Geosystems and Geoenvironment 2 (2023) 100159

Contents lists available at ScienceDirect

Geosystems and Geoenvironment

journal homepage: www.elsevier.com/locate/geogeo

Tropical cyclone data calibration for the estimation of a path of a cyclone along the coast of Bangladesh

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ARTICLE INFO

Article history:
Received 26 May 2022
Revised 10 October 2022
Accepted 4 December 2022

Handling Editor: E. Shaji

Keywords:
Tropical cyclone
d4PDF
AGCM
Disaster
Cyclone track
Bangladesh

ABSTRACT

A small regionally based probabilistic cyclone track estimation method has been developed in this study. The study domain was split into twelve equally spaced areas with the random number of cyclone eye points. The random number of cyclone eye point data was taken from the output of the dynamic climate simulations model MRI-AGCM (Atmospheric General Circulation Model) and d4PDF (Database for Policy Decision-Making for Future Climate Change) cyclone track data, that used to improve the influence measurement analysis and adaptation planning for global warming. The probability theory, especially the Probability Density Function (pdf) under the normal distribution was then applied to the individual small area to find the most probable cyclone track. This virtual cyclone path shows the direction of the present and the future cyclone path that gives more information for the cyclone disaster prevention.

1. Introduction

Bangladesh is a riverine country with a high-density population, located on the northern tip of the Bay of Bengal. Some well-known disasters like tropical cyclone strikes in Bangladesh every year, causes huge death and economic losses and Bangladesh will face various problems due to the prevalence of climate change (Al Mohit et al., 2018a). According to the oceanographer, five to seven cyclones strike this terrain every year (Debsarma, 2009) and the study of (Al Mohit et al., 2018b) shows 7.7 cyclones. As we know, cyclone track will play an important role in preventing cyclone disaster. The historical cyclones in Bangladesh 1970, 1985, April 1991, 1997, SIDR 2007, Nargis 2008, AILA 2009 are well known for their destructiveness (Mizanur Rahman et al., 2011). Due to the catastrophes of a cyclone (Gayathri et al., 2016; Rahaman and Esraz-Ul-Zannat, 2021), it will not be a threat only to human life but also to the socioeconomic risk for a country. In the present day, although the death toll from the cyclone disaster has decreased, the economic losses have increased. According to the red cross society and the ministry of disaster management and relief of Bangladesh, the historical cyclones BOB 1991, SIDR (2007) and AILA (2009) had economic losses $1390 million, $1.7 billion and $296.6 million respectively. On the other hand, the death toll was 138,000, 10,000, and 339 respectively. So, some oceanographers studied the tropical cyclones along this region (Das, 1972; Meah et al., 2017; Paul et al., 2014) and the Arabian Sea (Dube et al., 1986). Some research on track features associated with simulation models (Al Mohit and Towhiduzzaman, 2022). Their studies were based on surge simulation, but for the surge simulation an acceptable cyclone track information is needed. That's why it is important to investigate the probable cyclone path along the Bay of Bengal to measure the losses by disaster due to the present and future cyclone. Some worth mentioning work on the cyclone track detection was done around the world, considering the individual basin with the clustering method (Blender et al., 1997; Elsner, 2003; Nakamura et al., 2009; Srivastava et al., 2021; Terry and Kim, 2015). The statistical cyclone track detection novel concept of (Rumpf et al., 2007) is now widely used for stochastic modeling for cyclone track detection. Some similar works (Hall and Jewson, 2007; James and Mason, 2005) are very useful for cyclone track analysis and risk correlation analysis (Oo et al., 2018; Rabby et al., 2019). According to the scientists (Chenoweth, 2006; Scheitlin et al., 2010), they created a probable cyclone track (Terry and Kim, 2015) by averaging the analog cyclone tracks. (Camargo et al., 2007) developed a probabilistic clustering method for typhoon tracks (Zhang et al., 2013). These

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https://doi.org/10.1016/j.geogeo.2022.100159
2772-8838/

studies can detect the cluster-based cyclone path, but their studies have some limitations on operation error and storage capacity of data. (Sahoo and Bhaskaran, 2016) introduces a mathematical process for finding a synthetic track. In their study, they used the inverse distance weighted interpolation method to find a synthetic track considering the two extreme historical cyclone tracks. But to investigate the most probabilistic cyclone path huge number of cyclone track information is needed. Recently, the regression mixture model (Wedel and DeSarbo, 2009) is used for cluster-based cyclone track detection. Though this method needs the structured value of the dependent and independent variable. But this is useful for statistical cyclone track detection.

In our study, a probabilistic cyclone tracking process has been developed depending on the location of a particular region based on storm information. We have considered more than thousand simulated cyclone track information for the estimation of probabilistic cyclone track. The one-sample Kolmogorov-Smirnov test was performed to examine the normality of the time-based random position of a cyclone observed data to apply the probability density function. The present and future cyclone tracking paths represent the different disaster-prone locations along the Bay of Bengal, which is very important for the disaster prevention caused by present and future catastrophic cyclones.

2. Material and methods

2.1. Data

The data that we have used in this study is AGCM (Atmospheric General Circulation Model), d4PDF (Database for Policy Decision-Making for Future Climate Change), and BMD (Bangladesh Meteorological Department) cyclone track data. The Japanese Government has taken some initiatives to make contributions to the IPCC Fifth assessment report, among them being a significant operational numerical weather prediction model known as MRI-AGCM (Meteorological Research Institute-Atmospheric General Circulation Model) (Mizuta et al., 2006). Extensively modified community climate model (CCM1) is now known as AGCM model (Williamson and Rasch, 1989). In the present AGCM model, the spectrum conversion method is used horizontally for mass, heat, and momentum, and 60 vertical layers were used in the sigma level-adjusting system. This high-resolution model is conducted for 20×20 km grid spacing with the truncation number T959 and the vertical level number L60. The time slice method was used in this method for different types of climate condition simulation under the different sea surface temperature (SST) as a boundary condition. The present climate condition was treated as 1979 to 2003, near future climate condition treated as 2015 to 2040, and the future climate condition treated as 2075 to 2099. Some researchers also explain the behavior of Climatological characteristics of Bay of Bengal (Bhardwaj and Singh, 2020; Wang et al., 2017). In this study, we have used the present and future climate condition data to analyze the climate change scenario.

The IPCC has derived four representative concentration pathways (RCPs) for future GHG emissions in the coming century. RCP-2.6 shows aggressive in limiting GHG and RCP-8.5 shows the continued increase in yearly emissions, causing an increase in global mean temperature of +4° by the end of the century. The global historical and future simulations were performed for a Database for Policy Decision-Making for Future Climate Change which is known as d4PDF. The present data consists of 100 members (individual simulations) of 60 years in 1951 to 2010 with perturbed observed SST (COBE-SST2) as the lower boundary condition. The future climate data has been simulated with 6 different CMIP5 sea surface temperature (SST) warming patterns for a + 4 K climate as the lower boundary condition. The six models were chosen to represent the differences in CMIP5 model results of the second experiment. Each of the 6 SST warming patterns has been run for 60 years in 15 members after removing the long-term trend in the SST and with GHG concentrations equal to the year 2090 in the RCP-8.5 scenario. The six SST models are CC (CCSM4) operated by the National Center for Atmospheric Research (USA), GF (GFDL-CM3) operated by Geophysical Fluid Dynamics Laboratory, NOAA (USA), HA (HadGEM2-AO) operated by the Met Office Hadley Center (UK), MI (MIROC5) operated by AORI, NIES, JAMSTEC (Japan), MP (MPI-ESM-MR) operated by Max Planck Institute for Meteorology (Germany), and MR (MRI-CGCM3) operated by the Meteorological Research Institute (Japan). For the d4PDF data, we have used the same time slice (25 years) data for the investigation of the cyclone position at present and future climate conditions. The observed data were collected from the Bangladesh Meteorological Department.

2.2. Methodology

This study is a statistical estimation of a cyclone track from the mega-ensemble climate simulation model output data and analyzed the present and future climate condition data under the probability theory to find a probabilistic synthetic cyclone track. For this reason, a probability density function is used to investigate the probability of a cyclone occurrence in a specific area. In this study, we have used the longitude and latitude data to investigate the position of a cyclone eye point. The longitude and latitude data were collected from the designated study domain and the considering study area was 76–99° East longitude and 5–28° North latitude (see Fig. 1). We have divided our study area into twelve separate small areas (Yasuda et al., 2010). This selected study area was split 8° along the longitude and 6° along the latitude. The latitude band was divided under the consideration of the lifetime position of a cyclone like genesis, developing, cyclolysis and landfall. So, for this reason the genesis band was divided into 3 different parts and these are G1, G2 and G3. In the similar way, D1, D2, D3 are the area of the development zone, C1, C2, and C3 are the area for the cyclolysis zone and L1, L2, L3 are the area of the Landfall zone. The area resolution may have some effect on the probable direction of a storm, the standard deviation of the probabilistic synthetic track can get rid of that effect. A non-parametric one-sample Kolmogorov-Smirnov test (Massey, 1951) was performed to check the normality of the data at the individual area. Fig. 2 represents the one sample K-S test result for latitude data of cyclone eye point. It shows the similarity of the empirical cumulative distribution and the standard normal distribution. The difference between the blue and red line indicates the K-S statistics. At the higher latitude the difference has no significant impact on K-S statistics.

The Kolmogorov-Smirnov statistics is

$$D_x = \operatorname*{Sup}_x |F_n(x) - F(x)| \tag{1}$$

$$F_n(x) = \frac{1}{n}\sum_{i=1}^{n} I_{[-inf,\ x]}(X_i) \tag{2}$$

where, F_n is empirical distribution function and $I_{[-inf,\ x]}(X_i)$ is an indicator function, $i =$ counter, $n =$ number of observation, $x =$ evaluated point, $X_i =$ observation point and $D =$ critical value. At the higher latitude the difference has no significant impact on K-S statistics. So, the statistics show that the data comes from the normal distribution. After checking the normality test, we have applied the probability density function under normal distribution in the individual zone and found the most probabilistic area from the individual zone (see, Fig. 3). The general formula of probability density function of the normal distribution is

$$f\left(x;\ \mu,\ \sigma^2\right) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\mu)^2}{(2\sigma^2)}} \tag{3}$$

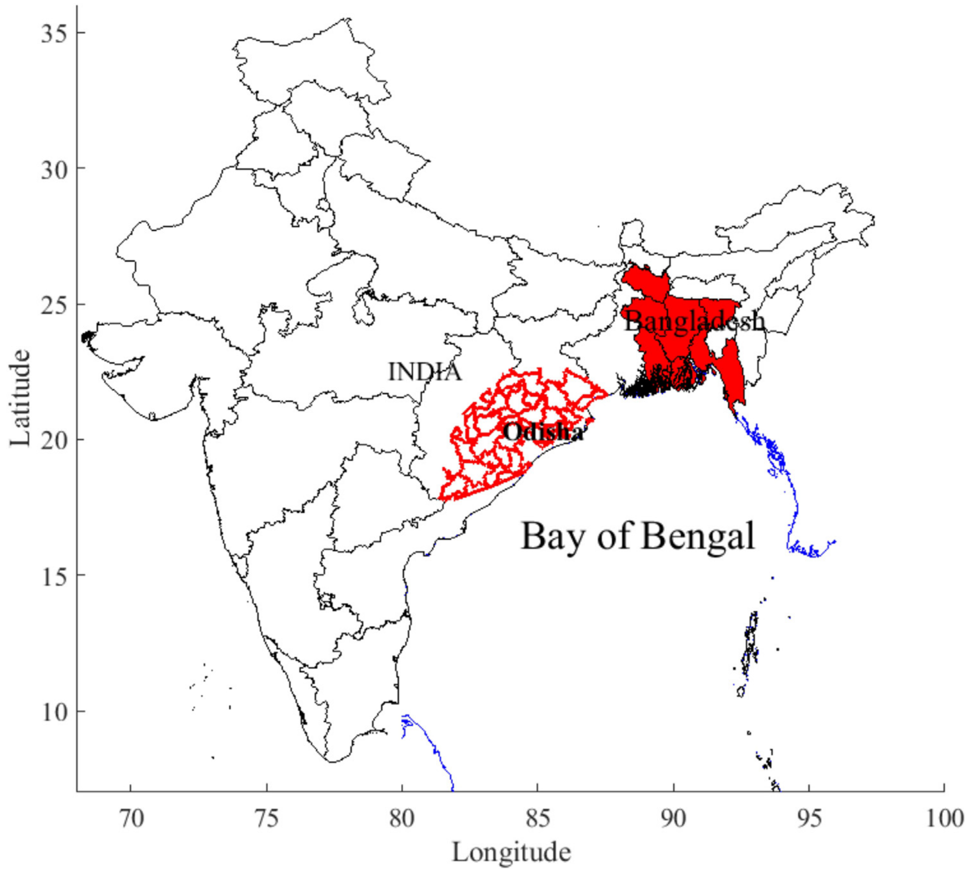

Fig. 1. Study area shows the total Bay of Bengal with Bangladesh coast, Indian coast, Sri-Lankan coast and Myanmar coast. Color parts represent Bangladesh and Visakhapatnam (India). The color part is prone region for storm disaster.

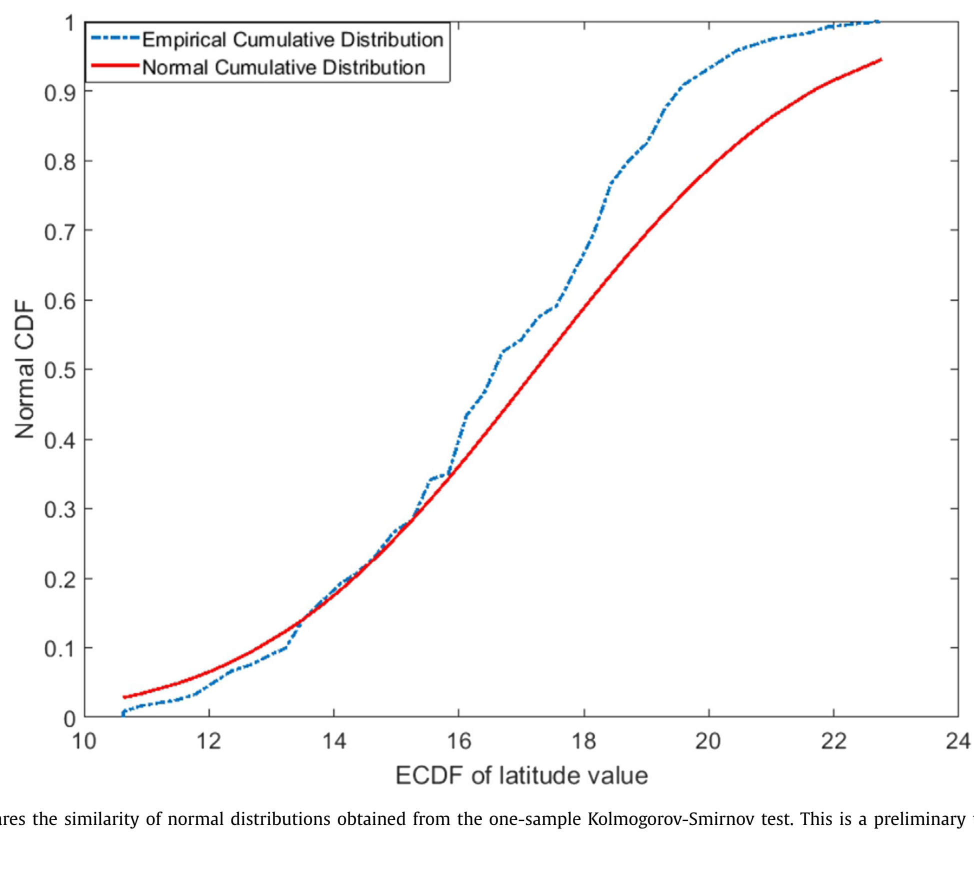

Fig. 2. The figure compares the similarity of normal distributions obtained from the one-sample Kolmogorov-Smirnov test. This is a preliminary test of k-means clustering.

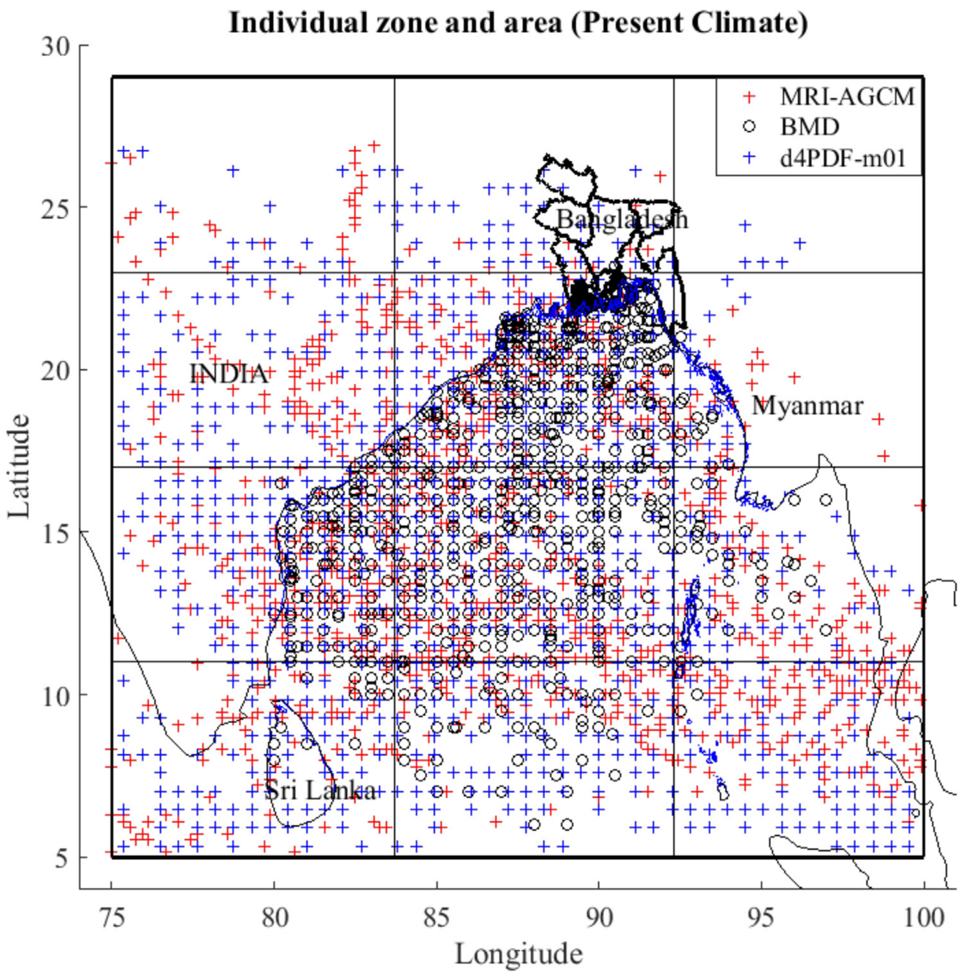

Fig. 3. Point locations of storm eye points derived from BMD, AGCM, and d4PDF-data. which are indicated by different symbols. This information is obtained from the current climate or the current state of the storm.

where, μ = sample mean and σ = standard deviation. The most probabilistic area was then found by the highest percentage of the probability of cyclone position data. To find the probable cyclone eye point from the maximum probable area, we have applied the pdf again in the data of the maximum probable area. After that, the same process has been applied to the other probabilistic area of the individual zone. A moving average filter was then applied to the acquired probabilistic cyclone eye point data to remove the high-frequency fluctuations of the data pattern. Finally, adding the acquired probabilistic point to get the most probabilistic synthetic cyclone track. Different cyclone tracks are found from the different data set of observed and model output data. This is the nested process of finding the probabilistic cyclone eye point.

3. Results

The global environment simulation model output data have been used to investigate the cyclone track under the present and future climatic conditions. To understand the condition of cyclone behavior Figs. 3 and 4 may explain the cyclone eye point and its position in present and future climate conditions. The present data represents the AGCM, d4PDF member one and BMD data. To region-based investigation of the data, we have separated our study region into four different zones according to the modification of the (Rumpf et al., 2007) technique. After that, the individual zone was divided into three vertical zones to make twelve individual areas. Every six hours' interval cyclone position information is plotted here.

We have collected all the scenarios of d4PDF and splatted every data based on the individual splatted area. But, here we present only one member of d4PDF data. The C0 SST criteria for AGCM data and CC SST condition one-member simulation data are represented in Fig. 4. In every small area, there is some cyclone information for proper investigation. The region-based separation of data made by the arbitrary choice of latitude band. There is no significant change of track trend due to arbitrary choice of latitude band. For our study, we have separated the data from twelve individual areas. After that, we have applied the statistical analysis of present and future cyclone track trend analysis.

The analysis of the small area data can represent better accuracy with proper investigation. Figs. 5 and 6 represent the possible point of AGCM data under present and future climate conditions associated with the individual area of a probabilistic point. In this figure, G1, G2, and G3 are the small areas of the genesis zone. The probability and the number of storms that occurred in the small area are shown in the box in the same figure. The G1 area of the genesis zone shows the probability 37.74801% and cyclone occurrence numbers (57). In a similar way, 20.52600% and 41.72600% cyclone occurrence probability for G2 and G2 area under Genesis zone.

After that, we tried to find the maximum probabilistic area and we found the maximum probability of the Genesis zone is G3 area and this area is considered the most probable area of cyclone

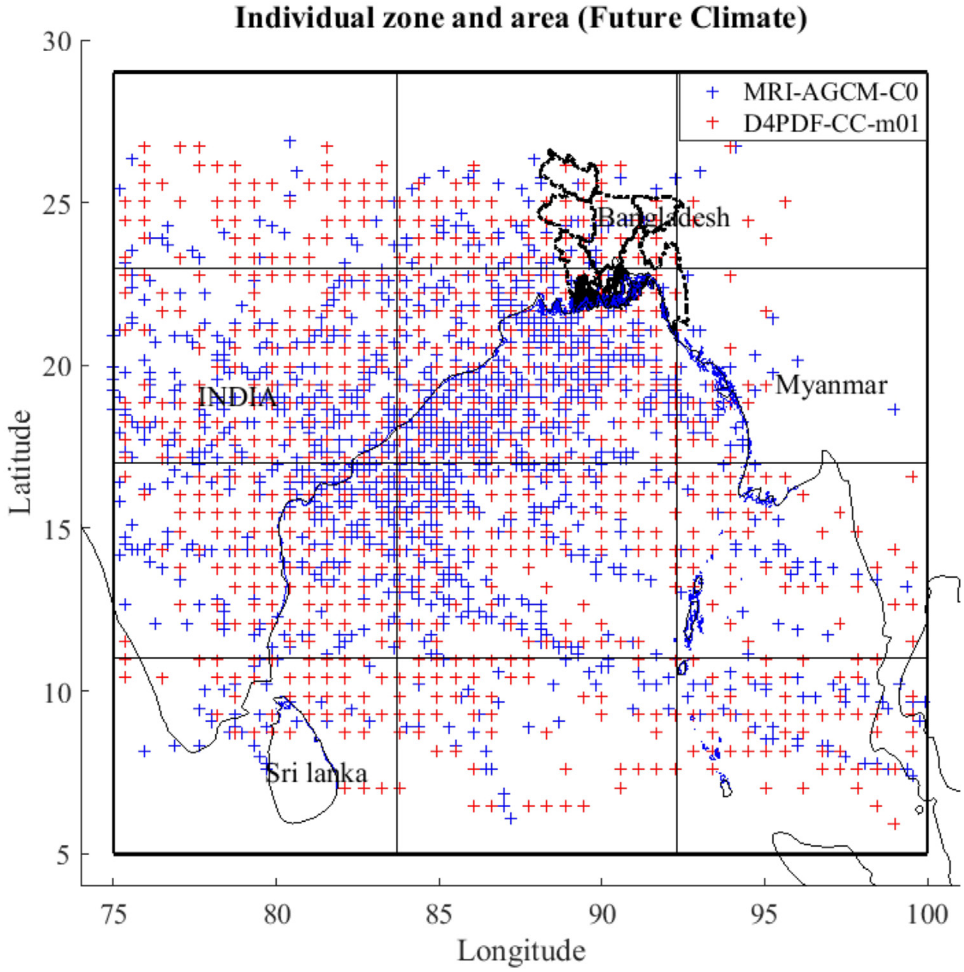

Fig. 4. Point locations of storm eye points derived from AGCM, and d4PDF-data. which are indicated by different symbols. This information is obtained from the future climate or the future state of the storm.

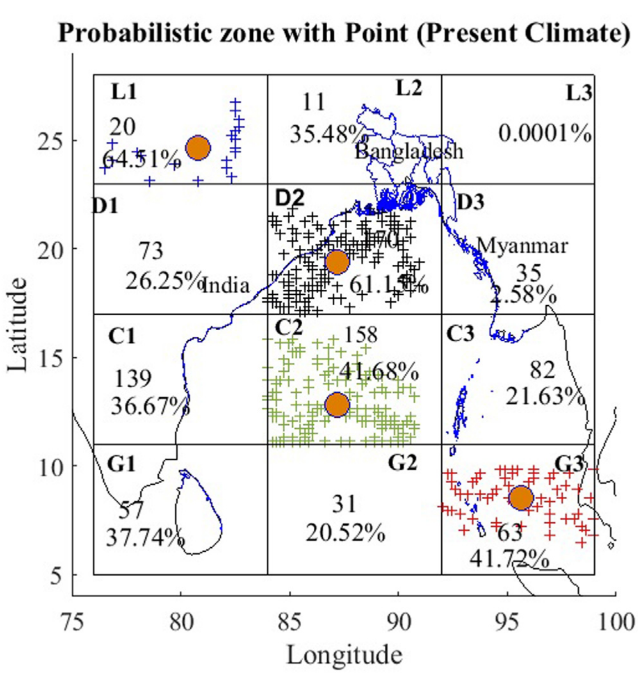

Fig. 5. Probable point of the storm in a given area after K-mean clustering of data obtained from current climate conditions.

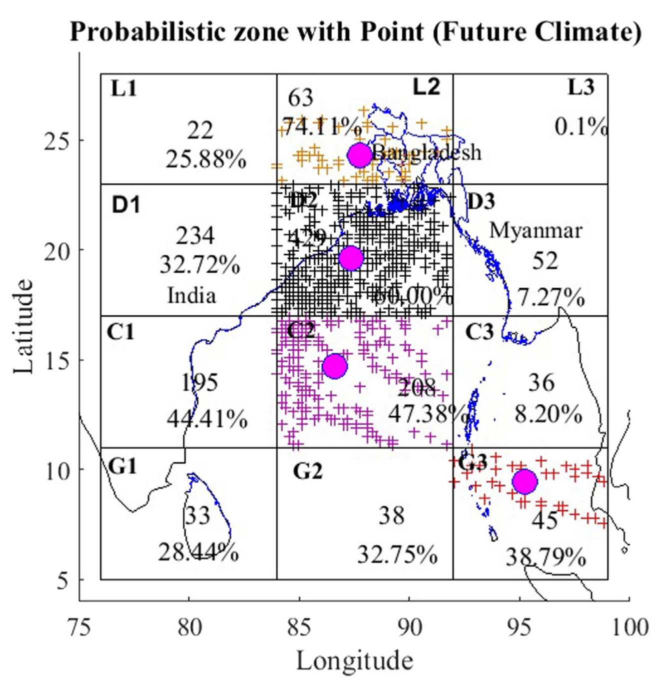

Fig. 6. Probable point of the storm in a given area after K-mean clustering of data obtained from future climate conditions.

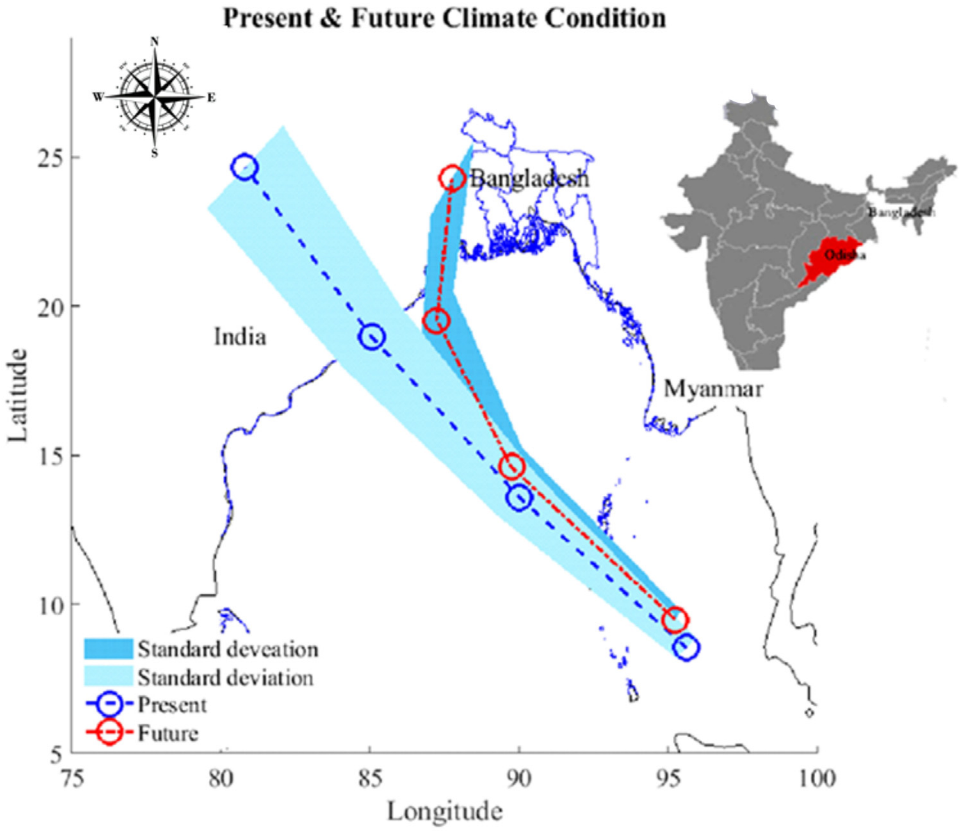

Fig. 7. Probable synthetic cyclone tracks of the data based on the results of the clustering method. Probable storm tracks of storms obtained under current climate and future climate conditions.

genesis zone. The same probability theory applies to the other zones like cyclolysis, develop and landfall zone. The same processes have been applied to the future climate condition data and the result shows in Fig. 6. In the individual probabilistic area, we have applied the pdf to find the most probabilistic points from the probabilistic zones. Before applying the pdf, the one-sample Kolmogorov test has been used to test the normality of the small area cyclone data. The path joining of the probabilistic point of small areas can represent the synthetic track of a probabilistic cyclone. For removing the high-frequency fluctuation a moving average filtering process has been used. After the average is processed the standard deviation value is added and subtracted from the probabilistic point to make a probabilistic shaded area of a probabilistic synthetic cyclone track. Fig. 7 represents the probabilistic shaded area of present and future cyclone probabilistic synthetic track.

4. Discussion

Basically, to find the most probable path along the Bay of Bengal coast, we have performed this work. For the different climate condition data, we have applied the similar investigation for the different cases of simulation output result. The simulation output was constructed for the different climate conditions under the consideration of different SST. Tables 1–4 represent the probability of cyclone observation points. The tables also show the probability percentage of the individual area of an individual zone, which can easily explain the probabilistic cyclone track direction. The possibility of each region was calculated for the different zones. The * (asterisk) marked values represent the maximum probability of the individual area. For example, The G2 area is the probable area of the Genesis region under the Bangladesh Meteorological Department observed cyclone data. Finally, all the probabilistic synthetic

Table 1
The probability of a cyclone position in the Genesis zone with different conditions.

	Genesis		
	G1 (%)	G2 (%)	G3 (%)
AGCM (Present)	37.74	20.52	41.72*
d4PDF (Present)	32.69	31.73	35.56*
BMD (Present)	5.32	93.85*	0.81
AGCM (Future)	28.44	32.75	38.79*
d4PDF (CC) (Future)	27.88	25.60	46.50*
d4PDF (GF) (Future)	35.44	26.23	38.32*
d4PDF (HA) (Future)	15.17	24.58	60.24*
d4PDF (MI) (Future)	39.59	42.20*	18.20
d4PDF (MP) (Future)	37.45	18.37	44.17*
d4PDF (MR) (Future)	17.75	24.61	57.63*

Remarks: * (asterisk) marked values signs indicate the maximum percentage.

Table 2
The probability of a cyclone position in the Cyclolysis zone with different conditions.

	Cyclolysis		
	C1 (%)	C2 (%)	C3 (%)
AGCM (Present)	36.67	41.68*	21.63
d4PDF (Present)	38.28	39.87*	21.38
BMD (Present)	25.05	71.83*	3.10
AGCM (Future)	44.41	47.38*	8.20
d4PDF (CC) f(Future)	41.40	43.80*	14.78
d4PDF (GF) (Future)	42.57	47.97*	9.45
d4PDF (HA) (Future)	41.39	42.07*	16.53
d4PDF (MI) (Future)	74.00*	24.46	1.53
d4PDF (MP) (Future)	44.47	46.21*	9.31
d4PDF (MR) (Future)	43.60	43.92*	12.47

Remarks: * (asterisk) marked values signs indicate the maximum percentage.

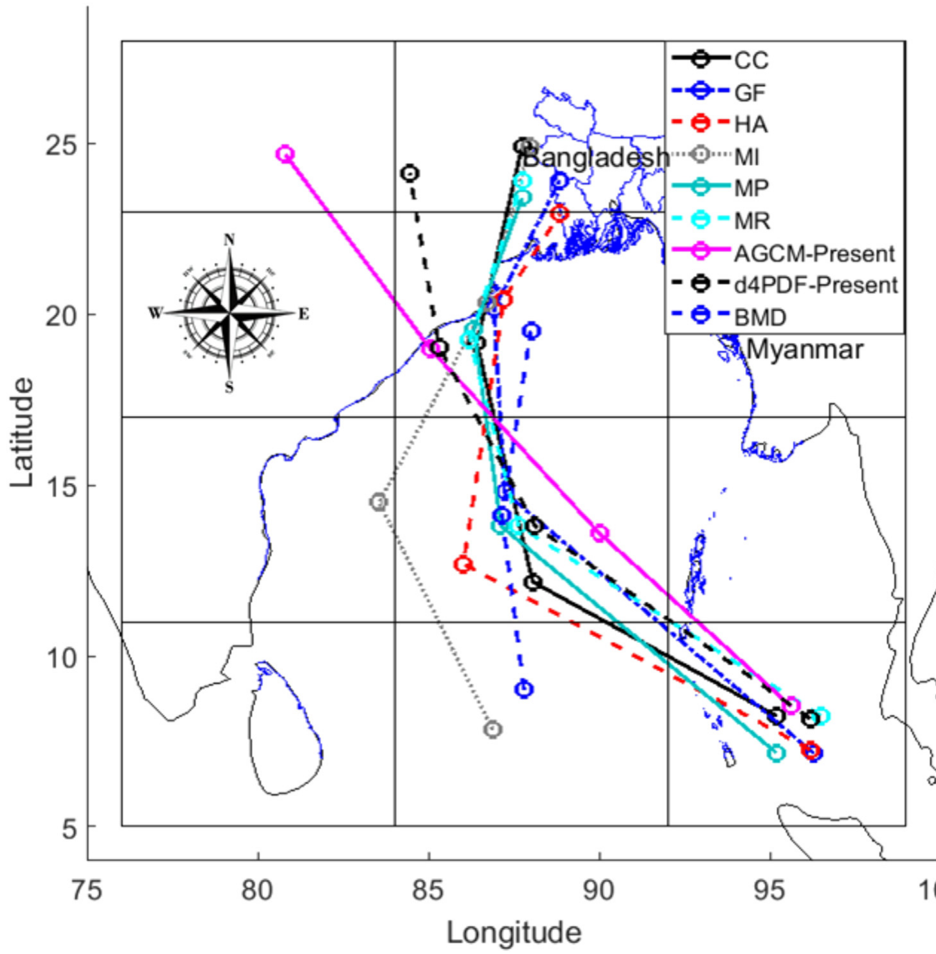

Fig. 8. Probable synthetic cyclone tracks of the data based on the results of the clustering method. Future storm trajectories are derived based on the data obtained considering different climate scenarios.

Table 3
The probability of a cyclone position in the Develop zone with different conditions.

	Develop		
	D1 (%)	D2 (%)	D3 (%)
AGCM (Present)	26.25	61.15*	12.58
d4PDF (Present)	22.15	70.38*	7.45
BMD (Present)	0.06	99.86*	0.06
AGCM (Future)	32.72	60.00*	7.27
d4PDF (CC) (Future)	14.28	84.05*	1.66
d4PDF (GF) (Future)	12.92	85.91*	1.15
d4PDF (HA) (Future)	15.56	83.47*	0.96
d4PDF (MI) (Future)	8.67	89.36*	1.95
d4PDF (MP) (Future)	13.45	85.76*	0.78
d4PDF (MR) (Future)	16.81	82.37*	0.80

Remarks: * (asterisk) marked values signs indicate the maximum percentage.

Table 4
The probability of a cyclone position in the landfall zone with different conditions.

	Landfall		
	L1 (%)	L2 (%)	L3 (%)
AGCM (Present)	64.51*	35.48	0.00
d4PDF (Present)	30.62	62.18*	7.19
BMD (Present)	–	–	–
AGCM (Future)	25.88	74.10*	0.01
d4PDF (CC) (Future)	26.61	72.61*	0.77
d4PDF (GF) (Future)	38.77	60.18*	1.03
d4PDF (HA) (Future)	44.78	54.86*	0.34
d4PDF (MI) (Future)	18.68	78.96*	2.35
d4PDF (MP) (Future)	28.05	70.97*	0.96
d4PDF (MR) (Future)	48.25	50.92*	0.81

Remarks: * (asterisk) marked values signs indicate the maximum percentage.

tracks are shown in Fig. 8. This figure can explain probabilistic synthetic cyclone track direction under present and future climate conditions. In other words, the figure can explain the future scenario of a cyclone direction that can be useful information for the people of the coast of Bangladesh.

5. Conclusion

In this study, a statistical analysis was performed to investigate the cyclone track direction. In this statistical Investigation, synthetic cyclone track trends were found in present and future climate conditions. It is found from this investigation that the possibility of the future storm hitting (62.25%) the southwestern region of Bangladesh due to Global warming under the +4 K temperature increase. Under the present climate condition, the probability of cyclone strike rate is high for the Odisha state of India. From this probabilistic investigation, there is a visible change in the direction of the storm track due to the global warming scenario. We infer that future storms will have a greater tendency to hit the Sundarbans in the southwestern region of Bangladesh.

Acknowledgment

The author would like to express his deepest appreciation to the UGC of Bangladesh for giving the facilities to do this job. The authors are thankful to the authority of the SOUSEI, Japan for policy Decision making for Future climate change (d4PDF) data and the Bangladesh Meteorological Department for providing the necessary data. The first Author gives thanks to the authority of the Department of Mathematics, Islamic University, Kushtia, Bangladesh.

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