Climatological Analysis of Tropical Cyclones over the Bay of Bengal: 1972–2023

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Executive Summary

Tropical cyclones (TCs) in the Bay of Bengal (BoB) continue to pose severe threats to coastal regions such as Bangladesh, India, and Myanmar, with their devastating winds, heavy rainfall, and storm surges. The problem has intensified with climate change, as rising sea surface temperatures (SSTs) contribute to stronger cyclones and shifting tracks, increasing the vulnerability of densely populated, low-lying areas. This study aims to analyze the spatial and temporal distribution of TCs in the BoB from 1972 to 2023, examine trends in cyclone frequency and intensity using Maximum Sustained Wind (MSW) and Minimum Sea Level Pressure (MSLP), and assess the influence of environmental factors like SSTs and atmospheric dynamics on cyclone behavior. Methodologically, best-track data from the Joint Typhoon Warning Center (JTWC) were processed using Python to filter storms with wind speeds ≥34 knots. The study conducted spatial and temporal analyses, generating visualizations of cyclone tracks, seasonal patterns, and correlations between MSLP and MSW. The finding reveals that most cyclone genesis occurs between 8°N–14°N and 86°E–90°E, with the post-monsoon season (October–November). While no significant long-term trend in cyclone frequency was observed (average 3.285 TCs/year), interannual variability is evident. The study found a strong inverse correlation ($R^2 = 0.974$) between MSLP and MSW, with rapid intensification (RI) events more frequent in pre-monsoon seasons. In conclusion, the BoB remains highly susceptible to intense cyclones, with growing risks due to climate change, despite relatively stable frequency trends. To address these challenges, the study recommends improving historical cyclone datasets and integrating high-resolution sources like ERA5 and IBTrACS, developing regional models for better Rapid Intensification prediction, and implementing policy measures focused on coastal resilience, early warning systems, and community preparedness.

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Table of Contents

List of Figures

List of Tables

Abbreviations

TC - Tropical Cyclone

BoB - Bay of Bengal

SST - Sea Surface Temperature

MSW - Maximum Sustained Wind

MSLP - Minimum Sea Level Pressure

RI - Rapid Intensification

JTWC - Joint Typhoon Warning Center

GBM - Ganges-Brahmaputra-Meghna

BMD - Bangladesh Meteorological Department

CS - Cyclonic Storm

SCS - Severe Cyclonic Storm

VSCS - Very Severe Cyclonic Storm

ESCS - Extremely Severe Cyclonic Storm

SupCS - Super Cyclonic Storm

ITCZ - Intertropical Convergence Zone

IPCC - Intergovernmental Panel on Climate Change

ACE - Accumulated Cyclone Energy

PDI - Power Dissipation Index

ERA5 - ECMWF Reanalysis 5th Generation

IBTrACS - International Best Track Archive for Climate Stewardship

NOAA - National Oceanic and Atmospheric Administration

INSAT - Indian National Satellite System

1. Introduction

A tropical cyclone is a powerful rotating storm that forms over warm ocean waters, characterized by strong winds (greater than 34 knots or 62 km/h), heavy rain, and low atmospheric pressure. It typically develops in tropical or subtropical regions and can cause severe damage when making landfall. Tropical cyclones are powerful storms that help balance the Earth's atmosphere by moving heat and moisture from the oceans to the atmosphere. They play a natural role in regulating the planet's climate. A new global observational and theoretical study of tropical cyclone genesis analyzes cyclone genesis locations over a 20-year period (1952–1971) and links seasonal cyclone frequency to six key parameters: low-level relative vorticity, the Coriolis parameter, vertical wind shear, ocean thermal energy, moist stability, and middle troposphere humidity, resulting in a seasonal forecast model that accurately predicts cyclone location and frequency (Gray, 1975).

The life cycle of a tropical cyclone (TC) involves several distinct stages characterized by complex interactions between the atmosphere and the ocean. It begins with the formation (genesis) stage, where favorable environmental conditions over warm tropical oceans, such as sea surface temperatures above 26.5°C, high relative humidity, and low vertical wind shear, lead to sustained convection (Gray, 1968; Emanuel, 1991). This process helps develop a surface mesoscale or synoptic vortex, allowing the system to become self-sustaining (McBride and Gray, 1981). Once formed, the storm enters the intensification stage, where it extracts enormous energy from the ocean through latent heat release, strengthening through internal and external processes(Holland, 1997). During this phase, the cyclone's structure becomes more organized, with increasing wind speeds and rainfall intensity (Emanuel, 1991). At its peak, the cyclone reaches the maturity stage, where it achieves maximum intensity and may undergo intensity oscillations, often attributed to eyewall replacement cycles (Willoughby, Clos and Shoreibah, 1982). This stage is marked by the cyclone's ability to maintain powerful winds, a distinct eye, and heavy rainfall (Knaff, Longmore and Molenar, 2014). Eventually, the cyclone enters the decay stage when it moves into an unfavorable environment, such as cooler sea surface temperatures, strong vertical wind shear, or land interaction(Demaria and Kaplan, 1994). These factors lead to a gradual or rapid loss of intensity, causing the cyclone to weaken and eventually dissipate. Throughout its life cycle, the cyclone's development, movement, and intensity are influenced by complex multi-scale interactions between internal dynamics and large-scale environmental forces (Frank and Ritchie, 1999).

The Bay of Bengal is a hotspot for cyclones due to its unique geographic and climatic conditions. It is a warm, semi-enclosed ocean basin with high sea surface temperatures (above 26.5°C), providing the ideal energy source for cyclone formation(Ali, 1999). The bay is also surrounded by land on three sides, which helps trap warm, moist air, fueling storm development (Dube et al., 1997). Additionally, the intertropical convergence zone (ITCZ) often shifts over the region, creating favorable atmospheric conditions such as low vertical wind shear and high relative humidity (Mohapatra et al., 2012). Seasonal weather patterns, like the southwest and northeast monsoons, contribute to cyclone activity, with two peak seasons — pre-monsoon (April–May) and post-monsoon (October–November) (Singh, Khan and Rahman, 2001). Furthermore, the shallow waters of the bay allow storms to gain intensity quickly (Shankar, Vinayachandran and Unnikrishnan, 2002). These factors, combined with the region's high population density and low-lying coastal areas, make the Bay of Bengal highly vulnerable to frequent and intense cyclones (Unnikrishnan, Nidheesh and Lengaigne, 2015).

Tropical cyclones (TCs) play a significant role in both the natural environment and human society. They act as a crucial mechanism for balancing heat and moisture in the Earth's atmosphere by transferring energy from the warm oceans to the atmosphere (Emanuel, 2003). Despite their destructive power, which includes strong winds, heavy rainfall, and storm surges causing widespread damage and loss of life (Pielke et al., 2008), Tropical cyclones also bring essential rainfall that can temporarily relieve drought conditions, benefiting agriculture and water resources(Shepherd, Grundstein and Mote, 2007). Understanding the formation, structure, and intensity changes of Tropical cyclones is vital for improving early warning systems and disaster preparedness (Elsberry, 2002). Accurate forecasting helps mitigate the devastating impacts on coastal communities, infrastructure, and economies, emphasizing the importance of continuous research on tropical cyclone behavior (Landsea and Franklin, 2013).

Understanding climatological patterns aids in minimizing economic losses, safeguarding lives, and supporting sustainable development in cyclone-prone regions. As extreme weather events become more frequent due to global warming, studying these characteristics becomes even more critical for building climate resilience (Kossin, Emanuel and Vecchi, 2014). Recent high-resolution climate model simulations have improved predictions of category 4 and 5 hurricanes, emphasizing the importance of continuous research on tropical cyclone behavior (Murakami et al., 2015).

Studying the climatological characteristics of tropical cyclones is essential for understanding their behavior, improving prediction accuracy, and enhancing disaster preparedness. By analyzing long-term patterns—such as cyclone frequency, intensity, seasonal variations, and track movement—scientists can identify trends and anomalies linked to climate change and natural variability (Knutson et al., 2020). This analysis helps anticipate future cyclone activity and explains how factors like sea surface temperature, wind shear, and atmospheric moisture contribute to storm development. For instance, warmer sea surface temperatures have been associated with increased cyclone intensity(Wu et al., 2022).

One of the key benefits of this research is its potential contribution to early warning systems. Accurate forecasting of tropical cyclones enables timely evacuations and disaster preparedness measures, reducing casualties and economic losses (Walsh et al., 2014). The need for a climatological analysis over this period is further emphasized by the socio-economic vulnerabilities of the region. Coastal areas in Bangladesh, India, and Myanmar are highly susceptible to cyclone-induced storm surges, which have historically caused immense loss of life and economic damage (Dube et al., 1997). By examining past cyclone trends, researchers can identify patterns in landfall locations, seasonal variations, and changes in storm surge impacts, leading to improved risk assessment and disaster preparedness. Improved understanding of cyclone behavior also allows policymakers and disaster management authorities to design more effective coastal protection infrastructure and emergency response plans.

Moreover, as extreme weather events become more frequent due to global warming, studying cyclone climatology becomes increasingly important for building climate resilience. By assessing the relationship between climate factors such as sea surface temperature and cyclone intensity, this study will provide valuable insights into how future cyclones might behave under different climate change scenarios. Moreover, technological advancements since the 1980s have enhanced the accuracy of tropical cyclone tracking and intensity estimation. The availability of satellite data, such as those from NOAA and INSAT series satellites, allows for a more refined analysis of cyclone genesis, movement, and dissipation. This period also covers significant improvements in global and regional climate models, contributing to better cyclone prediction capabilities.

This research will contribute to sustainable development in cyclone-prone regions by strengthening disaster resilience and promoting climate-smart policies. As extreme weather events become more frequent due to global warming, understanding past cyclone trends is crucial for building climate resilience. A climatological analysis of TCs from 1972 to 2023 reveals how climate variability influences cyclone activity, helping policymakers create adaptive strategies for vulnerable communities. By combining historical data with modern forecasting techniques, the study aims to enhance early warning systems and mitigation measures. Additionally, it bridges the gap between scientific research and disaster management, supporting efforts at local, national, and international levels to reduce risks from tropical cyclones in the Bay of Bengal.

2. Literature Review

Several studies have examined the climatological characteristics of tropical cyclones (TCs) in the Bay of Bengal, shedding light on trends in their frequency, intensity, and seasonal patterns. The Bay of Bengal experiences more severe cyclones during the post-monsoon season (October–November) compared to the pre-monsoon season (April–May) (Kotal, Kundu and Roy Bhowmik, 2009). The seasonal variability of cyclone activity is crucial for understanding its timing and severity. During the post-monsoon period, cyclones are often more intense and disruptive, posing a greater threat to coastal areas. Studies emphasized that atmospheric conditions, such as the monsoon trough and variations in the dipole mode index, significantly influence cyclone occurrence (Bhardwaj and Singh, 2020). These factors contribute to a higher frequency and intensity of cyclones in the post-monsoon season, making it particularly hazardous for coastal regions in the Bay of Bengal.

The Bangladesh Meteorological Department (BMD) classifies tropical cyclones based on their maximum sustained wind speeds to assess their intensity and potential impact. These classifications help in issuing timely warnings and improving disaster preparedness, particularly for vulnerable coastal regions.

Table 2.1: The following table outlines BMD's cyclone categories over the Bay of Bengal:

Classification	Wind Speed (km/h)	Wind Speed (knots/mps)
Cyclonic Storm (CS)	62–88	34–47 (18–24)
Severe Cyclonic Storm (SCS)	89–118	48–63 (25–32)
Very Severe Cyclonic Storm (VSCS)	119–165	64–89 (33–46)
Extremely Severe Cyclonic Storm (ESCS)	166–220	90–119 (47–61)
Super Cyclonic Storm (SupCS)	221 or more	120 or more (62 or more)

Several studies have shown an increasing trend in the proportion of Category 3–5 TCs globally, attributed to rising sea surface temperatures (SSTs) that enhance cyclone energy potential(Emanuel, 2003) . Alongside this, RI events—where a cyclone's wind speed increases drastically over a short time—have become more common. Report states statistically significant increases in RI occurrences in several ocean basins, including the North Indian Ocean, implying a direct link with warming ocean waters (Kossin, Emanuel and Vecchi, 2014). Additionally, cyclone tracks have exhibited spatial shifts; for example, a study found that projected changes in global atmospheric circulation under future warming scenarios could alter the typical landfall locations of TCs, particularly in the North Indian and Western Pacific Oceans (Murakami et al., 2015). These changes are echoed by the findings of the Intergovernmental Panel on Climate Change (IPCC), which confirms that it is “likely” that the global proportion of intense TCs has increased due to anthropogenic warming. Regional climate models focusing on South Asia further support these observations, suggesting increasing cyclone activity over the Bay of Bengal under enhanced greenhouse gas scenarios. Such changes emphasize the urgent need for updated risk assessments and climate-resilient infrastructure in vulnerable coastal regions.

In terms of cyclone intensity, historical data analysis has shown a clear upward trend in the strength of cyclones in the region. Studies pointed to an increasing occurrence of severe cyclonic storms in recent decades, which they attribute to rising sea surface temperatures and the impacts of climate change (Balaguru et al., 2014). As the global climate warms, the Bay of Bengal's oceanic conditions are altering, providing more energy for cyclones, thus enhancing their intensity. The intensity of post-monsoon cyclones in the Bay of Bengal has increased by approximately 25% over the past few decades, highlighting a significant shift towards more destructive storms (Bhardwaj and Singh, 2020). This trend has led to an increased frequency of more powerful cyclones that are capable of causing more damage, particularly in densely populated coastal regions.

The role of anthropogenic factors, such as greenhouse gas emissions, in the intensification of tropical cyclones is another key area of focus in the literature. It is emphasized that both climate models and observational data suggest significant contributions from human activities to the rising intensity of cyclones in the Bay of Bengal (Evan et al., 2011). The Sea Surface Temperature (SST) in the Bay of Bengal increased by approximately 4°C over the past 31,000 years, from the Last Glacial period to the Early Holocene (Sakthivel et al., 2024). The warming of sea surfaces, as a direct result of global warming, has been identified as a crucial factor in the growing intensity of cyclonic events in the region. Moreover, the shift in cyclone behavior specifically, changes in the tracks of cyclones has been observed, with more storms making landfall in vulnerable coastal areas (Bhardwaj and Singh, 2020). This shift is thought to be influenced by changes in atmospheric circulation patterns, which have been altered by the warming climate.

The growing frequency and intensity of cyclones in the Bay of Bengal present considerable risks to the socio-economic stability of the coastal populations. Singh (2007) discussed the potential consequences of this increasing cyclone activity, which threatens the livelihoods of millions of people who live in the low-lying coastal zones. These areas are particularly vulnerable to the impacts of extreme weather events, including flooding, property damage, loss of life, and disruption of local economies. The increase in cyclone frequency also places greater pressure on local governments and disaster management systems, which must respond to the growing challenges posed by these storms.

Furthermore, the changing patterns of cyclone tracks have implications for disaster preparedness and response. As cyclones increasingly make landfall in regions that were previously less affected, local communities are faced with the dual challenge of adapting to a heightened risk while also dealing with limited resources for disaster management. Effective forecasting and early warning systems are therefore essential in mitigating the risks posed by these storms, and there is a growing need for robust disaster resilience strategies.

Several studies have examined the climatological characteristics of tropical cyclones (TCs) in the Bay of Bengal, focusing on trends in frequency, intensity, and seasonal variability. Research indicates that the Bay of Bengal experiences more severe cyclones during the post-monsoon season (October–November) compared to the pre-monsoon season (April–May) (Kotal, Kundu and Roy Bhowmik, 2009). Historical data analysis shows an increasing trend in the intensity of cyclones, with a growing number of severe cyclonic storms in recent decades, often linked to rising sea surface temperatures and climate change (Balaguru et al., 2014). Climate models and observational studies suggest that anthropogenic emissions and global warming contribute significantly to the intensification of tropical cyclones in this region (Evan et al., 2011). Moreover, there is evidence of a shift in cyclone tracks, influenced by changing atmospheric dynamics, leading to more landfalls in vulnerable coastal areas. The growing frequency of intense cyclones poses substantial risks to the socio-economic stability of densely populated coastal regions (Singh, 2007).

Coastal regions, particularly in countries like Bangladesh and India, are extremely vulnerable to tropical cyclones due to factors such as high population density, low-lying topography, and limited adaptive capacity. In densely populated coastal areas, even relatively moderate cyclones can result in widespread destruction, displacing thousands of people and causing significant economic losses. For instance, the Ganges-Brahmaputra-Meghna delta is home to over 165 million people living in low-elevation areas highly susceptible to storm surges and flooding (Bernard et al., 2022). Historical events such as Cyclone Gorky in 1991, which resulted in approximately 140,000 deaths and displaced millions, highlight the catastrophic human and economic toll of such disasters (Bernard et al., 2022) . These storm surges not only inundate vast areas but also contaminate freshwater supplies, destroy agricultural lands, and disrupt livelihoods, particularly affecting vulnerable and marginalized communities(Dasgupta et al., 2009). In the Bay of Bengal, cyclone-induced storm surges have historically led to catastrophic flooding in countries like Bangladesh and India, where large portions of the population live in low-lying deltaic regions. These surges not only inundate vast areas but also contaminate freshwater sources, damage agricultural land, and disrupt livelihoods for extended periods. The socioeconomic impacts are often severe, with the poorest communities bearing the brunt of the devastation due to inadequate housing and limited access to resources for recovery

Advancements in technology, such as satellite observations and reanalysis datasets, have greatly enhanced the understanding of cyclone behavior. These tools allow scientists to analyze cyclone track patterns, landfall locations, and genesis points with greater precision, providing valuable insights for improving early warning systems. Accurate predictions help authorities plan better evacuation strategies and allocate resources more effectively, ultimately reducing loss of life and property. Although technological advancements such as satellite observations and reanalysis datasets like ERA5 have significantly improved cyclone tracking, genesis identification, and landfall predictions(Botto et al., 2024), the growing frequency and intensity of cyclones—fueled by rising sea surface temperatures—continue to pose significant risks. Strengthening resilience requires not only technological solutions but also inclusive planning, better infrastructure, and proactive community engagement(UNDRR, 2019). However, despite technological progress, the increasing frequency and intensity of cyclones due to climate change present ongoing challenges for disaster risk management. Building resilience in vulnerable coastal regions requires a combination of improved infrastructure, community preparedness, and sustainable development strategies.

Despite extensive research on tropical cyclones (TCs), several critical gaps remain, particularly concerning the Bay of Bengal (BoB). High-resolution cyclone datasets before the year 2000 are limited, making it difficult to detect precise long-term trends. Furthermore, there is a noticeable scarcity of localized case studies that directly link regional climate change impacts to cyclone frequency, intensity, and shifting tracks in the BoB. The phenomenon of rapid intensification (RI), while increasingly observed, remains inadequately documented in this region, primarily due to insufficient real-time observational data. Another significant shortcoming is the lack of interdisciplinary studies that integrate climatological insights with socioeconomic vulnerabilities—vital for comprehensive disaster risk reduction. The reviewed literature reveals contrasting findings: while some studies indicate a rise in cyclone frequency, others highlight a shift toward more intense but not necessarily more frequent storms. These inconsistencies underscore the urgent need for a long-term, high-resolution climatological analysis of BoB cyclones over the 1972–2023 period. This study aims to bridge these gaps by offering a robust, region-specific understanding of cyclone behavior, trends, and potential climate linkages, providing a foundation for improved forecasting, preparedness, and policy response.

3. Objectives

- To analyze the spatial and temporal distribution of tropical cyclones over the Bay of Bengal, identifying seasonal and monthly variation patterns.

- To analyze the seasonal and monthly spatial variation of genesis locations of tropical cyclones in the Bay of Bengal.

- To examine trends in cyclone frequency highlighting any significant changes.

- To assess the intensity of cyclones using metrics such as Maximum Sustained Wind (MSW), Minimum Sea Level Pressure (MSLP).

4. Data Collection

4.1 Sources

The Joint Typhoon Warning Centre (JTWC), USA, has the best track data for the North Indian Ocean. Beginning in 1972, JTWC began using satellites to detect BoB TCs in the North Indian Ocean. In this study, BoB TCs from 1972 to 2023 (52 years) were analyzed using JTWC best track data, which can be found at https://www.metoc.navy.mil/jtwc/jtwc.html?north-indian-ocean. This JTWC dataset is appropriate and reliable for the long-term climatological study of BoB TCs. At 6-hour intervals (0000, 0600, 1200, and 1800UTC), the dataset includes TCs' name, position (latitude and longitude), MSLP, and 1-min MSW speed.

4.2 Study Area

The Bay of Bengal is chosen as the study area due to its high vulnerability to tropical cyclones, which significantly impact millions of lives and economies in surrounding regions (Ali, 1999) . This semi-enclosed ocean basin is known for its warm sea surface temperatures, a crucial factor for cyclone formation (Dube *et al.*, 1997). Additionally, the region experiences two distinct cyclone seasons — pre-monsoon (April–May) and post-monsoon (October–November) — making it ideal for studying seasonal variability and intensity trends (Singh, Khan and Rahman, 2001).

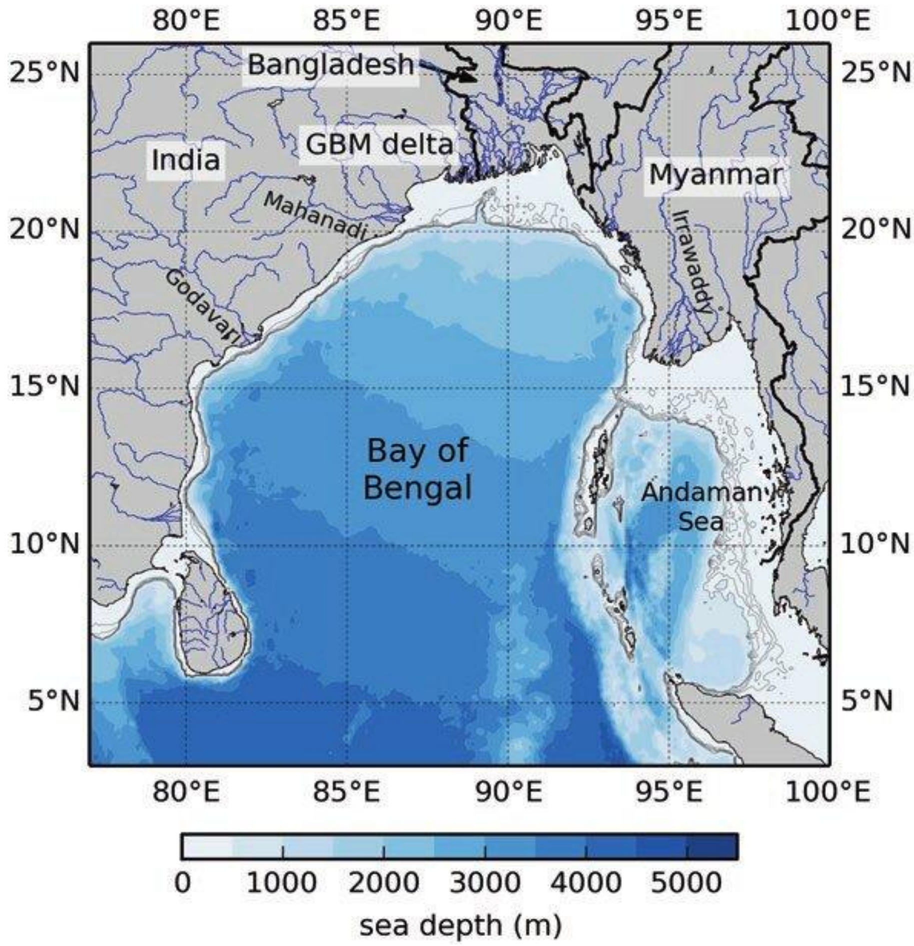


Figure 4.2.1: Map showing the Bay of Bengal with key features, including the Ganges-Brahmaputra-Meghna (GBM) delta, major rivers, and the Andaman Sea. (Kay, Caesar and Janes, 2018))

The Bay of Bengal is surrounded by densely populated and low-lying coastal regions, particularly in Bangladesh, India, and Myanmar, which are frequently affected by cyclone-induced storm surges and flooding(Unnikrishnan, Nidheesh and Lengaigne, 2015). This socio-economic vulnerability makes it essential to understand cyclone behavior, improve prediction accuracy, and enhance disaster preparedness(Mohapatra *et al.*, 2012) . Moreover, the period from 1972 to 2023 provides a comprehensive timescale to analyze the long-term trends and the potential impact of climate change on tropical cyclone characteristics (Knutson *et al.*, 2020).

5. Methodology

The data that has been utilized for this analysis has been taken from the Joint Typhoon Warning Center (JTWC), which provides complete information about tropical cyclones, including their maximum wind speed, location, and various other parameters. The data was then combined with the assistance of Python and saved in CSV format to easily analyze and manipulate the data. To ensure that the data dealt with the relevant cyclonic activity, filtering was carried out in order to only include Cyclonic Storm (CS) data. This process was important to condense the dataset so that only the cyclones which had actually taken place within the most productive intervals of time remained, and it helped in making the analysis more specific and applicable.

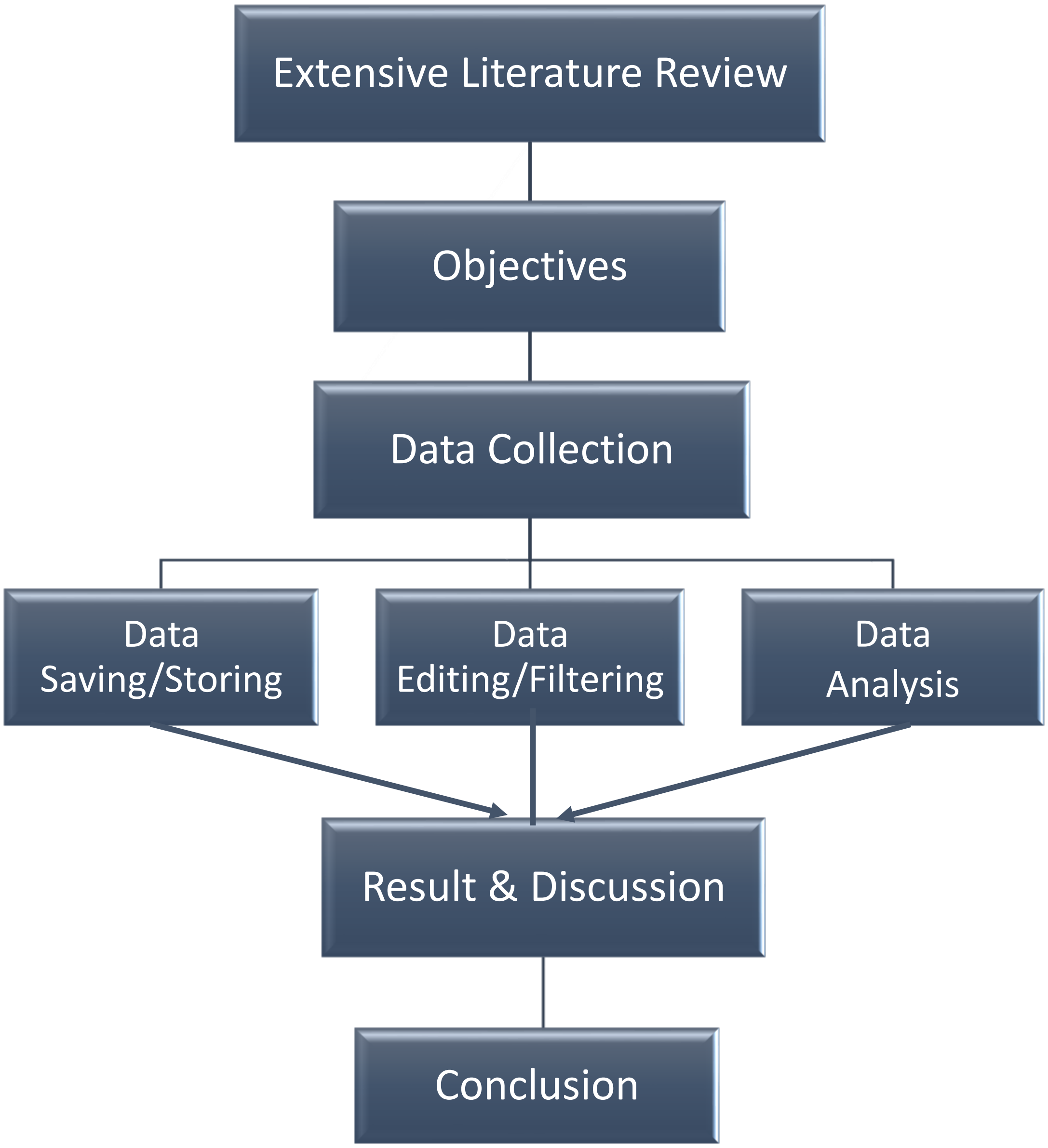
Further refinement was obtained by monthly filtering of the data using Python scripts, which allowed the analysis to focus on specific time frames. This was carried out to ensure that only monthly data points for each cyclone event were accessed, thereby eliminating unwanted information and making the dataset easier to analyze in depth.To choose data for this study, only tropical cyclone data with a maximum sustained wind speed of more than 34 knots were utilized from the cyclone datasets (CS). This cut-off value is the minimum wind speed that qualifies a system to be called a tropical storm such that only significant cyclonic occurrences with highly developed shapes and considerable intensities were applied for the analysis. Data in increasing order of tropical cyclones over the Bay of Bengal, between latitudes 22.2°N to 3.7°N, and longitudes 96.6°E to 75.5°E.

Visualization of the cyclone data was also included in the methodology. Python tools were used to create images showing cyclone tracks, intensity, and distribution patterns. These images helped in representing the trends and providing a clear visual picture of cyclone activity over the research period. The data was seasonally filtered to research cyclone activity with regard to different monsoon or post-monsoon seasons. This seasonal screening provided information about the variability of cyclone frequency and intensity within different periods of the year, which is important in understanding the seasonal nature of cyclone trends within the Bay of Bengal. Further image processing was carried out to represent the seasonality in the occurrence of cyclones with emphasis on intensity and frequency variation between different seasons. These images assisted in defining significant cyclone activity patterns that were associated with specific seasons.

Finally, cleaning and editing of data was carried out in Excel in various stages of the analysis. Excel was used to check data manually and repair any mistakes for reasons of accuracy and consistency. It was a critical stage in cleansing the dataset, particularly in cases of inconsistency or missing data, and facilitated proper checking prior to proceeding to additional statistical and visual analysis.

6. Frame Work

This section outlines the complete structure of the study, detailing each step followed from the literature review, methodology, and data analysis, to the discussion and final conclusion.



7. Data Analysis

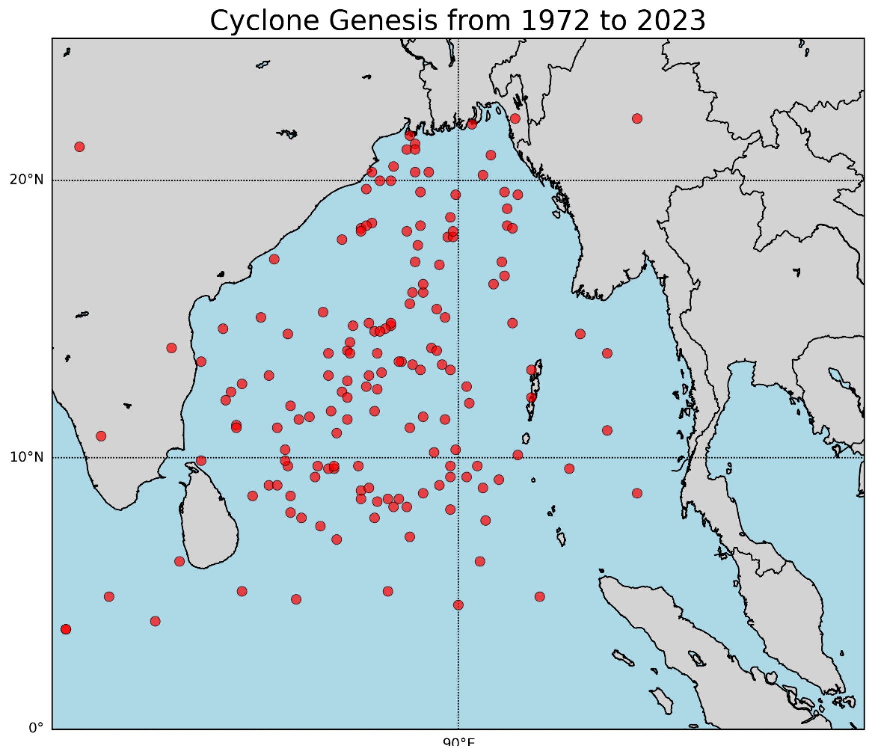


Figure 7.1: Distribution of genesis locations (dots) of TCs formed in the BoB during the period 1972–2023

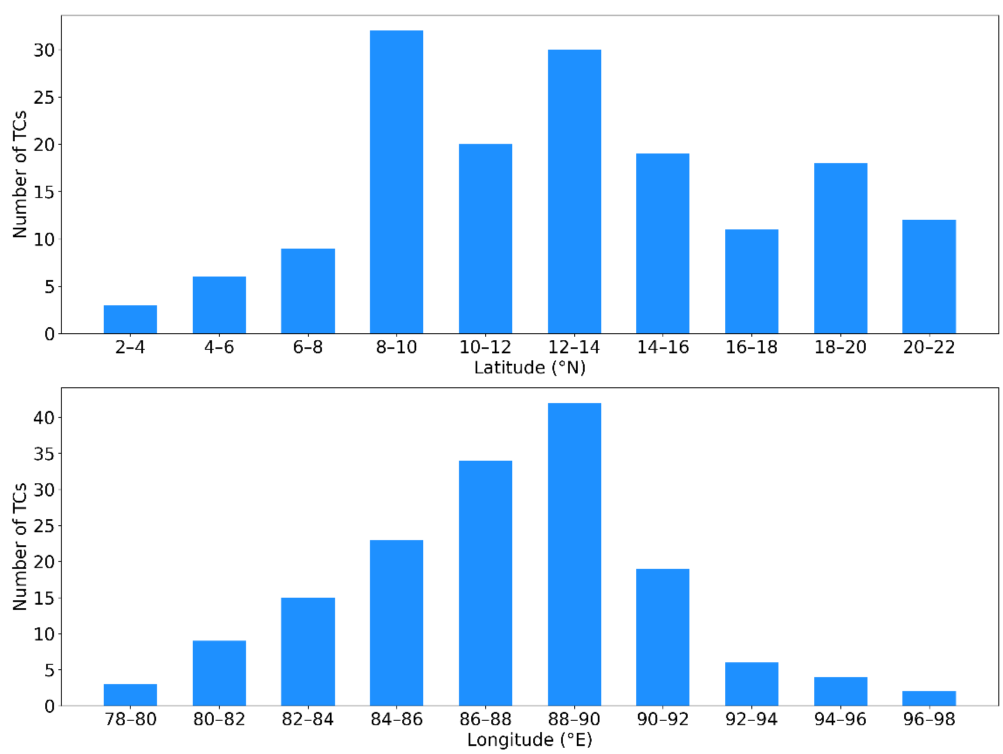


Figure 7.2: (a) Latitudinal and (b) longitudinal distribution of TCs genesis frequency in the BoB during the period 1972–2023

Figure 7.1 exhibits the annual distribution of genesis locations of TCs formed in the BoB during the 1972-2023 (52-year) period. The TCs formed in all the parts of the BoB and made landfall over the coasts of India, Bangladesh, Myanmar, and Sri Lanka. TCs genesis points are between latitude 3.7^{0}N to 22.2^{0}N and longitude 75.5^{0}E to 96.6^{0}E. Average genesis latitude and longitude is 13.11^{0}N and 87.167^{0}E.

In Figure 7.2 we see that a few TCs formed in the lower latitudes. Higher the latitude higher the formation of TC occurred. 32 TCs formed in between 8-10^{0}N, 30 TCs formed in between 12-14^{0}N. Then again after 14^{0}N latitude increasing the latitude TCs formation is less than 8-14^{0}N. Almost same cases occurring in case of longitude. Very few TCs formed in the 78-82^{0}E. Then again increasing the longitude higher number of TCs formed. In 88-90^{0}E longitude TC fomes 42. In between 96-88^{0}E TC formed 34. Then again TCs formation decreases after 92^{0}N. In those two figures we saw that in the BoB basin, 1st increasing latitude & longitude increased the trend of forming more TC, but further increasing the latitude and longitude the formation TC is decreasing. 8-14^{0}N latitude and 86-90^{0}E longitude are most suitable for TC formation.

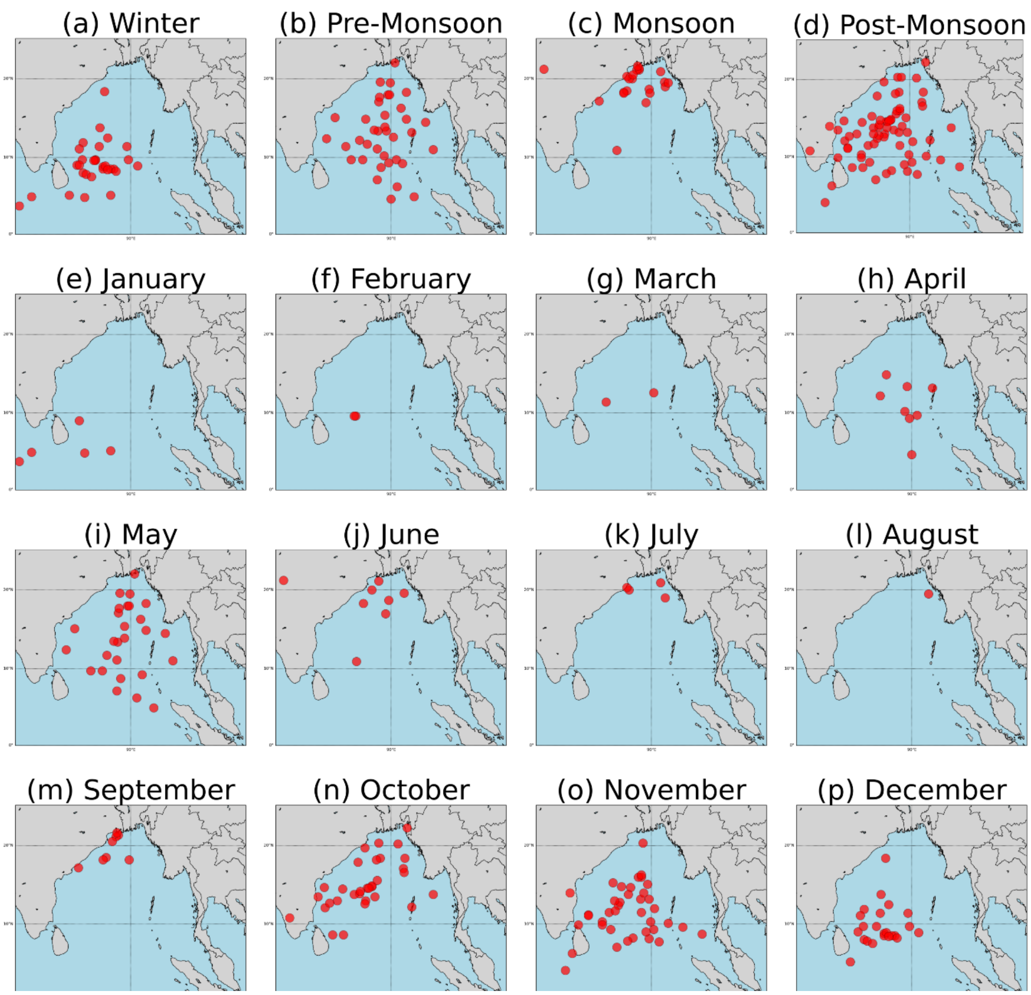


Figure 7.3: a-d Seasonal and e-p monthly distribution of genesis locations (dots) of TCs formed in the BoB during the period 1972-2023

Table 7.1: Monthly mean genesis location of TCs in the BoB during the period 1972–2023

Month	Latitude (°)	Longitude (°)
January	5.5	81.46
February	9.6	85.3
March	12	87.2
April	10.9375	89.275
May	13.66296	89.17778
June	18.35	86.8125
July	20.05	89.225
August	19.5	92.2
September	19.575	87.3125
October	14.96875	86.69063
November	11.52051	86.91026
December	9.813043	86.06522

Figure 7.3 a–d shows the seasonal distribution of genesis locations of TCs in the BoB. During the winter season, the frequency of TCs was very less and formed in southern parts of the BoB and followed the westward (Fig. 7.3 a). In the pre-monsoon season, the frequency of TCs increases rapidly with a shift in their genesis locations towards north (Fig. 7.3 b). Most of the TCs of this season had followed the northward and may made their landfall over Bangladesh and Myanmar coast. The genesis locations continuously shifted towards north and majority of TCs were formed in the monsoon trough region near the head of the BoB during the monsoon season; however, the TC genesis significantly reduced in monsoon session (Fig. 7.3 c). During the post-monsoon season, frequency of TCs had increased significantly and was formed in all parts of the BoB (Fig. 7.3 d). Majority of the TCs were formed in this season.

Figure 7.3 e–p shows the monthly distribution of TCs genesis locations and tracks in the BoB. A large variation in the TCs genesis locations was witnessed in different months. The mean genesis location of BoB TCs almost followed the northward and southward shifting of Sun (Table 7.1). The mean genesis location of TCs shifted northward from the month of January to July and then moved southwards continuously, although no TCs were formed during the months of February and August in the BoB during a 52-year study period. In these 7.3 e-p images we see that maximum number TCs were formed in the month of November, October, May then December. Very less amount of TCs formed in the month of February, August, March and July. Moderate in June and September. In the Table 7.1 we also see the mean genesis latitude and longitude locations were mentioned. Over the past 52 years, the mean genesis points of tropical cyclones in the Bay of Bengal show a clear seasonal migration. From January to July, cyclones tend to form progressively farther north, peaking around July. After that, the genesis locations gradually shift southward toward the end of the year, reflecting the seasonal movement of the sun and monsoon dynamics.

Table 7.2 : Total frequency and mean of TCs in the BoB during the period 1972–2023 in various seasons.

Season	Total TC	Mean TC
Winter	35	0.673077
Pre-Monsoon	38	0.716981
Monsoon	23	0.442308
Post-Monsoon	77	1.45283
Total	173	3.285

From table 7.2 Total TCs occurred during 52 years (1972-2023) period is 173. Mean of TCs during 52-year period highest in post-monsoon season, least has monsoon season. During 52-year period annual mean of TC is 3.285. Most number of TC occurred during the post-monsoon season and it is 77. Least number of TC occurred during monsoon season. In pre-monsoon and winter season TC occurred 38 and 35.

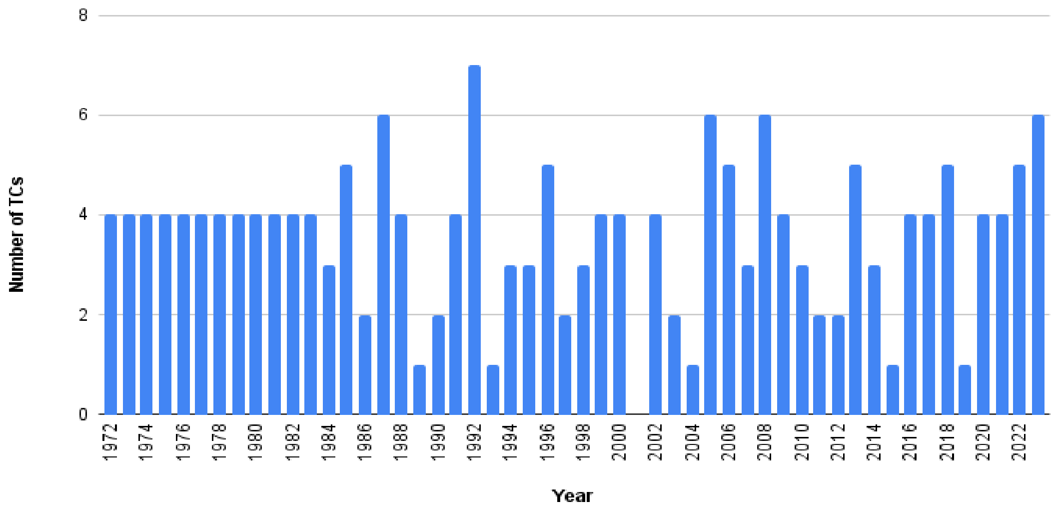


Figure 7.4: Annual distribution of number of TCs during 1972-2023 in the BoB.

The frequency of tropical cyclone in the fig. 7.4, which ranges from 0 to 7 over the years indicating non-uniform activity and influence of external environmental factors. Year 1992 had highest number of cyclones in the Bay of Bengal with seven cyclones recorded. Six cyclones were recorded in year 1987, 2005, 2009 and 2023. These periods elevated cyclones may indicate favorable environmental conditions such as sea surface temperature or atmospheric dynamics conductive to cyclone formation and intensification. In the year 2001, zero cyclone occurred in BoB suggesting unfavorable condition in BoB in that particular year. Although no clear linear trend is evident from the dataset, the data reveals periodic clustering of years with intensified tropical cyclone activity in the BoB. These clustering pattern may be related to big climatic phenomena like El-nino or other long-term cycles. This shows how the genesis of TCs can be affected by how the atmosphere and ocean change over the large areas.

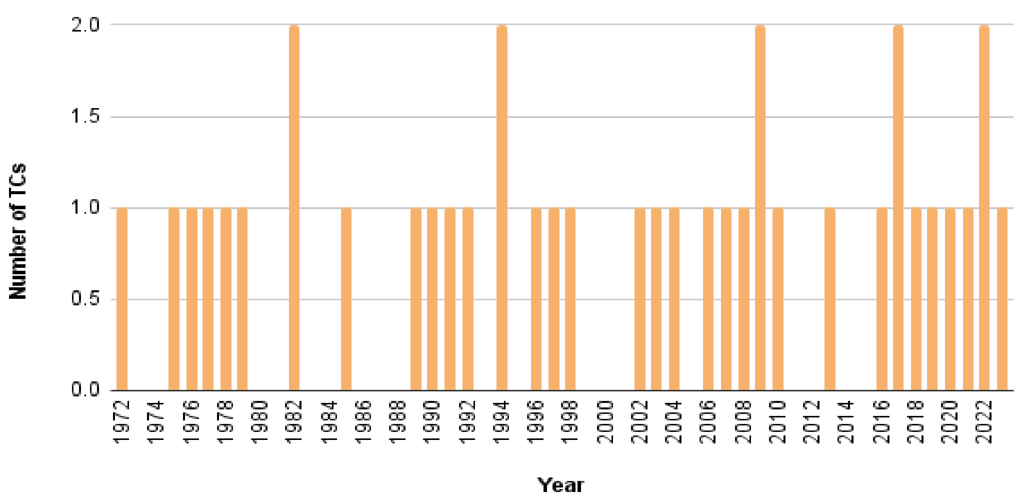


Figure 7.5: Annual distribution of number of TCs in the pre-monsoon season during 1972-2023 in the BoB.

The annual distribution of tropical cyclone occurring during pre-monsoon and post-monsoon period from 1972-2023 is illustrated in the fig. 7.5 were also analyzed for understanding the pattern of formation of TCs during the most favorable season in the Bay of Bengal. The number of pre-monsoons TCs fluctuates between 0 to 2 per year. The prevalence of one TC suggests a baseline level of cyclone activity during pre-monsoon season. Years such as 1982, 1994, 2009, 2017 and 2022, which recorded two cyclones, represent the period of heightened cyclone activity suggesting favorable conditions in those years. Years with no cyclone activity during pre-monsoon are equally important. This suggests that even though pre-monsoon season is favorable for cyclone formation, it is possible that no cyclone forms in pre-monsoon season for 2-3 consecutive years such as 1986 to 1988 as well as 1999 to 2001 had no cyclone during this season. This can occur due to long term climatic condition that are very unfavorable for cyclone formation.

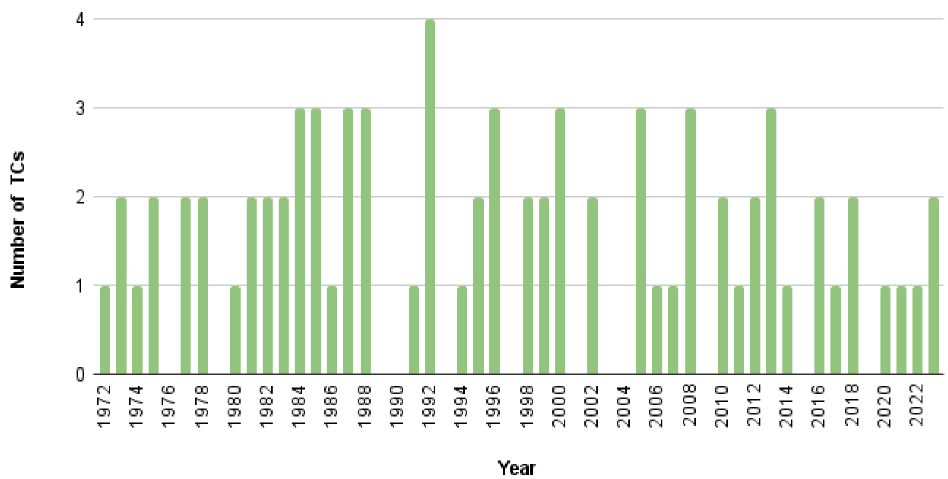


Figure 7.6: Annual distribution of number of TCs in the pre-monsoon season during 1972-2023 in the BoB

The annual distribution of tropical cyclone in the fig. 7.6 during post-monsoon season reveals that the number of TCs during this season ranges from 0 to 4 with Year 1992 recording highest number of TCs. Most years recorded two to three cyclones, indicating this as the typical range of cyclonic activity during this season indicating that conditions conducive to cyclogenesis are frequently present in this season. Several years recorded no TCs during post-monsoon which suggests that even most favorable season for TCs formation can become unfavorable for cyclogenesis. Unlike Pre-monsoon season, post-monsoon TC frequency is more consistent over time. This consistency aligns with the climatological understanding that post-monsoon is the prime period for TC formation due to favorable atmospheric and oceanic conditions.

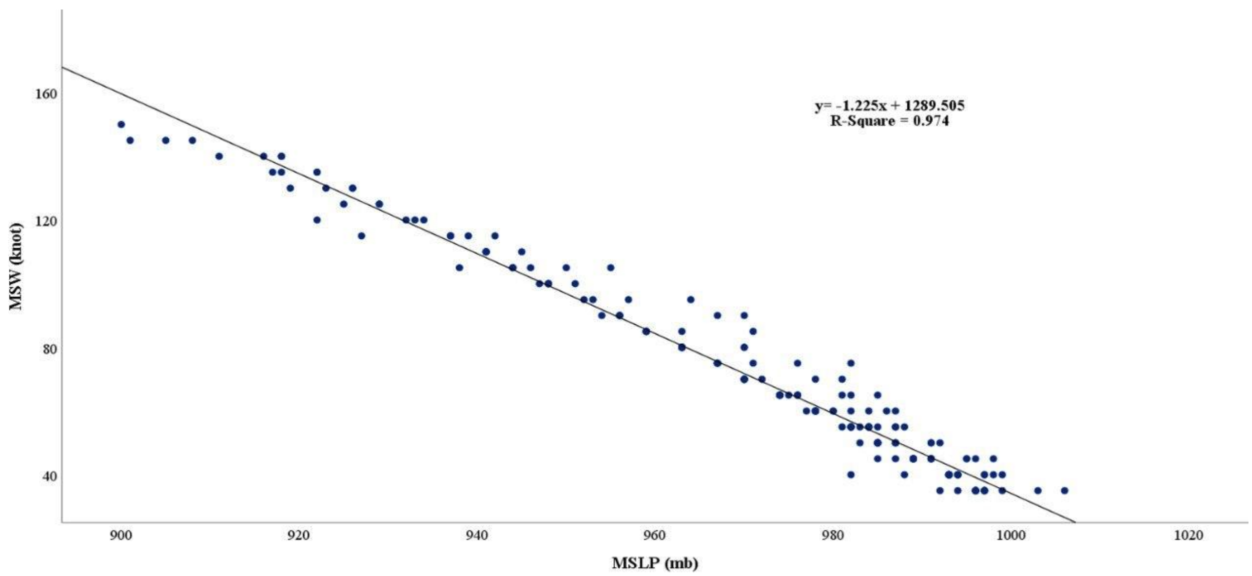


Figure 7.7: Relationship between MSLP and MSW in tropical cyclones based on observational data from the BoB.

The scatter plot in fig. 7.7 illustrates the relationship between Minimum Sea Level Pressure (MSLP) and Maximum Sustained Wind (MSW) for tropical cyclones, revealing a strong inverse linear correlation between the two variables. The regression equation derived from the data is $y=-1.225x+1289.505$, with an exceptionally high coefficient of determination (R^2) of 0.974. This indicates that approximately 97.4% of the variation in wind speed can be explained by changes in sea level pressure. As the MSLP decreases, the MSW increases significantly, suggesting that lower central pressures within a cyclone are associated with more intense wind speeds. This finding is consistent with the physical principles of tropical cyclone dynamics, where stronger pressure gradients lead to more powerful winds.

8. Conclusion

This study aims to develop a comprehensive climatology of BoB TCs using the Joint Typhoon Warning Center (JTWC) dataset spanning 52 years (1972–2023). By analyzing cyclone frequency, seasonal and monthly genesis patterns, seasonal variability of TCs and relation between MSLP and MSW, this research provides valuable insights into the behavior of TCs in the BoB and their relationship with large-scale atmospheric and oceanic conditions. A total of 173 TCs with an average of 3.285 TCs per year were formed in the BoB without any significant increasing or decreasing trend. The TCs were formed in all parts of the BoB and made their landfall over the coasts of India, Bangladesh, Myanmar, and Sri Lanka. Cyclogenesis predominantly occurred between latitude 80N -140N and longitude 860E -900E with average genesis points at 13.110N, 87.1670E. A wide variation in the genesis locations was observed during two peak TC seasons (pre- and post-monsoon seasons). Over the last 52 years, average genesis points of tropical cyclones in the Bay of Bengal have followed a distinct seasonal pattern. Cyclones typically originate farther north between January and July, peaking around July. Following that, the genesis locations gradually shift southward toward the end of the year, corresponding to the sun's seasonal migration and monsoon dynamics. The post-monsoon season (October- November) recorded highest TC frequency (77 TCs) followed by the pre-monsoon season (March – May, 38 TCs) while monsoon season (June- September) showed least cyclone activity (23 TCs). This analysis gives the clear conclusion that monsoon is the most unfavorable season for TC formation is BoB. Annual TC frequency illustrated significant variation with peak activity in 1992 (7 TCs) and 2001 having the least cyclone activity (0 TCs). Pre-monsoon cyclones' irregular nature suggests they are more vulnerable to year-to-year fluctuations in large-scale climate patterns. Unlike the pre-monsoon season, post-monsoon TC frequency remains steady throughout time. This consistency corresponds with the climatological knowledge that post-monsoon is the optimal time for TC formation because to suitable atmospheric and oceanic conditions. The relation between Minimum Sea Level Pressure (MSLP) and Maximum Sustained Wind (MSW) in tropical cyclones reveals a substantial inverse correlation between the two variables. The fluctuations in sea level pressure account for approximately 97.4% of the variation in wind speed. As the MSLP lowers, the MSW increases dramatically, implying that lower central pressures within a cyclone correspond with greater intense winds. Understanding these trends is critical not only for academic purposes, but also for developing adaptive measures to address climate-related challenges.

9. Limitation & Recommendations

This study faced several challenges that influenced the depth and accuracy of the analysis. One major issue was the lack of clearly defined genesis points for many cyclones in the data. Although we had access to a significant number of cyclone records, the starting locations were not always available or accurate, which reduced the number of usable genesis points. This gap limited our ability to fully trace the development of each cyclone. In some cases, genesis points appeared to be located over land, which is not typical for tropical cyclones that usually form over warm ocean waters. This raised questions about the precision of the data quality, particularly in earlier years when observation techniques were not as advanced. The reliability of these older records was further challenged by the fact that, before 2005, many entries lacked key information such as the specific basin in which the cyclone formed.

The quality and consistency of the data also varied significantly over time. While recent records are completer and more standardized, earlier data entries were often inconsistent, incomplete, or presented in different formats. This inconsistency made it difficult to conduct a uniform analysis and required significant effort to clean and verify the data. Additionally, sorting the data was time-consuming and complex. Many records needed manual adjustments due to formatting issues or naming variations. This process introduced an extra layer of difficulty and left some room for human error. Despite these limitations, the study still provides meaningful insights into cyclone behavior in the Bay of Bengal and highlights the importance of improving data collection practices for future research.

Due to time constraints, several important aspects of tropical cyclone analysis could not be addressed in this study. The cyclone tracks were not extracted, which limited the ability to assess spatial movement patterns and landfall behaviors. As a result, it was not possible to calculate the travel distance of cyclones or analyze their directional shifts across the Bay of Bengal. Additionally, intensity-wise and category-wise variations were not explored in detail. This restricted the understanding of how cyclone strength has changed over time or varied between seasons. The duration of individual cyclones was also not examined, which is an important factor in evaluating their potential impact.

This study focused primarily on monthly genesis points, without incorporating cyclone frequency distribution across different time scales or intensity classes. Furthermore, advanced indicators such as Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI), which are essential for assessing the total energy and destructive potential of cyclones, could not be computed within the current scope.

The accuracy of such analyses heavily depends on the quality and consistency of cyclone datasets. Inconsistencies or gaps in data, especially in earlier years, make it difficult to extract detailed information necessary for these advanced evaluations. Future research should aim to dedicate more attention to these aspects by utilizing high-resolution datasets such as ERA5 and IBTrACS, which are capable of capturing more detailed characteristics, including weaker or short-lived storms that may be missed in conventional records. Including these dimensions would provide a more holistic view of tropical cyclone behavior, especially in the context of evolving climate patterns.

Additionally, the inconsistencies observed between major datasets underline the importance of improving data standardization and calibration across regions. Variations in how storms are recorded and classified can lead to challenges in comparing results and identifying long-term trends. Establishing uniform criteria for storm intensity, lifecycle tracking, and naming conventions would greatly benefit both scientific research and operational forecasting. Moreover, given that different ocean basins exhibit unique storm behaviors due to local environmental conditions, region-specific studies are highly recommended. These focused analyses would support the development of tailored early warning systems, strengthen seasonal outlooks, and guide infrastructure planning in cyclone-prone areas. As the global climate continues to shift, investing in deeper, more consistent research on tropical cyclones will play a vital role in enhancing resilience and reducing vulnerability in high-risk communities.

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Appendices

For Data Merge (Each Year)

```
import pandas as pd
import glob

# Get all .txt files in the folder
txt_files = glob.glob("*.txt")  # Change from "*.dat" to "*.txt"

# Debug: Print the list of found files
print("Found files:", txt_files)

# Read and combine all text files
#df_list = [pd.read_csv(file) for file in txt_files]
#df_list = [pd.read_csv(file, delim_whitespace=True, error_bad_lines=False,
warn_bad_lines=True) for file in txt_files]
df_list = [pd.read_csv(file, delim_whitespace=True, names=["BASIN",
"ANNUAL_CYCLONE_NUMBER", "DATE_TIME", "TECH_NUM", "BEST_TRACK" ,
"FOrecast_Period", "Lat", "Lon", "Vmax", "MSLP", "Co11"], on_bad_lines="skip") for file in
txt_files]

# Check if there are valid files to concatenate
if df_list:
   merged_df = pd.concat(df_list, ignore_index=True)
   merged_df.to_csv("year.csv", index=False)
   print("Merged CSV created successfully!")
else:
   print("No valid files to merge.")
```

For Data Merge (All Year)

```
import pandas as pd
import glob

# Get all CSV files in the folder
csv_files = glob.glob("*.csv")
```

```
# Print the list of found files
print("Found files:", csv_files)

# Define the first 11 common column names
common_columns = [
    "BASIN", "ANNUAL_CYCLONE_NUMBER", "DATE_TIME", "TECH_NUM", "BEST_TRACK",
    "Forecast_Period", "Lat", "Lon", "Vmax", "MSLP", "Co11"
]  # Ensure these match your actual CSV structure

# Read and process each CSV file
df_list = []
for file in csv_files:
    df = pd.read_csv(file, low_memory=False)  # Read each CSV file

    # Ensure all common columns exist (fill missing ones with NaN)
    for col in common_columns:
        if col not in df.columns:
            df[col] = None  # Fill missing common columns with NaN

    # Add a "Year" column from the filename (assuming filename is like 2023.csv)
    df["Year"] = file.split(".")[0]

    # Append DataFrame to the list
    df_list.append(df)

# Merge all CSV files, keeping all columns
if df_list:
    merged_df = pd.concat(df_list, ignore_index=True, sort=False)

    # Save merged data to a new CSV
    merged_df.to_csv("merged_data.csv", index=False)

    print("Merged CSV file created successfully: merged_data.csv")
else:
    print("No valid files to merge.")
```

Sorting data monthly

```
import pandas as pd

# Load the merged CSV file
df = pd.read_csv('filename.csv')

# Extract year and month from 'date_time' column
df['year'] = df['DATE_TIME'].astype(str).str.slice(0, 4).astype(int)
df['month'] = df['DATE_TIME'].astype(str).str.slice(4, 6).astype(int)

# Loop through each month and save separate CSV files
for month in range(1, 13):
    month_data = df[df['month'] == month]
    month_data.to_csv(f'data_{month:02d}.csv', index=False)
```

Draw genesis map

```
from mpl_toolkits.basemap import Basemap
import matplotlib.pyplot as plt
import numpy as np
import pandas as pd

# Load cyclone genesis data
df = pd.read_csv(r'forgenesis.csv')
latlon = df[['Lat', 'Lon']]

# Create figure
fig = plt.figure(figsize=(12, 9))

# Initialize Basemap with higher resolution
m = Basemap(projection='mill',
            llcrnrlat=0,
            urcrnrlat=25,
            llcrnrlon=75,
            urcrnrlon=105,
            resolution='i')  # Use 'i' (intermediate) or 'h' (high) for better borders
```

```
# Draw map details
m.drawcoastlines()
m.drawcountries(linewidth=1)  # Increase linewidth for clearer borders
m.drawstates(linewidth=0.5)  # Optional: Draw state/province borders for more detail
m.drawmapboundary(fill_color="lightblue")  # Optional: Add background color
m.fillcontinents(color="lightgray", lake_color="lightblue")  # Fill continents

# Draw lat/lon grid
m.drawparallels(np.arange(-90, 90, 10), labels=[True, False, False, False])
m.drawmeridians(np.arange(-180, 180, 30), labels=[0, 0, 0, 1])

# Plot cyclone genesis points
sites_lat_y = latlon['Lat'].tolist()
sites_lon_x = latlon['Lon'].tolist()

m.scatter(sites_lon_x, sites_lat_y, latlon=True, s=50, marker='o', color='red', alpha=0.7,
edgecolor='k', linewidth=0.5, zorder=2)

# Title
plt.title('Cyclone Genesis from 1972 to 2023', fontsize=20)


plt.savefig("cyclone_genesis_map.png", dpi=300, bbox_inches="tight")

# Show the map
plt.show()
```

Merging all the genesis map together

```
import matplotlib.pyplot as plt
from PIL import Image

# Generate filenames from 1.png to 16.png
image_files = [f"{i}.png" for i in range(1, 17)]  # No folder path needed

# Load images using PIL
images = [Image.open(img) for img in image_files]
```

```
# Create a figure with 4 rows × 4 columns
fig, axes = plt.subplots(nrows=4, ncols=4, figsize=(12, 12))

# Add images to the grid
for ax, img in zip(axes.flat, images):
    ax.imshow(img)
    ax.axis("off")  # Hide axes for a clean look

# Adjust layout: Reduce row spacing while keeping columns normal
plt.subplots_adjust(wspace=0.05, hspace=0)  # Reduce vertical spacing (hspace)

# Save the combined image with tight cropping
plt.savefig("combined_images.png", dpi=300, bbox_inches="tight", pad_inches=0)

# Show the final image
plt.show()
```

Code for latitudinal and longitudinal distribution of TC

```
import pandas as pd
import matplotlib.pyplot as plt

# Step 1: Load cyclone data
df = pd.read_csv("forgenesis.csv")

# Step 2: Define bin ranges
lat_bins = list(range(2, 24, 2))     # 2-4, 4-6, ..., 22-24
lon_bins = list(range(78, 100, 2))   # 78-80, 80-82, ..., 98-100

# Step 3: Bin the data
df['Lat_bin'] = pd.cut(df['Lat'], bins=lat_bins)
df['Lon_bin'] = pd.cut(df['Lon'], bins=lon_bins)

# Step 4: Count TCs
lat_counts = df['Lat_bin'].value_counts().sort_index()
lon_counts = df['Lon_bin'].value_counts().sort_index()
```

```
# Step 5: Convert Interval objects to string labels without brackets
lat_labels = [f"{int(interval.left)}–{int(interval.right)}" for interval in lat_counts.index]
lon_labels = [f"{int(interval.left)}–{int(interval.right)}" for interval in lon_counts.index]

# Step 6: Combined Plotting (Latitude + Longitude)
fig, (ax1, ax2) = plt.subplots(2, 1, figsize=(16, 12))  # Bigger figure

# Latitude bar chart
ax1.bar(lat_labels, lat_counts.values, color='dodgerblue', width=0.6)
ax1.set_xlabel("Latitude (°N)", fontsize=20)
ax1.set_ylabel("Number of TCs", fontsize=20)
ax1.tick_params(axis='x', labelsize=20)
ax1.tick_params(axis='y', labelsize=20)

# Longitude bar chart
ax2.bar(lon_labels, lon_counts.values, color='dodgerblue', width=0.6)
ax2.set_xlabel("Longitude (°E)", fontsize=20)
ax2.set_ylabel("Number of TCs", fontsize=20)
ax2.tick_params(axis='x', labelsize=20)
ax2.tick_params(axis='y', labelsize=20)

# Save the combined figure
plt.tight_layout()
plt.savefig("TC_by_Lat_Lon.png", dpi=300)
plt.close()

# Step 7: Save to CSV
output_df = pd.DataFrame({
   'Latitude Bin': lat_labels,
   'Number of TCs (Lat)': lat_counts.values,
   'Longitude Bin': lon_labels,
   'Number of TCs (Lon)': lon_counts.values
})
```