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Impact of Climate Change on Maximum Sustained Wind Radius and its Associated Storm Surge Estimation along the Coast of Bangladesh

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ABSTRACT

This research is a basic study on cyclones. The changing behaviour of storm surge in the Bay of Bengal due to the impact of climatic changes has been analyzed in this study. Certain characteristics of cyclones, such as the maximum sustained wind radius, have been analyzed, and their effect due to climatic change has been determined. The correlation between the maximum sustained wind radius and surge height was observed for this purpose. To accurately determine surge height, the vertically integrated shallow water wave model equation was employed, and it was solved using the semi-implicit finite difference method through the Arakawa-C grid. The surge model was performed by increasing and decreasing its wind radius by 10% to 20%, based on changes in the maximum sustained wind radius due to the effects of climate change. A strong conclusion was reached from the obtained results, indicating a significant effect of the maximum sustained wind radius on storm surge. But if it increases, there is a visible change in storm in some area of the coast of Bangladesh. For example, 1% increase in wind radius, the surge height increases by 0.032m, where the storm strikes. In some areas far away from where the storm hits the rising rate of the surge height is much lower. Finally, it may be stated that the surge height is affected by the maximum sustained wind radius and that it is altered by climatic impacts.

1. INTRODUCTION

Bangladesh, a land of glorious beauty, is one of the most natural disaster-prone countries in South Asia and its area is 1,47,570 square km. Due to its geographical location, plain and low-land topography, high population density, funnelling shape of coast, El-Nino Southern Oscillation, and illegal human activities, socio-economic environment, etc. every year this country faces a number of different types of natural calamities, such as tropical cyclones, floods, droughts and earthquakes [1]. Tropical cyclones are one of the most devastating natural disasters in Bangladesh. Around 160 cyclones have hit this country since 1860 and in the last five decades, about a half million people have died from this cyclone [2]. The inundation due to cyclone induced storm surges causes significant loss in the coastal livelihood that leads to long term damage to coastal ecosystem and land shape [3]. Climatic change and global warming are the major fact to change the characteristics of the storm (wind speeds, humidity and heavier rainfall) in every year which makes coastal region of Bay of Bengal (BOB) more vulnerable [4]. According to [5], there are 269 depressions found in the BOB in the last 44 years. But it is found in the last 25 years (1974-1999) that the average depression rate of that period is 7.7 numbers of cyclones, 3.46 of the depression formed as a fully developed storm, 3.12 of these storms make landfall on the Bay of Bengal coast. A study by the [6] has shown that if the

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sea level rises by 1 meter in the next 100 years, 15-17 percent of the land area of Bangladesh will be submerged and 20 million people will be displaced. The increased flood frequency will reduce water quality and safe water access and increase water borne infectious diseases in Bangladesh. The coast of Bangladesh is very complex and the offshore region is full of low lying big and small islands. Thus, it is essential to possess a sound understanding of the elements influencing storm surges, and there is a significant need for an effective storm surge model specifically tailored for the coastal regions of Bangladesh.

Many analyses and predictions on storm surge, tide and their interaction have been investigated by many authors for the Bay of Bengal region. At first, [7] developed a linear storm surge model which was the first nested model for storm, after that the development was done by [1], [8]. Author [1] concluded that the interaction with tide and surge at the same time is difficult to consider. Author [8] first incorporated the stair step representation of the Bay of Bengal coast to develop the storm surge model, which considered the dynamic effect of the Ganges–Brahmaputra–Meghna River system and offshore islands of Bangladesh coast. However, in their stair step representation model, the accuracy of the coastal and island boundaries is depending upon the grid resolution. In their study, it is not ensured that the fine grid resolution can produce better results. So, keeping the above limitation, [9] developed the model of [8], which is known as the nested grid model. But the study was conducted considering only the Meghna estuarine region including only two major offshore islands Sandip and Hatiya through proper stair steps.

To consider the whole coast of Bangladesh, [10] investigated the storm surge problem including all major islands. But in their study the interaction of tide and surge was linear. It is known that the tide will interact with surge nonlinearly, and so this result should be far from reality. Therefore, [11] developed the model of [9] as a very fine nested grid model, which is also a non-linear interaction model of tide and surge. Nonetheless, in the Bangladesh coast, there is a big river inlet, which has a noticeable impact in storm surge simulation. Author [12] developed a one directional river model and two-dimensional bay model for a couple model. In subsequent, [13] introduced a two-dimensional bay-river coupled model, which incorporates the east coast of India. Author [14] used 50-year cyclone track data to investigate the cyclone characteristics. To find the surge height accurately, [10] also developed a two-dimensional bay-river coupled model incorporating the Ganges–Brahmaputra–Meghna River system. These works were done for the storm surge simulation in the Bangladesh coast; however, none of them considers the climate change impact on surge simulation.

The government of Bangladesh is not always fully successful in recovering the situation and gives a sustainable livelihood to the coastal people. So, proper forecasting and surge estimation is important. For the storm surge simulation, the important factors are low central pressure of a storm, maximum sustained wind radius, forward movement, storm size, coastal shape, landfall angle etcetera. In this study, the analysis of past storm surge data and simulated future cyclonic data is intended to be conducted to investigate the behaviour of a cyclone, providing accurate surge forecasting. The aim is also to develop sustainable adaptation techniques for the coastal region of Bangladesh.

2. MATERIAL AND METHODS

2.1 Study Area

Bangladesh is the world's largest deltaic country which is formed by three major rivers, namely the Ganges (Padma), Brahmaputra (Jamuna), and Meghna, its astronomical position extends from 20°34'N to 26°38'N latitude and from 88°01'E to 92°41'E longitude. The country is trapped between the great Himalayas on the north and the vast Bay of Bengal to the south with 711 km long coastline [15] and it is divided into three regions: the deltaic eastern region (Pacific type), the deltaic central region, and stable deltaic central region (Atlantic type). The Bay of Bengal is considered the breeding grounds of the pertinent cyclonic events. Every year at least one cyclone occurs in the Bay of Bangle and on average a severe cyclone strikes the country every three years. The coastal zone of Bangladesh covers 19 districts with 147 Upazila which is 32% of the total area and 28% of the population of Bangladesh. But, the 12 districts and 51 police station areas are vulnerable to surge disaster risk [16].

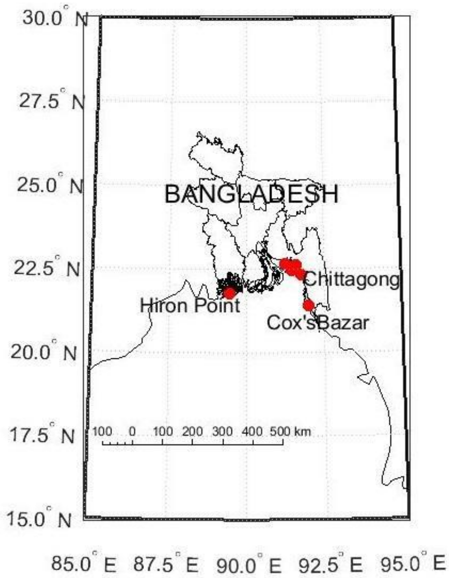

Fig. 1. Bangladesh coastal area with the tidal station location information [17]

2.2 The Data

This investigation utilizes data from the d4PDF, AGCM, and BMD datasets. The MRI-AGCM (Meteorological Research Institute Atmospheric General Circulation Model) is a specific atmospheric model developed by the Meteorological Research Institute of the Japan Meteorological Agency (JMA). Initially, [18] created an NCAR Community Climate Model version 1 (CCM1), now recognized as an Atmospheric Global Circulation Model (AGCM). In this model, heat momentum, dynamic mass were used in the horizontal spectrum conversion method where 18 vertical levels were used to adjust the system. Within each atmospheric layer, the delta-Eddington calculation was executed, a method derived from the solar radiation scheme introduced by [19]. In the present situation, the Meteorological Research Institute (MRI) and Japan Meteorological Agency (JMA) jointly develop a new operational numerical weather prediction model known as MRI-AGCM [20]. The MRI-AGCM present data can explain the present situation well because the MRI-AGCM is forced with observed SST, but the model input SST from CIMP3 has some biases. For the 21st century (2075– 2099, 25 years), the global simulation under the consideration of the future scenario MRI-AGCM3.2H model forecasts the future climate.

d4PDF (Database for Policy Decision-making for Future climate change) is a climate model dataset developed by the Meteorological Research Institute (MRI) of the Japan Meteorological Agency. The d4PDF data was produced from the weather prediction model of Japan Meteorological Agency [21] with the modified model of MRI-AGCM 3.2 [22]. The data was represented on a global scale using a 60 km grid and on a regional level for Japan with a 20 km grid. The data were collected from the Data Integration and Analysis System (DIAS) under the Global environmental information integration program [23], [24]. The data is divided in three features with past experiments (1951 to 2011), non-Global warming experiment (1951 to 2010), and 4º C rise experiment (2051 to 2110).

In addition, the experimental result of the global atmospheric-ocean coupled model contributes to the Coupled Model Inter-comparison Project Phase 5 (CMIP 5). There are 100-member simulations for present climate conditions, and 90-member simulations for future climate conditions. In the future climate simulation, there are six different ensemble simulation model of CC (CCSM4), GF (GFDL-CM3), HA (HadGEM2-AO), MI (MIROC5), MP (MPI-ESM-MR), and MR (MRI-CGCM3). Responsibility for future-climate model simulations falls under the purview of relevant authorities. The authorities are National Centre for Atmospheric Research (USA), NOAA Geophysical Fluid Dynamics Laboratory (USA), Met Office Hadley Centre (UK), AORI, NIES, JAMSTEC (Japan), Max Planck Institute for Meteorology (Germany), and Meteorological Research Institute (Japan). Different SST conditions are used for different climate simulations [25].

2.3 Maximum Sustained Wind Radius

The maximum sustained wind radius serves as a crucial parameter in the context of tropical cyclones. This factor relies on both central pressure and wind velocity. To explain the tropical cyclone, the tropical cyclone is considered a function of some parameters like wind speed, central pressure, maximum sustained wind radius etc. The maximum sustained wind radius has a substantial impact on the height of surges. Due to global warming, the maximum sustained wind radius of a cyclone may change. To comprehend its nature along the Bangladesh coast, the cyclone information has been examined for six distinct climate scenarios in this study. From the study of [26] the mean R_{max} was 47 km for the central pressures of 909–993 hPa in 1893– 1979. Author [27] found that the typhoon with central pressure ≤ 980 hPa that hit the Japan main islands has the R_{max} of 84–98 km. The maximum sustained wind radius R_{max} is depending on the cyclone track and the characteristics of each cyclone. Therefore, some scientist proposed several estimation models for R_{max} [28], [29]. However, the maximum wind velocities are differently defined depending on different ocean basins where the tropical cyclone transits. Different countries classified the sustained wind in different considerations. For instance, 10 min maximum sustained wind speed was considered for Japan Meteorological Agency (JMA) and 1 min for United States National Weather Service (NWS). In this study, the cyclone track data has been calibrated under present and future climate conditions to determine the appropriate empirical relation. The modified empirical relation from [30] is

$$P_c = 1013 - \left(\frac{V_{max}}{13}\right)^{\frac{1}{0.644}} \tag{1}$$

$$R_{max} = 94.89 * exp^{\left(\frac{P_c - 967}{61.5}\right)} \tag{2}$$

Where, P_c = Central pressure (hPa); V_{max} = maximum velocity (m/s); R_{max} = maximum sustained wind radius (km).

2.4 The Basic Shallow Water Equations

For any atmospheric or oceanic phenomenon, if the horizontal length scale is much larger than the vertical scale, the z-component of the momentum equation may be approximated by the hydrostatic equation. Furthermore, if variations in density in all directions are negligible, the continuity equation simplifies to express the non-divergence of velocity. With these shallow water approximations and neglecting the molecular viscosity, the basic set of shallow water equations is given by [31].

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} \tag{3}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} \tag{4}$$

$$\frac{\partial p}{\partial z} = -\rho g \tag{5}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{6}$$

Where u, v and w are the instantaneous components of velocity in the directions of x, y, and z, respectively; t is the time; p is the pressure; ρ the density of the sea water supposed homogenous and incompressible; $f = 2\Omega \sin\varphi$ the Coriolis parameter, where Ω is the angular speed of the Earth rotation and φ is the latitude of the place of interest; g the acceleration due to gravity.

After averaging procedure and vertically integrated the equation, the model equation can be written in the final form

$$\frac{\partial \zeta}{\partial t} + \frac{\partial \tilde{u}}{\partial x} + \frac{\partial \tilde{v}}{\partial y} = 0 \tag{7}$$

$$\frac{\partial \tilde{u}}{\partial t} + \frac{\partial (u\tilde{u})}{\partial x} + \frac{\partial (v\tilde{u})}{\partial y} - f\tilde{v} = -g(\zeta + h)\frac{\partial \zeta}{\partial x} + \frac{T_x}{\rho} - \frac{C_f\, \check{u}\sqrt{(u^2 + v^2)}}{\zeta + h} \tag{8}$$

$$\frac{\partial \tilde{v}}{\partial t} + \frac{\partial (u\tilde{v})}{\partial x} + \frac{\partial (v\tilde{v})}{\partial y} + f\tilde{u} = -g(\zeta + h)\frac{\partial \zeta}{\partial x} + \frac{T_y}{\rho} - \frac{C_f\, \check{v}\sqrt{(u^2 + v^2)}}{\zeta + h} \tag{9}$$

Where $(\tilde{u}, \tilde{v}) = (\zeta + h)(u, v)$ and u, v are the Reynolds averaged components of velocities in the directions of x and y respectively; $f = 2\Omega \sin\varphi$ is the Coriolis parameter, where Ω is the angular speed of the earth rotation and φ is the latitude of the field of view; g is the acceleration due to gravity. ρ is the density of seawater that is considered to be uniform at the same density.

In the above equations, u and v in the bottom stress terms have been replaced in order to solve the equations numerically in a semi-implicit manner.

3. RESULTS AND DISCUSSION

The mean and standard deviation of the maximum sustained wind radii for different parts of the Bangladesh coastline are presented. Fig. 2 (a) and (b) represent the mean value for intense and low-intense cyclones and Fig. 2 (c) and (d) represent standard deviation. From this analysis, it found that the mean radius range is 62-64 km for the cyclone of Bangladesh.

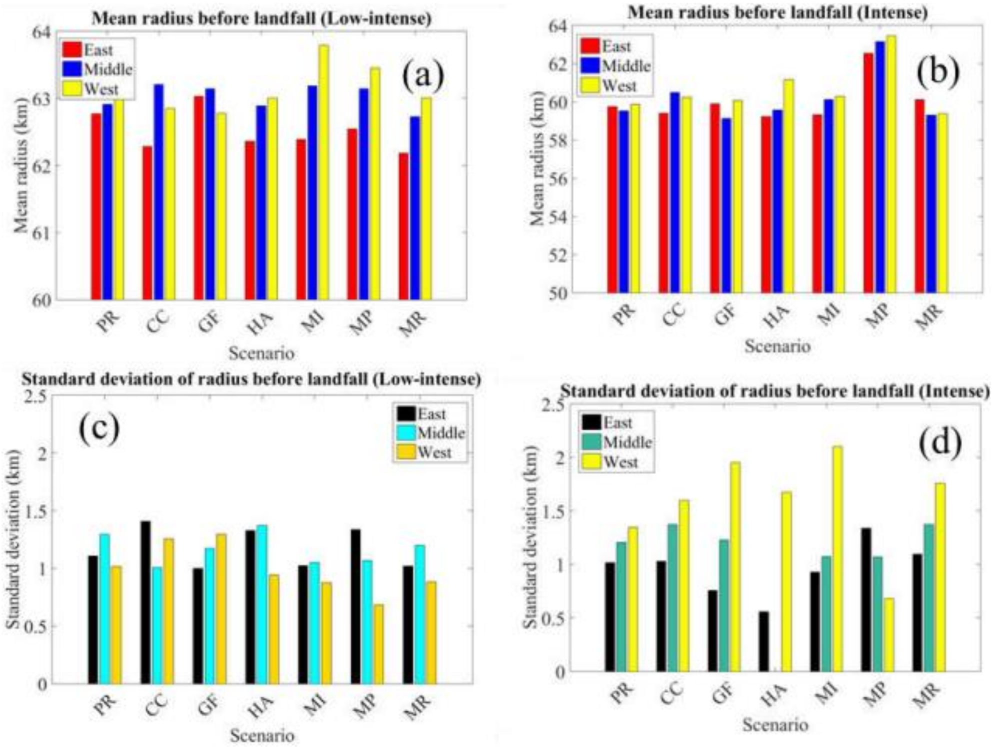

Fig. 2. Mean and standard deviation of maximum sustained wind radius

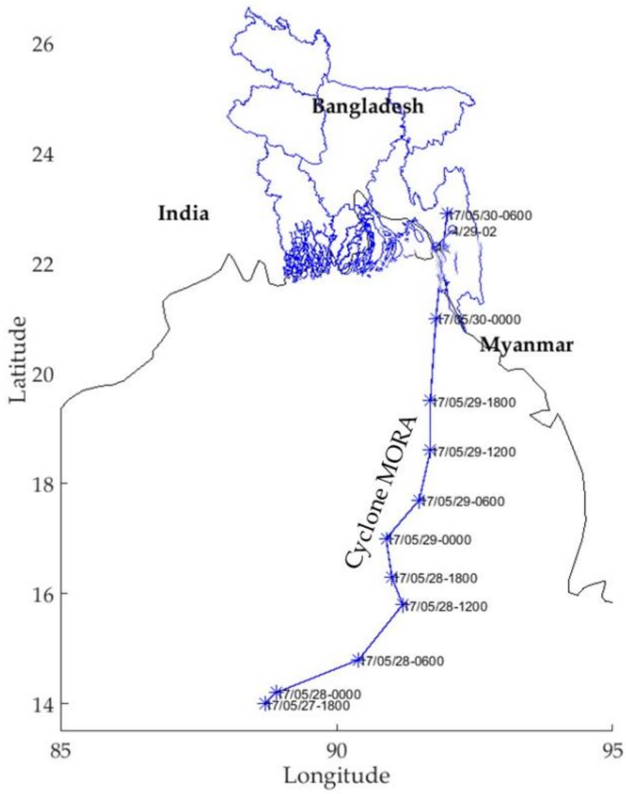

Fig. 3. Track information (landfall location and time) of cyclones MORA-2017

This study found that the maximum sustained wind radius decreases in the east coast and increases in the middle and west coast in future. From the wind-pressure relation, it is evident that the intense cyclone activity will increase in the east coast. It also found that the fluctuation of maximum sustained wind radius is very high along the east coast of Bangladesh.

To validate our model simulation, the cyclone information of MORA-2017 has been employed to compare the results with the Finite Difference Method (Shallow water model) [31]. The simulation was executed by completing the calculation of input data, wind pressure, and wind velocity.

The simulation was computed for 60 hours and presented for the last 24 hours from 1:00 UTC (Local time 08:00 AM) May 29 to 1:00 UTC (Local time 08:00 AM) May 30, 2017. The numerical computation is considered in such a way that the model runs 3296-time steps, the model storing data after every 10 min, 145 was the number of data the model stores and the model started to store data after it was run 1846 times. However, all the information shown in the figure is given according to the local time of Bangladesh. Fig. 4 explains the water level elevation due to the cyclone MORA and the different colour shows the surge height at different tide stations. However, as per the previous discussion, it has been established that the surge height is influenced by the maximum sustained wind radius, and the maximum sustained wind radius undergoes changes due to the impact of climate change.

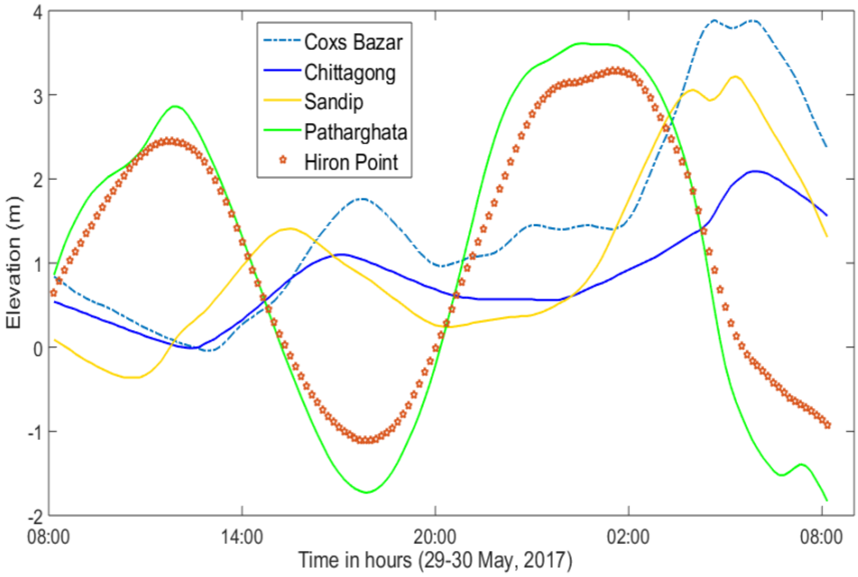

Fig. 4. Observed tide height at five different tidal stations on coast of Bangladesh

For this reason, the effect of the maximum sustained wind radius on water level elevation has been analyzed. We altered the maximum sustained wind radius for different cases and observed fluctuations in surge height due to this effect.

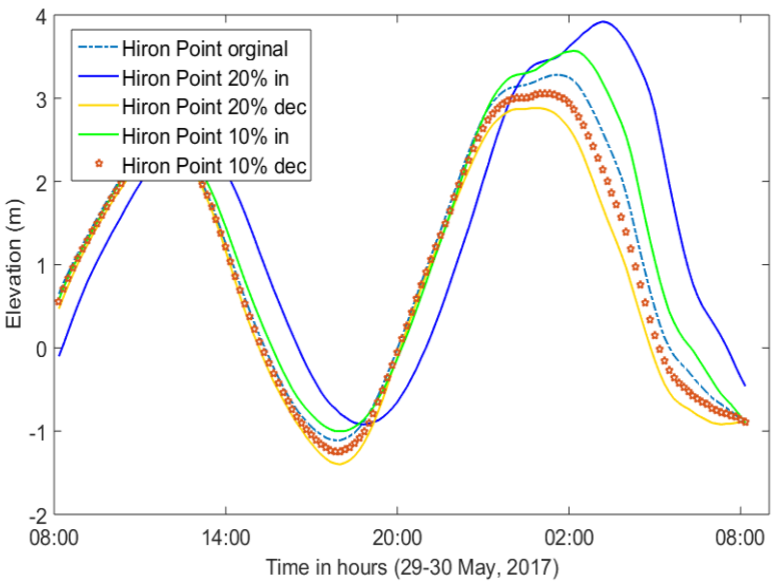

Fig. 5. Comparison of Observed and simulated data in Hiron Point

Here all of these comparison figures the word "in" and "dec" means the increase and decrease of wind radius. Simulation calculations were conducted by varying the wind radius, including 20% and 10% increases and decreases. In Fig. 5 at Hiron Point, it is observed that the maximum and minimum water level elevations are 3.9m and 2.8m, respectively, for a 20% increase and decrease at local times 4:00 AM and 2:00 AM. Again for 10% increase and decrease the water level is 3.6m and 3m at Local time 3:00 and 2:30 AM. Here the original maximum surge height is 3.30m at Local time 3:20AM. Various rescission times are observed for different wind radius parameters. According to the calculations from Fig. 5, for a 1% increase and decrease in wind radius, the surge heights are determined to be 0.03m and 0.02m, respectively.

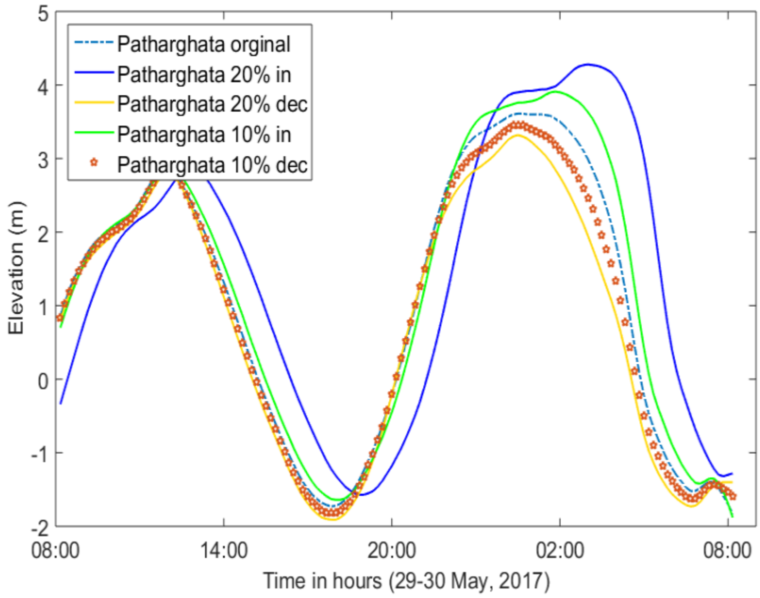

Fig. 6. Comparison of Observed and simulated data in Patharghata

In Patharghata the fluctuation rate of surge height is too much i.e., 0.03m for 1% increase and 0.02m for 1% decrease. Additionally, it is noted that the rescission period remains the same, and there is no occurrence of extreme storm surge in this context. Here maximum water elevation is 4.2m for 20% increasing of its wind radius, which hit this tidal station at Local time 4:30 AM.

In Fig. 7, it is observed that the surge of water level increases gradually, and at Local time 5:30 AM, the tidal station Sandip is impacted, with its original maximum surge height being 3.00m. Here the water level elevation is 0.04m and 0.02 for 1% increase and decrease of maximum sustained wind radius.

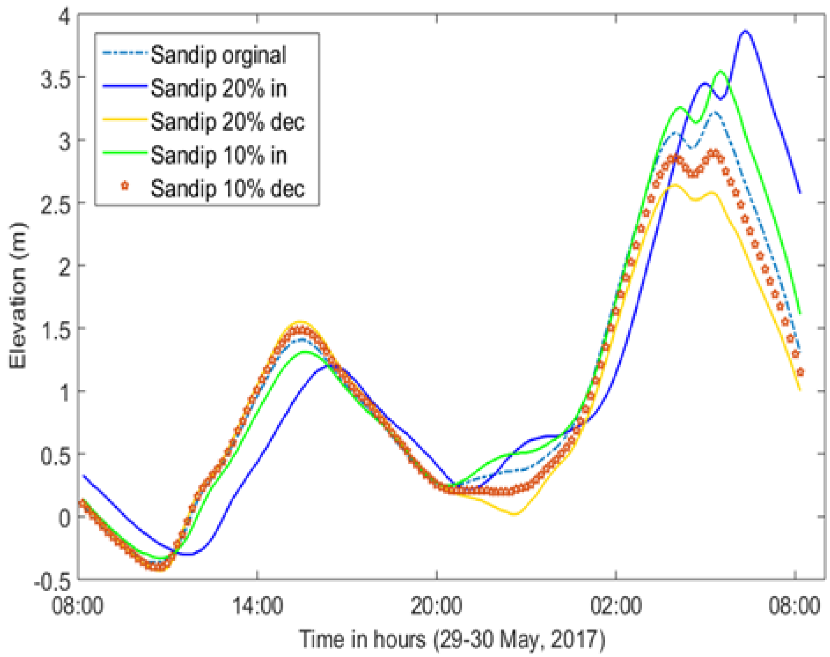

Fig. 7. Comparison of Observed and simulated data in Sandip

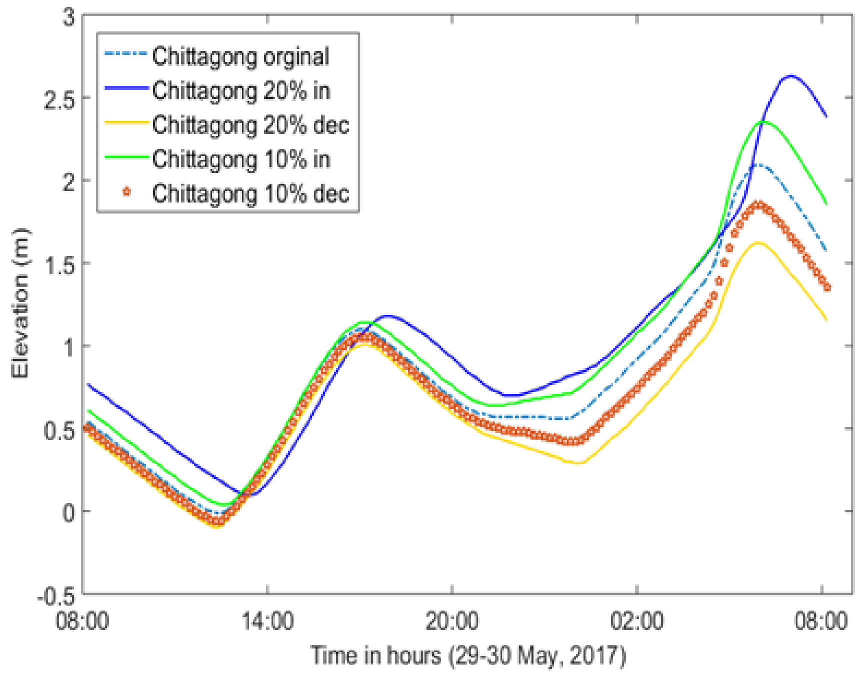

Fig. 8. Comparison of Observed and simulated data in Chittagong

In Chittagong coast the maximum surge height of cyclone MORA is 2.1m at Local time 6:00 AM. Here the maximum and minimum surge height is 2.1 to 2.7 and 1.9 to 2.4m according to wind radius. Here for 1% increasing and decreasing of wind radius, the water level rises 0.03m and falls 0.03m.

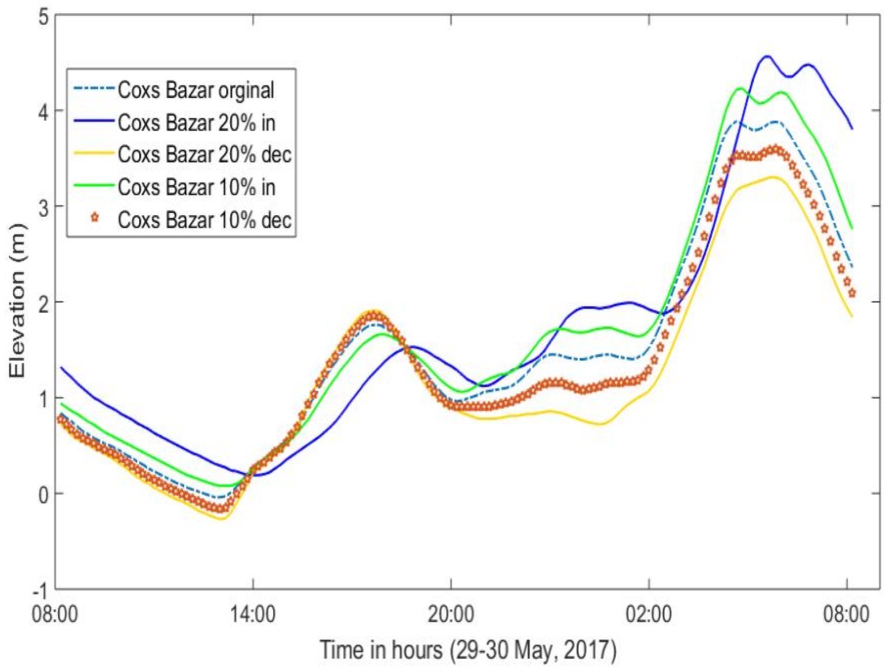

Fig. 9. Comparison of observed and simulated data in Cox's Bazar

From the track data of cyclone MORA, it is established that it made landfall on the Cox's Bazar coast at local time 6:00 AM on 30 May. Observing the simulation in Fig. 9, it is noted that the maximum surge height is 3.9m. Different changes in wind radius result in a variety of water level elevations. From the simulation Fig. 9, shows the rise and fall of water level is 0.03m and 0.035m for 1% increasing and decreasing of maximum sustained wind radius. Certainly, tropical cyclones are indeed influenced by climate change [32]. Simulated water level elevations of cyclone Mora with respect to observed data are shown in Table 1.

Table 1. Simulated water level elevation of cyclone Mora with respect to observed data.

Coastal Location	Observed Maximum Surge Height (m) with time (in hours)	Simulated Maximum Surge Height (m)			
		(20% increase)	(20% decrease)	(10% increase)	(10% decrease)
Hiron Point	3.3 30, May, 03:00AM	3.9	2.8	3.6	3.0
Patharghata	3.6 30, May, 12:00AM	4.2	3.2	3.9	3.3
Sandwip	3.0 30, May, 05:30AM	3.8	2.6	3.5	2.9
Chittagong	2.1 30, May, 06:00AM	2.7	1.5	2.4	1.9
Cox's Bazar	3.9 30, May, 06:00AM	4.5	3.2	4.2	3.3

4. CONCLUSION

This study investigates the cyclonic activity along the Bay of Bengal region. From this study, it is evident that changes in the track behaviour of a cyclone have an impact on its height. The origin of cyclones will shift into higher latitudes and the number of occurrences will decrease under future climate conditions. It has also been observed that the monsoon has an influence on the cyclones formed in the Bay of Bengal. The current climate condition shows that the post-monsoon season is a season prone to cyclone occurrence. But, due to the impact of climate change, the seasonal behaviour of cyclones will change in the future. It is also observed that maximum sustained wind radius plays a significant role in storm surge. For example, a small change in maximum sustained wind radius results in a drastic change in storm surge. Due to the impact of climate change, it has been observed that the behaviour of cyclones is anticipated to change in the future. As a result, the conclusion is drawn that storm surges will undergo changes due to increases or decreases in the maximum sustained wind radius under future climate conditions i.e. 0.032m rise and 0.026m fall due to 1% increase and decrease of wind radius.

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CONFLICT OF INTEREST

The authors declare no competing financial or personal interests that may appear and influence the work reported in this paper.

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