Evaluation of WRF Microphysics for Port-Specific Cyclone Forecasting over Bangladesh

Rashedul Alam[1], Fatima Akter[1*], Mohan Kumar Das[1,3,4], Saurav Dey Shuvo[1], S.M. Quamrul Hassan[2], Md. Shahidul Haque[5], M.M.A. Sarker[1] and Sadia Afrin Sayfa Negaban[1]

[1]Department of Meteorology, University of Dhaka, Dhaka-1000, Bangladesh
[2]Bangladesh Meteorological Department, Agargaon, Dhaka-1207, Bangladesh
[3]Hydro-Climate and Ocean Centre, Dhaka, Bangladesh
[4]Yunnan University, Yunnan, China
[5]Institute of Bay of Bengal and Bangladesh Studies, Bangladesh Maritime University, Dhaka-1216, Bangladesh

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ABSTRACT: This study simulates cyclonic storms Hamoon and Remal using Weather Research and Forecasting (WRF) configuration to determine the most suitable microphysics schemes for early warning over seaports of Bangladesh. The North Indian Ocean region lacks localized, high-resolution forecasting, which affects port operations and coastal preparedness. WRF was configured with nested domains at 9km and 3km resolution using WSM6, WSM7, and SBU-YLin schemes for 168-hour and 96-hour simulations. Five-variables (surface wind, precipitation, sea-level pressure, temperature, and vertical relative humidity) were evaluated using MAE, MB, RMSE, and track errors. GFS provided boundary conditions, while validation used ERA5, GPM rainfall, BMD and BAF station data, and RSMC best track observations. Results show strong agreement between the simulations and observations, confirming the reliability of model. WSM6 and WSM7 performed best for Hamoon at Chattogram Port, whereas SBU-YLin produced better short-range forecasts for Remal at Mongla Port, where 96-hour wind RMSE reached 6.8kmh^{-1} (Hamoon, WSM6) and 6.2 kmh^{-1} (Remal, SBU-YLin). Therefore, 96-hour forecasts better capture track, wind, and pressure, while 168-hour runs sometimes better represent precipitation trends. Future work should incorporate additional physics, data assimilation, and more cyclone cases to strengthen localized-forecasting and enhance port safety and coastal resilience in Bangladesh.

Keywords: Cyclonic Storms; WRF Model; Microphysics Schemes; Port Area; Sensitivity

INTRODUCTION

Tropical cyclones (TC) typically form in the Bay of Bengal during the pre-monsoon and post-monsoon seasons. And before recurving in a north-northeasterly direction, these cyclones first travel west-northwest. While cyclones that recur landfall along the shores of Bangladesh or Myanmar, those that move west-northwest frequently traverse eastern coast of India (Karmakar & Das, 2019). The Northern Indian Ocean (NIO) is one of the most important basins for tropical cyclone (TC) activity, accounting for about 7% of all TCs worldwide each year (Osuri et al., 2012). Over the BoB, an average of four TCs form each year, many of which result in significant losses in terms of both human life and financial resources. With death tolls ranging from 5,000 to over 300,000 in individual incidents, the BoB and AS ranks eighth out of ten deadliest worldwide TCs over the previous three centuries (Osuri et al., 2012).

Both dynamical and thermodynamic factors influence the development of tropical cyclones (TCs). Moreover, the factors like warm climate, low vertical wind shear, and sea surface temperature (SST) above 26.5°C in the North Indian Ocean (NIO) make it a perfect place for tropical disturbances to form (Mukherjee & Ramakrishnan, 2022). These natural hazards frequently affect port areas of Bangladesh during both pre monsoon and post monsoon seasons, emphasizing the need for accurate TC prediction. High atmospheric moisture, weak wind shear, and warm sea surface temperatures characterize economic and geographic setting of Bangladesh, increasing its vulnerability to TCs (Singh et al., 2021). The nation is particularly vulnerable to storm surges, intense rainfall, and strong winds due

Corresponding Author: Fatima Akter
Email: fatima.geoenv@du.ac.bd

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to its low-lying terrain and densely populated coastal regions. The devastating impacts of past cyclones, including Cyclone Aila (2009), Cyclone Sidr (2007), and the Bhola Cyclone (1970), which caused an estimated 300,000 to 500,000 fatalities, highlight the urgent need for accurate cyclone forecasting systems (Chutia et al., 2018).

The Severe Cyclone (SC) Hamoon and Remal are the two cyclonic events that were considered for simulation in this study. As per the RSMC report, in October 2023, a severe cyclonic storm called Hamoon formed over the Northeast Bay of Bengal, bringing with it rainfall and winds to portions of Bangladesh. By October 24, 2023, a distinct low-pressure system had developed, grown into a depression, and then gotten stronger into a powerful cyclonic storm. Around 150 km east-southeast of Khepupara, Bangladesh, and 80 km south-southwest of Chittagong, Bangladesh, the center of storm was located at latitude 21.6°N and longitude 91.6°E at 1800 UTC on October 24. With gusty winds up to 110 km/h, the system maintained a maximum sustained wind speed of 90 to 100 km/h while moving northeast at 19 km/h. The estimated central pressure of system was approximately 994 hPa. Additionally, severe cyclonic storm Remal, which formed over the North Bay of Bengal in May 2024 and which is caused significant damage to western Bangladesh and eastern India. It developed into a powerful cyclonic storm by May 26, 2024. As per the RSMC report, around 220 km south-southwest of Khepupara (Bangladesh), 260 km south of Mongla (Bangladesh), 210 km southeast of Sagar Island (West Bengal), and 230 km south-southeast of Canning (West Bengal) were the center points of Remal at 1800 UTC on May 26 with a maximum wind speed of 135 km/h. And the estimated central pressure of the system was 982 hPa.

The seaports of Bangladesh are vital to economy of the country, which is situated on the southern border of the country. Chattogram and Mongla ports handle over 90% of foreign trade of Bangladesh and serve as main maritime gateways of the country. These ports are also important for neighboring countries, including Myanmar, Thailand, and landlocked nations such as Nepal, Bhutan, and northeastern India. Chattogram Port has strategic importance in the Bay of Bengal region and supports regional trade and connectivity with Myanmar's Sittwe and Yangon ports, as well as Thailand's Ranong Port (Bose, 2023). Localized forecasting systems offer several benefits over more general regional models by focusing on the unique geographical and meteorological features of the port region, which can give more precise and useful forecasts. Moreover, there are many factors, such as boundary conditions, physical parameterizations, and grid resolution that can greatly affect the performance of the model (Arasa et al., 2016).

Weather forecasting has been updated using NWP models that can simulate complex meteorological processes. Heavy rainfall and other weather associated with tropical cyclones are often examined and analyzed using WRF-ARW models (Hong & Lee, 2009; Routray et al., 2010). Its flexibility in configuring physical and dynamic processes makes it ideal for predicting extreme weather, such as TCs, especially as it's operational at finer, higher resolution (Mukherjee & Ramakrishnan, 2022). Many have examined the performance of WRF model in simulating TC track, intensity, and related phenomena, such as heavy rainfall. For instance, sensitivity analyses of cyclones in the NIO using the WRF model showed that particular combinations of convection schemes, such as the Kain-Fritsch scheme (KF) (Kain, 2004) and Yonsei University scheme (YSU) and planetary boundary layer (PBL) schemes (S. Y. Hong et al., 2006) brings out more precise forecasts (Mukherjee & Ramakrishnan, 2022).

The main objective of this study is to use an NWP model for port areas of Bangladesh to analyze and assess an accurate weather forecasting system. Although several studies have explored coastal WRF configuration for port regions (e.g., Arasa et al., 2016), port-specific cyclone forecasting sensitivity studies remain limited in the Bay of Bengal region, particularly for major seaports of Bangladesh. As a result, various microphysics schemes were evaluated to identify the one that provides the most accurate simulation of cyclonic storms. WSM6, WSM7, and SBU-YLin are selected for evaluation, as their distinct physical assumptions regarding hydrometeor classes, riming intensity, and mixed-phase processes make them suitable candidates for assessing scheme sensitivity in tropical cyclone forecasting over the Bay of Bengal port regions. Specifically, the study focuses on simulating SC Hamoon and Remal, which passed near ports of Bangladesh, in order to compare the model outputs with observed data and determine the most effective approach for precise weather forecasting in the port region. Therefore, this research is focused on the need for accurate and timely weather forecasts in port regions of Bangladesh, which are critical for maritime safety, trade operations, and disaster preparedness. Section 1 of this study provides an overview of the study and a summary of the chosen cyclones. Section 2 provides a detailed description of the methodology used to conduct the optimal WRF configuration for the operational forecast, results and analysis are given in section 3, and finally, the conclusion is reported in section 4.

DATA AND METHODOLOGY

The following sections describe the characteristics of the study region, the simulation domains and periods analyzed, and the modeling approach and evaluation process in detail.

Study Area, Simulation Domains and Selected Simulations

The methods describe the process for obtaining the optimal WRF configuration applied to port areas. Chattogram Port is the largest and busiest seaport in Bangladesh (Fig. 1), which is located near the Bay of Bengal and the Karnaphuli River estuary. It is a significant maritime hub that is vital to trade and connectivity throughout the region. The Port of Chattogram, situated along the Karnaphuli River, is adjacent to second largest metropolitan area of Bangladesh and serves as the principal maritime gateway of country. The river flows through a tropical, high rainfall region and supports extensive urban, industrial, and ecological activities. Chattogram Port plays a dominant role in international trade of Bangladesh, handling the majority of national export import cargo, and its strategic importance has been strengthened through continuous infrastructure expansion, modernization of cargo handling facilities, and enhanced regional connectivity (Saha, 2023; Munim et al., 2022).

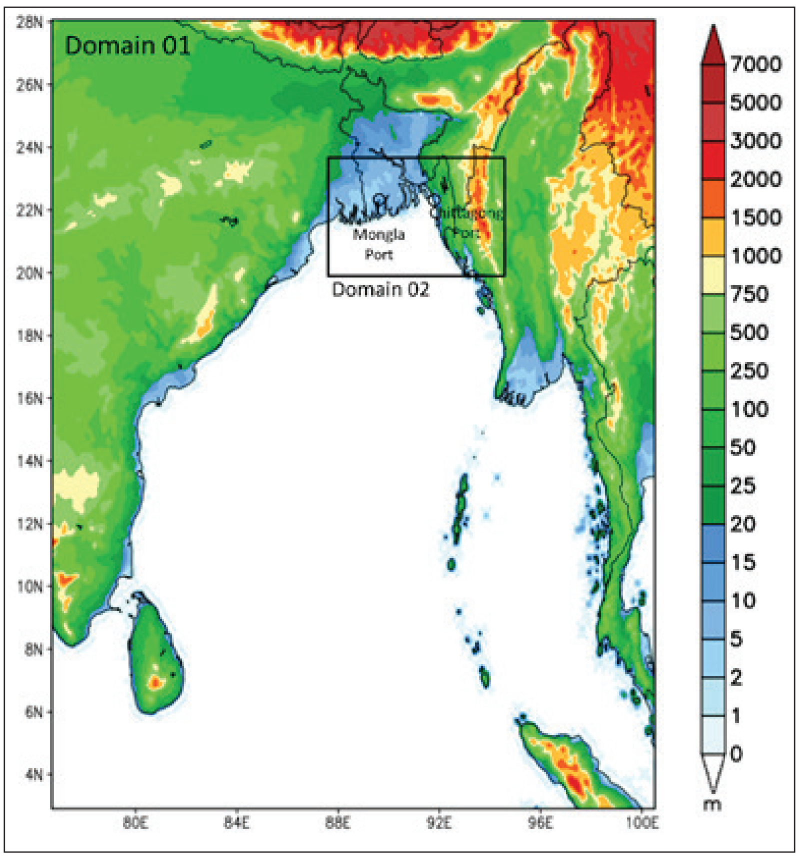

Figure 1: The Model Domain Used in WRF for the Simulation of a Cyclone with a Mother and the Nested Domain of 9 and 3 km Resolution, Respectively. The Shading in the Figure Indicates the Terrain Height in Meters

Mongla Port is the second largest sea port of Bangladesh, which is situated along the Pasur River on the east bank, close to the Bay of Bengal. This port supports key industrial and economic activities for the economy. However, due to its proximity to the Sundarbans, which is the largest mangrove forest in the world, the site has been deemed important for environmental purposes. Also, due to its location in tropical zone, the local conditions feature temperatures generally ranging from 19°C to 31°C with yearly rainfall is approximately 1,290 mm (Chakraborty et al., 2022). The Mongla Export Processing Zone (EPZ) is positioned next to the port and encourages commercial, residential, and industrial zones. Moreover, despite the environmental challenges, the port remains essential for promoting economic growth, trade enhancement, and connectivity to the region (Chakraborty et al., 2022).

Table 1: Total Run of the SC Hamoon and Remal

Cyclone & Period	Microphysics Tested	Other Schemes
Hamoon (20–27 Oct 2023) Hamoon (23–27 Oct 2023) Remal (23–30 May 2024) Remal (26–30 May 2024)	• WSM6 • WSM7 • SBU-YLin	➢ **PBL** Scheme: YSU ➢ **Surface** Layer Scheme: MM5 ➢ **Cumulus** Scheme: KF ➢ **Shortwave** Radiation: Dudhia ➢ **Longwave** Radiation: RRTM

The mother domain of model for WRF is 9 km in spatial resolution and centered at 15.87˚N, 88.59˚E. The total area for this domain is 285 × 315 grid points (~2565 × 2835 km at 9-km resolution), which occupies the land represented from central India to Sri Lanka and includes the Bay of Bengal, the Seven Sisters, and nearly all of Myanmar (Fig. 1). The goal of this sector is to record large-scale weather circulation and patterns. A smaller, nested domain with a better resolution of 3 km is focused exclusively on the coastline region of southern Bangladesh.

Table 2: WRF Model Configuration and Parameter Set

Parameters	Specifications
Model domain	Domain 1: 76.6862˚E to 100.504˚E and 2.90859˚S to 28.0585 ˚N Domain 2: 88.2724˚E to 94.7247˚E and 17.8205˚N to 23.8474 ˚N
Grid Resolution	Domain 1: 9km x 9km Domain 2: 3 km x 3 km
Projection	Mercator
Topographical data	USGS (10 m)
No of grid points X direction	285
No. of grid points in Y-direction	315
Forecast Interval	3 hourly
Time Step	30s
No of vertical levels	45
Forecast Lead time	24 to 168 Hours
Parameters archived (3 hourly)	Total 128 variables

This study conducted a total of twelve simulations (Table 1), selecting six for each of the two events, Hamoon and Remal, for the experiment. Events were repeated in two phases, with the first one with time frame of 168 hours and the second one with 96 hours, using different microphysics based on the severity of the cyclones. Thus, the three different microphysics configurations (WSM6, WSM7, and SBU-YLin) were used. The first simulation of cyclone Hamoon began at 0000 UTC on October 20, 2023, and ended at 0000 UTC on October 27, 2023 and the second simulation for Hamoon started at 0000 UTC on October 23, 2023, and ended at 0000 UTC on October 27, 2023. Using a similar methodology, Cyclone Remal was simulated from 0000UTC 23 May 2024 to 0000UTC 30 May 2024 and from 0000UTC 26 May 2024 to 0000UTC 30 May 2024.

Modeling Approach

The WRF model was developed by the National Centre for Atmospheric Research (NCAR) in collaboration with National Oceanic and Atmospheric Administration

(NOAA), National Centre for Environmental Prediction (NCEP), and several other universities. The physics, dynamics, and equations of WRF model are described in detail by Skamarock et al. (2008).

Microphysics parameterization in NWP models governs the representation of cloud and precipitation processes, including the formation, growth, and fallout of hydrometeors such as water vapor, cloud droplets, rain, ice, snow, graupel, and hail (Skamarock et al., 2008). Different microphysics schemes vary in the number of hydrometeor classes they predict and the physical assumptions they make regarding mixed-phase processes, riming intensity, and latent heat release, all of which directly influence simulated cyclone intensity, track, and precipitation (Hong & Lim, 2006; Lin & Colle, 2011). In this study, three microphysics schemes are evaluated: WSM6 (Hong and Lim, 2006), WSM7 (Bae et al., 2019), and SBU-YLin (Lin and Colle, 2011). WSM6 is a single-moment six-class scheme predicting mixing ratios of water vapor, cloud water, rain, ice, snow, and graupel. WSM7 extends WSM6 by adding hail as a seventh hydrometeor class, while SBU-YLin incorporates riming intensity and temperature-dependent ice characteristics for improved mixed-phase process representation. These physical differences form the basis of the sensitivity analysis aimed at identifying the most suitable scheme for cyclone forecasting over the major seaports of Bangladesh. In addition to microphysics, complementary physical parameterization schemes are employed to ensure a comprehensive model configuration. The Kain-Fritsch (KF) cumulus scheme (Kain, 2004) is used to represent sub-grid scale convective processes, while the Yonsei University (YSU) scheme (Hong et al., 2006) is applied for the Planetary Boundary Layer (PBL) to account for vertical diffusion and entrainment processes. For radiation, Dudhia's scheme (Dudhia, 1989) is used for shortwave radiation and the Rapid Radiative Transfer Model (RRTM; Mlawer et al., 1997) is used for longwave radiation. The complete model domain configuration and detailed parameter specifications are presented in Table 2.

Data Used

The GFS data, updated every three hours with a horizontal resolution of 0.25°×0.25°, was used for the initial and boundary conditions of the model, provided by the National Centre for Environmental Prediction (NCEP). The most recent track information for tropical cyclones Hamoon and Remal was supplied by the Regional Specialized Meteorological Centre (RSMC). In addition, data from the Bangladesh Air Force (BAF), the ERA5 reanalysis, the Bangladesh Meteorological Department (BMD) stations, and GPM were used to meet the evaluation objectives.

Methodology

WRF model version 4.5 is used in this study to show the forecasted paths and intensities of Tropical Cyclones Hamoon and Remal, using two domains with horizontal resolutions of 3 km and 9 km. Hence, by simulating the model, it was possible to examine the cyclone shape and intensity in relation to meteorological factors such as temperature, relative humidity, precipitation patterns, sea level pressure, and surface wind. Moreover, the model was also used to predict the landfall of cyclones. Thus, simulating the model allowed climatic variables to be investigated for cyclone intensity and track. This study evaluated the track prediction and sensitivity of model using statistical metrics, including Mean Bias (MB), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE), to identify the microphysics scheme that best matches the cyclone's intensity and landfall. The following equations were applied for the evaluation:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Observed\ value_i - Predicted\ value_i)^2}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|Observed\ value_i - Predicted\ value_i|$$

$$MB = \frac{1}{n}\sum_{i=1}^{n}(Observed\ value_i - Predicted\ value_i)$$

RESULTS AND DISCUSSION

The simulated and observed values of every meteorological parameter, including temperature, wind speed, relative humidity, mean sea level pressure, precipitation, and optimal track have been compared. Results from numerous statistical analyses carried out in different microphysics are also shown. And the tables show the outcomes of sensitivity assessments of the model.

Surface Wind Field

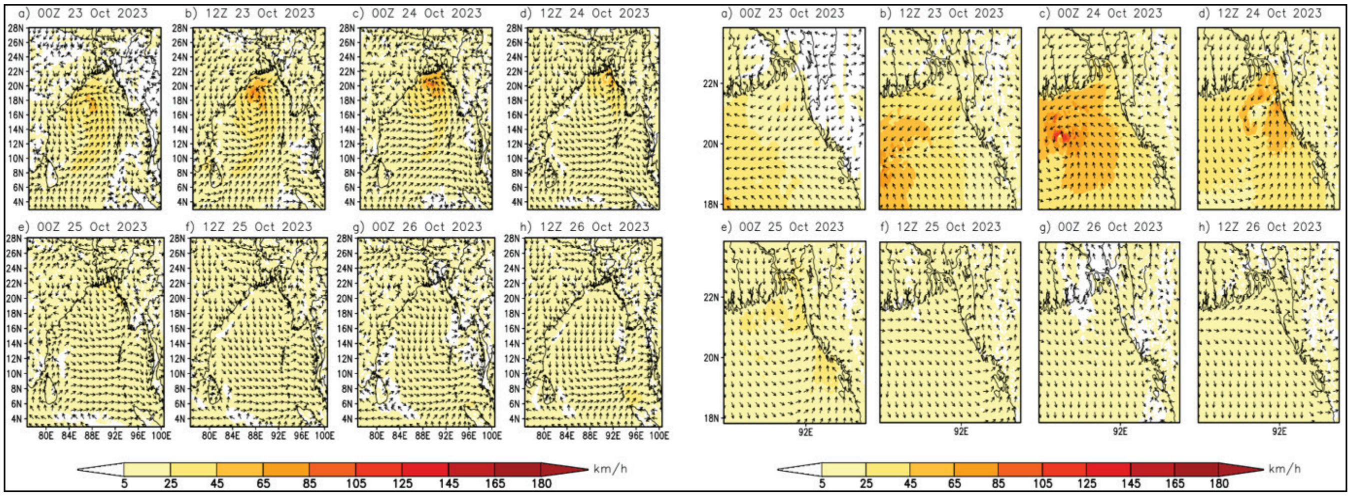

Figure 2: Model Simulated SC Hamoon 10m Height Wind Flow of Domain 01(left panel) and Domain 02 (right panel) using WSM6 Microphysics on 0000 UTC 23 Oct 2023 Valid for (a) 00Z 23 Oct 2023, (b) 12Z 23 Oct 2023, (c) 00Z 24 Oct 2023, (d) 12Z 24 Oct 2023, (e) 00Z 25 Oct 2023, (f) 12Z 25 Oct 2023, (g) 00Z 26 Oct 2023 and (h) 12Z 26 Oct 2023

The development of 10-meter wind fields for Hamoon and Remal was examined. The simulation (Fig. 2) for Cyclone Hamoon demonstrated clear phases in the evolution of the wind field. From 20 to 22 October, moderate wind rates of 45-85 km/h were seen across the central Bay of Bengal, marked by a prevailing southwesterly flow that transported moist air toward the Bangladesh coast. Wind speeds increased to about 126 km/h during the intensification of the system on October 23–24, with the strongest winds concentrated in the northeastern quadrant. And as the system moved inland after landfall, the wind fields decreased to 65-85 km/h, due to increased surface friction across the terrain, this shift was accompanied by a notable shift to westerly winds. Furthermore, on October 24, the high-resolution domain 02 simulation (Fig. 2) revealed wind shear patterns close to the Chittagong Hill Tracts and detected coastal wind maxima exceeding approximately 125 km/h along southeast Bangladesh.

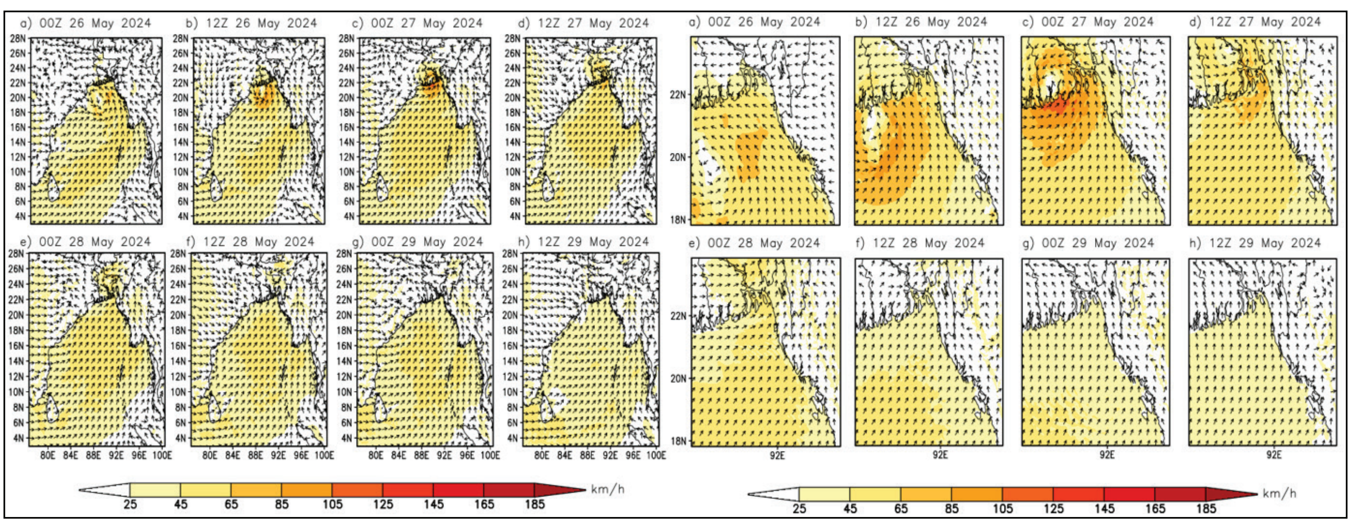

Figure 3: Model Simulated SC Remal 10m Height Wind Flow of Domain 01(left panel) and Domain 02 (right panel) using SBU-YLin on 0000 UTC 26 May 2024 Valid for (a) 00Z 26 May 2024, (b) 12Z 26 May 2024, (c) 00Z 27 May 2024, (d) 12Z 27 May 2024, (e) 00Z 28 May 2024, (f) 12Z 28 May 2024, (g) 00Z 29 May 2024 and (h) 12Z 29 May 2024

The domain 01 of Cyclone Remal simulation (Fig. 3) shows the formation phase from 23 May to 25 May, with easterly winds ranging from 65 to 85 km/h predominating over the system. Rapid intensification transpired by 26 May, with wind velocities around 126 km/h in the southeastern quadrant. Resulting in a bimodal wind distribution characterized by vigorous southerlies over the Bay of Bengal and weaker westerlies inland. The domain 02 simulations (Fig. 3) indicated small-scale vortices measuring 20-25 km in diameter along Remal's northwestern flank on 27-28 May, phenomena that likely intensified convective activity and precipitation. Upon landfall, the high-resolution domain distinctly documented the decay phase, with winds decreasing by 29-30 May as the cyclone engaged with coastal topography.

With RMSE values of 13.4 km/h (168 hr) and 6.8 km/h (96 hr) (Table 3), the WSM6 experiment gave Cyclone Hamoon the most accurate forecasts combined with lower MAE and MB than other methods. Though WSM7 showed favorable results, WSM6 microphysics is more stable. SBU-YLin had the worst performance, with the highest number of errors and significant negative bias. By comparison, WSM7 overestimated wind speeds, whereas for SBU-YLin microphysics Cyclone Remal fared best with the lowest RMSE (Table 3) and negligible bias.

Sea Level Pressure

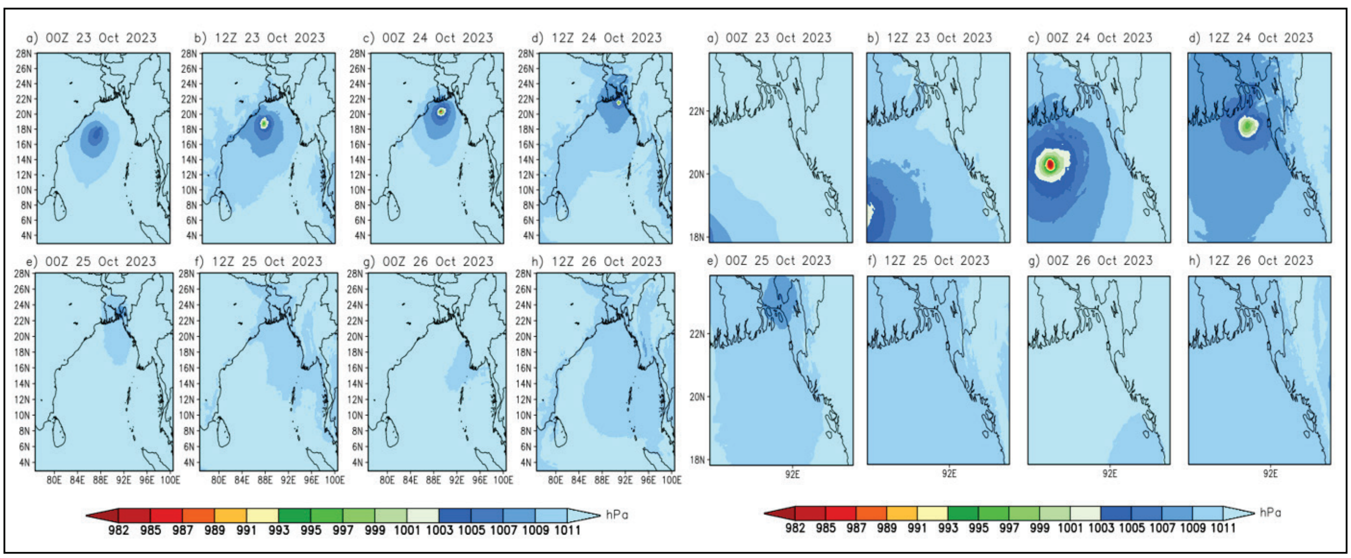

Figure 4: Model Simulated SC Hamoon Sea Level Pressure of Domain 01(left panel) and Domain 02 (right panel) using WSM7 Microphysics on 0000 UTC 23 Oct 2023 Valid for (a) 00Z 23 Oct 2023, (b) 12Z 23 Oct 2023, (c) 00Z 24 Oct 2023, (d) 12Z 24 Oct 2023, (e) 00Z 25 Oct 2023, (f) 12Z 25 Oct 2023, (g) 00Z 26 Oct 2023 and (h) 12Z 26 Oct 2023

A minor pressure disturbance first developed over the central BoB, according to the SC Hamoon Sea Level Pressure (SLP) evolution. As the system gradually strengthened, it acquired a clear cyclonic structure by October 23 (Fig. 4). A simulation around the landfall on the late night of 23 Oct 2023 point indicates a low SLP of 995 hPa. The cyclone moved north before making landfall over southeast Bangladesh. Out of the three microphysics schemes analyzed, WSM6 and WSM7 showed better results than SBU-YLin in accurately simulating the strength of cyclone and accurately reflecting the pressure gradient and WSM7 showed better output among WSM6 and WSM7 (Table 3).

The low-pressure system of SC Remal started to develop over the eastern and central Bay of Bengal. On May 26, the cyclone had significantly intensified; a stronger storm was indicated by the simulated lowest central pressure falling to 984 hPa. SC Remal moved northwest before making landfall along the southwest coast of Bangladesh (Fig. 5). WSM6 and WSM7 schemes performed well in reproducing the sea-level pressure evolution of SC Remal, though WSM7 performed well; however, SBU-YLin showed more significant variability and more departures from published data (Table 3).

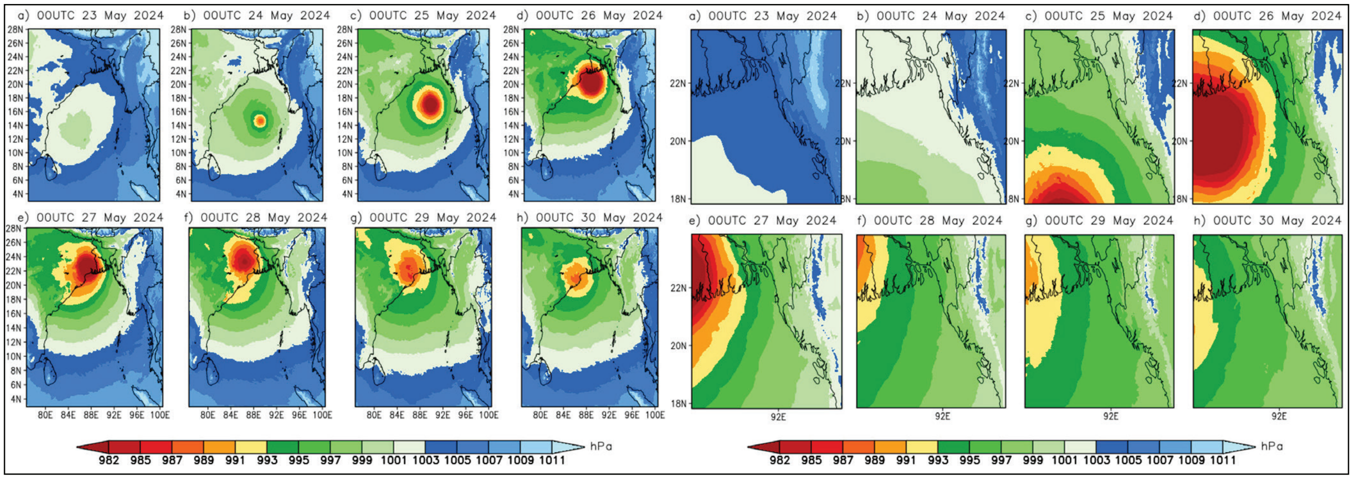

Figure 5: Model Simulated SC Remal Sea Level Pressure of Domain 01(left panel) and Domain 02 (right panel) using WSM7 Microphysics on 0000 UTC 26 May 2024 Valid for (a) 00Z 26 May 2024, (b) 12Z 26 May 2024, (c) 00Z 27 May 2024, (d) 12Z 27 May 2024, (e) 00Z 28 May 2024, (f) 12Z 28 May 2024, (g) 00Z 29 May 2024 and (h) 12Z 29 May 2024

Temperature

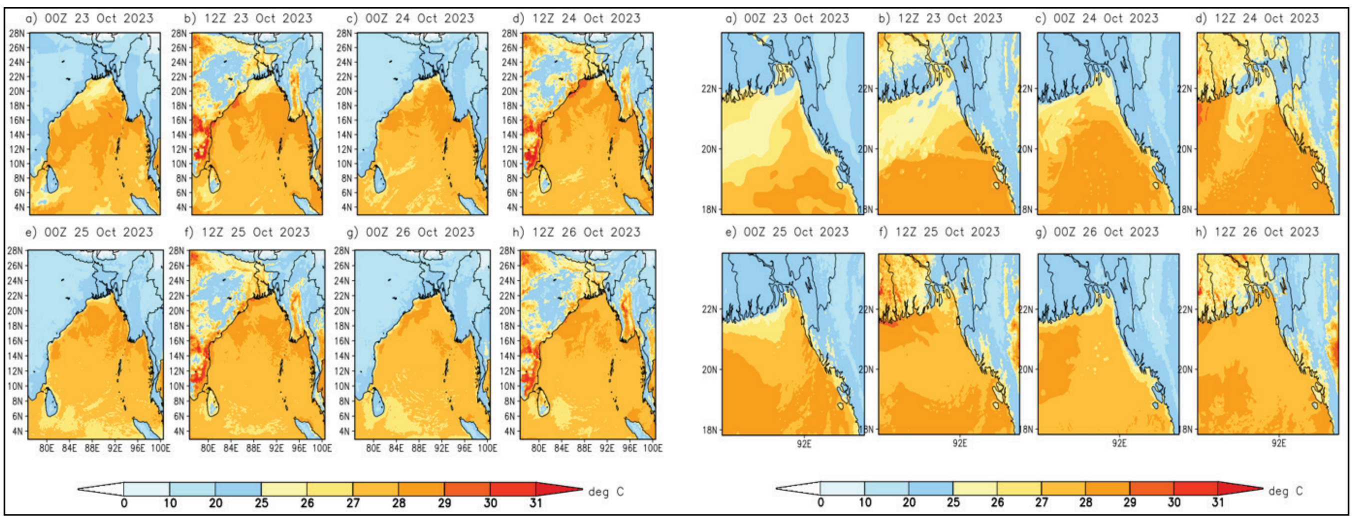

Figure 6: Model Simulated SC Hamoon 2-Meter Temperature of Domain 01(left panel) and Domain 02 (right panel) using WSM6 Microphysics on 0000 UTC 23 Oct 2023 Valid for (a) 00Z 23 Oct 2023, (b) 12Z 23 Oct 2023, (c) 00Z 24 Oct 2023, (d) 12Z 24 Oct 2023, (e) 00Z 25 Oct 2023, (f) 12Z 25 Oct 2023, (g) 00Z 26 Oct 2023 and (h) 12Z 26 Oct 2023

The surface temperature over the Bay of Bengal has a major impact on the formation and strengthening of tropical cyclones. Warm anomalies were visible in the temperature distribution of Bay by 23 Oct 2023 during SC Hamoon (Fig. 6), with surface temperatures over 27°C in significant areas. The warmth increased even further on October 24 and 25, reaching the maximum recorded temperatures of 30 to 31°C in certain areas. The temperature distribution remained relatively steady through 26 Oct, indicating that the cyclone would still have energy available. WSM6 and WSM7 both showed better results in microphysics, and SBU-YLin is unstable.

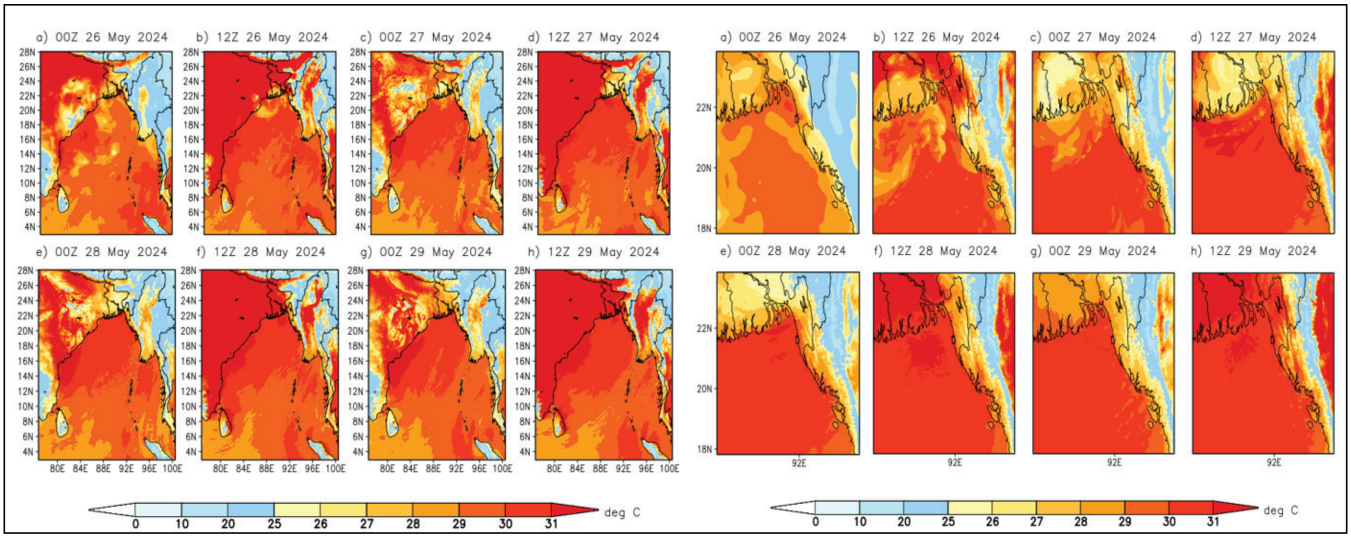

Figure 7: Model Simulated SC Remal 2-Meter Temperature of Domain 01(left panel) and Domain 02 (right panel) using WSM6 Microphysics on 0000 UTC 26 May 2024 Valid for (a) 00Z 26 May 2024, (b) 12Z 26 May 2024, (c) 00Z 27 May 2024, (d) 12Z 27 May 2024, (e) 00Z 28 May 2024, (f) 12Z 28 May 2024, (g) 00Z 29 May 2024 and (h) 12Z 29 May 2024

The surface warming significantly in Bay of Bengal, with average temperatures rising beyond 28°C, according to model predictions for SC Remal from May 23 to May 30, 2024 (Fig. 7). Following May 26, the temperature rose sharply, reaching a high of almost 30°C. The rapid intensification of SC Remal is consistent with this warm anomaly. The SBU-YLin microphysics was accurate with the time for SC Remal, but WSM6 showed better stability. 168-hour result was better for WSM6 than SBU-YLin, but with time, accuracy was increased for both the microphysics (Table 3).

Table 3: Error Calculation of SC Hamoon and Remal

Variables	Evaluation Procedure	Run Hour	Hamoon			Remal		
			WSM6	WSM7	SBU-YLin	WSM6	WSM7	SBU-YLin
Wind	RMSE	168	13.4	11.9	18.1	13.7	14.3	12.1
		96	6.8	6.8	7.3	7.1	7.5	6.2
	MAE	168	8.9	7.9	13.8	10.1	10.5	9.1
		96	4.7	4.8	5.2	6.2	6.6	5.4
	MB	168	-7.5	-6.5	-12.7	-4.8	-5.1	-6.8
		96	-2.2	-2.6	-4.3	0.9	1.3	0.1
Sea Level Pressure	RMSE	168	3.3	2.8	5.1	5.5	5.4	6.2
		96	1.9	1.8	2.7	3.2	3.1	4.5
	MAE	168	1.4	1.3	2.4	4.5	4.5	4.9
		96	1.2	1.1	1.8	2.7	2.7	3.9
	MB	168	2	1.9	3.2	3.4	3.3	3.8
		96	1.6	1.5	2.2	1.9	1.7	1.9
Temperature	RMSE	168	3.1	3.1	2.7	2.6	2.2	2.7
		96	2.4	2.5	2.7	1.2	1.3	1.1
	MAE	168	2.6	2.6	2.3	1.6	1.6	1.9
		96	2.1	2.2	2.4	1	1.1	0.8
	MB	168	0.2	0.2	0.03	-1.1	-1.1	-1.4
		96	0.1	0.03	-0.2	0.2	0.2	-0.003

Relative Humidity	RMSE	168	14.6	14.8	14.3	11.8	12.1	13.5
		96	11.8	16.3	11.7	7.8	7.3	7.4
	MAE	168	13.4	14	13	9.1	9.5	10.6
		96	9.7	12.4	10.7	6.4	5.6	6.4
	MB	168	3.3	3.6	2.5	5.4	6.9	9.2
		96	1.7	9	3.6	-1.6	-1.8	-0.8

Vertical Profile of Relative Humidity

The model-generated vertical profile of relative humidity along the cyclone track of Hamoon is illustrated in the figure (Fig. 8). High relative humidity values (>80%) were observed concentrated within a deep vertical column spanning from the lower to the upper troposphere, indicating significant moisture saturation linked to the core of cyclone. A specific region of extreme humidity (surpassing 90%) was detected in a vertically narrow yet widespread column extending to the upper atmosphere, indicative of vigorous convective activity and persistent updrafts inside the storm system.

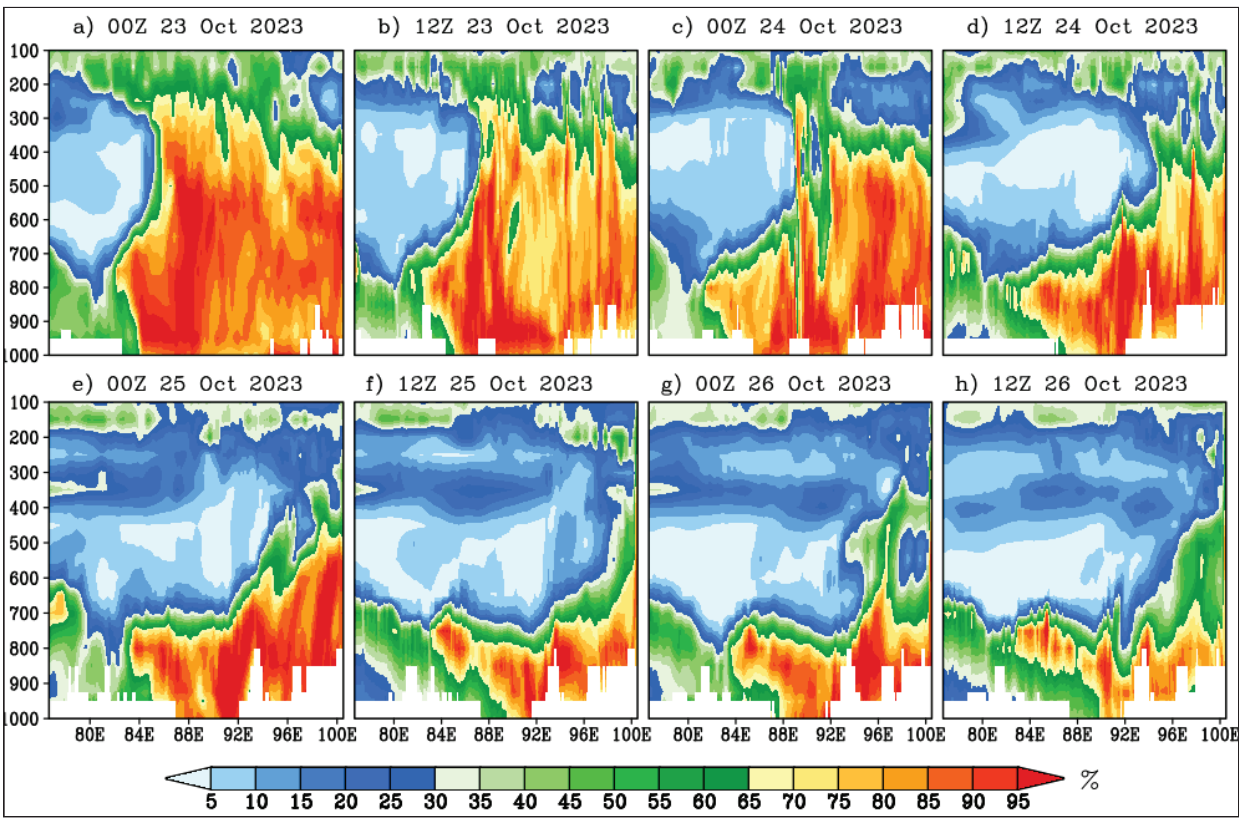

Figure 8: Model Simulated SC Hamoon Vertical Relative Humidity of Domain 01 using WSM6 Microphysics on 0000 UTC 23 Oct 2023 Valid for (a) 00Z 23 Oct 2023, (b) 12Z 23 Oct 2023, (c) 00Z 24 Oct 2023, (d) 12Z 24 Oct 2023, (e) 00Z 25 Oct 2023, (f) 12Z 25 Oct 2023, (g) 00Z 26 Oct 2023 and (h) 12Z 26 Oct 2023

With peak values strongly collocated with the convective center of the storm, WRF-simulated vertical profiles of relative humidity along track of Cyclone Remal (26–29 May 2024) expose a deep, moisture-saturated core (>90% RH) spanning from the surface to the upper troposphere (Fig. 9). The persistent vertical column of high humidity underscores sustained updrafts and effective moisture convergence, which are key to the survival of cyclone. The humidity structure stays vertically consistent across all time steps; minor dry intrusions at mid-levels (12Z 27 May) seem to be unsteady and probably affect transient intensity fluctuations. Microphysics WSM7 outperformed the other schemes for both cyclones. SBU-YLin showed better results with the time, but WSM6 was more stable during simulations of 168 and 96 hours.

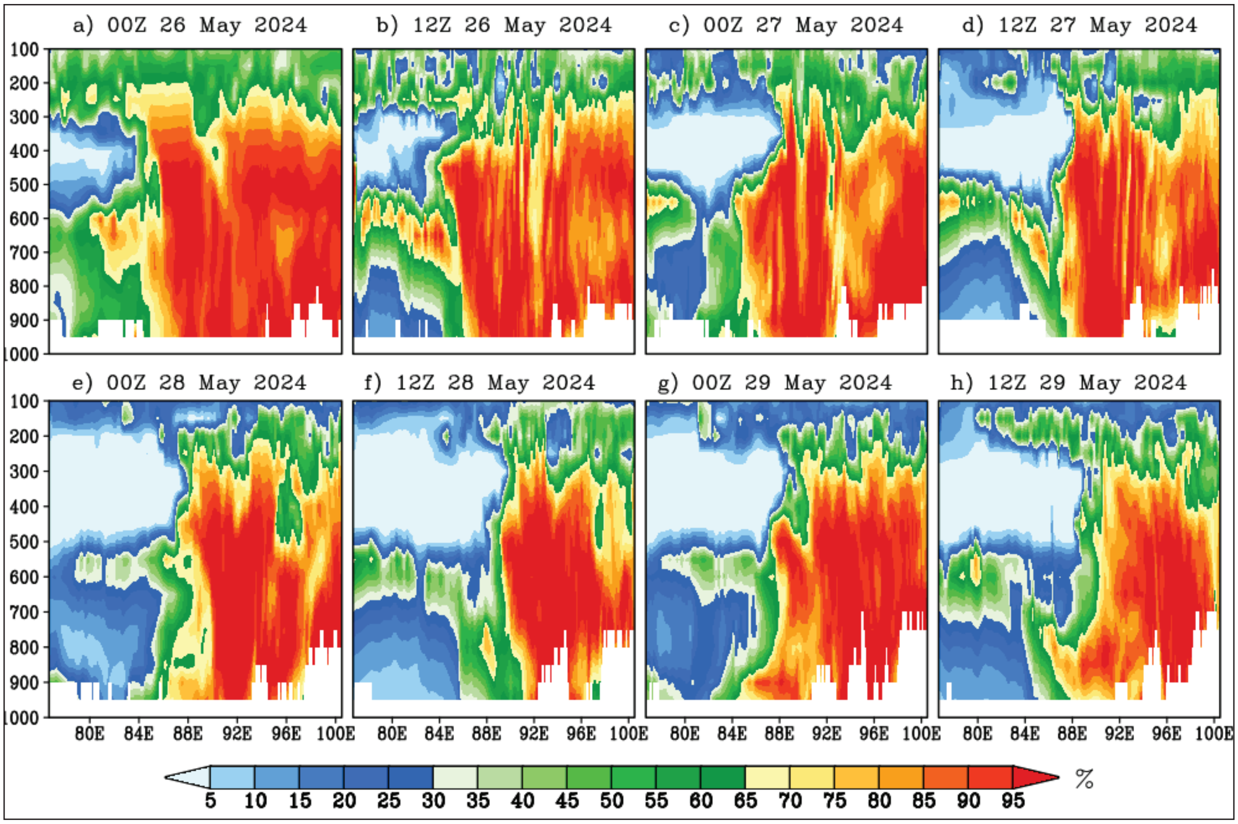

Figure 9: Model Simulated SC Remal Vertical Relative Humidity of Domain 02 using WSM6 Microphysics on 0000 UTC 26 May 2024 Valid for (a) 00Z 26 May 2024, (b) 12Z 26 May 2024, (c) 00Z 27 May 2024, (d) 12Z 27 May 2024, (e) 00Z 28 May 2024, (f) 12Z 28 May 2024, (g) 00Z 29 May 2024 and (h) 12Z 29 May 2024

Precipitation

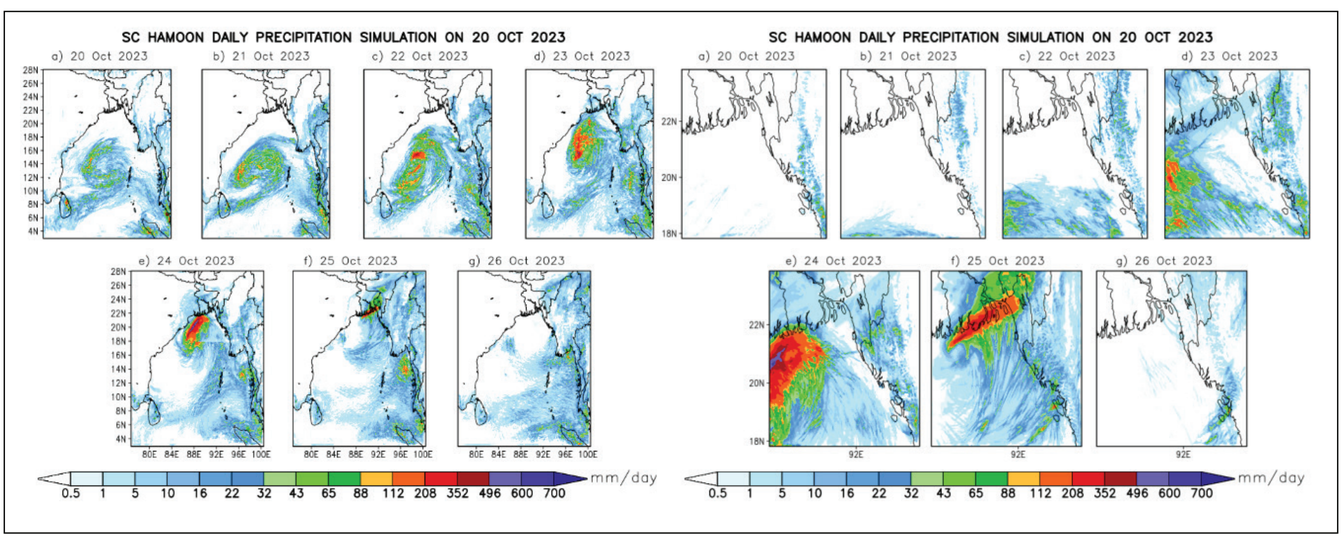

Figure 10: Model Simulated SC Hamoon Precipitation of Domain 01(left panel) and Domain 02 (right panel) using Microphysics WSM6 on 20 Oct 2023 Valid for 0000 UTC of (a) 20 Oct 2023, (b) 21 Oct 2023, (c) 22 Oct 2023, (d) 23 Oct 2023, (e) 24 Oct 2023, (f) 25 Oct 2023 and (g) 26 Oct 2023

As the storm Hamoon developed stronger over the Bay of Bengal, the amount of precipitation progressively rose. The maximum precipitation amounts recorded on October 23 and 24 were associated with the peak strength of storm (Fig. 10). The model simulations captured the maximum precipitation well, though variations existed across microphysics schemes.

Remarkably, the WSM7 scheme generated an extreme maximum of 1000 mm on October 23 (Table 4), which was significantly larger than the observed results and had a tendency to overestimate in shorter forecasts. The same situation goes for WSM6 and SBU-YLin. The 168-hour run showed better results compared to the 96-hour run, and WSM6 is stable, though SBU-YLin outputs were good. The domain 02 (Fig. 10) displays heavy precipitation localized in the landfall area.

Table 4: Comparison between Observed and Simulated Maximum Precipitation of Severe Cyclone Hamoon

Date	GPM Maximum Precipitation (mm)	Model Simulated SC Hamoon Maximum Precipitation (mm)					
		168 hours			96 hours		
		WSM6	WSM7	SBU-YLin	WSM6	WSM7	SBU-YLin
20 Oct 2023	220	350	350	240			
21 Oct 2023	270	240	240	300			
22 Oct 2023	240	500	450	400			
23 Oct 2023	270	550	650	450	900	1000	550
24 Oct 2023	300	700	700	700	450	600	350
25 Oct 2023	130	350	450	450	200	160	240
26 Oct 2023	130	270	240	350	160	200	220

Table 5: Comparison between Observed and Simulated Maximum Precipitation of Severe Cyclone Remal

Date	GPM Maximum Precipitation (mm)	Model Simulated SC Remal Maximum Precipitation (mm)					
		168 hours			96 hours		
		WSM6	WSM7	SBU-YLin	WSM6	WSM7	SBU-YLin
23 May 2024	300	350	300	400			
24 May 2024	600	600	550	500			
25 May 2024	700	700	800	650			
26 May 2024	650	700	700	650	350	350	400
27 May 2024	300	550	400	450	650	500	400
28 May 2024	180	300	270	330	500	350	650
29 May 2024	300	300	270	450	270	240	300

The 96-hour forecasts, which showed significant increases in precipitation on May 26–27 (Table 5), captured the intensification period of SC Remal more effectively. SC Remal maintained high precipitation levels for a considerable amount of time after landfall.

SC Remal had a significant amount of convective activity; there was a lot of precipitation in the Bay of Bengal and along the coast (Fig. 11). The observed intensification is consistent with peak precipitation, which the 168-hour simulations show happens between May 25 and May 27. On May 25, the maximum precipitation values in all models were around 700 mm (Table 5), which is consistent with GPM measurements.

The precipitation distribution in the simulations was more in line with the WSM6 scheme for SC Hamoon. However, WSM7 displayed significant overestimations throughout the 96-hour forecast, particularly for SC Hamoon. In contrast, the WSM6 system generated more reasonably consistent forecasts than SBU-YLin and performed well for SC Remal, too. 168-hour simulations were more accurate in capturing overall precipitation trends.

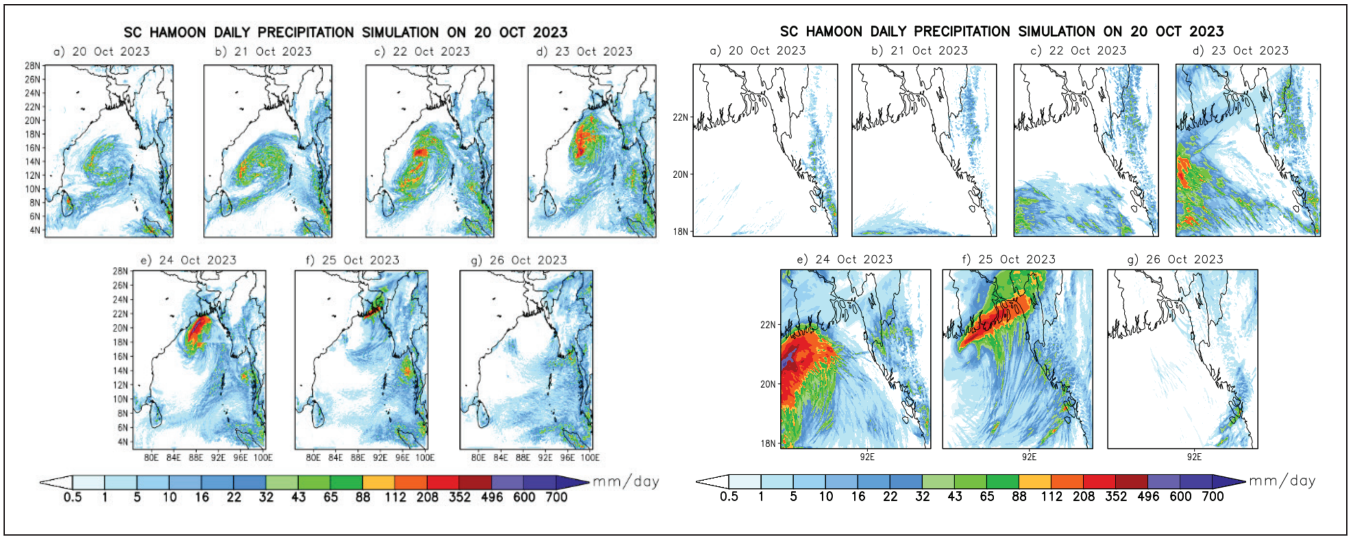

Figure 11: Model Simulated SC Remal Precipitation of Domain 01 (left panel) and Domain 02 (right panel) using Microphysics WSM6 on 23 May 2024 Valid for 0000 UTC of (a) 23 May 2024, (b) 24 May 2024, (c) 25 May 2024, (d) 26 May 2024, (e) 27 May 2024, (f) 28 May 2024 and (g) 29 May 2024

Track Error Prediction (SC Hamoon)

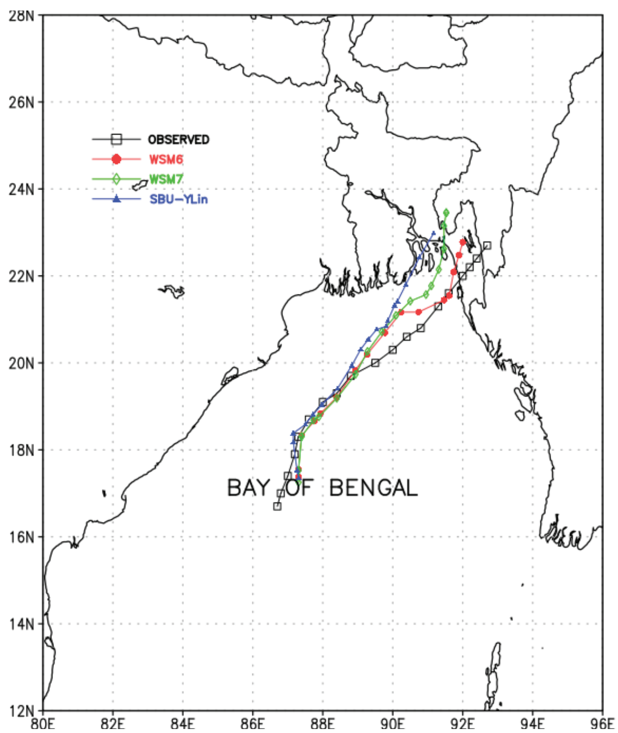

Figure 12: Comparison of Model Simulated SC Hamoon Forecast Track (based on 0000 UTC of 23 Oct 2023) using Microphysics WSM6, WSM7 and SBU-YLin with the Observed Track of RSMC Best Track

SC Hamoon originated over the Bay of Bengal and moved north-northeast before making landfall over southeast Bangladesh. Figure 12 compares the three microphysics schemes (WSM6, WSM7, and SBU-YLin) with the observed track. The disagreement between simulated and observed tracks is expected in NWP-based cyclone forecasting. It is primarily due to uncertainties in GFS-derived initial and boundary conditions, which amplify progressively over the simulation period causing cumulative positional drift. Additionally, model resolution limitations may not fully capture the inner core structure of cyclone, while differences in microphysics assumptions further influence the simulated track. Despite this, SBU-YLin has the highest mean error and standard deviation, showing considerable changes in cyclone placement (Table 6). Compared to SBU-YLin, WSM6 and WSM7 did rather well; the 96-hour simulations produced improved track predictions with a notable decrease in errors. The WSM6 scheme produced the least amount of variance. Given that WSM6 is better than the other two schemes in predicting the track of SC Hamoon, with RMSE of 62.8 km in the 96-hour simulation, these results show that shorter prediction periods increase track accuracy.

Track Error Prediction (SC Remal)

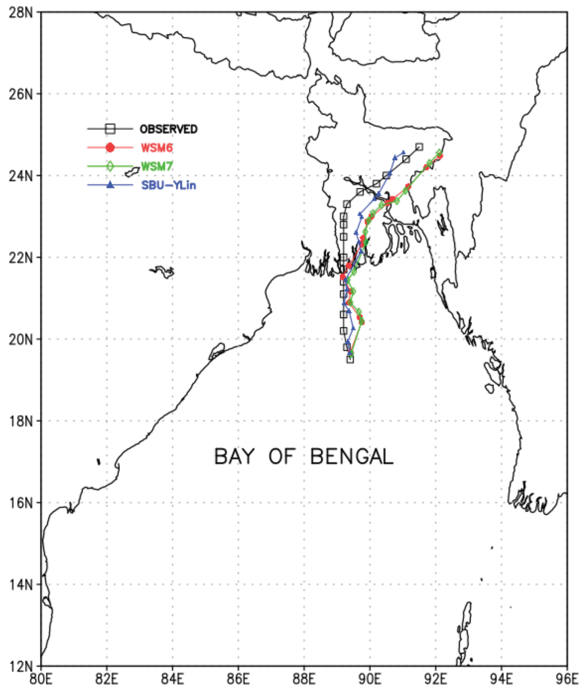

Figure 13: Comparison of Model Simulated SC Remal Forecast Track (based on 0000 UTC of 26 May 2024) using Microphysics WSM6, WSM7 and SBU-YLin with the Observed Track of RSMC Best Track

When SC Remal formed in May 2024, its simulated tracks showed greater inter-scheme divergence compared to Hamoon, as reflected in the higher standard deviations across all microphysics schemes (Table 6). The observed track and model simulations are shown (Fig. 13). This wider spread among the simulated tracks may be linked to more complex convective structure of Remal and asymmetric moisture distribution, which are inherently harder to capture in NWP models. For the 168-hour simulation, WSM6 shows the lowest ME, followed by WSM7 and then SBU-YLin. Notably, WSM6 remains the most consistent from the long to the short forecast ranges. SBU-YLin produced the highest ME and SD for 168-hour simulation and showed the most variation. However, it has the lowest ME of 38.1 km and SD of 16.9 for 96-hour. These results imply that SBU-YLin exhibits significant improvement in shorter periods but becomes less dependable over a long period of time.

These findings indicate that forecast accuracy depends on lead time and cyclone characteristics. WSM6 provides greater stability for extended simulations, whereas SBU-YLin performs better in short-range forecasts, suggesting that microphysics selection should depend on forecast duration.

Table 6: Model Simulated SC Remal and SC Hamoon Track Position Error

Events	Microphysics	Forecast Period (hrs)	Track Position Error (km)	
			Mean Error (km)	Standard Deviation (km)
Hamoon	WSM6	168	268.5	86.96
		96	**62.8**	28.24
	WSM7	168	**242.4**	61.83
		96	86.3	32.9
	SBU-YLin	168	352.7	172.70
		96	99.4	68.4
Remal	WSM6	168	**206.9**	174.19
		96	59.3	27.6
	WSM7	168	215.5	177.4
		96	59.3	27.6
	SBU-YLin	168	373.5	306.5
		96	**38.1**	16.9

CONCLUSION

The study tested several microphysics schemes by modeling the recent cyclones Hamoon and Remal in order to determine the best forecast in the area. Although there were some differences, the simulated results closely matched the observed data, demonstrating the WRF model's dependability for regional cyclone forecasting. The model adequately captured surface wind, sea level pressure, and temperature throughout both cyclone lifecycles. Notably, the vertical profiles of relative humidity revealed a deep moisture-saturated core exceeding 90% RH spanning from the surface to the upper troposphere for both cyclones, indicative of vigorous convective activity and persistent updrafts within the storm systems. Similarly, precipitation progressively intensified as both storms strengthened, with peak amounts for Hamoon recorded on October 23–24 and for Remal during May 25–27, broadly consistent with GPM observations, though variations in magnitude existed across microphysics schemes. Regional differences in performance were found through a comparative analysis of various microphysics schemes. Hence, WSM6 and WSM7 both performed reliably for Chattogram Port during Hamoon, with WSM6 yielding the most accurate results and SBU-YLin showing variability. At 96 hours, WSM6 and WSM7 show comparable skill for Hamoon, while SBU-YLin performs best for Remal wind and temperature and WSM7 provides the most balanced accuracy across variables. Moreover, at 168 hours WSM7 consistently performs best for Hamoon, while for Remal no single scheme dominates and SBU-YLin and WSM6 demonstrate variable-specific strengths. WSM6 performed better for Hamoon due to its strong deep convective core and graupel dominated heat processes over open warm waters. SBU-YLin performed better for Remal because it handled asymmetric convection and coastal moisture interactions more effectively in the short range. These results highlight that SBU-YLin was more successful for short-range forecasting at Mongla Port, while WSM6 was the best microphysics scheme for Chattogram Port. The 96-hour forecasts show improved performance for track, wind, and pressure, while 168-hour simulations occasionally capture precipitation trends more effectively. These findings directly support the development of port-specific operational forecasting frameworks, providing actionable guidance for early warning systems, maritime safety planning, and real-time decision-making for major seaports of Bangladesh. The accuracy of cyclone forecast can be greatly increased by incorporating real-time observational data, employing sophisticated models for numerical weather prediction, and optimizing microphysics parameterization. Consequently, future studies with more events should investigate different combinations of physics, such as cumulus, PBL, and microphysics.

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