Statistical Analysis of Historical Tropical Cyclone Tracks and Their Predictability over the Bay of Bengal

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Abstract:
The Bay of Bengal is one of the most active regions for tropical cyclone formation, causing massive loss of life and property through strong winds, storm surges, and heavy rainfall over densely populated coastal areas of Bangladesh, India, and Myanmar. Understanding the historical behavior of cyclone tracks is essential for improving forecasting and disaster preparedness. This study analyzes the statistical characteristics of historical tropical cyclone tracks over the Bay of Bengal using long-term cyclone best-track datasets from Regional Specialized Meteorological Centre (RSMC), New Delhi. The study evaluates the predictability of cyclone tracks by comparing Bangladesh Meteorological Department (BMD) best-track data with numerical weather prediction (NWP) outputs of Weather Research and Forecasting (WRF) and European Centre for Medium-Range Weather Forecasts (ECMWF). Results indicate that cyclone tracks in the Bay of Bengal exhibit distinct seasonal clustering, with pre-monsoon and post-monsoon peaks and a strong tendency toward northward and northeastward movement prior to landfall. This research contributes to a better understanding of cyclone behavior in the Bay of Bengal and provides insights that can enhance track prediction models and risk mitigation strategies in vulnerable coastal regions.

Keyword: Regional Specialized Meteorological Centre (RSMC), Weather Research and Forecasting (WRF), European Centre for Medium-Range Weather Forecasts (ECMWF), risk mitigation.

1. INTRODUCTION

Tropical cyclones are intense low-pressure systems that develop over warm ocean waters, typically between 5° and 20° latitude. Their formation is associated with the Inter-Tropical Convergence Zone (ITCZ), where trade winds converge.

The Formation Conditions of Tropical Cyclones [1]:

- Sea surface temperature > 26.5°C
- High humidity in the mid-troposphere
- Low vertical wind shear
- Coriolis force sufficient for rotation

Movement of Tropical Cyclones [2]:

- Initially move westward under easterly winds
- Recurve northward or northeastward at higher latitudes due to westerlies

Tropical cyclones are among the most destructive natural hazards, producing strong winds, heavy rainfall, and storm surges [1,3]. The Bay of Bengal is particularly vulnerable due to its warm sea surface temperatures, shallow bathymetry, and densely populated coastal regions [4].

Cyclones in this region have historically caused massive loss of life and economic damage. Understanding the statistical characteristics of cyclone tracks and their predictability is essential for improving early warning systems and disaster risk reduction strategies [5,6].

1.1 Objective of the Present Study: Previous studies have shown that cyclone activity in the Bay of Bengal exhibits strong seasonal variability, with peaks during pre-monsoon (April–May) and post-monsoon (October–November) periods. Recent research also suggests that climate change may be influencing cyclone intensity and behavior.

This study aims to:

- Analyze historical cyclone tracks over the Bay of Bengal
- Examine spatial and temporal distributions
- Identify long-term trends
- Evaluate prediction accuracy of WRF and ECMWF models

2. DATA USED AND METHODOLOGY

2.1 Data Source: Historical cyclone data were obtained from the Regional Specialized Meteorological Centre (RSMC), New Delhi, covering the period 1891–2025. Statistical analyses including monthly distribution, spatial distribution, and trend analysis were performed. Model verification was conducted using WRF and ECMWF datasets [7] with BMD best track data.

2.2 Methodology: The analysis includes:

i. **Monthly Track Analysis (1982–2025)**
Cyclone tracks are plotted for each month to understand variability using python.

ii. **Climatological Statistics (1891–2025)**
   - Frequency of cyclones by region
   - Monthly distribution
   - Yearly trends

iii. **Trend Analysis**
Linear regression is applied to determine long-term changes in cyclone frequency and intensity.

iv. **Model Verification**
   - Comparison of observed and predicted tracks
   - Case studies: Cyclone Mocha (May 2023) and Cyclone Hamoon (October 2023)
   - Models used:
      - WRF model (regional)
      - ECMWF model (global)

The Weather Research and Forecasting (WRF) model version 4.5.2 is used in this study. The WRF model has been developed by the National Center for Atmospheric Research (NCAR) and provides a flexible and portable open-source community model for both atmospheric research and operational forecasting [8]. It is a limited-area, non-hydrostatic primitive equation model with multiple options for various parameterization schemes for different physical processes.

The 0.25°-resolution GFS data covering the entire globe every 6-hr were taken as the initial and lateral boundary condition. 30 sec United States Geological Survey (USGS) data (Interpolated depending on resolution) GTOPO30 were used as Topography and 25 Categories United States Geological Survey (USGS) data were taken as vegetation/landuse (Modis and Hi-Def Lakes) coverage.

The experiment was performed on a single domain of 9 km horizontal resolution. The domain configuration in WRF model for the present study is shown in Fig. 1. The Domain has 215×215 grid points in the west-east and north-south directions, respectively. The domain was configured to have the same vertical structure of 33 unequally spaced sigma (non-dimensional pressure) levels. The selected physical parameterization schemes in this study are Kain-Fritsch (new Eta) scheme for cumulus parameterization [9] and WRF Single-Moment 3-class (WSM3) Scheme for microphysics [10], Yonsei University scheme [11] for planetary boundary layer.

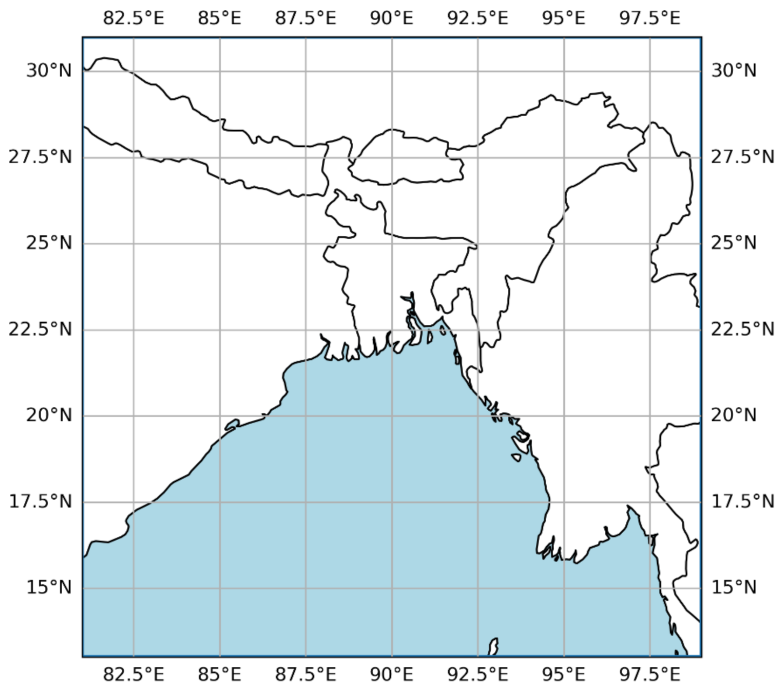


Fig. 1: WRF Model Domain.

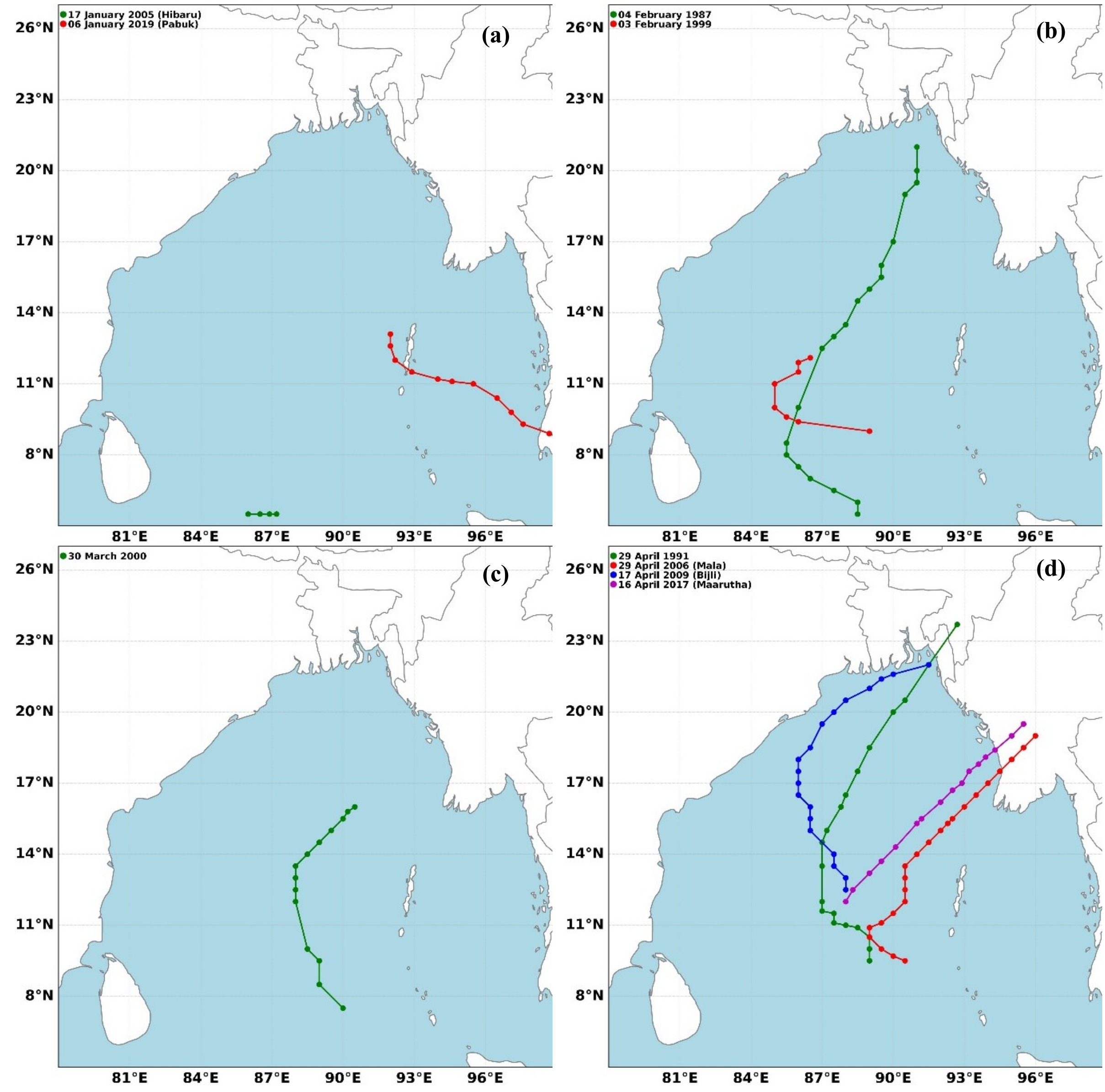
3. RESULTS AND DISCUSSION

3.1 Monthly Distribution of Cyclone Tracks: Analysis of cyclone tracks from 1982–2025 reveals that a smaller number of cyclonic activities are found during January-March (Fig. 2) due to cool sea surface. Whereas a higher number of cyclonic activities are found during April-May (Fig. 2) due to solar heating of sea surface and cyclone mainly move toward Bangladesh and Myanmar.

In monsoon period (June-September), cyclone frequency is reduced (Fig. 3). Because solar heating mainly occurred over land in this period and cyclones are weakened due to strong vertical wind shear. In this period, tropical cyclones mainly move toward Odisha of India.

The highest number of cyclonic activities are found during Post-Monsoon (October–November) season (Fig. 3). This time, cyclones move toward Andhra Pradesh and Tamil Nadu of India but if the cyclones recurve about 17° of latitude, move toward Bangladesh and Myanmar.

In December, number of cyclones are reduced, and cyclones mainly move toward Tamil Nadu of India and Sri Lanka. Because this time, the sun position is near the equator.



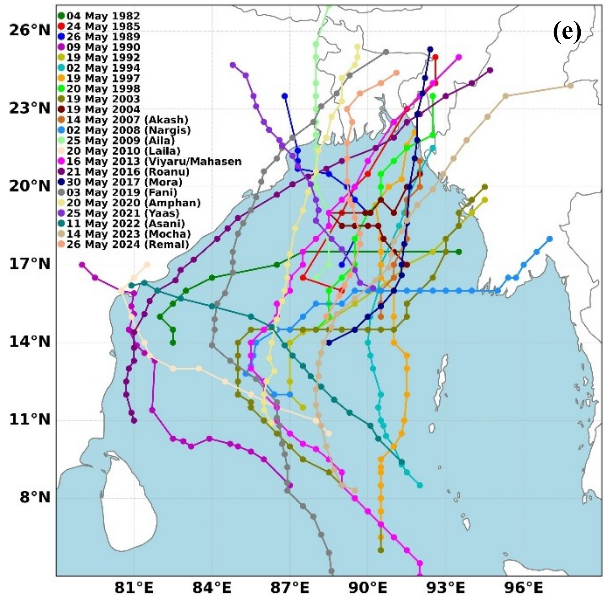
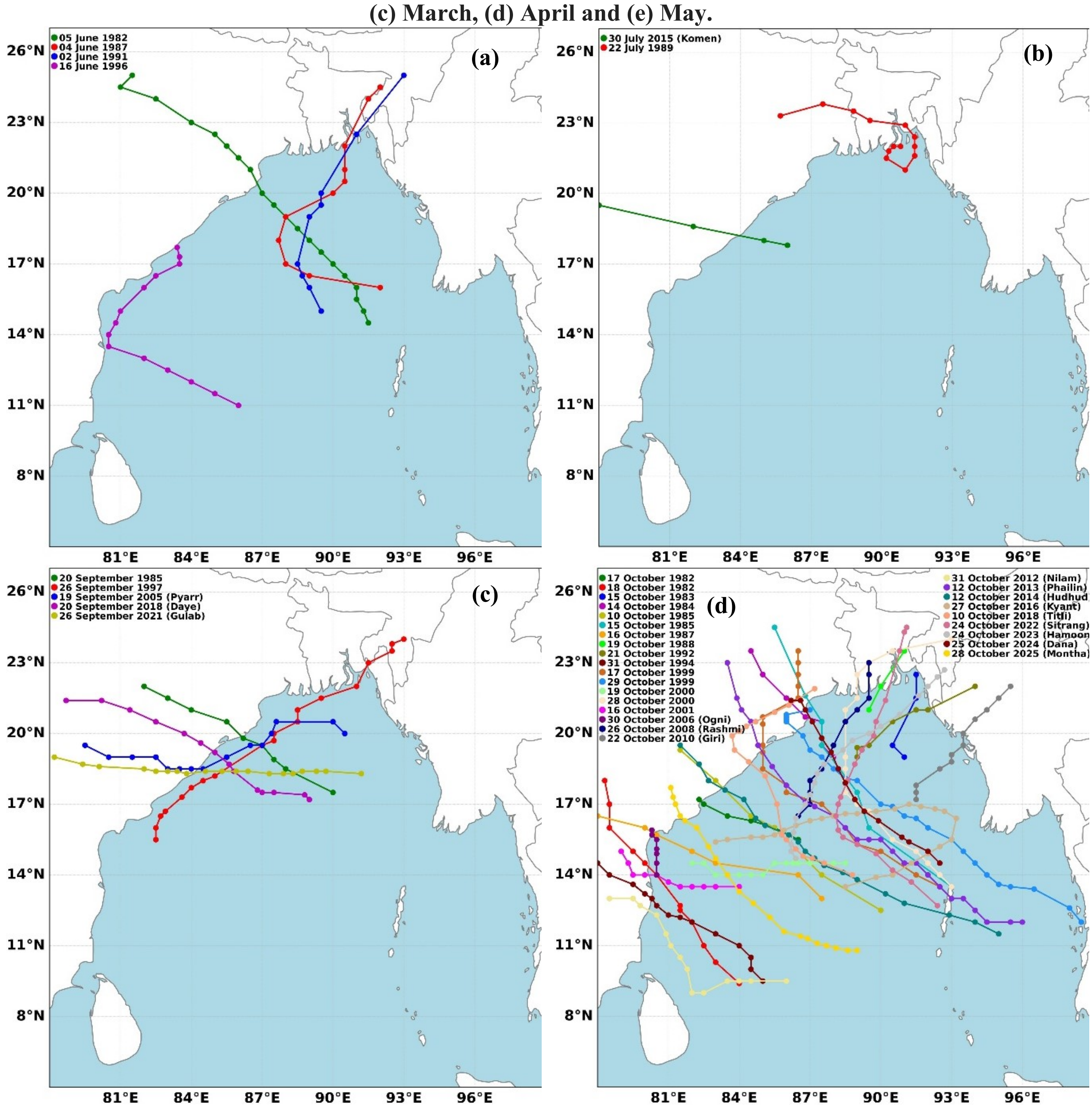


Fig. 2: Observed track of Cyclone over the Bay of Bengal during 1982-2025 for (a) January, (b) February, (c) March, (d) April and (e) May.



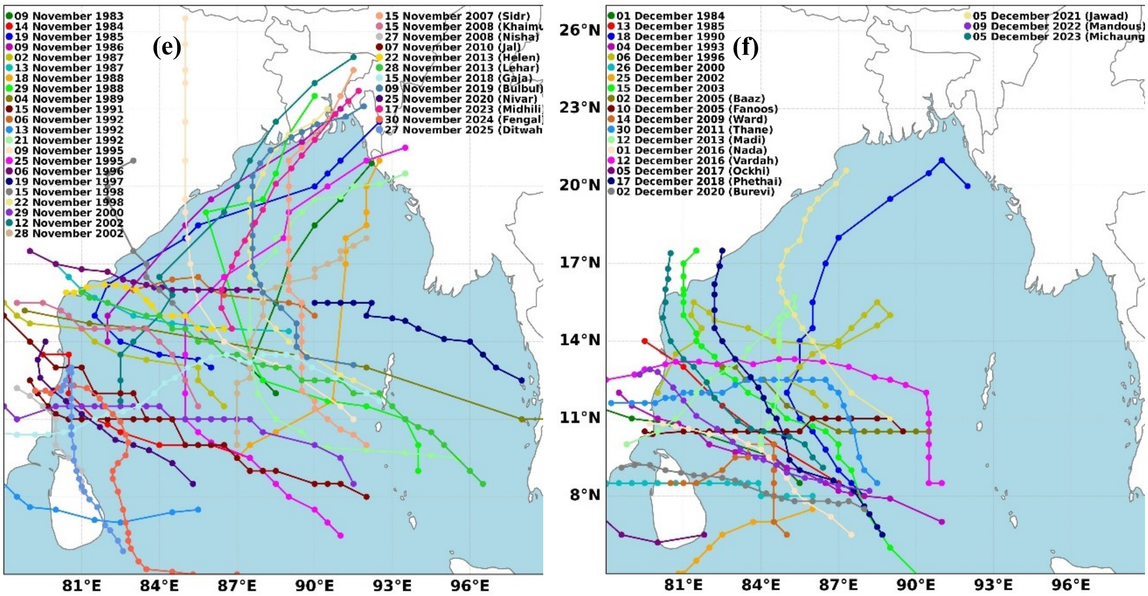


Fig. 3: Observed track of Cyclone over the Bay of Bengal during 1982-2025 for (a) June, (b) July, (c) September, (d) October, (e) November and (f) December.

3.2 Long-Term Trends Analysis: Yearly Cyclone Frequency is a decreasing trend for cyclones and all types of cyclones but it is an increasing trend for severe cyclones during 1891-2025 over the Bay of Bengal (Fig. 4) due to the following Possible Causes:

- Ocean warming
- Climate variability
- Changes in atmospheric circulation

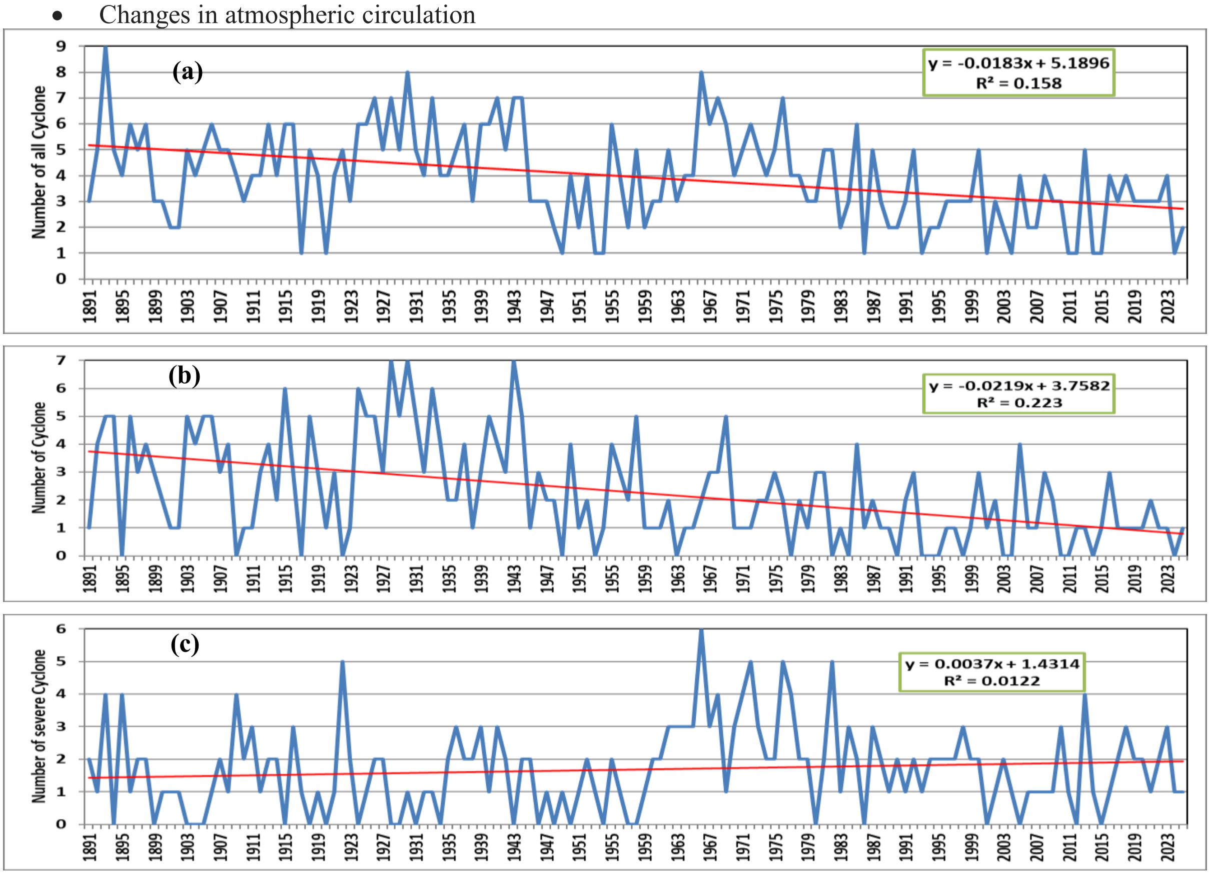


Fig. 4: Yearly distribution of cyclones over the Bay of Bengal and trend during 1891-2025 for (a) all types of cyclones, (b) cyclones and (c) severe cyclones.

3.3 Cyclone Track Prediction: I have selected two case study from all cyclones over the Bay of Bengal. One is cyclone Mocha which hit Bangladesh - Myanmar coast near Sittwe, Myanmar as a Very Severe Cyclonic Storm (i., e. strong cyclone) at the evening of 14 May 2023 and another is cyclone Hamoon which is hit Cox's Bazar-

Chattogram Coast Near Kutubdia, Bangladesh as a Cyclonic Storm (i., e. week cyclone) at midnight of 24 October 2023. WRF (regional) and ECMWF (global) models are used for track prediction and validation is conducted with BMD best track data.

3.3.1 Case Study-1: Cyclone Mocha: WRF and ECMWF model output is collected for initial condition based on 00 UTC of 11, 12, 13 and 14 May 2023. Both models captured well with the observed track with small positional errors (Fig. 5). The average positional errors are found 152.9 km, 165.6 km, 30.8 km and 35.1 km for WRF based on 00 UTC of 11, 12, 13 and 14 May 2023 respectively and 86.5 km, 77.4 km, 40.2 km and 23.7 km for ECMWF based on 00 UTC of 11, 12, 13 and 14 May 2023 respectively. From the positional error, it is clear that error is decreased when lead time is decreased. This error comes from initial condition uncertainty, model resolution limitations and atmospheric dynamics complexity.

3.3.2 Case Study-2: Cyclone Hamoon: WRF and ECMWF model output is collected for initial condition based on 00 UTC of 22 and 23 October 2023. Both models captured with the observed track but big positional errors is found due to landfall time error (Fig. 5). The average positional errors are found 327.9 km and 145.9 km for WRF based on 00 UTC of 22 and 23 October 2023 respectively and 130.9 km and 79.9 km for ECMWF based on 00 UTC of 22 and 23 October 2023 respectively but if it is considered model landfall position and observed landfall position, positional errors is found 56.6 km and 24.8 km for WRF based on 00 UTC of 22 and 23 October 2023 respectively and 70.2 km and 24.8 km for ECMWF based on 00 UTC of 22 and 23 October 2023 respectively. So, positional errors are reduced. Because week cyclones move faster than strong during landfall and model cannot predict well these types of week cyclones with time and position basis.

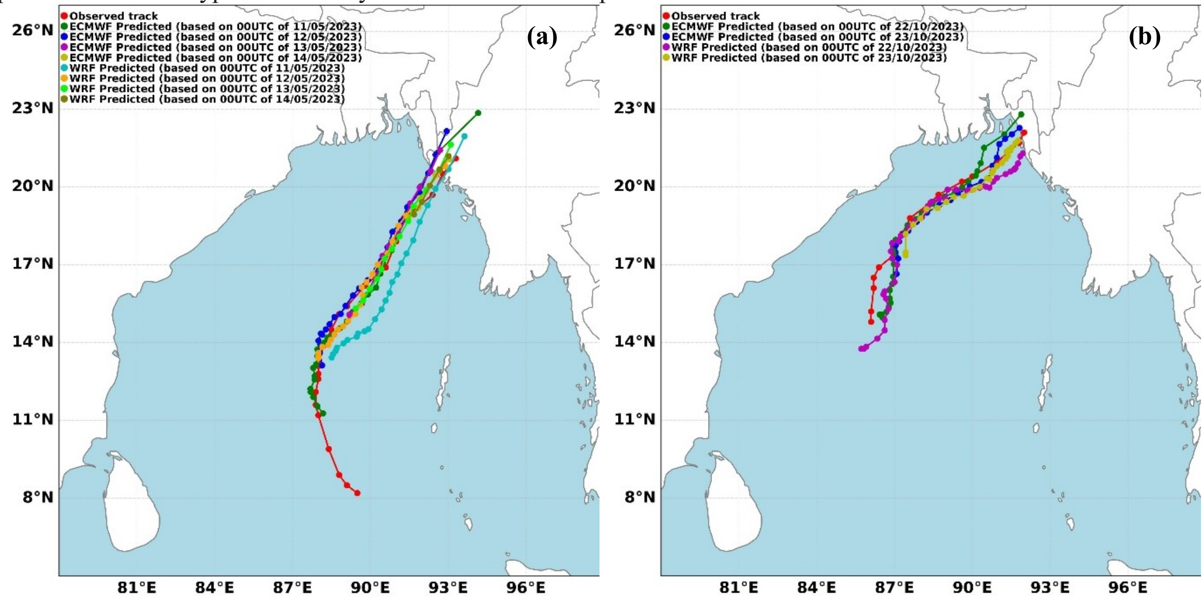


Fig. 5: WRF and ECMWF predicted and observed track: (a) Cyclone 'Mocha' (14 May 2023) and (b) Cyclone 'Hamoon' (24 October 2023)

4. Conclusion

i. The analysis highlights important climatological features:
   - Strong seasonal dependence of cyclone activity.
   - Increasing intensity despite decreasing frequency.
   - High vulnerability of Bangladesh coast.

ii. Model evaluation shows that:
   - Forecast accuracy has improved when lead time decreased.
   - Still requires refinement for precise landfall prediction.

iii. This study provides a comprehensive analysis of tropical cyclone tracks over the Bay of Bengal. The key findings are:
   - Cyclone frequency is decreasing, but severe cyclones are increasing.
   - Maximum cyclone activity occurs during pre- and post-monsoon seasons.
   - Bangladesh and Odisha coasts are most vulnerable.
   - Numerical models (WRF and ECMWF) show good performance but with positional errors.

These findings are crucial for improving early warning systems and disaster management strategies in the region.

5. References

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