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Investigation of the Effects of Climate Change on the Properties of Tropical Cyclones in the Bay of Bengal

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INFORMATION

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ABSTRACT

The effects of climate change due to global warming are having an adverse effect on the environment of Bangladesh. Cyclones are a catastrophic disaster in our subtropical region, which is a terrible thing for coastal countries like Bangladesh. However, more research on the nature of these storms and other factors is essential for the region. This research was performed from the data of the atmospheric general circulation model (AGCM) and the Database for Policy Decision-Making for Future Climate Change (d4PDF), Bangladesh Meteorological Department (BMD) and Joint Typhoon Warning Center. Statistical calibration of 40 years of current and future storms in the Bay of Bengal has been given importance along with storm activity and related issues. The characteristics of storms during the pre-monsoon and monsoon seasons has also been investigated. The bilateral relation has been found for the seasonal activity of a tropical cyclone (TC) in Bangladesh as well as we have shown that seasonal storms have a significant impact on this region. However, the main focus of this study is to review the seasonal behavior and other characteristics of cyclones in future due to the effects of climate change.

1. Introduction

As a South Asian Country, Bangladesh is extremely prone to disasters for its location: 20^0 45′ N to 26^0 40′ N latitude and from 88^0 05′ E to 92^0 40′ E longitude and also for the funneling shape of the sea border. It has 710km coastline with long continental shelf with shallow bathymetry. Among the disasters the TC is most hazardous. Huge number of tropical cyclones and its associated surge always cause a great loss of many lives and properties along this region. The concern is that Bangladesh will face various catastrophic cyclones every year due to global warming (Al Mohit et al., 2018a).

According to Al Mohit et al. (2018b), About 500000 people were died by the past cyclone in this region (History record from 1970-2018). A proper cyclone warning system can reduce the human death and economic losses, resulting from the surge within the coastal area of Bangladesh. On average, 15,000 people were died annually by storms and tide (Smith, 2012). To investigate the cyclone behavior, the factors associated with cyclone are investigated according to the study of different literature review. Maximum Potential Intensity (MPI) was introduced by (Emanuel, 1987) after that a simple thermodynamic MPI model (Holland, 1997) was improved, classified the intense cyclone was predicted by (Henderson-Sellers et al., 1998). For the Large scale thermodynamic conditions (Knutson and Tuleya, 1999; 2001).

Knutson and Tuleya (1999) and Knutson and Tuleya (2004) developed a hurricane model simulation. Some study developed the study of special and temporal history of cyclone (Bhardwaj and Singh, 2020), some of them force to summarize the physical characteristics (Wang et al., 2017).

Cyclone risk was also analyzed depending on social risk assessment (Marín-Monroy et al., 2020). Their study was directly related to the study of severity and hazard (Cutter and Finch, 2008; Oo et al., 2018; Rabby et al., 2019). The change of landfall is also an important part of activity analysis. The track changing behavior was investigated by the author (Pandey and Liou, 2020; Terry and Gienko, 2019; Zhang et al., 2013).

Recently, (Mondal et al., 2022) has investigated the special and temporal behavior, which is based on the present data. In our study, we have analyzed present and future data with more than hundred simulation results. All the relevant issues were discussed for better understanding. Bangladesh, India, and Myanmar coast contain the Bay of Bengal (BoB) where, one an average, two peaks of cyclones occur every year. Pre monsoon and post monsoon are the peak time of cyclone occurrence. This study also found that the post monsoon shows the height occurrence with time in this area. Basically this study focuses on the cyclone behavior (parameter characteristics) due to climate change and its associated Natural inconsistencies.

2. Data Material and Methods

2.1. The Data

The Meteorological Research Institute (MRI), AGCM, d4PDF, Joint Typhoon Warning Center (JTWC), and BMD were exercised in this study. The MRI-AGCM and d4PDF data is the model-simulated data for present and future climate scenarios. The BMD and JTWC data are the best track data or observed data. At first, (Williamson et al., 1987) developed a NCAR Community Climate Model version 1 (CCM1) which is now known as an AGCM. In this model, heat momentum, dynamic mass was used in the horizontal spectrum conversion method where 18 vertical levels were used to adjust the system. In each layer, the Delta-Eddington calculation was performed which was developed from the solar radiation scheme of (Thompson and Ramaswamy, 1987).

In the present situation, the MRI and Japan Meteorological Agency (JMA) have jointly developed a new operational numerical weather prediction model known as MRI-AGCM (Mizuta et al., 2006). For the further development, a semi Lagrangian three-dimensional advection scheme was used, which is accelerating the time integration with 20 km horizontal grid and 60 level altitude 0.1 hPa vertical grid spacing (Yoshimura and Takayuki, 2005).

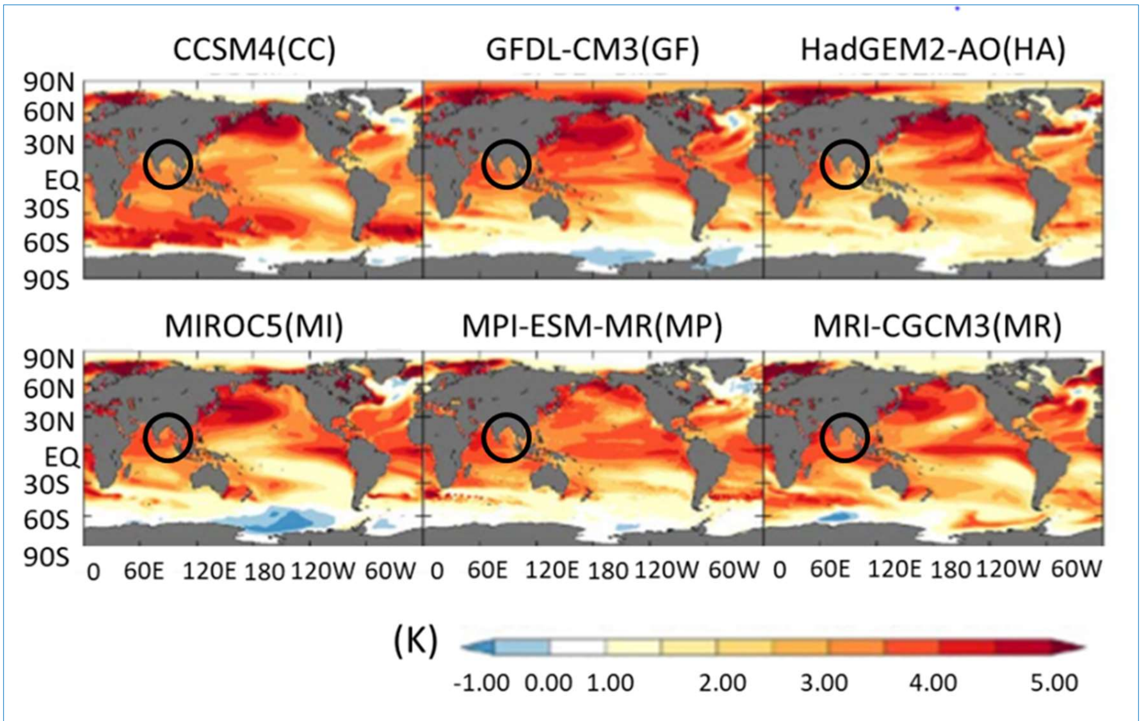

Fig. 1. Monthly mean inters annual variation of SST

The higher resolution (20 km) AGCM experiment was performed by time-slice method, which has two layers, one is the global warming projection system that consists with an Atmospheric-Ocean General Circulation Model (AOGCM), and the higher part of the vertical level AOGCM generated by AGCM. For the further development of the climate experiment, the d4PDF data was revised for global experiment data. The d4PDF data was produce from the weather prediction model of Japan Meteorological agency (Borowitz, 2018) with the modified model of MRI-AGCM 3.2 (Mizuta et al., 2012). 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). The boundary conditions of the model were sea surface temperature (SST) and sea-ice concentration (SIC, and sea-ice thickness (SIT) for lower boundary. The external forcing was considered as Global-mean concentrations of greenhouse gases, three-dimensional distributions of ozone and aerosols (Mizuta et al., 2012).

The data were collected from the Data Integration and Analysis System (DIAS) under the Global environmental information integration program (Kitamoto et al., 2009). The data is divided into three features with past experiment (1951 to 2011), Non-Global warming experiment (1951 to 2010), and 4^0 C rise experiment (2051 to 2110).

In addition, the experiment result of global atmospheric-ocean coupled model contributes to the Coupled Model Intercomparison Project Phase 5 (CMIP 5). There are 100 members' simulation for present climate condition, and 90-member simulation for future climate condition. 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). The authorities are responsible for the future-climate model simulation. 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 Plank Institute for Meteorology (Germany), and Meteorological Research Institute (Japan). Different SST condition is used for different climate simulation.

Fig. 1 represents the SST pattern (Mizuta et al., 2017). 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 are the radiative forcing of the model (Hirahara et al., 2014). For the analysis of cyclones, (Murakami et al., 2012) developed a TC detection model. After summarizing the technique and adopting the new definition of cyclone, the model was developed by (Oouchi et al., 2006). The assumption of their study was: the vorticity greater than 8.0×10^{-5} s^{-1}, 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 hours.

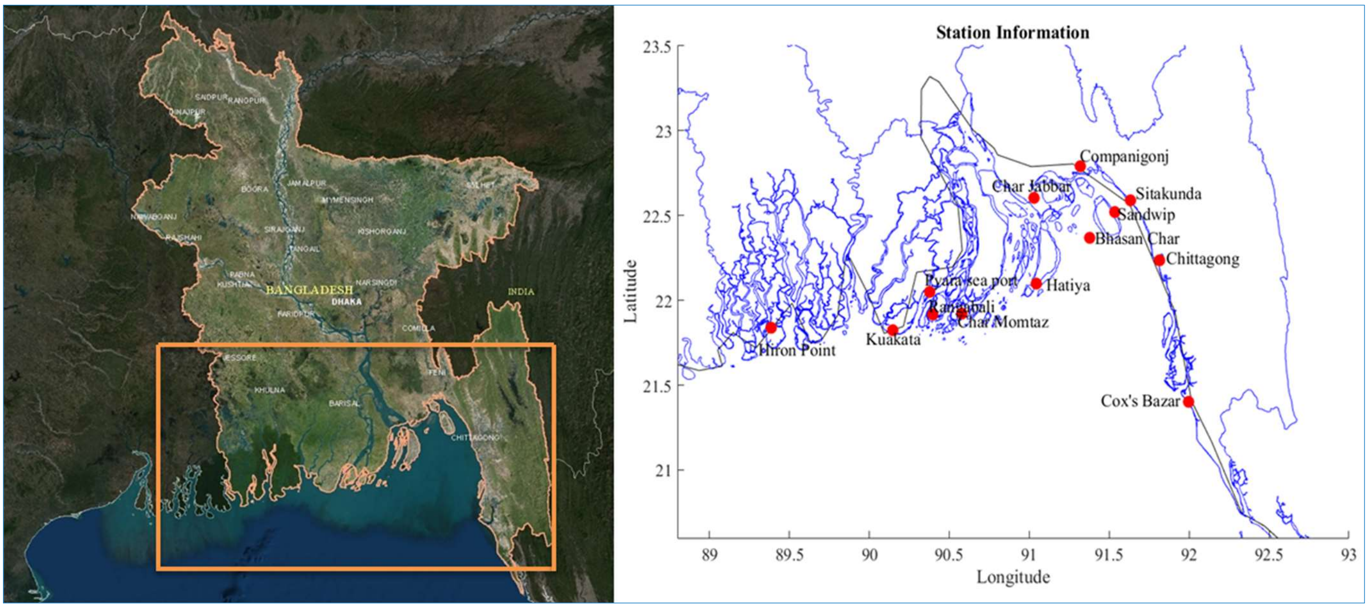

Fig. 2. Bangladesh Coastal area with tide station location information

2.2. Study area

The present study area of this research is the coastal area of Bangladesh. The coastal zone of Bangladesh covers 19 districts out of 64, and153 police station area. This coastal area covers 32% area and 28% of the population of Bangladesh (Alam et al., 2003). Among these, 12 districts and 51 police station areas are vulnerable to surge disaster risk. The lowest landmass of Bangladesh is known as delta that makes the coastal zone of Bangladesh, which is an extended Himalayan drainage ecosystem. The river system of Bangladesh is highly complex and dominated by three major rivers, namely the Gauges, Brahmaputra & Meghna, which formed this world's largest delta. Bangladesh coast is the region, which faces about 5% of the global tropical cyclones.

In 1970, one of the most devastating cyclones of the century struck the Meghna estuary of Bangladesh killing about 300,000 people. 1991 April Cyclone made landfall near Chittagong which killed about 1,38,000 people. The interested study region and the nearest tidal station is shown in Fig. 2

2.3. Power Dissipation Index (PDI) and Accumulated Cyclone Energy (ACE) analysis

To understand the cyclone activity, it is important to analyze the Power dissipation index (PDI) and Accumulated cyclone energy (ACE). The TC energy of different ocean basins is different. The PDI and ACE of Bay of Bengal storm for present and future climate conditions are calculated from the relation of (Emanuel, 2005). For this analysis, track archives from MRI-AGCM and d4PDF are used.

$$PDI = 2\pi \int_{0}^{\tau} v_{max}^{3}\, dt \tag{1}$$

where v_{max} is the maximum sustained wind speed and τ is the lifespan of the cyclone. The ACE can also be obtained from the relation of (Emanuel, 2005) as

$$ACE = \int_{t=0}^{\tau} v_{max}^2 \, dt \quad (2)$$

where v_{max} is the maximum sustained wind speed and τ is the total duration of the cyclone. The square velocity of maximum sustained wind is the kinetic energy of a cyclone. The total summation of kinetic energy of a cyclone represents the accumulated cyclone energy (CE) of a cyclone. This CE approximates the wind energy, which can be calculated every six hours by a tropical system over its lifetime.

3. Results

BMD classified the TC based on the maximum sustained wind speed and lowest central pressure for warning and evacuation purposes. Basically, the intensity of the storm depends on the velocity of the wind during the storm. The bulletins of cyclone warning are issued by the BMD based on the specified cyclone classification. Detailed classification is shown in Table 1.

This analysis can explain the destructiveness of a cyclone for the specified ocean basin. Stronger cyclones may be more destructive in this region. The overall analysis of ACE for AGCM and d4PDF is presented in Table 2 and Table 3, respectively.

Table 2 can represent the ACE of present and future cyclones, which is calculated from the MRI-AGCM data. Consecutive five years interval cyclones are used to calculate the ACE, which is presented in table 2.

Table 1. Cyclone category along the Bay of Bengal

Category	Maximum wind speed (in knots)
Low (L)	<10kt
Well Marked Low (WML)	10-16kt
Depression (D)	17-27kt
Deep Depression (DD)	28-33kt
Cyclonic Storm (CS)	34-47kt
Severe Cyclonic Storm (SCS)	48-119kt
Severe Cyclonic Storm with a core of Hurricane Winds (SCS (H))	>120kt

Table 2. Detailed summary of accumulated cyclone energy from MRI-AGCM data

AGCM present (1979-2003)		AGCM future (2075-2099)					
Year	ACE (kn^2)	Year	ACE (kn^2)				
			C_0	C_1	C_2	C_3	Mean
1979-1983	80.20	2075-2079	0	0	6.38	129.55	33.98
1984-1988	39.57	2080-2084	24.41	35.04	3.67	1.06	16.04
1989-1993	36.22	2085-2089	50.42	27.65	10.21	19.1	26.84
1994-1998	55.25	2090-2094	15.91	0	12.58	0	7.12
1999-2003	67.23	2095-2099	7.98	11.87	62.03	0	20.47

Table 3. Detailed summary of accumulated cyclone energy of d4PDF data

D4PDFpresent (1979-2003)		d4PDF future (2075-2099)						
Year	ACE (kn^2)	Year	ACE (kn^2)					
			CC	GF	HA	MI	MP	MR
1979-1983	9.73	2075-79	29.15	27.39	9.07	2.83	9.26	14.7
1984-1988	14.03	2080-84	18.55	14.56	8.02	6.38	6.01	25.0
1989-1993	10.67	2085-89	23.49	17.38	25.50	6.66	11.79	24.3
1994-1998	7.44	2090-94	10.43	11.60	13.60	6.28	5.84	18.4
1999-2003	13.95	2095-99	15.3	10.64	18.32	4.66	4.11	16.1

In both the present and future climate scenarios of AGCM, it is found that the ACE of future cyclones is lower than present cyclone ACE. But, the d4PDF data shows different cases.

Table 3 shows the ACE analysis result of d4PDF data with six different climate scenarios. For the future climate condition, the data were reviewed for the different cases like CC, GF, HA, MI, MP and MR. It is found that the accumulated cyclone energy of a cyclone will be increased in future. The analysis result clearly identifies that cyclones at present and future that form over the Bay of Bengal have sufficient oceanic thermal energy which is conducive for the intensification of cyclones in this region. PDI metrics of present and future cyclones in the Bay of Bengal during 25 years (Fig. 3)

Finally, it is found that the future occurrence will decrease in this region but the accumulated cyclone energy will be increased, which may represent the strongest cyclone formation probability. Thus, it is important to investigate the cyclone behavior properly within this region to understand the future probability of cyclone characteristics.

4. Discussion

4.1. Activity analysis

Bangladesh has six seasons. The seasons depend upon the latitude change of the earth axis relative to the sun. However, the cyclone season depends upon the occurrence behavior in each month. According to the climate conditions, Bangladesh is mainly a subtropical monsoon country. To understand the cyclone seasonal behavior, we have investigated the cyclone formation analysis along the Bay of Bengal. The present scenario of the cyclone eye point of AGCM, d4PDF (member 1), and BMD is shown in Fig. 4.

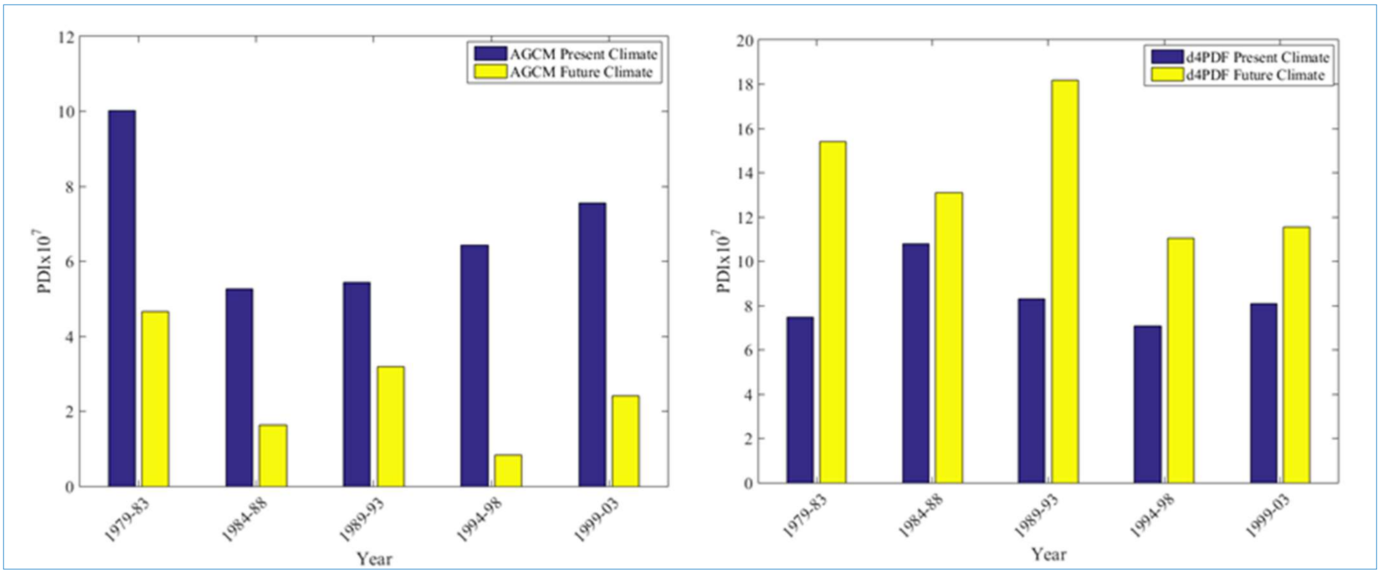

Fig. 3. PDI analysis of present and future climate conditions

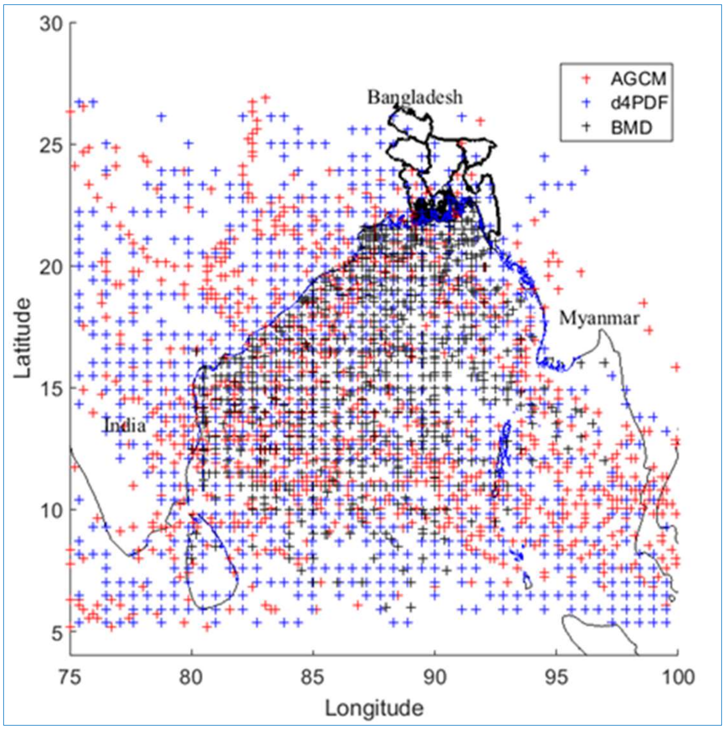

Fig. 4. Cyclone eye point for present climate condition

In addition, to simulate the future scenario, four different multi-model projected SST distributions were considered. The internal variability of the climate system was calculated by the two distinct initial conditions, which were compared with two different simulations. So, the future simulation output was four SST distributions with two initial conditions, 24 ensemble experiments with three convection schemes, and 25-years integration period of simulation. The four SST distributions were obtained from the projected change of SST which was collected from the cluster analysis of multi-model projected changes SST of CIMP3. The future projection M, C1, C2, and C3 represents a mean of future SST projections. In this projection system, the SST ranges from 1.95 °C to 2.14 °C (Pinzón et al., 2017). The projected pattern of SST is similar to the Pacific Ocean and the Caribbean Sea. The SST pattern in the Caribbean Sea was large to small and the Pacific Ocean is different, from small to large. The pattern of future cyclone path for Bay of Bengal are represented in the Fig. 5. with different scenarios of C0, C1, C2, and C3 for the AGCM future climate condition.

From the Fig. 5, it is evident that the cyclone probability was found near the east coast of India. However, some cyclones were also found near the east part of Bangladesh coast for the C0 and C3 scenario, and the west part of Bangladesh for C1 and C2 scenario. For the detailed analysis of future cyclone activity, we have analyzed the d4PDF data. The Fig. 6 represents the cyclone activity of a 90-member ensemble simulation for six scenarios of future climate conditions. Most of the cyclones were found near the east coast of India in each scenario except MI scenario. In the MI experiment, some cyclones were found near Bangladesh, India and Sri-Lanka. Most of the cyclones of Bay of Bengal form in the CC scenario also Bangladesh coast faces some cyclones in different scenarios. Most of the cyclones that strike the Bangladesh coast are found in the CC, GF, MI, MP, and MR scenario. This figure only shows the cyclone path, which can explain the general behavior of cyclones and the probability of cyclones in each scenario. To understand the cyclone behavior properly, we have investigated the cyclone genesis point in each scenario.

4.2. Genesis analysis

We have considered the initial detection point of tropical disturbance as a genesis point. Genesis is an important issue for cyclone movement behavior. Due to climate change, the genesis location may change. There are some factors that depend on the cyclone genesis occurrence. Leipper and Volgenau (1972) suggested that the SST and high magnitude ocean thermal energy is the key factor for the existence of cyclones.

In the earlier 19th century, (Dunn, 1940, 1951) observed that the earth rotation near the equator is an important factor for developing a genesis in the upper part of the equatorial area. Because, in the 4^0-5^0 latitude band the wind is very weak. Therefore, there is no possibility to create the cyclone genesis area near the 5^0 equatorial belts.

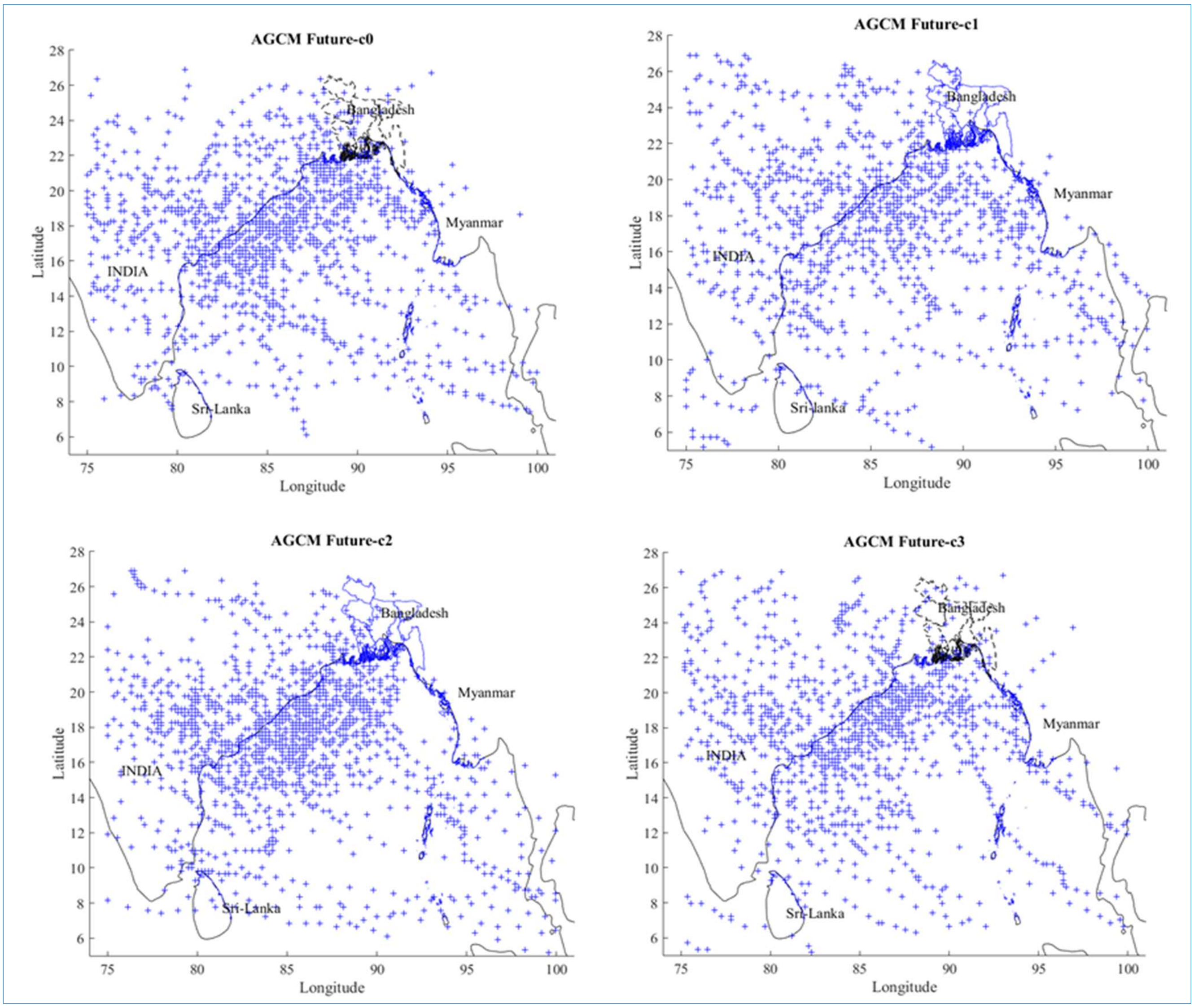

Fig. 5. Cyclone activity for the future climate scenario of AGCM

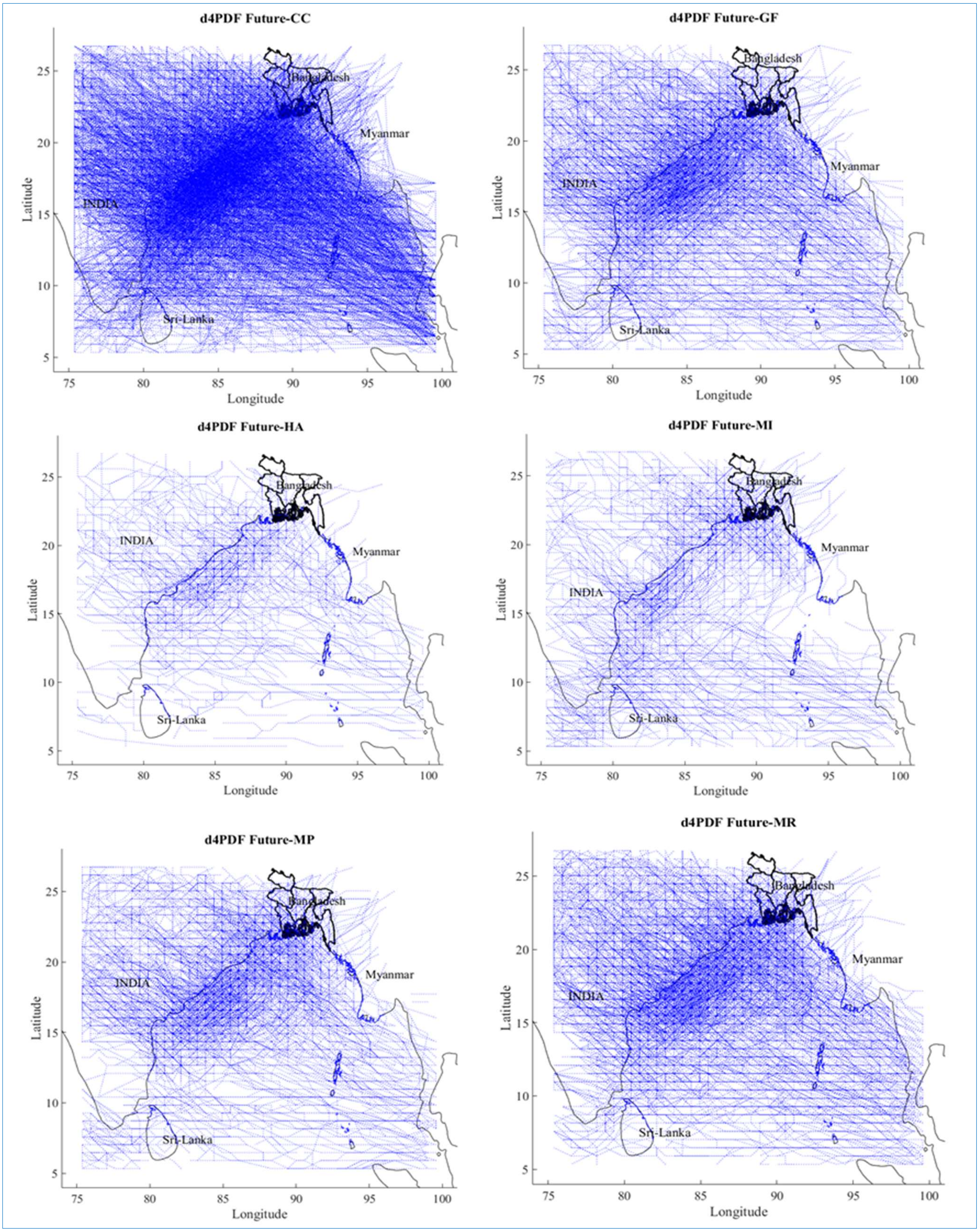

Fig. 6. Cyclone activity for the future climate scenario of d4PDF

However, in the future climate conditions the genesis location may change. To understand the probability of the genesis location of each (2^0 x2^0) latitude longitude area, we have investigated the genesis probable area. From this analysis, it is found that the area of cyclone genesis probability will be shifted in the near future. In the present climate condition, the genesis area is found in the middle of the Bay of Bengal. But, in the near future, it will be shifted to the upper latitude and the maximum probability of its location would be found near the east coast of India. Fig. 7 shows the cyclone genesis probability of present climate conditions.

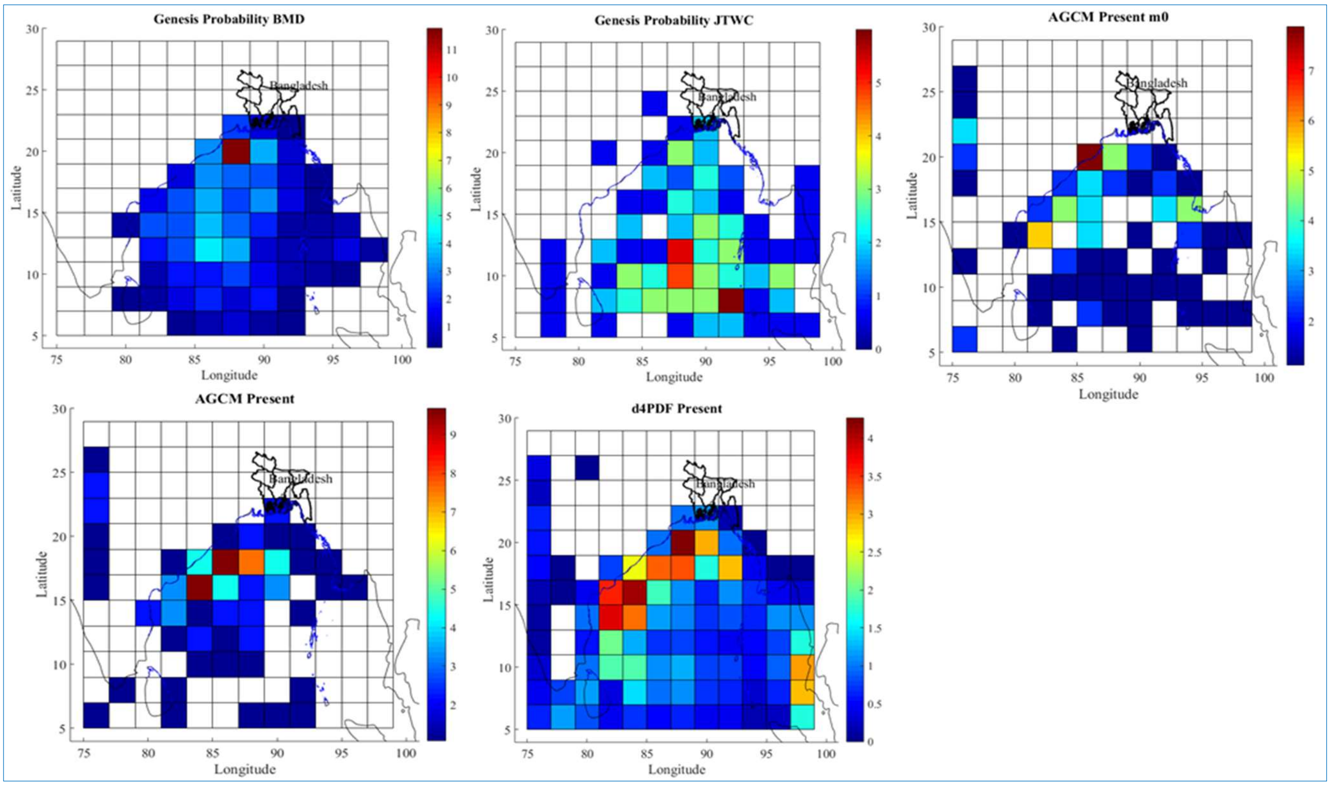

Fig. 7. Genesis probable area of present climate condition

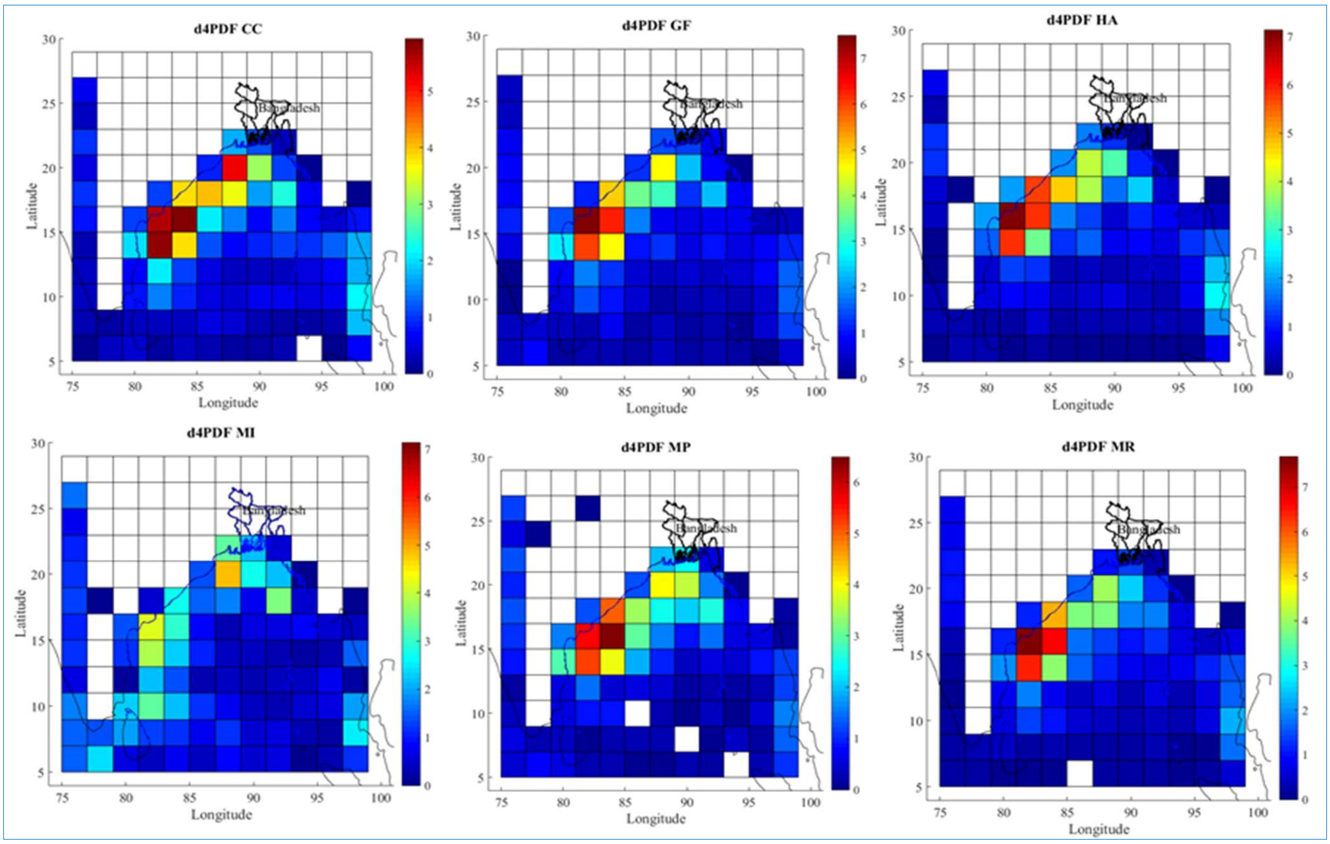

Fig. 8. Genesis probability area of d4PDF future climate scenario

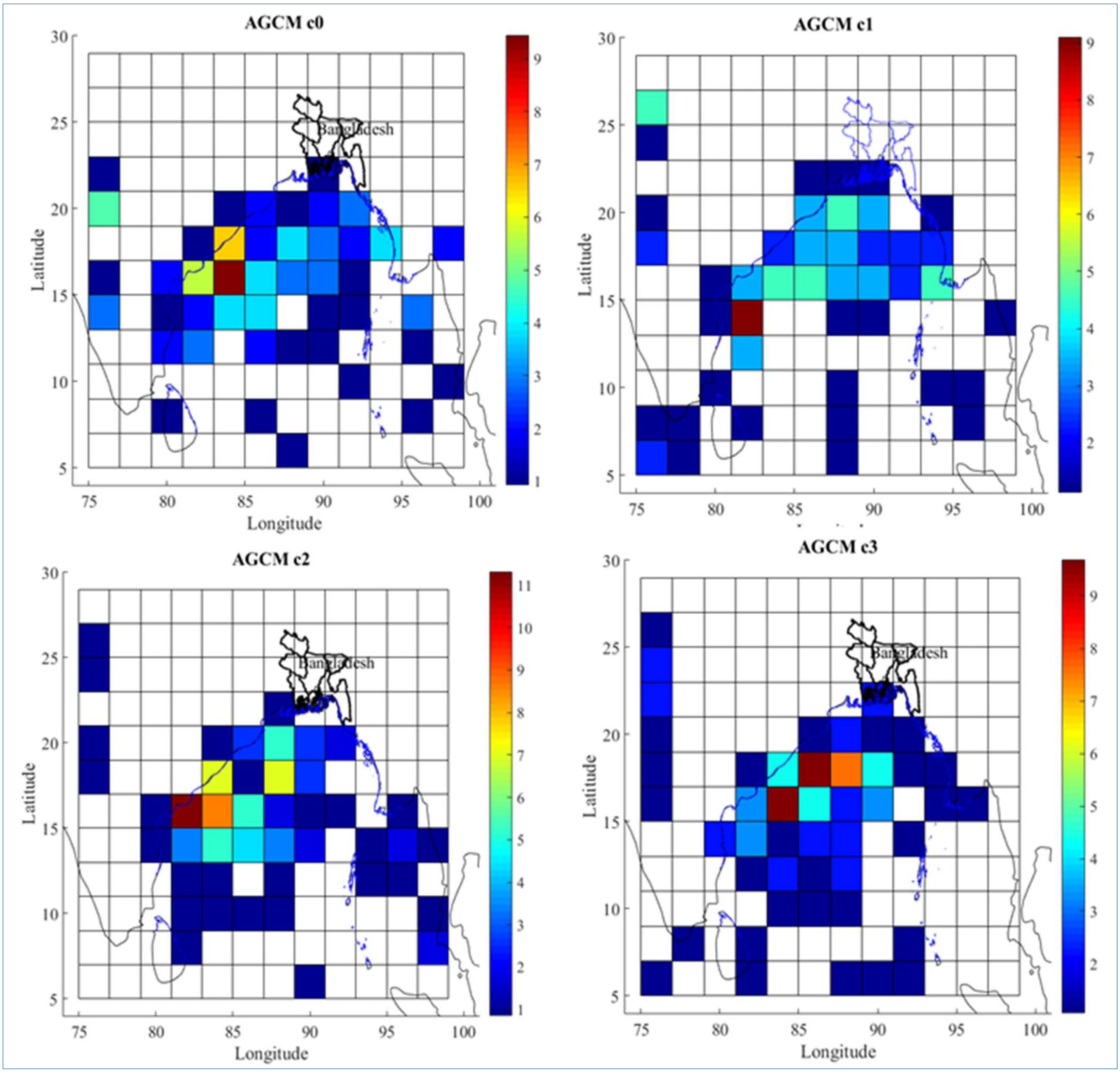

Fig. 9. Genesis probability area of AGCM future climate scenario

Color bar indicates the genesis probability in each individual area. We have found some genesis areas outside the Bay of Bengal area due to selecting the first point of depression as a genesis point. Some genesis areas are also found outside of the area due to select a big cyclone track separate region.

Due to global warming, future climate will change and its associated cyclone genesis will also change. Fig. 8 shows the cyclone genesis probability of future climate conditions of d4PDF data. Most of the scenarios show the same genesis probability area except MI scenario.

So, it is evident that climate change has an impact on cyclone genesis. From the analysis, we have seen that the east coast of the Indian region and its adjacent area is the most genesis prone area. Also, Fig. 9 shows the future genesis prone area for the different scenarios of AGCM.

4.3. Occurrence analysis

4.3.1. Yearly and monthly activity

We have investigated the occurrence of TC within the Bay of Bengal. The overall occurrence behaviors of Bay of Bengal are investigated for yearly occurrence and monthly occurrence. In both cases, we have investigated present climate conditions and future climate conditions. The yearly occurrence of cyclones represents the formation number of cyclones in a year. In this analysis, we have investigated the present climate for 1979 to 2003 cyclone information.

We have collected the cyclone information for each scenario of JTWC, BMD, AGCM and d4PDF. After analyzing the cyclone information, we have found that the yearly average number of cyclone occurrences is 4-7 along this region. Fig. 10 shows the yearly average number of cyclone occurrences in present climate condition and future climate condition.

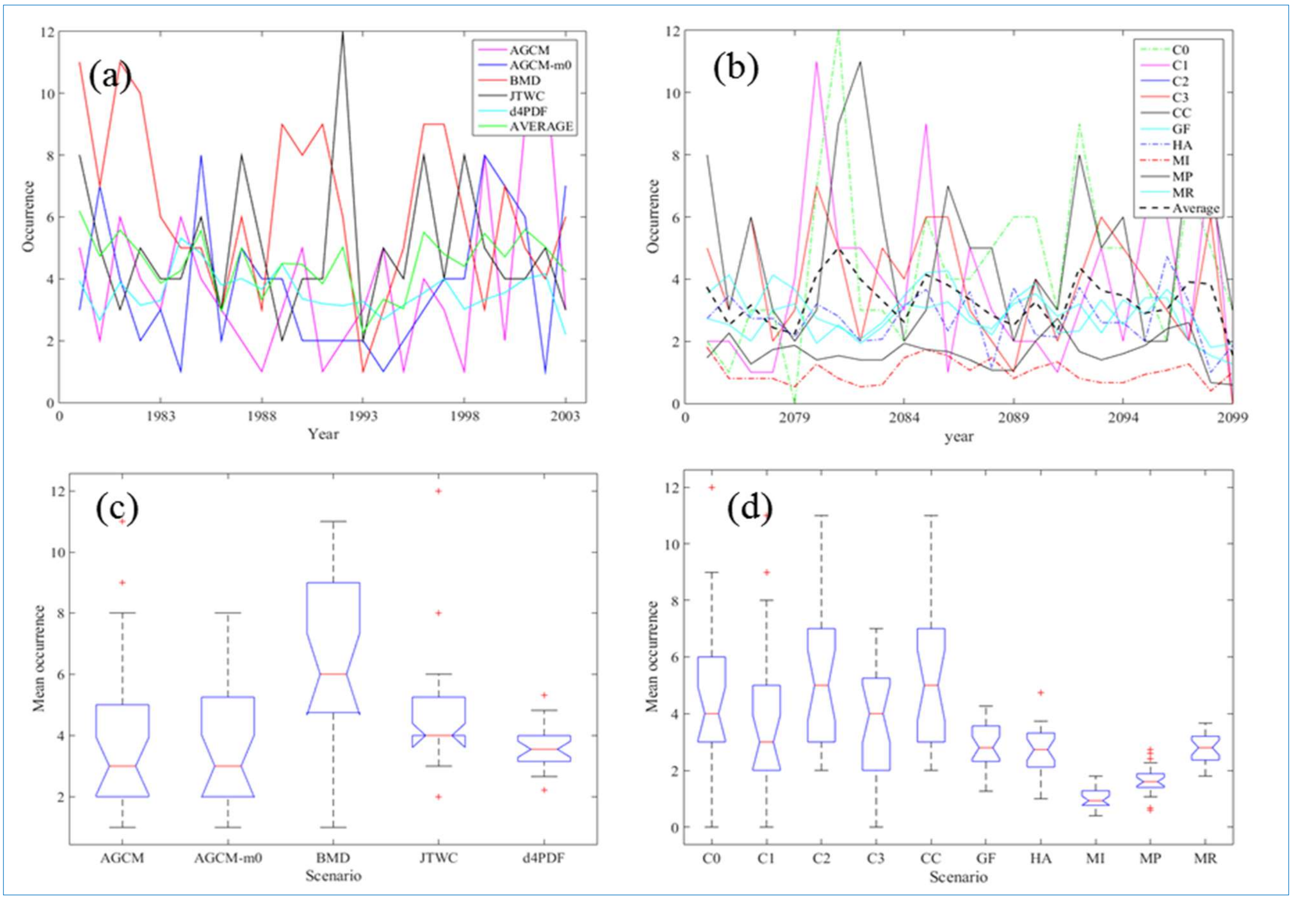

Fig. 10. Yearly average number of cyclone occurrences for present and future climate scenarios. The upper left and lower left figure (a)(c) shows the yearly occurrence number in the present scenario. The upper right and lower right figure (b)(d) represents the future scenario

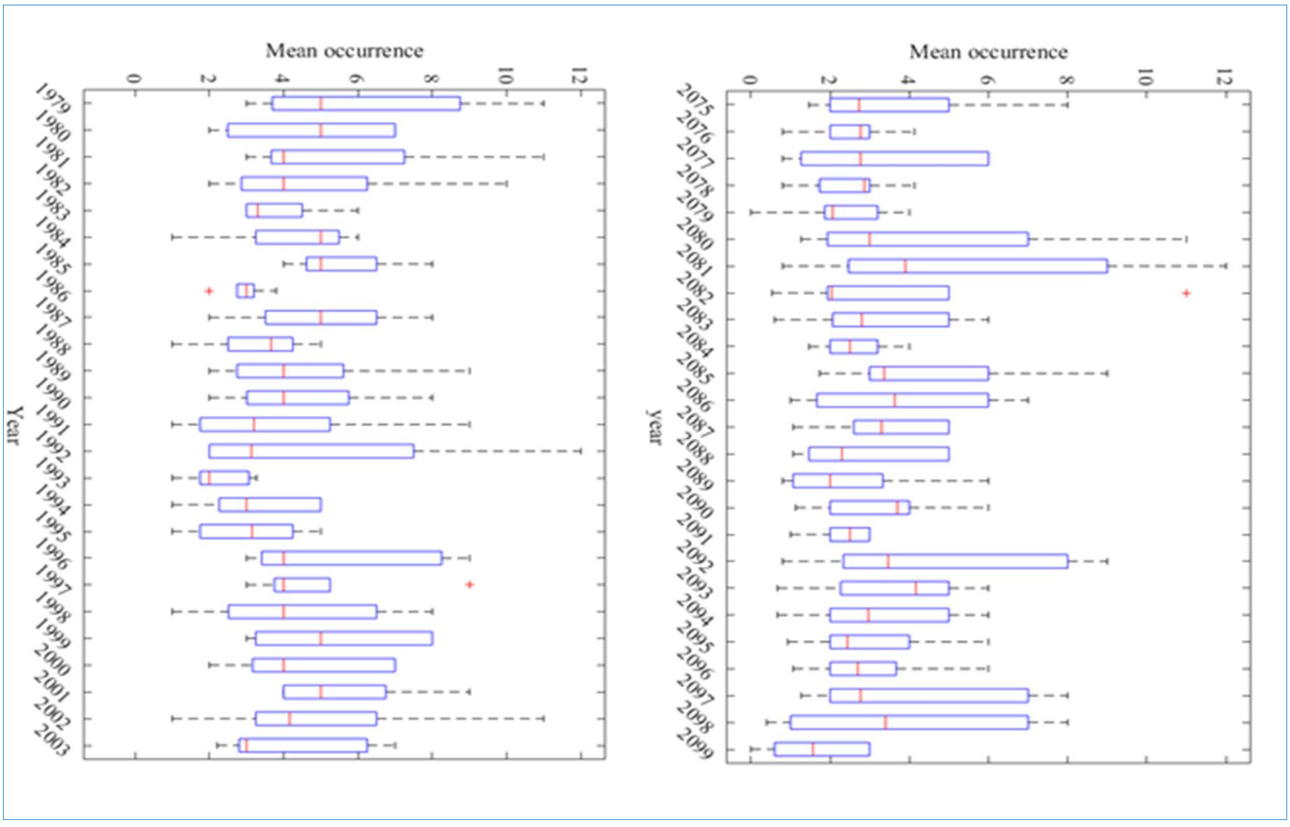

Fig. 11. Average occurrence number of each scenario in each year for present and future climate conditions (Left side present and right side future)

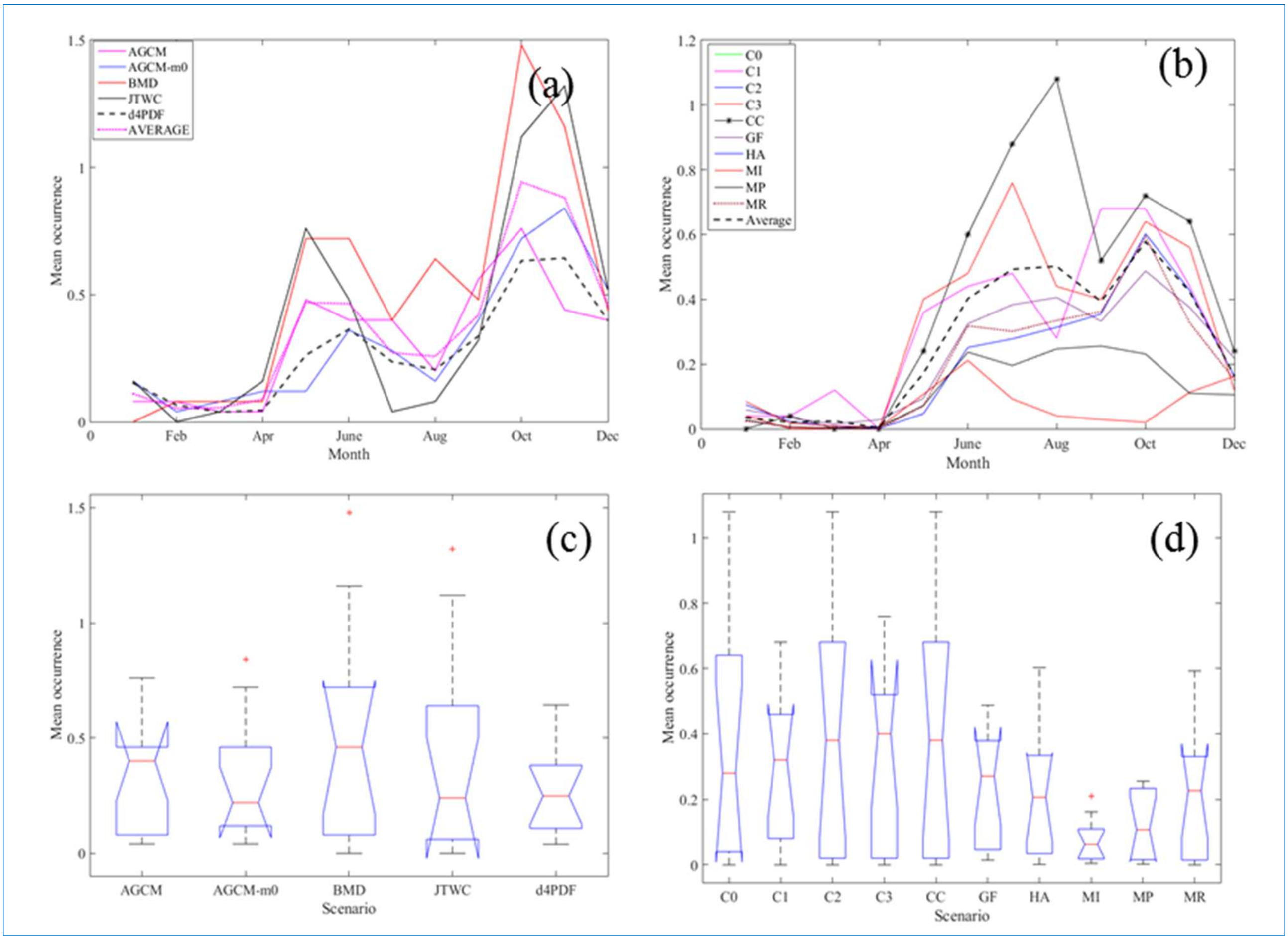

Fig. 12. Monthly average of cyclone occurrence: (a) Present climate situation, (b) Future climate situation, (d) Average of Present climate scenario data and (d) Average future climate scenario data

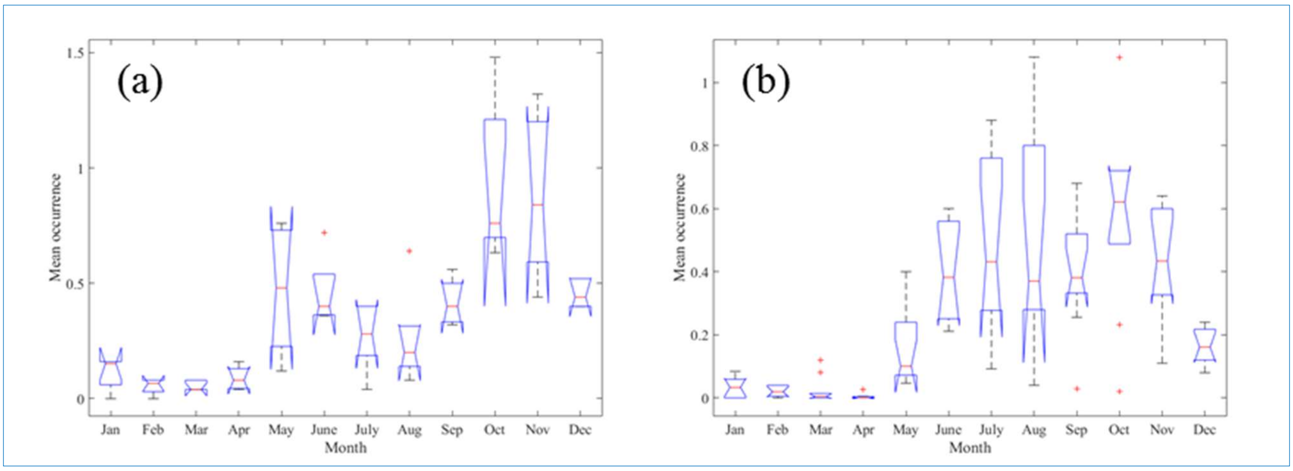

Fig. 13. Monthly mean occurrence: (a) Present climate scenario and (b) future climate scenario

From the Fig. 10, it is found that the occurrence fluctuation is lower for the d4PDF scenario than the AGCM future scenario and the future cyclone occurrence will decrease along this region. To understand the yearly occurrence more clearly, Fig. 11 represents an average occurrence number of each scenario in each year for present and future climate conditions. So, it is evident that the future cyclone occurrence will decrease along this region.

Actually, the box plot or whisker diagram is a standardized way of displaying the distribution of data based on some characteristics. The lower and upper part of the box spans represents the first quartile to the third quartile. The segment line between the two parts of the box shows the median number of cyclone events and whiskers above and below in the box show the maximum and the minimum number of cyclone events.

After analyzing the yearly occurrence of cyclone events, we have analyzed the monthly and seasonal activity. The above study is not the brief assumption of occurrence behavior. Therefore, for this region, we have investigated the cyclone occurrence behavior in each month and checked the seasonality (Fig. 12).

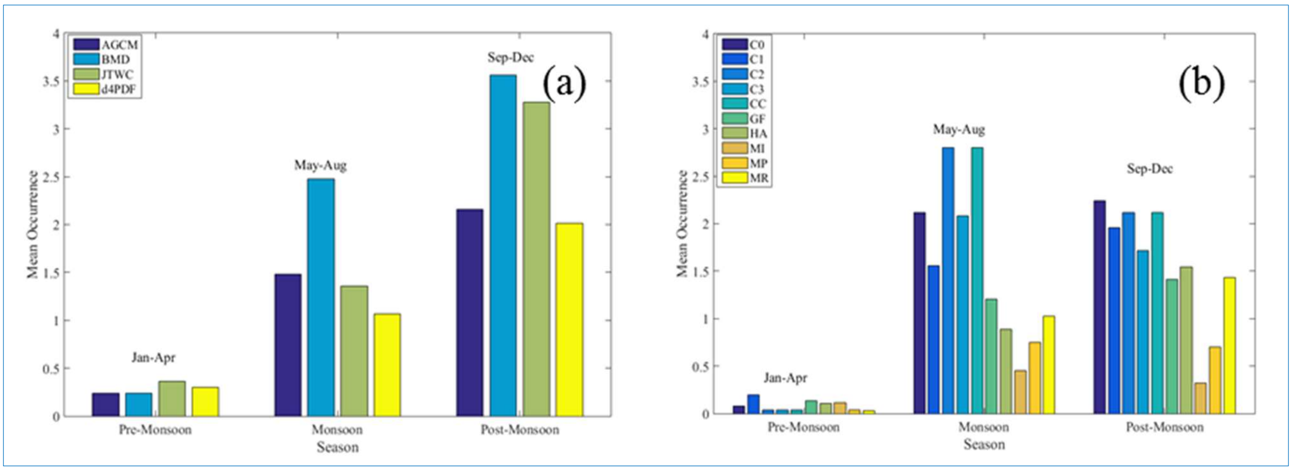

Fig. 14. Seasonal occurrence behavior: (a) Present climate condition and (b) Future climate condition

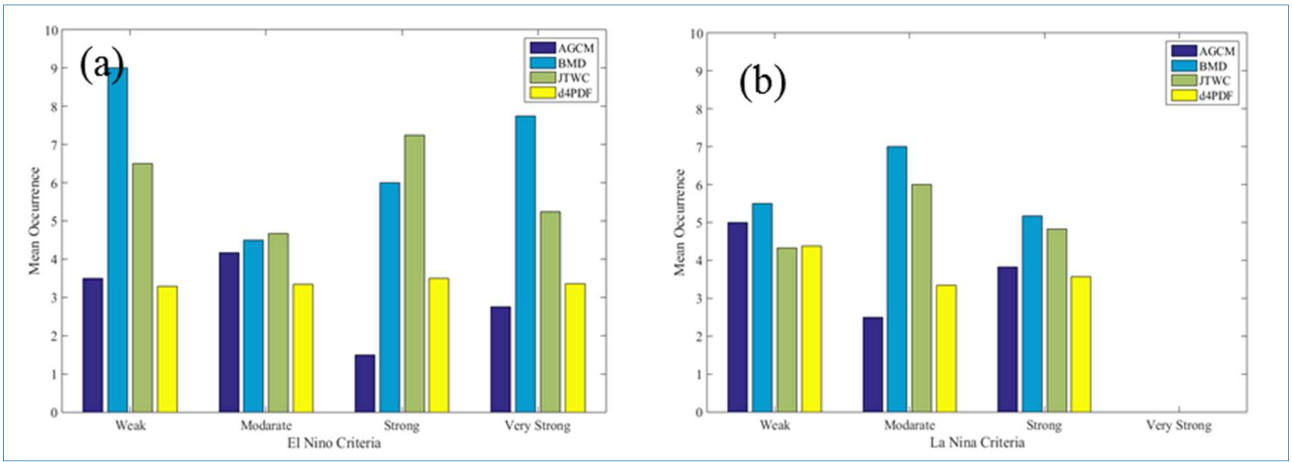

Fig. 15. Cyclone occurrence behavior at El Niño and La Niña climate pattern

From this analysis, we have found that the monthly occurrence of present climate cyclones has a periodic nature. However, future occurrences have no such activity. Fig. 13 can explain the general behavior of the monthly occurrence of tropical cyclones along the Bay of Bengal.

The present cyclone occurrence has seasonal impact; it shows the higher occurrence probability at the post-monsoon season (October-December). But, in the future climate conditions will change. To find the present and future occurrence with the inter variability of each scenario; we have analyzed the data to find the general behavior of monthly occurrence behavior.

4.3.2. Seasonal activity

Due to seasonal diversity, the effects of the storm in the Bay of Bengal region are also different. For the Bangladesh and the west part of Indian region, there are six seasons usually observed, for example, summer (mid-April to mid-June), rainy season (mid-May to late-October), Autumn (mid-August to mid-October), Late autumn (mid-October to mid-December), Winter (mid-December to mid-February) and spring (mid-February to mid-April).

In this study, we have divided the three seasons of cyclones, which are pre-monsoon, monsoon and post monsoon respectively. The pre-monsoon season is from January to April, monsoon season is from May to August and the post monsoon season is from September to December.

The post monsoon season is the prone season for cyclone occurrence in this area. The seasonal occurrence behavior under present and future climate conditions are shown in Fig. 14. Different scenarios show the same seasonal activity of cyclone occurrence for this region. But, in the future the present occurrence behavior of cyclones will be changed due to climate change

The seasonal activity analysis explains the cyclone events of the pre-monsoon, monsoon and post monsoon which can play an important role in cyclone activity analysis along this region.

4.3.3. Occurrence activity at El Niño and La Niña

To understand the tropical circulation pattern effect of cyclone occurrence behavior, El Niño and La Niña impact has been investigated. It is found that the Model simulation and observed cyclone occurrence behavior show the different characteristics. Due to El Niño, the cyclone occurrences is higher than La Niña, but for the moderate case of La Niña shows higher occurrence than El Niño. The occurrence behavior of cyclones at El Niño and La Niña climate patterns are explained in the Fig. 15. The El Niño and La Niña are the opposite faces of climate patterns. In this study, it is found that the El Niño and La Niña has a negligible impact on cyclone occurrence behavior.

5. Conclusion

This study investigates cyclone activity along the Bay of Bengal region. From this study, it is observed that the constructed storm in the Bay of Bengal has multi-dimensional behavior. The cyclone genesis will be shifted to the upper latitude and the number of occurrences will decrease in the future climate condition. It is also observed that the constructed storm in the Bay of Bengal has seasonal effects. Present climate shows that the post monsoon season is the prone season for cyclone occurrence. But, due to the climate change impact, the seasonal behavior of cyclone occurrence will be changed in future climate. However, the cyclone occurrence number will decrease in future but the accumulated cyclone energy will be higher. This analysis indicates that the changes of different climate scenarios has the potential influence on cyclone parameters and the probability of dangerous cyclone formation in this region will be higher.

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