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A Study On Twenty First Century Cyclones and Their Lifetime Behavior in The Bay of Bengal

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Abstract— Bangladesh is a small disaster prone country in South Asia. Therefore, in this study, an informative search analysis of the lifetime activity of cyclones in the Bay of Bengal is carried out. For this study, we analyzed data on cyclones occurring in the Bay of Bengal during the 21st century. We used spline, shape-preserving, cubic, quadratic, and linear methods to investigate a statistical and mathematical projection of trends in cyclones occurring in the Bay of Bengal during the 21st century. As a result, a significant change in characteristics was found due to the change in time, which plays an important role in changing the wave behavior and related environmental parameters within this area. From this study we found that there is an increasing trend in the occurrence behavior of cyclones. We also found that although cyclone lifetimes fluctuate due to climate change, cyclone lifetimes will increase in the future. This means that future cyclones will gather more strength and power. So, Bangladesh will face the risk of stronger cyclones in the near future.

Keywords: Bangladesh, Climate, Cyclone, Disaster, and Spline.

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1. Introduction

A disaster prone low-lying country of south Asia is Bangladesh. The extended area of this country is $20^0 45'$ N to $26^0 40'$ N latitude and from $88^0 05'$ E to $92^0 40'$ E longitude. This area has a 710 km coastline with a long continental shelf with shallow bathymetry. Many small and big flat islands make the coastline more complex and the geographical location of this country makes it more vulnerable for the different kinds of coastal disasters. The well-known coastal disasters are tropical cyclones, tornadoes, coastal flooding, salinity, and so on. The rapid climate changes make this area more disaster prone, which makes the ecological imbalance. 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 [1]-[2]. According to [3], About 500000 people were killed by the last 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.

The government of Bangladesh is not always fully successful in recovering the situation by using this warning system. So, proper forecasting and the surge estimation is important. In the near future, Bangladesh will be the number one country of South Asia that is mostly affected by the world climate change impact. Therefore, for this reason, the cyclone disaster will be increasing in this area. To make a disaster plan and adaptation for the coastal people of Bangladesh, a well investigation of future cyclone characteristics and its associated surge is needed. The Bangladesh government should take some proper policy to mitigate the cyclone disaster, as we cannot prevent the natural phenomenon. Thus, an effective storm surge modeling is highly desirable for making a future-disaster prevention policy. Through such

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a type of modeling, a proper warning system can be made which can minimize the huge losses resulting from storm surge. But, before modeling, we have to investigate cyclone path and activity properly. The early onset of the South Asian summer monsoon occurs in the Bay of Bengal (BoB) during May, followed by the onset over the South China Sea, and then over India Together with the formation of the Bay of Bengal monsoon trough the seasonal warming of sea surface temperature, which peaks in May, provides favorable conditions not only for rainfall but also for tropical cyclones. In contrast to other tropical cyclone basins, the Bay of Bengal has two distinct seasonal peaks in TC (Tropical cyclones) occurrence. The first TC season occurs in May before the SASM (South Asian Summer Monsoon) onset (pre-monsoon), and the second spans from October to November, after the monsoon (post-monsoon); after the monsoon matures, prevailing low-level southwesterly winds and upper level easterly winds together create a strong vertical wind shear, prohibiting TC formation and development. As a result, tropical disturbances that form at the heart of the monsoon season (June-August) seldom develop into TCs; instead they form monsoon depressions Intra seasonal oscillations affect monsoon development and TC formation in the BoB.

While key conditions necessary for TC formation such as high SST, low vertical shear and low-level vorticity are present in the BoB during the pre-monsoon season, TCs do not arise simply because these conditions are met. Additional forcing such as ISO is needed to trigger tropical cyclogenesis. As was pointed out by [4]-[5], about 60% of TCs that form over the Indian Ocean do so in association with significant ISO events. The Madden-Julian Oscillation (MJO) is the dominant component of intra seasonal oscillations observed in the global tropics. Because of its connection with these and other weather systems, the MJO affects medium and extended range weather forecasts globally [6]-[7]. The MJO is characterized by large regions of both enhanced (i.e. positive phase) and suppressed (i.e. negative phase) convection, which propagates eastwards slowly through the portion of the Indian and Pacific oceans where the sea surface is warm, with a period of about 30 to 60 days. The MJO constantly interacts with the underlying ocean and influences many weather and climate systems [8]. In the tropics, the MJO modifies the large-scale circulation anomalies conducive for TC development; this is the case in the BoB. During the positive phase of the MJO (based upon convergence over the Indian Ocean-western Pacific region), synoptic conditions that are favorable for TC development are considerably enhanced [9]–[11]. In addition to the day-to-day fluctuations of weather with timescales of five to seven days, a characteristic feature of monsoon rainfall is prolonged spells of dry and wet conditions often lasting for two to three weeks. Extended periods of such monsoon inactivity are known as monsoon breaks, and have long been associated with ISOs. The dry and wet spells of active and 3 break conditions represent intra seasonal variation of the monsoon with timescales longer than synoptic variability (1–10 days) but shorter than a season. While the positive phase of the MJO (enhanced convection) affects both the timing and intensity of the SASM, the negative phase (suppressed convection) initiates breaks in the monsoon and can even prematurely end the monsoon [12]-[13]. Although the BoB is the least active TC basin in the world, it has the tendency of generating some of the world's deadliest TCs. Bangladesh is highly vulnerable to the impact of tropical cyclones that form in the BoB, as was exemplified by tropical cyclone Nargis in May 2008. According to the United Nations, tropical cyclone Nargis caused catastrophic destruction with at least 130,000 reported fatalities [14] and an estimated $4 billion in damages, making it the most destructive storm ever to hit the basin. But although destructive, tropical cyclones are important rain bearers. Tropical cyclone characteristics depend upon some basic parameter of a cyclone. The well-known parameters of a tropical cyclone are landfall angle, maximum sustained wind radius, translation speed, central pressure, wind velocity and so on.

Every year Bangladesh faces some cyclone disaster, on an average, 5-6 storms form in this region every year, but with 80% of the global casualties [15]. Most of the researchers will develop the model but cyclone path is the main factor for the storm surge estimation. So, the cyclone path investigation is necessary. For this reason, in this study, we investigate the lifetime of a cyclone in the Bay of Bengal. In this study, we have investigated the 21st century cyclone data that was taken from the Bangladesh Meteorological Department (BMD). The data range is 2002 to 2021 cyclone data that was generated in the Bay of Bengal region but for the decay analysis, we have used 2004 to 20021. We have focused on the cyclone lifetime in this research.

2. Material and Methods

2.1. 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, and 153 police station areas. This coastal area covers 32% area and 28% of the population of Bangladesh [16]. But, the 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 and Meghna, which formed this world's largest delta. On average, 15,000 people die annually by storms and tide [17]. 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.

Some parts of coastal areas are under severe threat of future disaster like future severe cyclones, future sea-level submergence, salinity, and so on. Most of the farmers already adapted their cultivation process in a dangerous situation of surge and inland flood. However, they are worried about the future disaster. Coastal zone of Bangladesh is geo-morphologically and hydrologically dominated by the Ganges Brahmaputra Meghna (GBM) river system and Bay of Bengal. The coastal zone of Bangladesh covers an area of 47,201 km 32% of the country, being the landmass of 19 districts. Around 35 million people, representing 29% of the population, live in the coastal zone. Coastal zone of Bangladesh consists of 19 coastal districts that are Jessore, Narail, Gopalganj, Shariatpur, Chandpur, Satkhira, Khulna, Bagerhat, Pirozpur, Jhalakati, Barguna, Barisal, Patuakhali, Bhola, Lakshmipur, Noakhali, Feni, Chittagong, and Cox's Bazar. Depending on geographic features, the coastal zone of Bangladesh consists of three parts, (a) The eastern zone, (b) The central zone, (c) Western zone. The western region known as Ganges tidal plain comprises the semi-active delta and is crisscrossed by numerous channels and creeks. The central zone is the most active and continuous process of growth and decay. Meghna river estuary lies here in this zone. The eastern region is covered by a hilly area that is more stable.

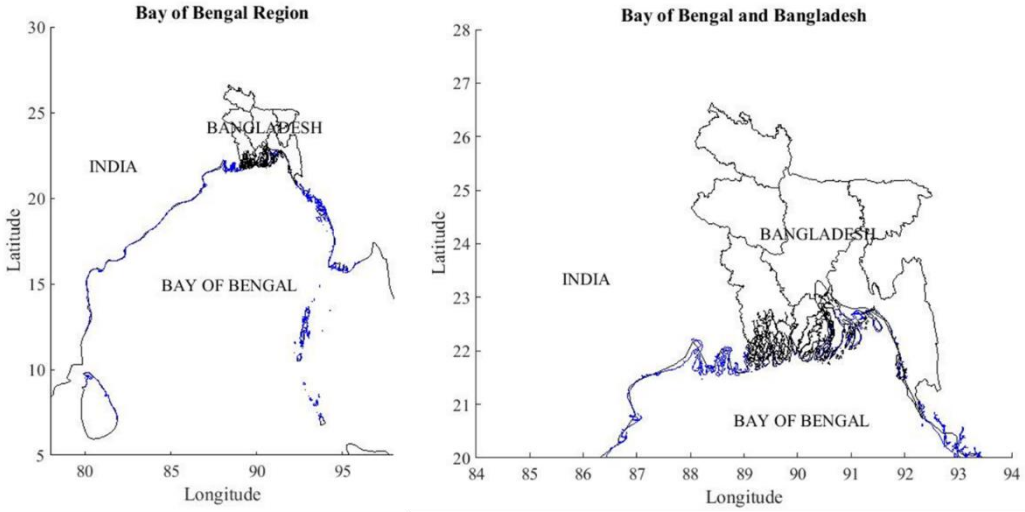


Figure 1. Study area of this research

2.2. The Data

In this study, we have exercised the BMD observed data from 2002 to 2021 to find the lifetime of a cyclone in this region. The responsible authority of the data is Bangladesh Meteorology Department (BMD). Bangladesh Meteorological Department (BMD) is a government organization under the administrative control of the Ministry of Defense. Their vision is to be a world class meteorological center providing excellent services nationally and internationally. This is their mission for acquiring data, providing data and other responsibilities. The most common responsibility of the organization is

to monitor and issue forecasts and warnings of all meteorological extreme events like tropical cyclones, severe thunderstorms/tornadoes, heavy rainfall, drought, cold and daily routine forecast around the clock with heat waves.

2.3. Data Calibration and Investigation

Some well-known data that explain the scenario clearly, that's are the Meteorological Research Institute (MRI)- Atmospheric Global Climate Model (AGCM), Database for Policy Decision-Making for Future Climate Change (d4PDF), Joint Typhoon Warning Center (JTWC), and Bangladesh Meteorological Department (BMD). 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, [18] developed a NCAR Community Climate Model version 1 (CCM1) which is now known as an Atmospheric Global Circulation Model (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 [19]. In the present situation, the Meteorological Research Institute (MRI) and Japan Meteorological Agency (JMA) jointly develop a new operational numerical weather prediction model known as MRI-AGCM [20]. 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 [1]. 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 of 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 database for policy decision making for future climate change (d4PDF) data was revised for global experiment data. The d4PDF data was produced from the weather prediction model of Japan Meteorological Agency [21] with the modified model of MRI-AGCM 3.2 [22]. The data was 60 km grid for global simulation and 20km grid for Japan area. The developed model used triangular truncation with a linear Gaussian grid (TL319) and the 64 vertical levels with the top at 0.01 hPa [23]. It is clear that the model wave number is 319 and the grid resolution is 60 km in horizontal level and 64 for vertical level. The boundary conditions of the model were sea surface temperature (SST) (See, Figure 2) and sea-ice concentration (SIC, and sea-ice thickness (SIT) for lower boundaries. The external forcing was considered as Global-mean concentrations of greenhouse gasses, three-dimensional distributions of ozone and aerosols [22]. The data were collected from the Data Integration and Analysis System (DIAS) under the Global environmental information integration program [24]. The data is divided into three features with past experiments (1951 to 2011), Non-Global warming experiments (1951 to 2010), and 4^0 C rise experiment (2051 to 2110). In addition, the experiment result of the global atmospheric-ocean coupled model contributes to the Coupled Model Intercomparison Project Phase 5 (CMIP 5). There are 100 members' simulation for present climate conditions, and 90-member simulation for future climate conditions. In the future climate simulation, there are six different ensemble simulation model of CC (CCSM4), GF (GFDL-CM3), HA (HadGEM2-AO), MI (MIROC5), MP (MPI-ESM-MR), and MR (MRI-CGCM3).

The authorities are responsible for the future-climate model simulation. The authorities are National Center for Atmospheric Research (USA), NOAA Geophysical Fluid Dynamics Laboratory (USA), Met Office Hadley Center (UK), AORI, NIES, JAMSTEC (Japan), Max Planck Institute for Meteorology (Germany), and Meteorological Research Institute (Japan). Different SST (See, Figure 2) conditions are used for different climate simulations. Figure 2 represents the SST pattern [25]. Monthly mean inter-annual variation of SST (See, Figure 2) 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 [26]. For the analysis of cyclones, [27] developed a tropical cyclone (TC) detection model. After summarizing the technique and adopting the new definition of cyclone, the model was developed by [28]. 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 0.8^0 C, maximum wind speed greater than 13 ms^{-1} at 850 hPa, and the duration of life-time longer than 36 hours.

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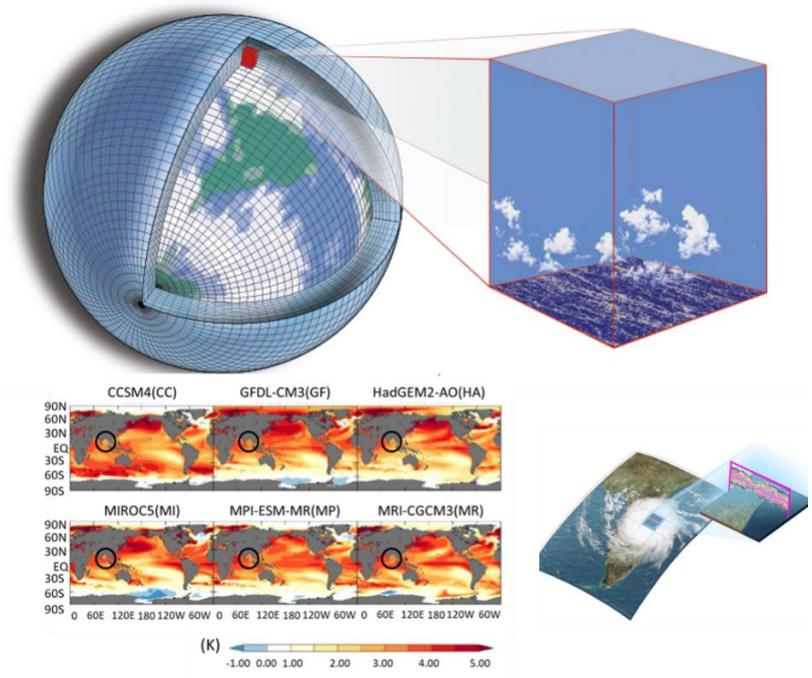


Figure 2. Monthly mean inter annual variation of SST with AGCM grid

3. Results

Last 50 years' record shows that some strong cyclones struck the Bangladesh coast, notable of them are AILA, SIDR, and Cyclone 1991 (BoB 01) [29]. This study investigates the data from 2002 to 2021 because of 21st century data availability. At first we plotted all the cyclone paths within the Bay of Bengal to investigate the pattern of the cyclone Behavior. Figure 3. shows the cyclone tracks from 2002 to 2021.

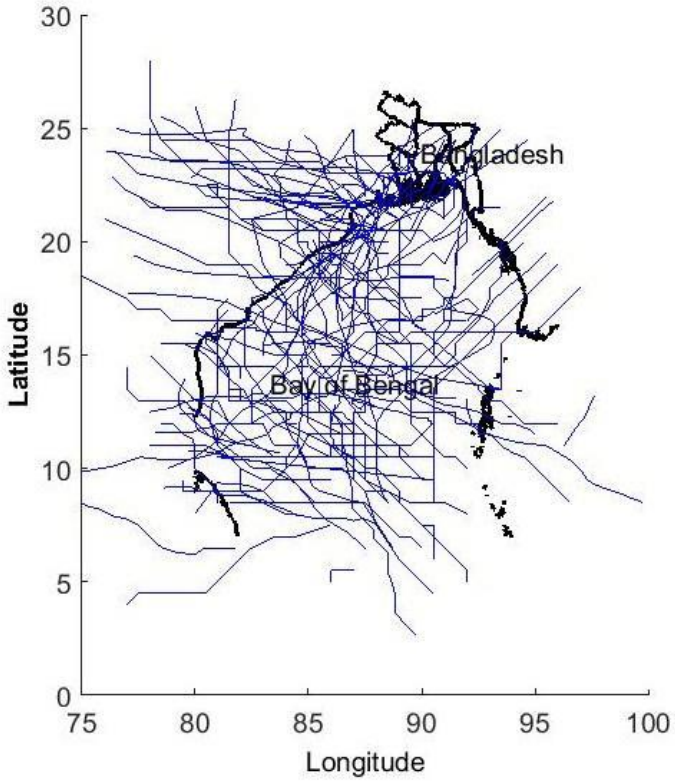


Figure 3. Cyclone tracks from 2002 to 2021

From this figure we have found that the cyclone in the 21st century struck near the western side of the Bangladesh coast. To find the periodic behavior we have investigated the data in three slots of time. The time split was 2004 to 2009, 2010 to 2015 and 2016 to 2021.

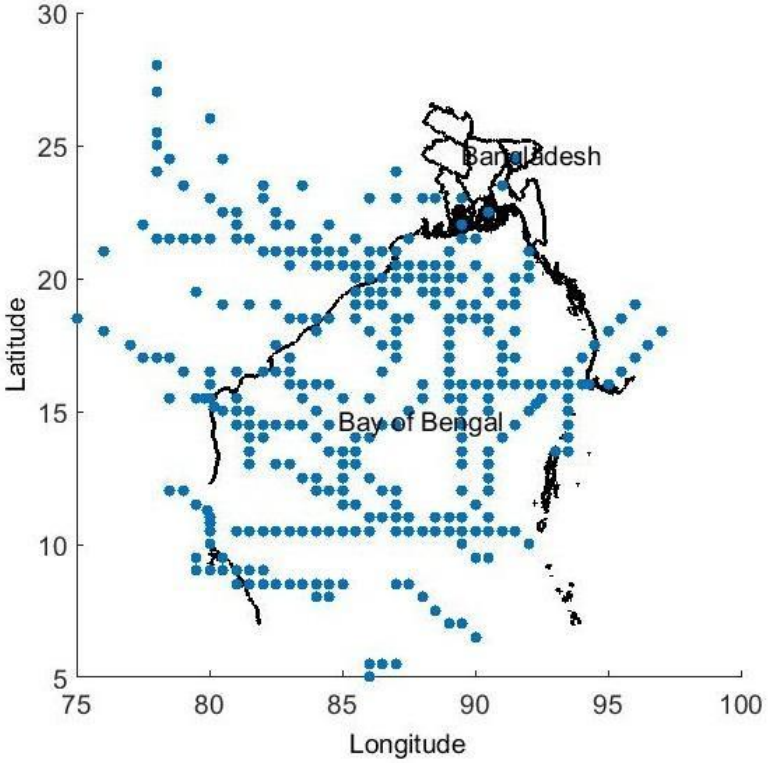


Figure 4. Activity for 2004 to 2009

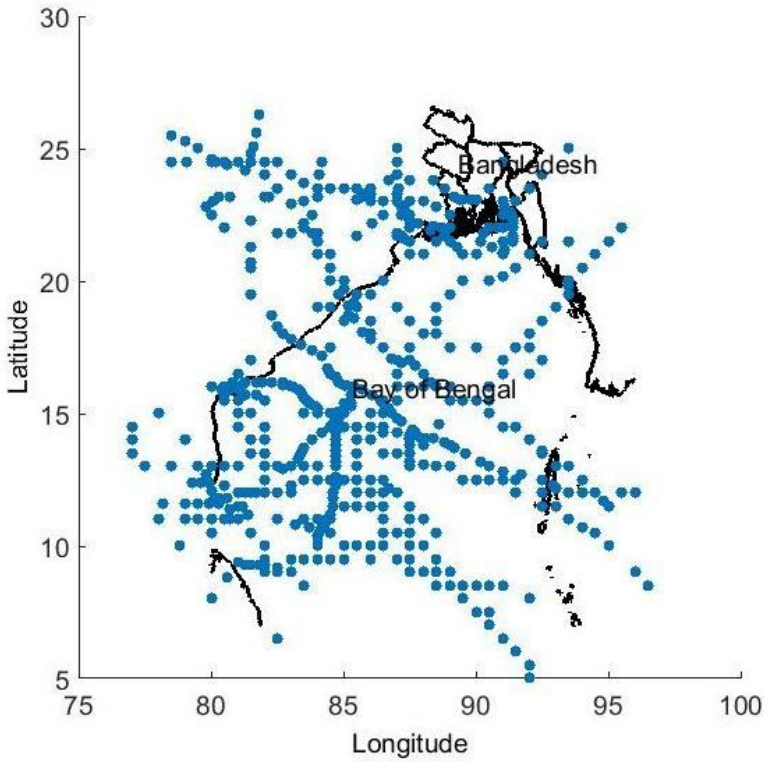


Figure 5. Activity for 2010 to 2015

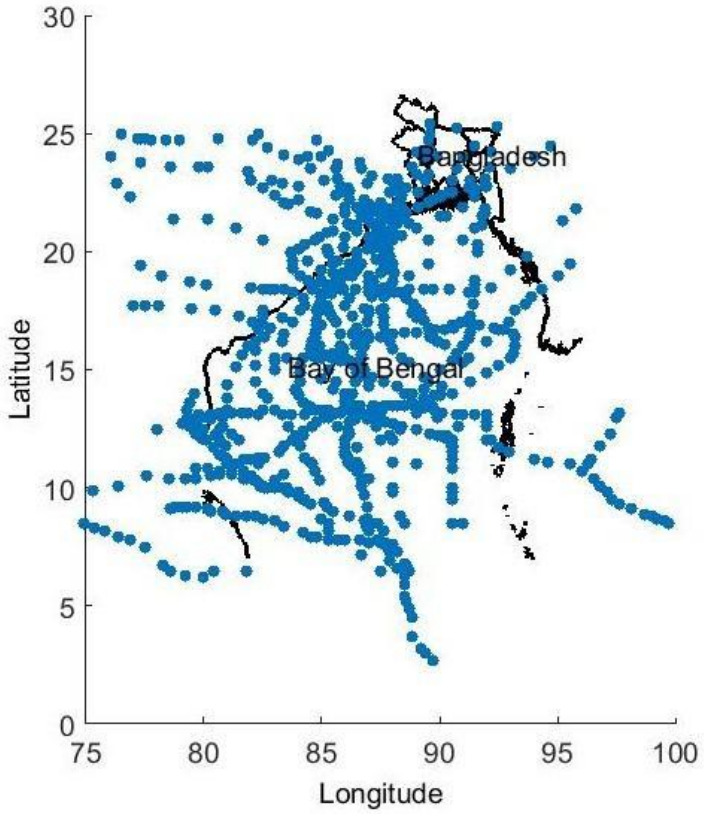


Figure 6. Activity for 2016 to 2021

From this investigation we have found that the last split of the time frame number of cyclones increases. We have also found that most of the probable area of cyclone is near Visakhapatnam (India) but, the dangerous cyclone strike region is the west part of Bangladesh coast. That means the Sundarbans Area (Bangladesh) will be a more probable region for cyclone strike.

4. Discussion

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. The seasons are the summer season (mid-April to mid-June), the rainy season (mid-June to mid-August), the autumn season (mid-August to mid-October), the Late autumn season (mid-October to mid-December), the winter season (mid-December to mid-February), and the spring (mid-February to mid-April).

We have analyzed the cyclone data of Bay of Bengal from 2004 to 2021 and found that a total of 55 storms occurred from 2004 to 2009, but 65.46% of them strike (landfall) in Bangladesh and 34.54% strike in India. In the similar fashion, for 2010 to 2015, a total number of 53 cyclones occurred and 58.5% strike in Bangladesh and the remaining 41.5% in India. A total number of 65 cyclones occurred from 2016 to 2021, of which 61.54% strike in Bangladesh and the remaining 38.46% in India. From this analysis we have found that the first 5 years' cyclone strike rate increased then decreased and again increased. So, this may represent the periodic nature of cyclone occurrence and strike.

Table 1. Occurrence and landfall (strike) behavior

Year Decay	Total Occurrence	Strike in Bangladesh (%)	Strike in India (%)
2004-2009	55	65.46	34.54
2010-2015	53	58.50	41.50
2016-2021	65	61.54	38.46

To understand the cyclone occurrence behavior, we have investigated the cyclone number in the Bay of Bengal. Figure 7 shows the occurrence within the Bay of Bengal. It is clear that the future cyclone number will increase. The trend of the cyclone represents a positive increase in the future.

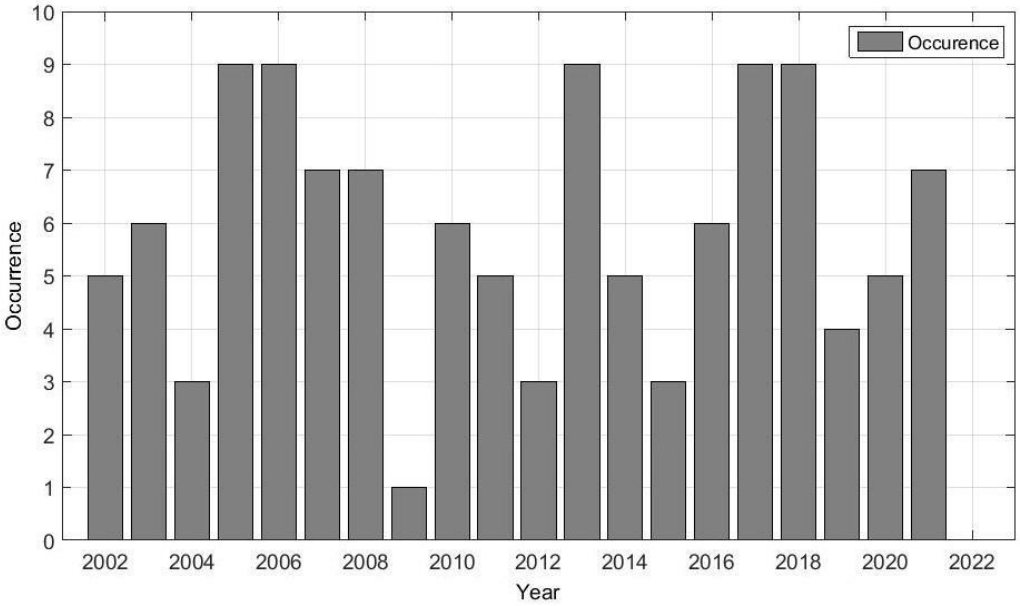


Figure 7. Cyclone occurrence within the Bay of Bengal

To understand the future occurrence, we have investigated the best fit technique. That's why we have investigated the fitted line of occurrence. And, we finally found the result and it shows in Figure 8. The statistical fitted lines of the quadratic, cubic and linear fit are given below.

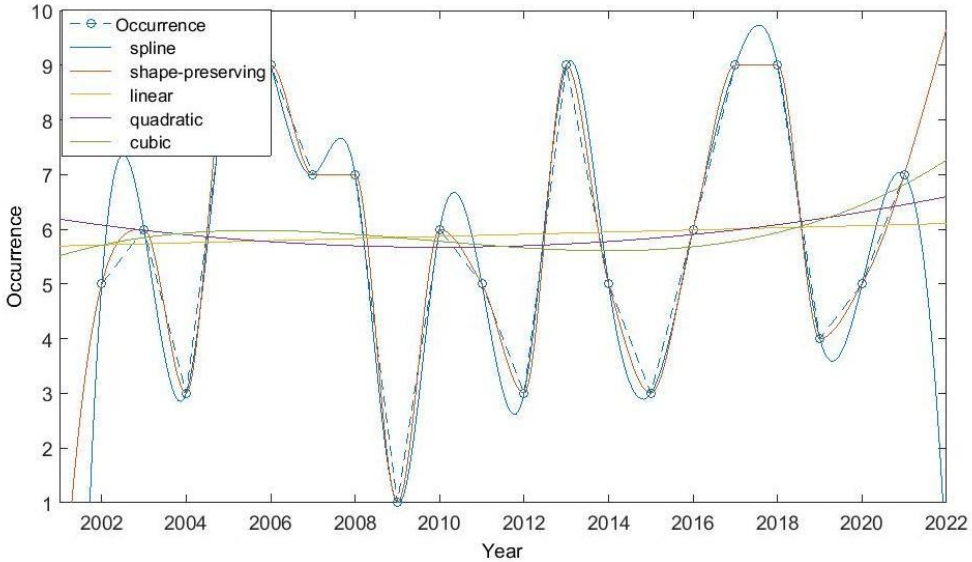


Figure 8. Fitted line of cyclone occurrence

For Cubic: $y = p_1x^3 + p_2x^2 + p_3x + p_4$
Coefficients: $p_1 = 0.0012618, p_2 = -7.6078, p_3 = 15290, p_4 = -1.0243e^{+07}$
Norm of residuals: 10.302
For Linear: $y = p_1x + p_2$
Coefficients: $p_1 = 0.019549, p_2 = -33.423$
Norm of residuals: 10.37
For Quadratic: $y = p_1x^2 + p_2x + p_3$
Coefficients: $p_1 = 0.0063796, p_2 = -25.646, p_3 = 25779$
Norm of residuals: 10.336

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In a similar Fashion, we have investigated the lifetime of a cyclone. Lifetime of a cyclone means the total operation hour of a cyclone.

Lifetime= Dissipation time - Genesis time (1)

Dissipation time means the cyclone ending time. When the environmental condition is balanced after a cyclone is called Dissipation time and the genesis time is the format time of a cyclone.

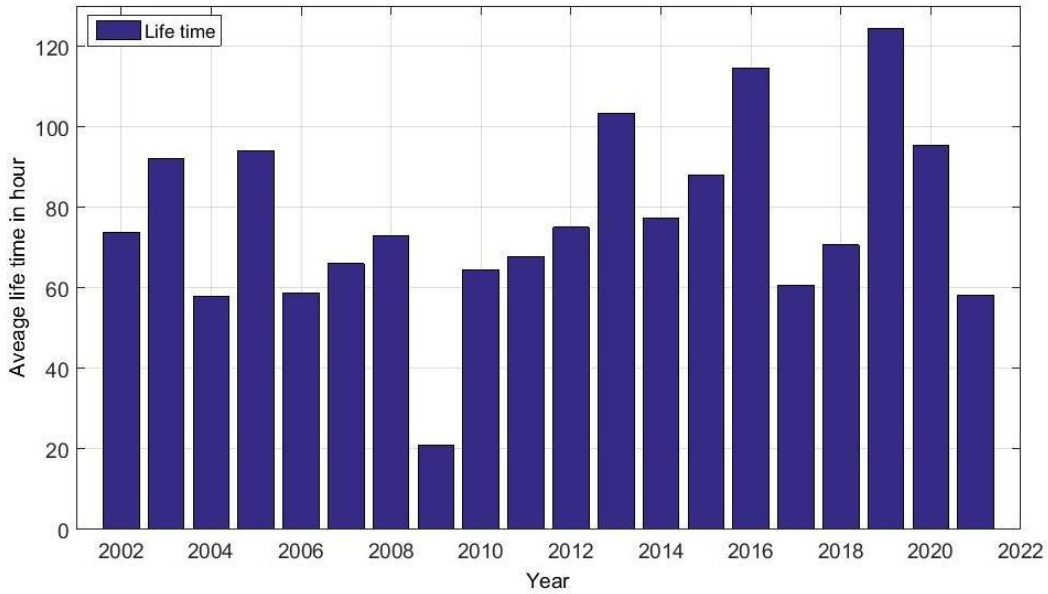


Figure 9. Cyclone lifetime within the Bay of Bengal

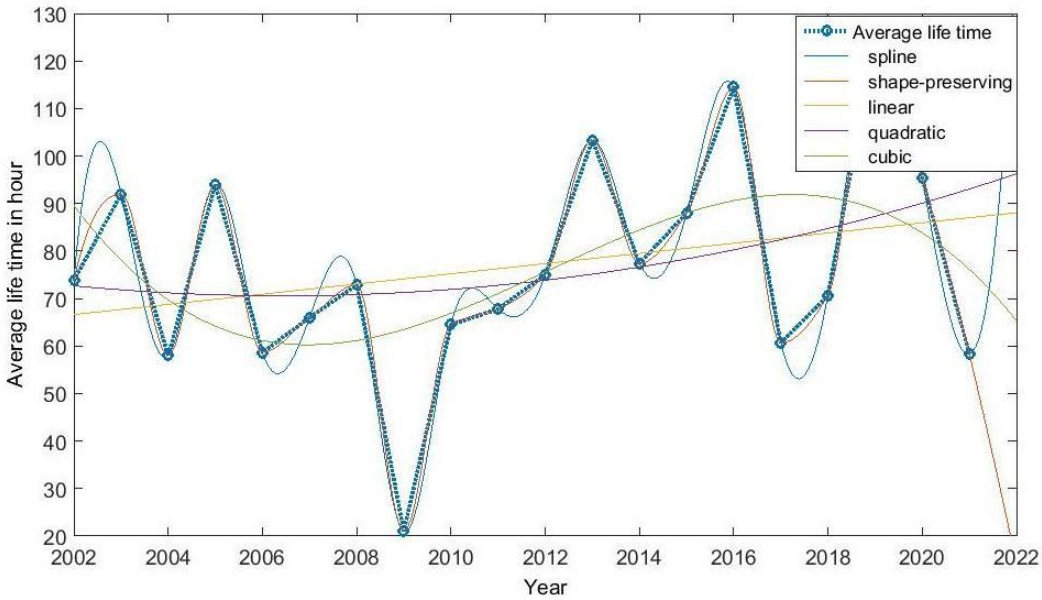


Figure 10. Fitted line of cyclone lifetime

Sometimes, various research was performed with the model simulation data. Researchers are worried about the future climate and its changes due to global warming and ice concentration. The MRI-AGCM present data can explain the present situation well because the MRI-AGCM is forced with observed SST, but the model input SST from CIMP3 has some biases. For the 21st century (2075–2099, 25 years), the global simulation under the consideration of the future scenario MRI-AGCM3.2H model forecasts the future climate. At the first step, the Couple Model Intercomparison Project 3 (CMIP3) multi-modeled data set was used to project the Multi-Model Ensemble (MME) of SST. The second stage represents the linear trend in MME of SST that projected the MIP3 data set. At the third step, a difference between the 20th century experiment of Intergovernmental Panel on Climate Change (IPCC) fourth

assessment report [30] and future simulation under the Special Report on Emission Scenario (SRES) A1B emission Scenario [31] in MME of SST. 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-year 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 range is from 1.95°C to 2.14°C [32]. 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 Bay of Bengal cyclone information for the different scenarios of C0, C1, C2, and C3 are represented in the above figure. It is evident that the probable cyclone eye point was found near the east coast of India. The cyclone activity information of the Bay of Bengal for the different scenarios of C0, C1, C2, and C3 can represent the cyclone formation probability along the Bay of Bengal for the 21st century. 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. 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. It is observed that the Bangladesh coast faces some cyclones in different scenarios. Most of the cyclones that strike in 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. Finally, we can say that the lifetime will increase in the future within the Bay of Bengal region. The statistical information of the lifetime analysis is given below.

For Cubic: $y = p_1x^3 + p_2x^2 + p_3x + p_4$
Coefficients: $p_1 = -0.058297, p_2 = 351.9, p_3 = -7.0805e^{+05}, p_4 = 4.7489e^{+08}$
Norm of residuals: 88.029
For Linear: $y = p_1x + p_2$
Coefficients: $p_1 = 1.0732, p_2 = -2081.8$
Norm of residuals: 97.193
For Quadratic: $y = p_1x^2 + p_2x + p_3$
Coefficients: $p_1 = 0.10607, p_2 = -425.65, p_3 = 4.2709e^{+05}$
Norm of residuals: 96.171

5. Conclusion

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. A significant change of the characteristics has been found due to change of time, which plays a vital role in changing the surge behavior and associated environmental parameters within this area. An increasing trend of occurrence behavior has been found from this study. Significant information comes from this study and the information is about the lifetime of a cyclone. Cyclone lifetime fluctuated due to change of climate conditions but in future cyclone lifetime will increase. This means that the future cyclone gathers more energy and power. So that, in near future Bangladesh will face more powerful cyclone hazards. It is found from this investigation that the possibility of the future storm hitting the southwestern region of Bangladesh due to Global warming under the +4K temperature increase. From this probabilistic investigation, it can be said that there is a visible change in the direction of the storm track due to the global warming scenario.

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