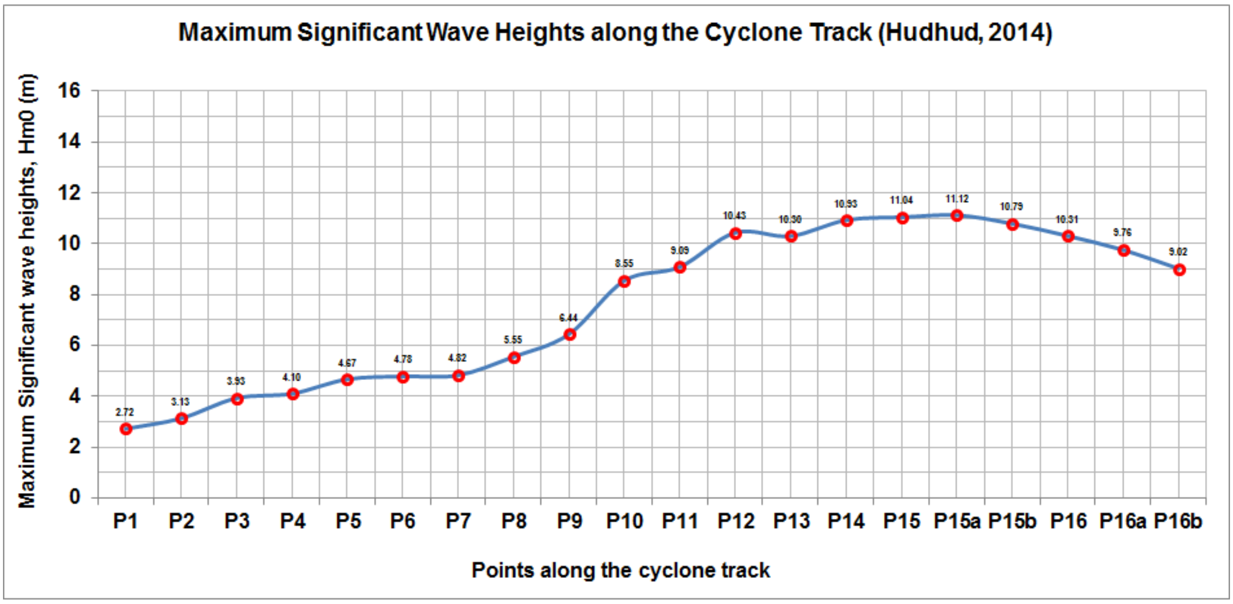

Fig. 9 Graphical presentation of maximum significant wave heights (Hm0) at various points along the track Cyclone Hudhud

6. CYCLONE HUDHUD 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 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 type and Smagorinsky eddy viscosity type 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 +2.6 m was imposed at the three open boundaries at the south, north-west and south-east. An initial water level of +2.6 m was maintained over the entire model domain.

6.3. Model Validation

Observed and modelled surge at various locations from previous studies by [9], [11] and [12] are provided in Table 3. The table also shows the modelled surge from the present study. A reasonable agreement was found between the previous studies and the present study. It should be noted that local survey bathymetry data is required to reliably predict surge at a location which was not available for the present study. Nevertheless, Table 3 provides surge at Visakhapatnam reported by various authors which could be useful to researchers and practitioners.

Table -3 Maximum surge (m) comparison

Sources	At Visakhapatnam
Samiksh et al. (modelled) [9]	1.2
Samiksh et al. (observed) [9]	1.4
E-Book India (observed) [11]	1.4
E-Book India (modeled) [11]	1.1
Present study	1.1

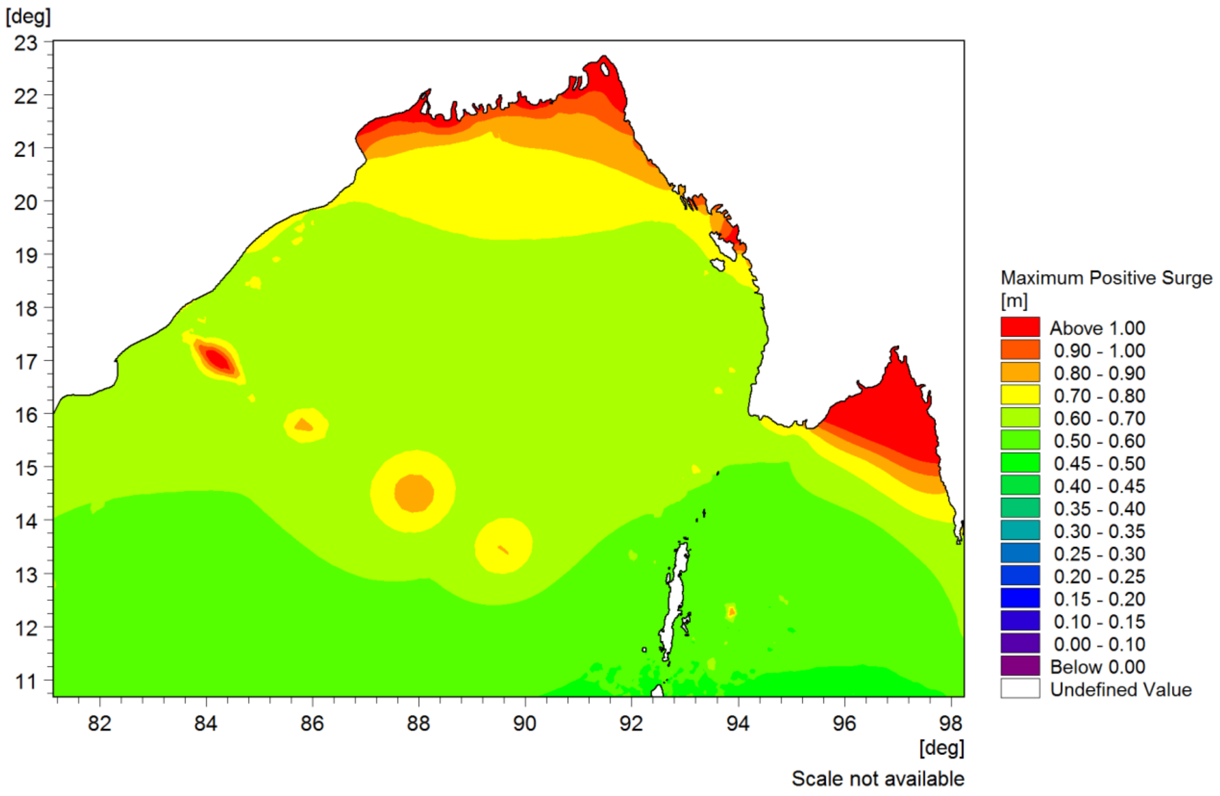

Fig. 10 Maximum positive surge during the entire duration of Cyclone Hudhud

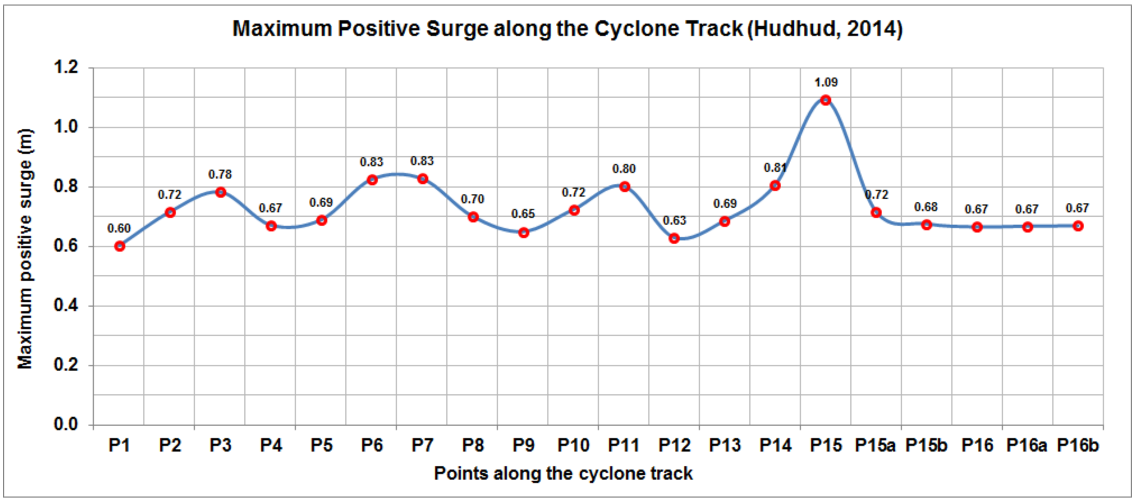

Fig. 11 Maximum positive surge at various points during the entire duration of Cyclone Hudhud

6.4. Model Results and Discussions

Statistical analyses of model results were carried out using the MIKE21 Tool [5] to derive mean and maximum surge values over the whole model domain during the entire duration of Cyclone Hudhud. Figure 10 (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 and in the Gulf of Martaban (in Myanmar).

The maximum positive surge was extracted from Figure 10 at various points along the cyclone track and presented in Figure 11 to provide clearer comparison of surge values at various points along the cyclone track. The horizontal axis in this figure shows the selected locations along the track (a total of 18 points as illustrated in Figure 7) and the vertical axis shows the maximum positive surge value at these points. The line in this figure shows the maximum positive surge value along the cyclone track and the points (and the values) in this figure show the maximum positive surge value (in meter) at selected 18 points along the cyclone track. The figure shows that the highest positive surge value of 1.09m was found at point P15 [84.1°E, 17.1°N, 2724m depth].

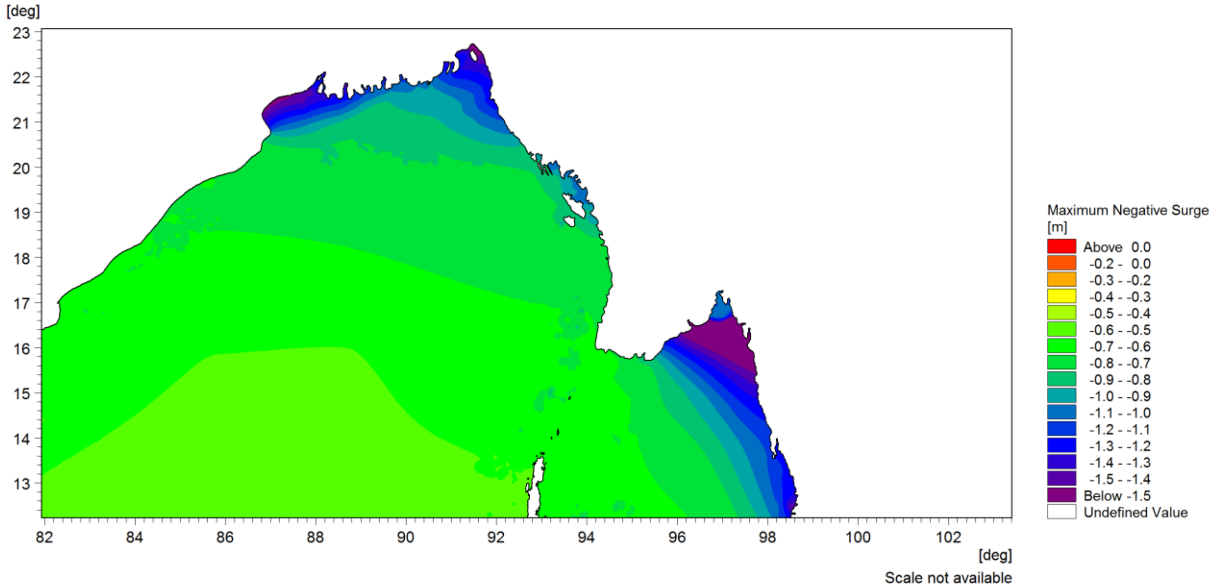

Fig. 12 Maximum negative surge during the entire duration of Cyclone Hudhud

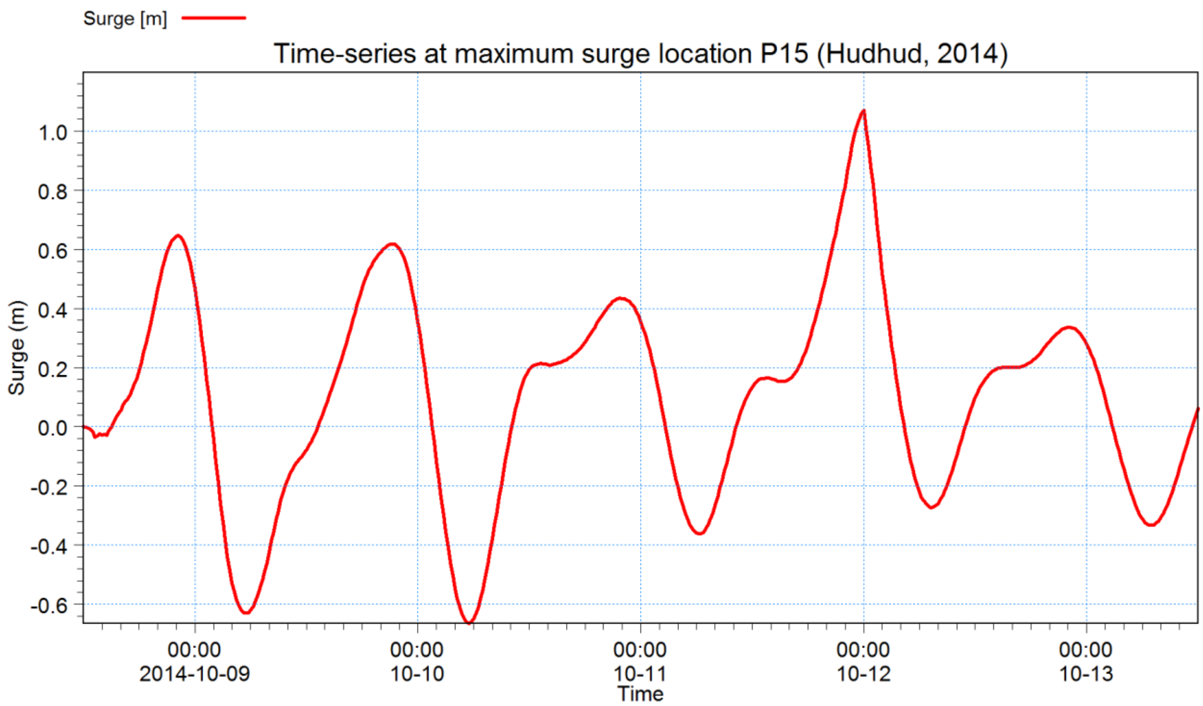

Fig. 13 Time-series of surge over the entire duration of Cyclone Hudhud at point P15 [84.1°E, 17.1°N, 2724m depth]

Positive storm surges (rises in water level) bring the risk 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 model results were also carried out using the MIKE21 Tool [5] to derive the maximum negative surge values over the whole model domain during the entire duration of Cyclone Hudhud as shown in Figure 12 (zoomed-in view). Higher negative surge were found in the northern part of the Bay of Bengal (up to 1.6m) and in the Gulf of Martaban (up to 2m).

The temporal variation of surge at the location of the highest surge (point P15) during the entire duration of the cyclone is shown in Figure 13. The maximum surge of approximately 1.1m was found on 12 October 2014 00:00:00. Therefore, the highest surge and the maximum significant wave height occurred 2 hours apart albeit at slightly different locations near the Indian coast. The figure indicates that surges higher than 0.5m were sustained for duration of about 6.3 hours and surges higher than 1.0m were sustained for duration of about 1.3 hours.

Higher positive surge was found along the cyclone path where the intensity of the cyclone was the highest (with the maximum surge of 1.1m near the Indian coast). Higher surge was also found in the northern part of the Bay of Bengal (up to 1.4m) and in the Gulf of Martaban (up to 1.8m) 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.

6. 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 path of the cyclone where the cyclone intensity was the highest. Maximum significant wave height of 11.1m was found near the Indian coast before the cyclone made the landfall.

Higher positive surge was found along the cyclone path where the intensity of the cyclone was the highest (with the maximum surge of 1.1m near the Indian coast). Higher surge was also found in the northern part of the Bay of Bengal and in the Gulf of Martaban 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 2 hours apart albeit at slightly 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.

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