Synoptic climatology of weather parameters associated with tropical cyclone events in the coastal areas of Bay of Bengal

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Abstract
Tropical cyclones (TCs) are the most devastating weather phenomena that trigger massive loss of property and life in the coastal areas of the Bay of Bengal (BoB). Scientific understanding of TC occurrence can aid policy-makers and residents in coastal areas to take the necessary actions and do appropriate planning in advance. In this study, we aimed to examine the possible linkage of weather parameters with the deadly 22 TC events in the BoB from 1975 to 2014 using principal component analysis, K-mean clustering, and general circulation model (GCMs). Results showed that among 22 TCs, cluster 1 belongs to 12 TCs that occurred under the same atmospheric situation when the sea level pressure (SLP) was below 990 hPa, and the temperature ranged from 30 to 39 °C. A deep negative anomaly in SLP and temperature was observed up to 500 hPa levels. In contrast, a negative depression was found at 300 hPa geopotential height (GPH) over the study area. Cluster 2 consisted of 9 TCs when SLP was below 1000 hPa, and the average temperature was 33.5 °C. A strong negative anomaly was noticed at surface level up to 500 hPa GPH, but dramatically, this depression was completely absent at 300 hPa geopotential height over the BoB and entire coastal region. Cluster 3 contained only 1 TC when the atmospheric circumstances were completely diverse, and the SLP was above 1000 hPa. The results of the GCM model revealed that the SLP was lower, and the temperature was higher over BoB compared to the North Indian Ocean. We identified the larger depression of SLP and unpredictable temperature anomalies in the upper atmosphere that can trigger enormous unpredictability throughout the atmospheric level, leading to severe TCs. The outcomes of this study can improve our understanding of weather variables in the upper atmospheric column for forecasting the TC system more accurately in the future.

1 Introduction
Tropical cyclones (TCs) are the extreme damaging and potentially life-threatening weather events in the tropical coastal regions, including Bangladesh (Alam et al. 2003; Parker et al. 2017; Wahiduzzaman et al. 2021a). TCs are the weather-associated disasters over the Bay of Bengal (BoB), which trigger enormous damage to properties and lives in these coastal regions (Palivai and Patwardhan 2013; Vissa et al. 2013; Balaguru et al. 2014; Rajasekhar et al. 2014; Mohapatra et al. 2014). TCs can cause hazardous effects via heavy winds and floods triggered by related storm surges and heavy precipitation over the BoB (Wahiduzzaman et al. 2020a; 2020b). Although the North Indian Ocean had only a small percentage (7%) of the global TC frequency, the social and economic effects of TCs in the vital region were much greater than those in other TC regions (Wahiduzzaman et al. 2021a). For instance, in 2008, due to severe cyclone Nargis, more than 38,000 casualties and a US $10 billion loss occurred in Bangladesh (Webster 2008). Apart from the deadly costs to human life, TCs pose a considerable monetary risk to the nearby coastal inhabitants (Rumpf et al. 2009). The high fatalities in the BoB coastline area are due to the low-lying deltaic topography, landfall, shallow bathymetry level of the continental shelf zone, and funnel-shaped shoreline, which creates a region highly susceptible to storm surge–induced flooding and direct wind speed (Wahiduzzaman et al. 2021b). Moreover, the residents’ high population growth and poor social and economic situation along the BoB coastline were also found to be driving factors behind the damage generated by TCs. Thus, a thorough
understanding of synoptic climatology of the weather parameters associated with TCs over the BoB is highly important (Singh et al. 2012).

Extreme weather events, i.e., severe TCs, pose a challenging situation for scientists, planners, and decision-makers as these TC events affect society and the eco-environment (Seneviratne et al. 2012). A few studies have reported that it is challenging to study and forecast these weather extremes because of their nature, rarity, and severity; thus, the datasets are inadequate (Sillmann et al. 2017; Maw and Jinzhong 2017; Islam et al. 2020; Wahiduzzaman and Yeasmin 2019). Sometimes less noteworthy coastal floods result in huge losses of lives and property, even greater than extreme events like TC landfall (Moftakhari et al. 2017). In this context, the current study has been motivated to address the inadequacy of the TC occurrence dataset of upper atmospheric zones in the BoB coastal region over the last 40 years. Furthermore, glacier and ice melting caused by rising mean sea level was restarting the occurrences of TC events, claiming enormous economic and social losses that went unnoticed (Bamber et al. 2018; Cazenave et al. 2019; Spada 2017; Chen et al. 2018; Cazenave et al. 2019; Spada 2017; Chen et al. 2017). It is proven that if the possible landfall of TCs could be identified at an earlier time, probable damage control would be possible (Paliwal and Patwardhan 2013; Weinkle et al. 2012; Singh et al. 2012).

Synoptic climatology has been proven as a potential field of research to identify regional and global climate patterns around the globe using statistical analysis (Barry and Carleton 2001; Wahiduzzaman et al. 2020b; Wahiduzzaman et al. 2021a). Statistical analysis of weather variables associated with TC activity can help policy-makers, land planners, and coastal residents take proper action in advance. To link the statistical relationship between TCs and weather parameters, it is crucial to know the influential factors such as weather regimes, geopotential height, sea level pressure, and wind flows that affect TC genesis and landfall (Reinhold and Pierrehumbert 1982; Michelangeli et al. 1995; Rudeva et al. 2019). A few cited works have explored the impact of upper atmospheric and oceanic conditions on the variation of TC events in the BoB (Sengupta et al. 2007; Girishkumar and Ravichandran 2012; Felton et al. 2013; Wahiduzzaman et al. 2017; Sattar and Cheung 2019). Gaona et al. (2018) and Zhou et al. (2018) studied TC activity over the BoB, resulting in disastrous impacts from heavy floods and winds with the association of enormous rainfall and surges. However, these earlier works have hardly examined the statistical association between synoptic climatology and TC events over the BoB and the surrounding coastal regions.

Multivariate statistical approaches like principal component analysis (PCA) and clustering have been potential tools that have been used in many fields (i.e., Blasius et al. 2014; Bro and Smilde 2014; Hair et al. 2006; Hou et al. 2015; Kline, 2014; Shlens 2014; Dube et al. 1985). PCA has also been used by many scientists, i.e., Farukh and Yamada (2014), Farukh and Yamada (2014), and Islam et al. (2021), to identify severe snowfall, flood, and tropical cyclone phenomena and their synoptic climatology. PCA has been proven effective in studying vulnerability assessment, health vulnerability, and disaster risk reduction (Miller 2014; Howe et al. 2013; Zhu et al. 2014; Fisher et al. 2015; Tasnuva et al. 2020; Siddique et al. 2021). On the other hand, the general circulation model (GCM) has been used to determine the effect of climate extremes on agriculture (Glibert et al. 2014; Iyalomhe et al. 2015; Rahman et al. 2017; Farukh and Yamada 2014; Das 2021), rising sea level, and coastal surges (Neumann et al. 2015) and so on. Ruane et al. (2013) found that increased emissions also affected coastal agriculture when coupled with the changing climate. Some GCM models have been used to predict storm surge and atmospheric circulation patterns (Maw et al. 2017). Many scientists have successfully used GCM models to simulate the level of inundation, but the coastline structures with definite progresses of wave circulation, breaking, and interface remain poorly understood (Sielecki and Wurtele 1970; Flather and Heaps 1975). On the other hand, Ghosh et al. (1983), Flather and Khandker (1987), and Katusura et al. (1992) were able to develop some numerical models to simulate storm surges in the BoB. Additionally, Esteban et al. (2005) applied both PCA and clustering in daily sea level pressure rotations and found that snowfall was less than 30 cm per day in patterns. Due to a lack of direct observations and instruments, the upper atmospheric conditions of climatic parameters triggering TC events and possible future changes in their frequency and intensity caused by climate change are poorly understood in the BoB.

This work fills a knowledge gap in the existing body of literature. The study’s primary objective is to examine the synoptic climatology of weather parameters associated with extreme TC events in the BoB and to explore the reasons behind severe TC formation in the nearby coastal regions. This study adopted PCA and clustering methods to identify the most responsible variables (i.e., sea level pressure, temperature) that play a pivotal role in forming severe TC events. The GCM model was also used to visualize the instability of those weather variables (sea level pressure and temperature) in the total atmospheric column on the TC occurring days.

2 Data and methods

2.1 Study region description

The southern coastal region of Bangladesh, which lies within 21°23′N and 89°93′E, was chosen as the study area where the occurrence of monsoon cyclones is frequent and
affects the current agriculturally based economy (Fig. 1) (WARPO 2006). The average temperature in these areas ranges from 180 to 28 °C, with May being the warmest month and January being the coldest (Rahman and Ferdousi 2011; Das and Islam 2021).

From 1975 to 2014, lots of TCs hit Bangladesh. For example, some of the disastrous cyclones were reported in 1985, 1988, 1991, 1994, 1995, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2007, 2009, and 2013 (Table S1). Among these, cyclones SIDR in 2007 and AILA in 2009 were most destructive in terms of damage to properties and fatalities (BBS 2014). In this paper, we define the extreme TC events as those events that were the most destructive and claimed the loss of hundreds of lives and millions of properties. Most importantly, all the cyclones struck in the southern part, as the area is a coastal area of Bangladesh (Table 1). That is why this area has been selected for the synoptic study of cyclone events in the past 40 years (Table 1). Datasets were collected from Satkhira, Khulna, Mongla, Khupupara, Barishal, Bholo, Putukhali, Hatiya, Chandpur, Feni’s meteorological station Sandwip, Sitakunda, Chittagong, Kutubdia, Cox’s Bazar, and Teknaf (Fig. 1).

2.2 Data sources and quality check

We collected data on 22 TCs that hit the coastal region from 1975 to 2014 and caused severe destruction. Weather variables, i.e., sea level pressure (SLP) and temperature data, were collected from the BMD of the study areas. Three hourly datasets of every parameter were collected and then compiled, tabulated into daily data to avoid any deviance, and analyzed according to the study’s objectives.

Historical records of TCs that attacked Bangladesh were collected from the Disaster Preparedness Center, Asian Institute of Technology (AIT), and Bangladesh Bureau of Statistics (BBS). These data were then plotted following the arrangement of day/month/year. We collected air pressure data between 120 and 320°N latitude and 78°E and 102°E longitude from the NCEP (National Centers for Environmental Prediction) Reanalysis of NOAA (National Oceanic and Atmospheric Administration) / ESRL (Earth System Research Laboratory), Physical Science Division, USA (United States of America). NCEP (National Centers for Environmental Prediction) global circulation modeling was applied to develop a map and analyze air pressure. We also concentrated on the possible association of TC events with the synoptic climatology of SLP and air temperature. The BMD staff initially checked the quality control of the dataset. A two-sample Student t-test was performed to assess the dataset’s statistical significance where the outcomes are significant at a 95% confidence level for all TC occurrence days.

2.3 Principal component analysis

We used PCA to understand the core affiliation among the allied variables through a small set of factors. PCA is used to convert variables that are correlated in any way into uncorrelated observations that are linear in principal components. Lastly, PCA produced a set of variables of vectors that were not associated in orthogonal basis (Zhu et al. 2014; Jolliffe 1986). Yarnal (1993) used S
mode (grid points as variables and days as observations) centered data matrix PCA, which used the standardized spatial SLP data, and also maintained the original characteristics such as the original daily temporal scale (Esteban et al. 2005). Barry and Carleton (2001) showed that the correlation matrix provides the most proficient demonstration. Lastly, we used the varimax procedure, which assists the spatial analysis of principal components used by Yarnal (1993). We used the scree test to define the factors that describe the special ratio of the total variance introduced by Cattel (1966). The KMO values range from 0 to 1, where the value between 0.8 and 1 indicates that the number of samples is adequate, where a value of less than 0.6 means that the sampling is not sufficient, and possible remedial measures should be taken. The scree test results showed in our study that it was acceptable according to the range of the KMO values.

### Table 1 Chronology of major cyclones in Bangladesh (compiled from Murty et al. 1986; Khalil 1992; Murty and El-Sabh 1992; Ahmed et al. 2012)

| Year of occurrence       | Velocity (km/h) | Number of death | Other losses                                                                 |
|--------------------------|-----------------|-----------------|------------------------------------------------------------------------------|
| 9–12 May 1975            | 96.5 to 112.6 km/h | 5               | Not found                                                                    |
| 9–12 May 1977            | 112.63 km/h     | Not found       | Not found                                                                    |
| 14–15 October 1983       | 122 km/h        | 43 people; 150 fishermen | 20% of the aman rice crops in the affected regions were destroyed |
| 5–9 November 1983        | 136 km/h        | 300 fishermen went missing | 50 boats missing, 2000 houses destroyed |
| 24–25 May 1985           | 154 km/h        | 11,069 people, 135,033 cattle | 94,379 houses and 74 km of road, and embankments destroyed |
| 8–9 November 1986        | 110 km/h        | 14 people       | 972 km² of paddy fields was inundated; schools, mosques, warehouses, hospitals, houses, and buildings were destroyed at Amtali upazila in Barguna District |
| 24–30 November 1988      | 162 km/h        | 5708 people, and numerous wild animals at the Sundarbans (deer 15,000, royal Bengal tiger 9), cattle 65,000 | Total damage to crops reached Taka 9.41 billion |
| 18 December 1990         | Not found       | Not found       | Not found                                                                    |
| 29–30 April 1991         | 225 km/h        | 150,000 people, 70,000 cattle | Loss of property was estimated at about Tk 60 billion |
| 31 May–2 June 1991       | 110 km/h        | Not found       | Not found                                                                    |
| 29 April–3 May 1994      | 210 km/h        | 400 people, 8000 cattle | Not found                                                                    |
| 21–25 November 1995      | 210 km/h        | 650 people, 17,000 cattle | Not found                                                                    |
| 16–19 May 1997           | 225 km/h        | 126 people      | Not found                                                                    |
| 25–27 September 1997     | 150 km/h        | Not found       | Not found                                                                    |
| 16–20 May 1998           | 150 km/h        | Not found       | Not found                                                                    |
| 19–22 November 1998      | 90 km/h         | Not found       | Not found                                                                    |
| 14–15 May 2007           | 120 km/h        | 14 people       | Damages amounted to US$982 million |
| 15 November 2007          | 260 km/h        | 500 deaths      | Several millions                                                             |
| 26–27 October 2008       | 85 km/h         | 15 people       | Thousands of homes were damaged                                            |
| 19–21 April 2009         | Not found       | Not found       | Not found                                                                    |
| 27–29 May 2009           | 120 km/h        | 150 persons     | 2 lac houses and 3 lac acres of cultivated land and crops losses             |
| 16–17 May 2013           | 85 km/h         | 17 people       | Nearly 1.3 million people were affected across the country. Losses to crops exceeded US$35.3 million |

2.4 K-mean clustering method

We used the nonhierarchical K-means method to cluster the remarks (Hair et al. 1998). Cluster analysis is used to group a set of data that has the very homogeneous characteristics of algorithms. Many scientists have used clustering in their studies to separate homogenous data into groups (Anderberg 2014; Duran and Odell 2013; Tan et al. 2013). In this study, we also used this wide-ranging method to identify groups of cyclones with similar characteristics, i.e., temperature and SLP. The number of groups and centroids was decided according to the PCA results, which establish the spatial variation patterns. Centroids and groups were created using...
the Birkeland et al. (2001) and Tait and Fitzharris (1998) methods. PCA followed by clustering has been a strong tool to describe the climatological analysis of many studies (i.e., Hair et al. 1998; Farukh and Yamada 2014). K-means was used to classify the distribution of temperature and SLP values with similar characteristics. For temperature and SLP, atmospheric circulation clusters were formed by using the synoptic map.

### 2.5 General circulation model

The GCM is the most complicated climatic model developed by Viner (2000), which displays the three-dimensional climatic scenario of the components used to represent the components. We followed the method applied by Onogi et al. (2007). The data for deadly 22 TC landfalling periods, i.e., with synoptic weather parameters like SLP and temperature, were obtained from the Japanese 25-year reanalysis project (JRA-25) by the Japan Meteorological Agency (JMA) with a 1.125° spatial resolution encircling 12°N–32°N and 78°E–102°E. A detailed description of the GCM model can be found in Onogi et al. (2007).

### 3 Results

#### 3.1 Clustering analysis

Figure 2 represents the clustering of 22 cyclones from 1975 to 2014 (40 years). From Fig. 2, it is clearly understood that the most important factors, i.e., SLP and temperature responsible for the formation of 22 TCs, have been grouped into 3 clusters (centroid). As shown in the diagram, the circle with the green color is considered cluster 1, and the circle with the red color is considered cluster 2 where the temperature was 41.7 °C, and sea level pressure was 995.7 hPa. So, cluster 1 indicates that 41.7 °C temperature was responsible for one cyclone out of 22 TCs from 1975 to 2014. In cluster 2, nine circles of red have been presented, which have been considered the same characteristics as the nine cyclones that occurred in the 40 years we studied. The temperature triggered by the formation of 9 TCs was from 30 to 36.2 °C where the sea level pressure was from 991.8 to 999.7 hPa. The centroid points at 33.5 °C, which is the average of these nine red circles. So, these results indicate that temperatures above 30 °C are mostly responsible for low atmospheric pressure, which turns into cyclonic activity. The rest of the 12 black circles have been considered under the third centroid, where the circles have the same characteristics as the remaining 12 TCs from 1975 to 2014. The SLP responsible for the formation of these TCs was less than 990 hPa, and the temperature ranged from 30 to 39 °C.

#### 3.2 Sea level pressure anomaly and severe TCs

This section described the scenario of the different atmospheric pressure levels and temperatures of the 22 TC occurring days.

##### 3.2.1 Cluster 1

Figure 3 represents the composite geographical distribution of SLP anomalies compared with the climatology from 1975 to 2014 of cluster 1 for surface level, 850 hPa, 700 hPa, 500 hPa, and 300 hPa. Figure 3 illustrates SLP (hPa) from 12°N to 32°N latitude and 78°E to 102°E longitude derived from NCEP, NOAA/ESRL Physical Science Division. In the clustering part, we have seen that only one cyclone has passed in the last 40 years, following different characteristics among 22 TCs.

It is indicated that a tough negative anomaly was present over the BB and the southern part of Bangladesh (Fig. 3a). A deep depression of SLP was observed over the south-eastern and southern coastal regions. A slightly lighter depression was observed throughout the whole of Bangladesh except in the easternmost part of the country. A dice-shaped strong negative anomaly of SLP was observed over Myanmar at 850 hPa. A deep depression of SLP was observed over the south-eastern and southern coastal regions. A slightly lighter depression was observed throughout the whole of Bangladesh except in the easternmost part of the country.

A deep depression at pressures above 700 hPa, the adverse abnormality vanished completely (Fig. 3b). This positive anomaly was expanded all over Bangladesh and over BB. Deep negative depression of SLP was observed in the southwestern part of Myanmar. It can also cause a very unstable condition in the upper atmosphere. At 500 hPa height, a strong negative anomaly was observed over India in the north-eastern part of Bangladesh (Fig. 3d). This oval-shaped deep depression was as large as Bangladesh.
A relatively low depression could be observed all over Bangladesh on those cyclone occurring days. In Fig. 3e, it is seen that at 300 hPa height, a deep depression was observed in the northern part of Bangladesh over India. A positive anomaly was also observed in the atmosphere over Bangladesh. This positive anomaly at this higher atmosphere could create a very unstable weather condition in this height of the atmosphere.

A comparison of the amalgamated geographical dispersal of synoptic temperature from the specified level is shown in Fig. 4. Figure 4a shows the surface air temperature anomaly. There is a progressive external air temperature irregularity region above the eastern and south-eastern parts of Bangladesh. This positive anomaly is prominent over the whole coastal part of Bangladesh, which is noticeable over West Bengal of the Indian Territory. This positive anomaly zone was also available on the eastern border of Bangladesh, covering India and some parts of Myanmar also. A negative anomaly zone has been indicated in the southern-eastern part of Myanmar and the northern-western parts of Thailand and Laos. From the results, we can say that the outward level air temperature in Bangladesh and India was somewhat warmer than in Myanmar, Thailand, and Laos, where the air was much cooler on this cyclone occurring day.

Figure 4b shows a tough, positive air temperature irregularity region at 850 hPa level over south-western Bangladesh. The strong positive zone anomaly covers the part of Bangladesh from 24.5°N to the south of its area. The alteration region between warmer and cooler anomalies occurred over the central part of Myanmar, keeping one strong positive zone over south-eastern India and the central-western portion of Myanmar.

But at around 3000 m above (~700 hPa) from outward, there was the complete vanishing of warmer zones (Fig. 4c). The appearance of some parts of the negative zone was found in the south-eastern part of Bangladesh and from central to the southern part of Myanmar. Thus, this cooler zone at a relatively upper atmosphere would not affect creating an unstable atmosphere.

The temperature distribution map showed that the temperature anomaly in the most influential weather zone of the upper atmosphere was at 500 hPa level (Fig. 4d). A strong negative area at 500 hPa level surrounded the south-western part of Bangladesh, and BB was noticed. This situation implies the formation of a cooler region at around 6000 m (~500 hPa) over the surface. At 300 hPa level (~10,000 m above), occurrences were observed where a wide-ranging area was covered by warmer air from Tibet to NIO and the eastern part of India (Fig. 4e), where the regions of

Fig. 3  a SLP (Pa) at surface level. b SLP at 850 hPa level. c SLP at 700 hPa level. d SLP at 500 hPa level. e SLP at 300 hPa level for cluster 1
Bangladesh were subjugated by a deep warmer area which could result in severe instability throughout the whole atmospheric column.

### 3.2.2 Cluster 2

In the clustering part, we have seen that nine TCs passed in the last 40 years, all following the same characteristics as the 22 TCs. These conditions, which have played a big role in forming those cyclones, have fallen under cluster 2.

Figure 5a–e show a climatological comparison of the combined geographical dispersal of SLP variances from 1975 to 2014 for surface level, 850 hPa, 700 hPa, 500 hPa, and 300 hPa.

From Fig. 5a, it can be seen that a strong negative depression of SLP was prominent in the southerly region of Bangladesh and above the BB. This oval-shaped depression was as large as the size of Bangladesh. In contrast, the rest of the BoB has a low SLP, except in the north-eastern and north-western parts of the country.

From Fig. 5a, it can be seen that a strong negative depression of SLP was prominent in the southerly region of Bangladesh and above the BB. This oval-shaped depression was as large as the size of Bangladesh. In contrast, the rest of the BoB has a low SLP, except in the north-eastern and north-western parts of the country.

Figure 5b shows that at 850 hPa, a strong negative anomaly existed over the BoB, and it was prominent toward the Bangladesh coastal and hilly regions. The rest of the parts had a normal SLP at this height. These two states of weather conditions at this height can cause a very unstable condition, resulting in very extreme cyclonic events.

At 700 hPa, about 3000 m above, we can observe a relatively large shaped negative depression of SLP above BB and the south-easterly region of Bangladesh, which was larger than Bangladesh in diameter. In the rest of the country’s area, the weather conditions were very normal (Fig. 5c). These two different conditions can result in a very unstable weather event. At 500 hPa, from Fig. 4d, a very strong negative anomaly was observed over BoB and the south-eastern parts of Bangladesh and India.

A complete disappearance of negative anomaly zones was observed at 300 hPa (10,000 m above) height from the surface (Fig. 5e). A severe weather-related extreme event can be caused by these two distinct zones of negative and positive anomaly.

Evaluation of the combined geographical dispersal of synoptic temperature from the specified level can be seen in Fig. 6. The warmer outer air temperature irregularity region is prominent above the easterly and south-easterly portions of Bangladesh. The day the cyclone hit, a cooler zone was expanding from the Indian terrain toward the south-western landscape of Bangladesh. At the same time, a strong cooler zone is also seen in the southern coastal region of Bangladesh.

These two coexistences of the negative zone over Indian Territory and the southern part of Myanmar possessed the moving area over Bangladesh’s southern part to the BoB.
The results suggest the domination of comparatively colder temperatures in the southerly region not much above the exterior level, especially on cyclone incidence. The area was mostly cooler in the southern-western part than in the southern-central and southern-eastern regions of Bangladesh on the cyclone’s befalling days at surface level.

An irregularly warmer air temperature area above the north-easterly region of Bangladesh was seen at 850 hPa level. Two negative and positive anomaly zones above south-eastern India and southern Myanmar and BoB created a transitional site (Fig. 6b). However, it is nearly 3000 m (700 hPa) above sea level (Fig. 6c). This warmer zone surrounded the northeast, south-east, and above BB. An unstable atmospheric situation might have resulted from this unstable situation, which could interact with the surface.

A tough warmer area surrounding the south-westerly region of Bangladesh and above the surface level of BoB pointed to a progression of positive parts nearly over 6000 m (5000 hPa) (Fig. 6d). An intense occurrence was seen in Fig. 6e at 300 hPa (10,000 m above) level, where an expanded area was concealed by progressive irregularity encompassing Tibet to the North Indian Ocean (NIO) via eastern Indian Territory. Bangladesh was subjugated by an advanced irregularity zone forming a profoundly warmer area above these zones. A large unstable zone can result in the atmospheric column.

3.2.3 Cluster 3

The conditions that have played a pivotal role in forming the remaining 12 TCs have fallen under cluster 3. Figure 7 represents the merged geographical dispersal of SLP irregularities paralleled with the climatology from 1975 to 2014 of cluster 3 for surface level, 850 hPa and 700 hPa, and 500 hPa and 300 hPa. From Fig. 7a, it is clear that a strong negative anomaly existed over BoB. This negative anomaly was prominent in Bangladesh.

From Fig. 7b, at 850 hPa from the surface, the same situation was observed over the BoB, and it was also prominent toward Bangladesh. The same situation was observed at the height of 700 hPa, as shown in Fig. 7c, but the negative anomaly was relatively bigger than in the other levels. This strong negative anomaly over BB also covers the southern lower part of the Bangladesh coastal region. But a slightly lighter negative anomaly was observed throughout Bangladesh. But noticeably, an enormous area from Myanmar to India was encompassed by a positive anomaly.
Fig. 6 The patterns of composite air temperature (°K) anomaly for cluster 2 compared with 1975–2014 climatology for the passing days of cyclones at a surface level, b 850 hPa level, c 700 hPa level, d 500 hPa level, and e 300 hPa level.

Fig. 7 a SLP (Pa) at surface level. b SLP at 850 hPa level. c SLP at 700 hPa level. d SLP at 500 hPa level. e SLP at 300 hPa level for cluster 3.
At the 500 hPa height, deep depression of SLP is observed over the BoB and India. This circular deep depression also covered the southern part of the coastal region and a small part of the south-eastern Bangladesh. The perimeter of this depression is almost equal to the size of Bangladesh. On these cyclonic days, a slightly lower depression was observed over BB and India, with a prominent NIO.

The most dramatic situation was observed at 300 hPa height in these cyclones’ occurring days (Fig. 7b). A positive anomaly throughout Bangladesh is observed. However, a slightly negative anomaly was observed over NIO and south-eastern India. The positive anomaly at this height and negative anomaly below this height could result in serious instability throughout the whole atmosphere.

A comparison of the composite geographical distribution of synoptic temperature from the specified level is shown in Fig. 8. Figure 8a shows the surface level air temperature anomaly. It was clearly shown that the positive surface air temperature anomaly region had almost disappeared from the map except for some small areas of NIO though they are not strong enough. On the day of cyclones, the robust adverse irregularity region from the Indian Territory extended toward all of Bangladesh and expanded to the entire South-east Asia. A transition zone over the Bay of Bengal to the NIO Territory was observed since the positive zone and negative zone coexist over the Indian Territory and the whole part of Myanmar. On the day of the occurrence, relatively cooler air temperature dominance was observed in the southerly region, especially near the surface. The area is mostly cooler in the southern-western and central-western parts than in the southern-central and southern-eastern parts of Bangladesh due to the cyclone occurring at the surface level.

Figure 8b represents a serious negative air temperature irregularity region over the southern-western area of Bangladesh at 850 hPa level. A transitional zone above BB with a double negative region above south-westerly India and southerly Myanmar was observed. Around 3000 m (700 hPa), a disappearance of this zone was noticed over Bangladesh. A warmer zone existed from the northeast to the southern parts of Bangladesh, and it extended up to BoB. This warmer region in a comparatively upper atmosphere might result in an unbalanced atmosphere over the thermal uncertainty relating to surface level.

The 500 hPa level is considered the most influential upper atmospheric weather zone (Fig. 8d). A positive anomaly zone circling above the south-westerly region of Bangladesh and above BB dictates the progress of the warmer region.

![Fig. 8 The composite air temperature (°C) anomaly for cluster 3 at a surface level, b 850 hPa level, c 700 hPa level, d 500 hPa level, and e 300 hPa level](image-url)
at a height of 6000 m near the surface. At 300 hPa level (~10,000 m above), a larger area covered by the positive irregularity region expanded from Tibet to NIO via eastern Indian Territory caused the major instance occurrence (Fig. 8e). The total area of Bangladesh was subjugated by a positive irregularity zone, which indicates a huge warmer region over these areas. The development of a larger unstable zone through the whole atmosphere could result from this larger warm air mass.

4 Discussion

The climate of the North Indian Ocean region is highly affected by oceanic variability on different spatiotemporal levels (Schott and McCreary 2001). Because of the rarity and nature of these extreme events, many scientists have studied them (Ali 1999; Webster 2008; Mohapatra et al. 2014; Wahiduzzaman et al. 2017; Wahiduzzaman et al. 2020a; Islam et al. 2020; Wahiduzzaman et al. 2021a). This study intends to examine the association of the atmospheric conditions responsible for the TCs occurring on the 22 deadliest TC from 1975 to 2014. It was found that among the 22 TCs, we studied 12 TCs that happened under the same atmospheric situation when the SLP was below 990 hPa, and the temperature ranged from 30.9 to 39 °C. In these cyclone ensuing days, a serious negative anomaly of SLP was observed at surface level, 850 hPa level, 700 hPa level, and 500 hPa level, whereas a complete absence of negative depression was observed at 300 hPa GPH over the BoB and southern part of the country.

On the other hand, a positive temperature was observed at the surface level and at the 850 hPa and 700 hPa levels. On the contrary, the complete disappearance of the positive anomaly zone was prominent at 500 hPa. Again, a positive anomaly zone at 300 hPa was the most dramatic situation at this GPH, resulting in the severe instability of the atmospheric zone, causing deadly cyclones. Farukh and Yamada (2014) found a negative anomaly that triggered the extreme snowfall event at 300 hPa GPH. Furthermore, it was observed that the SLP negative anomaly had an impact on the equatorial eastern Pacific El-Nino and the Central Pacific El-Nino (Sun et al. 2013; Maw and Jinzhong 2017; Wahiduzzaman et al. 2021b). A recent study was done by Gaona et al. (2018) and Zhou et al. (2018) using synoptic climatology, which showed that tremendous rainfall and surges occurred, which was the consequence of heavy floods and winds caused by extreme TCs passing over the BoB, resulting in huge damage to the society and economy. This also confirms that synoptic study of extreme events is essential for advancing the field of planning, forecasting, and management.

Nine TCs were formed where the SLP was below 1000 hPa, and the temperature ranged from 30 to 36.2 °C. A strong negative anomaly of SLP was observed at surface level, 850 hPa level, and 700 hPa level over BB on these TC occurring days. The depression turned larger at 500 hPa level height, but dramatically, this depression completely disappeared at 300 hPa GPH over the BoB and the entire coastal region of Bangladesh. On the other hand, a cooler air temperature was observed at the surface level, where a complete departure was followed at 850 hPa and 700 hPa levels. This co-existence of positive and negative temperature zones at the immediate atmospheric level could be triggering the most destructive atmospheric instability at these levels. This kind of phenomenon was observed to cause many unusual atmospheric phenomena in many parts of the world; i.e., negative anomalies at the 700 hPa height over the eastern North Pacific Ocean and the western USA also affected above-average snowfall accumulation (McCabe and Legates 1995). Yamane and Hayashi (2006) observed an elevated thermal instability region and vertical wind shear in the higher atmospheric zone during the pre-monsoon season. Our research also indicates that negative anomalies in different atmospheric levels trigger deadly TC events over the BoB. A study done by Farukh et al. (2019) showed that a higher temperature at 850 hPa to 300 hPa levels could be followed by extreme weather phenomena like TCs when agricultural production was seriously damaged. Several other researchers have reported similar findings (e.g., Glibert et al. 2014 and Iyalomhe et al. 2015; Islam et al. 2020). Ruane et al. (2013) showed that coastal agriculture is being affected by higher emissions of pollutants under the climate change scenario.

Of these 22 TCs, only one event was formed when the atmospheric circumstances were completely different, and the SLP was above 1000 hPa, and the temperature was 41.7 °C. On this TC occurring day, the total coastal area was subjugated by a negative anomaly zone up to 300 hPa level, which indicates the development of a huge depression region over this zone. Many researchers also reported that the larger depression area in the upper atmosphere develops bivertical wind shear and perpendicular wind shear through the total atmospheric column, resulting in severe weather events. Yamane et al. (2012) also noticed a trough at 550 hPa on severe local convective storm days.

Synoptic climatology is an emerging field in scientific research for planning, forecasting, managing disaster damage, and reducing disaster risk. Scientists have identified that tremendous economic and social losses are being unnoticed due to extreme cyclone events boosting sea level rising due to the upward temperature trend (Spada 2017; Chen et al. 2017; Bamber et al. 2018; Cazenave et al. 2019). If the possible landfall of TCs could be forecasted earlier, the damage control would be significant (Paliwal and Patwardhan 2013;
Weinkle et al. 2012; Singh et al. 2012; Maw et al. 2017). However, the limitations of the study cannot be overlooked. Although unbiased correction was performed in this work, some missing datasets were found from the BMD. We removed the missing datasets before tabulating the TC event. There was the unavailability of recent weather variables and TC datasets. The more current and updated datasets can be used in this research to obtain better results. Synoptics features like sea surface temperature, relative humidity, vertical wind shear, vorticity, and moisture budget are the basic favorable condition for the development of TCs. These deserve further examination.

5 Conclusion

This paper explores the association between the weather parameters and TC events and discusses TC genesis using multivariate statistics and the GCM model. In this study, we found that the atmospheric instability in different atmospheric zones of the upper ambience triggered many disastrous TCs in the coastal regions and the whole country in the last four decades. From the outcomes of the GCM model, it is observed that TC events and SLP might be very promising variables for disaster scientists to aid in the early forecasting of deadly TCs. We identified a large depression of SLP and erratic temperature anomalies in the upper atmosphere that can cause an unstable atmospheric level that leads to extreme TC events. The findings of this study will aid in the development of a policy and preparedness plan for TC prediction. For planning and disaster management, forecast, intensification, and the movement of the TCs, this study will be helpful to measure the vulnerability due to climate change with a special emphasis on extreme TCs. Composite mapping of climate change indices using GCM technology is a strong tool to analyze extreme weather events, especially TCs. Determination of synoptic climatology is very useful for policymaking, planning, disaster mitigation, and saving local inhabitants and the agricultural sector from cyclone hazards. So, the present work will assist in understanding the synoptic climatology associated with SLP and temperature to identify the reasons behind extreme TC formation in the BoB.

References

Ahmed S, Rahman MM, Faisal MA (2012) Reducing cyclone impacts in the coastal areas of bangladesh: a case study of Kalapara Upazila. J Bd Inst Planners 5:185–197
Alam MdM, Hossain MdA, Shafee S (2003) Frequency of Bay of Bengal cyclonic storms and depressions crossing different coastal zones. Int J Climatol 23:1119–1125
Ali A (1999) Climate change impacts and adaptation assessment in Bangladesh. Climate Res 12:109–116
Anderberg MR (2014) Cluster analysis for applications: Probability and mathematical statistics: A series of monographs and textbooks, Vol. 19. Academic press
Balaguru K, Taraphdar S, Leung LR, Foltz GR (2014) Increase in the intensity of postmonsoon Bay of Bengal tropical cyclones. Geophys Res Let 41:3594–3601
Bamber JL, Westaway RM, Marzeion B, Wouters B (2018) The land ice contribution to sea level during the satellite era. Environ Res Lett 13(6):063008. https://doi.org/10.1088/1748-9326/aac2f0
Barry RG, and Carleton AM (2001) Synoptic and dynamic climatology. Routledge, p 620
BBS (Bangladesh Bureau of Statistics) (2014) Bangladesh Bureau of Statistics, Statistics Division, Ministry of Planning, Statistical Year Book of Bangladesh – 2010, BBS, Dhaka, Bangladesh
Birkeland KW, Mock CJ, Shinker JJ (2001) Avalanche extremes and atmospheric circulation patterns. Ann Glaciolog. https://doi.org/10.3189/172756401781819030
Blasius J, Greenacre M (eds) (2014) Visualization and verbalization of data. (1st ed). Chapman and Hall/CRC. https://doi.org/10.1201/b16741
Bro R, Smilde AK (2014) Principal component analysis. Anal Methods 6(9):2812–2831
Cattell RB (1966) The scree test for the number of factors. Mult Vib Behavol Res 1:245–276
Cazenave A, Hamilton B, Horwath M et al (2019) Observational requirements for long-term monitoring of the global mean sea level and its components over the altimetry era. Front Mar Sci 6(582):2296–7745
Chen XY, Zhang XB, Church JA, Watson CS, King MA, Monselesan D, Legresy B, Harig C (2017) The increasing rate of global mean sea-level rise during 1993–2014. Nat Clim Change 7(7):492–495
Das S (2021) Extreme rainfall estimation at ungauged locations: information that needs to be included in low-lying monsoon climate regions like Bangladesh. J Hydrol 601:126616

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Declarations

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Das S, Islam ARMT (2021) Assessment of mapping of annual average rainfall in a tropical country like Bangladesh: remotely sensed output vs. kriging estimate. Theor Appl Climatol. https://doi.org/10.1007/s00704-021-03729-3

Dube SK, Sinha PC, Roy GD (1985) The numerical simulation of storm surges along the Bangladesh coast. Dynat Atmos Oceans 9(2): 121–133

Duran BS, Odell PL (2013) Cluster analysis: a survey, vol 100. Springer Science & Business Media

Esteban P, Jones P, Martin J, Mases M (2005) Atmospheric circulation patterns related to heavy snowfall days in Andorra, Pyrenees. Int J Climatol 25:319–329

Farukh MA, and Yamada JT (2014) Synoptic climatology associated with extreme snowfall events in Sapporo city of northern Japan. Atmos Sci Lett 15:259–265. https://doi.org/10.1002/asl2.497

Farukh MA, Hossen MAM, Ahmed S (2019) Impact of extreme cyclone events on coastal agriculture in Bangladesh. Progress Agric 1(3):33–41

Felton CS, Subrahmanyan B, Murty VSN (2013) ENSO-modulated cyclogenesis over the Bay of Bengal. J Clim 26:9806–9818

Fish, B, Ellis AM, Adams DK, Fox HE, Selig ER (2015) Health, wealth, and education: the socioeconomic backdrop for marine conservation in the developing world. Mar Ecol Prog Ser 530:233–242

Flather RA, and Khandker H (1987) The storm surge problem and possible effects of sea level changes on coastal flooding in the Bay of Bengal. Int. Workshop on Climatic Change, Sea Level, Severe Tropical Storms and Associated Impacts, UNEP. Norwich, England

Flather RA, Heaps NS (1975) Tidal computations for Morecambe Bay, Geophys. J R Astr Soc 42:489–517

Gaona MFR, Overeem A, Raupach TH, Leijnse H, Uijlenhoet R (2011) Impact of snowmelt on hydrological extreme events in the Netherlands: the roles of river discharge and air temperature. Water Res 45(17):5302–5314. https://doi.org/10.1016/j.watres.2011.09.003

Glibert PM, Overeem A, Raupach TH, Leijnse H, Uijlenhoet R (2011) Impact of snowmelt on hydrological extreme events in the Netherlands: the roles of river discharge and air temperature. Water Res 45(17):5302–5314. https://doi.org/10.1016/j.watres.2011.09.003

Glob Change Biol 20(12):3845–3858

Hair JF, Anderson RE, Tatham RL, Black WC (1998) Multivariate data analysis, 5th edn. New Jersey, NJ, Prentice-Hall International

Hair JF, Black WC, Babin BJ, Anderson RE, Tatham RL (2006) Multivariate data analysis, vol 6. Upper Saddle River, NJ: Pearson Prentice Hall

Hou K, Li X, Zhang J (2015) GIS analysis of changes in ecological vulnerability using a ZPAC model in the loess plateau of Northern Shaanxi, China. Int J Environ Res Public Health 12(4):4292–4305

Howe C, Suihc H, van Gardingen P, Rahman A, Mace GM (2013) Elucidating the pathways between climate change, ecosystem services and poverty alleviation. Curr Opin Environ Sustain 5(1):102–107

Islam ARMT, Nafiuzzaman M, Rifat J, Rahaman MA, Chu R, Li M (2020) Spatiotemporal variations of thunderstorm frequency and its prediction over Bangladesh. Meteorol Atmos Phys 132(6):793–808. https://doi.org/10.1007/s00703-019-00720-6

Ilyomfe H, Rizzi J, Pasini S, Torresan S, Ciritto A, Marcomini A (2015) Regional risk assessment for climate change impacts on coastal aquifers. Sci Total Environ 537:100–114

Jolliffe IT (1986) Principal component analysis. Springer-Verlag, New York, NY

Katusura J, Hayashi T, Nishimura H, Isobe M, Yamashita T, Kawata Y, Yasuda T, and Nakagawa H (1992) Storm surge and severe wind disasters caused by the 1991 cyclone in Bangladesh. Research Report, No. B-2, Japanese Ministry of Education, Science and Culture

Khalil GM (1992) Cyclones and storm surges in Bangladesh: some mitigative measures. Nat Haz 6:11–24

Kline P (2014) An easy guide to factor analysis. Routledge

Maw KW, Jinzhong M (2017) Impacts of microphysics schemes and topography on the prediction of the heavy rainfall in western Myanmar associated with tropical cyclone ROANU (2016). Advan Meteorol 2017:1–22. https://doi.org/10.1155/2017/7325203

Maw KW, Islam ARMT, Sien ZMM et al (2017) Simulation of storm surge in Myanmar coast. Earth Syst Environ 1(2):15. https://doi.org/10.1007/s41748-017-0017-7

McCabe GJ Jr, Legrates DR (1995) Relationships between 700 hPa height anomalies and 1 April snowpack accumulations in the western USA. Int J Climatol 15:5. https://doi.org/10.1002/joc.3370150504

Michelangeli PA, Vautard R, Legras B (1995) Weather regimes: recurrence and quasi stationarity. J Atmos Sci 52:1237–1256

Miller SD (2014) Indicators of social vulnerability in fishing communities along the west Coast Region of the U.S. MPP Essay. Oregon State University. Presented December 1, 2014

Mofutahari HR, AghaKouchak A, Sanders BF, Matthew RA (2017) Cumulative hazard: the case of nuisance flooding. Earth’s Future 5(2):214–223. https://doi.org/10.1002/2016EF000494

Mohapatra M, Bandyopadhyay BK, Tyagi A, Mohanty UC (2014) Status and plans for operational tropical cyclone forecasting and warning systems in the North Indian Ocean region in. In: Mohapatra M, Singh OP, Bandyopadhyay BK, Rathore LS (eds) Monitoring and prediction of tropical cyclones in the Indian Ocean and climate change

Murtu-Ts, El-Sahb M (1992) Mitigating the effects of storm surges generated by tropical cyclones-A proposal. Nat Hazards 6(3):251–273

Neumann JE, Emanuel KA, Ravela S, Ludwig LC, Verly C (2015) Risks of coastal storm surge and the effect of sea level rise in the red river delta, Vietnam. Sustainability 7(6):6553–6572

Onogi K, Tsutsui J, Koyde H, Sakamoto M, Kobayashi S, Hataashika H, Matsumoto T, Yamazaki N, Kamahori H, Takahashi K, Kadokura S, Wada K, Katu O, Oyama R, Ose T, Mannori N, Taira R (2007) The JRA-25 reanalysis. J Meteorol Soc 85:369–432

Orong K, Tsumui J, Joko H, Sakamoto M, Kobayashi S, Hataashika H, Matsumoto T, Yamazaki N, Kamahori H, Takahashi K, Kadokura S, Wada K, Katu O, Oyama R, Ose T, Mannori N, Taira R (2007) The JRA-25 reanalysis. J Meteorol Soc 85:369–432

Paliwal M, Patwardhan A (2013) Identification of clusters in tropical cyclone tracks of North Indian Ocean. Nat Hazards 68:1–12

Parker CL, Lynch AH, Mooney PA (2017) Factors affecting the simulated trajectory and intensification of Tropical Cyclone Yasi (2011). Atmos Res 194:27–42

Rahman MM, Ferdous N (2011) Rainfall and temperature scenario for Bangladesh using 20km mesh AGCM. Intr J Clim Change Strat Manag 4(1):66–80. https://doi.org/10.1108/17568691211200227

Rahman MA, Yunsheng L, Sultana N (2017) Analysis and prediction of rainfall trends over Bangladesh using Mann-Kendall, Spearman’s rho tests and ARIMA model. Meteorol Atmos Phys 129(4):429–430. https://doi.org/10.1007/s00703-016-0479-4

Rajasekhara M, Kishitawal CM, Prasad MYS, Seshagiri Rao V, Rajeevan M (2014) Extended range tropical cyclone predictions for east
