PERFORMANCE ANALYSIS OF MRI STORM SURGE MODEL: A CASE STUDY IN THE BAY OF BENGAL

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ABSTRACT

The Bay of Bengal experienced some of the most catastrophic cyclones in the 21st century. The presence of favourable conditions for cyclone formation makes it one of the most cyclone-prone basins of water worldwide. Disaster management strategies are widely recognised as being inherently connected to preparation and a timely response. In order to do so, Bangladesh needs to have accurate measures to perfectly forecast the occurrence and intensity of tropical cyclones. This research aims to simulate storm surge levels generated by major tropical cyclones that have hit the Bay of Bengal in the 21st century, like Cyclone Sidr (November 2007; landfall close to the Sundarbans inside Bangladesh) and Cyclone Aila (May 2009; landfall outside Bangladesh). And compare the acquired simulated values with actual observed data at a specific water station situated near the Bay of Bengal. This research aims to assess the MRI storm surge model's viability and validity and come to a conclusion about whether it can be used to predict or study storm surges effectively. The model was run using observed track data obtained from the International Best Track Archive for Climate Stewardship (IBTrACS) with assistance from the Bangladesh Meteorological Department (BMD). The model accurately replicated the storm surge levels seen at different water stations during both storms. A time series of storm surges for both cyclones at a location close to Hiron Point, Bangladesh, situated near the coastal belt, was simulated and studied during the landfall period (48 forecasting hours) of both cyclones. The simulated time series of the surge height for the cyclones was then compared with the observed value recorded at the water station situated at the chosen location. The simulated storm surge peak for cyclones Sidr and Aila showed a difference of 5.7% and 12.0%, respectively. The simulated value of Aila attained peak 3 hours prior to the actual peak being observed, and during Sidr, the peak was simulated after 1 hour of the actual recorded peak.

Keywords: *Bay of Bengal, 21st Century, MRI Storm Surge Model, Simulated timeseries, Storm surge*

1. INTRODUCTION

A tropical cyclone is a specific kind of whirling storm system that occurs over tropical or subtropical waters. Tropical cyclones are characterized by the presence of a low-pressure system, strong winds, and substantial precipitation. Tropical cyclone generation and strengthening need warm ocean temperatures, abundant humidity, and convergent winds at high altitudes. The storm system has the potential to expand and intensify, generating wind gusts reaching several hundred kilometers per hour. Tropical storms may cause significant damage to coastal regions due to strong winds, heavy rainfall, and storm surges. Tropical cyclones originate when the rise of warm and humid air from the ocean's surface leads to cooling, cloud formation, and the release of heat energy. The development and strengthening of tropical cyclones are affected by monsoons, geographical considerations, and atmospheric conditions. Tropical cyclones can develop and strengthen in the Bay of Bengal because of their location in an area with very favorable weather conditions. Factors such as high humidity, minimal vertical wind shear, and wind convergence at higher altitudes contribute to these circumstances. A huge continental shelf and a large basin are encircled by three landmasses. This geographical arrangement may slow down cyclones, cage them, and then cause floods due to excessive rainfall (Tasnim et al., 2014). Bangladesh, a country spanning around 144,000 square kilometers, is home to more than 150 million people. The coastal area is home to 28% of these individuals (Paul, 2009).

The coastal population of Bangladesh has been greatly affected by the surges caused by tropical storms. On average, 5.5 tropical cyclones form in the Bay of Bengal each year (Chowdhury et al., 2012), and every two to three years, a superstorm hits the region, wreaking havoc (Alam and Dominey-Howes, 2015). The world’s largest surge records are held at this location, with an average of five surges of at least five meters per 10 years (Needham et al., 2015). Nearly 60% of tropical cyclones with fatalities of 5,000 or more have occurred in this area (Needham et al., 2015). Super typhoon Sidr killed an estimated 3,406 people in Bangladesh’s coastal areas in 2007. (Paul, 2009). Approximately 190 lives were lost in the southwest region of Bangladesh (Khulna Division) and West Bengal, India, as a result of Cyclone AILA on May 25, 2009 (Khatun et al., 2017).

Simulations of potential surges following a natural disaster were conducted using the MRI Storm Surge Model in this research. The Japanese Meteorological Research Institute (MRI) created software called the MRI Storm Surge Model to simulate storm surges in coastal areas. The MRI Storm Surge Model incorporates several additional variables that may have an impact on storm surge. The factors that may influence a given coastline’s appearance and characteristics are air pressure, wind speed and direction, ocean currents, and water temperature (Hossain et al.ly 2017). The MRI Storm Surge Model guarantees storm surge forecasts that are more precise and dependable in comparison to conventional approaches by considering these intricate factors.

2. METHODOLOGY

The meteorological research institute (MRI) affiliated with Japan Meteorological Agency (JMA) was the originator of the MRI Storm Surge Model. The model works on the Ubuntu operating system, derived from the Linux distribution. The primary focus of the initial architecture of this model was on local observations due to its minimal computational resource demands. The command lines of the model are run using the terminal feature. CTL files are used for the calculation of the model. Text documents are used to input data on the model.

2.1.1 Area of study

The coastal zone of Bangladesh is located in the most northern section of the Bay of Bengal (BoB). Just the BoB area is included in the model's adjustments. Latitudes 18.5° North to 27° North and longitudes 86° East to 94° East makes up the region. The General Bathymetric Chart of the Oceans (GEBCO) bathymetry data is used to obtain the topographical information for the border.

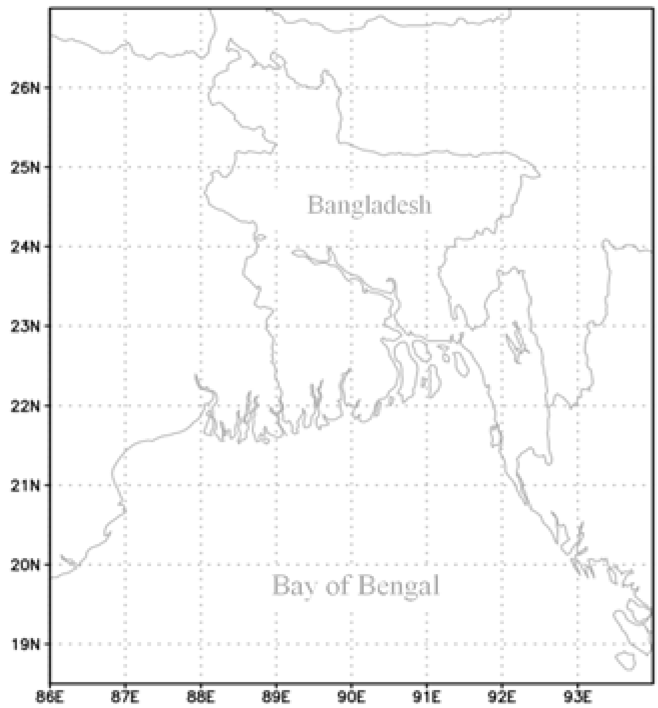


Figure 1. Location of study area (of present study)

2.1.2 Model Experimental Setup

Table 1 provides details on the geographical area covered by the model being studied in the current research. It spans from 86.0°E to 94.0°E in terms of longitude and from 18.5°N to 27.0°N in terms of latitude. The table describes the pressure profile, grid resolution, hours of forecast, and visualization tools utilized for the result.

Table 1. MRI Storm Surge Model Description (Soeb et al., 2023)

Model	2D ocean model, vertically integrated
Coordinate	Lat /Lon Cartesian grid Arakawa C-Grid
Area	18.5-27° North, 86-94° East
Grid Resolution	2 min mesh
Hours of Forecast	48 hours
Run Time Interval	6 hourlies
Initial time (UTC)	0000, 0006, 0012, 0018

Pressure Profile	Fujita (1952)
Visualization Tool	GrADS
Topographic Data	GEBCO 30 sec resolution (Used by converting into 2mins)

2.1.3 Data Used

The model was designed to simulate the behavior of a cyclone using track data obtained from the storm. Cyclone trajectories are tracked every six hours by the International Best Track Archive for Climate Stewardship (IBTrACS). Cyclone Sidr and Aila's track data was most accurately retrieved from IBTrACS. Cyclone latitude and longitude in degrees, estimated central pressure in hPa, maximum wind radius in km, coefficient, and atmospheric pressure in hPa were the input variables used in the simulation. Every cyclone was monitored for 48 hours, with six-hour intervals in between. The following inputs were feed to the model to run the simulation. For instance, the details for cyclone Aila were recorded as follows in "Cyclone_Aila.txt":

```
-------------------------------------------------------------------------------------------------------
Cyclone Aila        Start= 052400   End= 052600                    (←TC name, Start, End)
48 hours calculation                                           (← forecast hours)
6 hourly data                                                  (← interval time)
 date        Pcenter      lon        lat    RØ    Coef        Pfar
 052400       996.00      88.5       17.0         40.0        0.70        1012
 052406       988.00      88.5       18.0         40.0        0.70        1012
 052412       986.00      88.5       18.5         40.0        0.70        1012
 052418       986.00      88.5       19.0         40.0        0.70        1012
 052500       980.00      88.0       20.0         40.0        0.70        1012
 052506       974.00      88.0       21.5         40.0        0.70        1012
 052512       970.00      88.0       22.5         40.0        0.70        1012
 052518       980.00      88.0       23.5         40.0        0.70        1012
 052600       982.00      88.0       25.0         40.0        0.70        1012
--------------------------------------------------------------------------------------------------------
```

Note:
date: MMDDHH (month, day, hour)
Pcenter: Estimated central pressure (hPa)
lon, lat: Location of TC center (in degree)
RØ: Radius of maximum wind (km)
Coef: Coefficient, c1 (=0.70 usual case)
Pfar: Environmental pressure (hPa)
Similarly, for all the simulations, relevant cyclone data were documented as such with proper adjustments.

2.2 Model Set-up

The MRI model replicated the specified storm surge scenario near Hiron Point with a location of 89.5° East and 21.8° North during Cyclones Sidr and Aila. The simulation used a parametric dataset collected from IBTrACS. The model generated a time series of 48 hours, which was then compared to the existing observed and recorded data. The model was run for Cyclone Sidr from 0000 UTC on November 14, 2007, to 0000 UTC on November 16, 2007, and for Cyclone Aila from 0000 UTC on May 24, 2009, to 0000 UTC on May 26, 2009. The time span of 48 hours was chosen to accurately recreate the maximum storm surge value by ensuring that the documented landfall timings of the storms fell within this range.

2.2.1 Settings of calculation

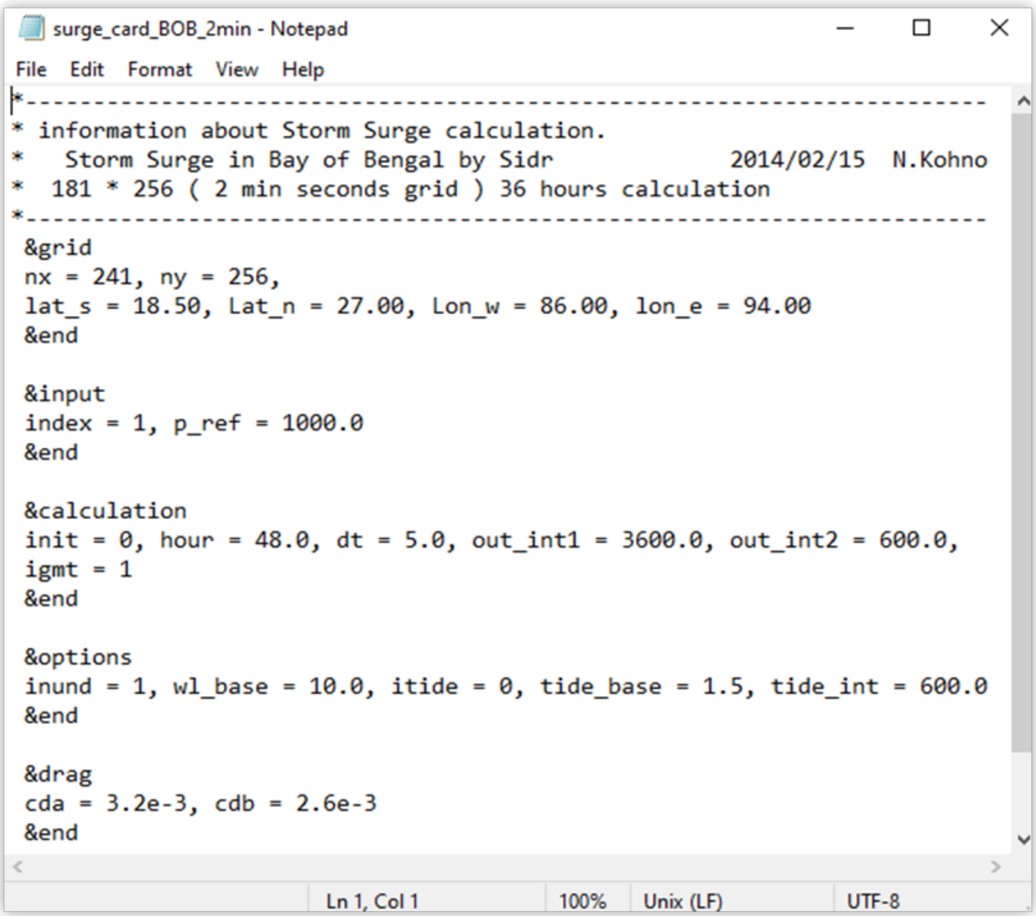
The file "surge_card_BOB_2min.txt" in the "{work directory}/Model/DATA" directory included the calculation parameters. In this file, for simulation most calculations are specified. The file contains five namelist groups input, grid, calculation, drag, and options. The settings for the grid, options, and drag were maintained as constant as the model domain and resolution. The following parameters were modified:

2.2.2 The "index" in the Namelist "input"

The system for meteorological input was defined. The use of parametric data from TC information has two choices for meteorological input. One is called the "Fujita profile" while the other is called "Myer's profile". Input parameters was selected from the following values:

a) Fujita profile from Rref
b) Fujita profile from RØ
c) Myers profile from Rref
d) Myers profile from RØ

Fujita profile from Rref was selected for the simulation. The "index" value was set as 1 (index=1). Rref was set as 1000.0 hPa in the namelist parameter "p_ref".



```
surge_card_BOB_2min - Notepad
File Edit Format View Help
*---------------------------------------------------------------------
* information about Storm Surge calculation.
*   Storm Surge in Bay of Bengal by Sidr           2014/02/15  N.Kohno
*  181 * 256 ( 2 min seconds grid ) 36 hours calculation
*---------------------------------------------------------------------
 &grid
 nx = 241, ny = 256,
 lat_s = 18.50, Lat_n = 27.00, Lon_w = 86.00, lon_e = 94.00
 &end

 &input
 index = 1, p_ref = 1000.0
 &end

 &calculation
 init = 0, hour = 48.0, dt = 5.0, out_int1 = 3600.0, out_int2 = 600.0,
 igmt = 1
 &end

 &options
 inund = 1, wl_base = 10.0, itide = 0, tide_base = 1.5, tide_int = 600.0
 &end

 &drag
 cda = 3.2e-3, cdb = 2.6e-3
 &end
Ln 1, Col 1   100%   Unix (LF)   UTF-8
```

Figure 2. Calculation settings for the model (Author)

2.2.3 Forecast Hour in the Namelist "calculation"

The 'calculation' namelist's hour parameter was used to specify the maximum forecast hour. TC was introduced into the model with a 48-hour runtime. The value for "hour" was supplied as 48.0.

2.2.4 File condition settings

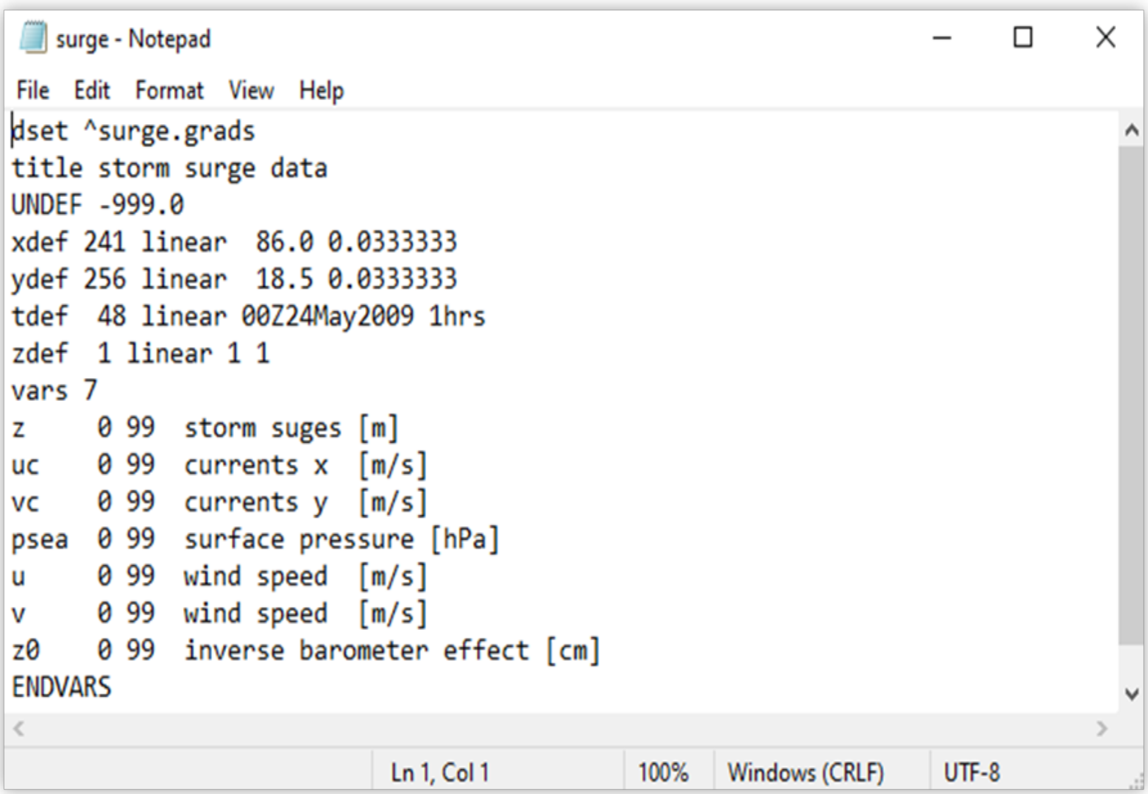
The "surge_cal.sh" script file was created in the "{work directory/Model" directory. The script had the TC data, bathymetry, and computation parameters, and the file was then saved.
The TC data input was done by changing the marked line to direct the model data to Cyclone Aila input saved in the "{work directory}/Model/DATA" directory as "Cyclone_Aila.txt".

2.2.5 Running the model

At the "{work directory}/Model" directory, the shell script was run in the UBUNTU terminal by mounting the work directory by the command:
[command] $> cd /mnt/{work directory}/Model
Then the shell script was run using the following command:
[command] $> ./surge_cal.sh yyyy mm dd start forecast_hour

2.2.6 Visualizing Output by Using GrADS

The GrADS tool was used to visualize the graphic results. In the area of meteorology, GrADS is frequently utilized and well-liked by various meteorological service providers. The output results from the model were automatically saved in the "{work directory}/Plot/GrADS" directory once it had finished running. A control file, "surge.ctl" was prepared in the "{work directory}/Plot/GrADS" directory. In the same directory, the control file creates a "surge.grads" file that stores all of the graphical outputs.


surge - Notepad

File Edit Format View Help

```
dset ^surge.grads
title storm surge data
UNDEF -999.0
xdef 241 linear  86.0 0.0333333
ydef 256 linear  18.5 0.0333333
tdef  48 linear 00Z24May2009 1hrs
zdef  1 linear 1 1
vars 7
z     0 99  storm suges [m]
uc    0 99  currents x  [m/s]
vc    0 99  currents y  [m/s]
psea  0 99  surface pressure [hPa]
u     0 99  wind speed  [m/s]
v     0 99  wind speed  [m/s]
z0    0 99  inverse barometer effect [cm]
ENDVARS
```

Ln 1, Col 1 | 100% | Windows (CRLF) | UTF-8

Figure 3. Control file for GrADS output (Author)

To operate GrADS in Windows OS a program "1 GrADS Command Line" was installed. After opening the program "enter key" has to be pressed in order to open the "Output Window" of size 11

by 8.5. To open the control file “surge.ctl” it was first copied to the work directory of the “1 GrADS Command Line” program along with the “surge.grads” file. An example being
{work directory}/OpenGrADS-2.2/Contents/Resources/SampleDatasets (Copied files were pasted here)
Then the control file “surge.ctl” was opened in GrADS by using the following commands on the newly opened OpenGrADS window
[command] $> open surge.ctl

2.2.7 Storm surge map

The OpenGrADS command tool allows users to inspect seven target outputs. Storm surges, surface pressure, inverse barometer effect, wind speeds, water currents, and wind velocity are some of these. To see the outputs, the following commands were used:

2.2.7.1 Data Plot Commands

$> set mpdset hires
$> set gxout shaded
$> set t time_value
$> d target
The target variables are:
z: storm surges (m); psea: surface pressure (hPa); zØ: inverse barmeter effect (cm);
u,v: wind velocities (m/s); uc, vc: water currents (m/s)

2.2.7.2 Wind Plot Commands

$> set gxout barb
$> d skip(u,10,10);v

2.2.7.3 Current Plot Commands

$> set gxout vector
$> d skip(uc,10,10);vc

2.2.7.4 Visualizing surge animation

The tropical cyclone (TC) surge height simulation is animated by the model for the integrated forecast hour. The following commands were used to display the animation:
$> set mpdset hires
$> set gxout shaded
$> set t 1 t_max
$> *d z*

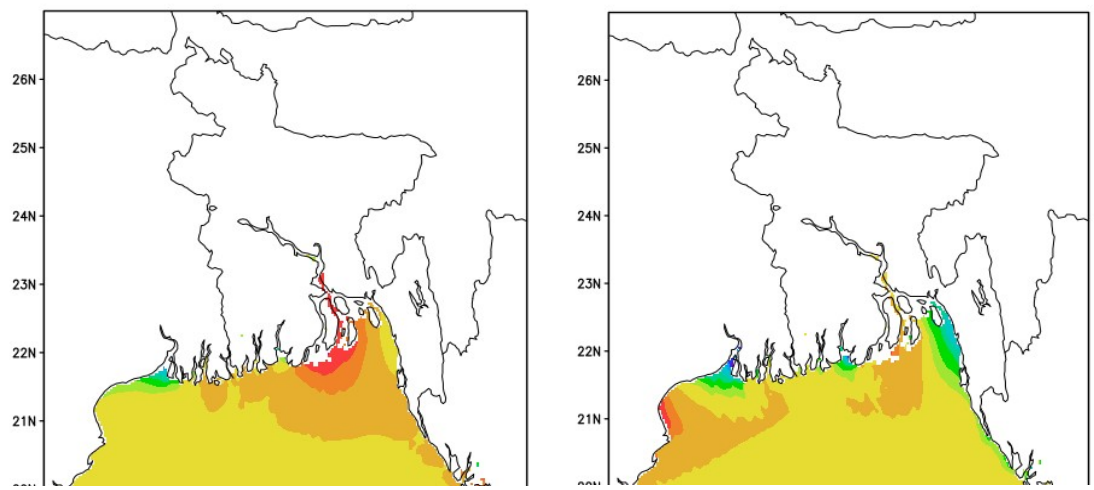
2.2.7.5 Time series at a location

The model generates the TC's surge during the integrated forecast period at a given coordinate by using latitude and longitude. It is possible to see the largest surge that the TC at a particular place generated. The given commands were as follows:
$> set t 1 t_max
$> set lon lon_value
$> set lat lat_value
$> d

3. RESULTS AND DISCUSSIONS

3.1 Cyclone Sidr

A surge height ranging from 1.5 to 3 meters was calculated by the model for the 48-hour running period. Because of its geographic location, the Meghna Estuary experienced the greatest surge. Figure 4 represents the surge height generated during different hours of the cyclonic event and illustrates the model's maximum 3-meter surge during a cyclonic event.



(a) (b)

Figure 4: Model computed storm surge (meter) generated by cyclone Sidr at a) 09Z UTC 15 Nov, 2007 b) 10Z UTC 14 Nov, 2007 (author)

Hiron Point's water station data was compared to the time series produced by the MRI Storm Surge model. The simulated peak (1.3 m) of the storm surge showed a variation of about 0.07 m from the actual peak (1.23 m), and there was some time variation in the case of attaining the peak. The actual peak was seen at 1100 UTC on November 15, and the simulated peak was at 1200 UTC on November 15, 2007. Meaning the actual peak was obtained 1 hour prior to the simulated peak surge.

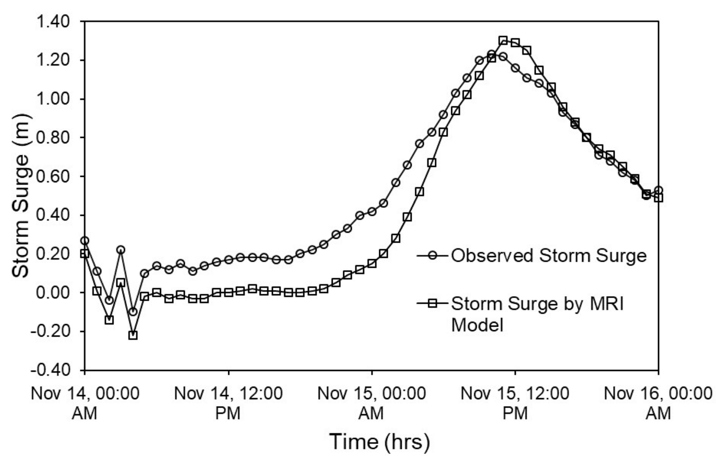


Figure 5: Simulated surge of Cyclone Sidr compared with observed data at Hiron Point water station (89.5° East, 21.8° North) (Author)

3.2 Cyclone Aila

A surge height ranging from 0.2 to 0.7 meters was calculated by the model for the 48-hour running period. Similar to cyclone Sidr, cyclone Aila also generated the greatest surge at the Meghna Estuary. Figure 6 illustrates the model's maximum 0.7-meter surge during a cyclonic event.

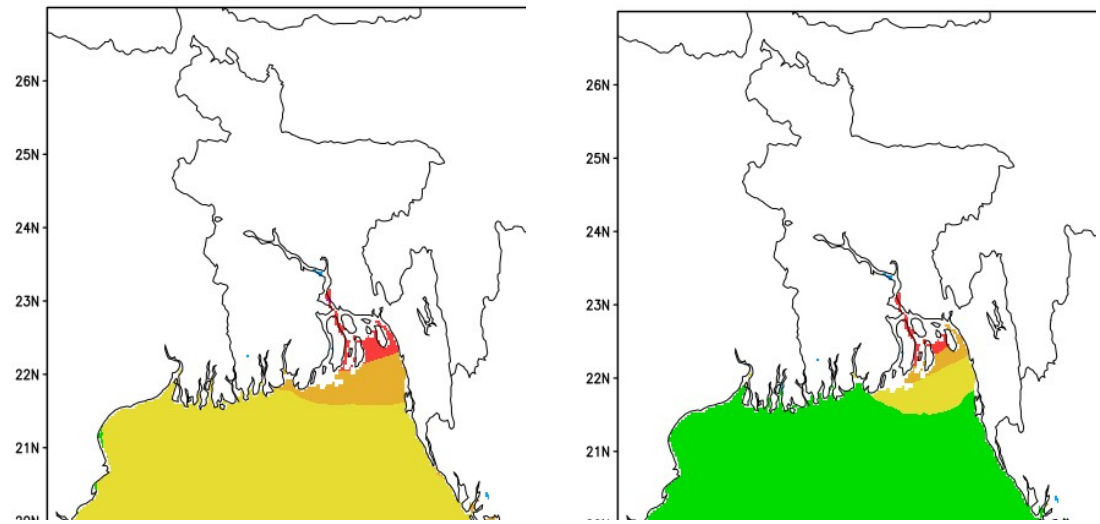


Figure 6: Model computed maximum storm surge (meter) generated by cyclone at a) 11Z UTC 26 May, 2009; b) 18Z UTC 25 May, 2009 (Author)

The time series generated by the MRI Storm Surge model at Hiron Point was compared to the data collected at the water station situated there. The simulated peak (0.56 m) of the storm surge showed a variation of about 0.06 m from the actual peak (0.50 m), and there was some time variation in the case of attaining the peak. The actual peak was seen at 1600 UTC on May 25, and the simulated peak was at 1300 UTC on May 25, 2009.

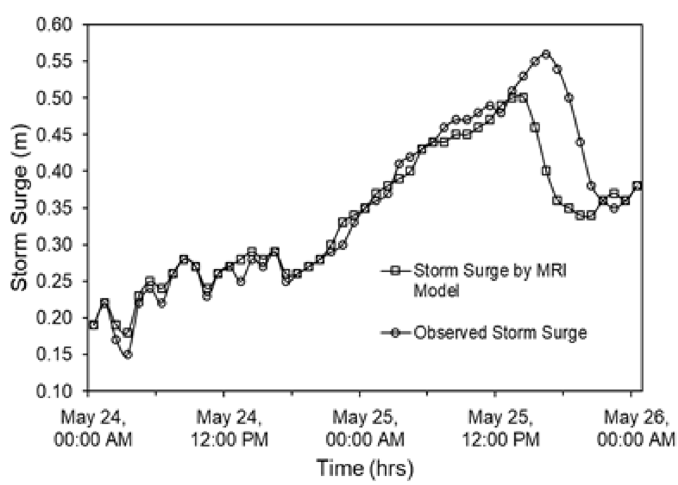


Figure 7: Simulated surge of Cyclone Aila compared with observed data at Hiron Point water station (89.5° East, 21.8° North) (Author)

4. DISCUSSION

The model was used to generate a two-dimensional timeseries for both cyclones. The magnitude of the cyclone is defined by the differences in the central pressure and the ambient pressure. As the cyclone's central pressure went up, the height of the surge also went down. The "inverse barometer effect" states that for cyclones, atmospheric pressure must be lower than barometric pressure (1 atm or 1012 hPa). Due to this, the relationship between surge height and cyclone central pressure is inverse. A greater surge than the actual cyclone was produced as the pressure dropped. Storm surges were graphed for Hiron Point, located at a latitude of 21.8° North and a longitude of 89.5° East, over a 48-hour time period. Both Sidr and Aila had a maximum radius of 40 kilometers. Hiron Point saw a maximum residual surge of 1.23 m during Cyclone Sidr, although the model predicted a surge peak of 1.3 m (Table 2). The generated surge height profile of the model closely matched the real hourly observed data, with a variance of just 5.7% for the peak value. The simulation reached its highest point around 1 hour before the actual observed peak.

Table 2: Tabulated Data of the Peak Simulation & Observed Peak

Simulated Cyclone	**Simulated Maximum Surge (m)**	**Actual Maximum Surge (m)**	**Variation (b~c) (m)**	**% [(b~c)/c]**
(a)	(b)	(c)	(d)	(e)
Sidr	1.30	1.23	0.07	5.7
Aila	0.56	0.50	0.06	12.0

During Cyclone Aila, Hiron Point had a residual surge of 0.50 m, whereas the model predicted a maximum surge of 0.56 m with a difference of just 12.0% (Table 2). The model's time series showed striking similarities to the values of the observed surge. Three hours after the field-observed peak surge, the simulation showed that Hiron Point had its maximum surge thereafter.

There was little deviance from the observed data in terms of both the chronological variation and the associated peak amplitude throughout the 48 hours. What this means is that the simulation seems to have simulated the exact moment and size of the surge at Hiron Point during Cyclones Aila and Sidr. The model's capacity to accurately simulate surge episodes is supported by the high degree of agreement between its predictions and the observed data.

5. CONCLUSIONS

The MRI Storm Surge Model allows for the simulation of storm surges and their display against time. There is a high degree of agreement between the predicted and observed storm surge heights for that period. It is clear from the findings that a high-resolution model is required to provide reliable storm surge predictions for the coastal regions of Bangladesh. The Model utilizes intricate algorithms and data from several sources to accurately predict the heights of storm surges. The model can provide important information on the possible effects of cyclones on Bangladesh's coastal areas by integrating crucial factors including wind speed, air pressure, and tide movements. With these precise forecasts, catastrophe planning may be much easier, and the devastating impacts of storm surges could be lessened. Storm surges caused by strong cyclonic storms that might strike coastal areas in this area can be predicted in real-time using the MRI model. The model's ability to gather and analyze past storm data is a result of its high-accuracy forecasting capability. To accurately simulate tidal heights, it is essential to have access to reliable real-time tide data. Factors including cyclone-related heavy rainfall, freshwater outflow, and river seaward flow may significantly affect surge levels; however, these factors were not taken into consideration while calculating the surge estimates in this research.

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