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SPATIO-TEMPORAL PATTERN OF TROPICAL CYCLONES: THE CASE OF CYCLONES OF THE BAY OF BENGAL

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Abstract: For the last few decades, the generalized pattern of tropical cyclones has gone through an unstable system transformation in the global changing climatic scenario. Thus, the broad aim of this research work was to explore the spatio-temporal changing pattern of tropical cyclones in the basin of the Bay of Bengal between 1985 and 2019. Cyclone track information data have been collected from Emergency Events Database (EM-DAT) server and Bangladesh Meteorological Department. The loss and damage statistics has been collected from different published sources. Geographical distributional characteristics such as mean center and standard directional distribution have been explored using the spatial statistical tool of ArcMap. The mean geographic center has been identified near the district of Bhola and Patuakhali. The cyclonic occurrences in the research area are oriented north–west to south–east according to standard directional distribution. Hot spot analysis was used to identify the most affected parts in the study area and found that there are no significant hotspots, but the distribution pattern is rather random. However, there are two minor concentration zones in the study area, one near Barguna and another one near Sandwip coast. SPSS software was also used here to analyze the relationship between cyclonic events and the loss/damage scenarios of the study area. The relationship between cyclonic velocity and damage of life and livelihood showed a strong correlation of .804 with a significance level of 99% (p < .01). Random cyclonic trends and patterns indicate a change in this region's climatic variability over the past 35 years.

Keywords: tropical cyclone; coastal region; cyclonic magnitude; cyclonic trend and pattern; Bangladesh

Introduction

South Asian countries, especially areas adjacent to the Bay of Bengal, are the most vulnerable to tropical cyclones originated in the Indian ocean. The Bay of Bengal is responsible for around 80% of all tropical cyclones in the north Indian Ocean. Every year, around 5–6 tropical cyclones form in the Bay of Bengal, with about two of them reaching severe levels. The post-monsoon season between October and November is when the majority of the Bay of Bengal's strong cyclones form. Although a few strong cyclones could occur in May, the post-monsoon cyclones are the most severe, hence this season is also known as storm season in South Asia (Singh, 2007). Within this region, Bangladesh witnesses great devastation because of the funnel shape of the Bay of Bengal ending in this part, i.e., most of the cyclones of the Bay of Bengal make their landfall on the coast of

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Bangladesh. In Bangladesh, tropical cyclones get their energy from strong evaporation over the warm sea, rather than from contrasting temperatures between cold and warmer air masses, as in mid-latitude storms (O'Hare, 2001). The effective temperature for the formation of cyclones is around 27 to 29 °C, which is responsible for category 1 to 4 cyclones in Bangladesh (Khan, Sattar, & Farukh, 2015; Kumar, Done, Dudhia, & Niyogi, 2011). Cyclones form as a result of low air pressures over the Bay of Bengal (Hossain & Mullick, 2020). Cyclones in Bangladesh are currently classified based on their intensity, with the following nomenclature in use: depression (winds up to 62 km/h), cyclonic storm (winds 63 to 87 km/h), severe cyclonic storm (winds 88 to 118 km/h), and severe cyclonic storm of hurricane intensity (winds above 118 km/h) (Banglapedia, 2020). The Bay of Bengal is increasingly suffering from frequent severe tropical cyclones and storm surge, affecting thousands of people due to its unique geographic location. Some of the most catastrophic cyclones with significant casualties in the recorded history were tropical cyclones that devastated the region of present-day Bangladesh (Hossain & Mullick, 2020).

High wind speeds, heavy rains, and storm surges (unusually high sea levels) contribute to casualties, property losses, and destruction in cyclone-prone areas. Winds of the speed greater than 117 km/h frequently destroy or severely damage fragile structures (Hossain & Mullick, 2020). During a short period of time (up to and over 50 cm in three to seven days), heavy rainfalls can result in catastrophic floods and significant crop damage (Dasgupta et al., 2010). The loss of life and property can increase with intense cyclones. The most damaging aspect of a cyclone is a storm surge, which is pushed up to high levels when the storm advances inland (Hossain & Mullick, 2020). In order to determine whether the results of our research were in line with the above studies, the focus of this study was on the examination of consistency between cyclone magnitude and damage.

In the last 35 years, the Bay of Bengal has been hit by numerous cyclones causing enormous disruptions, damages, and a remarkable number of casualties (Hossain, Islam, Sakai, & Ishida, 2008; Islam, Hossain, & Ishida, 2011). The cyclones that occurred in the years of 1970 (Bhola), 1991 (Hurricane), 1997 (BOB 07), 2002 (O6B), 2007 (Sidr), 2008 (Rashmi), 2009 (Aila), 2013 (Mahasen), 2015 (Komen), 2016 (Rohanu), 2017 (Mora), and 2019 (Fani) are some of the examples (Figure 3, Table 3). The 1970 Bhola cyclone, which struck on November 12, 1970, was a devastating cyclone which caused one of the deadliest (more than 250,000 people) natural disasters in modern times (Islam & Peterson, 2009). Cyclone death rates from the two most severely affected islands, Urir Char and Sandwip, were studied in 1985 to establish the risk variables for cyclone-related mortality. In Urir Char, where there were no cyclone shelters, 40% of the family members died, compared to 3.4% in Sandwip, where there were at least eight cyclone shelters (Siddique & Eusof, 1987). The cyclone of hurricane intensity crossed the Chittagong coast, which is located in the northeast of Bay of Bengal, at a speed of 240 km/h at 19:00 UTC on April 29, 1991, killing some 150,000 people in Bangladesh (Chowdhury, Bhuyia, Choudhury, & Sen, 1993).

The people most vulnerable to cyclones worldwide include those with limited economic resources, lack of adequate technology, insufficient knowledge and skills, and inadequate infrastructure. Such groups are unable to adequately prepare for and protect themselves from cyclones, as well as to respond to and cope with their consequences (O'Hare, 2001). Climate changes indicate random cyclonic occurrences (Karim & Mimura, 2008). The broad theme of this study was to explore the cyclonic storms' trend, pattern, major hot spot, and consistency between cyclone magnitude and the threat of loss of life, and to explore the role of the changing nature of weather variables on livelihood in Bangladesh between 1985 and 2019. This research explores the cyclonic event and its natural behavioral change depending on the period and relationship between cyclonic magnitude and damages. It carried out the proper monitoring and planning of cyclonic pre, during, and post-environment. The cyclonic trends, patterns, and distribution have been found in the affected areas of Bangladesh. The government's effective adaptation policy and mitigation measures and the local people's higher resilience to the cyclonic trends, patterns, and distribution indicate decreasing loss and damages. This output has the tremendous potentiality to suggest better policy for sustainable mitigation and adaptation to reduce damage and build a good management system for cyclonic events and climatic variability.

The broad aim of this research work is to analyze the trend of tropical cyclones and explore the cyclonic pattern over the coastal area of Bangladesh. To fulfil this research, specific objectives are:

- To extract the cyclonic track of the coastal area of Bangladesh from the satellite imageries;
- To explore the trend and pattern of tropical cyclones in Bangladesh; and
- To analyze the correlation between cyclone magnitude and loss and damage in Bangladesh.

Materials and methods

The sub-basin (Bay of Bengal) cyclonic frequency spatial data and Bangladesh district boundary shapefile were managed by Space Research and Remote Sensing Organization (SPARRSO, 2019), Bangladesh Meteorological Department (BMD, 2019), Emergency Events Database (EM-DAT, 2019), and the United States Geological Survey (USGS, 2020) from 1985 to 2019. The Bay of Bengal is roughly triangular in shape, located in the northwestern Indian Ocean between 5°N and 22°N and 80°E and 100°E. It is surrounded on the west by Sri Lanka's and India's east coastlines, on the north by Bangladesh, and on the east by Malay Peninsula that stretches up to the Andaman and Nicobar ridges (Morgan, Verlaan, & Balakrishna, 2009). Cyclonic magnitude, landfill location, exposed area, and damages data collected from published books, journals, articles, web pages, downloaded satellite images, and raster layer stack operations performed to standardize the images—standard Bangladesh Transverse Mercator (BTM) projection parameters—were used for the projection standardization. ArcMap was used for extracting cyclonic tracks from satellite images. Spatial line density analysis was also helpful for exploring the trend and pattern of the cyclonic track. SPSS was used for correlation analysis and data presentation.

Spatial analysis is a type of geographical analysis that seeks to explain spatial expression patterns in terms of mathematics and geometry—locational analysis (Artimo, 1995). In addition, spatial data inherently contain geometric and topological properties (Quiroga, Singh, & Iyengar, 1996). In this research, spatial analysis has been conducted for measuring the tropical cyclonic pattern, hot spots, spatial autocorrelation, directional distribution, and mean center analysis in the Bay of Bengal.

Spatial autocorrelation (such as Moran's Index) in ArcMap helps to understand the degree of dependency between two variables in which one object is similar to other nearby objects. Moran's Index measures of spatial autocorrelation replicates Tobler's first law of geography (Tobler, 1970). Moran's Index autocorrelation can recognize whether similar characteristics are clustered, dispersed, or randomly distributed over the space. That's why Moran's Index has been used to identify whether there is any relationship between the cyclone magnitude and the damages. Moran's Index uses the Equation 1 for calculation (ESRI, 2005a):

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} z_i z_j}{\sum_{i=1}^{n} z_i^2} \tag{1}$$

where z_i and z_j are the deviations of an attribute for the feature *i, j* from its mean, $w_{i,j}$ is the spatial weight between cyclone magnitude, and loss and damage *i* and *j*, n is the total number of features, and S_0 is the aggregate of all the spatial weights.

Pearson correlation coefficient and regression analysis were conducted in SPSS to observe the relationship pattern among the considered loss and damage with cyclonic magnitude. Equation 2 was used for correlation coefficient and regression analysis (Freedman, Pisani, & Purves, 2007):

$$r = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{\sum(x - \bar{x})^2} \sqrt{\sum(y - \bar{y})^2}} \tag{2}$$

where *r* represents the correlation coefficient, $\bar{x}$ represents the mean of *x* variables, and $\bar{y}$ represents the mean of *y* variables.

$$r = A + Bx \tag{3}$$

Where,

$$A = \frac{(\sum y)(\sum x^2) - (\sum x)(\sum xy)}{n(\sum x^2) - (\sum x)^2} \tag{3a}$$

$$B = \frac{n(\sum xy) - (\sum x)(\sum y)}{n(\sum x^2) - (\sum x)^2} \tag{3b}$$

In Equation 3, *y* represents the dependent variables of loss and damage, *x* represents independent variables of cyclone magnitude, *A* and *B* represent the constants which respectively describe the y-axis intercept and the slope of the line.

The hot spot analysis reveals statistically significant spatial clusters of high (hot spots) and low (cold spots) values. The *z*-scores and *p*-values are statistical significance measures that indicate whether the observed spatial clustering of high or low values is more prominent than it would be expected in a random distribution of the same values. Equation 4 was used for calculation (ESRI, 2005b):

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - (\sum_{j=1}^{n} w_{i,j})^2\right]}{n-1}}} \tag{4}$$

where x_j is the attribute value for feature *j*, $w_{i,j}$ is the spatial weight between features *i and j*, *n* is equal to the total number of features (Getis & Ord, 1996) and:

$$\bar{X} = \frac{\sum_{i=0}^{n} x_j}{n} \tag{5}$$

$$S = \sqrt{\frac{\sum_{i=0}^{n} x_j^2}{n} - (\bar{X})^2} \tag{6}$$

where the sample mean ($\bar{X}$) and the sample variance (*S*) of cyclones, which were the distribution of the G_i^* statistic, are normal when the underlying distribution of cyclones is likewise normal. The test statistic, on the other hand, becomes nonnormal when the underlying distribution is nonnormal. In such instances, increasing the number of geographical units in the clusters under investigation will assist the G_i^* statistic's distribution approach normalcy (Songchitruksa & Zeng, 2010).

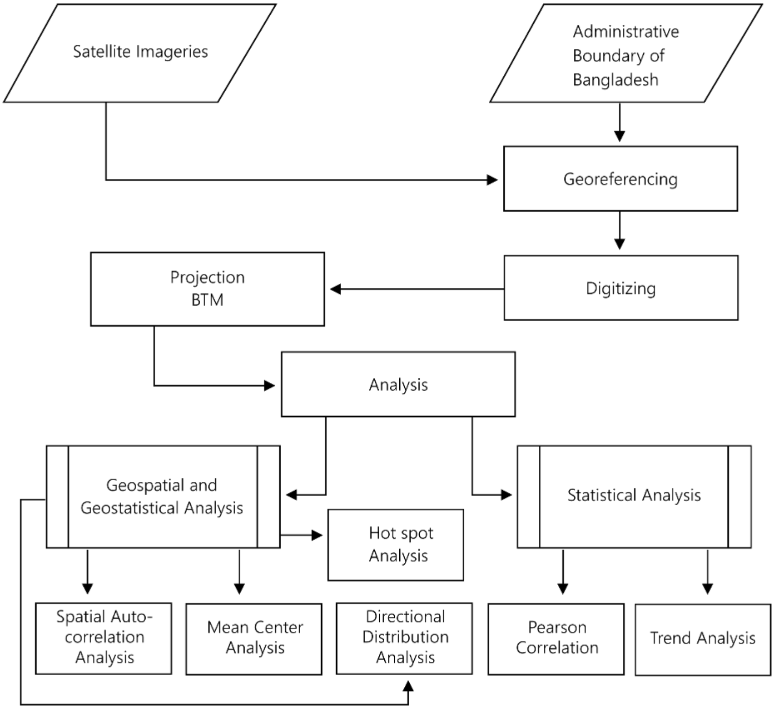

Figure 1. Research methodology.

Study area

Bangladesh lies between 20°34' N and 26°38' N, and 88°01' E and 92°41' E. With its 724 km long coastline, it is highly vulnerable to tropical cyclones (Alam, Sammonds, & Ahmed, 2020). It is the eighth most populous nation in the world, with a population of more than 163 million people living in an area of 148,560 km^2 (57,360 mi^2), making it one of the world's most densely populated countries (World Bank, 2020). Bangladesh is physiographically divided into three major units: hills in the north, northeast, and southeast covering about 12% of the total area; Pleistocene terraces covering only 8% of the total area; and floodplains covering 80% of the total area (Banglapedia, 2021). There are eight administrative divisions in Bangladesh. The divisions are further subdivided into 64 districts (Bangladesh Bureau of Statistics, 2011). Cyclones affect Bangladesh's coastal areas practically every year, with the maximum wind speed of up to 220 km/h and a tidal range of 3 m high, which may grow to 7 m farther west at the entrance of Meghna Estuary, to the east of Bhola (*Bangladesh Tropical Storm/Cyclone*, 2018). The storms have impacted almost five million people in 30 districts (Asian Disaster Reduction Center [ADRC], 2007). The districts most impacted by the cyclone include Khulna, Patuakhali, Barishal, Noakhali, and Chittagong. This region also includes the offshore islands of Bhola, Hatiya, Sandwip, Manpura, Kutubdia, Maheshkhali, Nijhum Dwip, Urir Char, and many other recently created char islands (Center for Environmental and Geographic Information Services, 2016). The most cyclone-affected districts are shown below (Table 1 and Figure 2).

Table 1
Cyclone-affected area

High Risk Area	Moderate Risk Area	High Wind Area
Barguna, Bhola, Patuakhali, Cox's Bazar	Barguna, Bhola, Patuakhali, Cox's Bazar, Pirojpur, Chittagong, Noakhali, Lakshmipur	Chattogram, Noakhali, Laxmipur, Feni, Chandpur Barishal, Jhalokathi, Bagerhat, Khulna, Satkhira, Gopalgang, Khulna, Madaripur, Shariatpur

Note. Adapted from "Investment and Financing Strategy for Coastal Zone Development in Bangladesh," by Program Development Office for Integrated Coastal Zone Management Plan, 2005 (http://old.warpo.gov.bd/index.php/home/iczmp). In public domain.

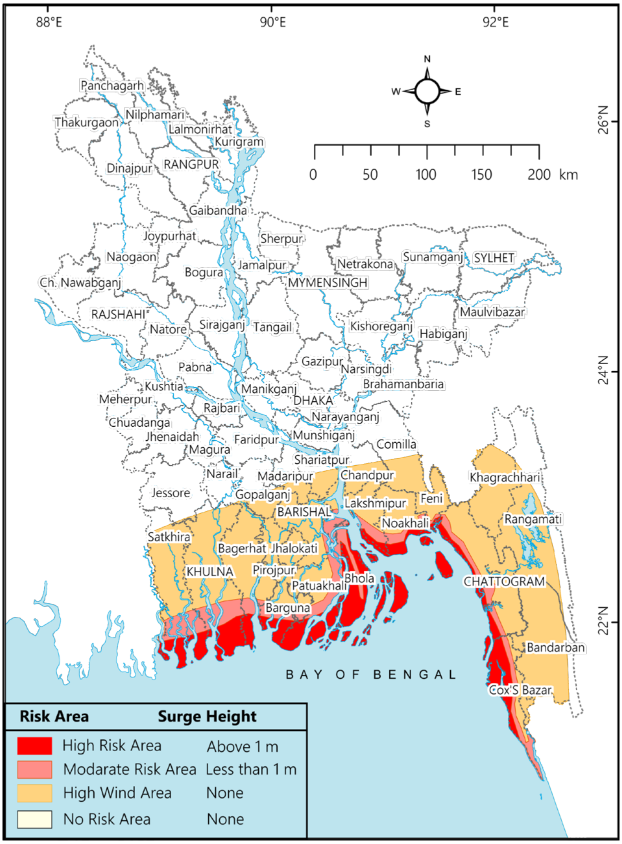

Figure 2. Cyclone-affected area in Bangladesh. Reproduced after "Investment and Financing Strategy for Coastal Zone Development in Bangladesh," by Program Development Office for Integrated Coastal Zone Management Plan, 2005 (http://old.warpo.gov.bd/index.php/home/iczmp). In public domain.

Bangladesh has one of the world's most extensive deltas. Due to its geographical location, lowland relief, population density, poverty, illiteracy, lack of institutional infrastructure, and other conditions, it is one of the countries most vulnerable to natural disasters in the world (Khatun, Rashid, & Hygen, 2016). The SPARRSO, a government body under the Ministry of Defense, forecasts and issues early warnings for storms utilizing NASA and NOAA satellites. The warnings are often issued on a ten-point scale, with ten being assigned to the most dangerous storms.

Results and discussion

The key findings regarding the tropical cyclone indicate that Bhola, Patuakhali, and Barguna districts are more affected and highly vulnerable to loss and damages due to the cyclonic velocity. The pattern of tropical cyclones has occurred randomly in the last 35 years. This research analyzed the cyclonic trend, pattern, vulnerability, and relationship between cyclonic velocity, and loss and damages.

An overview of the major cyclones occurrences in the period 1985–2019

The high magnitude and duration of storms were mainly influenced by higher wind speed. The wind speed of cyclones before the 1970s was not as high as of the recent cyclones (in 1991, 1998, and 2007), the number of casualties was severe at that time (Hossain et al., 2008; Islam et al., 2011; Parvin, Sakamoto, Shaw, Nakagawa, & Sadik, 2019). The increase in wind speed is the main cause for extending the duration of a storm. Cyclonic devastating might be illustrated with velocity and peak duration as in the examples of 1985, 1988, 1991, and 2007 cyclones (Table 2 and 3).

Table 2
Velocity, peak duration, and affected districts during the major cyclones of Bangladesh in the past 35 years

Cyclone year	Cyclone month	Cyclone name	Velocity (km/h)	Peak duration (min)	Affected district
1985	May	—	154	1	Chittagong, Cox's Bazar, Patuakhali, Barguna, Noakhali, Barishal, Bhola
1986	November	—	110	1	Barguna, Patuakhali, Barishal, Khulna, Laxmipur, Feni, Noakhali, Chittagong
1988	November	04B	205	1	Jessore, Kushtia, Faridpur, Barishal, Khulna
1990	December	BOB	100	3	Cox's Bazar
1991	May	Hurricane	240	3	Chittagong, Cox's Bazar, Bhola
1997	May	BOB 07	165	3	Chittagong, Cox's Bazar, Noakhali, Bhola
2002	November	O6B	100	3	Patuakhali, Barishal, Pirojpur, Satkhira, Noakhali, Chittagong
2007	November	Sidr	215	3	Bagerhat, Barguna, Barishal, Bhola, Gopalganj, Jhalokati, Khulna, Madaripur, Patuakhali, Pirojpur, Satkhira, Shariatpur
2007	May	Akash	115	3	Barguna, Patuakhali, Laxmipur, Feni, Noakhali, Chittagong
2008	October	Rashmi	85	3	Barishal, Bhola, Jhalokati, Khulna
2009	May	Aila	110	3	Bagerhat, Barguna, Barishal, Bhola, Jhalokati, Patuakhali, Pirojpur, Satkhira, shariatpur
2009	April	Bijli	75	3	Patuakhali, Barguna, Pirojpur, Jhalokati, Bagerhat, Khulna, Satkhira
2013	May	Mahasen	85	3	Chittagong, Cox's Bazar, Feni, Patuakhali, Barguna, Noakhali, Barishal, Bhola
2015	May	Komen	75	3	Chittagong, Bandarban
2016	May	Rohanu	85	3	Chittagong, Cox's Bazar, Noakhali, Feni
2017	May	Mora	110	3	Chittagong, Cox's Bazar, Rangamati
2019	May	Fani	70	2	Chittagong, Noakhali, Laxmipur, Feni, Chandpur, Barguna, Bhola, Patuakhali, Barishal, Pirojpur, Jhalokati, Bagerhat, Khulna, Satkhira

Note. Data in columns were collected from: "Cyclone" by Banglapedia, *National Encyclopedia of Bangladesh*, 2020 (https://en.banglapedia.org/index.php/Cyclone). In the public domain; *Bangladesh Tropical Storm/Cyclone - Disaster Summary Sheet (8 April 2018)*, 2018 (https://reliefweb.int/report/bangladesh/bangladesh-tropical-stormcyclone-disaster-summary-sheet-8-april-2018). In public domain; "Cyclone and Bangladesh: A Historical and Environmental Overview from 1582 to 2020" by I. Hossain and A. R. Mullick, 2020, *International Medical Journal, 25*(6), p. 2595–2614; "Bangladesh: Tropical Cyclone: 2007/11/15," by ADRC, 2007 (https://www.adrc.asia/view_disaster_en.php?lang=&KEY=1111). In the public domain; "Historical Cyclones," by BMD, 2019 (http://live3.bmd.gov.bd/p/Historical-Cyclones/). In the public domain.

In 1985, the number of districts affected by the cyclone was 7, which is not as many as during the 1970s cyclones (Banglapedia, 2020). The number of districts impacted by the 1988 cyclone was approximately five. All other cyclones hit more than 14 districts in this period, 1 district was hit by cyclones that occurred in 1990, 3 districts by 1991 Hurricane, 4 districts by 1997 BOB 07, 6 districts by 2002 Zoe, 12 districts by 2007 Sidr, 4 districts by 2008 Rashmi, 9 districts by 2009 Aila, 7 districts by 2009 Bijli, 8 districts by 2013 Mahasen, 2 districts by 2015 Komen, 4 districts by 2016 Rohanu, 3 districts by 2017 Mora, and 14 districts by 2019 Fani. The distribution of cyclone storm surges over 14 districts in Bangladesh is shown in Figure 3 and Table 2.

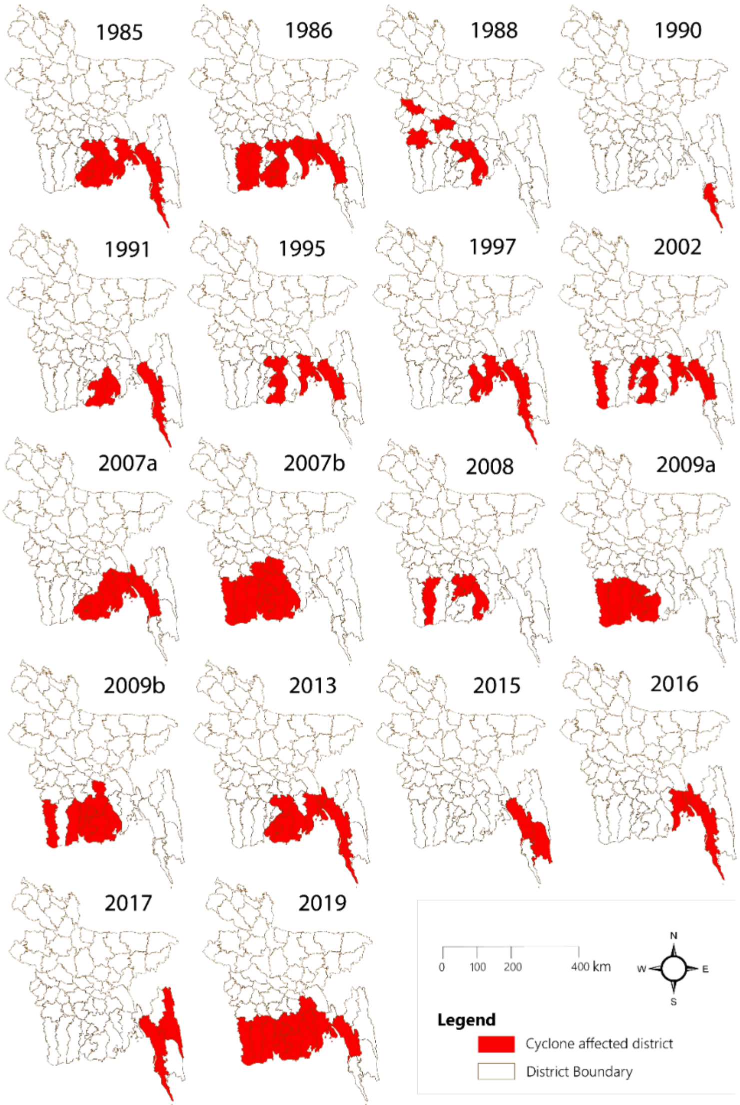

Figure 3. Cyclone-affected district in the respective years.

Data on fatalities and economic losses caused by cyclones between 1985 and 2019 are presented in Table 3. In 1991, the tropical cyclone was the deadliest and struck greater Chittagong with strong winds and storm surges, killing more than 150,000 people. In terms of fatality, the 1985 cyclone is considered to be the second most catastrophic one, during which more than 11,069 people died. On the other hand, another cyclone (1997) occurred at or near high frequency in 1985 and a cyclone frequency in 1991, but mortality was relatively low (except for Sidr in 2007) due to well-managed preparedness for tropical cyclones. The losses of animals (cattle) were catastrophic during the 1985 tropical cyclonic storm. Most agricultural destruction and economic damage have occurred in the 1991 Hurricane. After that, the 2007 Sidr cyclonic storm caused catastrophic damages.

Table 3
Fatalities, animal losses, agricultural losses, and the total economic losses for the last 35 years

Cyclone year	Cyclone name	Fatalities (human)	Animals losses (cattle)	Agricultural losses (million $)	Total economic losses (million $)
1985	—	11,069	135,033	168.19	353.96
1986	—	14	35,670	25.2	73.14
1988	04B	5,708	65,000	110.3	1049.0
1991	Hurricane	150,000	70,000	703.24	1488.53
1997	BOB 07	863	9,700	24.61	88.37
2002	O6B	51	17,600	36.92	108.53
2007	Sidr	4,234	55,000	353.96	1354.90
2007	Akash	14	1,700	10.78	966.81
2008	Rashmi	15	1,730	11.49	34.57
2009	Aila	179	34,580	79.7	220.93
2009	Bijli	3	1,370	3.4	9.14
2013	Mahasen	17	870	4.69	5.04
2015	Komen	132	690	60.95	160.8
2016	Rohanu	56	1,100	29.30	84.97
2017	Mora	9	1,750	5.27	651.79
2019	Fani	5	580	14.06	16.99

Note. Data in columns were collected from: "Cyclone" by Banglapedia, *National Encyclopedia of Bangladesh*, 2020 (https://en.banglapedia.org/index.php/Cyclone). In the public domain; *Bangladesh Tropical Storm/Cyclone - Disaster Summary Sheet (8 April 2018)*, 2018 (https://reliefweb.int/report/bangladesh/bangladesh-tropical-stormcyclone-disaster-summary-sheet-8-april-2018). In public domain; "Cyclone and Bangladesh: A Historical and Environmental Overview from 1582 to 2020" by I. Hossain and A. R. Mullick, 2020, *International Medical Journal, 25*(6), pp. 2595–2614; "Bangladesh: Tropical Cyclone: 2007/11/15," by ADRC, 2007 (https://www.adrc.asia/view_disaster_en.php?lang=&KEY=1111). In the public domain; "Historical Cyclones," by BMD, 2019 (http://live3.bmd.gov.bd/p/Historical-Cyclones/). In the public domain.

Cyclone trend analysis for the period 1985–2019

The pre-monsoon cyclone season in the Bay of Bengal is in March, April, and May, monsoon cyclone season occurs in June, July, August, and September, and post-monsoon cyclone season is in October and November. Pre-monsoon cyclones are twice as likely to occur as monsoon and post-monsoon cyclones, according to previous storms during the last 35 years. On the other hand, the post-monsoon cyclone is more likely to be a super cyclone with more destructive effects, e.g., 1988 O4B, 2007 Sidr. In the period 1985–2019, the seasonal fluctuation of cyclones during the pre-monsoon season showed increasing occurrences. During the monsoon season, a small number of cyclones occurred, and the post-monsoon cyclonic number demonstrated an increasing trend (Figure 4).

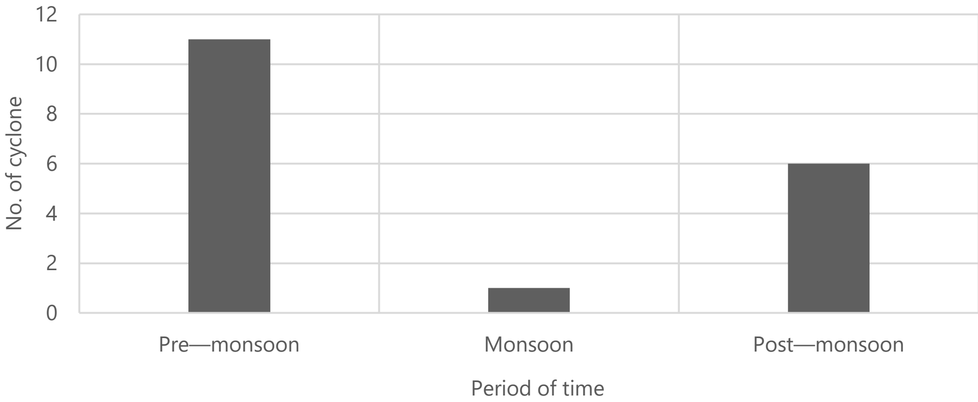

Figure 4. The number of cyclones before, during, and after the monsoon season cyclones in Bangladesh in the last 35 years.

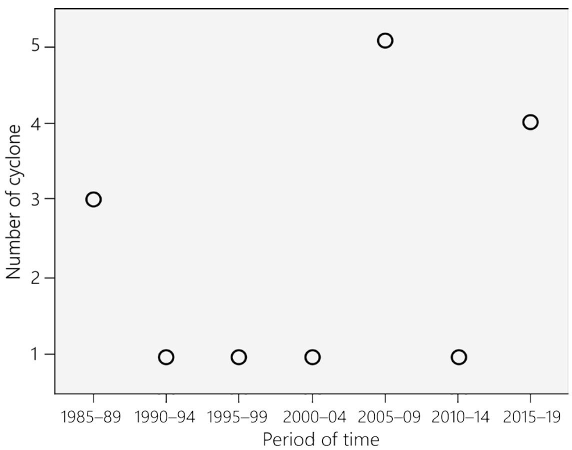

Figure 5. Number of cyclones that occurred in past 35 year.

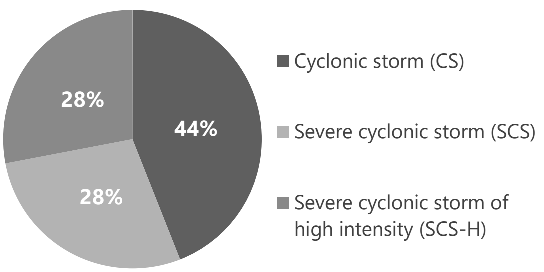

Figure 6. According to the cyclonic intensity, the major cyclone occurrence in past 35 years.

The occurrence frequency of the tropical cyclones in the Bay of Bengal, Bangladesh, in the 5-year periods, during the past 35 years (1985–2019) is shown in Figure 5. According to the number of occurrences, most of the cyclones occurred in 2005–2009, 2015–2019, and 1985–1989.

Cyclones are presently classified into four categories, from depression to severe cyclonic storm of hurricane intensity according to their intensity (Banglapedia, 2020). In this research, out of the total of 18 cyclones that hit Bangladesh in the period 1985–2019, the most common were those of the lowest intensity, cyclonic storms (63–87 km/h), which hit the coast eight times; severe cyclonic storms (88–118 km/h), which hit the coast five times; and the severe cyclonic storm of high intensity (> 118 km/h), which hit the coast five times (Figure 6).

Cyclone pattern analysis for the period 1985–2019

Cyclones in the Bay of Bengal typically move northwest at first and subsequently curve eastward. However, this pattern is not uniform, as seen from the tracks of various cyclones (Figure 7). In this hotspot analysis in the past 35 years, cyclones in the Bay of Bengal are usually not significant. In this study, the hot spot analysis has been done based on the cyclone landing point. However, if the hot spot analyses were done based on the affected district or region, the result would be different. This cyclonic pattern could not identify any hot or cold spots, which might occur randomly along the coast. Among the cyclone-hit areas, Bhola, Patuakhali, and Barguna are the most impacted locations. Barguna and the region along Sandwip coast are two minor concentration zones in the study area. According to this study, the directional distribution was north-west to south-east (Figure 7).

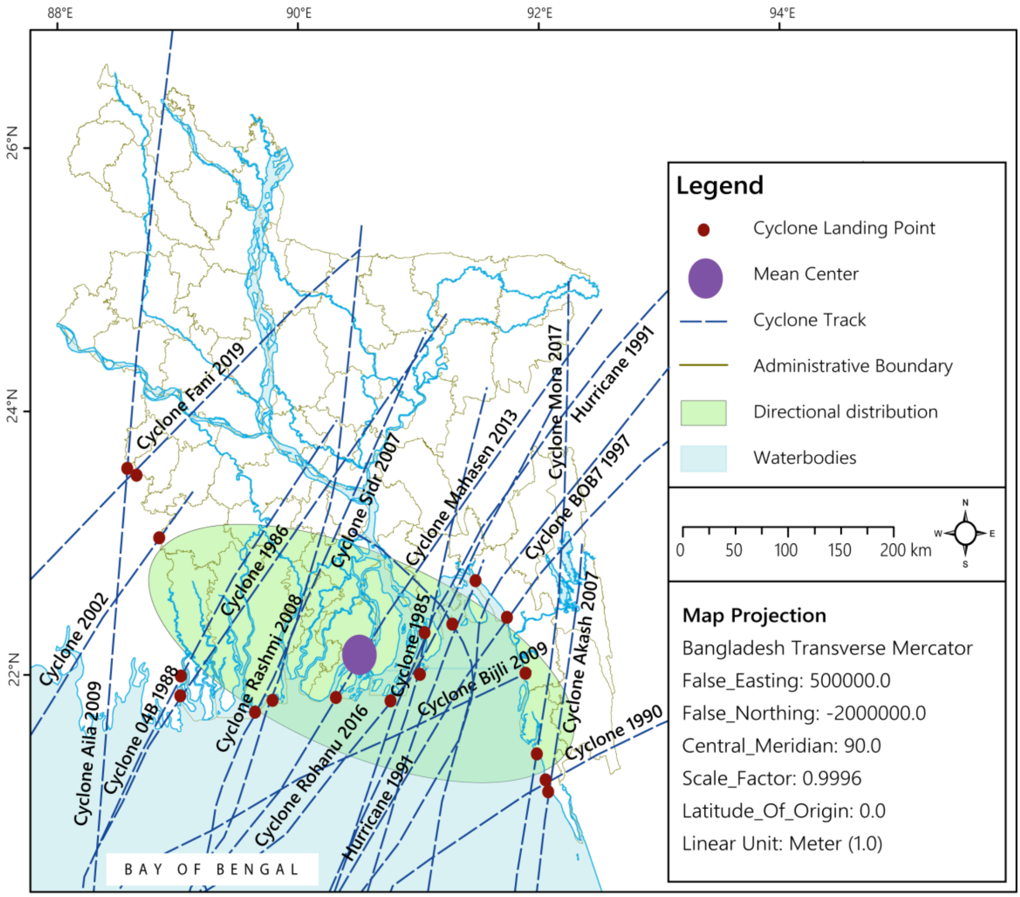

Figure 7. Cyclone pattern and track of Bangladesh during the last 35 years.

Spatial autocorrelation is multi-directional and multi-dimensional, which makes it practical for detecting patterns in complicated data sets. It is comparable to correlation coefficients and ranges from –1 to +1 (Glen, 2016):

- –1 is perfect clustering of dissimilar values (it can also be considered as perfect dispersion);
- 0 is no autocorrelation (perfect randomness);
- +1 indicates perfect clustering of similar values (it is the opposite of dispersion).

Moran's Index tool has been widely used for the geo-statistical calculation of spatial autocorrelation based on feature locations and attribute values using the Euclidean distance formula. Moran's Index determine whether the given dataset has a clustered, dispersed, or random spatial pattern. A cluster pattern with a higher value of Moran's Index indicates a positive correlation among the variables, while a dispersed pattern represents a negative correlation, and a random pattern does not exhibit any significant relationship among the variables. The *z*-score and *p*-value generated with Moran's Index value can be wisely used to test the level of significance of the analyzed result. In this research, Moran's Index value of .247 indicates a random cyclonic pattern where the spatial pattern and distribution of feature values result from random spatial processes. The negative *z*-value –.817 apprises that the pattern does not appear to be significantly different than random. On the other hand, *p*-value of .413 is not maintaining a significant level which deals with the random cyclonic pattern. The random cyclonic pattern might result in devastation when tropical cyclones hit any place in the coastal region without any criteria.

Pearson Correlation Analyses

Pearson correlation coefficient formulae are used to determine the strength of a relationship between variables. It returns a value between –1 and 1, with 1 denoting a strong positive relationship, –1 denoting a strong negative relationship, and 0 denoting no relationship at all (Taylor, 1990). In this research, the correlation coefficient between velocity and peak duration; velocity, and the number of affected districts; and peak duration and the number of affected districts have been analyzed. The negative correlation between the velocity and peak duration and velocity and the number of the affected district have been found, which indicates there is no consistency between these variables. On the other hand, a weak positive correlation between peak duration and the number of affected districts shows weak consistency between these variables. The significant correlation between peak duration and velocity is –.579, which is a highly negative correlation between these variables. The negative correlation value indicates the velocity was not dependent on the peak duration or the contrary dependency between the two variables (Table 4).

Table 4
Correlation of velocity, peak duration & number of the affected districts

		Velocity (km/h)	Peak duration (min)	Number of affected district
Velocity (km/h)	Pearson correlation	1	–.579*	–.062
	Sig. (2-tailed)		.038	.842
	N	13	13	13
Peak duration (min)	Pearson correlation	–.579*	1	.186
	Sig. (2-tailed)	.038		.459
	N	13	18	18
Number of affected district	Pearson correlation	–.062	.186	1
	Sig. (2-tailed)	.842	.459	
	N	18	18	18

Note. *Correlation is significant at the .05 level (2-tailed).

Table 5 shows the correlation of velocity and losses of human lives, losses of cattle, agricultural loss, and total economic loss. These variables have a significant linear relationship. The direction of the relationship is positively correlated, meaning that these variables tend to increase or decrease together.

When the velocity increased, losses of human lives and losses of cattle, agricultural loss, and total economic loss occurred more frequently. When the loss of cattle increased, people faced total economic losses because the losses of cattle and total economic losses have a significant linear relationship, which is a perfect positive relationship between velocity and agricultural losses. When the velocity increased, then agricultural losses were frequently higher. Also, according to Table 5, the total economic losses depend on the velocity. There is a significant correlation between velocity and losses of human lives and losses of cattle, agricultural losses, and the total economic losses, respectively. The most significant correlation has been found between the cyclonic velocity and losses of cattle that indicates the level of relationship between the two variables.

Table 5
Correlation coefficients between cyclone velocity, loss of human lives, loss of cattle, agricultural losses, and total economic losses

		Velocity (km/h)	Human lives losses	Losses of cattle	Agricultural losses (million $)	Total economic losses (million $)
Velocity (km/h)	Pearson correlation	1	.804**	.899**	.770**	.260
	Sig. (2-tailed)		.003	.000	.003	.415
	N	13	11	12	12	12
Human lives losses	Pearson correlation	.804**	1	.403	.895**	.582*
	Sig. (2-tailed)	.003		.136	.000	.018
	N	11	16	15	16	16
Losses of cattle	Pearson correlation	.899**	.403	1	.588*	.405
	Sig. (2-tailed)	.000	.136		.017	.120
	N	12	15	16	16	16
Agricultural losses (million $)	Pearson correlation	.770**	.895**	.588*	1	.759**
	Sig. (2-tailed)	.003	.000	.017		.000
	N	12	16	16	17	17
Total economic losses (million $)	Pearson correlation	.260	.582*	.405	.759**	1
	Sig. (2-tailed)	.415	.018	.120	.000	
	N	12	16	16	17	17

Note. **Correlation is significant at the .01 level (2-tailed); *Correlation is significant at the .05 level (2-tailed).

Cyclonic vulnerability level

Institutional disaster reduction and adaptable approaches to individual, social, and livelihood experiences are required for decreasing the effects of natural hazards rising in terms of loss of lives and injuries in poorer nations (International Strategy for Disaster Reduction, 2002). Vulnerability is considered to play a significant role in the disaster studies. In this study, the cyclonic vulnerability zones are classified into five categories depending on the previously formed cyclones. The regions with very high vulnerability to cyclonic storms are located along the coast with the funnel shape of the Bay of Bengal, where most of the cyclones' land. The zones with high vulnerability are also bordered by the coast where cyclones randomly hit in a comparably lower number than in the zones with very high vulnerability. The zones moderately vulnerable to the cyclonic storm are hit with relatively low cyclonic intensity, and a low number of cyclones occur. The low-vulnerability zones are located at a distance from the coast or cyclone landing point. Finally, cyclone intensity and damage rate are very low due to the lower chance to face a high cyclonic storm in the zones with very low vulnerability. Kushtia has very low vulnerability, but Meherpur, Chuadanga, and Jhenaidah are not included in these categories. Kushtia was under a weak cyclonic storm adaptation and mitigation policy in 1988. A severe cyclonic storm 04B occurred in 1988, and Kushtia is one of the impacted districts among the four districts (Figure 8).

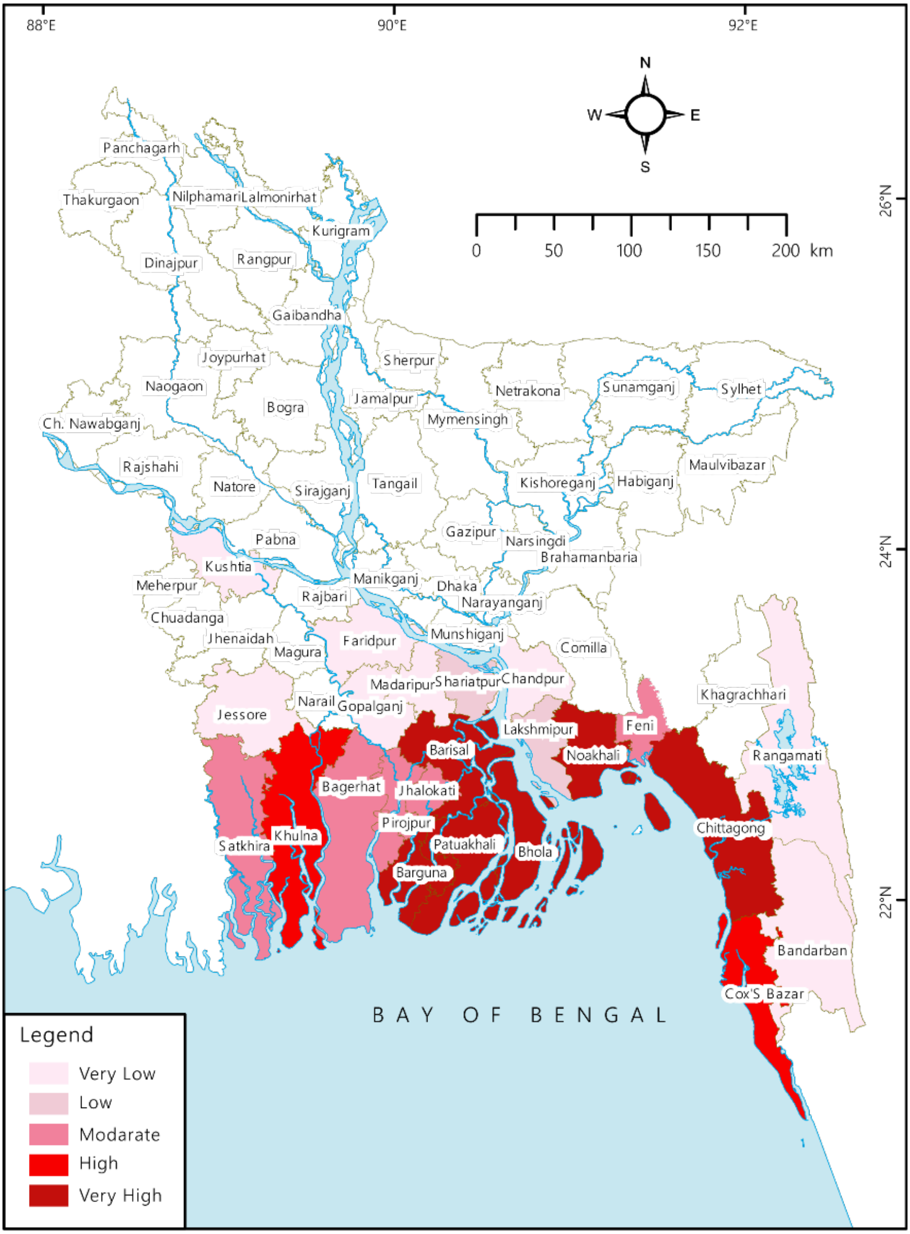

Figure 8. District wise Cyclonic vulnerability level of Bangladesh.

Conclusion

Bangladesh could be one of the greatest affected communities of tropical cyclone scenarios. The increased magnitude of cyclones and uneven occurrence pattern produces a serious level of uncertainty for the coastal community of Bangladesh. These uncertainties were also hindering the formulation of a comprehensive cyclone management policy for the country. This research revealed that over the last 35 years (1985–2019), cyclones' intensity and average wind speed changed significantly. The directional distribution was found to be north–west to south–east in the coastal area of Bangladesh. Cyclonic random pattern indicates that tropical cyclones could hit any place in the coast. The loss and damage depend on the cyclonic velocity, and there is a highly positive correlation between them. It is now essential for the government and policy makers to focus more attention to the investigation of the changing scenario of cyclonic events in Bangladesh. The research finds that with the recent uncertain changing pattern of cyclonic events, the loss and damage scenarios increase many times, which could weaken the resilience of the coastal community. Although the entire coastal region of the country is subject to high vulnerability, the scenario will be worse in the districts close to the cyclonic hot spots.

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