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A track analysis of historical tropical cyclones making landfall on the coast of Bangladesh

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ABSTRACT

This study provides a thorough examination of the past trajectories of tropical cyclones (TCs) that reached the coast of Bangladesh between 1991 and 2023. The study analyzed the spatial and temporal patterns of TC occurrences and their impacts on coastal regions by using data on cyclone tracks, maximum wind velocity, central atmospheric pressure, and precipitation. The methodology entailed the utilization of Arc GIS to map cyclone tracks, enabling the visualization of cyclone paths, wind speeds, and central pressures. This spatial analysis was enhanced by studying the seasonal and zonal distributions of TCs, specifically focusing on the characteristics before and after the monsoon season, as well as the varying impacts on the eastern, central, and western coasts. The results of our study show a notable clustering of TC landfalls along the eastern coast, specifically in the Chittagong region. This area accounted for approximately 65% of all the landfalls observed. This pattern emphasizes the increased susceptibility of this region to the effects of cyclones. In addition, the analysis showed that the month of May had the highest occurrence rate of cyclones, with November coming in second. This emphasizes the importance of the periods before and after the monsoon season for cyclone formation. The study also examined the wind and pressure attributes of TCs, revealing that cyclones with lower central pressures are generally more intense, as demonstrated by significant cyclones like Sidr, Amphan, and the 1991 super cyclone. The analysis of precipitation data further demonstrated the magnitude of rainfall linked to significant cyclones, offering valuable understanding of the hydrological effects on coastal areas. This research enhances the current knowledge by providing in-depth understanding of the behavior and effects of TCs in the Bay of Bengal (BoB). As a result, it informs strategies for managing and reducing the impact of disasters. The meticulous examination of space and time carried out in this study is essential for improving our comprehension of the movements and patterns of TCs in the area. The results underscore the necessity of implementing focused measures to mitigate and adapt to enhance the ability of susceptible coastal communities to withstand and recover from adverse impacts. This research provides a historical perspective TC landfalls, offering valuable insights for policymakers, disaster management authorities, and stakeholders involved in efforts to prepare for and respond to cyclones.

INTRODUCTION

Tropical cyclones are highly concentrated circular storms that originate over warm tropical oceans. They are characterized by powerful winds and substantial rainfall (Walsh et al., 2016). These phenomena are highly destructive, resulting in significant damage due to a combination of strong winds, intense rainfall, flooding on land, and sudden increases in water levels (Peduzzi et al., 2012). An illustrative instance of their influence is that despite the fact that only 5% of TCs across the globe originate in the Bay of Bengal, this particular region witnesses nearly 75% of the overall cyclone-related death toll, significantly impacting countries such as Bangladesh, India, and Myanmar (Lal et al., 2012).

Due to its geographical location, Bangladesh is highly susceptible to significant damage caused by severe TCs. The conical-shaped northern region of the BoB intensifies storm surges, which, when

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combined with TCs, have a substantial effect on a large number of people (Farid and Nasreen, 2023). Since 1965, the nation has experienced a minimum of 12 significant TCs, resulting in a devastating death toll of 479,490 individuals. Bangladesh is recognized by the Ministry of Disaster Management and Relief as one of the countries most affected by cyclones, resulting in significant loss of life. Out of the 88 cyclones documented in the larger Bengal area, the most affected coastal regions have been Cox's Bazar, Chattogram, Patuakhali, Noakhali, Teknaf, Sonadia coast, and Kutubdia Island. The Sundarbans, on the other hand, encountered 18 cyclones (Hossain & Mullick, 2020).

Bound by Bangladesh to the north, Myanmar to the east, and India to the west, the BoB is critically important as a major TC formation region. The primary cause of this phenomenon is the elevated sea surface temperatures and favorable atmospheric conditions that occur during the pre-monsoon (April-May) and post-monsoon (October-November) periods (Kikuchi & Wang, 2010). TCs originating in the often exhibit a north-northwestward course, leading to their eventual landfall on the eastern coast of India. Alternatively, they may move in a north-northeast direction, affecting Bangladesh or Myanmar. The trajectories of these cyclones exhibit seasonal variations; typically, they follow a north-northeast direction prior to the monsoon season and a north-northwest direction after the monsoon season (Alam & Dominey-Howes, 2014).

The research conducted by Bhardwaj & Singh (2020) examined the seasonal fluctuations in the occurrence of TCs over the BoB from 1972 to 2017. The study findings suggested a notable decrease in the number of TCs during the winter season. Furthermore, it is observed that these cyclones usually have their genesis in the southern areas of the Bay and move towards the west. In contrast, the period before the monsoon season experiences a significant rise in tropical cyclones, as the areas where they form move towards the northern regions. In this season, most TCs move in a northward direction and mostly hit the coasts of Bangladesh and sometimes Myanmar. Cyclones formed during the monsoon season often move along the coastline of the Indian state of Orissa. During the post-monsoon season, there is a notable increase in the occurrence of cyclones in the BoB. Throughout history, cyclones that have originated in the BoB have had a significant influence on the loss of human lives and the destruction of livelihoods and property in Bangladesh. The objective of this study was to enhance the current understanding of cyclone dynamics in the BoB area through a comprehensive examination of tropical cyclone paths and seasonal variations in Bangladesh. The research aims to improve the preparedness and response strategies of policymakers, disaster management authorities, and researchers by examining the factors that influence cyclone behavior and their resulting impacts on Bangladesh. This improvement is essential for reducing the socio-economic consequences and safeguarding lives in one of the most cyclone-prone regions across the tropics (Nasreen et al., 2023).

The primary objective is to analyze the seasonal and geographical fluctuations in tropical cyclone landfalls spanning a period of 54 years. This entails scrutinizing the monthly allocation of cyclone genesis and investigating the temporal shifts in these patterns. The study also examines the geographical distribution of cyclones, with a specific emphasis on the variation in where they make landfall along the coast. It highlights that the eastern coast, including the Chittagong region, has been the area most frequently impacted by cyclones. Furthermore, the objective of the research is to map the trajectories of TCs that have originated in the BoB within the past 33 years. This entails a meticulous analysis of cyclone trajectories, which unveil their predominant westward motion influenced by trade winds and their inclination to shift towards the poles and then curve eastward owing to the Coriolis force.

Additionally, the study examines the core atmospheric pressure and peak wind speed of these cyclones. The study emphasizes the importance of these meteorological attributes in determining the strength of cyclones. Cyclones with lower central pressures, such as cyclones Sidr, Amphan, and the 1991 super cyclonic storm, are typically stronger and have caused significant damage due to their exceptionally low central pressures. The examination of wind velocity also emphasizes its significance as a gauge of cyclone intensity, as higher wind speeds result in elevated storm surges and extensive destruction. Moreover, the study demonstrates the precipitation patterns of the latest tropical cyclones. Although the relationship between cyclone intensity and precipitation patterns is intricate, the research emphasizes the significant amount of rainfall that is linked to powerful cyclones. These precipitation maps offer valuable insights into the potential consequences of cyclones that go beyond just wind and pressure attributes.

The study utilizes sophisticated software such as ArcGIS and QGIS to map the paths of cyclones, their wind speeds, and central pressures, even though it encounters difficulties in obtaining comprehensive data. Due to the unavailability of certain track information and central pressure data, certain cyclones were excluded from the analysis. Although there are some limitations, the study offers valuable results that enhance our comprehension of the dynamics of the TCs originating in the BoB and making landfall on the coast of Bangladesh.

This study intent to improve the comprehension of TC behavior in the BoB and across the coastal regions of Bangladesh. The objective is to offer valuable information regarding the seasonal and geographical fluctuations in the occurrence of cyclones making landfall, the historical paths of these cyclones, and their meteorological attributes, such as wind speed and central atmospheric pressure. The results will play a crucial role in providing information for cyclone & storm surge preparedness and risk mitigation strategies, ultimately leading to a decrease in cyclone-related deaths and destruction in Bangladesh. This thorough analysis will not only facilitate comprehension of historical and current cyclonic patterns but also assist in predicting future events and equipping coastal communities to mitigate potential hazards and risks.

MATERIALS AND METHODS

Study Area

This study specifically examined TCs that originated in the BoB and then eventually made landfall along the coast of Bangladesh. Hence, the study area includes both the BoB region and the coastal districts of Bangladesh that are regularly affected by cyclones. The BoB spans an area of approximately 2,173,000 square kilometers, located between latitudes 5° and 22° North and longitudes 80° and 90° East. The bay possesses a mean depth of 2600 meters, rendering it a substantial aquatic expanse in relation to its physical measurements and its impact on local climatic and meteorological patterns (Gadgil & Gadgil, 2006).

Although the BoB accounts for only 0.6% of the total ocean area worldwide, it is particularly important because it experiences high death tolls caused by cyclones in the surrounding areas. Surprisingly, half of all fatalities caused by cyclones worldwide take place in the coastal areas next to this bay. According to historical data, the Bay of Bengal has been the origin of eight out of the ten most lethal tropical cyclones ever recorded (Pinto, 2020). This highlights the crucial significance of the region for studies related to cyclones.

The Bay of Bengal's geographical and climatic conditions render it highly susceptible to cyclone formation. The frequent formation of tropical cyclones in this area is primarily due to elevated sea surface temperatures and favorable atmospheric conditions, especially during the pre-monsoon (April-May) and post-monsoon (October-November) periods (Kikuchi & Wang, 2010). Cyclones originating in the BoB generally travel in a north-northwest (NNW) trajectory, frequently hitting the eastern coast of India, or in a north-northeast (NNE) direction, affecting the coastal districts of Bangladesh and Myanmar. The trajectory of these cyclones is influenced by seasonal variations, with pre-monsoon cyclones typically moving in a north-northeast direction and post-monsoon cyclones moving in a north-northwest direction (Alam & Dominey-Howes, 2014).

This study specifically concentrates on the coastal districts in Bangladesh that are most frequently impacted by tropical cyclones, due to their significant influence. In addition, the study area encompasses the Sundarbans region, which has also experienced substantial effects, as stated by Hossain and Mullick (2020).

The justification for choosing this study area is reinforced by historical data that shows Bangladesh has experienced a minimum of 12 significant tropical cyclones since 1965, leading to the loss of 479,490 lives (Dasgupta et al., 2014). This remarkable statistic emphasizes the susceptibility of the area and underscores the need for a thorough investigation to comprehend the intricacies of cyclone development, trajectory, and consequences. Bangladesh's Ministry of Disaster Management and Relief has officially recorded a significant number of deaths caused by cyclones, establishing Bangladesh as one of the most profoundly impacted nations globally.

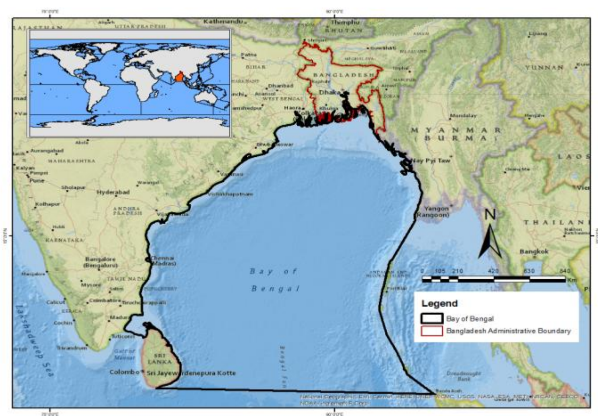


Figure 1: Map of the study area

Data Acquisition

The TC track data used in this study was collected from the Bangladesh Meteorological Department (BMD) and the International Best Track Archive for Climate Stewardship (IBTrACS). The BMD utilizes the Japanese satellite HIMAWARI 8 to monitor tropical cyclones (TCs) in the BoB. It delivers this data to users in JPEG format, which requires additional processing on the ArcGIS platform.

The International Best Track Archive for Climate Stewardship (IBTrACS) is a comprehensive repository of tropical cyclone data that consolidates information from multiple agencies to facilitate inter-agency comparisons (IBTrACS, 2021). IBTrACS provides data collected from the Joint Typhoon Warning Centre (JTWC), located in the United States, for the purpose of measuring the highest sustained wind speed and the lowest atmospheric pressure at the center of the TCs. In this study, we utilized the shapefile obtained from IBTrACS, which encompasses the JTWC best track data spanning from 1991 to 2023. Our objective was to examine the maximum wind speed and minimum central pressure. The data source for this study was NOAA in the year 2024.
The study utilized the GIOVANNI platform and obtained the time-averaged maps, along with cyclone track analysis, to assess the mean precipitation within the eyewalls of several notable TCs. GIOVANNI provides access to multiple satellite data sources, such as the Tropical Rainfall Measuring Mission (TRMM) and the Global Precipitation Measurement (GPM), for measuring precipitation at different time intervals, including every 3 hours, daily, and monthly. This study utilized daily precipitation rate data obtained from the TRMM satellite, which had a spatial resolution of 0.25 degrees. The data covered the time span from 1998 to 2019. Since the TRMM satellite ceased operations in 2019, we have been using GPM data with a spatial resolution of 0.1 degrees in recent years.

Analysis of Cyclone Tracks and Seasonal Variations

The JPEG file containing cyclone track data, obtained from BMD, was imported into ArcMap. Afterward, the projections for each cyclone point were adjusted to fit the Geographic Coordinate System (WGS) of 1984 (Decker, 1986) by using a designated Bangladesh map as a reference. In order to ensure accurate alignment between the image and map, we utilized the georeferencing process to align the data with the map. Subsequently, we established connections between each cyclone point by utilizing the "Points to Line" tool. The zonal classification of each tropical cyclone was determined by analyzing the location where the cyclone made landfall in three specific coastal zones: the western zone, the central zone, and the eastern zone.

Table 1: Details of data used in the study

Data	Satellite	Data Type	Duration	Projection System	Source
Tropical Cyclone Track	HIMAWARI 8	3-hourly JPEG-formatted imagery Captures high-resolution images across 16 spectral bands (visible and infrared)	1991-2023	Geographic coordinate system (GCS WGS- 1984)	Bangladesh Meteorological Department (BMD)
Maximum Sustained Wind Speed and Minimum Central Pressure		6- hourly data was provided in a combined shape file	1991-2023	Geographic coordinate system (GCS WGS- 1984)	IBTrACS best track archive (NOAA, 2024)
Average precipitation level	TRMM (Tropical Rainfall Measuring Mission)	Daily precipitation rate data (0.25° spatial resolution)	1998-2019	Geographic coordinate system (GCS WGS- 1984)	NASA's Goddard Space Flight Center (GSFC) Giovanni https://giovanni.gsfc.nasa.gov/giovanni/
Average precipitation level	GPM (Global Precipitation Measurement) data	Daily and 3-hourly precipitation data	2020-2023	Geographic coordinate system (GCS WGS- 1984)	NASA's Goddard Space Flight Center (GSFC) Giovanni https://giovanni.gsfc.nasa.gov/giovanni/

The "Calculate Geometry" function was employed to indicate the longitude and latitude coordinates (Karali et al., 2020). The precise documentation of the distribution of tropical cyclones (TCs) was conducted to enable comparative analysis across specific years. Finally, the TCs were categorized by month in order to delineate the seasonal fluctuations.

Assessing the Maximum Sustained Wind Speed, Central Pressure, and Mean Daily Precipitation

The IBTrACS dataset, which includes information about cyclones from 1980 to the present year, was imported into ArcGIS (Knapp et al., 2010). In order to filter the data according to our criteria, we employed the "Query Builder" tool located in the properties tab. We specifically selected the cyclones that made landfall in our coastal area. Subsequently, the cyclone points were linked together using the "Point to Line" tool, and heat maps were created in the QGIS platform to visualize the highest sustained wind speed and atmospheric pressure at the eye during the cyclonic event (Ostadabbas et al., 2019).

The daily average precipitation level for certain cyclones was determined by analyzing time-average maps obtained from the GIOVANNI platform (NASA, 2024). The maps were subsequently classified to illustrate the distribution and slope of rainfall during specific cyclone periods.

RESULTS AND DISCUSSION

Seasonal distribution of Cyclones

We have analyzed data from the past 54 years of cyclones to identify seasonal patterns in the formation and landfall of cyclones. Table 2 and Figure 2 depict a month-by-month breakdown of TCs that made landfall on the coasts of Bangladesh. Our analyses are consistent with the characteristics typically observed during cyclone seasons in the BoB, which are predominantly characterized& explained by pre-monsoon and post-monsoon conditions. In Bangladesh, the month of May, preceding the monsoon season has recorded the highest number of cyclones in the past 54 years, with a total of 14 TCs. According to Tiwari et al. (2022), November had the highest number of TCs during the post-monsoon season, with at least 11 occurrences. During the month of October, a minimum of four TCs had developed. There were a minimum of two TCs that took place in the months of April and December. Nevertheless, cyclones also reached land during the monsoon season, with at least one tropical cyclone being recorded each month from June to September over the course of 54 years.

Table 2: Month-wise distribution of cyclone formation

Time Period	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1970 – 1980		2			1			4	1
1981 – 1990		1					1	3	1
1991 – 2000	1	3	1			1		2	
2001 – 2010	1	2					1	1	
2011 – 2023		6		1			2	1	
Total (54 years)	2	14	1	1	1	1	4	11	2

Nevertheless, the monthly distribution data indicate a notable pattern in the formation of cyclones. Traditionally, there has been a high occurrence of TCs in November, which typically occurs after the monsoon season. Nevertheless, there has been a notable change in this trend in recent decades, with a higher occurrence of cyclones happening in the months before the monsoon season, specifically in May. Between 1970 and 2000, there were a total of 9 TCs that hit land in November, compared to only 2 cyclones in the following two decades. In contrast, the number of cyclones occurring in May rose from 6 between 1970 and 2000 to a combined total of 8 in the subsequent two decades.

The change in the timing of cyclone seasons has important consequences for the planning and implementation of measures to prevent and respond to disasters. The heightened occurrence of cyclones in May indicates the necessity for earlier preparedness and mitigation strategies, particularly in susceptible coastal areas. The results are consistent with worldwide climate change trends, which have been linked to modifications in cyclone behavior, such as shifts in their seasonal occurrence (Knutson et al., 2010).

The observed pattern underscores the significance of ongoing surveillance and flexible management strategies to alleviate the detrimental effects of TCs. Gaining a more comprehensive comprehension of the seasonal fluctuations and changing trends in cyclone formation can assist in improving the accuracy of predictions and readiness, ultimately mitigating the socio-economic impact of these natural calamities. Further investigation should prioritize the analysis of the fundamental reasons behind these changes, such as the possible impact of climate change, anomalies in sea surface temperature, and other meteorological factors (Murphy et al., 2009). Based on the examination of the seasonal occurrence of cyclones over the last 54 years, it is evident that there has been a significant rise in pre-monsoon cyclones, especially in the month of May. This emphasizes the importance of implementing adaptive disaster management strategies to protect lives and property in one of the most cyclone-prone regions across the tropics.

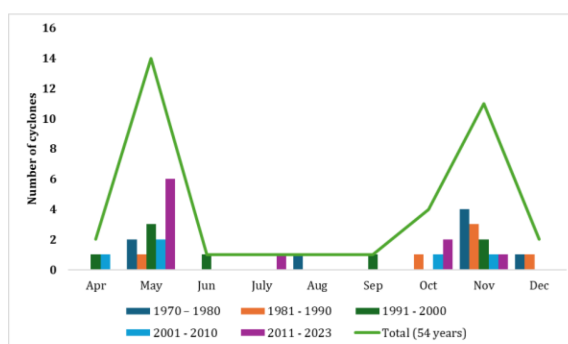


Figure 2: Monthly distribution of cyclone formation

Zonal Distribution of Cyclones

An examination of the zonal distribution of TCs that reached the coast of Bangladesh showed notable variations in the effects experienced in different coastal areas. During the past 33 years, it was noted that a significant majority, comprising at least 65% of all TCs, struck the eastern coast, predominantly impacting the Chittagong region. The clustering of tropical cyclone landfalls underscores the increased susceptibility of the eastern coastal region to cyclonic events. More precisely, among the 23 tropical cyclones that made landfall during this time frame, 15 specifically affected the eastern region, emphasizing the unequal influence felt by this particular coastal area. On the other hand, the western coast dealt with the landfall of only 5 TCs, whereas the central coast endured the impact of the remaining 3 TCs. The variation in where tropical cyclones make landfall highlights the importance of developing customized strategies to mitigate and adapt to the specific vulnerabilities of each coastal area. This will help minimize the social and economic consequences of cyclonic events. Furthermore, Table 3 and Fig. 3 offer comprehensive visual depictions of the variation in TC landfall along the coast, emphasizing the differences in impact among various coastal areas.

Table 3: Coast-wise variation of TC landfall

Time Period	Western Coast	Central Coast	Eastern Coast
1991 - 2000	0	1	8
2001 - 2010	2	1	2
2011 - 2023	3	1	5
Total (33 years)	5	3	15

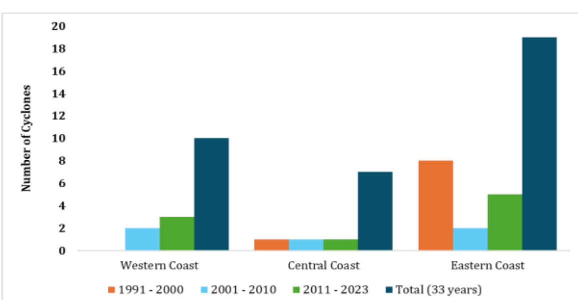


Figure 3: Coast-wise variation of cyclone landfall

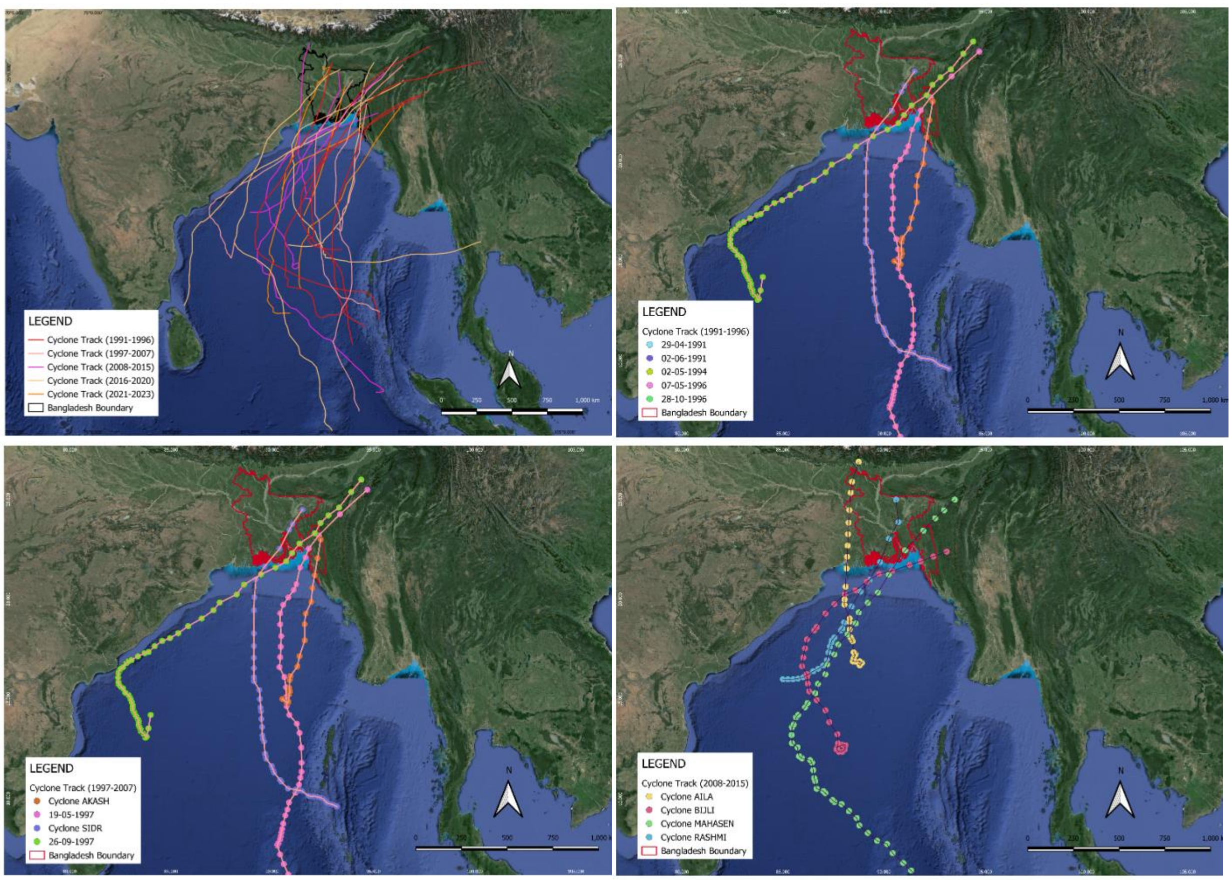
The aforementioned results underscore the regional discrepancies in cyclone exposure and underscore the necessity for focused mitigation and adaptation strategies customized to the distinct vulnerabilities of each coastal area (Sarkar et al., 2024). The Eastern coast's disproportionate impact highlights the significance of bolstering resilience measures and infrastructural preparedness in this region to alleviate the detrimental consequences of future cyclonic events (Tiwari et al., 2022). Furthermore, the fluctuation in the distribution of tropical cyclone landfall over time demonstrates the ever-changing nature of cyclone behavior and underscores the significance of ongoing monitoring and adaptable management strategies to effectively address evolving risks (Webster et al., 2005).

The coastal region of Bangladesh, specifically the Chittagong area, encounters a variety of complex obstacles in reducing the effects of tropical cyclones (Farid and Nasreen, 2023). Population density, insufficient infrastructure, and environmental degradation worsen the susceptibility of coastal communities to cyclonic hazards (Sarkar et al., 2024). Therefore, it is crucial to consider these contextual factors when developing thorough risk assessment and management strategies. This will help strengthen the resilience of vulnerable populations and reduce the socio-economic consequences of cyclonic events (Tiwari et al., 2022). Therefore, by clarifying the geographical patterns of tropical cyclone landfalls, this analysis offers valuable knowledge for policymakers, authorities in charge of disaster management, and community stakeholders engaged in cyclone preparedness and response efforts. In addition, the identification of districts and regions with high levels of activity, such as the Chittagong region, highlights the immediate requirement for focused interventions to enhance the capacity to withstand and subsequently minimize the effects of future cyclonic events in these susceptible coastal zones (Sarkar et al., 2024).

Track Information of the Tropical Cyclones Hitting the Bay of Bengal

The track data of TCs originating in the BoBand making landfall on the coast of Bangladesh offers a comprehensive overview of their paths and points of origin. An extensive examination of 21 tracks of TCs, covering a time frame of 33 years from 1991 to 2023, provides valuable observations regarding their behavior and patterns of movement (Fig. 4). Most of these cyclones were found to originate from the BoB, specifically near the Andaman and Nicobar Islands. Nevertheless, there has been a discernible change in recent years, as certain cyclones have started to develop in the central region of the Bay, rather than near the islands (Balaguru et al., 2014). The change in the starting point of genesis can be ascribed to alterations in sea surface temperatures and atmospheric conditions, which are influenced by global climate variability (Emanuel, 2005).

According to the analysis, almost all TCs have a consistent pattern of moving towards the west. This movement is primarily influenced by the trade winds, which blow from east to west in the tropics (Amador et al., 2006). The westward movement is a typical feature of cyclones in tropical regions, propelled by the dominant easterly winds. As cyclones move forward, they gradually shift towards the poles because of the Coriolis force. In the Northern Hemisphere, this particular force causes air masses to be deflected to the right (Terry, 2007). The deflection of the cyclones results in a northward curvature, which is in line with the observed track patterns.



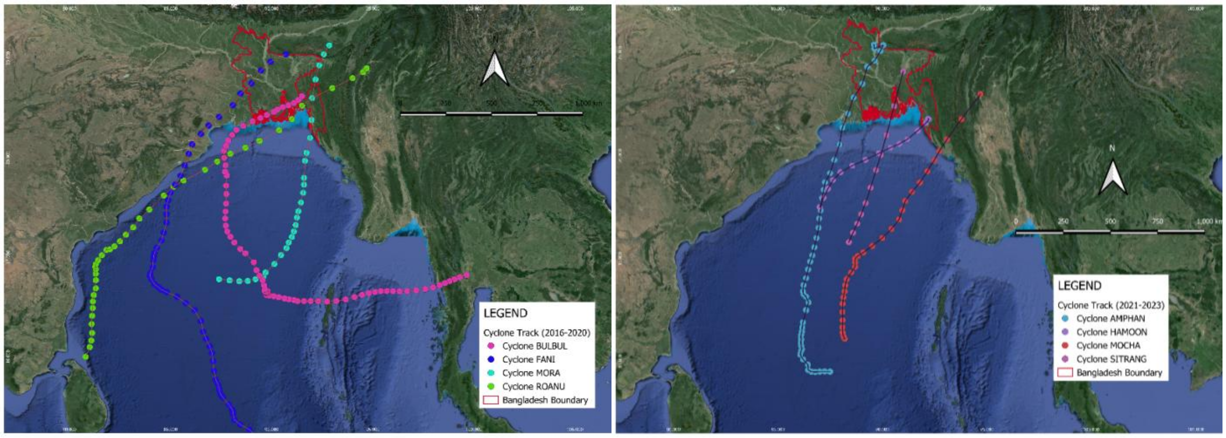


Figure 4: Track Information of the TCs since 1991

As the cyclones progress towards the poles, another important factor comes into effect, causing them to change direction and move towards the east. The recurvature is affected by the mid-latitude westerlies, which are west-to-east winds in the temperate zones (Camargo et al., 2007). The cyclones and westerlies interact, causing the cyclones to turn eastward and move towards the coastlines of neighboring countries such as Bangladesh, India, and Myanmar. The recurvature of cyclone tracks is a crucial factor in determining where they make landfall and the areas that may be affected by their impact (Chen and Lin, 2011).

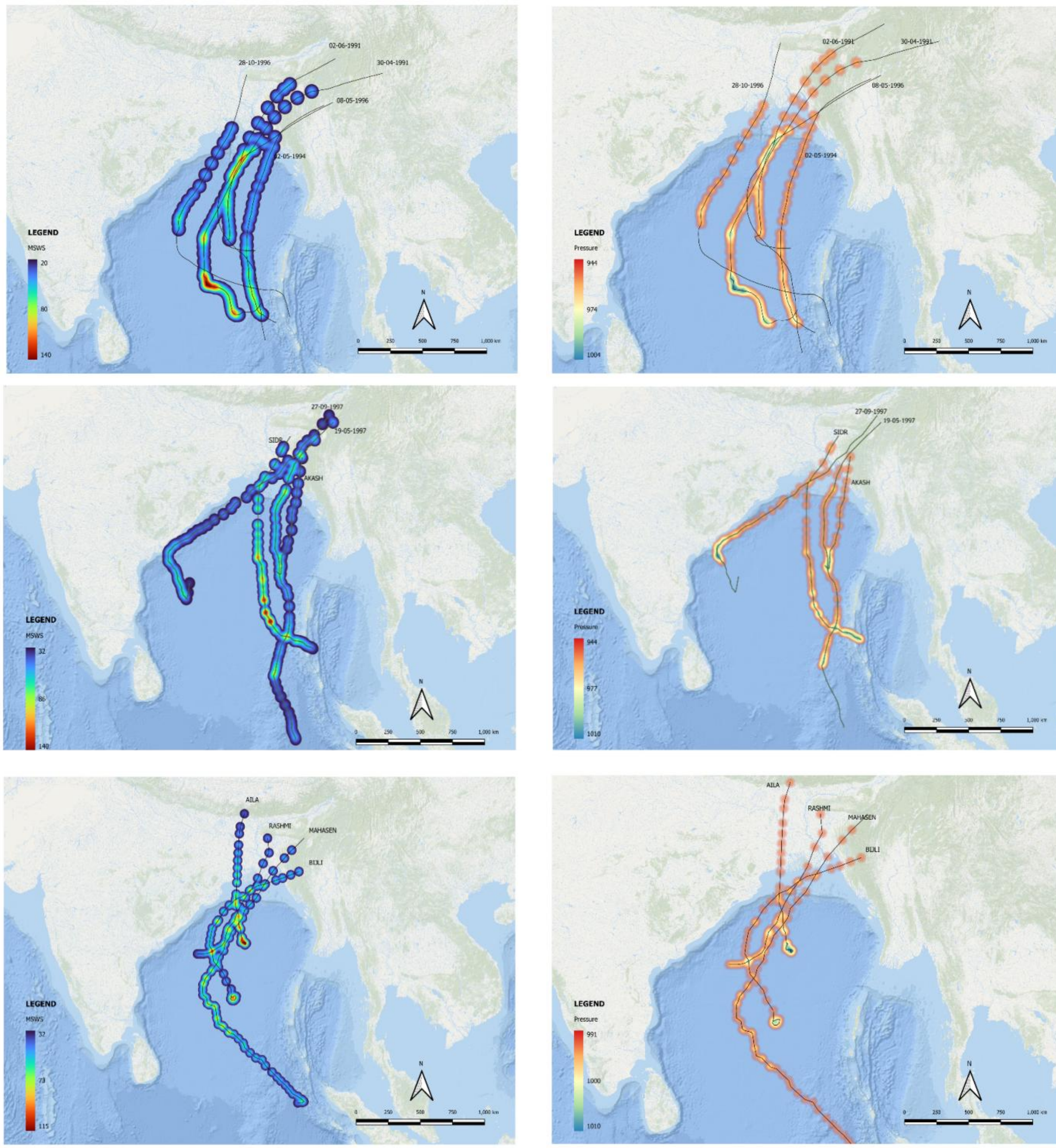
The historical data on cyclone tracks demonstrates the intricate and fluctuating nature of tropical cyclone paths over the Bay region. The alterations in the genesis location and movement patterns are indicative of larger climatic patterns and emphasize the significance of ongoing monitoring and research (Webster et al., 2005). Gaining insight into these patterns is essential for enhancing predictive models and optimizing disaster preparedness and response strategies in the impacted areas (Balaguru et al., 2014).

Furthermore, the examination of cyclone tracks not only reveals the westward and poleward shifts but also emphasizes the influence of local atmospheric conditions and abnormal sea surface temperatures. These factors have the potential to greatly modify the intensity and path of cyclones, resulting in increased unpredictability in their behavior (Emanuel, 2005). The variability in the paths and intensity of cyclones highlights the necessity for resilient and flexible disaster management frameworks that can effectively address the ever-changing nature of these natural phenomena (Camargo et al., 2007). However, through comprehending the track information and movement patterns of TCs, it is feasible to create more precise forecasting models and execute efficient mitigation strategies. Improved understanding of cyclone behavior can result in more resilient communities and decreased socio-economic consequences caused by these catastrophic natural phenomena (Elsner & Liu, 2003).

Wind and Pressure Characteristics of the TCs

The wind and pressure characteristics of tropical cyclones (TCs) offer essential information regarding their intensity and potential for causing destruction. The main focus of our study was to analyze the highest wind speed (measured in knots) and atmospheric pressure (measured in millibars) at the center of the cyclones, as shown in the accompanying images (Fig. 5). Typically, the atmospheric pressure at the Earth's surface is approximately 1000 millibars. Nevertheless, at the center of a TC, the atmospheric pressure can decrease considerably, usually reaching around 950 millibars but potentially dropping as low as 880 millibars in the most severe cyclones (Chavas et al., 2017).

It is widely accepted in meteorological research that the intensity of a TC increases as the central pressure decreases. An example of a powerful cyclone is Sidr, a category 4 cyclone that devastated the coast of Bangladesh in 2007. It had a record-breaking lowest central pressure of 944 millibars and sustained wind speeds of 3 minutes (Akter &Tsuboki, 2012). This cyclone inflicted extensive destruction on both the populace and the ecosystem along the coastline. Both the super cyclonic storm of 1991 and cyclone Amphan had exceptionally high central pressures of 918 and 920 millibars respectively, making them some of the most intense and devastating cyclones ever observed in the North Indian Ocean region (Ahmed et al., 2021).



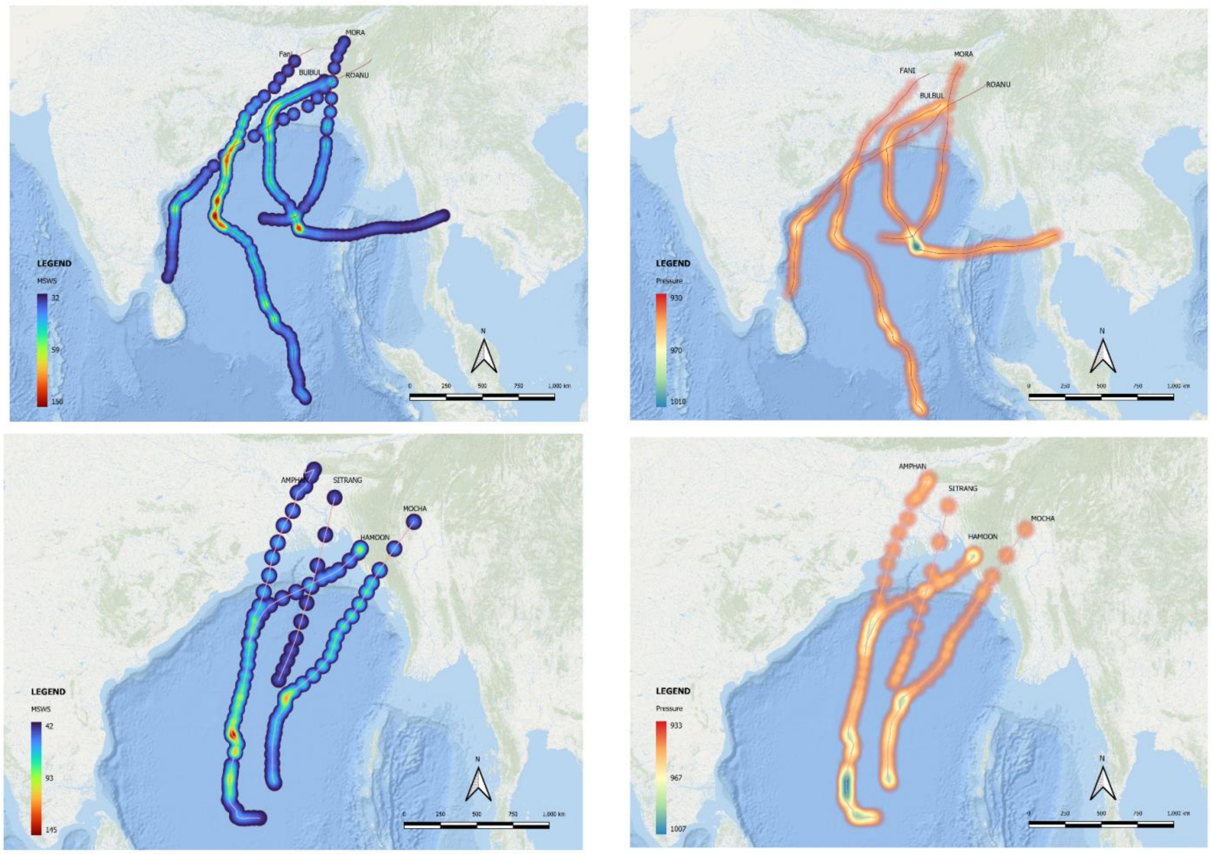


Figure 5: Wind Velocity and Central Atmospheric pressure of the Cyclones

Examining the wind velocity of cyclones is equally essential for comprehending their influence. Elevated wind speeds frequently correlate with heightened storm surges and substantial destruction. Cyclone Amphan's maximum wind velocity was measured at 145 knots, surpassing the peak velocity of 140 knots recorded in the 1991 cyclone (Ahmed et al., 2021). The correlation between wind speed and the potential for damage underscores the significance of precise wind velocity measurements in cyclone prediction and evaluation of its impact. It is essential to remark that the wind speed typically decreases drastically when cyclones make landfall, as evidenced by the examination of their tracks.

The analysis of these attributes goes beyond mere numerical values, illustrating the dynamic and devastating nature of these meteorological phenomena. The fluctuation in central pressure and wind velocity not only determines the categorization of the cyclone but also its capacity to inflict harm. Lower central pressures are a reliable indicator of more intense cyclonic activity, which is often associated with higher wind speeds and more severe consequences (Chavas et al., 2017). Once again, comprehending the interaction among these factors is crucial for enhancing predictive models and improving disaster preparedness. The historical data on cyclones such as Sidr, the 1991 cyclone, and Amphan, offer valuable case studies for examining the impacts of extremely low pressure and high wind speeds on coastal communities (Akter &Tsuboki, 2012; Ahmed et al., 2021). These case studies demonstrate the necessity of strong infrastructure and efficient emergency response plans to reduce the effects of such formidable cyclones.

Moreover, the observed patterns in cyclone intensity highlight the possible impacts of climate change on the behavior of TCs. Evidence indicates that the increase in sea surface temperatures and alterations in atmospheric conditions could potentially lead to the development of more powerful cyclones in the coming years (Emanuel, 2005). It is crucial to include climate projections in cyclone preparedness and response strategies in order to effectively anticipate and handle future risks (Balaguru et al., 2014).

Precipitation Information on Some of the Major Cyclones

We created a precipitation map using the available data on the amount of rainfall in some of the tropical cyclones (Figure 6). Although establishing a direct correlation between precipitation patterns and the intensity level of a cyclone is challenging, it is widely recognized that as cyclones become more intense, the amount of precipitation they produce increases. Nevertheless, cyclones have the potential to weaken prior to reaching land due to the presence of widespread precipitation patterns. The study did not analyze the rainfall patterns of the selected TCs. Instead, it focused on highlighting the extent of precipitation using these images. The precipitation level for the cyclones is depicted in units of millimeters per day.

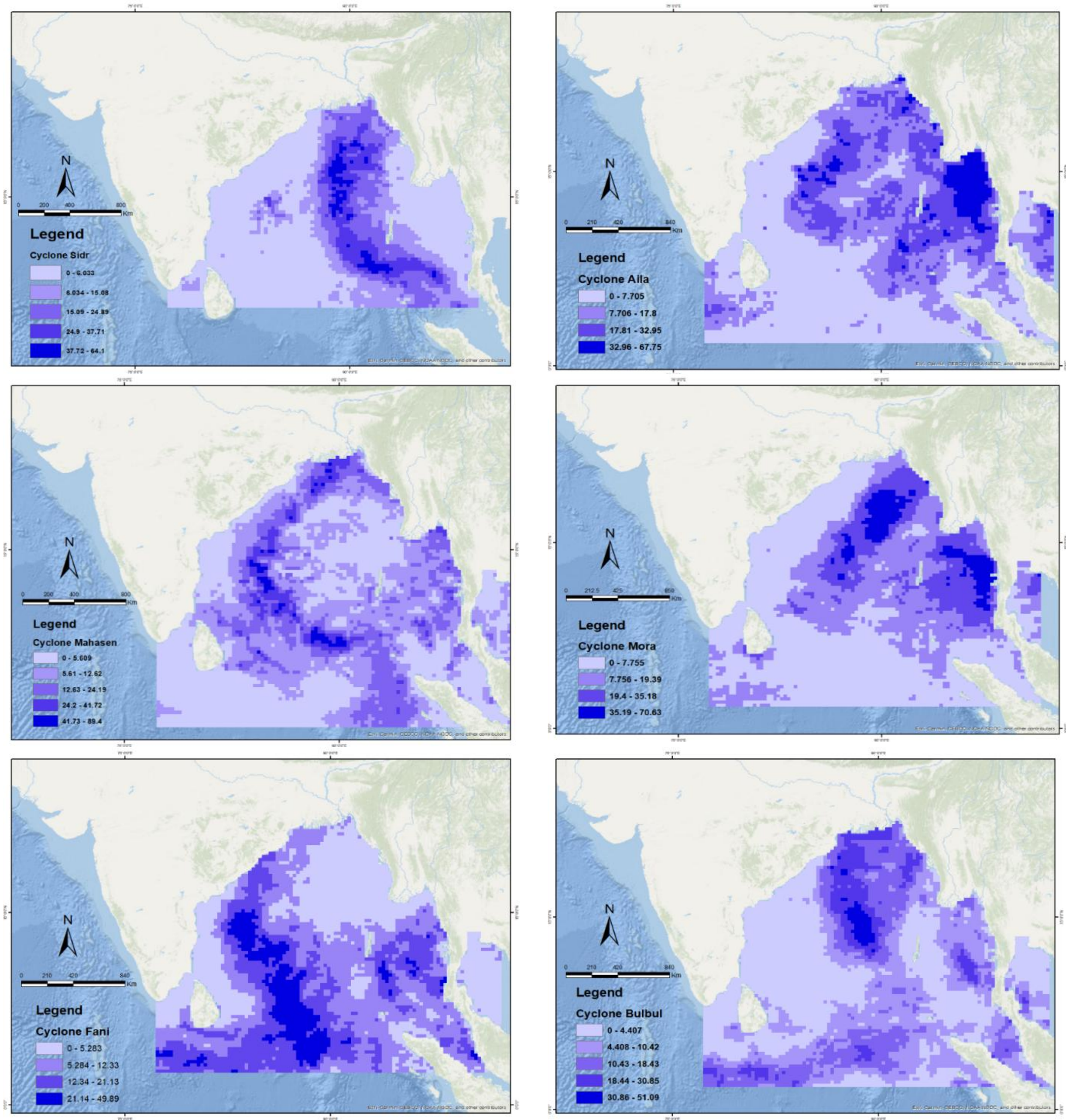


Figure 6: Precipitation information on some of the recent TCs

Although establishing a direct correlation between precipitation patterns and cyclone intensity is difficult, it is widely recognized that more intense cyclones typically result in greater levels of precipitation (Ramsay & Sobel, 2011). Nevertheless, this relationship is intricate and impacted by diverse factors including cyclone structure, trajectory, and environmental conditions. Intense cyclones frequently exhibit well-structured convection and larger eyewalls, resulting in substantial rainfall over a wider expanse (Lonfat et al., 2004).

Occasionally, cyclones may experience a decrease in strength before reaching land due to widespread patterns of rainfall, resulting in the redistribution of energy within the cyclone system (Tory et al., 2013). This weakening can occur when the cyclone interacts with land or experiences changes in atmospheric conditions, such as an increase in vertical wind shear or a decrease in sea surface temperatures. Although the amount of precipitation is an important factor in the effects of a cyclone, it does not necessarily indicate the cyclone's intensity when it reaches land.

Our study aims to emphasize the amount of rainfall linked to specific TC, rather than analyzing complex patterns. Figure 6 displays the precipitation levels, measured in millimeters per day, which visually depict the regions that experience significant rainfall during these cyclones. The provided information is essential for comprehending the wider hydrological consequences of cyclones, such as flooding and soil erosion, which pose significant concerns for coastal communities (Knight & Davis, 2009). Additionally, the data indicates that cyclones that generate greater amounts of precipitation have a tendency to encompass larger geographical regions, resulting in extensive flooding and the subsequent occurrence of related damages. An instance of this is cyclone Sidr, which struck Bangladesh in 2007, resulting in substantial wind destruction and substantial flooding caused by intense rainfall (Akter & Tsuboki, 2012). Furthermore, the occurrence of cyclone Amphan in 2020 resulted in a significant increase in rainfall, which worsened the already existing flooding in the affected areas (Ahmed et al., 2021).

Gaining insight into the precipitation characteristics of TCs is crucial for enhancing disaster preparedness and response strategies. Precise precipitation forecasts can assist in prompt evacuation and mitigation efforts, thereby minimizing the loss of life and property (Khouakhi et al., 2017). Moreover, the examination of historical precipitation data aids in the identification of trends and patterns that can provide valuable insights for future assessments of cyclone impacts and the development of climate adaptation plans. The study's findings suggest that although the relationship between precipitation and cyclone intensity is intricate, the amount of precipitation plays a crucial role in evaluating the overall impact of cyclones, particularly in the coastal region of Bangladesh.

Limitations

Despite producing useful outputs, the study encountered a few limitations.

An important obstacle was the arduous task of acquiring comprehensive and dependable data regarding the central pressure of tropical cyclones. The information regarding the intensity of cyclones and its correlation with other meteorological variables was not easily accessible.

The study encountered difficulties as a result of the lack of track information for certain tropical cyclones. The absence of data in these areas required the removal of these cyclones from the analysis in order to ensure consistency and coherence throughout the result sections.

The need to exclude cyclones with incomplete data points may have affected the study's comprehensiveness, potentially limiting a more comprehensive understanding of the behavior and effects of TCs in the BoB region.

CONCLUSIONS

The study utilized ArcGIS to map the trajectories of cyclones, as well as the highest wind speeds and central pressure within the cyclone's eye. This methodological approach facilitated a comprehensive visualization and analysis of past TCs that struck the coastal region of Bangladesh.

The study effectively demonstrated the intensity of these cyclones by emphasizing the maximum sustained wind velocity and atmospheric pressure at the cyclone's center. The precipitation maps provided additional insight by illustrating the magnitude of rainfall that occurs during cyclones, which frequently coincides with strong winds and intensifies the overall consequences on affected areas. The incorporation of these datasets yielded a thorough depiction of TC attributes and their consequences, offering valuable discernment for disaster readiness and administration. The comprehensive mapping and analysis underscore the necessity for enhanced data collection and accessibility to bolster future research endeavors. These enhancements would enable more precise modeling and forecasting of cyclone behavior, ultimately assisting in the creation of more efficient strategies to reduce and adapt to their impact. The findings highlight the significance of ongoing research and investment in meteorological infrastructure to enhance comprehension and control of the hazards linked to tropical cyclones in susceptible coastal regions of Bangladesh.

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