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The Sensitivity of Microphysical Parameterization Schemes on the Prediction of Tropical Cyclone Mora Over the Bay of Bengal using WRF-ARW Model

Md. Jafrul Islam[1], Ashik Imran[1], Ishtiaque M. Syed[1*], S.M. Quamrul Hassan[2] and Md. Idris Ali[3]

[1] *Department of Physics, Dhaka University, Dhaka-1000, Bangladesh*
[2] *Bangladesh Meteorological Department, Dhaka-1207, Bangladesh*
[3] *Department of Physics, Khulna University of Engineering and Technology, Khulna, Bangladesh*

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Abstract

The sensitivity of Microphysics Parameterization (MP) schemes has been analyzed in the prediction of intensity and track of tropical cyclone (TC) Mora (28th May-31st May, 2017), over the Bay of Bengal (BoB) using WRF model. The study of MP schemes in numerical simulation is important because it includes microphysical process and cloud dynamics that controls the latent heat release in clouds. In this study seven MP schemes (Kessler, Lin, WSM3, Eta, WSM6, MYDM7, and WDM5) are used to study the variation in Mean Sea Level Pressure (MSLP), Maximum Wind Speed (MWS), rainfall distributions, and Tracks. The root mean square error (RMSE) of MSLP, MWS and 72-h simulated tracks are found minimum for WSM3 scheme while the RMSE of rainfall, 48 and 24-h simulated tracks are found minimum for WDM5 scheme. In conclusion, WSM3 and WDM5 schemes may give better results in the prediction of slowly intensifying TC like Mora.

Keywords: TC, Bay of Bengal, Microphysical parameterization.

I. Introduction

Tropical cyclone (TC) is an organized system of clouds and thunderstorms that rotates around a low-pressure center near sea level. TCs derive their energy through the evaporation of warm tropical ocean surface water and move towards the land under the influence of ‘steering’ by the background environmental wind[1]. The destruction caused by TCs mainly depend on the intensity, size and location. The damages could be mitigated if we could accurately predict the intensity and track of the cyclones with a sufficient lead time. Fortunately, during the past two decades, the numerical weather prediction (NWP) capabilities have improved greatly. High-speed computers and advanced computational models allows forecasters to simulate the weather events quiet accurately within a short time. Despite of the development in NWP by various mesoscale models, further improvement is still needed in their performance considering diversity and inconsistency in atmospheric phenomena. A number of parameterization schemes which includes Microphysics (MP), Radiation options, Surface Layer physics, Planetary Boundary Layer (PBL) physics, Cumulus Parameterization (CP) have been developed by various researchers based on different assumptions. Yet these schemes have some limitations in the prediction of tracks and intensity of TCs. It was confirmed from the study of Chang et al.[2] that the Cumulus Convection and PBL parameterization schemes have great impact on the track and intensity prediction of TCs. Osuri et al.[3] have found that the Yonsei University (YSU) PBL scheme along with Kain-Fritsch CP scheme gives better prediction in central pressure and sustained maximum wind speed with errors of 13 hPa and 11 ms^{-1} respectively. However, as the microphysical processes play a major role in developing various weather phenomena, microphysics schemes may affect the weather predictions[4]. Several studies in the past had suggested that the representations of microphysical processes in NWP models have great impact on the intensity forecasts of TCs. Willoughby et al.[5] showed that the MSLP simulated by a warm-rain scheme is 18 hPa lower than by a mixed-ice-phase scheme. The stronger condensational heating rate in warm-rain microphysics scheme causes this rapid intensification[6]. Further study suggested that the exclusion of the melting of snow and graupel, and the evaporation of rain ensuring no downdraft produces the strongest storm with the most rapid intensification rate[6]. We’ve used seven MP schemes in this study which are Kessler, Lin, Eta, WSM3, WSM6, MYDM7, and WDM5. These schemes have variations in the inclusion or exclusion of different hydrometeors and the conversion processes among them. The purpose of this study is to see which microphysics scheme can predict the intensity and track of the TC Mora (28th -31st May, 2017) in a better way.

II. Experimental Setup and Methodology

Data used

For initial and lateral boundary condition we’ve used the National Centre for Environmental Prediction (NCEP) high-resolution Global Final (FNL) Analysis data on 1.0° × 1.0° grids which covers the entire globe every 6-hour. The simulated Minimum Sea Level Pressure (MSLP), Maximum Wind Speed (MWS) at surface and the tracks are compared with the estimated value given in the report on cyclone Mora by India Meteorological Department (IMD). Bangladesh Meteorological Department (BMD) estimated daily rainfall data is used to compare the model predicted rainfall.

WRF model description [7]

We’ve used the Weather Research and Forecasting (WRF-ARW Version 3.8.1) model for the simulation of cyclone MORA. The model is used for both research and operational forecasting and covers various meteorological phenomena ranging from tens of meters to thousands of kilometers. The WRF model includes fully compressible

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[*] Author for correspondence. e-mail: imsyed@du.ac.bd

non-hydrostatic Euler equations and different prognostic variables that have conservation properties[8]. The terrain following hydrostatic pressure is considered as the vertical coordinate[9]. The equations also include the effects of moisture, Coriolis and curvature terms. The equations are then augmented to comprise projections to the sphere. The model applies the Runge-Kutta second and third order time integration scheme. The Arakawa C-grid staggering is used as the horizontal grid. A few options for spatial discretization, diffusion, lateral boundary conditions and nesting are additionally incorporated into WRF model. The domain configuration and details in WRF model for this tudy are given in Fig. 1 and Table 1.

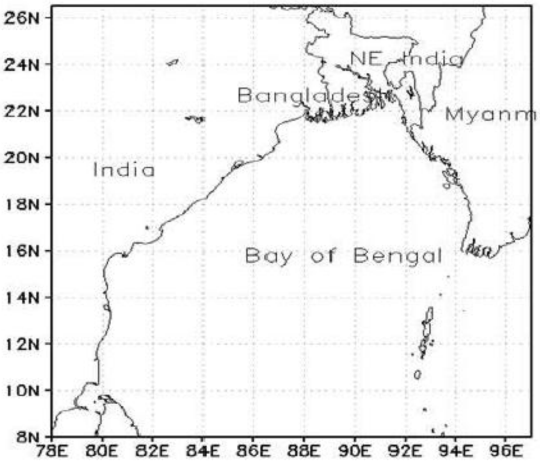


Fig. 1. WRF Model Domain for the NWP study

Table 1. WRF model configurations

No. of domain	1	**Horizontal grid**	Arakawa C-grid
Center of the domain	17.5°N, 87.5°E	**Time integration**	3rd order Runge-Kutta
Resolution	20 km	**Initial conditions**	3-D real-data (FNL: 1°×1°)
Vertical co-ordinate	40 sigma levels	**Micro-physics schemes**	Kessler, Lin et al., WSM3, Eta, WSM6, MYDM7, WDM5
No. of grid points	W-E 120, S-N 120	**CP scheme**	Kain-Fritsch (new Eta)
Run time (72 hours)	2017-05-28_00 to 2017-05 31_00	**PBL scheme**	Yonsei University Scheme (YSU)
Map projection	Mercator	**Radiation scheme**	RRTM long wave; Dudhia's short wave

The position error is calculated as the direct position error (DPE) between the observed point $(x_0,\ y_o)$ and model predicted point $(x_m,\ y_m)$. The equation is as follows:

$$\text{Error} = \sqrt{(x_0 - x_m)^2 + (y_o - y_m)^2} \qquad (1)$$

The root mean square error (RMSE)[10] is calculated as,

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=}^{N}(M_i - O_i)^2}$$

Where M_i is the model predicted value and O_i is the observed value.

III. Results and Discussions

Mean Sea Level Pressure (MSLP)

Fig. 2 compares the simulated and the observed MSLP[11] for different microphysics schemes. It is evident from the results that all the microphysics schemes overestimate the intensity of the cyclone in terms of MSLP. The observed MSLP indicates a severe cyclonic storm (SCS) while the WSM3 scheme produces a very severe cyclonic storm (VSCS) with minimum central pressure of 955 hPa. The WSM6 produces a extremely severe cyclonic storm (ESCS) with minimum central pressure of 940 hPa. Therefore the intensification in TC Mora is higher in WSM6 than in WSM3. However, the strongest cyclone is produced by LIN et al. scheme with a rapid deepening rate of 1.8 hPa/hr. This results agrees with the study of Maw and Min[12] where they've investigated the impacts of MP schemes on the prediction of TC Roanu (2016). The observed deepening rate from 24 hours prior to the maximum intensity is found to be 0.58 hPa/hr. Among the schemes warm rain KS predicts the quickest intensification with an extreme deepening rate of 2 hPa/hr while the WSM3 predicts the slowest intensification with a rate of 1.3 hPa/hr. This agrees with Li and Pu[6] in their investigation of early rapid intensification of hurricane Emily (2005). The deepening rate for WSM6 is 1.9 hPa/hr. The contrasts between WSM3 and WSM6 in predicting the intensity is because the WSM6 includes the mixed phase microphysical processes (i.e. the existence of super cooled water and gradual melting of snow below the melting layer) and graupel into cloud microphysical processes[6]. Again the weakening rate for WSM3 (1.25 hPa/hr) is also closest to the observed weakening rate (0.82 hPa/hr). Hence the WSM3 scheme is found to be better for the prediction of slowly intensifying TCs and WSM6 may give better result in predicting the intensity of rapidly intensifying TCs. Furthermore, the RMSE (Fig. 3) is also found to be lowest for WSM3 scheme. Our observations are in good agreement with the study of Mahala et al. [13]. In their study, they have concluded that the MSLP for the WSM3 scheme in the simulation of cyclone Phailin using WRF model is closest to the observed MSLP.

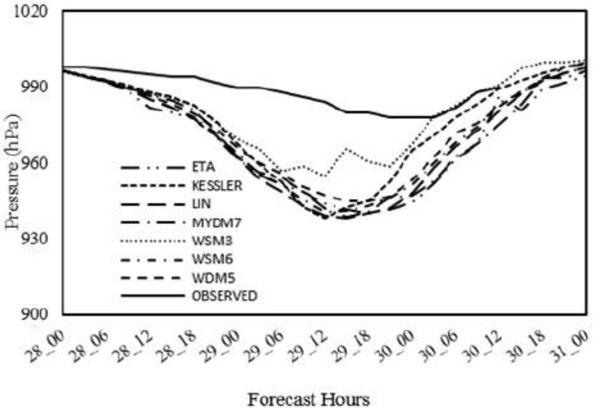


Fig. 2. Comparison of model simulated Minimum Central Pressure (MCP) (hPa) of the TC MORA with the estimated central pressure (hPa)[11].

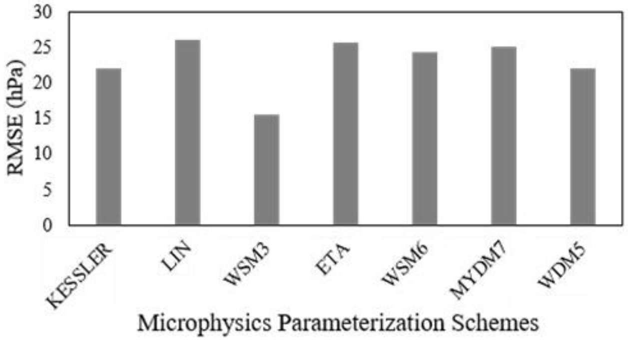


Fig. 3. RMSE of MSLP for different microphysics parameterization schemes.

Maximum Wind Speed (MWS) at Surface

Fig. 4 compares the model simulated MWS with the observed maximum sustained surface wind[11]. The MWSs are obtained at the standard meteorological height of 10 m. The intensity in terms of MWS is consistent with the intensity in terms of MSLP. Model simulated MWSs are higher than the observation until landfall but after the landfall, the MWSs come close to the estimated value. The calculated errors in measuring the intensity in terms of MWS are shown in Table 3. The RMSE of MWS for different MP schemes are shown in Figure 5. The figure depicts that Kessler scheme shows minimum RMSE of 8.57 ms^{-1} while Lin et al. and MYDM7 show maximum RMSE of 9.68 ms^{-1}.

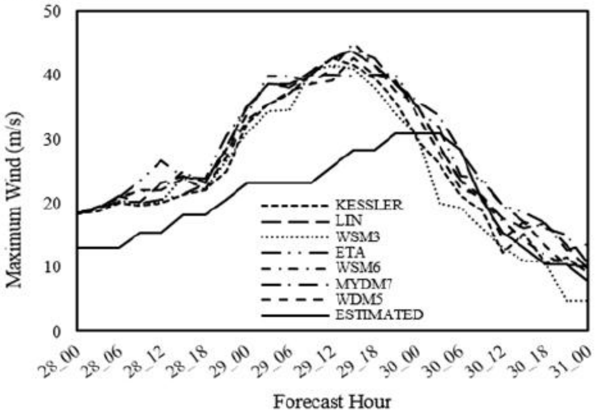


Fig. 4. Comparison of model simulated Maximum Wind Speed (MWS) and estimated maximum sustained surface wind[11].

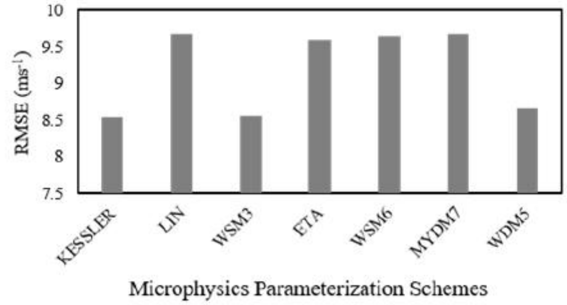


Fig. 5. The RMSE of MWS for different microphysics parameterization schemes.

Rainfall Analysis

The formation and growth of cloud droplets, ice crystals, and their fallout as precipitation depends on the microphysical processes. The spatial distributions of 72 hours accumulated rainfall (0000 UTC of 28th May to 0000 UTC of 31st May, 2017) for seven different microphysics schemes are shown along with the BMD[14] observed rainfall distribution in Fig. 7. The observed distribution shows a heavy rainfall of around 90-180 mm over Chittagong and the adjoining areas over the BoB. While rainfall over the northern area of Bangladesh is relatively low (< 60 mm). Among all the schemes the WSM3 and WDM5 schemes predicted distributions are close to the observed one. The amount of precipitation is found to be strongly correlated with the simulated intensity as shown in Table 2. The strongest system for Lin and MYDM7 corresponds to large amount of rainfall in most of the stations (Fig. 6). The RMSE in predicting the rainfall amount (Fig. 8) is calculated for the schemes as they show variations in measuring the rainfall over different stations. WDM5 scheme has the minimum RMSE of 40.47 mm while Eta microphysics scheme has the maximum RMSE of 105.15 mm. The study of Mahala et al.[13] concludes that the WSM3 predicts the rainfall quite accurately while, Maw and Min[12] founds that the RMSE is minimum for WSM6 in the simulation of TC Roanu. In our case, the RMSE for WSM3 and WSM6 are quite smaller in comparisons with LIN, ETA and MYDM7 schemes.

Table 2. Comparison of model simulated lowest MSLP with the observed lowest central pressure.

Schemes	Simul-ated MCP (hPa)	Minim-um ECP (hPa)	Error (hPa)	Time deviati-on (hr)	Deepen-ing rate (hPa/hr)
Kessler	942	978	36	06 E	2
Lin et al	938		40	06 E	1.8
WSM-3	955		23	09 E	1.3
Eta	940		38	03 E	1.5
WSM-6	940		38	09 E	1.9
MYDM-7	939		39	06 E	1.9
WDM-5	945		33	06 E	1.6

*E=Early

Table 3. Comparison of MWS (ms^{-1}) and the Estimated Wind Speed (ms^{-1}) using different microphysics schemes.

Schemes	Simulated MWS (ms^{-1})	Estimated MWS (ms^{-1})	Error=[Estimated -Simulated]	Time devia-tion
Kessler	42.5	30.87	11.63 ms^{-1}	09 E
Lin et al	43.5		12.63 ms^{-1}	06 E
WSM-3	41.5		10.63 ms^{-1}	09 E
Eta	40		9.13 ms^{-1}	00
WSM-6	44.9		14.03 ms^{-1}	06 E
MYDM-7	43.8		12.13 ms^{-1}	06 E
WDM-5	42.5		11.63 ms^{-1}	06 E

*E=Early

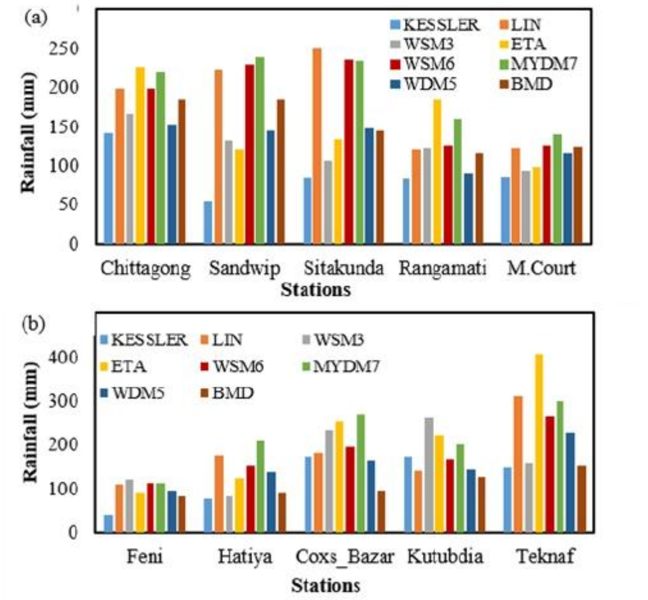
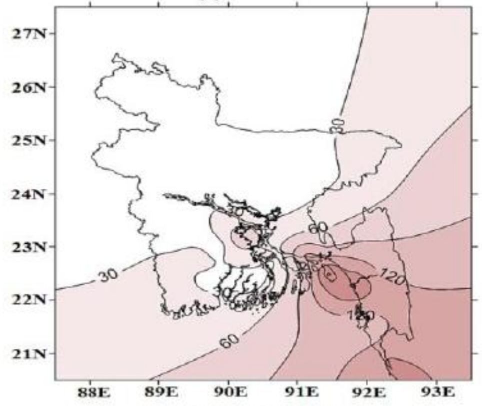
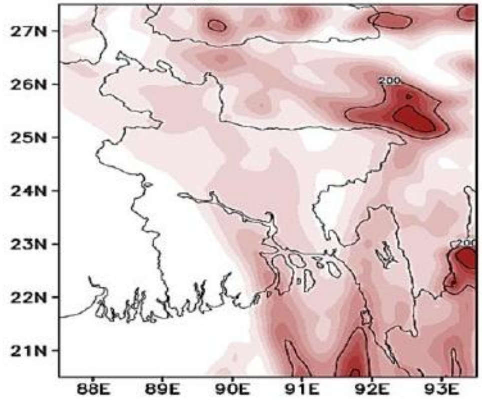
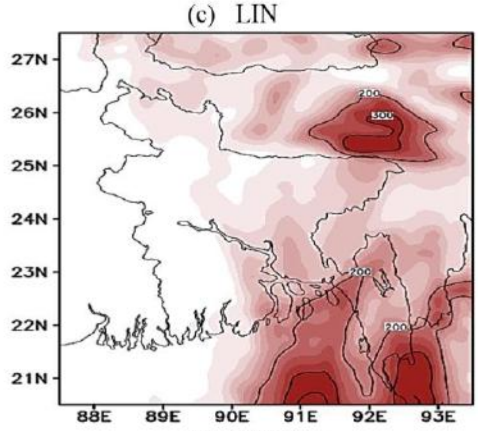
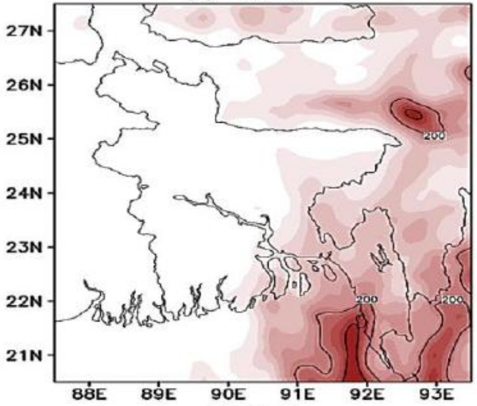


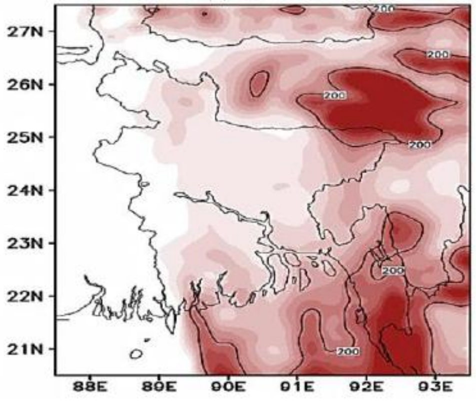
Fig. 6 (a, b). Comparison of 72 hours accumulated rainfall (measured over 10 different stations of Bangladesh) for different microphysics schemes with the BMD observed data.

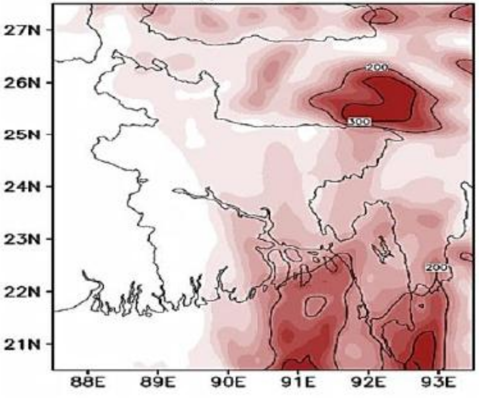

(a) BMD


(b) KESSLER


(c) LIN


(d) WSM3


(e) ETA


(f) WSM6

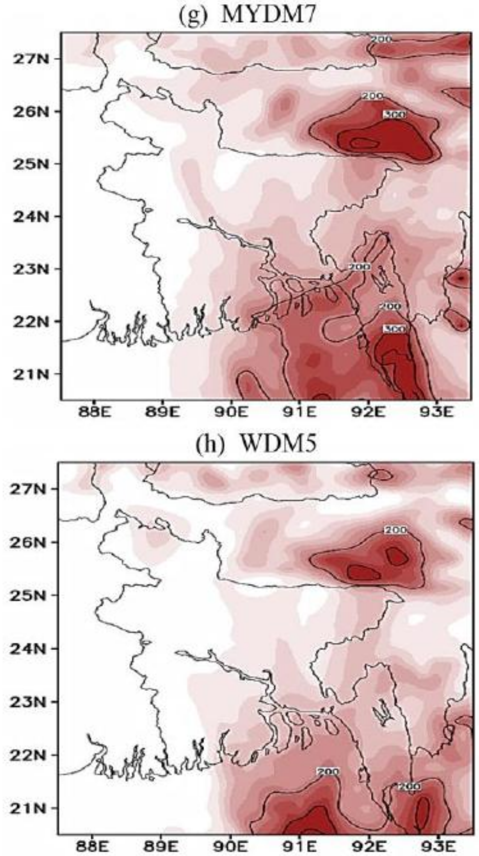


Fig. 7(a-h). The spatial distributions of 72 hours accumulated rainfall over Bangladesh.

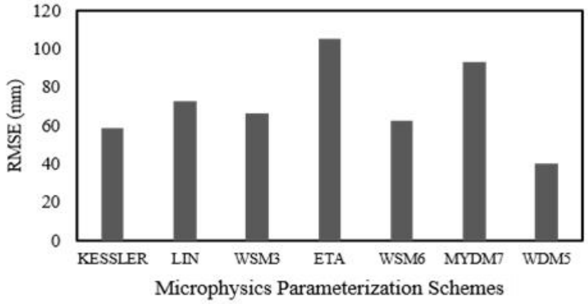


Fig. 8. The RMSE of rainfall for various microphysics schemes.

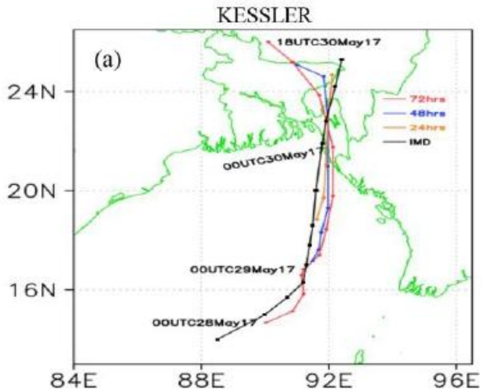
Tracks

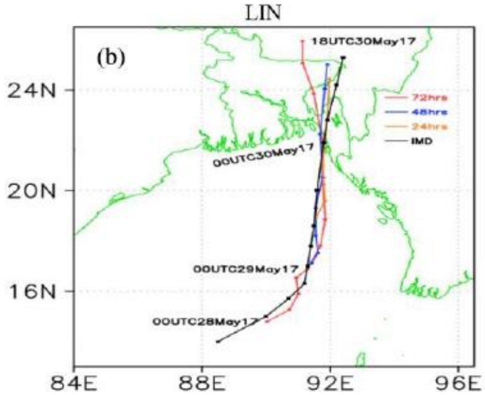
Fig. 9 compares the 72 (0000 UTC, 28th May – 0000 UTC, 31st May) , 48 (0000 UTC, 29th May – 0000 UTC, 31st May) and 24 hours (1200 UTC, 29th May – 1200 UTC, 30th May) model simulated tracks with the IMD observed track[11]. The model is quite able to reproduce the north-eastward movement of the TC. The simulated tracks initially is deviated to the right of the observed track. But before landfall, it again comes closer to the observed track. The corresponding errors in landfall positions and times are represented in Table 4. Certainly, the errors in probable landfall point decreases with decreasing forecast hours. This agrees with the study of Imran et al.[10] The RMSE of track positions are shown in Fig. 10. From the figure, it is clear that the RMSE decreases with the decrease of simulation runtime. For 72 hours simulation the RMSE is minimum for WSM3 scheme. For 48 and 24 hours simulations it is smallest for WDM5. Our study agrees with the study of Mahala et al.[13] for 72 hours simulated tracks. Li and Pu[6] and Reddy et al.[15] have found Eta to give minimum track error in their studies. In our study the average RMSE for Eta microphysics scheme is quite smaller in comparison with the others. Douluri et al.[16] have shown on their study that for 48 hours forecast, the Lin et al. scheme gives minimum error while in our study for 48 hours simulation, the RMSE for Lin et al. scheme (73.71 km) is quite closer to the smallest error of WDM5 scheme (68.20 km).

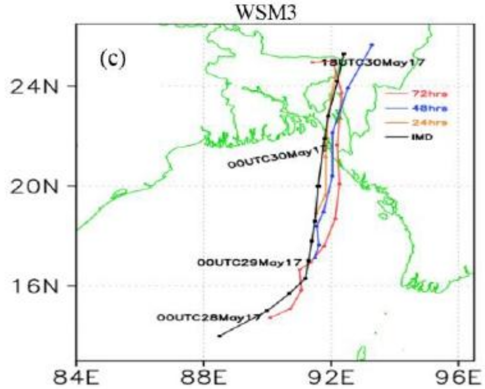
Table 4. Errors in Landfall position and time for different microphysics schemes

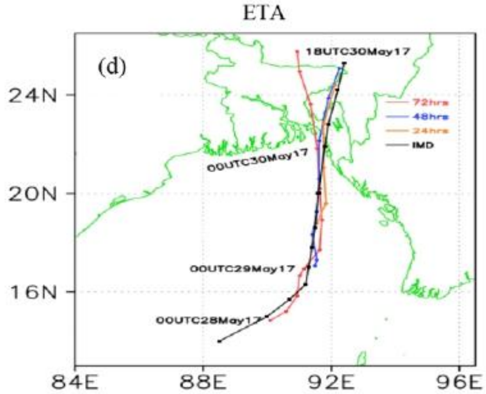
Schemes	Run time (hr)	Error	
		Distance (km)	Time (hr)
Kessler	72	94 SE	6.5 E
	48	40 SE	2 E
	24	40 SE	2.5 E
Lin	72	67 NW	2.5 E
	48	36 NW	1.5 D
	24	14 NW	1 E
WSM3	72	125 SE	7.5 E
	48	91 SE	1.5 E
	24	39 SW	2.5 E
Eta	72	65 NW	2.5 E
	48	43 NW	2.5 D
	24	43 NW	0
WSM6	72	24 NW	3 E
	48	37 NW	1.5 D
	24	43 NW	0
MYDM7	72	67 NW	1.5 E
	48	18 NW	1.5 D
	24	14 NW	1.5 E
WDM5	72	39 NW	3 E
	48	44 NW	1.5 D
	24	26 NW	0.5 E

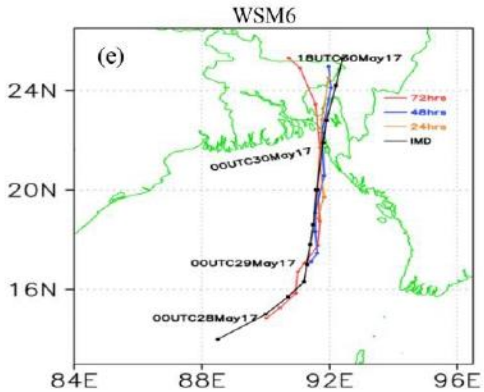
*SE-Southeast, NW-Northwest, SW-Southwest, D-Delay, E-Early

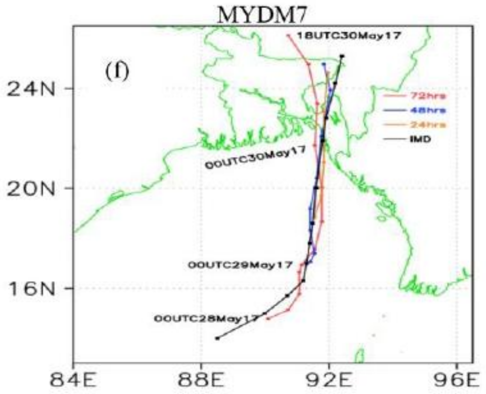



LIN


WSM3


ETA


WSM6


MYDM7

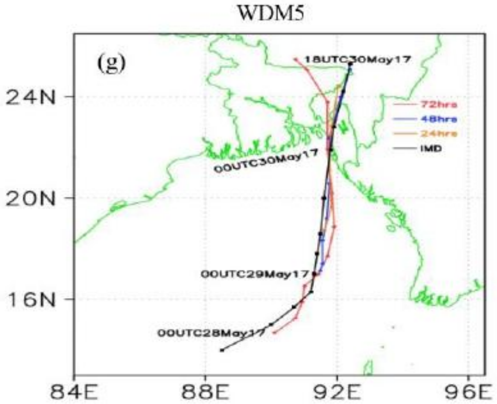

WDM5

Fig. 9. (a-g). Comparisons of 72, 48 and 24 hours model simulated tracks of Mora with the IMD observation.

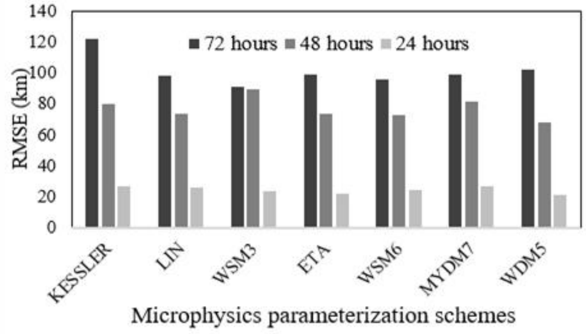


Fig. 10. RMSE of Track position for different microphysics parameterization schemes.

IV. Conclusions

Comparing seven different experiments we've found that the maximum intensity in terms of MSLP is best simulated by WSM3 scheme. The RMSE of MSLP is found to be minimum for WSM3 and Maximum for Lin et. al. scheme. Though the peak intensity in terms of MWS is found to be best for Eta, the RMSE is minimum for Kessler and WSM3 scheme while it's maximum for MYDM7 scheme. Except for WSM3 and WDM5 all the schemes overestimated the rainfall all over Bangladesh including coastal regions. The RMSE in measuring rainfall is minimum for WDM5 scheme and maximum for ETA scheme. The tracks are obtained for 72, 48, and 24 hours simulation. Among them the average RMSE is minimum for 24 hours simulation.

The RMSE for 72 hours simulation is minimum for WSM3 scheme and maximum for Kessler scheme. While the RMSE for 48 and 24 hours simulation is minimum for WDM5 scheme and maximum for WSM3 and MYDM7 respectively. In summary, WSM3 scheme gives minimum RMSE for MSLP, MWS and 72-h simulated tracks just like the study of Mahala et. al.[13] while WDM5 scheme gives minimum RMSE for Rainfall, 48-h and 24-h simulated tracks.

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