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Impact of Cumulus Convective and Planetary Boundary Layer Schemes to Apprehend the Best Track and Intensity of Tropical Cyclone Using WRF Model

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Abstract

This study endeavors to comprehend the dynamics of tropical cyclone (TC) from different dimensions with a view to saving lives and resources.The Advanced Research WRF (ARW) model has been used for the simulation of TCs.Three convective and two PBL parameterization schemes (PS) have been merged and integrated through operational run at Meteorological lab in Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh.

To have a systematic inter comparison of performances of PS for Bangladesh and its surroundings, a comprehensive sensitivity analysis on physical PS of WRF model have been carried out for the prediction of track and intensity of few TCs. For this, making six possible combinations of two PBL Schemes YSU (Yonsei University Scheme) and MYJ (Mellor Yamada Jainjic Scheme) and three convection schemes (Kain-Fritch, Betts-Miller, and Grell-Devenyi) of WRF-ARW model are employed to obtain the best combination for the prediction of TCs over Bay of Bengal. For this, Nargis,Thane and Mahasen TCs have been considered. The model domain is consist of single nested with 9 km horizontal resolution with 28 vertical sigma levels. The simulated track and intensity (pressure& wind) are compared with the IMD observed data and select the best combination. The tracks are also compared with those provided by the operational centers like NCEP and IMD. It is found that the combination of YSU PBL scheme with KF convection scheme (YKF) provides a better prediction of intensity, track, and rainfall.

Key words : WRF model, PBL, PS, CP and TC

1. Introduction

The physical parameterizations, which includes cumulus convection, surface fluxes of heat, moisture, momentum, and vertical mixing in the planetary boundary layer (PBL) play important role in the development and intensification of TCs (Anthes 1982). Among all, PBL and convection have long been recognized as processes of central importance in the genesis and intensification of TCs. In recent years, it has been realized that the PBL is a critical factor (Braun and Tao 2000) because of generation of the large fluxes of heat, moisture and momentum in this thin layer. Therefore, several PBL parameterization schemes (PBLSs) have been incorporated in the NWP models (e.g., Mellor and Yamada 1982; Hong et al. 2006). In addition, turbulent eddies in the PBL transport moisture into the free convection regime and thus favor intensification of TCs. As the scale of convective clouds is too small to be resolved by numerical models, a wide variety of cumulus parameterization schemes (CPSs) have also been developed and incorporated into three dimensional mesoscale models (e.g., Kuo 1974; Arakawa and Schubert 1974; Anthes 1977; Betts and Miller 1986; Kain and Fritsch 1993; Grell 1993, etc.). Most of the above schemes evaluated for a specific convective environment (Grell 1993; Kuo et al. 1996). Hence, the general applicability of these schemes to any geographical environment is not obvious. Therefore, a systematic inter comparison of performance of these parameterization schemes is essential for the customization of a mesoscale model to examine (1) how well do these schemes perform in a mesoscale model under a variety of intense convective conditions and (2) consistency in the performance of these schemes in different geographical environments.

2. Methodology and Data Used

Advanced Weather Research Forecasting (WRF-ARW) single state of the art of mesoscale model has been taken to evaluate the performance for the simulation of tropical cyclone events.

2.1 WRF Model

The Weather Research and Forecasting (WRF) model is a numerical weather prediction (NWP) and atmospheric simulation system designed for both research and operational applications. WRF is supported as a common tool for the university/research and operational communities to promote closer ties between them and to address the needs of both. The development of WRF has been a multi-agency effort to build a next-generation mesoscale forecast model and data assimilation system to advance the understanding and prediction of mesoscale weather and accelerate the transfer of research advances into operations. The WRF effort has been a collaborative one among the National Center for Atmospheric Research's (NCAR) Mesoscale and Microscale Meteorology (MMM) Division, the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Prediction (NCEP) and Earth System Research Laboratory (ESRL), the Department of Defense's Air Force Weather Agency (AFWA) and Naval Research Laboratory (NRL), the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma, and the Federal Aviation Administration (FAA), with the participation of university scientists. WRF reflects flexible, state-of-the-art, portable code that is efficient in computing environments ranging from massively-parallel supercomputers to laptops. Its modular, single-source code can be configured for both research and operational applications. Its spectrum of physics and dynamics options reflects the experience and input of the broad scientific community. Its WRF-Var variational data assimilation system can ingest a host of observation types in pursuit of optimal initial conditions, while its WRF-Chem model provides a capability for air chemistry modeling. WRF is maintained and supported as a community model to facilitate wide use internationally, for research, operations, and teaching. It is suitable for a broad span of applications across scales ranging from large-eddy to global simulations. Such applications include real-time NWP, data assimilation development and studies, parameterized-physics research, regional climate simulations, air quality modeling, atmosphere-ocean coupling, and idealized simulations. As of this writing, the number of registered WRF users exceeds 6000, and WRF is in operational and research use around the world. The WRF Software Framework (WSF) provides the infrastructure that accommodates the dynamics solvers, physics packages that interface with the solvers, programs for initialization, WRF-Var, and WRF-Chem. There are two dynamic solvers in the WSF: the Advanced Research WRF (ARW) solver (originally referred to as the Eulerian mass or "em" solver) developed primarily at NCAR and the Analysis.

S. N.	Physical Parameterization schemes		Name of Exp.
	PBLs	**CPs**	
01.	Yonsei University Schemes (YSU)	Kain Fristch (KF) Scheme	YKF
02.	Yonsei University Schemes (YSU)	Betts Miller Janjic (BM) Scheme	YBM
03.	Yonsei University Schemes (YSU)	Grell Devenyi (GD) Scheme	YGD
04.	Meller Yamada Janjic Scheme (MYJ)	Kain Fristch (KF) Scheme	MKF
05.	Meller Yamada Janjic Scheme (MYJ)	Betts Miller Janjic (BM) Scheme	MBM
06.	Meller Yamada Janjic Scheme (MYJ)	Grell Devenyi (GD) Scheme	MGD

Table1.1 : Design of the experiments.

2.2 Procedure

For achieving the objective of the study, the three convection and two Planetary Boundary Layer (PBL) schemes of Weather Research Forecasting (WRF) model are combined for simulation of TCs over Bay of Bengal (BoB) in near real time using the resultant combination of parameterization schemes. The Kain-Fritsch, Betts-Miller-Janjic, and Grell-Devenyi schemes are thereby referred as KF, BM, and GD schemes, respectively. The Yonsei University Scheme (YSU) and Mellor -Yamada -Jainjic (MYJ) scheme are henceforth referred as Y and M, respectively.

For the study six experiments are carried out with six possible combinations of three Cumulus Parameterizations Schemes (CPS) and two Planetary Boundary Layer Schemes (PBLS) taking the WRF Single Moment -3 Class (WSM 3-class) micro physics scheme (Hong et al. 2004) as common. All the six experiments with the combination of these schemes and name of the experiments are given in Table 1.1.

Three test cases have been considered for the tropical cyclone events those are Case 1 Nargis (26 April- 02 May, 2008), Case 2 Thane (25-31 December, 2011) and Case 3 Cyclonic Storm, Mahasen over Bay of Bengal (10 - 16 May, 2013). All the cyclones are integrated up to 96 hours from their respective real initial time. The initial and boundary conditions are obtained from National Centers for Environment Prediction (NCEP) Final (FNL) analyses (9 km grid resolutions). For evaluation the experiments of the three considered cases: Nargis (26 April- 02

May, 2008), Thane (25-31 December, 2011) and Mahasen (10 - 16 May, 2013), have been analyzed and thereby compared the output of all the parameters with the respective observed values for finding the best combination.

Three test cases, case 1 Nargis (26 April- 02 May, 2008), Case 2 Thane (25-31 December, 2011) and Case 3 Mahasen (10 - 16 May, 2013) are simulated with the optimum combination of physical parameterization schemes and expected result is achieved from the study. Table 1.1 describes the details of the total experiments in evaluation study. The NCEP Global Forecasting System (GFS) analyses and forecast products available in near real time are used as initial and boundary conditions to the model. The single domain is fixed between 780 E-990 E and 30 N-260 N for BoB TCs with 9-km horizontal grid resolution. The grid staggering is Arakawa C-grid. The complete model configuration with all the specifications is given in Table 3.1. Except different combinations of PBLSs and CPSs for customization study and the initial conditions for model evaluation study, the model configuration is kept identical in all aspects for all the experiments. All the model-simulated results are compared with those prepared by IMD.

3. Result and Discussion

Among the three tropical cyclones, at first TC Nargis has been taken and the WRF model is run using two types of Planetary Boundary Layer (PBL) along with three Cumulus Parameterization schemes (CP) and made six independent run. The simulated track and intensity (pressure & wind) are compared with the IMD observed data and select the best combination of the parameterization schemes. The procedure has been repeated for two other cases (TC Thane and Mahasen). The simulated SLP, wind and track of the tropical cyclones Nargis, Thane and Mahasen are plotted along with IMD observed data and are shown in Figures 1.1(a), (b) & (c), 1.1(d), (e) & (f) and 1.1(g), (h) & (i) respectively. Performances of the selected PBLs with the CPs are not same for all combinations which have been shown in Tables: 1.1, 2.1&3.1. In the Figures 1.1 (b), (e) and (g), it is visualized that with time variation of observed and model simulated Maximum Wind Speed (MWS) at the standard meteorological height of 10-m varies significantly for all the TCs Nargis, Thane and Mahasen respectively. It is observed that the output from no combination is coordinated exactly with the observed MWSs. Simulated tracks for all the TCs Nargis, Thane and Mahasen, shown in the Figures 1.1 (c), (f) and (i) respectively, are deviated mainly in the left or right to the respective observed track. Simulated SLPs, shown in the Figures 1.1 (a), (d) and (h), are more or less than observed. Considering the performance of PBL with CP for three TCs, it is seen from the Figures and Tables, no combination of PBL and CP perform absolutely better than others. But it seems that YSU PBL with KF CP performs better than any other combinations. This combination of PBL and CP may be used as an operational purpose for the TC prediction. But

Name of Exp.	RMSE OF TC Nargis			BEST EXP.
	Wind (ms^{-1})	**SLP (hPa)**	**Track (km)**	
YKF	3.265179	0.782243	0.502412	YKF
YBM	3.618005	2.097618	0.64337	
YGD	4.490867	2.305929	0.918923	
MKF	3.545487	4.053805	1.517197	
MBM	3.545487	3.977915	1.243621	
MGD	4.441189	2.837452	0.86933	

Table 2.1 : Best combination Selection for TC Nargis simulation

it is recommended that more combination may be done to search better option. Using the output of simulation for the best combination, pressure, wind (vector and scalar horizontal wind, radial, tangential and vertical wind), vorticity, temperature anomaly, water vapor mixing ratio and rainfall of the three tropical cyclones Nargis, Thane and Mahasen are studied.

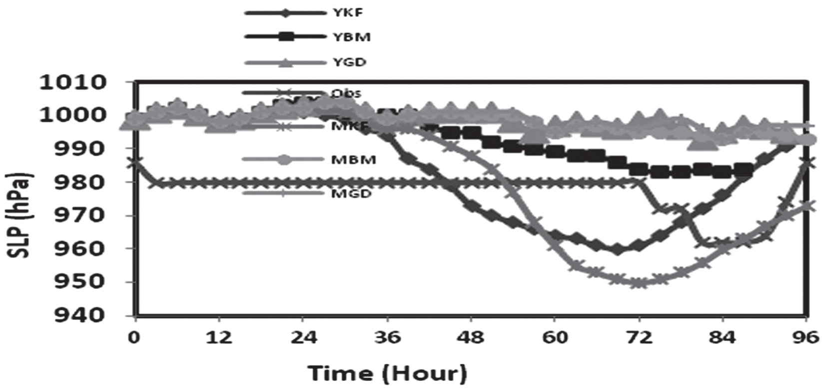

Figure 1.1(a) : Time variation of observed & model simulated SLP (hPa) for TC Nargis.

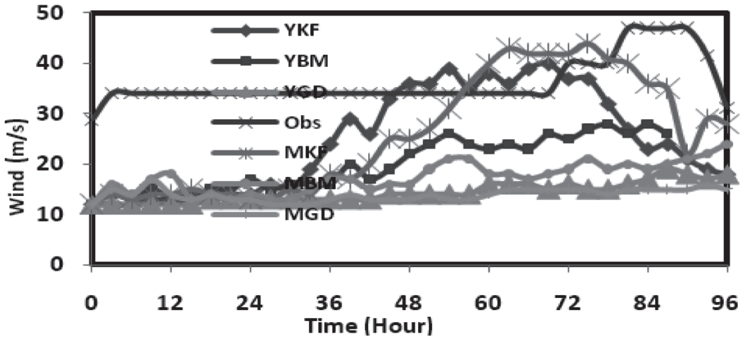

Figure 1.1 (b) : Time variation of observed & model simulated wind speed (m/s) for TC Nargis.

Name of Exp.	RMSE of TC Thane			BEST EXP.
	Wind (ms^{-1})	SLP (hPa)	Track (km)	
YKF	1.814948	0.782243	0.19235	YKF
YBM	2.440302	2.097658	0.28256	
YGD	1.990369	2.305929	0.27422	
MKF	2.406541	4.053805	0.22341	
MBM	2.406541	3.977915	0.25101	
MGD	2.892947	2.837452	8.66586	

Table 3.1 : Best combinations Selection for TC Thane simulation.

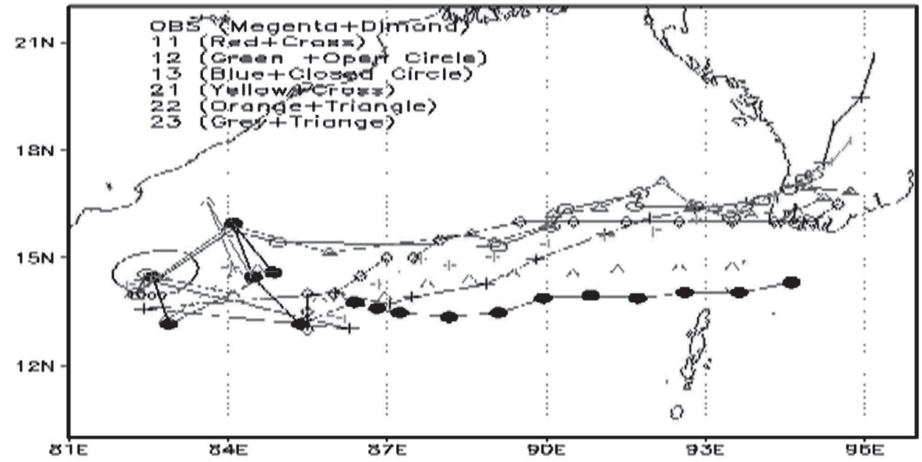

Figure 1.1(c) : Model simulated tracks in 6-h interval from different parameterization schemes for TC Nargis.

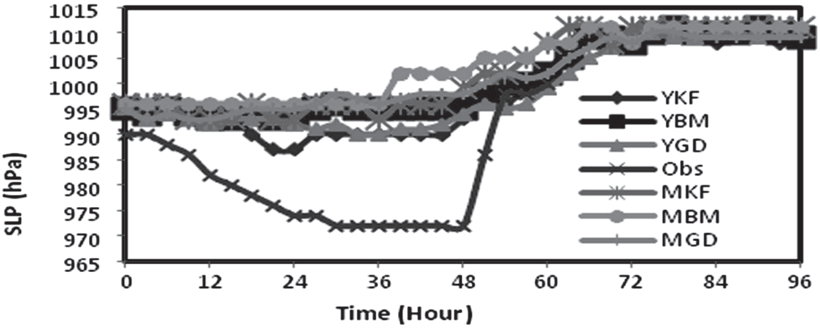

Figure 1.1(d) : Time variation of observed & model simulated SLP (hPa) for TC Thane.

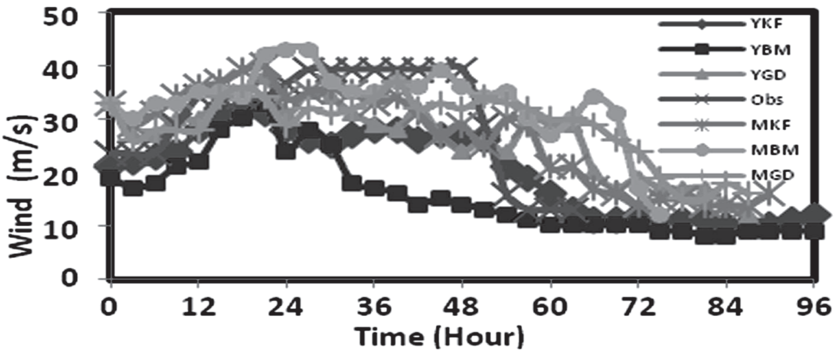

Figure 1.1(e) : Time variation of observed & model simulated wind (m/s) for TC Thane.

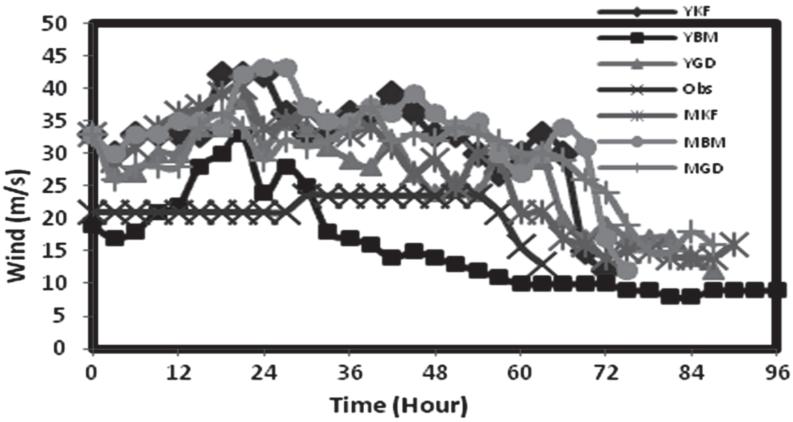

Figure 1.1(g) : Time variation of observed & model simulated wind (m/s) for TC Mahasen.

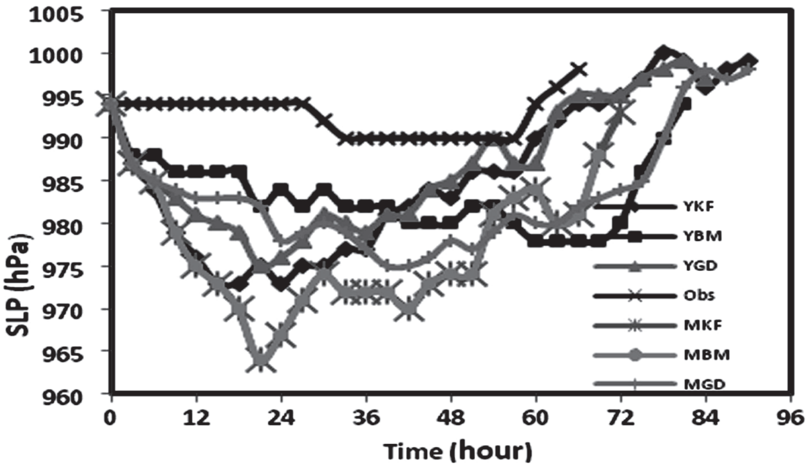

Figure 1.1(h) : Time variation of observed & model simulated SLP (hPa) for TC Mahasen.

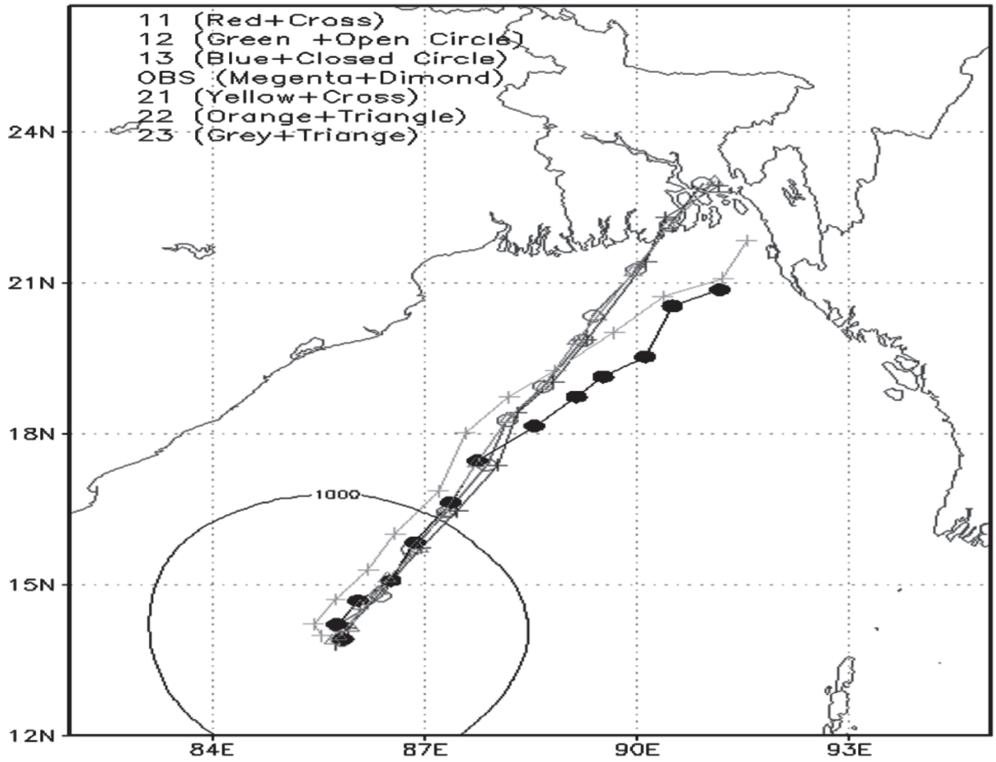

Figure 1.1(i) : Model simulated tracks in 6-h interval from different parameterization schemes for TC Mahasen.

Name of Exp.	**RMSE OF TC Thane**			**BEST EXP.**
	Wind (ms^{-1})	**SLP (hPa)**	**Track (km)**	
YKF	2.973754	0.782243	0.394868	
YBM	1.563753	2.097658	0.540921	
YGD	2.143721	2.395929	0.519803	YKF
MKF	2.46022	4.053805	0.575069	
MBM	2.46022	3.977915	0.544413	
MGD	2.342317	2.837252	0.630277	

Table 4.1 : Selection of Best combinations for TC Mahasen.

4. Conclusions

The convection and planetary boundary layer (PBL) processes play significant role in the genesis and intensification of tropical cyclones (TCs). To understand the dynamics of sensitivity, intensity (wind & slp), vorticity, temperature anomaly, accumulated rainfall, water vapor mixing ratio and track of Nargis, Thane and Mahasen have been simulated and thereby analyzed.

The broad conclusions materialized in this study are presented in the following: From this study, it is clear that the YSU PBL scheme with KF CP scheme shows less track and intensity error out of the six combinations.

1. The Mean RMSE of intensity in terms of CSLP with YSU PBL scheme with KF is 0.782243 hPa for Mahasen, Thane and Nargis respectively while that of MYJ with scheme is 3.61 for Mahasen, Thane and Nargis respectively.
2. Further, the YSU PBL scheme with KF convection scheme simulates the intensity in terms of wind with minimum errors of 2.2, 2.02, and 3.79 ms-1 for Mahasen, Thane and Nargis respectively. These errors are minimum than any other combinations in case of simulated TCs Mahsaen, Thane and Nargis respectively.

3. The KF with YSU PBL scheme returns with the mean track errors of 43.44 km for Mahasen, 21.16 km for Thane and 55.26 km for Nargis, while BM and GD with YSU PBL show 59.50 km and 57 km, 31 km and 30 km and 70.77 km and 101 km. These show the better performance of KF scheme than BM and GD. The KF scheme is also more successful in predicting the landfall compared with BM and GD. Further, the KF and YSU combination shows least track and landfall errors.

4. The landfall errors are spreaded from 30 to 110 km with the better prediction of track and intensity for different forecast lead times.

5. The YKF experiment could replicate much of the observed characteristics features such as vorticity, water mixing ratio which satisfy the development of the cyclone.

6. From the study of vertical structural characteristics of the cyclone inner core, it is clear that robust features are observed with YKF combination produced intense horizontal wind speed, strong convergence with intense updrafts within the warmer cyclone core. The enhanced updrafts and storm intensification rate in YKF experiment can be attributed to the feedback mechanism between low-level convergence of warm air, latent heat release in the eye wall, and a correspondent decrease of surface pressure in the inner core of the storm. From the study the warm core of temperature anomaly is also seen.

7. 24-h accumulated rain band is seen around the center of the cyclone.

Finally we can conclude that WRF model can predict the cyclone features. Further this combination can be tested for few TCs on real-time bases and compared the predicted tracks with those of leading operational centers.

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