Simulation of Storm Surge and its Variation for Bhola Cyclone using MRI Storm Surge Model

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Abstract

Bhola Cyclone (November 1970) remains the deadliest tropical cyclone ever recorded and one of the world's deadliest natural disasters. Most notable storm surge in history occurred in 1970 affecting Bangladesh and India's West Bengal which was caused by the Bhola cyclone. Bhola cyclone took lives of at least 300,000 people primarily as a result of the storm surge. An attempt was made in this study, to use MRI storm surge model for simulation of storm surge of Bhola cyclone and variations of Bhola cyclone. The event was simulated in the model for 48-hours using parametric data set. For variability of Bhola cyclone estimated central pressure was changed for the same corresponding coordinates. The estimated central pressure was decreased by 5%, 10% and 15% and increased by 5% and then used as input data for simulation. The maximum simulated surge height for Bhola cyclone was 5.4 meters. For variations of strength for Bhola cyclone i.e. 5% decrease, 10% decrease, 15% decrease and 5% increase of estimated central pressure, the model generated maximum 7.8 meters, 10.2 meters, 11.5 meters and 0.1 meters surge respectively.

Keywords: Tropical Cyclone, Bhola Cyclone, Storm Surge, MRI Model.

1. INTRODUCTION

Storm surge is abnormal rise in water level in coastal areas, over and above the regular astronomical tide, caused by forces generated from a severe storm's wind, waves, and low atmospheric pressure. Storm surges, especially those associated with tropical cyclone, represent major marine hazard, frequently resulting in the loss of life and property in many parts of the world. As Bangladesh is located in a region of high tropical cyclone activity zone, it often experiences storm surge disaster caused mainly by tropical cyclone. The coastal region of Bangladesh in particular, is extremely vulnerable to cyclonic storm surge flooding. On an average, Bangladesh accepts approximately 40% of the blow of total storm surges in the world but about 80% of the global casualties occur in this area [1]. Every year the coastal population of Bangladesh experiences huge loss of life and damage of property caused mainly by storm surges.

Of all the cyclones that affected the coastal region of Bangladesh, the deadliest was the great cyclone of 1970. Also known as the Bhola cyclone, It remains the deadliest tropical cyclone ever recorded and one of the world's deadliest natural disasters. Bhola cyclone struck Bangladesh (known as East Pakistan back then) and India's West Bengal on November 11, 1970. The total number of victims were never properly disclosed but it is estimated that at least 300,000 people lost their lives with some reports stating the number to be as high as 500,000 people The survivors claimed that approximately 85% of homes in the area were destroyed or severely damaged, with the greatest destruction occurring along the coast [2]. Ninety percent of marine fishermen in the region suffered heavy losses, including the destruction of 9,000 offshore fishing boats. Of the 77,000 onshore fishermen, 46,000 were killed by the cyclone, and 40% of the survivors were affected severely. In total, approximately 65% of the fishing capacity of the coastal region was destroyed by the storm, in a region where about 80% of the protein consumed comes from fish. Agricultural damage was similarly severe with the loss of US$63 million worth of crops and 280,000 cattle [3].

Interestingly, even though Bhola cyclone is considered as one of the most devastating natural disasters in human history, there have been little to no meteorological research conducted on the event. The reason could be the lack of availability of meteorological data due to lack of availability of proper equipment necessary for collection of data at the time. However, with the advancement of technology, research has been done on various recent tropical cyclone induced storm surges with the goal of developing a proper forecasting system. Debsarma (2009) calculated time sequence of storm surges caused by different cyclones and simulated storm surges of the severe cyclone of April 1991, the severe cyclone of September 1997, and the Orissa super cyclone of 1999 using IIT-D Storm Surge Model developed by Dube et al. [4]. Mallik *et al.* (2015) simulated the landfall and storm surge of Cyclone Viyaru using the Weather Research and Forecast Model (WRF) model and Meteorological Research Institute (MRI) model [5]. Ali *et al.* (2018) simulated Cyclone Aila using WRF model and simulated storm surge for the cyclone using MRI model and studied the storm surge event of cyclone Aila [6]. Sinha *et.al.* established a numerical model for the Indian coasts which is adjacent to the Bay of Bengal and the Arabian Sea [7]. Mohit *et. al.* used the MRI model to simulate storm surge for tropical cyclone activity with the goal of forecasting intensity of tropical cyclone [8]. Hossain *et. al.* used MRI model to simulate the storm surge of cyclone Roanu [9]. Aseer *et. al.* (2021) used the MRI model to simulate five storm surge events associated with tropical cyclones which occurred in the Bay of Bengal [10]. Aseer *et. al.* (2022) also used the MRI model to simulate the storm surge of Cyclone Bulbul [11].

In this study, Meteorological Research Institute (MRI) storm surge model from Japan Meteorological Agency (JMA) is used to simulate storm surge of Bhola cyclone (November 1970) with parametric data as input. The objective of the study is to understand the effectiveness of the MRI model in simulating Bhola cyclone and variations of Bhola cyclone.

2. MODEL EXPERIMENTAL SET-UP, DATA USED AND METHODOLOGY

2.1 MRI Storm Surge Model

MRI storm surge model was technologically developed at the Meteorological Research Institute (MRI) of JMA. The model is based on Princeton Ocean Model (POM) and the third-generation wave model. The model runs on Linux distribution-based Ubuntu operating system It was originally developed for local observations because for local observation this model does not require much computer resources. JMA also operate storm surge models in its supercomputer system. Two major factors are considered for calculating storm surge in this model. They are:

Inverse barometer effect: During a tropical cyclone, the atmospheric pressure decreases. It results in the rising of the water level. This untoward phenomenon is called the "inverse barometer effect". For every decrease of 1 hectopascal (hPa) pressure from the atmospheric pressure level, the associated sea rises by 1 centimeter (cm). Although this has only a little contribution of about 5-10% in the formation of a surge.

Considering balance between surface pressure and sea level,

$$\rho g \Delta h S = \Delta p S$$

Where, ρ = sea water density

g = gravitational acceleration

Δh = sea level rise

Δp = pressure depression

S = area

Hence, $\Delta h = \frac{\Delta p}{\rho g} = \frac{1.0\ [hPa]}{1.0\ [gcm^{-3}]*9.8\ [ms^{-2}]} \cong 1.0\ cm$

So, 1 hPa pressure decrease ≅ 1 cm sea level rise

Wind set up: The key influencing factor here is the high wind associated with a cyclone. During a cyclone, high wind pushes the raised seawater towards the coastline causing inundation. A storm surge is more deadly during a high tide. The magnitude and level of surge largely contribute to the meteorological parameters and geographical settings of the concerned location.

Wind force (stress) to local water

τ : wind stress

L: fetch (horizontal scale)

h: water depth

$$g\frac{\partial \eta}{\partial x} = \frac{\tau}{\rho g}$$

$$\frac{\partial \eta}{\partial x} = \frac{\tau}{\rho g h}$$

$\eta = \int_0^L \frac{\tau}{\rho g h} dx = \frac{\tau}{\rho g h} * L$

η: $\propto V^2$ (square of wind speed)

$\propto L$ (Horizontal scale of wind)

$\propto 1/h$ (Inverse of water depth)

The momentum flux and continuity of mass equations under the rotating field with gravitational acceleration are the basic equation of this storm surge model.

Momentum equations

$$\begin{cases} \frac{\partial Du}{\partial t} + \frac{\partial Du^2}{\partial x} + \frac{\partial Duv}{\partial y} = -\frac{1}{\rho_w g} D \frac{\partial(\zeta - \zeta_o)}{\partial x} - \frac{1}{\rho_w}(\tau_{ax} - \tau_{bx}) + fDv \\ \frac{\partial Dv}{\partial t} + \frac{\partial Duv}{\partial x} + \frac{\partial Dv^2}{\partial y} = -\frac{1}{\rho_w g} D \frac{\partial(\zeta - \zeta_o)}{\partial y} - \frac{1}{\rho_w}(\tau_{ay} - \tau_{by}) + fDu \end{cases}$$

Continuity of mass

$$\frac{\partial \zeta}{\partial t} + \frac{\partial Du}{\partial x} + \frac{\partial Dv}{\partial y} = 0$$

Where,

x = (x, y) indicates horizontal position,

U = (u, v) current velocity

ζ = height deviation

ζ_0 = balance level with surface pressure

ρ_w = sea water density

f = Coriolis parameter

g = gravitational acceleration

$\tau_a = (\tau_{ax}, \tau_{ay})$ indicates stresses to waters, at surface by winds and at bottom by friction respectively.

The local heights of water are expressed by D, which is defined to the summation of the static level (water depth H) and deviation ζ:

$D(x, y, t) = H(x, y) + \zeta(x, y, t)$

2.2 Model Experimental Setup

Table 1 describes the experimental model domain for the present study which ranges from 86.0ºE to 94.0ºE in case of longitudes and from 18.0ºN to 24.0ºN in case of latitude. Pressure profile, grid resolution, forecast hours and tools used for visualization of the output are described in the table.

Table 1: Description of JMA MRI storm surge model

Model	**2-dimentional ocean model, vertically integrated**
Coordinate	Lat/Lon Cartesian grid (Arakawa C-Grid)
Area	18.5 – 27°N, 86 – 94°E
Grid resolution	3.75 km x 3.75 km, 2 min mesh
Forecast Hours	48 hours
Calculation Run	4 times per day (6 hourly)
Pressure profile	Fujita (1952)
Visualization Tools	GrADS
Topographic data	Gebco 30 sec resolution

2.3 Data Used

For parametric simulation, the necessary cyclone track data, six hourly wind data and six hourly minimum sea level pressure data for Bhola cyclone (1970) were collected from Bangladesh Meteorological Department (BMD). The track data covers the cyclone's latitude, longitude, maximum sustained surface winds, and minimum sea level pressure at six hourly intervals.

2.4 Methodology

The selected storm surge case of Bhola cyclone (1970) was simulated in MRI model using parametric dataset. As central pressure is not precise but estimated, variations of estimated central pressure is used to simulate the storm surge for a better and more accurate representation of the meteorological event. To create the variability of Bhola cyclone estimated central pressure was changed for the same corresponding coordinates. The estimated central pressure was decreased by 5%, 10% and 15% and increased by 5% and then used as input data for simulation. Using these data, the model ran the simulation for 48 hours from 0000 UTC November 11, 1970 to 0000 UTC November 13, 1970. After simulation the results are visualized using Grid Analysis and Display System (GrADS). For each simulation of Bhola cyclone, maximum surge height and time-series variation of surge height at three different locations of the Bay of Bengal i.e., in the Meghna estuary (90.7° East, 22.8° North); near Hiron Point (89.5° East, 21.8° North); near Katka Sea Beach (89.8° East, 21.8° North) were observed in the study.

3. RESULTS AND DISCUSSION

3.1 Simulation of Bhola Cyclone and Variations of Bhola Cyclone

Bhola cyclone formed over the central Bay of Bengal on November 8 and traveled northward, intensifying as it did so. The storm intensified into a severe cyclonic storm on November 11, developing a clear eye and reaching its peak intensity later that day. The cyclone made landfall on the East Pakistan coastline during the evening of November 12, around the same time as the local high tide.

Simulation operations of Bhola cyclone and variations of Bhola cyclone in MRI model began from 11th November 0000 UTC. The model remained operational for the next 48 hours finishing the simulation on 13th November 0000

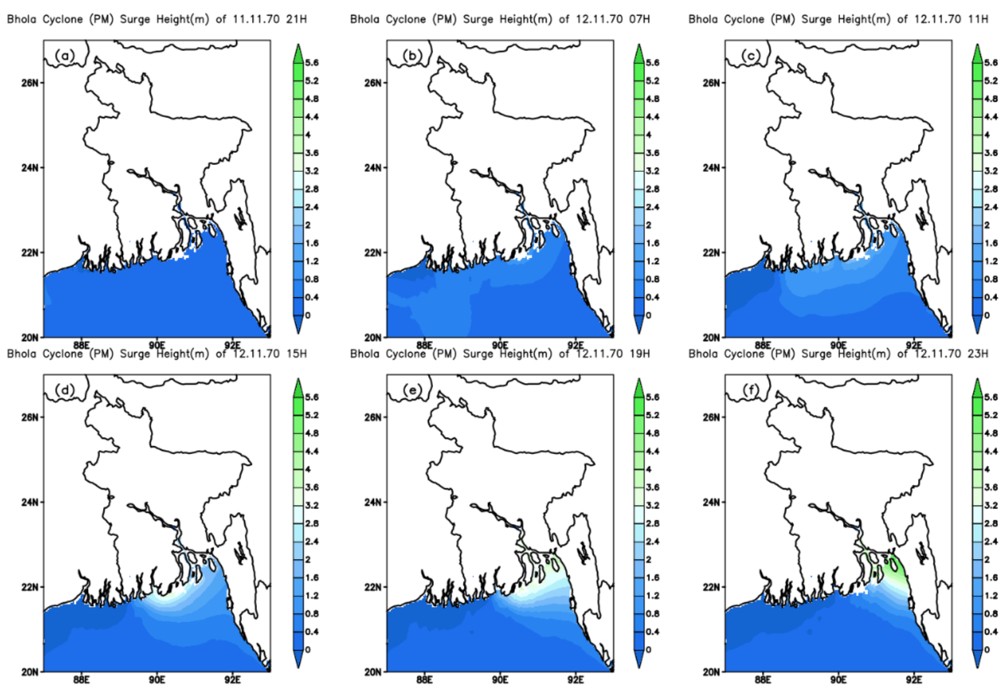

Figure 1: Simulated storm surge height (m) of Bhola cyclone on 11th and 12th November, 1970 (a) 11th November 2100 UTC; (b) 12th November 0700 UTC; (c) 12th November 1100 UTC; (d) 12th November 1500 UTC; (e) 12th November 1900 UTC; (f) 12th November 2300 UTC.

UTC. After simulation storm surge height and time series of storm surge are visualized using Grid Analysis and Display System (GrADS).

In case of simulation of Bhola cyclone using parametric data derived from track data, the MRI model generated maximum storm surge height of 5.4 meters. The model showed gradual increase in storm surge height as visualized in figure 1. Figure 1 displays the simulated storm surge height using parametric data for different moments in the tropical cyclone lifecycle. Height of the storm surge was relatively low during 11th November but it gradually increased in 12th November.

Figure 2 shows the simulated time series generated using parametric data at three different locations of the Bay of Bengal; in the Meghna estuary (90.7° East, 22.8° North); near Hiron Point (89.5° East, 21.8° North); and near Katka Sea Beach (89.8° East, 21.8° North). The maximum storm surge height computed by the model was 4.0 meters in the Meghna estuary, was 1.6 meters near Hiron Point and 2.7 meters near Katka Sea Beach.

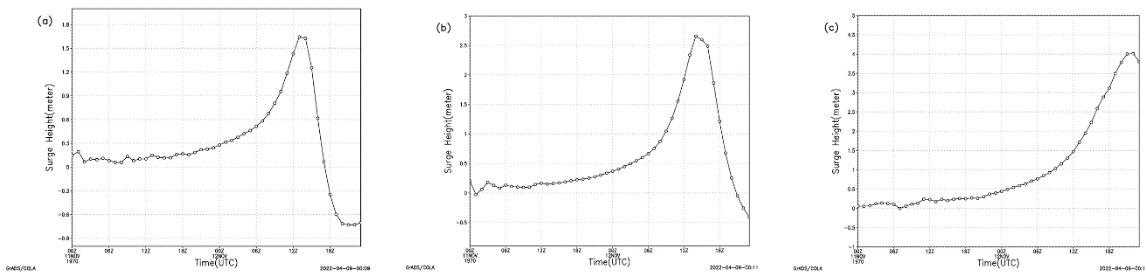

Figure 2: Time series of storm surge of Bhola cyclone on 11th and 12th November, 1970 (a) near Hiron Point (89.5° East, 21.8° North); (b) near Katka Sea Beach (89.8° East, 21.8° North); (c) in the Meghna estuary (90.7° East, 22.8° North).

Figure 3 displays the simulated storm surge height of 5% estimated central pressure decrease of Bhola cyclone at different moments in the tropical cyclone lifecycle. The model generated maximum surge height of 7.8 meters.

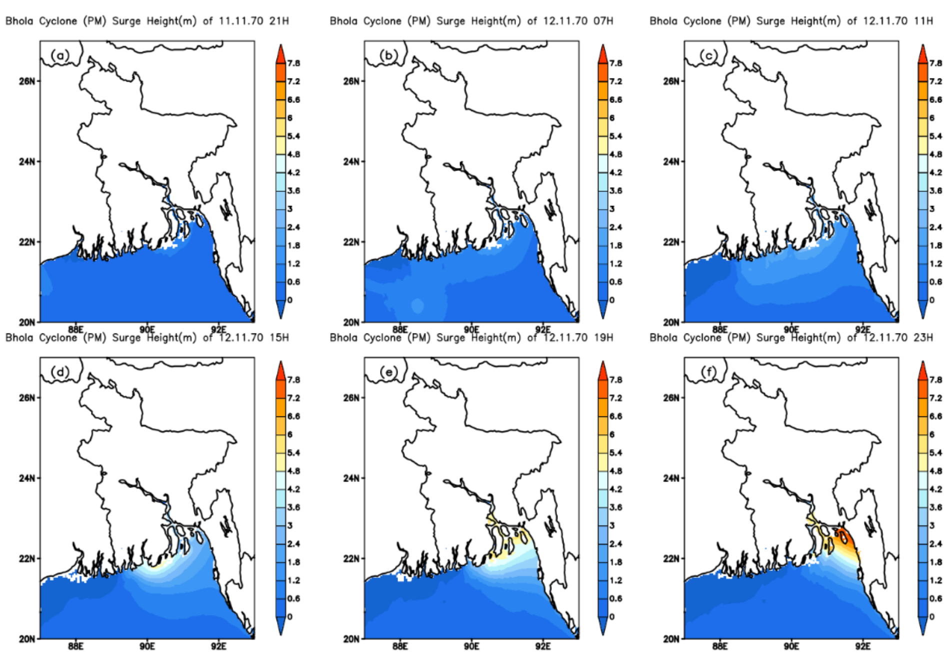

Figure 3: Simulated storm surge height (m) of 5% estimated central pressure decrease of Bhola cyclone on 11th and 12th November, 1970 (a) 11th November 2100 UTC; (b) 12th November 0700 UTC; (c) 12th November 1100 UTC; (d) 12th November 1500 UTC; (e) 12th November 1900 UTC; (f) 12th November 2300 UTC.

Figure 4 shows the simulated time series generated of 5% estimated central pressure decrease of Bhola cyclone at three different locations of the Bay of Bengal. The maximum storm surge height computed by the model was 5.9 meters in the Meghna estuary, was 2.5 meters near Hiron Point and 4.0 meters near Katka Sea Beach.

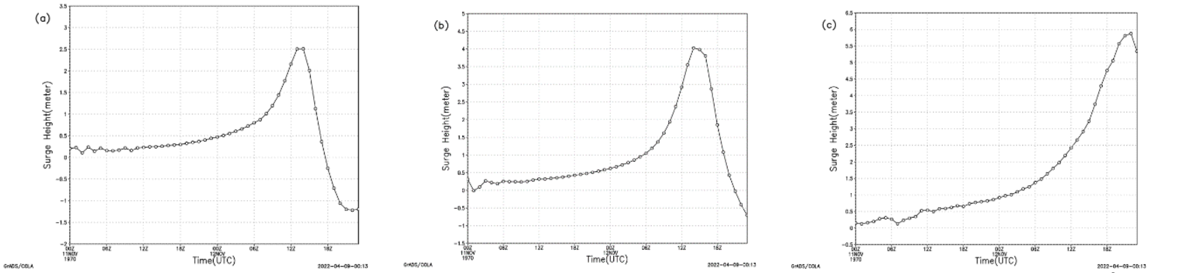

Figure 4: Time series of storm surge of 5% estimated central pressure decrease of Bhola cyclone on 11th and 12th November, 1970 (a) near Hiron Point (89.5° East, 21.8° North); (b) near Katka Sea Beach (89.8° East, 21.8° North); (c) in the Meghna estuary (90.7° East, 22.8° North).

Figure 5 displays the simulated storm surge height of 10% estimated central pressure decrease of Bhola cyclone at different moments in the tropical cyclone lifecycle. The model generated maximum storm surge height of 10.2 meters.

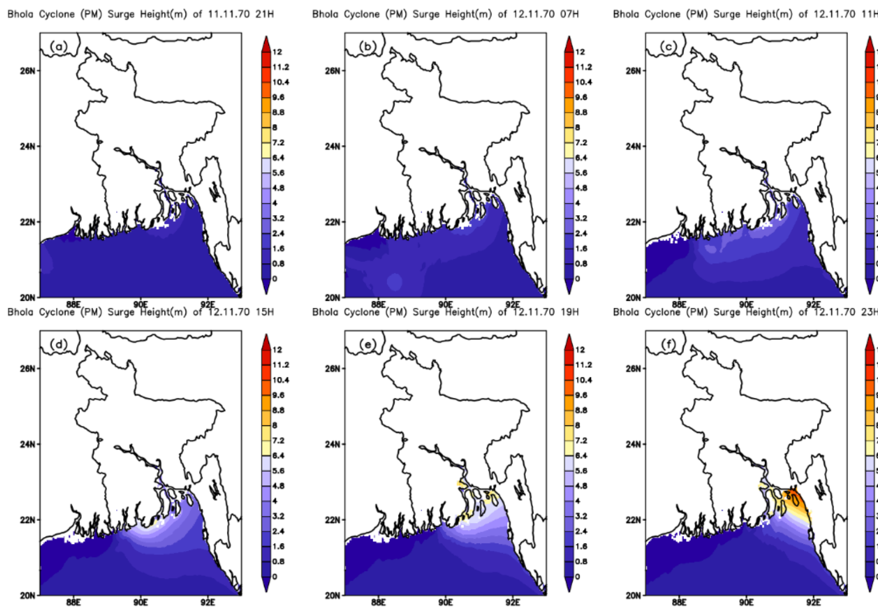

Figure 5: Simulated storm surge height (m) of 10% estimated central pressure decrease of Bhola cyclone on 11th and 12th November, 1970 (a) 11th November 2100 UTC; (b) 12th November 0700 UTC; (c) 12th November 1100 UTC; (d) 12th November 1500 UTC; (e) 12th November 1900 UTC; (f) 12th November 2300 UTC.

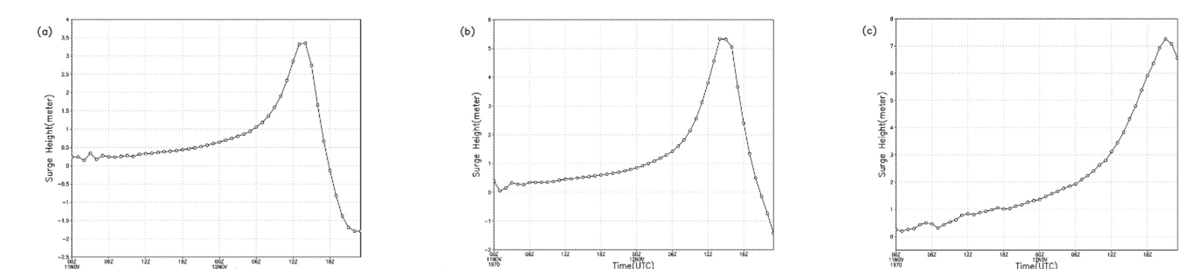

Figure 6: Time series of storm surge of 10% estimated central pressure decrease of Bhola cyclone on 11th and 12th November, 1970 (a) near Hiron Point (89.5° East, 21.8° North); (b) near Katka Sea Beach (89.8° East, 21.8° North); (c) in the Meghna estuary (90.7° East, 22.8° North).

Figure 6 shows the simulated time series generated of 10% estimated central pressure decrease of Bhola cyclone at three different locations of the Bay of Bengal. The maximum storm surge height computed by the model was 7.3 meters in the Meghna estuary, was 3.4 meters near Hiron Point and 5.4 meters near Katka Sea Beach.

Figure 7 displays the simulated storm surge height of 15% estimated central pressure decrease of Bhola cyclone at different moments in the tropical cyclone lifecycle. The model generated maximum storm surge height of 11.5 meters.

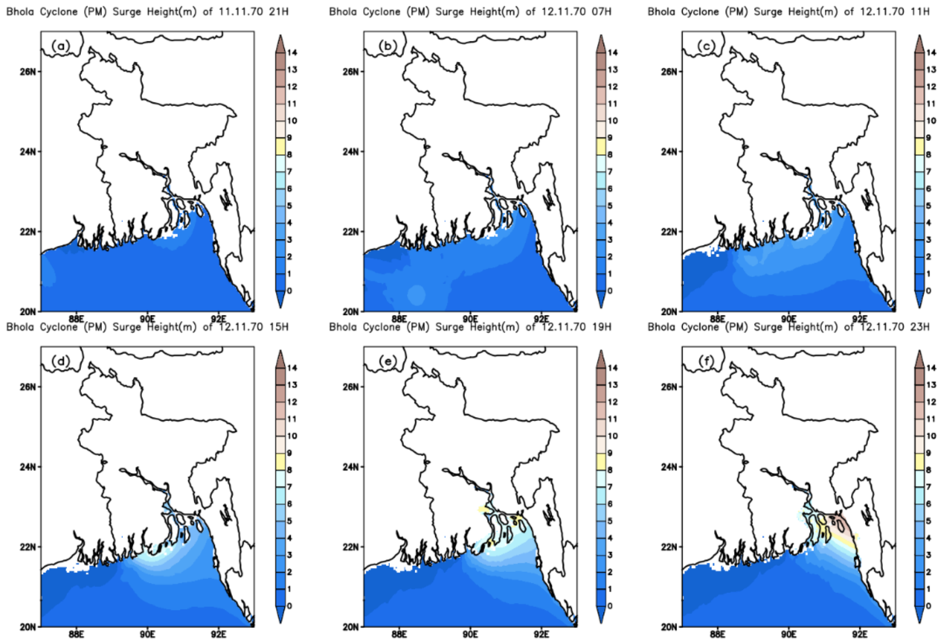

Figure 7: Simulated storm surge height (m) of 15% estimated central pressure decrease of Bhola cyclone on 11th and 12th November, 1970 (a) 11th November 2100 UTC; (b) 12th November 0700 UTC; (c) 12th November 1100 UTC; (d) 12th November 1500 UTC; (e) 12th November 1900 UTC; (f) 12th November 2300 UTC.

Figure 8 shows the simulated time series generated of 15% estimated central pressure decrease of Bhola cyclone at three different locations of the Bay of Bengal. The maximum storm surge height computed by the model was 8.3 meters in the Meghna estuary, was 4.3 meters near Hiron Point and 6.6 meters near Katka Sea Beach.

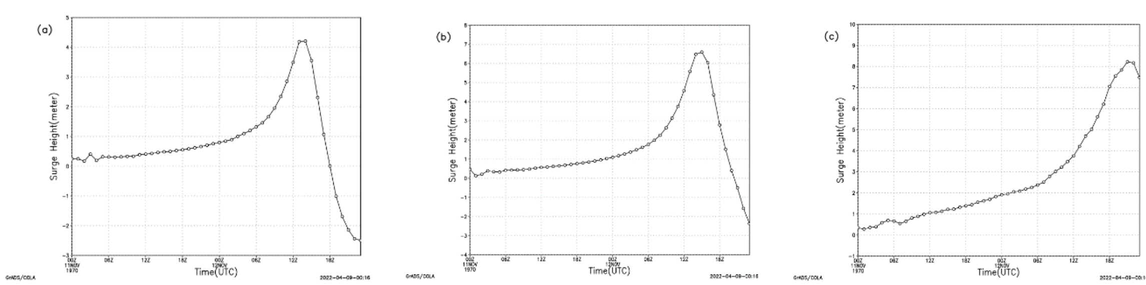

Figure 8: Time series of storm surge of 15% estimated central pressure decrease of Bhola cyclone on 11th and 12th November, 1970 (a) near Hiron Point (89.5° East, 21.8° North); (b) near Katka Sea Beach (89.8° East, 21.8° North); (c) in the Meghna estuary (90.7° East, 22.8° North).

3.2 Comparison of Simulation of Storm Surge

Maximum storm surge height of Bhola cyclone and variations of Bhola cyclone were generated by MRI model. Variations of Bhola cyclone were created by changing estimated central pressure. In addition, maximum storm surge height of three different locations for Bhola cyclone and all the variations of Bhola cyclone were also generated. In table 2 all the maximum storm surge height generated by MRI model from all the simulations are showcased.

The results show that increase in estimated central pressure decreases the maximum storm surge height. For storm surge to occur the central pressure needs to be less then standard sea level pressure (1013 hPa). the observation from the results also indicates that the further the decrease in central pressure the higher increase in maximum storm surge height. The gradual decrease in central pressure led to greater storm surge height. This validates the inverse barometer effect. 5% decrease of estimated central pressure led to increase in storm surge height of 2.4 meters or 44% increase of storm surge height in terms of percentage. 10% decrease of estimated central pressure led to increase in storm surge height of 4.8 meters or 89% increase of storm surge height in terms of percentage. 15% decrease of estimated central pressure led to increase in storm surge height of 6.1 meters or more than double the storm surge height. However, 5% increase of estimated central pressure led to decrease in storm surge height of 5.27 meters. As central pressure is always estimated, the central pressure of a cyclone will never be accurate. Therefore, in order to represent a more accurate maximum storm surge height generated by the MRI model variations of Bhola cyclone are simulated in the model. Also, these variations visualize the possible storm surge occurrence that would be caused by a similar cyclonic storm.

In case of tropical cyclone, maximum storm surge height occurs at the right side of a cyclone. The highest surge was generated on the southeast coast and in the Meghna estuary as shown by the results generated by the model. The storm surge height generated in the Meghna estuary was closest to the maximum storm surge height for each case simulated. In terms of comparison of surge height, Katka Sea Beach was found more than Hiron Point for each case as it is more exposed to the open sea.

Table 2: Maximum storm surge height generated by MRI model

Simulated Variations	Range of Estimated Central Pressure (in hPa)	Maximum Surge Height (in meters)	Maximum Surge Height near Hiron Point (89.5° East, 21.8° North) (in meters)	Maximum Surge Height near Katka Sea Beach (89.8° East, 21.8° North) (in meters)	Maximum Surge Height in the Meghna estuary (90.7° East, 22.8° North) (in meters)	Difference in Surge Height from Bhola cyclone
Bhola Cyclone	935 – 980	5.4	1.6	2.7	4.0	-
5% pressure decrease of Bhola Cyclone	888– 931	7.8	2.5	4.0	5.9	2.4 meters increased
10% pressure decrease of Bhola Cyclone	841– 882	10.2	3.4	5.4	7.3	4.8 meters increased
15% pressure decrease of Bhola Cyclone	833– 794	11.5	4.3	6.6	8.3	6.1 meters increased
5% pressure increase of Bhola Cyclone	981–1029	0.13	-	-	-	5.27 meters decreased

4. CONCLUSIONS

As Bhola cyclone is considered as one of the deadliest natural disasters in human history, a study on the intensity of its storm is necessary for future reference. Using MRI storm surge model the intensity of Bhola cyclone and variations of Bhola cyclone were produced. For the parametric input data, prediction in the MRI model depends largely on the data accuracy. To achieve higher accuracy, accurate information of cyclones track data especially coordinate, central pressure is required. The other four simulations were carried out to forecast storm surge levels for higher and lower intensities of tropical cyclones. The results exhibit the inverse barometer effect, with decreasing central pressure leads to increased storm surge height.

However, the model does not visualize proper inundation due to a lack of high-resolution Digital Elevation Modelling (DEM) data. In addition due to lack of accurate data for Bhola cyclone track data used for simulation can be considered close to the actual event and not same as actual event. In general, if there is a break in the coast, such as a river, it provides an additional path to the water to escape into the river, instead of getting piled up. MRI model does not take into account the effect of river discharge which communicates with the Bay of Bengal. However, the discharge of the fresh water carried by the one of the world's largest river systems (Ganga-Brahmaputra Meghna) joins the Bay of Bengal may modify the surge height along the Bangladesh coast.

The impact of climate change and a possible sea-level rise and changes in the frequency and intensity of storms may change flooding risks from storm surges, especially in the low lying areas of Bangladesh. However, this study still shows the importance of simulation of historical events using MRI model. Further research would complement the MRI model and increase its viability as a forecasting model for storm surge.

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