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A study on the future cyclone characteristics and its associated storm surge along the Bangladesh coast

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ABSTRACT

This study has investigated the surge height along the Bangladesh coast due to the changes in future cyclone characteristics. Cyclone characteristics mainly translation speed, landfall angle, maximum sustained wind radius, genesis behavior etc., were investigated with the present and future cyclone data calibration. We have used the d4PDF, AGCM data, and BMD data for calibration. An equation for a vertical shallow water model was developed and used to determine the water level elevation resulting from the modified cyclone information. The cyclone modification information was made by the calibration of present and past cyclone data. It is found from the study that the west part of Bangladesh will face intense cyclones but the East part may face the dangerous cyclone in the future. We have also seen that changes in the characteristics of storms result in a major change of storm surge.

1. Introduction

Bangladesh is a small disaster-prone country in South Asia. The natural hazards of this country increased due to global warming. According to the World Bank group, Bangladesh will face various problems due to the prevalence of climate change (Al Mohit et al., 2018a,b). Some factors are mainly responsible for this prevalence; the factors are densely populated, low-lying topography, coastal structure, funneling shape of the coast, El Nino Southern Oscillation, human activity, and so on. The major concern is that the catastrophic cyclone strikes Bangladesh in the next upcoming year due to global warming (Al Mohit et al., 2018a,b). According to (Al Mohit et al., 2018a,b), there are 269 depressions found in the Bay of Bengal from the last 44 years. But, the study of Alam et al. (2003) found that the average number of depression rate is 7.7 in the last 25 years (1974–1999), 3.46 depressions formed as mature storms and the number of 3.12 storms strikes the Bay of Bengal coast. In the context of the current development of Bangladesh, the discussion of cyclone behavior for the development plan of the coastal areas is an important issue. Because, according to (Debsarma, 2009; Paul, 2009), 80–90% of economic losses occurred in Bangladesh due to the outbreak of cyclones only. According to the Meteorological Department and the director of Disaster management, about 700,000 people have died in the past 200 years only due to the cyclone. The reason behind this huge death was abnormal surge height and fluctuating cyclone characteristics (Chowdhury et al., 1993). The characteristics of tropical cyclones are changing due to global warming and climate change. At present, the global simulation model is used to simulate the global climate condition, which may project the future cyclone behavior. To understand the global climate phenomena on a large scale, Coupled Model Intercomparison Project (CMIP) and its phase five is widely used.

Climate change is a big issue nowadays. We want to find out whether this issue has some influence on storm surge behavior or not. Bangladesh faces various disasters due to climate change and tropical cyclones are one of the well-known disasters in this country. So, for this reason, this study exercises the d4PDF to extract the change of cyclone characteristics due to global warming with +4K sea surface temperature (SST) condition. The d4PDF is the modified dataset of MRI-AGCM (Endo et al., 2012; Kitoh et al., 2018; Murakami et al., 2012) that represents the global climate dataset considering different sea surface temperature (SST) changes and this simulation is an ensemble simulation considering cumulus parameterization scheme. The ensemble big data was analyzed and summarized for appropriate findings of characteristics change of cyclone behavior along the coast of Bangladesh. (Hussain and Tajima, 2017) investigated the cyclone track features and tidal phase shift for the surge simulation. (Hussain et al., 2017) did further development of the same work. In their study, they investigated the parallel track features

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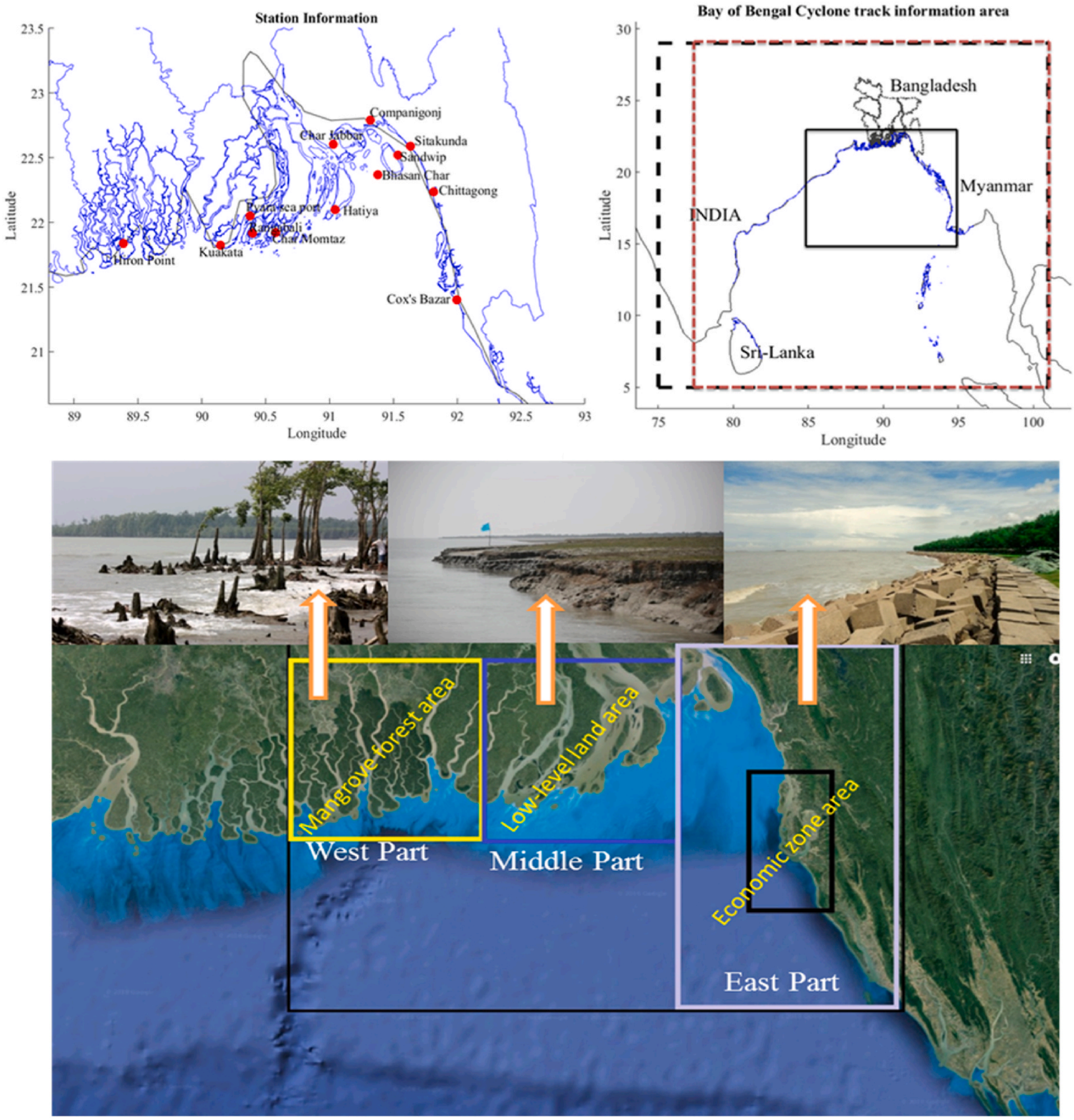

Fig. 1. Study area and its different sections: (a) Mangrove area, (b) Low level Land area, (c) Economic Zone.

impact on surge behavior. They found that the small changes of surge height occurred due to small angle difference (Hussain et al., 2017). It is seen from the literature point of view that the angle of the cyclone track may influence water levels associated with storm surge (Al Mohit and Towhiduzzaman, 2022). So, it is important to investigate the track features due to climate change and its associated surge which help us to develop a disaster mitigation plan.

The researcher (Lewis et al., 2014) used the different characteristics of a cyclone to find the uncertainty of flood behavior along this region. This study is useful for planning and decision-making but there is a lack of future investigation to make proper planning. (Hussain et al., 2017) used three track features to analyze the surge but the track features conditions preserved by their own opinion. In their study, they used the hypothetical track to investigate surge behavior. (Lewis et al., 2014) used 50-year cyclone track data to investigate the cyclone characteristics. Many analyses of storm surge due to the tropical storm have been made for the Bay of Bengal region covering the coastal area of Bangladesh and the east coast of India (Al Mohit, et al., 2018; Das, 1972; Paul and Ismail, 2012; Rahman et al., 2010; Roy, 1995). In the Bay of Bengal coast, the pioneering works are done by (Das, 1972; Flather, 1994). The linear storm surge model was developed by (Das, 1972) which was the first nested model for storm surge simulation. However, (Johns and Ali, 1980) developed the first nonlinear model. They incorporate the dynamic effect of the Ganges–Brahmaputra–Meghna river system in Bangladesh and offshore islands in their model. The proper stair step process represented the offshore islands. Nevertheless, they consider the Meghna estuarine region including only two major offshore islands Sandwip and Hatiya (Fig. 1). (Murty et al., 1986) provide the information about tide-surge interaction model and he concludes that it is very difficult to interact with tide and surge associated with a storm nonlinearly for the accurate prediction of the magnitude and time of the peak of water level on the oceanographic scale. (Paul and Ismail, 2013) found that the low-lying small and big lands and offshore islands might influence surge intensity. Furthermore, they developed the model of (Roy, 1995) by nesting a very fine grid model into the fine grid model as well as extending the fine grid model for the total coastal belt to incorporate the offshore island properly. To find the surge height accurately, (Al Mohit, et al., 2018) developed a two-dimensional bay-river coupled model incorporating the Ganges–Brahmaputra–Meghna river system. These works were done for the storm surge simulation on the Bangladesh coast; however, none of them considered the climate change impact on surge simulation.

Some well-known surge simulation models, FVCOM (Finite Volume Coastal Ocean Model) (Chen et al., 2003; Mao and Xia, 2017; Rego and Li, 2009), ADCIRC (Luettich et al., 1992), CH3D (Sheng and Paramygin, 2010; Sheng, 1987), and POM (Princeton Ocean Model) (Oey et al., 2006; Peng et al., 2004) are widely used to simulate the surge height but these models take long time to simulate. Therefore, it is difficult to analyze the surge behavior from the huge number of cyclone tracks. However, the SLOSH (Sea, Lake and Overland Surges from Hurricane) (Jelesnianski et al., 1992) is a light model to simulate storm surge but the developed bay-river couple model (Al Mohit, et al., 2018) also convenient to simulate the storm surge around this area.

In this study, we have analyzed 100 members of 60 years (1951–2011) simulation (6000 simulation) data for present climate scenarios and 90 members of 60 years (2051–2111) simulation (5400 simulation) data for future climate scenarios. After analyzing the cyclone track features, we have simulated the surge height along the Bangladesh coast for present and future climate scenarios. This study informs important information about cyclone behavior and surge height fluctuation in the present and future climate conditions, which will play a significant role in future disaster prevention planning. It has been observed from this study that the future severe cyclone-striking tendency is very high and the characteristics of track features are changeable. It is observed that the striking angle of future cyclones shifted from the Northeast to North-west direction and the water level elevation increases approximately 2–4 m along the coast of Bangladesh due to the storm of the future climate scenario.

2. Study area

This study mainly focuses on the southern part of Bangladesh, which is the coastal region of this country. The astronomical position of the country is 88° E to 92° E longitudes and 20° N–26° N latitudes. In this study, we have considered the study area 85° E to 95° E longitude and 15° N–23° N latitudes to investigate the surge height. We have considered this area in such a way to investigate a storm for at least three days within this domain. The major observed stations are incorporated in this study area (Fig. 1). However, the cyclone tracks are extracted from the ensemble simulation of d4PDF data from the region of 75° E to 101° E longitudes and 5° N–30° N latitudes. But the track features are extracted from those tracks that strike the area of the east coast of India, Bangladesh, Myanmar, and Sri-Lanka. The astronomical position of the track features area is 77° E to 101° E longitudes and 5° N–30° N latitudes. Fig. 1 explains the investigated study area properly. The color marked points indicate the tidal stations near the coast of Bangladesh, the black dotted color area represents the cyclone track information area, the red dot area represents the track feature analysis area and the bold black line represents the surge simulation domain area. This domain area is more vulnerable due to its characteristics, which are shallow bathymetry, long continental shelf, high astronomical tide and dramatic cyclone track (Ali, 1999; Debsarma, 2009; Paul and Ismail, 2012). Bangladesh Inland Water Transport Authority (BIWTA) has the exclusive legal rights to access the observed data within this area. However, not all the stations are digital at all, so, for this reason, the observed data scarcity is common in this region. Due to the low land area and complex coastal shape, the surge height fluctuation is high in this area. The d4PDF data represents the present and future cyclone information under different SST conditions but the data grid resolution is very low in this region. There is 60 km grid simulation data available in this region, which is not so good, but this can give the general information about the climate change impact on cyclone track behavior.

3. The data

In this study, we have used the 100 ensembles of historical (long-term trend of warming) simulation data d4PDF (Database for Policy Decision-Making for Future Climate Change), consisting of outputs from the well-known Atmospheric General Circulation Model (AGCM). This data was generated from the Global simulator of Meteorological Research Institute Atmospheric General Circulation Model known as MRI-AGCM 3.2 (Mizuta et al., 2012). This model developed from the weather prediction model of the Japan Meteorological agency (Borowitz, 2018). The developed model used triangular truncation with a linear Gaussian grid (TL319) and the 64 vertical levels with the top at 0.01 hPa (Imada et al., 2017). This represents 319 wave numbers and the grid resolution is 60 km in horizontal level and 64 vertical levels. The lower boundary conditions of model simulation are SST and sea-ice concentration (SIC, and sea-ice thickness (SIT). Global-mean concentrations of greenhouse gasses and three-dimensional distributions of ozone and aerosols were used for external forcing (Mizuta et al., 2012). The simulation period of the data set is 1951–2011 for present climate conditions and 2051–2111 for future climate conditions. The data consists of 100 members' simulation for present climate conditions, and 90-member simulation for future climate conditions. The future simulation is generated from six different ensemble simulation model of CC (CCSM4), GF (GFDL-CM3), HA (HadGEM2-AO), MI (MIROC5), MP (MPI-ESM-MR), and MR (MRI-CGCM3). The respective authorities of this simulation 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).

The radiative forcing of the model is monthly mean inter-annual variation of SST named Centennial Observation-Based Estimates of SST version2 (COBE-SST2) and the sea-ice concentration with +4k Global Warming condition (Hirahara et al., 2014). The detection method of tropical cyclones (TC's) from the d4PDF was firstly developed by (Oouchi et al., 2006), after that the method was further developed by (Murakami et al., 2012). In their study, they adopted some assumption to detect the TC, and the assumptions are: vorticity greater than 8.0×10^{-5}, the warm core at 300, 500 and 700 hPa exceeds 0.8 °C, maximum wind speed greater than 13 ms^{-1} at 850 hPa, and the duration of life-time longer than 36 h. The generated TC data consists of wind speed at 850 hPa, ground wind speed, sea-level barometric pressure, TC eye location every 6-h interval and so on. In this study, we have exercised the track features of d4PDF to investigate the cyclone track and find the surge behavior along the Bangladesh coast associated with the analyzed track features.

3.1. Data calibration and investigation

This study investigates the storm surge behavior along the Bangladesh coast due to the changes of cyclone characteristics of Bay of Bengal. In addition, for this investigation we have used d4PDF big data; however, to investigate some special features we have used few conditions. BMD categorized the cyclone as Low (L), Well Marked Low (WML), Depression (D), Deep Depression (DD), Cyclonic Storm (CS), Severe Cyclonic Storm (SCS), and Severe Cyclonic Storm with a core of Hurricane winds (SCS (H)) (Al Mohit, et al., 2018). According to the BMD, we have considered the cyclone in two different categories; one is a low-intense cyclone and another one intense cyclone. We have separated the cyclone in such a way that the central pressure between 1013 hPa and 970 hPa is considered a low intensity cyclone. On the other hand, if a cyclone has the central pressure below 970 hPa in its lifetime (Genesis to landfall) then we consider the cyclone as an intense cyclone. We have also separated the cyclone track for each country area like Bangladesh, Sri-Lanka, Myanmar, and India to investigate the track

Table 1
Number of cyclones strikes in different countries. The strike numbers are divided into two criteria: intense and low intensity.

		Present	CC	GF	HA	MI	MP	MR
	Total Track	21,862	2622	2563	2382	825	1934	2332
Sri-Lanka	Strike Track	412	17	28	15	13	13	4
	Low-intense	412	17	28	15	13	13	4
	Intense	0	0	0	0	0	0	0
India	Strike Track	7927	1098	1105	1029	277	588	1011
	Low-intense	7417	980	1033	939	245	541	920
	Intense	510	118	72	90	32	47	91
Bangladesh	Strike Track	952	154	107	93	51	89	110
	Low-intense	803	114	86	76	37	67	82
	Intense	149	40	21	17	14	22	28
Myanmar	Strike Track	1819	210	152	186	43	84	167
	Low-intense	1762	189	149	179	40	81	163
	Intense	57	21	3	7	3	3	4

Table 2
Number of cyclone strike in different part of Bangladesh coast.

			Present	CC	GF	HA	MI	MP	MR
	Total Track	All	952	154	107	93	51	89	110
		Low In.	803	114	86	76	37	67	82
		Intense	149	40	21	17	14	22	28
East Part	Strike Track		296	42	25	23	15	18	24
	Low-intense		253	31	20	17	11	15	17
	Intense		43	11	5	6	4	3	7
Middle Part	Strike Track		252	34	34	21	17	20	36
	Low-intense		203	26	26	20	14	12	26
	Intense		49	8	8	1	3	8	10
West Part	Strike Track		404	78	48	49	19	51	50
	Low-intense		347	57	40	39	12	40	39
	Intense		57	21	8	10	7	11	11

feature properly. Taking the concept of the studies (Jain et al., 2010; Rao et al., 2010), the area is separated for taking the track information. If the landfall occurred in the specified region, then we consider the track for that region. Therefore, for this reason, the sample size of cyclone parameters is different in each region. After that, the landfall angle was calculated from the study of the calculation process of azimuth distance. Those storms hit in different regions of the study area are used to analyze landfall properties of that region. Different cyclones have a different pattern and structure with a considerable wind-pressure relation (Knaff and Zehr, 2007). To find the relation between wind and pressure, some idealized model is very useful (Jelesnianski and Taylor, 1973) but there is some uncertainty (Lewis et al., 2014). In this study, we have used the relation of the study of (Lewis et al., 2014), but the estimation was taken from the big dataset of d4PDF. The estimated parameters are wind speed (V_{max}), latitude (ψ) and maximum wind radios (R_{max}) from equation (1).

$$R_{max} = 46.4 \times e^{(-0.0155 \times V_{max} + 0.0169 \times \psi)} \quad (1)$$

We have selected the parameter for storm surge simulation after analyzing the track features. Fig. 3 shows the future cyclone track that strikes the Bangladesh coast in different climate scenarios. In this study, we have found the cyclone-striking rate is different in various regions. After separating the cyclone track, we have investigated the features of those tracks in each scenario of CC, GF, HA, MI, MP, and MR. The landfall tracks are considered by their characteristics. If the position of the cyclone eye point is on the island or mainland, then we consider that the cyclone makes a landfall. If the two consecutive two-eye points represent sea and land, then we have determined the track as a landfall track. If the landfall happens in a specific country area, then the cyclone track is considered the landfall track of that country. The ratio of the number of strike cyclones and the total number of formations is considered as strike rate. Otherwise, it is treated as low depression inside the sea. The total number of strike rate is the accumulation of intense and low intense cyclone strike rate (see, Table 1). Both Bangladesh and India will face a huge number of cyclones, but Bangladesh may face more intense cyclones. It is evident from this research that Bangladesh will face more intense cyclones in future (see Table 2).

Therefore, it is our high attention to concentrate on the Bangladesh coastal area to make a useful plan to prevent the coast from future cyclone disaster. Fig. 2 represents the cyclone strike rate in different climate scenarios. The upper figure indicates the strike rate for the low intensity cyclone and lower figure shows the strike rate for the intense cyclone. If we analyze the trend of the relative items, we have found that the trend of low intensity cyclone strike rate would decrease in Bangladesh coast. But, the trend of intense cyclone strike rate is increasing in the future (See, Fig. 2). To understand the cyclone activity in the coast of Bangladesh, we have separated the coast into three different parts. Each coast has its own characteristics. The east part is an economic zone, middle part is low land zone and the west part is mangrove forest zone. The physical difference of the three different parts of Bangladesh coast is known as the eastern part, middle part and western Part (Khan and Kawasaki, 2015) (see, Fig. 1).

In a similar fashion of previous analysis, we have separated the cyclone track for the individual coastal area of Bangladesh. Fig. 3 shows the strike rate in different parts of the Bangladesh coast. From this investigation, we have found that the western parts of the Bangladesh coast will be more vulnerable due to the intense cyclone in future. But, most of the dangerous and catastrophic cyclones will strike on the eastern coast of Bangladesh. Based on the future cyclone central pressure behavior, it is found that the intense cyclones pass through the west part of Bangladesh coast but more dangerous and catastrophic cyclones pass through the east part of Bangladesh. So, it is important to concentrate on the development of the coastal structure and disaster prevention policy along the east part of Bangladesh coast. This part is also important for future disaster prevention plans due to the development of the coastal zone and Rohingya (people who come from Myanmar) future security. The Bangladesh government wants to settle 10 million Rohingya in the floating island Bhasan Char near the coast of Chittagong. There are 10 million Rohingya Settlement Islands in this

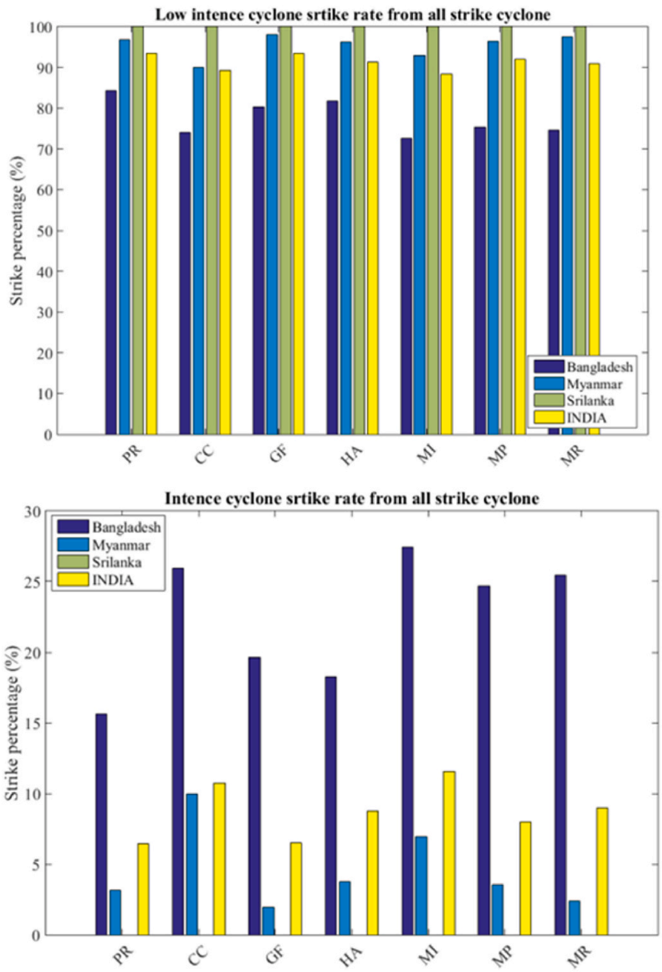

Fig. 2. Cyclone strike rate for low intensity cyclones and intense cyclones. The upper part of the figure shows low intense cyclone strike rate and the lower part of the figure shows intense cyclone strike rate.

eastern zone. Another important feature parameter of a cyclone is central pressure. The central pressure of the strike cyclone in each part of the coastal area of Bangladesh shows different characteristics under present and future climate conditions. In the scenario of CC, GF, HA, MI, MP and MR, the central pressure of a cyclone is unstable for intense cyclones but the low intensity cyclone represents the stable changes due to climate change. The mean and standard deviation uncertainty of cyclone central pressure for present and future scenarios is shown in the figure (see Fig. 4). In this figure, the left side green color figure shows the low intense cyclone central pressure and the right-side orange color figure shows the intense cyclone central pressure with mean and standard deviation. The bar line indicates the standard deviation uncertainty and the circle mark shows the lowest central pressure. From this study, it is evident that the eastern part of Bangladesh coast faces dangerous cyclones but most of the intense cyclones strike western part of Bangladesh. Another important track feature is the landfall angle. For the different climate scenarios, we have observed the characteristics of cyclone landfall angles. The overall characteristics of landfall angle depend upon the coastal structure and environmental conditions.

The figure shows the central pressure behavior for the intense and low intensity cyclone in different parts of Bangladesh coast.

In this study, we have found that the landfall angle would be shifted northeast to northwest direction in the future climate scenario along the coast of Bangladesh. Fig. 5 shows the histogram of the landfall angle for the different climate scenario in the east part of Bangladesh coast.

The landfall angle behavior varies in different parts of Bangladesh coast. The landfall angle changed due to present and future climate conditions. The east direction landfall is considered as zero degrees and the next 90° considered counter-clockwise direction as north, west and East part. To understand the actual phenomenon of landfall angle, we have collected the mean angle from each scenario of CC, GF, HA, MI, MP and MR. The maximum sustained wind radius size reduces for the intense cyclone with stable conditions under present and future climate conditions, but for the low intense cyclone, the wind radius changes is negligible. For future disaster mitigation and adaptation planning, different model simulation data is needed but there are some uncertainties in the data for future prediction. This study has some limitations but it can give some good information to the planner. In this study, the simulation conditions are taken from the intense cyclone conditions that strike the eastern part of Bangladesh coast (see, Table 3 and Table 4).

4. Numerical model setup and methods

4.1. Mathematical formulation

To measure the water level due to a storm, we have developed a numerical bay-river couple model to estimate the surge height along this region, where we have used the obtained track features from the d4PDF data to a known cyclone track BOB 01. The known cyclone track is used to estimate water level accurately and compare the simulated water level with observed data to understand the fluctuation of water level in different scenario surge simulation results. Considering the oceanic and atmospheric phenomenon, when the horizontal length is wider than the vertical length then the vertical component of momentum equations is approximated by the hydrostatic equation. The density variation is also negligible in all the directions. Then, the depth-averaged vertically integrated bay-river couple model is considered from the study of (Al Mohit et al., 2018a,b). The rectangular Cartesian coordinate model was constructed to consider the origin point at Northwest corner, the displaced position of the free surface as $z = \zeta(x,y,t)$ and position of the sea floor as $z = -h(x,y)$. The development of the bay-river coupled model takes into account the nonlinear interaction between river and bay dynamics in order to incorporate the big river system. Both the bay and river model simultaneously work for the bay-river couple model. For the fluid motion in the sea surface calculation, the basic set of shallow water equations for the bay and river model can be written as (Al Mohit et al., 2018a,b)

$$\zeta_t + \widetilde{u}_x + \widetilde{v}_y = 0 \tag{2}$$

$$\widetilde{u}_t + (u\widetilde{u})_x + (v\widetilde{u})_y - f\widetilde{v} = -g(\zeta + h)\zeta_x + \frac{T_x}{\rho} - \frac{C_f\widetilde{u}\sqrt{(u^2 + v^2)}}{\zeta + h} \tag{3}$$

$$\widetilde{v}_t + (u\widetilde{v})_x + (v\widetilde{v})_y + f\widetilde{u} = -g(\zeta + h)\zeta_y + \frac{T_y}{\rho} - \frac{C_f\widetilde{v}\sqrt{(u^2 + v^2)}}{\zeta + h} \tag{4}$$

$$(\xi_{riv})_t + (Hu_{riv})_x + (Hv_{riv})_y = 0 \tag{5}$$

$$(Hu_{riv})_t + \left(Hu^2_{riv}\right)_x + (Hu_{riv}v_{riv}) - Hfv_{riv} = -g(\xi_{riv})_x + \frac{T_x}{\rho} - C_f u_{riv}\left(u^2_{riv} + v^2_{riv}\right)^{1/2} \tag{6}$$

$$(Hv_{riv})_t + (Hv_{riv}u_{riv}) + \left(Hv^2_{riv}\right)_y + Hfu_{riv} = -g(\xi_{riv})_y + \frac{T_y}{\rho} - C_f v_{riv}\left(u^2_{riv} + v^2_{riv}\right)^{1/2} \tag{7}$$

where $(\widetilde{u}, \widetilde{v}) = (\zeta + h)(u, v)$, the Reynolds averaged components of velocities are u,v in the directions of x any y respectively; $f = 2\Omega$ *sinsin* φ is the Coriolis parameter, where Ω is the angular speed of the earth rotation and φ is the latitude of the place of interest; g is the acceleration due

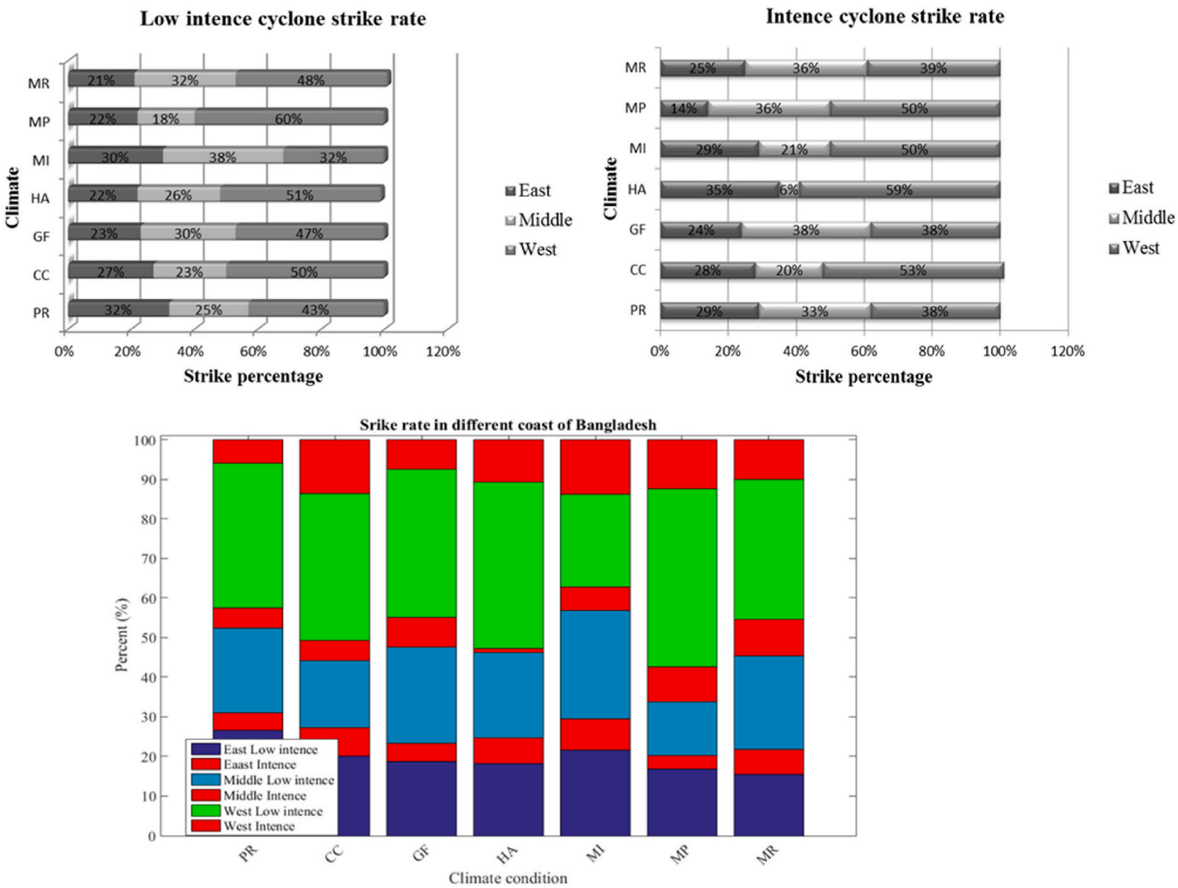

Fig. 3. Cyclone strike rate in each part of Bangladesh coast. The lower part of the figure shows the intense and low intensity cyclone strike rate. The upper figure shows the general overall strike rate in different parts of Bangladesh coast.

to gravity; ρ is the density of the sea-water supposed to be homogeneous of the same density. The total water column depth is $H = [\xi_{riv}(x,y) + h_{riv}]$. The boundary conditions are taken from the study of (Al Mohit et al., 2018a,b). In this study, we have used radiation boundary conditions to invite the M_2 tide in the southern boundary to estimate the surge height for the known cyclone BOB 1991 track with the result of model simulation and field survey data. But we don't use the tidal effect to simulate the surge height for future climate condition scenarios like CC, GF, HA, MI, MP, and MR. A conventional quadratic law of (Johns and Ali, 1980) is used to find the wind stress component from the relation

$$(T_x,T_y) = \rho_a C_d \left(u_a^2 + v_a^2\right)^{\frac{1}{2}} (u_a,v_a) \tag{8}$$

where the surface drag coefficient is $C_d = 2.8\times10^{-3}$ from the study of (Roy, 1999); ρ_a is the density of the air; u_a,v_a are the surface wind of x and y components. (Jelesnianski and Taylor, 1973) model was used to derived the surface wind field from the following equation

$$V_a = \begin{cases} V_0\sqrt{(r_a/R)^3} & \text{for all} \quad r_a \le R \\ V_0\sqrt{(R/r_a)^3} & \text{for all} \quad r_a > R \end{cases} \tag{9}$$

Where V_0 is the maximum sustained wind, R is the radial distance and r_a is the radial distance at which the wind field is desired.

4.2. Model setup and simulation procedure

In order to estimate the appropriate water level due to a surge in the designated study area, it is important to investigate the activity of the cyclone over the area at least 3 days before crossing the coast. It is observed that the surge response along the coast becomes significant well before crossing the coast. Therefore, the mesh size (two consecutive grid points distance) should be smaller to incorporate the major islands of the estuary. To make smaller the mesh size, we have faced two practical problems over the whole study area: (i) Number of grid points where the computation parameter ζ,u,v need to be computed there takes more space of computer memory and much CPU time in each time step of the solution process. (ii).In order to maintain the stability of an explicit finite difference scheme, a reduced mesh size necessitates a correspondingly diminished time step. So that, the time step, Δt, should be related to the mesh size of Δx, Δy, and the ocean depth, h, by the following relation of CFL (Courant-Friedrichs-Lewy) condition $\Delta t \le \frac{\Delta x}{\sqrt{2gh}}$, where, g = gravitational acceleration.

Considering this fact, a nested mesh scheme has been used to predict the water level due to a storm. The physical location of the scheme is shown in Fig. 6. The prescribed nested schemes are: fine mesh scheme (FMS), coarse mesh scheme (CMS) and a very fine mesh scheme (VFMS). In this study, the nesting is made sequentially from the CMS to FMS and FMS to VFMS. The CMS covers the domain 15° N–23° N latitudes and 85° E to 95° E longitude. In this mesh size, the grid space is $\Delta x = 15.08$ km and $\Delta y = 17.52$ km associated with the 60x61 grid points in the computation domain. In a similar fashion, FMS cover the area between the latitude 21°-15′ to 23° N and 89° E to 92° E longitudes with 92 × 95-grid point associated with the grid distance $\Delta x = 2.15$ km and $\Delta y = 3.29$ km. To incorporate the landfall target area properly, the VFMS covers the area between 21.770 N to 23° N latitudes and 90.40° E to 92° E longitudes. In this scheme, the grid size of the x-axis (north-south direction) is $\Delta x = 720.73$m and the y-axis (east-west direction) $\Delta y = 1142.39$ m with 190 × 145-grid points. The process of representing the approximation of island boundaries through a rectangular grid is known

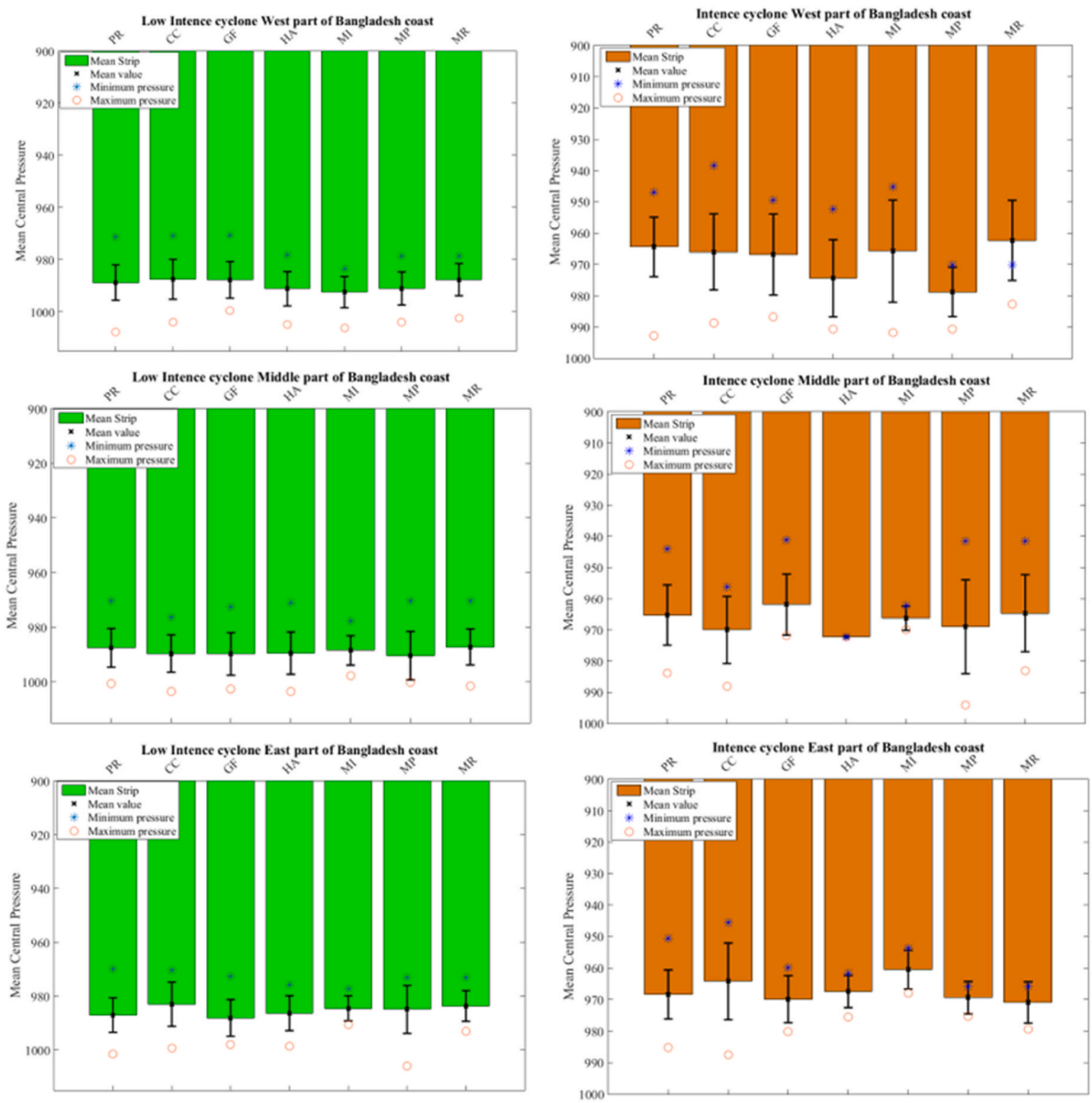

Fig. 4. Mean and standard deviation uncertainty of cyclone central pressure.

as stair-step representation (see, Fig. 6).

The boundary condition of the CMS scheme is taken from the study of (Al Mohit et al., 2018a,b). The CMS scheme is fully independent and the parameter ζ prescribed from those obtained in CMS in each time step of the solution process used as boundaries of the FMS. In a similar way for VFMS, parameter ζ prescribed from those obtained in FMS in each time step of the solution process used as boundaries of the VFMS. But, for the bay-river couple model, the matching condition is used to simulate the surge considering the river dynamics. The bay and river exchange the information from the relation taken from (Al Mohit et al., 2018a,b) as

$$u_{bay} = u_{riv} + \frac{Q}{B_{riv}(h_{riv} + \xi_{riv})} \tag{10}$$

where Q represents the river discharge and B_{riv} is the river breath. The river discharge was considered $Q= 5100.00m^3$ from the study of (Jain et al., 2007). However, for this simulation, the external forces data are taken from the track features analysis of d4PDF data and the known track information collected from the Bangladesh Meteorological Department (BMD). The water depth data was collected from the General Bathymetric Chart of the Oceans (GEBCO) bathymetry data of 30-s arc resolution. BMD provided 3-h time intervals cyclone track data with central pressure and wind speed conditions. In our simulation, we have presented the last 48-h's simulation result because of the stable condition.

5. Results

In this research, we focused on a severe cyclone that occurred in 1991 near Chittagong, Bangladesh. To assess the influence of alterations in cyclone characteristics on water level elevation, we adjusted the path of Cyclone BOB 1991 while accounting for the unique features of cyclones in various climate scenarios. For the six scenarios, we undertook a calibration process for the cyclone track feature. This involved making adjustments to the 1991 cyclone's characteristics, specifically focusing on factors such as translation speed, landfall angle, maximum sustained wind radius, and other relevant parameters. To get better understanding, the path of the cyclone for different scenarios and actual cyclone BOB 1991 is shown in Fig. 7.

In the first stage of our investigation, we validated alterations in water level elevation corresponding to the actual trajectory and

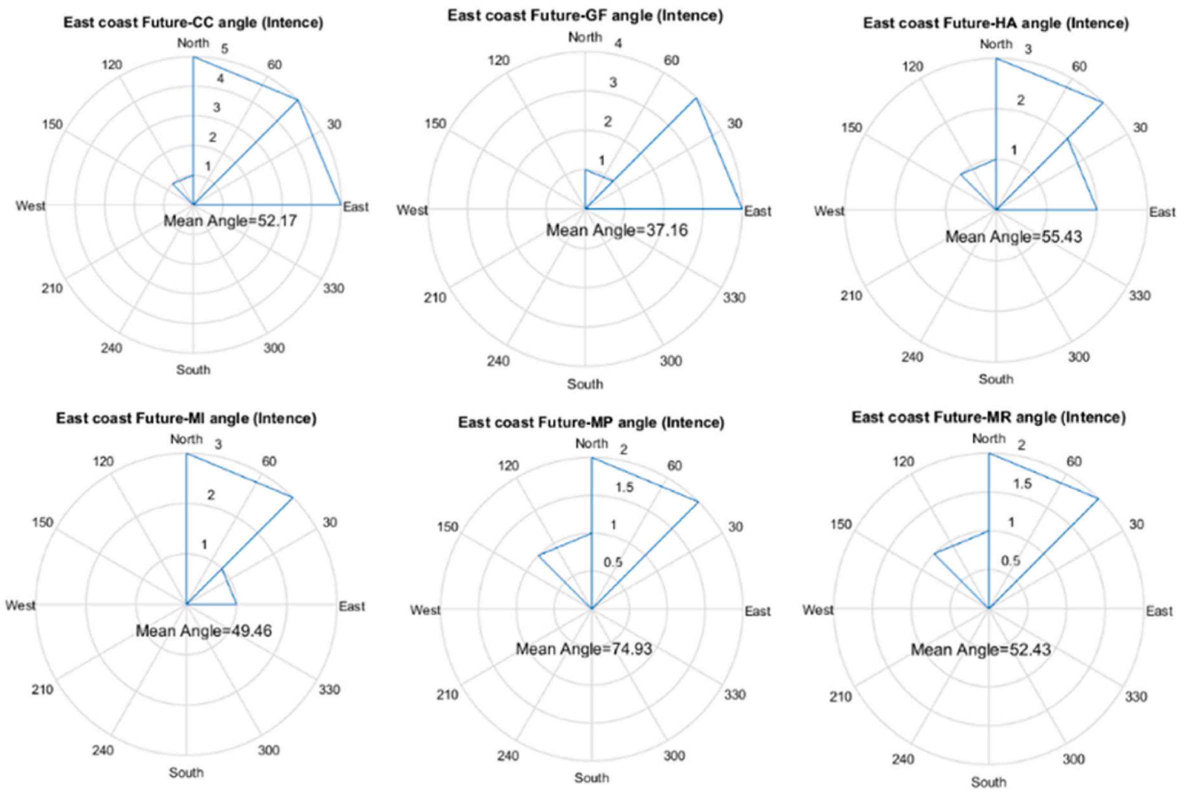

Fig. 5. Histogram of future cyclone landfall angle in East part of Bangladesh coast.

Table 3
Cyclone track features of different climate scenario for east part of Bangladesh coast.

		Landfall Angle	Translation speed	Max. wind speed	Central Pressure before landfall	Central pressure all
Present	Max	116.6	35.9	62.0	985.1	1003.5
	Min	0	9.77	57.52	950.62	929.36
	Mean	53.19	21.71	59.73	968.36	980.26
CC	Max	90.0	28.6	60.8	987.6	1008.6
	Min	26.36	10.37	57.41	945.54	929.65
	Mean	52.17	19.80	59.38	964.21	976.13
GF	Max	63.02	35.85	60.65	980.24	994.92
	Min	0	9.68	58.60	959.82	959.82
	Mean	37.15	19.39	59.87	969.85	980.82
HA	Max	90.0	28.6	60.1	975.4	1004.4
	Min	23.36	20.94	58.56	961.62	956.05
	Mean	55.42	24.32	59.22	967.46	984.80
MI	Max	63.02	22.94	60.69	968.00	993.27
	Min	26.76	14.20	58.63	953.75	953.75
	Mean	49.45	20.56	59.32	960.48	976.83
MP	Max	90.0	32.8	61.2	975.3	1002.2
	Min	63.43	22.87	59.38	965.87	945.75
	Mean	74.93	28.99	64.08	969.38	977.08
MR	Max	90.00	32.8	61.2	979.4	1000.9
	Min	26.36	14.24	57.93	961.41	935.60
	Mean	52.43	23.39	60.12	970.89	976.27

Table 4
Comparison of tidal result.

Tide station	Estimated tide (m)	Observed tide (m)
Cox's Bazar	2.28	3.00
Chittagong	2.80	3.40
Hiron Point	2.42	2.60

attributes of Cyclone BOB 1991, substantiating our findings with observed data. Subsequently, we utilized our model to estimate tides. Our results demonstrated a robust concurrence between the estimated tidal values and the observed tide data at a specific location, presenting simulated time series data for tides at the Cox's Bazar tide station.

This simulation is only for the M_2 tide condition. M_2 tide refers to a specific type of tidal component, known as the M_2 tidal constituent, which represents one of the dominant tidal cycles observed in coastal areas. It is characterized by its semi-diurnal nature, meaning it has two high tides and two low tides in approximately 24 h and 50 min. This dataset covers the period from April 28, 1991, to April 30, 1991, providing valuable insight into tidal behavior during that time period. After that, we have run the model for surge simulation. When the simulation result gives us the correct result, we run the model for changing the cyclone track with calibrated future cyclone characteristics. Finally, we get the water level elevation due to the changes of cyclone characteristics. We have found that the model result can make a good agreement with observed data. The simulation results and observed data are shown in Fig. 9.

From this figure, we have found that the maximum surge height was 6 m (approximate) near the Cox's Bazar and Chittagong tide station. But, the Hiron Point tide station shows 2.8 m water elevation. The water level fluctuation occurred due to the direction of the cyclone path. In the discussion section, we have explained details about the water level elevation for different climate scenarios.

Following this, we executed the model under various scenarios for the cyclone. The outcomes illustrate the water level elevation associated with the cyclone, highlighting its unique distribution. These findings offer a comprehensive overview of water level variations at different tide stations during the cyclone event. Furthermore, the results delve into more detailed insights about the fluctuations in water levels across diverse climate scenarios, contributing to subsequent modeling outcomes.

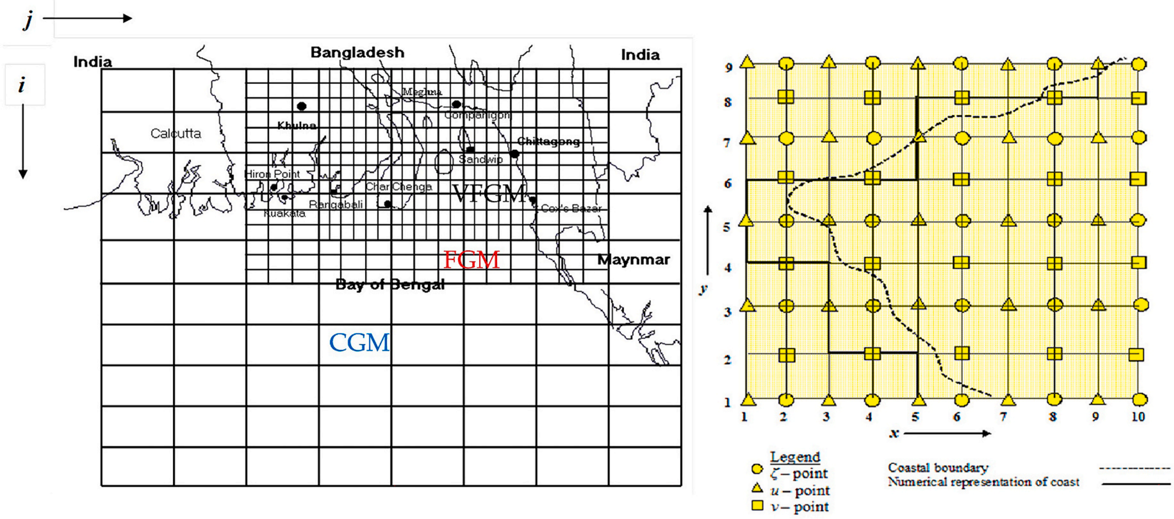

Fig. 6. Mesh scheme with Arakawa C grid: (a) Fictitious grid for model simulation, (b) Arakawa pattern.

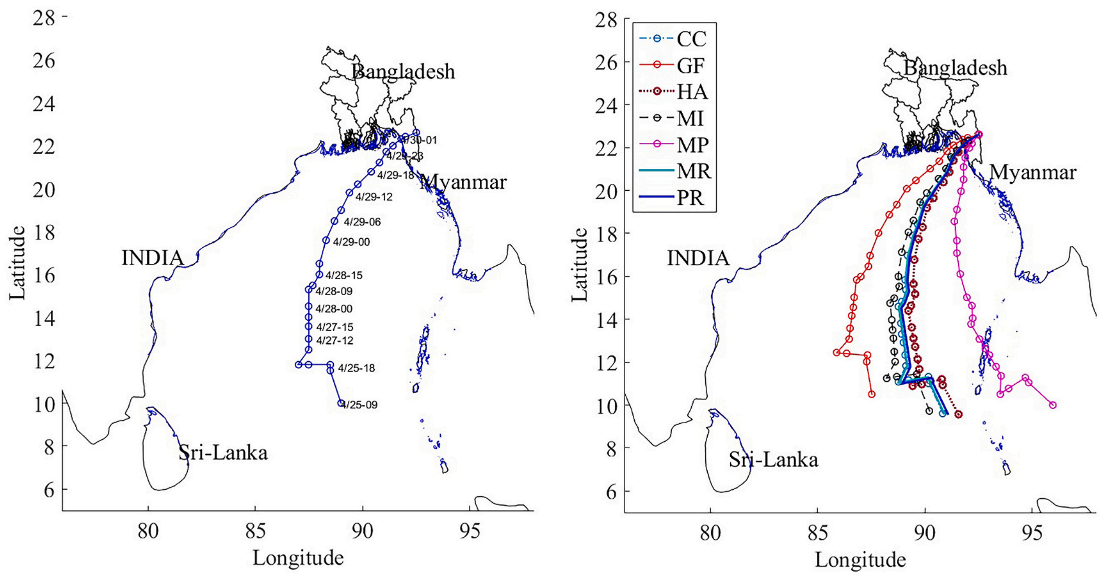

Fig. 7. Observed cyclone track of 1991 (left). Cyclone track changes by the characteristics in each scenario (right).

6. Discussion

Last 50 years' record shows that some strong cyclones struck the Bangladesh coast, research found from the researcher famous among them are AILA, SIDR, and Cyclone 1991 (BoB 01) (Rahman et al., 2017). This study investigates the 1991 cyclone to simulate the surge, because the cyclone was most dangerous due to its devastation (Roy, 1995). Record from BMD, it has been determined that Cyclone 1991 was the most intense cyclone of the 19th century, with a maximum wind speed reaching 235 km/h. The eastern part of the Bangladesh coast, Chittagong, Cox's Bazar is the aggrieved area due to this devastating cyclone. Fig. 7 shows Cyclone 1991 track and its associated track, which changed by the characteristics in each scenario. The left side of the figure shows the observed cyclone track with 3-h time intervening eye position. The right-side figure shows the different cyclone track of different climate scenarios, which strikes the same position. The model runs for three days' simulation but the last 48 h' result is displayed. From this analysis, we have found that the maximum surge height is 4–6.5 m around the eastern part of Bangladesh coast. To investigate the surge height

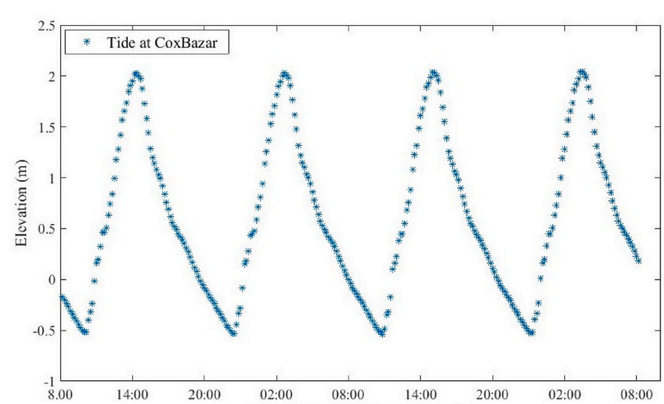

Fig. 8. Simulated Time series data of tide at a tide station named Cox's Bazar. The time series data represent for April 28, 1991 to April 30, 1991.

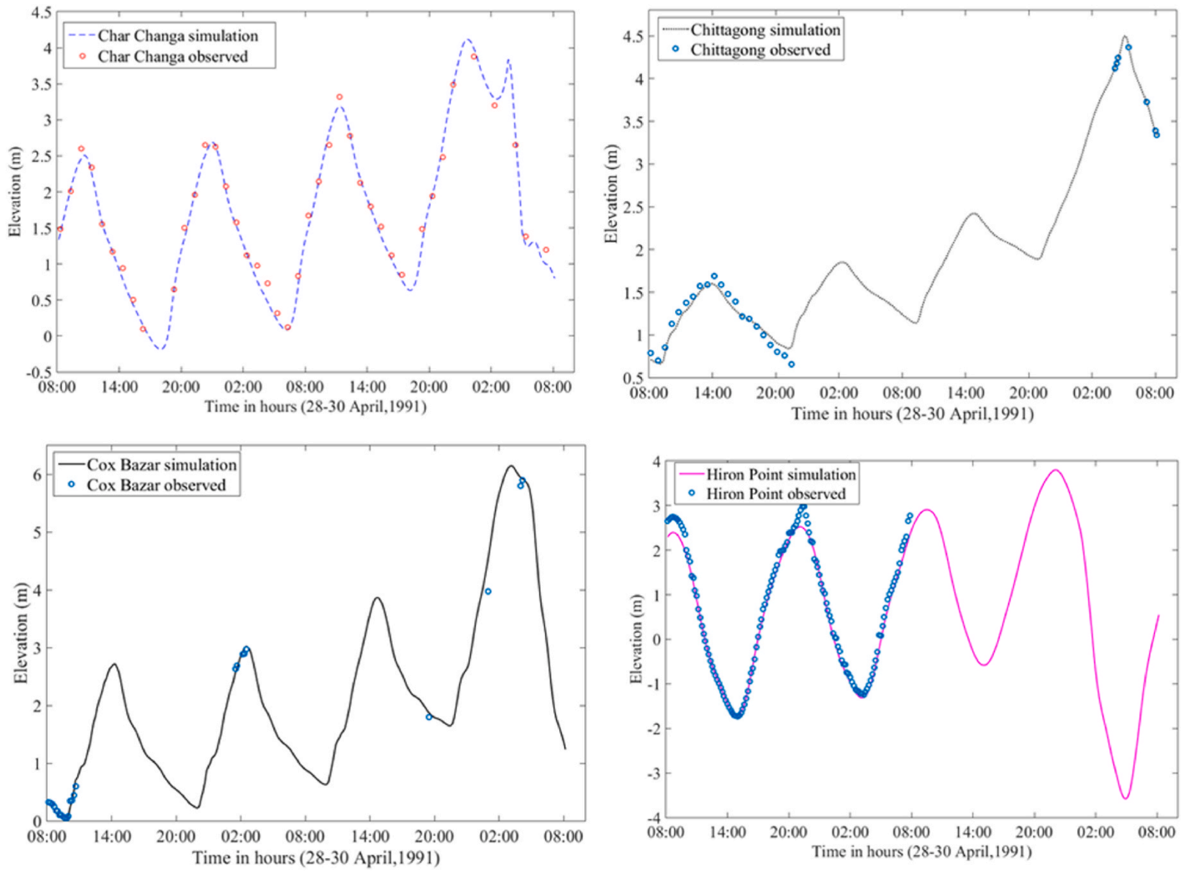

Fig. 9. Observed and predicted water level in different tide stations. The upper left figure represents the Char Changa island water level elevation and the upper right, lower left and lower right represent the tide station Chittagong, Cox's Bazar and Hiron point tide station.

accurately, tide and surge interaction is necessary. In our simulation model, a non-linear interaction of M_2 tide and surge is used. The simulation result of the tide is shown in Fig. 8. We have investigated the tide result and it makes good agreement with observed data.

Fig. 9 displays a time series dataset depicting water level elevations resulting from the 1991 cyclone. The simulated outcomes closely align with the observed water level data, demonstrating agreement. This figure illustrates water level elevations at four key coastal locations in Bangladesh. Limited observed data availability is attributed to challenging weather conditions and manual data collection processes in this region. Our research utilizes a consistent numerical model to replicate diverse cyclone paths under varying climate scenarios, enabling the simulation of storm surges based on distinct cyclone track characteristics. To discern the varied attributes of a cyclone track, we employed analyzed track features from a well-documented cyclone. Within this inquiry, we identified different values for landfall angle, maximum sustained wind radius, translation speed, and other parameters, as detailed in Table 3. Employing these track features, we modified the established track to represent different climate scenarios, namely CC, GF, HA, MI, MP, and MR. The selection of the initial track was informed by the destructive characteristics of historical cyclones. For an in-depth exploration of climate impacts on surge characteristics, we maintained a

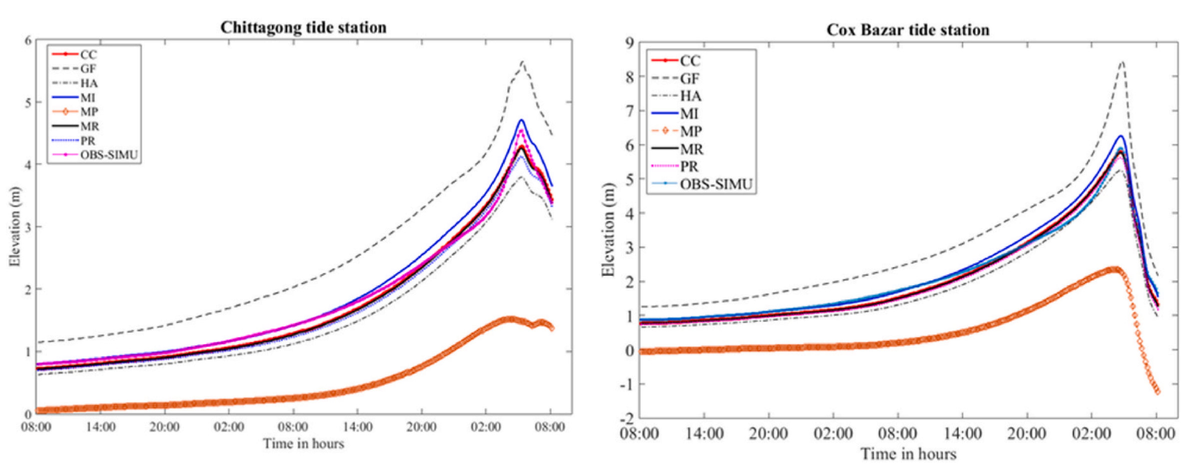

Fig. 10. Water level elevation due to the changes of track feature in different scenarios. The left figure shows water level elevation at Chittagong tide station and the right-side figure for Cox's Bazar tide station.

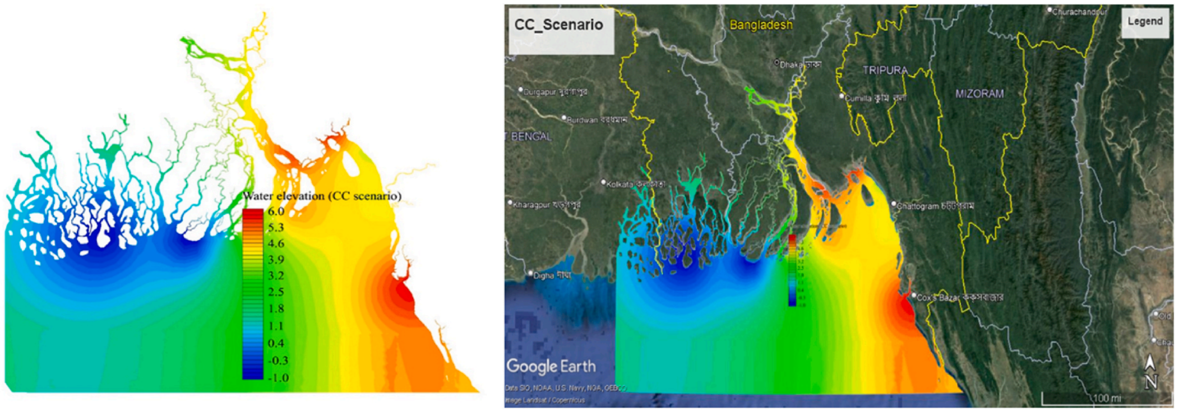

Fig. 11. The water level distribution along the coast of Bangladesh.

consistent landfall point. Fig. 9 illustrates the time series of water level elevation corresponding to scenarios CC, GF, HA, MI, MP, and MR.

This outcome illustrates those varying scenarios of sea surface temperature (SST) lead to distinct surge patterns. For the scenario of GF and MI, the maximum surge height was found for the same types of cyclones that strike the Bangladesh coast. In the GF scenario, the highest surge levels are observed along the coast of Bangladesh. One possible explanation for this elevated surge height could be the Sea Surface Temperature (SST) pattern. However, it's noteworthy that the landfall angle in this scenario is significantly lower compared to other scenarios. Conversely, the water level height in another scenario closely resembles that of current and historical observed cyclones. This discrepancy underscores the inherent instability in future cyclone characteristics, largely due to the substantial uncertainty associated with the region's future climate conditions. This uncertainty hinges on the projections generated by climate simulations. To enhance disaster preparedness planning in this region, it is advisable to analyze a broad spectrum of climate simulation data. Unfortunately, there is a dearth of data regarding future cyclone track features along this region. Consequently, we have conducted a comprehensive analysis encompassing a large dataset of current and future cyclone tracks from d4PDF, alongside historical cyclones from the year 1991. We have seen that climate change is causing a major change in the characteristics of tropical storms. As a result of which its effect is being observed in the field of water elevation due to surge.In this study, we may get the general information about the surge behavior in different climate scenarios, which give the general concept to disaster mitigation and adaptation plan for future cyclone risk. To understand the model performance, we have simulated the historical cyclone of 1991 and compared the water level elevation data with the observed data of BMD (Fig. 8). In this simulation, we have found that the landfall angle and maximum wind radius has great influence on surge height. The surge height fairly agreed with the study of (Flather, 1994; Paul and Ismail, 2012; Rahman et al., 2017; Roy, 1995). They found that the tidal influence at landfall time makes the surge height higher within this area. The cyclone tracks of future climate scenarios are modified through the track features of landfall angle, translation speed, and maximum wind radius. Then the modified tracks are used to simulate the surge for different scenarios. Fig. 10 shows the overall distribution of water level along the coast of Bangladesh for the CC climate scenario. In the similar fashion we check the distribution for GF, HA, MI, MP, and MR. We have found that the MI scenario is similar to the Bay of Bengal present scenario, because of the SST condition. We have found that the GF shows the maximum surge height. Though MI scenario shows most of the intense cyclone striking the Bangladesh coast in this scenario but, GF shows maximum surge height due the central pressure and landfall angle (see Fig. 11).

We have found the recession occurred in the western part of Bangladesh when the cyclone strikes the eastern part of Bangladesh. The most affected area is Cox's Bazar (see, Fig. 1) district when the cyclone passes the Chittagong area. The maximum surge height was found 6.8 m around the Cox's Bazar coastal area. In this study, the MP scenario shows the minimum surge height, which is comparatively lower than other climate scenarios. Fig. 9 shows the maximum surge height distribution along the coast of Bangladesh. In each scenario, the maximum surge height fluctuation is 2–4 m. The GF and MI scenario shows the maximum surge and the MP scenario shows minimum surge along the coast of Bangladesh, but the rest of the scenario shows the same features as the present scenario. Therefore, for disaster prevention and coastal protection Bangladesh government needs to check the future Bangladesh climate condition. If the condition is similar to the scenario of GF, then the disaster will be more dangerous for the east part of Bangladesh coast. This research helps us understand how cyclones affect the coastal areas of Bangladesh. When a cyclone hits the eastern part of Bangladesh, water levels in the western part go down. This shows that cyclones don't affect water levels the same way everywhere. Among the places affected, Cox's Bazar stands out as very vulnerable. When a cyclone goes through Chittagong, Cox's Bazar has the highest surges, with water going up by as much as 6.8 m. This means we really need to be ready and have plans to protect this area. In our study, we looked at different climate scenarios to see what might happen with surges. The "MP" scenario usually had the lowest surges, meaning it was less severe compared to the other scenarios. We made a picture (Fig. 9) to show where the highest surges happen along the Bangladesh coast. This picture helps us see how surges change in different places. It's important to know that in each scenario, surges can go up and down by 2–4 m. This shows that cyclones can be different, and we need flexible plans to stay safe. Out of all the scenarios, "GF" and "MI" usually have the highest surges, while "MP" usually has the lowest along the Bangladesh coast. The others are similar to what we have now. Our study focuses on understanding how likely future disasters are. If our climate becomes like the "GF" scenario, there's a higher chance of more severe disasters on the eastern part of Bangladesh's coast. This means we really need to make strong plans to protect the coast and prevent disasters in the future.

7. Conclusion

This study discusses the water level elevation due to the future cyclone of different climate scenarios along the coast of Bangladesh. The catastrophic cyclone of 1991 exhibited varying surge behaviors when subjected to different scenarios, highlighting the distinct impacts associated with each scenario. In this study, it appears that Bangladesh is highly vulnerable to a future cyclone disaster. More than half of the storm has a tendency to strike the west part of Bangladesh coast. But, the most catastrophic cyclone strike tendency is high in the east part of Bangladesh coast. In addition to this, there has been a reflection of the water level elevation due to a storm by the non-persistent SST and landfall angle. The tendency of the future cyclone to move from the northeast to the north-west is much higher in the coast of Bangladesh. Water level elevation due to the cyclone of GF and MI scenario is higher than the MP scenario. The overall fluctuation of water level in the different scenarios of CC, GF, HA, MI, MP, and MR is 2–4 m along the coast of Bangladesh. Eventually, to develop the future disaster and mitigation plan, this study may make a good impression.

CRediT authorship contribution statement

Md. Abdul Al Mohit: Conceptualization, Methodology, Software, Writing – original draft. **Masaru Yamashiro:** Conceptualization, Investigation, Visualization. **Md. Towhiduzzaman:** Data curation, Investigation, Software, Writing – review & editing. **Atish Kumar Joardar:** Investigation, Software, Validation, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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