Simulating Storm Surge of Tropical Cyclone "Bulbul" using MRI Model

Quazi Aseer Faisal[1*], Muhammad Arif Hossain[2], S. M. Quamrul Hassan[2]
Towhida Rashid[1] and Javed Meandad[1]
[1]*Department of Meteorology, University of Dhaka, Dhaka, Bangladesh*
[2]*Bangladesh Meteorological Department, Dhaka, Bangladesh*
[*]*e-mail address: quaziaseer-2nd-2018510805@met.du.ac.bd*

Abstract

Cyclone Bulbul, a strong and damaging tropical cyclone, struck Bangladesh in November 2019, causing storm surge, heavy rains, and flash floods which resulted in heavy damage to buildings and farmlands in the coastal area. An attempt has been made in this study, to use MRI storm surge model for simulation of storm surge of cyclone Bulbul (November 2019) to see its effectiveness. The event was simulated in the model for 48-hours using parametric data set and two NWP model datasets which are, European Centre for Medium-Range Weather Forecasts (ECMWF) data and Global Spectral Model (GSM) data. Simulated storm surge heights found from the MRI storm surge model are compared with the reported surge height from Bangladesh Inland Water Transport Authority (BIWTA) and Bangladesh Meteorological Department (BMD). The maximum storm surge height simulated by the model are of 1.8m for parametric data, 2.0m for ECMWF data and 1.5m for GSM data. Comparison of the maximum storm surge height for cyclone Bulbul shows simulated data for all data sets were close to the reported data and the difference are well within the margin of error.

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

1. Introduction

The coastal region of Bangladesh is extremely vulnerable to cyclonic storm surge floods. Three major factors can be attributed to the vulnerability, which are the location of Bangladesh coast being in the path of tropical cyclones, the wide and shallow continental shelf and the funneling shape of the coastal area [1]. This region is also frequently affected by tropical cyclone associated storm surge Bangladesh as coast is located in the tropical part of the world. According to statistics of different researches, about 7% of the creation of global tropical cyclone develops over this region and Bangladesh accepts approximately 40% of the blow of total storm surges in the world [2]. Every year the coastal population of Bangladesh experiences huge loss of life and damage of property caused mainly by storm surges.

To understand the process of storm surge several research has been conducted throughout the years. Many of these researches tried to develop a system for prediction of storm surge disasters with the goal being to reduce the possible effect of storm surge disaster with proper management. To understand the process of occurrence of storm surge various numerical weather models were developed with the advancement in technology. As Bangladesh is highly susceptible to storm surges many research focused on the coastal region of Bangladesh. Various numerical models were also used in this research.

As-Salek detected negative surges in the Meghna estuary and the duration was about 4-6 h [3]. These negative surges reduce the connections of maritime aquaculture and show extraordinary sensitivity to the astrological tides and to the circulation track of a cyclonic storm in the region. Debsarma calculated time sequence of storm surges due to different cyclones and a 3D vision of the highest surges has also been completed through landfall. He simulated storm surges due to 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]. Higaki *et al.* have developed the outline of the storm surge prediction model at the Japan Meteorological Agency (JMA). They used the model to simulate storm surge that occurred in the coast of Japan [5]. Mallik *et al.* used the Weather Research and Forecast Model (WRF) model and Meteorological Research Institute (MRI) model to simulate the landfall and storm surge of Cyclone Viyaru [6]. Paul *et al.* transformed the vertically integrated shallow water equations (SWEs) in Cartesian coordinates into ordinary differential equations (ODEs) of initial valued, which were then solved using the new RKARMS (4, 4) method which they used to simulate storm surge in the Meghna estuarine area [7]. Ali *et al.* studied the storm surge event of cyclone Aila by simulating data from WRF model for cyclone Aila and simulated storm surge for the cyclone using MRI model [8]. Again in 2019 Ali *et al.* used the WRF model to simulate cyclone Roanu and simulated storm surge for the cyclone using MRI model to compare with the observed surge height data [9]. Sinha *et al.* developed numerical model for in the Indian coasts adjacent to the Bay of Bengal and the Arabian Sea [10]. Mohit *et al.* used the MRI model to simulate storm surge for tropical cyclone activity for prediction of future intensity of tropical cyclone [11]. Hossain *et al.* simulated the storm surge of cyclone Roanu using MRI model [12]. Abdullah simulated the storm surge of three cyclones in Bay of Bengal using MRI model [13].

In this study, Meteorological Research Institute (MRI) storm surge model from Japan Meteorological Agency (JMA) is used to simulate storm surge of cyclone Bulbul (November 2019) with parametric data, European Centre for Medium-Range Weather Forecasts (ECMWF) data and Global Spectral Model (GSM) data as input. The objective of the study is to understand the effectiveness of the MRI model for more accurate storm surge forecasting.

2. Model Experimental Set-up, Data Used and Methodology

2.1 MRI Storm Surge Model: MRI storm surge model was technologically advanced at the Meteorological Research Institute (MRI) of JMA. It was originally developed for being used in local observations. For local observatory use, 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
- Wind set up

The new version also takes into account the wet and dry process for inundation approximation [14]. The model assumes tidal level as a constant parameter adding surges with a linear relation. Visualization of tidal components at some grid point is also an option. The results from the model output can be sent to various local meteorological stations that issue warnings of storm surge to their respective zones of responsibility. The information regarding the period and level of water of probable maximum surges are included in the warnings in the concerned area. This model can work in any regions of the world with suitable set of bathymetry data and meteorological imposing fields [15].

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

Momentum equations

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

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

$\boldsymbol{\zeta}$ = height deviation

$\boldsymbol{\zeta_0}$ = balance level with surface pressure

$\boldsymbol{\rho_w}$ = sea water density

$\boldsymbol{f}$ = Coriolis parameter

$\boldsymbol{g}$ = gravitational acceleration

$\boldsymbol{\tau_a}$ = (τ_{ax}, τ_{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 functions of the model including profile, selected area and importantly tools that are used to visualize the output. The experimental model domain for the present study ranges from 86.0°E to 94.0°E along the longitudes and from 18.0°N to 24.0°N along the latitude.

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	8.5 – 23.5°N, 80 – 100°E
Grid resolution	3.75 km x 3.75 km
Forcing Data	GSMGPV (25km) ECMWF (25 km)
Pressure profile	Fujita
Visualization Tools	GrADS
Topographic data	GEBCO 3 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 Cyclone Bulbul (2019) were collected from Bangladesh Meteorological Department (BMD) and from the Regional Specialized Meteorological Centre (RSMC) New Delhi which is found from the satellite and radar images and surface synoptic investigation. The finest track data were also used as it covers the cyclone's latitude, longitude, maximum sustained surface winds, and minimum sea level pressure at six hourly intervals.

European Centre for Medium-Range Weather Forecasts (ECMWF) are both a research institute and a 24/7 operational service, producing global numerical weather predictions and meteorological data. The Centre has one of the largest supercomputer facilities and meteorological data archives in the world. European Centre for Medium-Range Weather Forecasts (ECMWF) data were collected from Bangladesh Meteorological Department (BMD) for the selected cyclone Bulbul (2019). The resolution of the downloaded data is 0.25 degree.

Global Spectral Model (GSM) employs the primitive equations to express the resolvable motions and states of the atmosphere. It also includes sophisticated parameterization schemes for physical processes. GSM has been constructed on the framework of semi-implicit semi-Lagrangian global model. Three hourly Global Spectral Model (GSM) surface data of 0.25 degree resolution for 48 hours were downloaded from Japan Meteorological Agency (JMA) WIS server by BMD. This data was provided by Bangladesh Meteorological Department (BMD) for the selected cyclone Bulbul (2019).

The reported maximum storm surge height data for cyclone Bulbul (November 2019) are collected from Bangladesh Meteorological Department (BMD and from Bangladesh Inland Water Transport Authority (BIWTA).

2.4 Methodology

The selected storm surge case of cyclone Bulbul (2019) is simulated for 48-hours in MRI model using all three datasets. The simulated output is visualized using Grid Analysis and Display System (GrADS). Three parameters are selected from the simulated output for visualization. They are height of the Storm Surge (in meter), mean Sea level Pressure (MSLP) (in hectopascal) and wind (Both speed and direction of zonal and meridional wind) (in meter/second). All three simulated storm surge height data of cyclone Bulbul (2019) is compared with the BIWTA observed data and a time series is developed using python. A comparison graph of maximum storm surge height for all the events with reported data of Bangladesh Meteorological Department (BMD) are also prepared.

3. Results and Discussion

3.1 Cyclone Bulbul

Simulation operations of cyclone Bulbul in MRI model using all three datasets begin from 8th November 0000 UTC. The model remained operational for the next 48 hours finishing the simulation on 9th November 2359 UTC. Figure 1 shows the simulated storm surge height using NWP-ECMWF model data where the surge height increased gradually to 2.2 m near the shore at around 22°N Latitude and 92°E Longitude coordinates at 9th November 1200 UTC. Height of the storm surge was relatively low during 8th November but it gradually increased in 9th November.

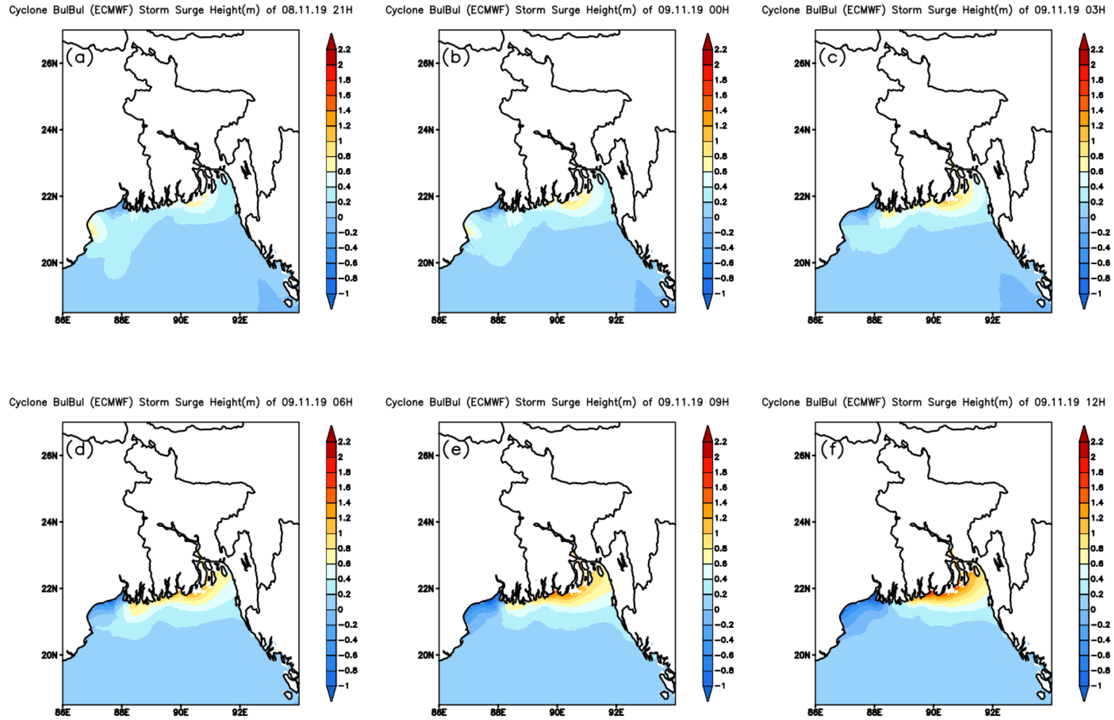

Figure 1: Simulated storm surge height (m) of Cyclone Bulbul (NWP-ECMWF data) on 8th and 9th November, 2019 (a) 8th November 2100 UTC; (b) 9th November 0000 UTC; (c) 9th November 0300 UTC; (d) 9th November 0600 UTC; (e) 9th November 0900 UTC; (f) 9th November 1200 UTC.

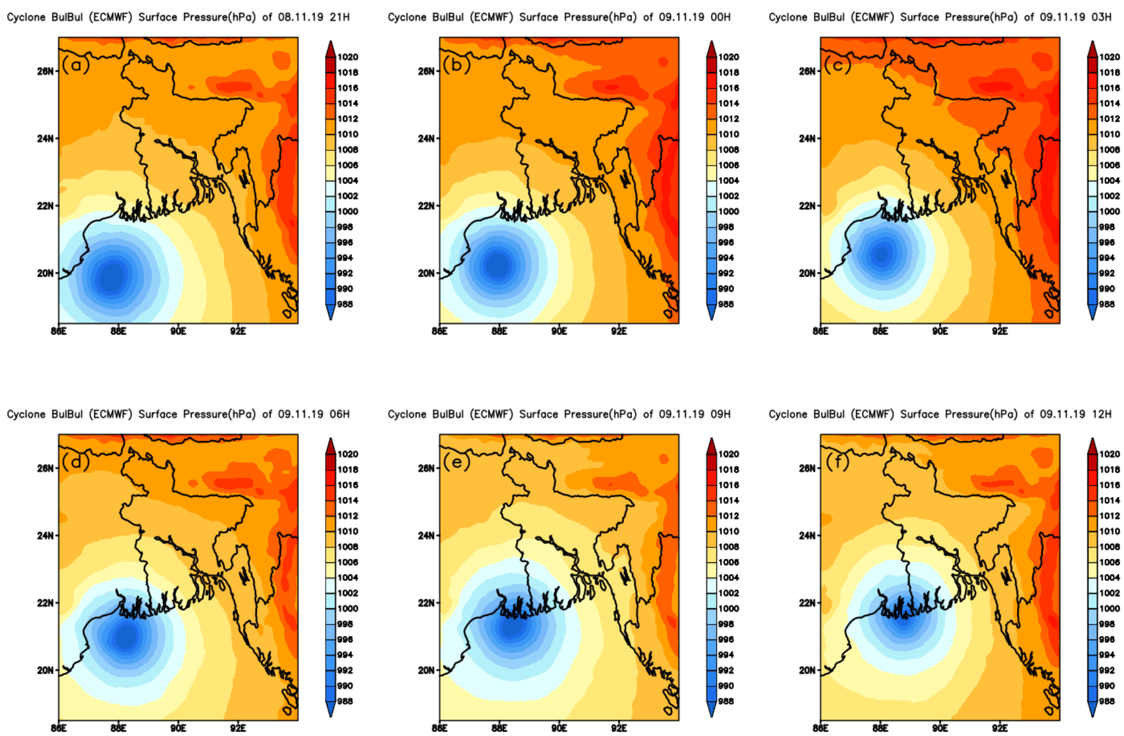

Figure 2: Simulated mean sea level pressure (hPa) of Cyclone Bulbul (NWP-ECMWF data) on 8th and 9th November, 2019 (a) 8th November 2100 UTC; (b) 9th November 0000 UTC; (c) 9th November 0300 UTC; (d) 9th November 0600 UTC; (e) 9th November 0900 UTC; (f) 9th November 1200 UTC.

Figure 2 shows the simulated mean sea level pressure using NWP-ECMWF model data where minimum pressure decreased to 988 hPa, with the low-pressure center moving to the shore indicating the landfall of the cyclone.

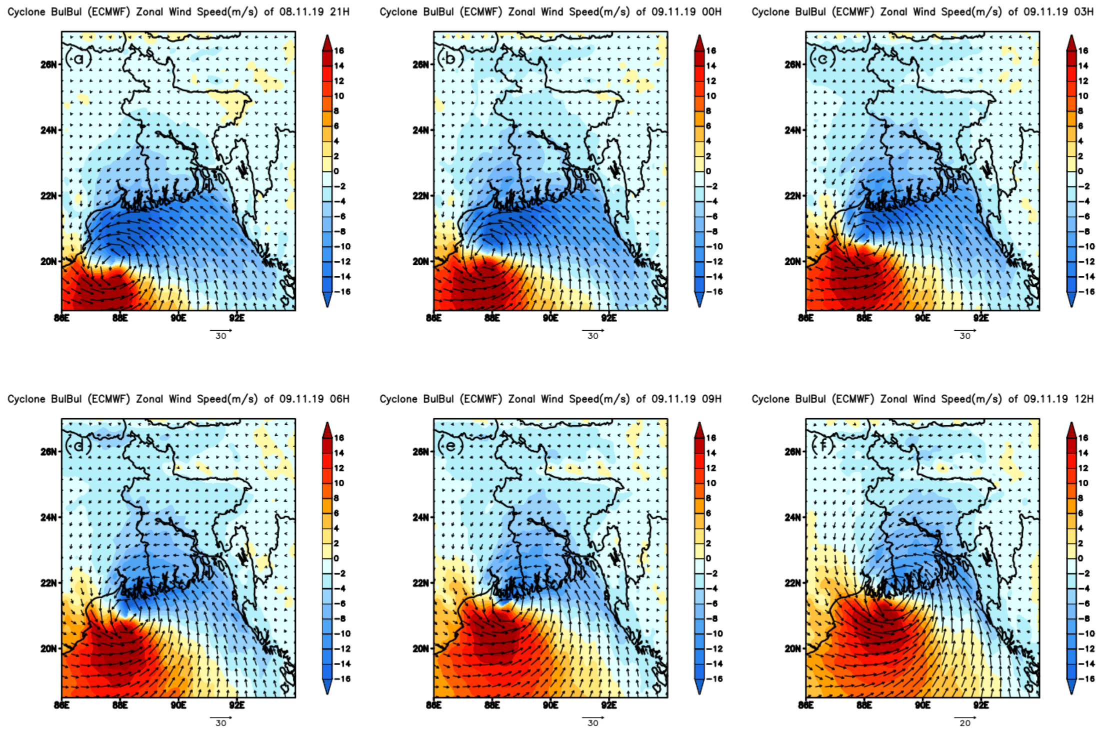

Figure 3: Simulated zonal wind speed (m/s) of Cyclone Bulbul (NWP-ECMWF data) on 8th and 9th November, 2019 (a) 8th November 2100 UTC; (b) 9th November 0000 UTC; (c) 9th November 0300 UTC; (d) 9th November 0600 UTC; (e) 9th November 0900 UTC; (f) 9th November 1200 UTC.

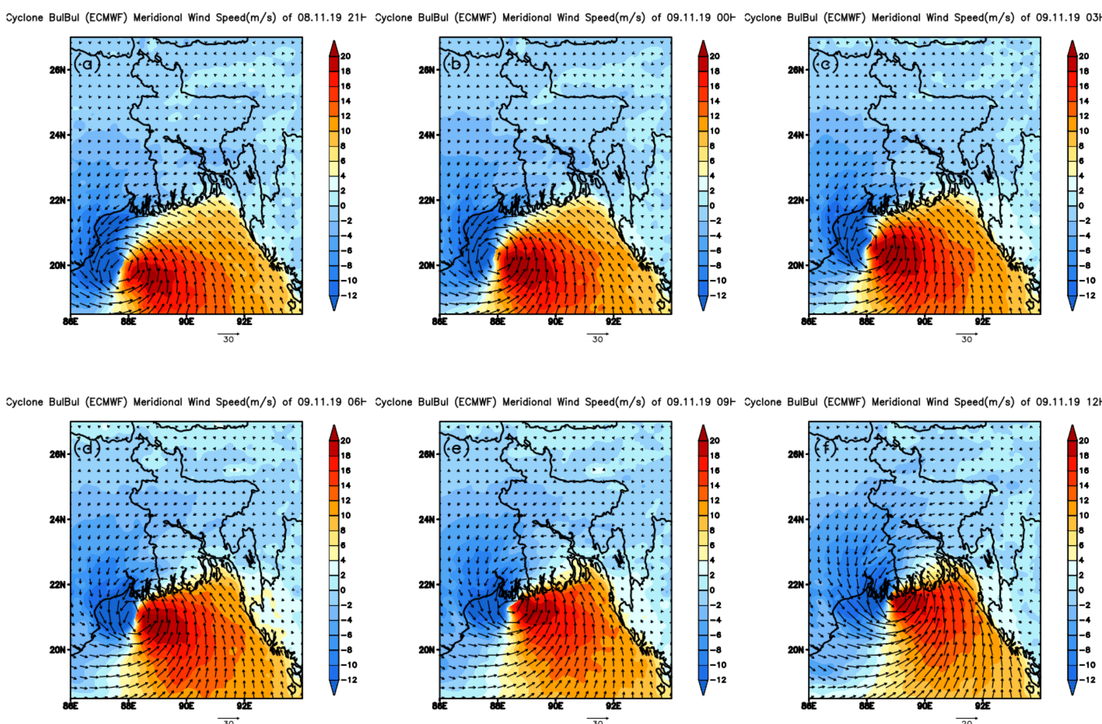

Figure 4: Simulated meridional wind speed (m/s) of Cyclone Bulbul (NWP-ECMWF data) on 8th and 9th November, 2019 (a) 8th November 2100 UTC; (b) 9th November 0000 UTC; (c) 9th November 0300 UTC; (d) 9th November 0600 UTC; (e) 9th November 0900 UTC; (f) 9th November 1200 UTC.

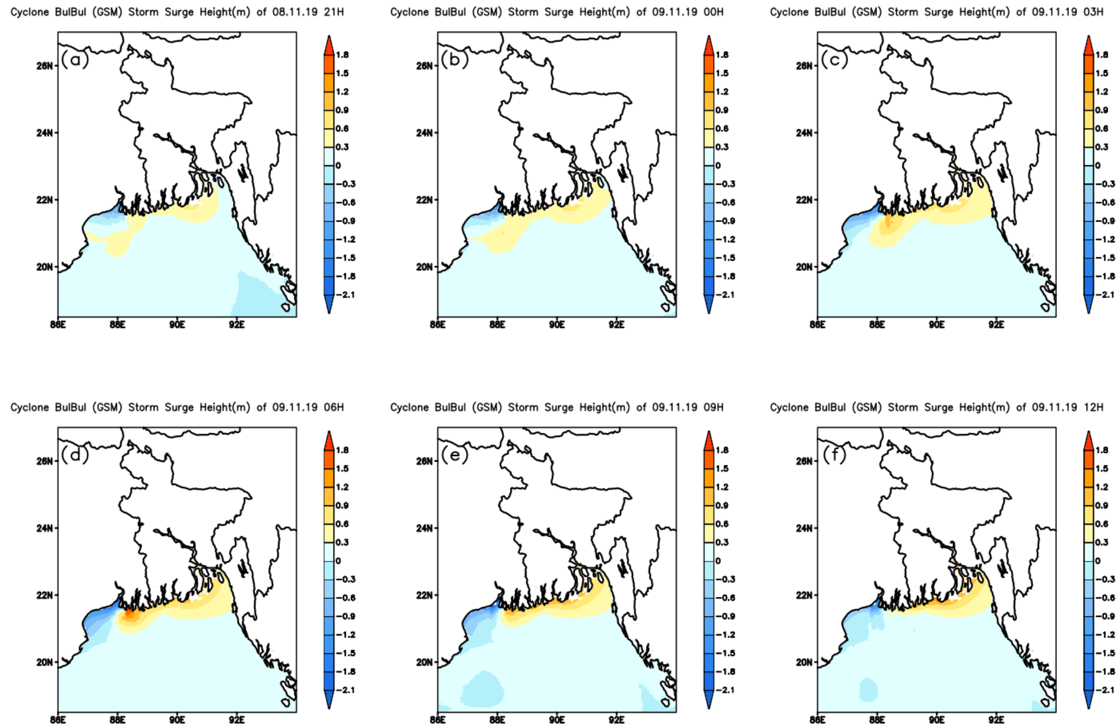

Figure 5: Simulated storm surge height (m) of Cyclone Bulbul (NWP-GSM data) on 8th and 9th November, 2019 (a) 8th November 2100 UTC; (b) 9th November 0000 UTC; (c) 9th November 0300 UTC; (d) 9th November 0600 UTC; (e) 9th November 0900 UTC; (f) 9th November 1200 UTC.

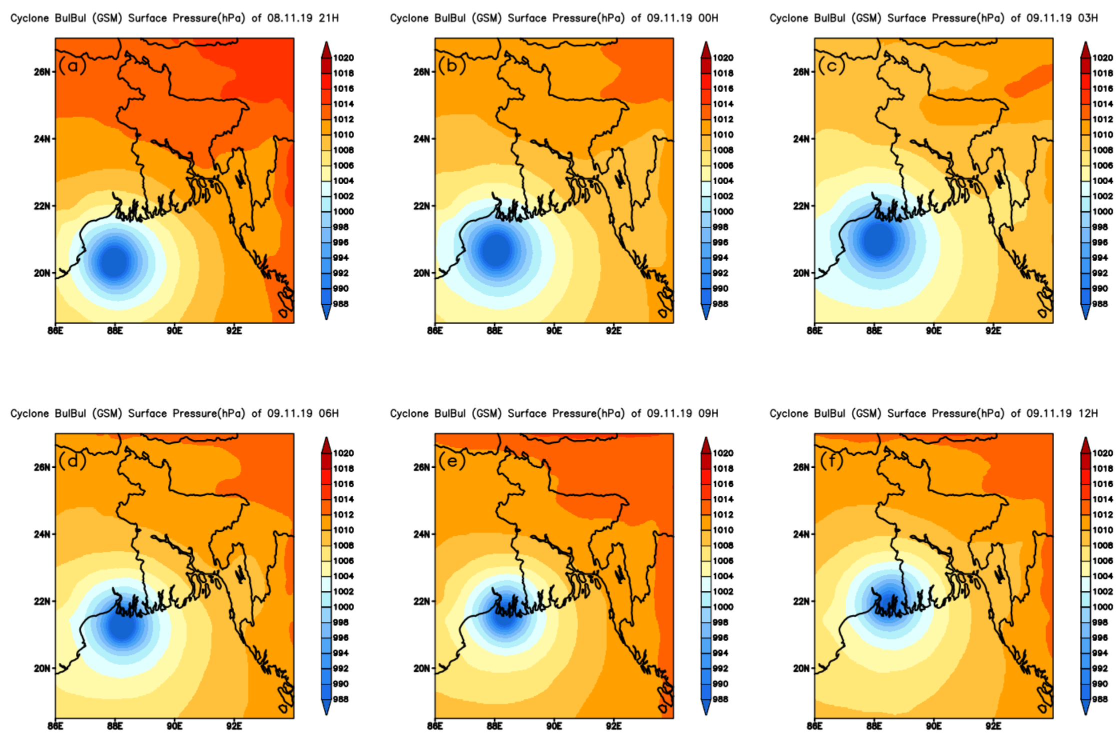

Figure 6: Simulated mean sea level pressure (hPa) of Cyclone Bulbul (NWP-GSM data) on 8th and 9th November, 2019 (a) 8th November 2100 UTC; (b) 9th November 0000 UTC; (c) 9th November 0300 UTC; (d) 9th November 0600 UTC; (e) 9th November 0900 UTC; (f) 9th November 1200 UTC.

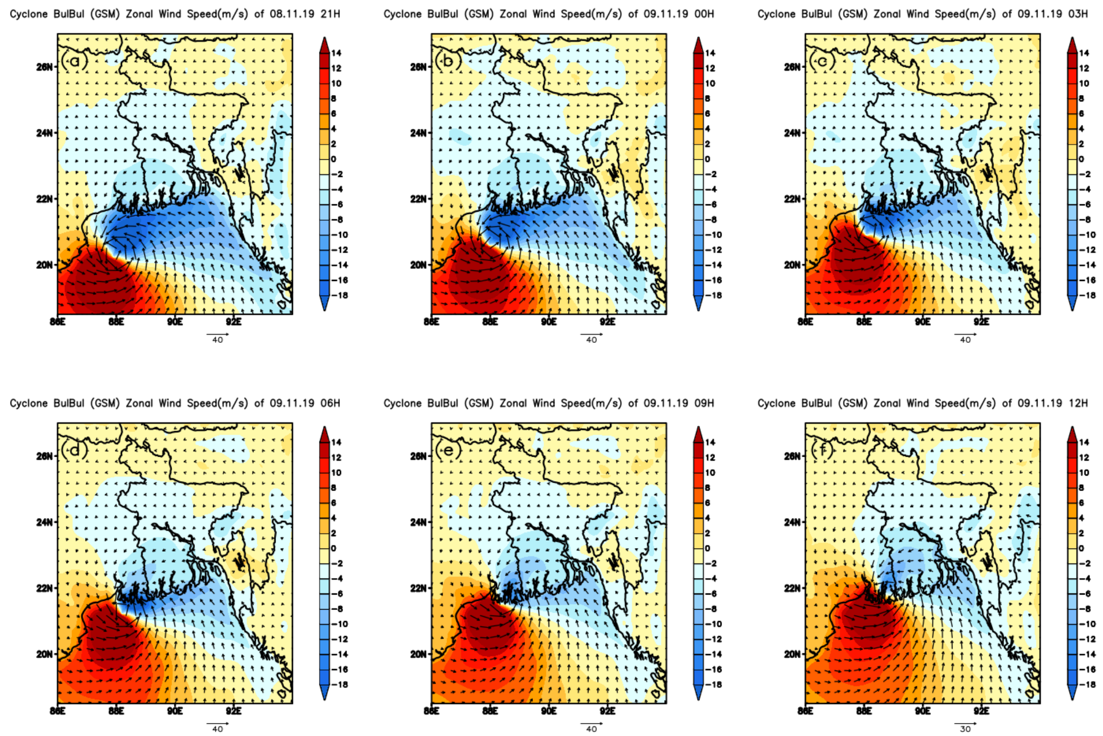

Figure 7: Simulated zonal wind speed (m/s) of Cyclone Bulbul (NWP-GSM data) on 8th and 9th November, 2019 (a) 8th November 2100 UTC; (b) 9th November 0000 UTC; (c) 9th November 0300 UTC; (d) 9th November 0600 UTC; (e) 9th November 0900 UTC; (f) 9th November 1200 UTC.

Figure 3 shows the simulated zonal wind speed and wind direction using NWP-ECMWF model data where the wind speed was close to 30 m/s. The wind directions showed circular motion moving gradually towards the coast with the center of the circular motion hitting the land at 22°N Latitude and 90°E Longitude coordinates at 9th November 1200 UTC which is close to the spot where the highest surge height is.

Figure 4 shows the simulated meridional wind speed and wind direction using NWP-ECMWF model data where the wind speed was around 30 m/s. The wind directions are in opposite directions to zonal wind speed. However, they show similar characteristics to zonal wind speed.

Figure 5 shows the simulated storm surge height using NWP-GSM model data where the surge height increased gradually. This simulated output showed less rapid increase in surge height Figure 5(f) shows surge height increasing to 1.8 m near the shore at around 22°N Latitude and 92°E Longitude coordinates at 9th November 1200 UTC.

Figure 6 shows the simulated mean sea level pressure using NWP-GSM model data where minimum pressure decreased to 988 hPa, with the low-pressure center moving to the shore indicating the landfall of the cyclone.

Figure 7 shows the simulated zonal wind speed and wind direction using NWP-ECMWF model data where the wind speed was 40 m/s. This simulation showed relatively higher wind speed with prominent circular motion compared to other simulated output. The wind directions showed circular motion moving gradually towards the coast with the center of the circular motion hitting the land at 22°N Latitude and 90°E Longitude coordinates at 9th November 1200 UTC which is close to the spot where the highest surge height is.

Figure 8 shows the simulated meridional wind speed and wind direction using NWP-ECMWF model data where the wind speed was 40 m/s. This simulation showed relatively higher wind speed with prominent circular motion compared to other simulated output. The wind directions are in opposite directions to zonal wind speed. However, they show similar characteristics to zonal wind speed.

Figure 9 shows the simulated storm surge height using parametric data where the surge height increased gradually. Figure 5(f) shows surge height increasing to 1.8 m near the shore at around 22°N Latitude and 92°E Longitude coordinates at 9th November 1200 UTC.

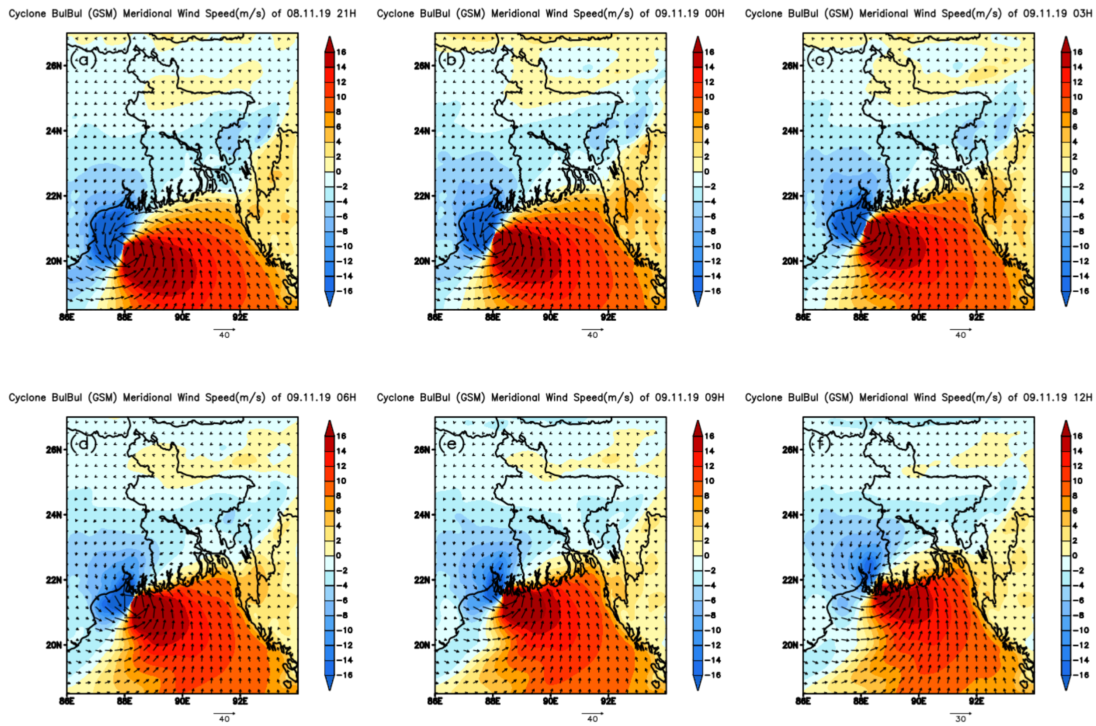

Figure 8: Simulated meridional wind speed (m/s) of Cyclone Bulbul (NWP-GSM data) on 8th and 9th November, 2019 (a) 8th November 2100 UTC; (b) 9th November 0000 UTC; (c) 9th November 0300 UTC; (d) 9th November 0600 UTC; (e) 9th November 0900 UTC; (f) 9th November 1200 UTC.

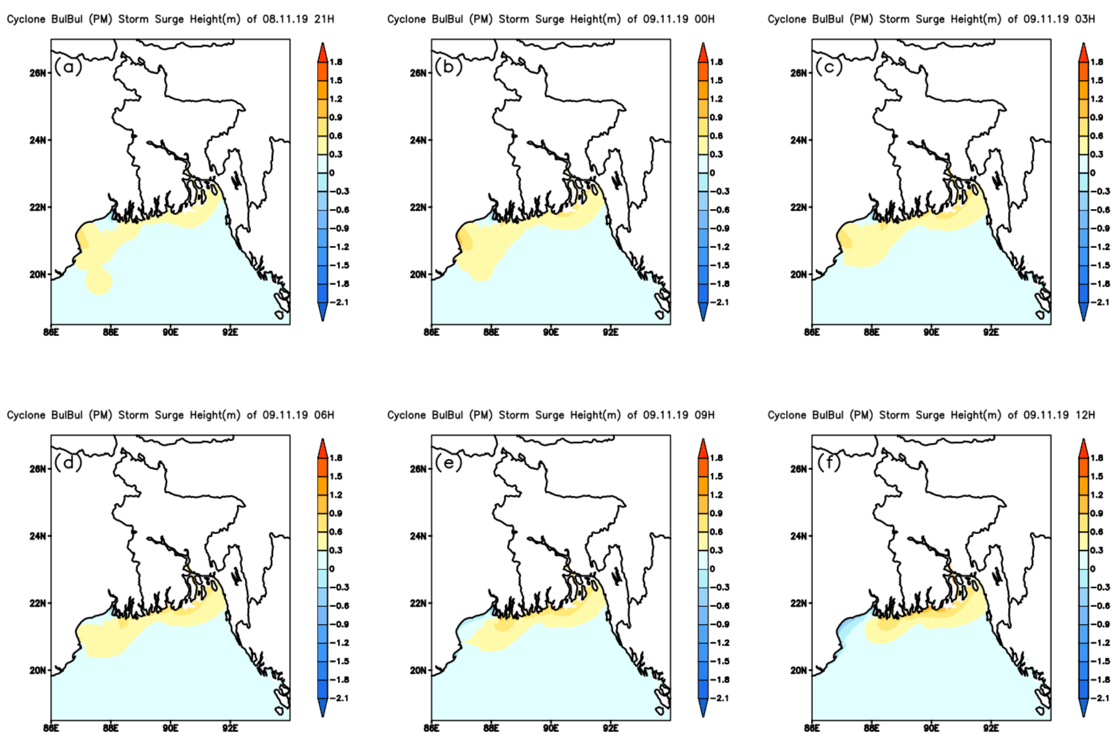

Figure 9: Simulated storm surge height (m) of Cyclone Bulbul (Parametric data) on 8th and 9th November, 2019 (a) 8th November 2100 UTC; (b) 9th November 0000 UTC; (c) 9th November 0300 UTC; (d) 9th November 0600 UTC; (e) 9th November 0900 UTC; (f) 9th November 1200 UTC.

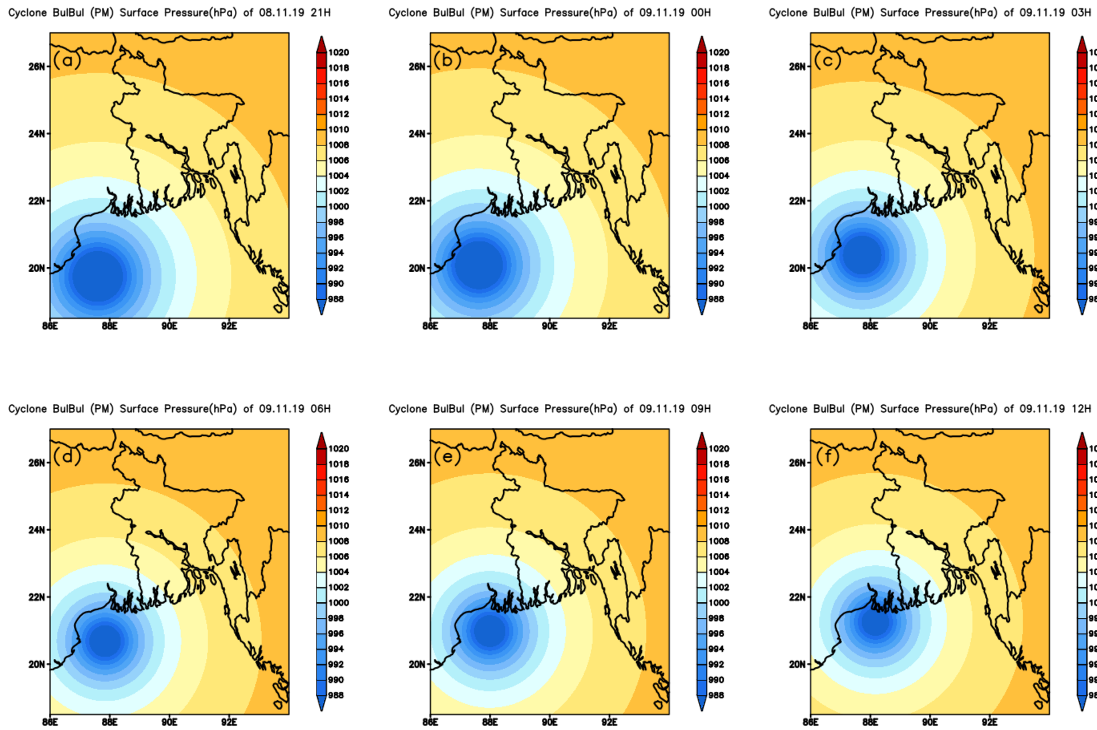

Figure 10: Simulated mean sea level pressure (hPa) of Cyclone Bulbul (Parametric data) on 8th and 9th November, 2019 (a) 8th November 2100 UTC; (b) 9th November 0000 UTC; (c) 9th November 0300 UTC; (d) 9th November 0600 UTC; (e) 9th November 0900 UTC; (f) 9th November 1200 UTC.

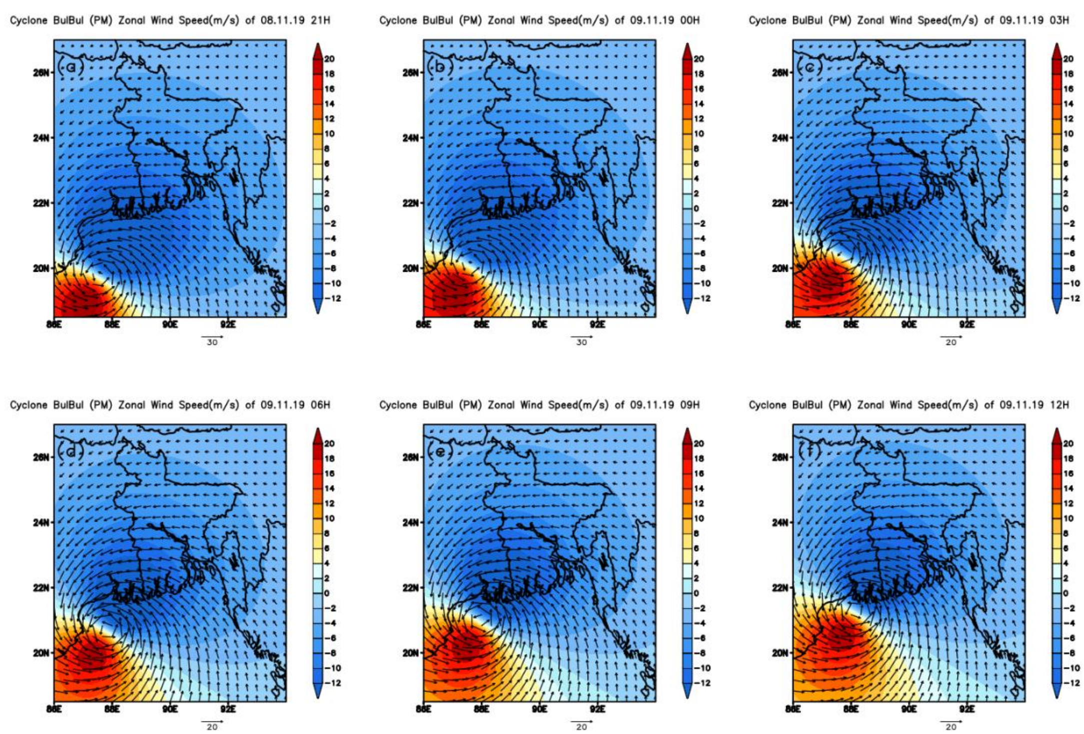

Figure 11: Simulated zonal wind speed (m/s) of Cyclone Bulbul (Parametric data) on 8th and 9th November, 2019 (a) 8th November 2100 UTC; (b) 9th November 0000 UTC; (c) 9th November 0300 UTC; (d) 9th November 0600 UTC; (e) 9th November 0900 UTC; (f) 9th November 1200 UTC.

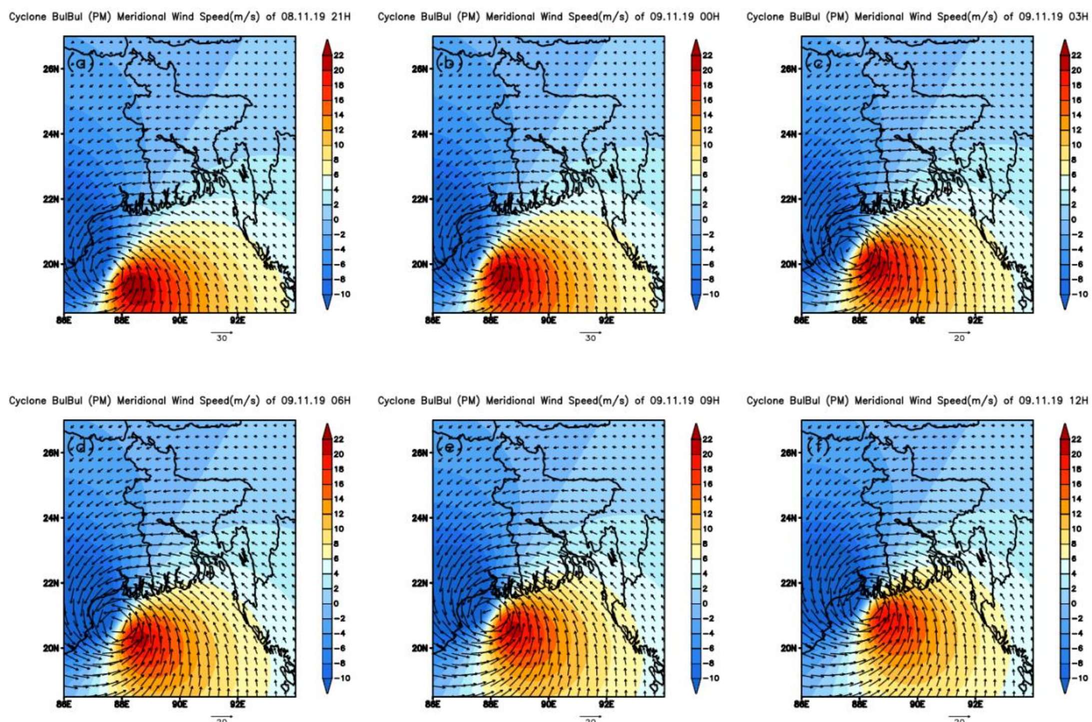

Figure 12: Simulated meridional wind speed (m/s) of Cyclone Bulbul (Parametric data) on 8th and 9th November, 2019 (a) 8th November 2100 UTC; (b) 9th November 0000 UTC; (c) 9th November 0300 UTC; (d) 9th November 0600 UTC; (e) 9th November 0900 UTC; (f) 9th November 1200 UTC.

Figure 10 shows the simulated mean sea level pressure using parametric data where minimum pressure decreased to 988 hPa, with the low-pressure center moving to the shore indicating the landfall of the cyclone.

Figure 11 shows the simulated zonal wind speed and wind direction using parametric data where the wind speed was close to 20 m/s. This simulation showed relatively lower wind speed compared to other simulated output. The wind directions show circular motion moving gradually towards the coast with the center of the circular motion hitting the land at 22°N Latitude and 90°E Longitude coordinates at 9th November 1200 UTC which is close to the spot where the highest surge height is.

Figure 12 shows the simulated meridional wind speed and wind direction using parametric data where the wind speed was around 20 m/s. This simulation showed relatively lower wind speed compared to other simulated output. The wind directions are in opposite directions to zonal wind speed. However, they show similar characteristics to zonal wind speed.

3.2 Comparison of Simulation of storm surge

Simulated results of storm surge height from all the datasets for cyclone Bulbul were compared with observed data and a time series graph was developed using python. Figure 13 shows the time series graph of observed values and simulated values for storm surge height of cyclone Bulbul for a specific location with the coordinates being 21.8°N Latitude and 90.1°E Longitude.

The observed data was collected from Bangladesh Inland Water Transport Authority (BIWTA). BIWTA measured the height using datum points with mean sea level as the base. The simulated values come from NWP-ECMWF model data, NWP-GSM model data and parametric data. The Figure 13 shows that the observed values have more of a sinusoidal curve due to high tide and low tide while the simulated values are straighter lines as the model doesn’t consider astronomical tide value. From the figure it is apparent that the simulated storm surge height of NWP-ECMWF data is closer to the peak of the observed data, the result from parametric data simulation is higher than NWP-GSM model data which is the lowest.

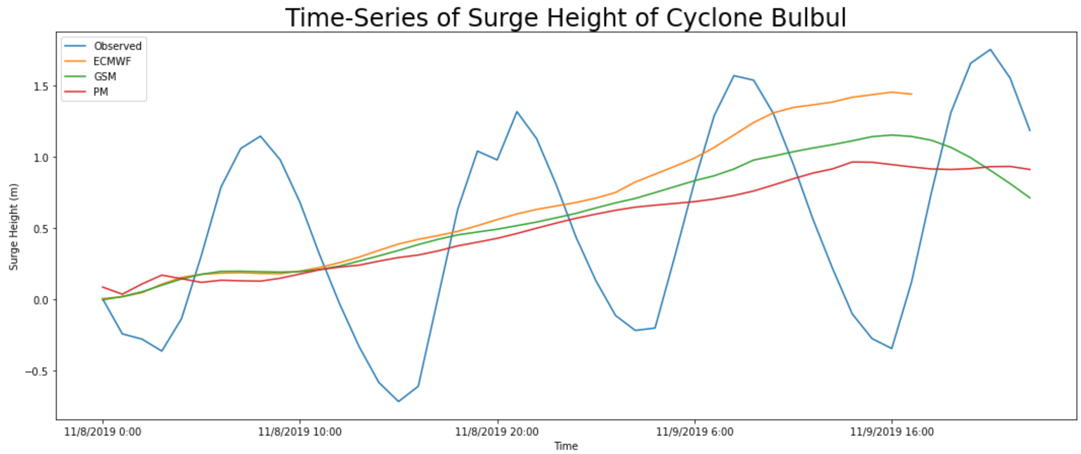

Figure 13: Comparative Time Series Graph of Observed and Simulated Data for Storm Surge Height of Cyclone Bulbul Using Python.

Table 2 includes the reported maximum storm surge height data of BMD and the simulated maximum storm surge height data of the three datasets for cyclone Bulbul. BMD collected the reported maximum storm surge height data from the local newspaper.

Table 2: Comparison of maximum surge height between simulated data and reported data for cyclone Bulbul.

Event	Maximum Surge Height (m)			
	Model			Reported data
	NWP-ECMWF data	NWP-GSM data	Parametric Data	
Cyclone Bulbul	2.20	1.80	1.80	2.13

Figure 14 shows that comparison graph of maximum surge height. From the graph and the table, it can be observed that for cyclone Bulbul NWP-ECMWF simulation slightly overestimates by 0.07m than the reported data. Both NWP-GSM simulation and parametric simulation are less by 0.33m than reported data which could be due to model's limitation.

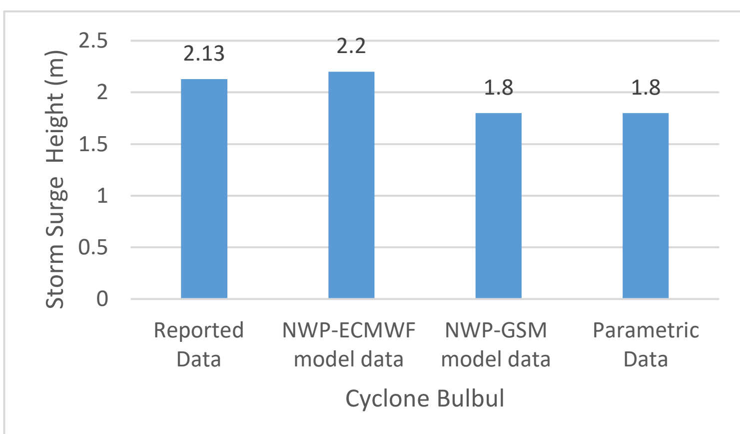

Figure 14: Comparative graph of reported and simulated data for maximum storm surge height of cyclone Bulbul.

4. Conclusion

The study shows that the MRI Storm Surge model is able to simulate and visualize storm surge height, mean sea level pressure and wind component of cyclone Bulbul for the datasets in an hourly basis for 48 hours using GrADS visualization tool. The time series graph comparing the simulated results and observed data of storm surge height for cyclone Bulbul shows that the simulated data of the datasets are more or less close to the observed data. And comparison of the maximum storm surge height shows that simulated data for the data sets are close to the reported data and the difference are well within the margin of error proving that the MRI model is capable of simulating storm surge events that occur in the coastal region of Bangladesh.

However currently there are no surge gauges installed along the coast of Bangladesh which hinders the availability of real time and dependable observation data. Installation of surge gauges will provide the data necessary for proper authentication of the model. This will further improve the accuracy of the model for forecasting storm surge events.

In addition, the impact of climate change and a possible sea-level rise and changes in the frequency and intensity of storms should be taken in account. These factors may change flooding risks from storm surges, especially in the low-lying areas of Bangladesh. Further research would complement the MRI model and increase its viability as a forecasting model for storm surge.

References

[1] Das, P.K., 1972. A prediction model for storm surges in the Bay of Bengal. Nature 239, 211–213.

[2] Gray, W. M. 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, 96, 669-700.

[3] As-Salek, J. A., and Takashi Y. (2001) Tide–Surge Interaction in the Meghna Estuary: Most Severe Conditions. Journal of Physical Oceanography, 31(10):3059–72.

[4] Debsarma, S. K. (2009). Simulations of Storm Surges in the Bay of Bengal. Marine Geodesy, 32(2), 178–198. doi:10.1080/01490410902869458.

[5] Higaki, M., Hayashibara, H. H., and Nozaki, F. (2009) Outline of the Storm Surge Prediction Model at the Japan Meteorological Agency. Tech. rep., Office of Marine Prediction, Japan Meteorological Agency, RSMC Tokyo-Typhoon Center Technical Review, Tokyo, 924.

[6] Mallik, M. A. K., Ahsan, M. N., and Chowdhury, M. A. M., (2015) Simulation of Track and Landfall of Tropical Cyclone Viyaru and Its Associated Strom Surges Using NWP Models. American Journal of Marine Science, 3(1):11-21. doi: 10.12691/marine-3-2-1.

[7] Paul, G.C., Senthilkumar, S. and Pria, R. (2018) Storm surge simulation along the Meghna estuarine area: an alternative approach. Acta Oceanol. Sin. **37,** 40–49 (2018). https://doi.org/10.1007/s13131-018-1157-9

[8] Ali, M., Imran, A., Syed, I., Islam, J., and Mallik, M. (2018) A Comparative Study of Storm Surge Phenomenon Associated with theb Tropical Cyclone Aila over the Bay Of Bengal Using NWP Models. Journel of Engineering Science, 09(02):33-40.

[9] Ali, M., Saifullah, M., Imran, A., Syed, I., and Mallik, M. A. K. (2019) Studying the Intensity and Storm Surge Phenomena of Tropical Cyclone Roanu (2016) over the Bay of Bengal Using NWP Model. Journal of Scientific Research, 12(1):55-68.

[10] Sinha, P. C., 1987: Hydrodynamic numerical modeling of storm surges- Application to the Bay of Bengal. *Sadhana,* Vol. 10, Parts 3 & 4, August 1987, 433-444.

[11] Al Mohit, M. A., Yamashiro, M., Ide, Y., Kodama, M., & Hashimoto, N. 2018. Tropical Cyclone Activity Analysis Using MRI-AGCM and d4PDF Data. International Society of Offshore and Polar Engineers, ISOPE-I-18-532

[12] Hossain, M.A., Hassan, S.M.Q., Rashid, M.B., Mallik, M.A.K. and Islam, M.S., 2017. Storm surge simulation of cyclone "Roanu" over coastal regions of Bangladesh using MRI storm surge model. DEW-DROP, 3, pp.46-54.

[13] M. Abdullah, 2018. Simulation of Storm Surge using Mri Model over Bangladesh, Thesis for: M.S.

[14] Hasegawa, H., Kohno N., and Itoh M., (2015) Development of storm surge model in Japan Meteorological Agency. Office of Marine prediction, JMA.

[15] Higaki, M., Hironori, H., and Futoshi N. (1998) Outline of the Storm Surge Prediction Model at the Japan Meteorological Agency. 25-38.