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A Parametric Study of Cyclone Intensity in the Bay of Bengal Using Calibrated Historical Data

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ABSTRACT

This research explores the dynamics of tropical cyclones in the Bay of Bengal by analyzing key meteorological parameters such as central pressure, wind velocity, and the radius of maximum wind. Historical cyclone data (1999-2023) from the Bangladesh Meteorological Department were used to calibrate a modified empirical model based on the Holland wind profile. Four major cyclones- AMPHAN, FANI, SIDR, and NARGIS- were selected for analysis due to their well-documented intensity variations, landfall proximity to the Bangladesh coast, and complete availability of meteorological records, making them representative of different cyclone categories in the region. Model performance was assessed by comparing observed and simulated wind fields, where the modified model demonstrated strong agreement with historical observations. The validation was supported through quantitative performance indicators, including root mean square error (RMSE) and correlation coefficients, which confirmed improved wind field representation. The study further reveals that cyclone intensity is highly sensitive to small variations in central pressure and wind radius, indicating their dominant role in cyclone dynamics. These findings highlight the potential of the model to enhance early warning systems, disaster preparedness, and policy planning in cyclone-prone coastal regions, particularly in Bangladesh. The model shows promise for integration into operational forecasting frameworks for more accurate and timely cyclone predictions.

1. INTRODUCTION

Tropical cyclones are highly destructive natural events, marked by powerful winds, intense rainfall, and rising sea levels known as storm surges. While these systems play a vital role in redistributing heat and energy across the Earth's atmosphere, they also pose significant threats to coastal regions- particularly those surrounding the Bay of Bengal. Due to its unique geographical and climatic conditions, the Bay of Bengal is highly susceptible to tropical cyclone formation and landfall, often resulting in catastrophic impacts on human populations, infrastructure, and ecosystems.

A fundamental aspect of understanding tropical cyclones is the relationship between wind speed and central pressure. This wind- pressure relationship serves as a crucial indicator of cyclone intensity, aiding in forecasting and risk assessment. Central pressure- the lowest atmospheric pressure at the cyclone's centre- significantly influences the surrounding pressure gradient, which drives wind circulation. Conversely,

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the maximum sustained wind speed is a primary measure of a cyclone's strength and destructive potential.

Situated on the northern coast of the Bay of Bengal, Bangladesh is especially prone to these types of natural disasters. Spanning an area of 147,570 square kilometres, the country's vulnerability arises from various geographical and environmental factors, including its low-lying terrain, dense population, and funnel-shaped coastline. Additional influences such as the El Niño–Southern Oscillation (ENSO), environmental degradation, and socio-economic challenges further exacerbate disaster risk. Since 1860, more than 160 cyclones have struck Bangladesh, resulting in extensive loss of life and property [1]-[4].

Cyclone-induced storm surges are particularly destructive, inundating coastal regions, disrupting livelihoods, causing long-term ecological damage, and reshaping landforms. In the last 44 years, a total of 269 depressions have developed in the Bay of Bengal, averaging about 7.7 per year between 1974 and 1999. Of these, 3.46 matured into storms, and 3.12 made landfall [5]-[9]. Furthermore, projections indicate that a one-meter rise in sea level over the next century could inundate 15-17% of Bangladesh's land area, potentially displacing around 20 million people [10].

While several cyclone modeling approaches- such as the Holland model, Kawai model, and Jelesnianski model- have been applied to the Bay of Bengal, many struggle to capture regional meteorological characteristics, including asymmetric wind structures, shallow water influences, and coastal boundary effects. These limitations highlight the need for a regionally calibrated model that can better represent cyclone wind dynamics.

The primary objective of this research is to analyze historical cyclone datasets in the Bay of Bengal to investigate the relationship among wind speed, central pressure, and the radius of maximum wind, and to calibrate a modified Holland wind profile model for improved cyclone intensity estimation. Instead of performing direct future climate projections, this study focuses on evaluating how variations in central pressure and wind-field structure influence cyclone intensity and associated surge potential. By emphasizing parameter sensitivity and regional storm characteristics, the study aims to enhance the accuracy, stability, and operational applicability of intensity estimation for real-time forecasting and coastal hazard preparedness.

2. MATERIALS AND METHODS

2.1 Study Area

Bangladesh, the largest deltaic nation in the world, is formed by the convergence of three major rivers- the Ganges, Brahmaputra, and Meghna. Geographically, it lies between latitudes 20°34′N to 26°38′N and longitudes 88°01′E to 92°41′E, with an approximate coastline of 711 km along the Bay of Bengal. The Himalayan mountain range lies to the north, while the Bay of Bengal bounds the southern region of the country. Topographically, Bangladesh can be divided into three principal regions: the eastern deltaic zone, the central deltaic area, and the stable central deltaic region.

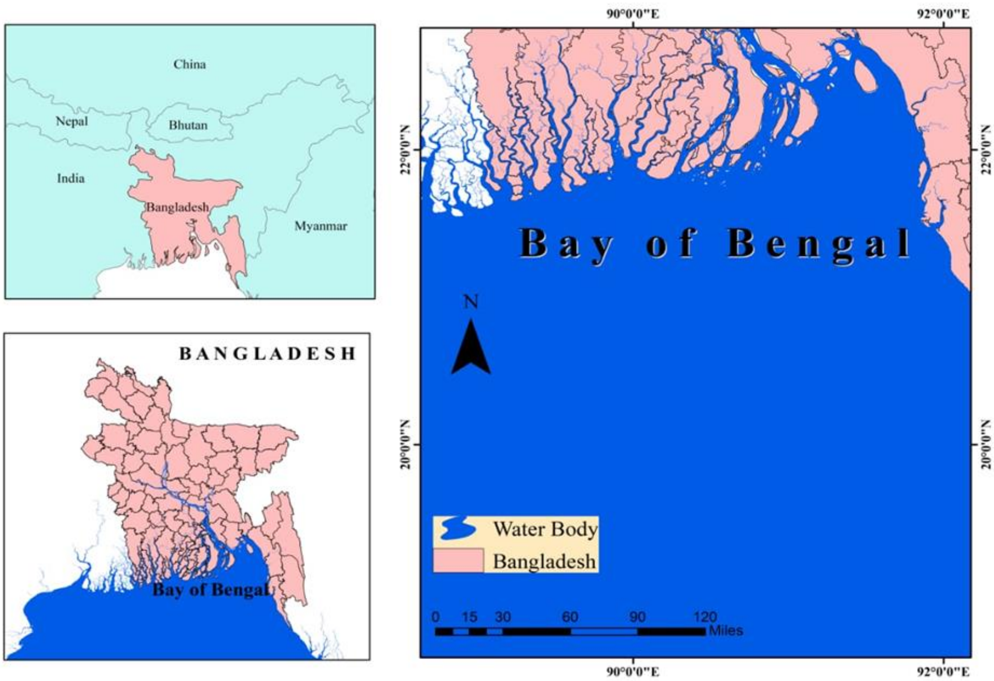

Fig. 1. Location of the Study Area

The Bay of Bengal plays a critical role in the formation, intensification, and landfall of tropical cyclones that frequently affect Bangladesh. On average, the nation experiences at least one cyclone per year, while severe cyclones occur approximately once every three years. Bangladesh's coastal region comprises 19 districts and 147 Upazilas, accounting for 32% of the national land area and 28% of the population [11], [12]. However, cyclone-induced storm surge risk is particularly concentrated within 12 districts and 51 coastal police station jurisdictions.

2.2 Wind-Pressure Relationship in Tropical Cyclones

Understanding the wind-pressure relationship is essential for estimating cyclone intensity, forecasting storm surge levels, and issuing early warning alerts. The empirical formula introduced in [13] is widely used to approximate the maximum sustained wind speed $V_{\max}$ from the central pressure P_{center}. The generalized Kawai relation [14] is expressed as:

$$V_{\max} = C\left(P_{ref} - P_{center}\right)^{\beta} \quad (1)$$

Where, $V_{\max}$ = Maximum sustained wind speed (in meters per second or knots); P_{center} = Central pressure of the cyclone (in hPa); P_{ref} = Reference pressure (often the average sea-level pressure, typically around 1010 hPa); C = Empirical constant that varies based on the region and specific cyclone characteristics (usually determined from historical cyclone data); β = empirical exponent (typically 1.5 to 2).

This power-law relationship reflects the non-linear increase in wind speed with decreasing central pressure. The constants C and β are region-specific and are determined from historical cyclone datasets.

2.3 Empirical Models for Wind-Pressure Dynamics

The wind speed within a cyclone is driven by the horizontal pressure gradient force. The pressure drop is defined as:

$$\Delta P = P_{ref} - P_{center} \quad (2)$$

Wind intensity increases as ΔP increases. Following Kawai's approach, the maximum sustained wind speed can be estimated using:

$$V_{\max} = C\left(\Delta P\right)^{\beta} \quad (3)$$

Here, both C and β vary with regional atmospheric and oceanic conditions. For the Bay of Bengal, previous empirical studies have identified $\alpha \approx 1.5 - 2.0$, indicating a nonlinear sensitivity of wind intensity to pressure drop.

2.4 Data and Its Calibration

Accurate monitoring and prediction of cyclonic disturbances over the North Indian Ocean rely on robust data collection, processing, and calibration methodologies. The Regional Specialized Meteorological Centre (RSMC), operated by the India Meteorological Department (IMD) in New Delhi, plays a key role in this effort. The RSMC sources data from satellites, radars, ships, and ocean buoys, supplemented by Numerical Weather Prediction (NWP) models. The Dvorak technique is used to estimate cyclone intensity through cloud structure interpretation.

In this study, cyclone data from the Bangladesh Meteorological Department (BMD) were compiled, including six-hourly central pressure, maximum wind speed, track location, and radius of maximum wind. Missing or incomplete entries were addressed using linear interpolation and cross-verification with IMD best-track datasets to ensure continuity.

To calibrate the empirical model, nonlinear least squares regression was applied to estimate the optimal values of constants C and β for the wind-pressure relationship. Calibration accuracy was assessed using Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE) between observed and model-estimated wind speeds. Additionally, the Pearson correlation coefficient (R) was computed to evaluate the strength of model-observation agreement.

This statistical calibration ensures that the modified empirical model reliably reflects the cyclone behaviour characteristic of the Bay of Bengal.

2.5 Development of the Model

The radius of maximum sustained wind ($R_{\max}$) is a key parameter influencing cyclone structure and storm surge generation. Historical studies reported typical values ranging from 47 km for central pressures between 909-993 hPa [15] to 84-98 km for typhoons affecting Japan [16]. Since $R_{\max}$ varies with cyclone track, intensity, and regional environmental conditions, several estimation models have been developed [17], [18].

In this study, cyclone track datasets under present and projected climate scenarios were calibrated to refine the empirical relationship originally proposed in [13], [19] and [20]. The modified model is given as:

$$P_c^{bay} = 1013 - \left(\frac{V_{\max}}{13}\right)^{\beta}, \beta = 1.5\, to\, 2 \quad (4)$$

$$R_{\max} = 94.89 e^{\left(\frac{P_C - 967}{61.5}\right)} \quad (5)$$

Where, P_c^{bay} = Central pressure (hPa) for the desired cyclone; V_{max} = maximum velocity (m/s); R_{max} = maximum sustained wind radius (km).

3. Results and Discussion

To investigate the relationship between storm velocity and atmospheric pressure, and to evaluate the accuracy of the developed model, storm datasets from the Bay of Bengal were calibrated using historical records from 2000 to 2023. Numerical analysis was performed, and the results are visualized through box plots (Figs. 2-5). Additionally, observed and simulated data for the 1999 storm were compared. The comparison shows that while the central pressure remained nearly constant initially, it gradually became unbalanced over time due to variations in storm structure, resulting in corresponding fluctuations in storm velocity.

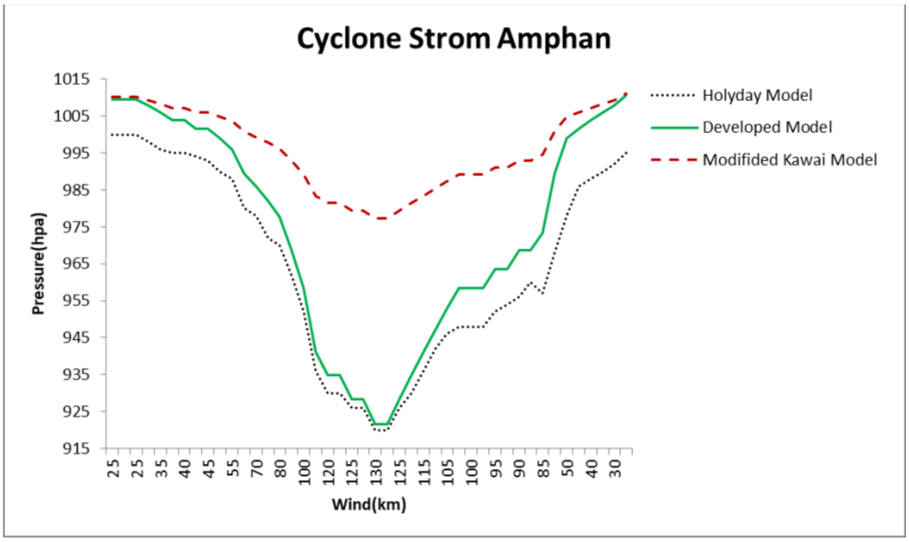

Fig. 2. Comparison result for Cyclone AMPHAN

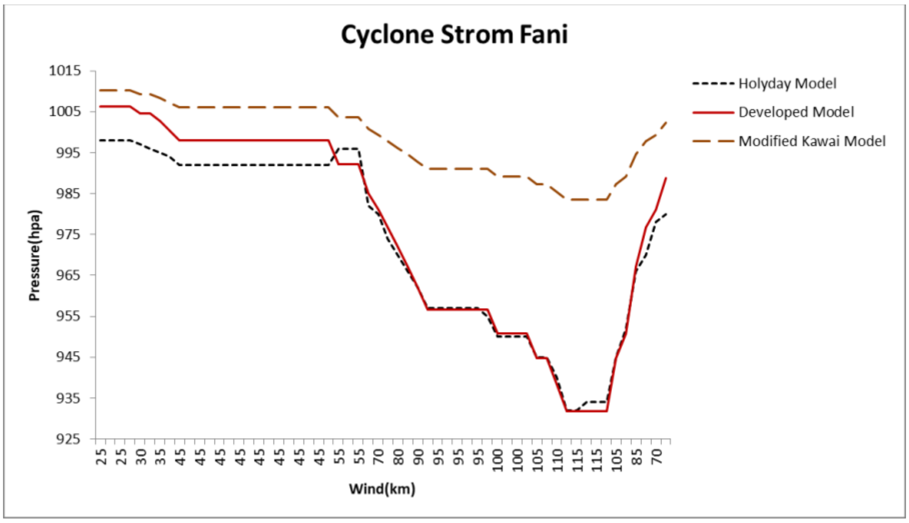

Fig. 3. Comparison result for Cyclone FANI

Comparisons were made between observed data, the dataset from [14], and the output from the modified empirical model. The results demonstrate consistent agreement across values of the parameter β ranging from 1.5 to 2. Further evaluations were conducted for major cyclones affecting Bangladesh, including AMPHAN, FANI, and SIDR.

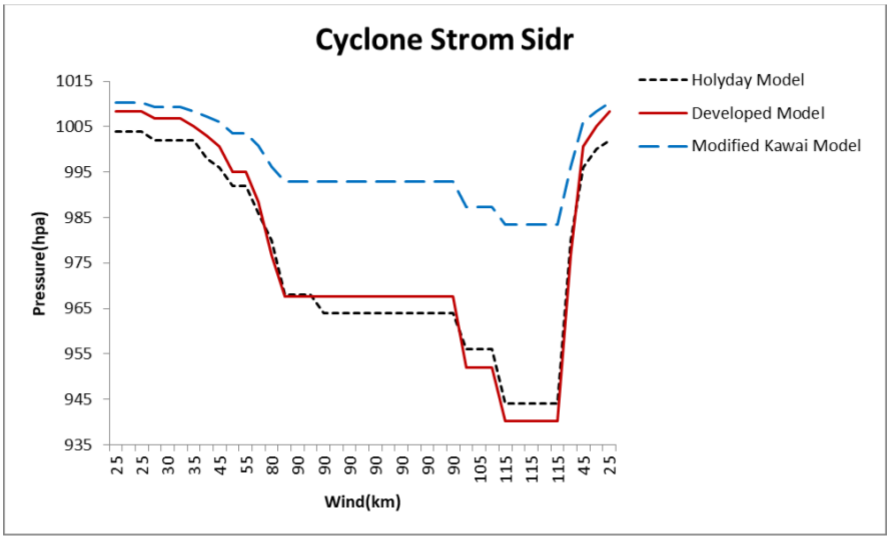

Fig. 4. Comparison result for Cyclone SIDR

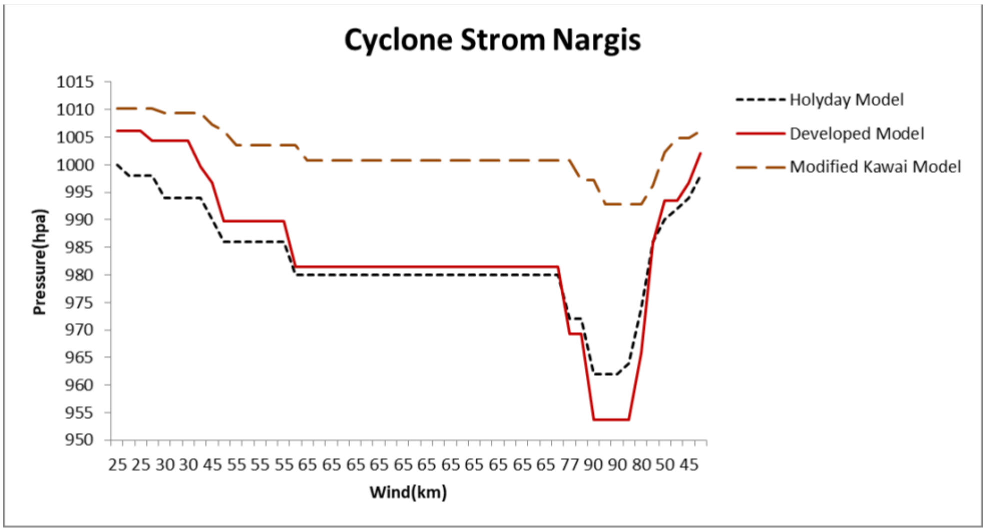

Fig. 5. Comparison result for Cyclone NARGIS

Analysis of the box and whisker plots shows a noticeable variation between the upper and lower quartiles, indicating changes in storm characteristics driven primarily by variations in mean central pressure. Importantly, no significant outliers were detected. For cyclones such as NARGIS and FANI, the pressure does not remain constant from the initial phase; instead, slight deviations arise due to evolving storm structure, resulting in corresponding changes in velocity.

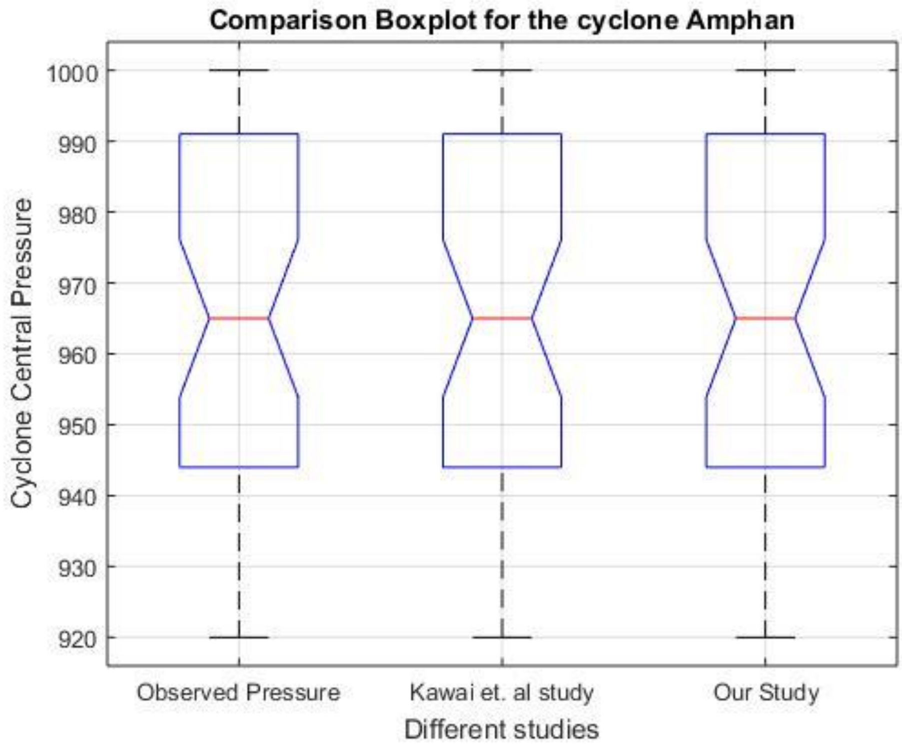

Fig. 6. Box plot comparison for Cyclone AMPHAN

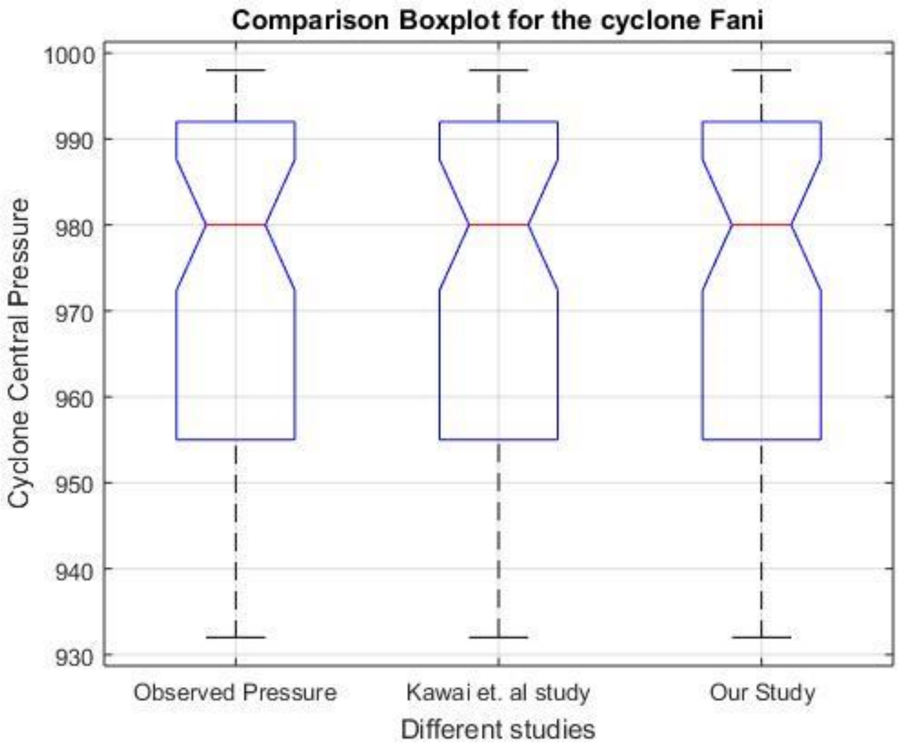

Fig. 7. Box plot comparison for Cyclone FANI

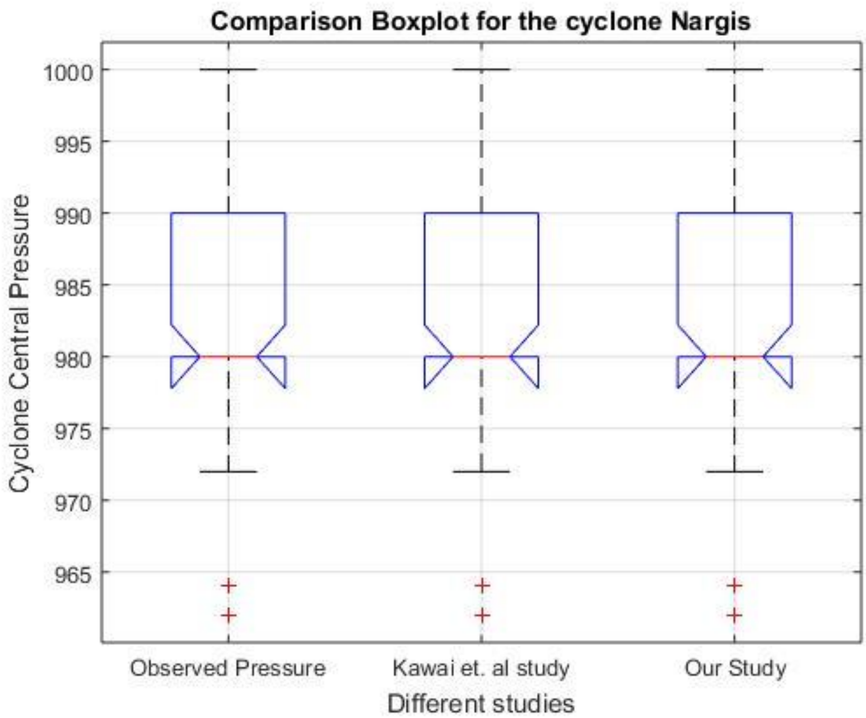

Fig. 8. Box plot comparison for Cyclone NARGIS

The box plot analyses indicate only minor differences between quartiles for AMPHAN, suggesting limited variability in pressure. Thus, the model demonstrates reasonable capability in capturing the velocity- pressure relationship. The wind field simulation results further support this observation, particularly for Cyclone AMPHAN, where surface wind patterns align closely with observed characteristics. The model estimates wind fields using cyclone track parameters such as latitude, longitude, maximum sustained wind speed, central pressure, and radius of maximum winds.

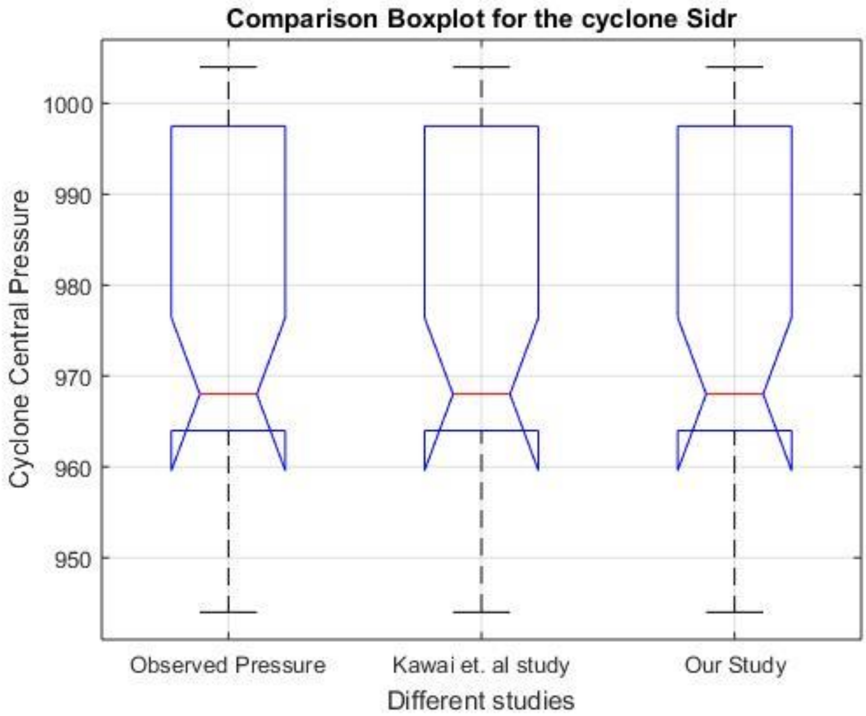

Fig. 9. Box plot comparison for Cyclone SIDR

This simulation framework applies the Holland wind profile model to generate surface wind fields with improved accuracy. By integrating real cyclone datasets and applying a physically consistent theoretical foundation, the model achieves better correspondence with observed wind patterns than several earlier approaches. The spatial variation in wind intensity along the cyclone track is effectively represented, and the radius of maximum wind (R_{max}) is modeled as a function of central pressure using the modified empirical relation. In the case of Cyclone AMPHAN, simulated surface wind speeds are slightly lower than values above the friction layer, consistent with expected boundary layer effects.

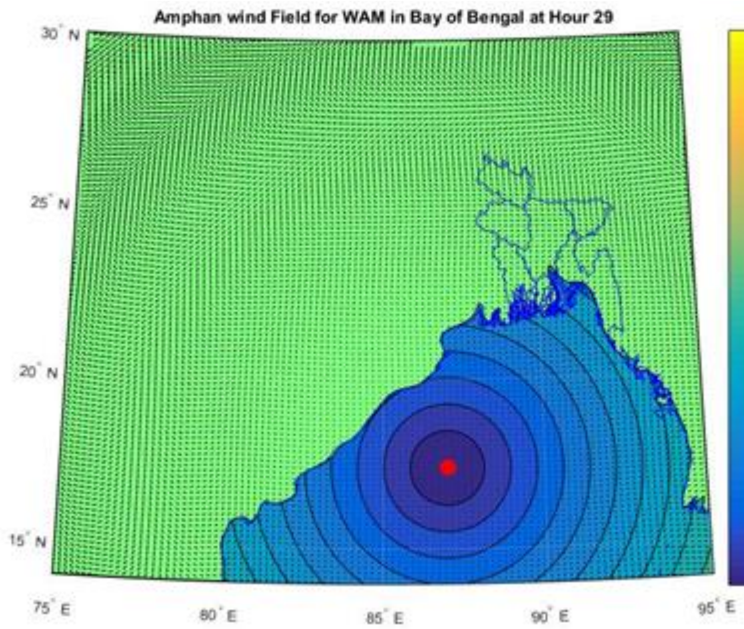

Fig. 10. Observed wind profile at 29 hours for AMPHAN

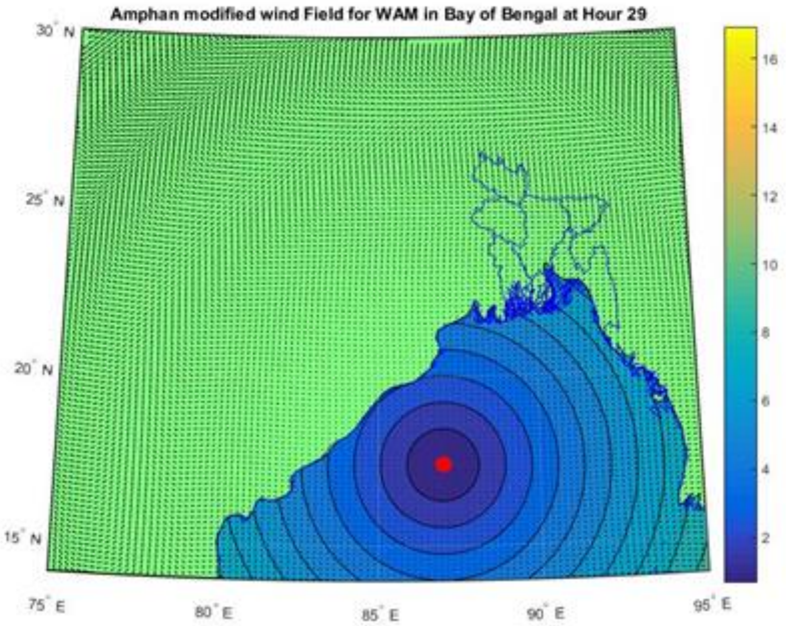

Fig. 11. Modified model wind profile at 29 hours for AMPHAN

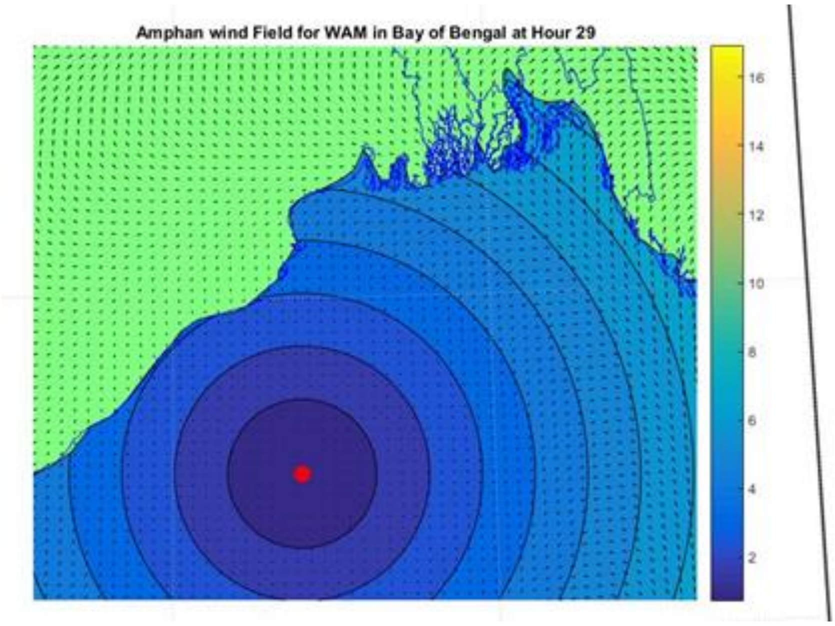

Fig. 12. Observed wind profile (clear view)

These results emphasize the importance of adopting empirical relationships tuned to the meteorological characteristics of the Bay of Bengal. The improved performance of the modified model is demonstrated in its ability to accurately represent both the magnitude and spatial structure of the wind field-critical components for cyclone impact assessment and forecasting.

Visualization using contour and vector plots confirms strong wind concentration near the cyclone core, decreasing radially outward, which aligns with established cyclone dynamics. Incorporating environmental factors such as the Coriolis effect and air density enhances physical realism. Calibration results also show consistency with the original Kawai formulation when $\beta = 1.5$, indicating effective adaptation for this region.

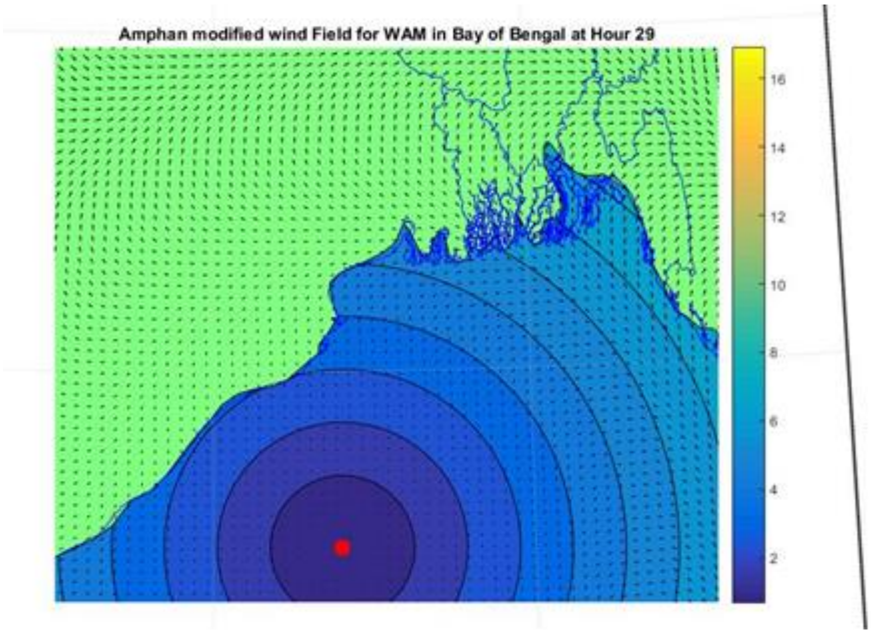

Fig. 13. Modified model wind profile at 29 hours (clear view)

The selected value of $\beta = 1.5$ yields a realistic pressure gradient slope and reliable wind field estimation. Moreover, the analysis suggests that data quality and structure directly influence simulation accuracy. The model successfully captures time-dependent changes in cyclone dynamics, particularly for Cyclone AMPHAN, where simulated behavior converges with observations after several hours. The lack of significant deviations across different cases supports model stability.

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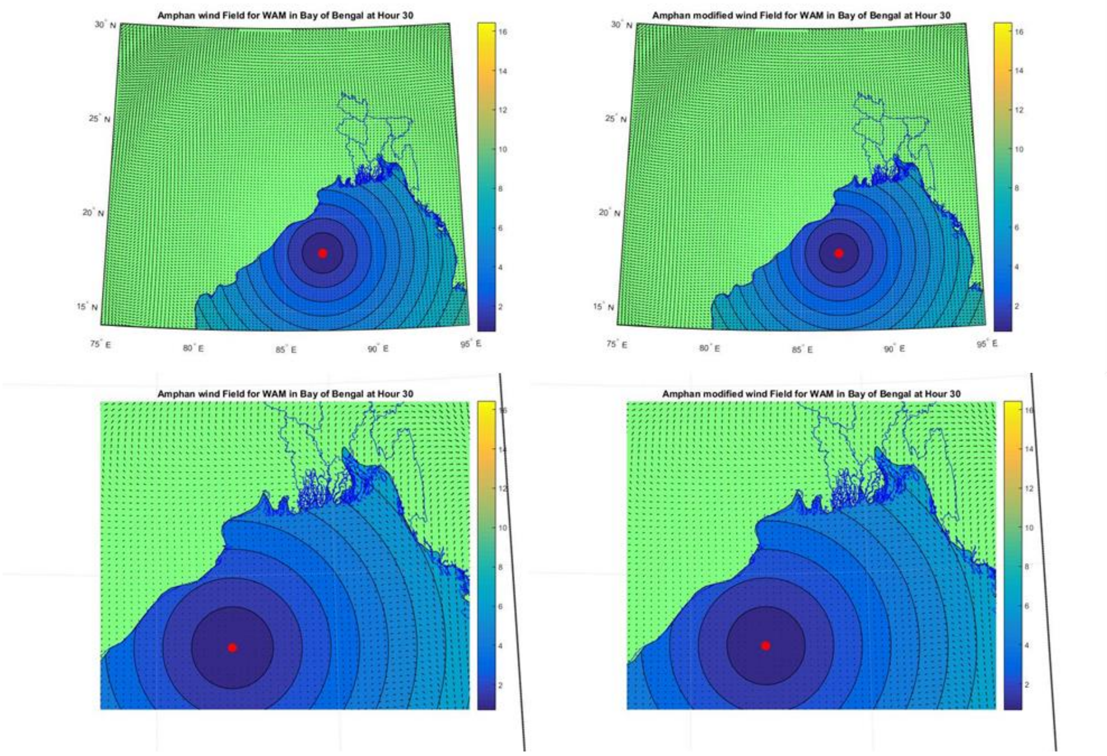

Fig. 14. Simulation comparison for all cases at 30 hours

Overall, the model demonstrates strong potential for operational cyclone forecasting and disaster preparedness. Its capability to produce detailed wind profile estimates and track variations makes it a valuable tool for assessing cyclone-related hazards in the Bay of Bengal region and for improving hazard mitigation strategies.

4. CONCLUSION

This study analyzed the dynamics of tropical cyclones in the Bay of Bengal by examining key parameters such as storm velocity, central pressure, and wind structure. A modified empirical wind-pressure relationship model was developed and calibrated using historical cyclone data spanning 1999-2023. The rationale for selecting the cyclones AMPHAN, FANI, SIDR, and NARGIS was based on the availability of reliable observational datasets and their representativeness of different cyclone intensity classes that have significantly impacted the Bangladesh coast.

The analysis identified central pressure and the radius of maximum wind as the most influential parameters governing cyclone intensity and spatial wind distribution. Model performance was evaluated using observed cyclone datasets, and quantitative validation metrics (RMSE, MAE, and correlation coefficient) demonstrated improved accuracy compared to earlier wind profile formulations. The modified Holland wind profile model showed a closer agreement with measured wind fields, particularly near landfall conditions, where traditional symmetric models often underperform. A comparative assessment between the original model and the modified version confirmed improved estimation of pressure gradients and wind decay patterns.

Furthermore, a sensitivity analysis revealed that even small variations in central pressure and maximum wind radius lead to significant differences in simulated wind fields, highlighting the necessity of precise parameter calibration. Although the present study focuses on wind and pressure-based intensity characterization, integrating coastal bathymetry and storm surge simulation in future work will allow for more comprehensive hazard prediction. Additionally, applying cross-validation and extending evaluation to more recent cyclones (e.g., YAAS, BULBUL) will further strengthen predictive robustness.

Overall, the findings emphasize the importance of refined cyclone parameter modeling for enhancing early warning systems and disaster risk preparedness in Bangladesh's coastal regions. The improved empirical framework may be incorporated into operational forecasting workflows, with potential for integration into Bangladesh Meteorological Department (BMD) cyclone advisory systems and coastal infrastructure risk assessment models. This work provides a foundation for future research linking wind field modelling with storm surge forecasting under evolving climate conditions.

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