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Predictability of tropical cyclone intensity using Weather Research and Forecasting model over the Bay of Bengal

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Abstract:
Tropical cyclones (TCs) pose significant threats to human lives and property, highlighting the critical importance of accurate forecasts and timely warnings for coastal communities. This study evaluates TC intensity prediction using the Weather Research and Forecasting (WRF) model, focusing on three specific TCs—Amphan (2020), Bulbul (2019), and Titli (2018) over the Bay of Bengal (BoB). The selected TCs are simulated across various forecast lead times (LT) using two two-way interactive nested domains. Global Data Assimilation System (GDAS)/Final analysis (FNL) data serve as these simulations' initial and lateral boundary conditions. The model-predicted intensity in terms of Maximum Wind Speed (MWS), and Minimum Sea Level Pressure (MSLP) are compared against the Regional Specialized Meteorological Centre (RSMC), New Delhi's best track data. Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) are calculated to quantify the model's performance relative to the best track data. The study reveals that MAE and RMSE decrease for all TCs as forecast lead time decreases. Specifically, MAE ranges between 5.75 to 11.55 knots for MWS and 1.40 to 5.39 hPa for MSLP within 48 hours of forecast LT. Similarly, RMSE for MWS ranges from 7.21 to 12.95 knots and for MSLP from 1.78 to 6.06 hPa over the same lead time. Furthermore, the WRF model's performance relative to the ECMWF model is assessed using Taylor Diagrams showing that the WRF model performs better than the ECMWF in predicting TC intensity when compared against the best track data. In conclusion, based on these findings, the WRF model demonstrates significant capability in accurately forecasting TC intensity with sufficient LT. This underscores its potential utility in enhancing early warning systems and preparedness efforts for tropical cyclones affecting coastal regions.
Keywords: *Tropical Cyclones, BoB, WRF model, MAE, RMSE*

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I. Introduction

Tropical Cyclones (TCs) are the most devastating natural disasters on the planet. The countries bordering the Bay of Bay (BoB), especially Bangladesh, India, and Myanmar are one of the most terribly affected regions in the world. The coastal zones of BoB are mostly vulnerable to hazards attributed to TCs, due to dense population over coastal regions and a shallow continental shelf that magnifies wind-driven storm surges[1]. Countries bordering the BoB basin are experiencing nearly 7% of the TCs globally, but attain 80% of TC-induced fatalities worldwide[2]. Most of the TCs are initiated over the BoB and make landfall over the east coast of India-Bangladesh and sometimes over the west coast of Myanmar. Hence, an accurate and timely forecast of TCs track and intensity with sufficient LT is crucial for disaster mitigation. Owing to the advent of the Numerical Weather Prediction (NWP) model, the prediction of TCs in track and intensity has improved significantly. The precise prediction of the TC intensity is still challenging for operational forecasters.

The intensity of TC largely depends on three factors, e.g., the initial strength of TC, the thermodynamic feature of the atmosphere, and the heat flux between the TCs and the underlying surface[3]. However, it is difficult to forecast TC intensity precisely due to the inadequate understanding of TC dynamics[4]. In the past three decades, the track prediction of TC has improved significantly with the application of meteorological satellites and the fame of ensemble forecasts for TC track[5,6]. The intensity prediction is still poor compared with the track forecast and is a worldwide challenge[7,8]. TC intensity is largely influenced by two key physical processes[9], which are synoptic variables such as vertical wind shear, humidity, sea surface temperature, water vapor, divergence, and climatological and persistent variables such as latitude, longitude, Julian day, and sea-land ratio[10,11].

The performance of NWP models in predicting the TC track and intensity has been assessed by many investigators over the North Indian Ocean (NIO). Scatterometer-derived wind vector data over NIO was assimilated into the Global Data Assimilation and Forecasting (GDAF) system[12]. They found betterment in the location of the TC center TC and intensity compared to the available best-track data. The ability of the Global Ensemble Forecasting System (GEFS) model was evaluated over NIO[13]. The results indicated that the TC intensity in terms of MWS is under-estimated. Atmospheric retrievals from hyperspectral instruments were assimilated into the WRF to improve the prediction of hurricanes Florence and Michael [14]. Besides, the insufficient knowledge of multifaceted physical processes, the imprecise vortex initialization, and huge calculations hinder the ability of NWP to predict accurately and competently[15]. The foremost objective of the present study is to evaluate the performance of the WRF model in predicting the intensity of TCs formed over the BoB. TC intensity forecast using the WRF model needs to be verified so that it can play a vibrant role in improving TC intensity prediction.

II. Model setup

The non-hydrostatic compressible WRF model was developed by the National Centre for Atmospheric Research (NCAR). It has features like a fully compressible, Eulerian non-hydrostatic control equation set, a terrain following, hydrostatic pressure vertical coordinate system with the constant pressure surface at the top level of the model. The staggering Arakawa-C grid, and a third-order Runge-Kutta time integration scheme is used for both horizontal and vertical directions in the model. The WRF model incorporates several processes like MP, CP, PBL, surface layer, land surface, long wave, and short-wave radiations with multiple options for each process[16]. The input details of the model are given in Table 1. The model domain selected for the study is given in Fig.1. Tracks of the selected TCs are presented in Fig. 2.

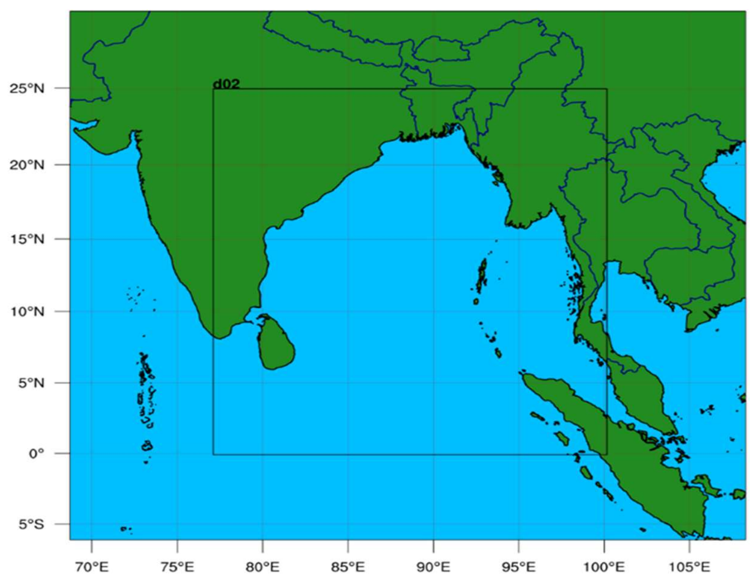

Fig. 1 Two-way nested domain selected for the study. The horizontal resolution of the outer domain is 27 km and the inner domain is 9 km

III. Data and methodology

The initial and boundary conditions for WRF are derived from the Global Tropospheric Analyses and Forecast Grids data (at 0.25°×0.25° resolution) of the Global Data Assimilation System (GDAS)/Final Analyses (FNL) of the National Centers for Environmental Prediction (NCEP).

The Sea Surface Temperature (SST) is kept constant during the integration, nonetheless, the lateral boundary conditions are updated every 6 hours. The United States Geological Survey (USGS) 10 min resolution terrain topographical data have been used in the WRF Preprocessing System (WPS).

The model was initialized at 120 hrs, 96 hrs, 72 hrs, 48 hrs, and 24 hrs LT before the landfall of Amphan and Bulbul. Again, for Titli it was initialized at 96 hrs, 72 hrs, 48 hrs, and 24 hrs LT before the landfall. Products from the inner domain with 9 km resolution are considered for the analysis. The model predicted intensity in terms of MWS and MSLP with positions calculated at every 3-hour interval. MAE and RMSE are calculated with respect to RSMC, New Delhi's best track data. The WRF model performance is evaluated using Taylor's performance diagram against the ECMWF model with respect to best track data provided by RSMC, New Delhi. Calculated MAE and RMSE for the selected TCs are presented in Table 2.

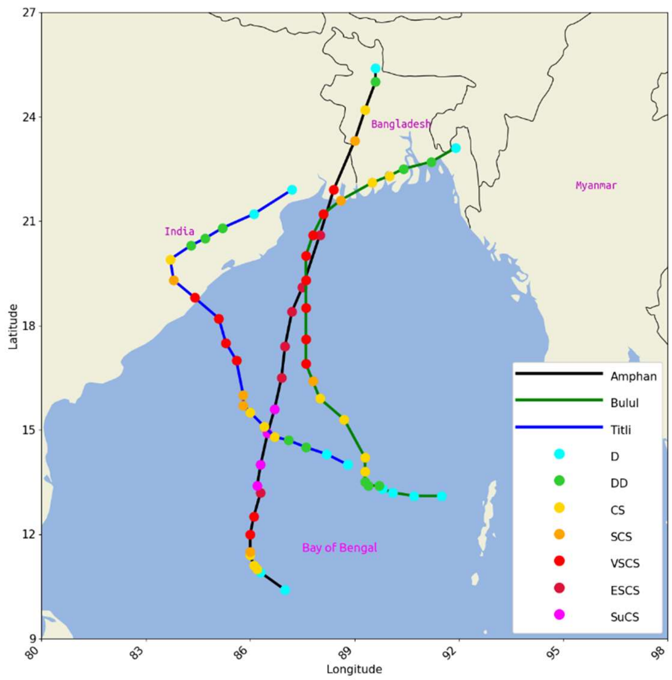

Fig. 2 Observed tracks of the selected TCs for the study. The black line represents Amphan, the green line represents Bulbul and the blue line represents Titli. Markers with different colors represent different intensity stages.

Table 1 Brief description of WRF model configuration

Model	WRF V4.2
Max_domain	2
Map Projection	Mercator
Resolution	27 km, 9 km
Time step	108s, 36s
Central point of the domain	17.5^0 N, 87.5^0E
No. Of grid points	152, 265(WE); 144, 298(NS)
No. Of Vertical levels	42 Sigma Levels
Horizontal Grid	Arakawa C Grid
Time Integration	Runge-Kutta second and third-order time
Radiation Scheme	Dudhia's short wave/RRTM long-wave
PBL Scheme	YSU scheme
Convection	Kain-Fritsch (new Eta) scheme
Micro Physics	WSM3-class simple ice scheme

IV. Results and discussion

The intensity of a TC is measured by two parameters, i.e., MWS and MSLP. The WRF model predicted intensity and observed intensity at different initial conditions are compared for all selected cases. The predicted intensity errors for the MWS and MSLP are verified in terms of MAE and RMSE. The intensity errors for all the individual cyclones are calculated. The MAE and RMSE are shown in Table 2. The MAE shows 8.85 - 20.12 kts; 2.92 - 14.59 hPa and the RMSE is 12.38 - 22.17 kts; 3.58 - 17.10 hPa for MWS and MSLP respectively for 24-120 hrs forecast LT in case of Amphan. Again, the MAE shows 5.75 - 9.78 kts; 3.65-6.58 hPa, and the RMSE is 7.21 - 11.87 kts; 4.29- 8.38 hPa for MWS and MSLP respectively for 24-120 hrs forecast LT in case of Bulbul.

Furthermore, Titli shows MAE of 7.51 - 11.55 kts; 1.40 - 11.55 hPa, and the RMSE is 9.59 - 13.40 kts; 1.78 - 9.89 hPa for MWS and MSLP respectively for 24-96 hrs forecast LT.

(a). Comparison of observed and predicted MWS and MSLP of Amphan

Amphan was a super cyclone that originated from the remnant of a low-pressure area. It was the first super cyclone over the BoB, after the Odisha super cyclone of 1999. The peak MWS of Amphan was 130 kts during 18 UTC 18 May to 00 UTC 19 May. The model predicted and observed MWS and MSLP of Amphan are presented in Fig. 3. Vertical bars represent wind speed (Blue: observed, Green: predicted) and lines represent MSLP (Black: observed, Red: Predicted). It is seen that the intensity in terms of MWS is over-estimated and MSLP is under-estimated up to 42 hrs at 120 hrs LT forecast, as in Fig. 3(a). After that MWS is under-estimated and MSLP is over-estimated by the model. As forecast LT decreases, intensity and time of peak intensity forecast are improved. In 96 hrs forecast LT, the intensity forecast is reasonably well, though it is under-estimated by the model. Again, the prediction of time of peak intensity is very similar to that of observed, as shown in Fig. 3(b). In 72 hrs LT forecast, the peak intensity in terms of MWS and MSLP is well judgment, though slightly under-estimated by the model,

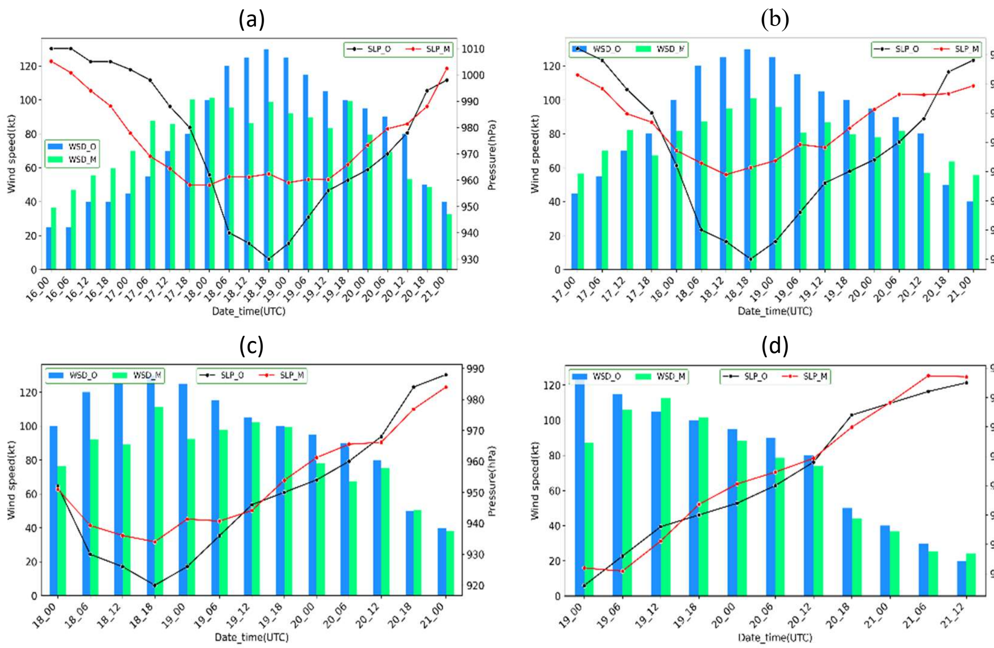

Fig. 3 Comparison of observed and predicted MSLP and MWS of Amphan. Vertical bars represent wind speed, where blue represents observed MWS and green model predicted MWS. Horizontal lines represent MSLP, where the black line represents observed and the red model predicted. (a) based on 00 UTC 16 May 2020, (b) based on 00 UTC 17 May 2020, (c) based on 00 UTC 18 May 2020, and (d) based on 00 UTC 19 May 2020.

as shown in Fig. 3(c). Intensity is very well predicted at 48 hrs LT, as in Fig. 3(d). MWS and MSLP are very close to the observation except for 00 UTC 19 May forecast. However, the peak intensity of the system in terms of MWS is under-predicted by the model by 19 kts.

(b). Comparison of observed and predicted MWS and MSLP of Bulbul

Bulbul was a very severe cyclonic storm that originated from the remnant of severe tropical storm 'Matmo' over the west Pacific Ocean that developed into the north Andaman Sea. The peak MWS of Bulbul was 75 kts from 06 UTC 08 Nov to 12 UTC of 09 Nov. Model predicted as well as observed MWS and MSLP are presented in Fig. 4. Intensity prediction in terms of MWS is over-estimated, MSLP is under-estimated for 120 hrs forecast LT and the peak intensity is predicted 06 hrs in advance, as shown in Fig. 4(a) by the model. MSLP is under-estimated up to 42 hrs at 120 hrs LT forecast, as in Fig. 3(a). Again, the MWS is over-estimated and MSLP is under-estimated up to 48 hrs for 96 hrs forecast LT, as shown in Fig. 4(b). Intensity in terms of MWS and MSLP are predicted reasonably well though there are some temporal biases. The model predicts the intensification of the system by 12 hrs in advance in case of 72 hrs forecast LT, as in Fig. 4(c). The model with 48 hrs forecast LT, shows tremendous performance for intensity prediction, though MWS is under-estimated and MSLP is over-estimated, as shown in Fig. 4(d).

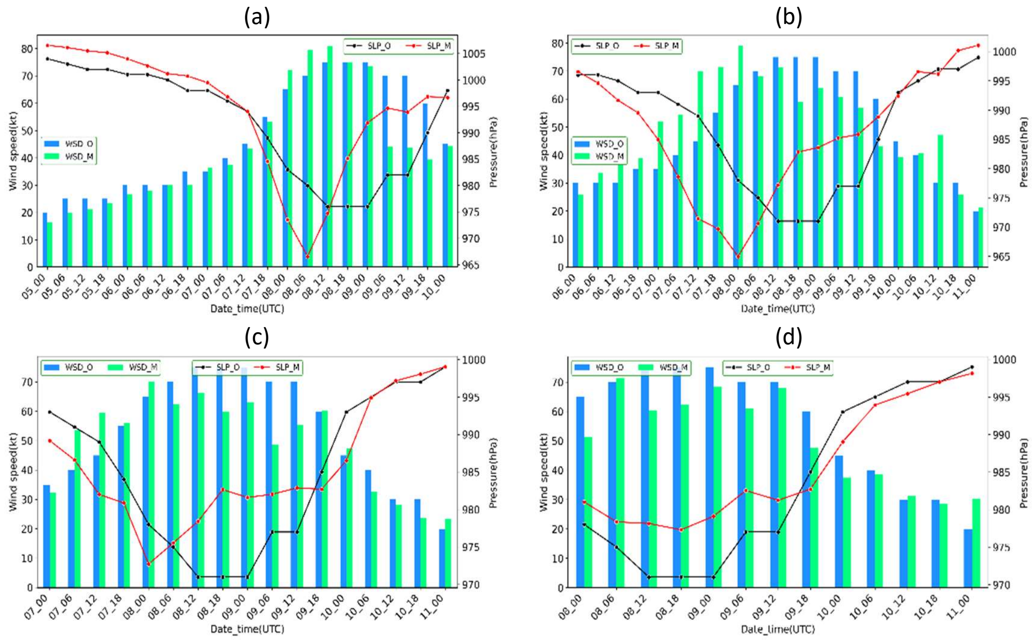

Fig. 4 Comparison of observed and predicted MSLP and MWS of Bulbul. Vertical bars represent wind speed, where blue represents observed MWS and green model predicted MWS. Horizontal lines represent MSLP, where the black line represents observed and the red model predicted. (a) based on 00 UTC 05 Nov 2019, (b) based on 00 UTC 06 Nov 2019, (c) based on 00 UTC 07 Nov 2019 and (d) based on 00 UTC 08 Nov 2019.

(c). Comparison of observed and predicted MWS and MSLP of Titli

Titli originated from a low-pressure area over southeast BoB and adjoining areas. The peak MWS of Titli was 80 kts from 12 UTC on 10 Oct to 00 UTC on 11 Oct. The model predicted as well as observed MWS and MSLP are presented in Fig. 5. Intensity prediction in terms of MWS and MSLP is very close to the observation up to 60 hrs, beyond that MWS is over-estimated and MSLP is under-estimated for 96 hrs forecast LT. Also, the time of the peak intensity is predicted reasonably well, as shown in Fig. 5(a). It is seen that the model over-estimated the intensity just after the peak intensity of the system, as in Fig. 5(a,b,c) for all initial conditions. However, the model prediction is rationally fine compared to the observation.

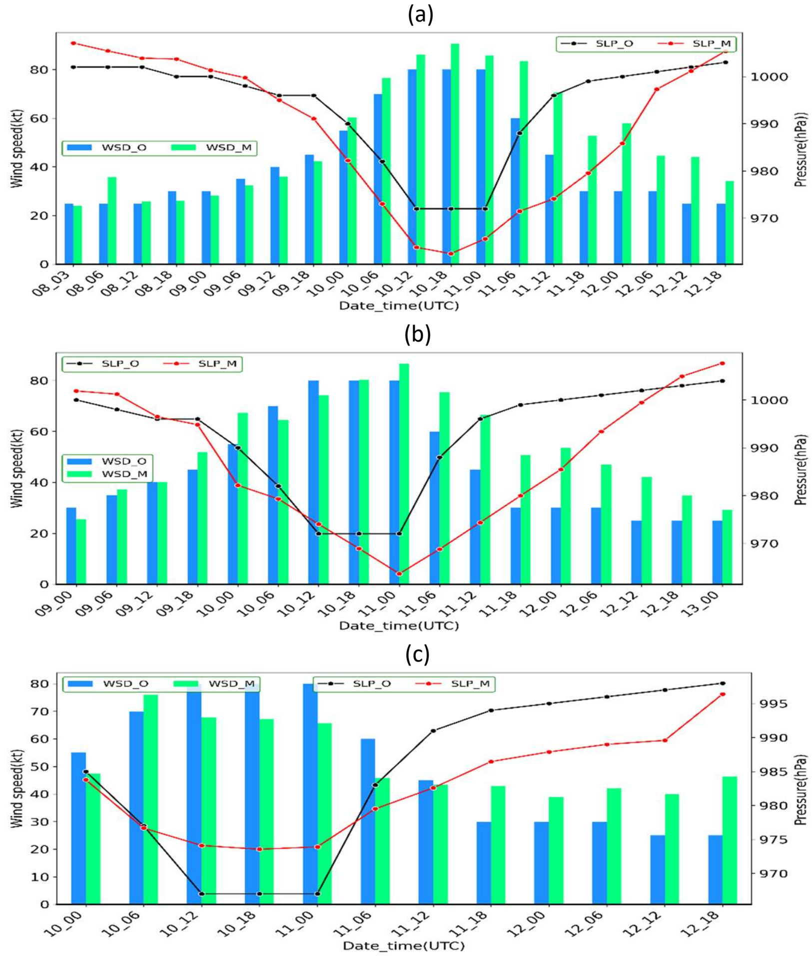

Fig. 5 Comparison of observed and predicted MSLP and MWS of Titli. Vertical bars represent wind speed, where cyan represents observed wind speed and magenta model predicted wind speed. The horizontal line represents minimum sea level pressure, where black represents observed and red model predicted. (a) based on 00 UTC 05 Nov 2019, (a) based on 00 UTC 08 Oct 2018, (c) based on 00 UTC 09 Oct 2018 and (d) based on 00 UTC 10 Oct 2018.

(d). Comparison of WRF and ECMWF model performance

The Taylor diagram is the mathematical diagram that provides a pictorial outline that permits a collection of variables from multiple models or reanalyses to be compared to reference data. The reference data can be observed or another model run. This diagram enables the relative evaluation of various models. It is used to assess model performance in terms of three statistics: the correlation coefficient, the root-mean-square deviation (RMSD), and the standard deviation(SD). The WRF model performance with 48 hrs forecast LT against the ECMWF model for best track data using Taylor performance diagrams are presented in Fig. 6. The Taylor diagram in Fig. 6 indicates the zero-line observed point where correlation is 1 and RMSD is 0. The RMSD is presented by a green dashed curved line. If the predicted value is close to the reference or observed value, then both are similar in terms of SD, correlation is high, and RMSD is close to zero. The black dashed curved line represents the SD of the observed data. If the predicted value is above the line, it means that the forecasted data set has a higher difference. The correlation between observed and predicted values is another useful piece of information gathered from the Taylor diagram. A higher correlation value means a high-level agreement between observed and predicted data. The correlation values are reduced when the predicted value goes toward higher parts in the diagram. RMSD displays the superiority of the simulation procedure. The blue marker represents WRF and the red cross marker represents ECMWF.

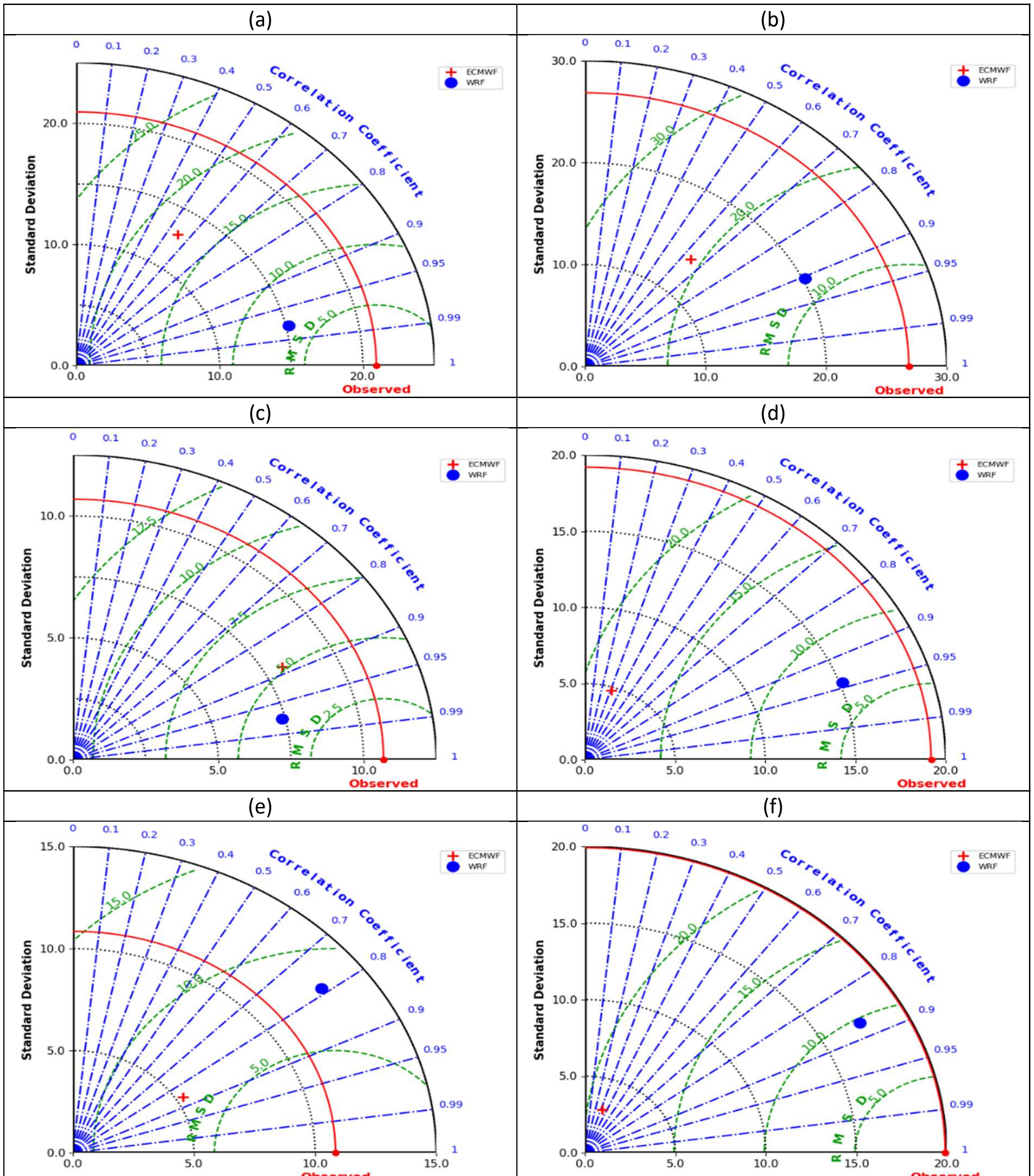

Fig. 6 Taylor diagrams indicate the standard deviation, the correlation coefficient, and the root mean square deviation. The left vertical panel represents MSLP and the right vertical panel MWS. Upper panel (a, b) for Amphan, middle panel (c, d) for Bulbul, and lower panel (e, f) for Titli. The blue marker represents WRF and the red cross marker represents ECMWF.

Fig. 6(a, c, e) represents model performance against MSLP. The blue marker has a lower SD, except for Titli where the SD is higher, the correlation is about 0.98, 0.97 and 0.79; the RMSD is close to 7, 3.5 and 8 respectively for Amphan, Bulbul, and Titli. The red cross marker has a lower standard deviation, the correlation is about 0.55, 0.88 and 0.85; the RMSD is close to 17.5, 5 and 7 respectively for Amphan, Bulbul, and Titli as in Fig. 6(a, c, e). Again, the Fig. 6(b, d, f) represents model performance against MWS. The blue marker has a lower SD, the correlation is about 0.91, 0.94 and 0.88; the RMSD is close to 13, 7 and 9 respectively for Amphan, Bulbul, and Titli. The red cross marker has a lower standard deviation, the correlation is about 0.64, 0.3 and 0.32; the RMSD is close to 21, 17 and 18 respectively for Amphan, Bulbul, and Titli as in Fig. 6(b, d, f).

Table 2 Calculated MAE and RMSE for the selected TCs

TC (name)	LT (hours)	MAE		RMSE	
		MWS	MSLP	MWS	MSLP
Amphan	120	19.56	14.43	22.17	17.10
	96	20.12	14.59	21.64	16.68
	72	15.79	6.61	19.92	7.92
	48	8.85	3.97	12.95	4.41
	24	11.17	2.92	12.38	3.58
Bulbul	120	6.18	5.21	9.96	7.03
	96	9.78	6.58	11.87	8.34
	72	8.10	4.40	10.06	5.59
	48	7.26	3.65	8.83	4.38
	24	5.75	4.29	7.21	5.03
Titli	96	10.24	7.14	13.40	9.43
	72	10.18	7.12	12.61	9.89
	48	11.55	5.39	12.54	6.06
	24	7.51	1.40	9.59	1.78

V. Conclusion

The objective of this study is to evaluate the performance of the WRF model in forecasting TC intensity over the BoB. Three TCs, i.e., Amphan, Bulbul, and Titli over the BoB are selected to achieve this. The WRF model is utilized to predict the corresponding TC center and intensity, specifically MWS and MSLP, for these selected TCs. These predictions are then compared with the Best Track data from the RSMC to assess the accuracy of the intensity forecasts. Statistical metrics such as MAE and RMSE are employed to verify the intensity predictions for all the TCs.

The intensity of TC in terms of MWS tends to be underestimated during the very intense stages of the TCs and overestimated during less intense stages. Conversely, the intensity in terms of MSLP is typically overestimated during very intense stages and underestimated during less intense stages of a TC. Across different forecast LT, the intensity predictions either overestimate or underestimate for all the TCs.

The maximum MAE for MWS reaches 20.12 knots for Amphan at 96 hours forecast LT, 9.78 knots for Bulbul at 96 hours LT, and 11.55 knots for Titli at 48 hours LT. For MSLP, the maximum MAE is 14.59 hPa for Amphan at 96 hours forecast LT, 6.58 hPa for Bulbul at 96 hours LT, and 7.14 hPa for Titli at 96 hours LT. The maximum RMSE for MWS is 22.17 knots for Amphan at 120 hours forecast LT, 11.87 knots for Bulbul at 96 hours LT, and 13.40 knots for Titli at 96 hours LT. For MSLP, the maximum RMSE is 17.10 hPa for Amphan at 120 hours forecast LT, 8.34 hPa for Bulbul at 96 hours LT, and 9.89 hPa for Titli at 72 hours LT.

The model demonstrates realistic performance in predicting TC intensity with 48 hours and 24-hour forecast LT based on MAE and RMSE for all the TCs. Specifically, RMSE for MWS is 12.38 knots for Amphan, 7.21 knots for Bulbul, and 9.59 knots for Titli in 24-hour forecast LT. RMSE for MSLP is 3.58 hPa for Amphan, 4.29 hPa for Bulbul, and 1.78 hPa for Titli in 24 hours forecast LT.

The intensity prediction for Amphan deteriorates significantly beyond 48 hours forecast LT, whereas for Bulbul and Titli, predictions remain reasonably accurate up to 120 hours forecast LT. Overall, the intensity prediction of up to 48 hours LT for all cases is reliable, reflecting the model's capabilities effectively within this LT.

The performance of the WRF model across various forecast LT is evaluated against the ECMWF model using Taylor performance diagrams, with the best track data serving as reference values. The intensity predictions, including MSLP and MWS, exhibit favorable results concerning SD, correlation, and RMSD compared to ECMWF. This suggests that the WRF model shows promising accuracy and reliability in forecasting TC intensity once compared to the ECMWF model, as indicated by the Taylor performance diagrams.

The results presented are derived from the study of only three specific TCs over the BoB. It is important to note that using best-track data from various meteorological centers can yield different error statistics. Therefore, further comparative studies using different best-track datasets are essential to understanding the WRF model's performance in TC intensity prediction. Nevertheless, the findings from this study strongly indicate that the WRF model demonstrates realistic performance in forecasting TC intensity over the BoB. Despite the need for broader comparative studies, the results obtained so far align well with the model's capability to provide accurate predictions of TC intensity in this region. This suggests that the WRF model holds promise for operational forecasting and research applications related to TCs in the BoB.

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