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SIMULATION OF CYCLONE RASHMI WITH DIFFERENT CUMULUS SCHEMES USING WRF MODEL

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ABSTRACT

High resolution Weather Research and Forecasting (WRF-ARW v3.8) model is used for the simulation of tropical cyclone (TC) Rashmi with different cumulus schemes which crossed Bangladesh coast on 27 October 2008. National Centers for Environmental Prediction (NCEP) final reanalysis (FNL) data (1°×1° resolution) are used as initial and lateral boundary conditions (LBCs) which are updated at six hourly intervals. The model domain is set up 3-27°N and 75-98°E and vertical level is 1000 to 100 hPa. The WRF model is run for using WSM6 microphysics scheme and Kain-Fritsch (KF), Betts-Miller-Janjic (BMJ), Grell-Fritsch (GF), Grell-3 (G3), Grell-Denenyi (GD) and Old Kain-Fritsch (OKF) cumulus parameterization schemes. Different physical parameterization schemes are used to observe the track and structure of low intensity tropical cyclone Rashmi. The track, minimum sea level pressure (MSLP), maximum wind speed (MWS) at 10m level, vorticity, temperature anomaly and water vapor mixing ratio (WVMR) have been analyzed to understand where the landfall of the TC Rashmi occurred. The G3 and OKF cumulus schemes have simulated almost equal intensity in terms of MSLP and MWS at 10m level and GD cumulus scheme has simulated lower intensity than that of observation. The center of the eye is flattened in the N-S direction and relaxed in the E-W direction and maximum wind speed is found in the southern and eastern boundary of the eye of TC Rashmi.

Keywords: *MSLP, MWS, Vorticity, Temperature anomaly, Water vapor mixing ratio.*

1. INTRODUCTION

Tropical Cyclone (TC) is a rapidly rotating system with low pressure center, strong winds and spiral arrangement that produce significant natural disaster all over the world. The cyclones formed over the Bay of Bengal (BoB) generally move in the north-northwest direction, recurve and crossed Bangladesh, Myanmar and eastern coast of India. The coastal regions are particularly vulnerable to damage from a TC as compared to inland regions. Heavy rain, significant flooding inland, and storm surges can produce extensive coastal flooding up to 40 km from the coastline. Several studies have conducted to study the TCs over the North Indian Ocean (NIO) using mesoscale models with the intention of evaluating them with respect to physics sensitivity, resolution, initial conditions and impact due to data assimilation etc. Akhter and Alam (2015) studied the prediction of track and intensity of tropical cyclone in the Bay of Bengal using NWP models. They have found that the mean landfall position errors are 140,113, 64 and 60 km for 96, 72, 48 and 24 hours run. Mallik *et al*. (2015) has simulated track and landfall of TC Viyaru and its associated storm surges using NWP models. They have found that the position errors of Viyaru in track forecasting are found to be 56, 222, 222 and 157 km for 24, 48, 72 and 96 hrs of predictions and time delay are 1, 7, 4 and 2 hrs respectively. Srinivas *et al.* (2007) has simulated the structure, intensity, evolution and movement of Andhra severe cyclonic storm (2003) using MM5. Their results indicate that the boundary layer processes play a significant role in determining both the intensity and movement; the convective processes especially control the movement of the model storm.

Mukhopadhyay *et al.* (2011) has studied the influence of moist processes on track and intensity forecast of cyclones over the NIO. Their results indicate that an inappropriate representation of moist convection in the high resolution numerical model is responsible for the failure of the forecast. Wada *et al.* (2012) has studied the relationship of maximum tropical cyclone intensity to sea surface temperature and tropical cyclone heat potential (TCHP) in the North Pacific Ocean. They have found that the use of daily data can reproduce the cooling effect of a passage of a TC, which caused a decrease of the TCHP values. Rayhun *et al.* (2016) has simulated the structure, track and landfall of tropical Deep Depression, using WRF-ARW Model. There was no time error and distance error was 55 km for 48 hours simulation. Wang and Seaman (1997) conducted a study of four convective schemes towards the simulation of six precipitation events over continental United States. There results suggest that 6-h precipitation forecast skill for these schemes is fairly good in predicting four out of six cases even for higher thresholds.

Pattanayak *et al*. (2010) has studied the simulation of very severe cyclone Mala over Bay of Bengal (BoB) with hurricane weather research and forecasting (HWRF) modeling system. They have found that the intensity forecast in terms of central sea level pressure (CSLP) and maximum sustainable wind is well captured by the model. Kumar *et al.,* (2016) has studied the simulation of TC 'Phailin' using WRF Model. Their study suggests that the WRF model

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frame work with the increased resolution have positive impact in the prediction of cyclonic storms. Radhika *et al*. (2014) have studied the weak intensity cyclones over Bay of Bengal using WRF model. Their results indicate that increase in the mid-tropospheric humidity causes higher production of the frozen hydrometeors and thus large amount of latent heat release, which in turn causes higher intensity of the cyclone. The structure and movement of cyclonic storms over the NIO simulated by WRF-ARW model was carried out by Basnayake *et al*. (2010). Their results indicate that the cyclonic disturbances in the NIO move predominantly along westerly/ northwesterly direction. Naresh *et al.* (2013) have studied the intensity of TCs during pre- and post-monsoon seasons in relation to accumulated tropical cyclone heat potential (ATCHP) over Bay of Bengal. They have found that requirement of higher ATCHP during pre-monsoon cyclones is required to attain higher intensity compared to post-monsoon cyclones.

In this study, 6 different experiments have conducted by using Kain-Fritsch (KF), Betts-Miller-Janjic (BMJ), Grell-Fritsch (GF), Grell-3 (G3), Grell-Denenyi (GD) and Old Kain-Fritsch (OKF) cumulus parameterization (CP) schemes for the TC Rashmi (2008) that formed in the Bay of Bengal and crossed Bangladesh coast. Minimum sea level pressure (MSLP), maximum wind speed (MWS), vorticity, temperature anomaly, water vapor mixing ratio (WVMR) and track have been analyzed to observe the structure and landfall of TC Rashmi. The objective of this study is to identify which parameterization scheme is suitable for predicting the track and structure of low intensity TC Rashmi that formed in the BoB.

2. SYNOPTIC SITUATION OF TC RASHMI

A low formed over west central Bay and adjoining area on 24 October 2008 and intensified into a well-marked low at 0000 UTC of 25 October 2008. At 0600 UTC of 25 October, the system concentrated into a depression at 16.5°N, 86.5°E and moved in a northerly direction. The depression turned into a deep depression (DD) over northwest Bay and adjoining west central Bay at 0300 UTC of October 26 with the wind speeds of 30 knots. At the same time the Joint Typhoon Warning Center (JTWC) declared it as Cyclone 04B. Later at 1200 UTC of the same day, the DD had intensified into a Cyclonic Storm (CS) Rashmi over northwest Bay and adjoining area (20.2°N, 88.2°E). During that evening, the India Meteorological Department (IMD) declared 3 minute wind speeds of 40 knots and Joint Typhoon Warning Center (JTWC) declared its wind speeds of 45 knots. The system started to cross Khulna-Barisal coast of Bangladesh near Patharghata at 2100 UTC of the same day and completed crossing the coast by 0300 UTC of 27 October and lay over south-central part of the country as a land depression.

Table 1: WRF Model and Domain Configurations

Number of domain	1
Central points of the domain	Central Lat.: 15.4°N, Central Lon.: 86.5°E
Horizontal grid distance	9 km
Number of grid points	X-direction 290 points, Y-direction 316 points
Map projection	Mercator
Horizontal grid distribution	Arakawa C-grid
Vertical co-ordinate	Terrain-following hydrostatic-pressure co-ordinate (32 sigma levels up to 100 hPa)
Microphysics	WSM 6-class graupel scheme
Radiation scheme	Dudhia for short wave radiation/ RRTM long wave (Mlawer *et al*., 1997)
Surface layer	Monin– Obukhov similarity theory scheme
Cumulus parameterization schemes	KF, BMJ, GF, GD, G3 and OKF
PBL parameterization	Yonsei University Scheme

3. MODEL DESCRIPTION AND METHODOLOGY

The Weather Research and Forecasting (WRF-ARW v3.8) model is utilized in the present study to simulate the different meteorological parameters of TC Rashmi. Third-order Runge-Kutta time integration scheme is used in the model. The model vertical coordinate is terrain following hydrostatic pressure and the horizontal grid is Arakawa C-grid staggering. The model domain consists of 3-27^{o}N & 75-98^{o}E and the vertical level is 1000 to 100 hPa. The model is configured in single domain (Central points of the domain: 15.4°N and 86.5°E), 9 km horizontal grid spacing with 290×316 grids in the west-east and north-south directions and 32 vertical levels. National Centers for Environmental Prediction (NCEP) final reanalysis (FNL) data (1°×1° resolution) have used as initial and lateral boundary conditions (LBCs) which are updated at six hourly intervals. The WRF model has run for 96 hrs before the landfall time by using KF, BMJ, GF, G3, GD and OKF cumulus parameterization schemes to simulate the structure of low intensity tropical cyclone Rashmi in the BoB. In this research WSM6 microphysics, Yonsei University Planetary Boundary Layer (PBL), Dudhia simple five-layer soil thermal diffusion for soil processes, Rapid Radiative Transfer Model (RRTM) for long wave and Dudhia short wave radiation schemes have used to simulate the TC Rashmi. The model results are presented in the graphical and tabular forms and compared with the IMD best track data to demonstrate the performance of the modeling exercise. For these purpose, Grid Analysis and Display System (GrADS) and Microsoft Excel soft ware is used. The structure, MSLP, MWS, vorticity, temperature anomaly, WVMR and tracks of TC Rashmi has been analyzed.

4. RESULTS AND DISCUSSION

Model simulated track, intensity in terms of MWS at 10m level, MSLP, vorticity, temperature anomaly and WVMR of TC Rashmi have analyzed and presented in different subsections. The MSLP and MWS are presented in Figures 1-4. Model simulated maximum zonal and meridional wind and vorticity have presented in Figures 5 and 6 respectively. The vertical distribution of temperature anomaly and WVMR are presented in Figures 7 and 8 respectively.

4.1 Intensity of TC Rashmi

The intensity of TC Rashmi in terms of simulated and observed MSLP using KF, BMJ, GF, G3, GD and OKF CPs for 96 hours is presented in Figure 1(a). The simulated and observed MSLP gradually drops and attains peak intensity just before the landfall and thereafter it increases. The simulated MSLP of 980, 986, 964, 983, 994 and 984 hPa (Table 2) are found using KF, BMJ, GF, G3, GD and OKF schemes and are found at 0600 UTC of 26, 1500 UTC of 26, 1500 UTC of 26, 0000 UTC of 27, 0000 UTC of 27 and 1500 UTC of 26 October 2008 respectively. The observed MSLP is 984 hPa at 2100 UTC of 26 October 2008. The pressure departures are found minimum for OKF, G3, KF and BMJ schemes and maximum for GF scheme compared with IMD observed value. The simulated pressure fall for all cumulus schemes indicate that the system has attained the intensity of cyclonic storm. The time of landfall delayed 3 hours for G3 and GD schemes and it was earlier at least 6 hours for other schemes than that of observed landfall.

The storm intensity forecasts for the TC Rashmi in terms of MWS at 10m level using KF, BMJ, GF, G3, GD and OKF for 96 hours (3 hourly intervals) along with observed MWS are presented in figure 1(b). The MWSs of 33, 33, 37, 26, 26 and 21 m/s (Table 2) are simulated using KF, BMJ, GF, OKF and G3 and GD schemes and are found at 0000, 1200, 1500, 1800 and 1500 UTC of 26 and 0000 and 0000 UTC of 27 October 2008 respectively. The observed MWS is 23 m/s. From Table 2 it is seen that the % of MWS are 91, 113 and 113 for GD, G3 and OKF schemes respectively. The G3 and OKF cumulus schemes have 13% more intense and GD cumulus scheme has 9% lower intensity than the observation. The simulated track errors have minimum for OKF and G3 schemes during 96 hour period and the minimum error are 110 and 112 km respectively.

The distribution of central SLP of the TC Rashmi along east-west cross section and north-south cross section using different cumulus schemes is shown in Figure 2(a-b). Variation of east-west and north-south elongated SLP at the center are clearly observed. The position of the center of TC Rashmi at its mature stage using KF, BMJ, GF, G3, GD and OKF are located at 88°E & 20.9°N, 86.1°E & 17.8°N, 89.1°E & 21.4°N, 88.5°E &21.8°N, 89.13°E & 21.15°N and 88.6°E & 21.35°N respectively. The mature stage of a TC is usually associated with the period in which the TC reaches its maximum intensity. The central pressure has reached a minimum and the surface winds have reached a maximum. The central pressure of TC Rashmi has reached a minimum and the winds at 10 m level have reached maximum for KF, BMJ, GF, OKF, G3 and GD schemes at 0006, 1500, 1500 and 1500 UTC of 26 October and 0000, 0000 UTC of 27 October respectively.

Figure 3(a) shows the spatial distribution of SLP at its mature stage of TC Rashmi using KF, BMJ, GF, G3, GD and OKF schemes and is simulated at 0006 UTC of 26, 15 UTC of 26, 1500 UTC of 26, 0000 UTC of 27, 0000 UTC of 27 and 1500 UTC of 26 October respectively. Intensity, position and time of mature stages are different for different cumulus schemes used in WRF model. The isobar has circular arrangement around the TC center with some asymmetric features in the outer periphery. The spatial distribution of wind speed at its mature stage for the TC Rashmi using KF, BMJ, GF, OKF, G3 and GD is simulated at 0600, 1500, 1500 and 1500 UTC of 26, and 0000 and 0000 UTC of 27 October 2008 respectively and are shown in Figure 3(b). From Figure 3(b), it is seen that the wind field is highly asymmetric in the horizontal distribution. Wind is organized with strong bands around and minimum at the center. The 10 m wind speed is simulated maximum for GF scheme and minimum for GD scheme. The figure 3(b) shows that the pattern has an asymmetric wind distribution with strong bands in the front right side, rear left and rear right sides close to the center of north directed moving storm.

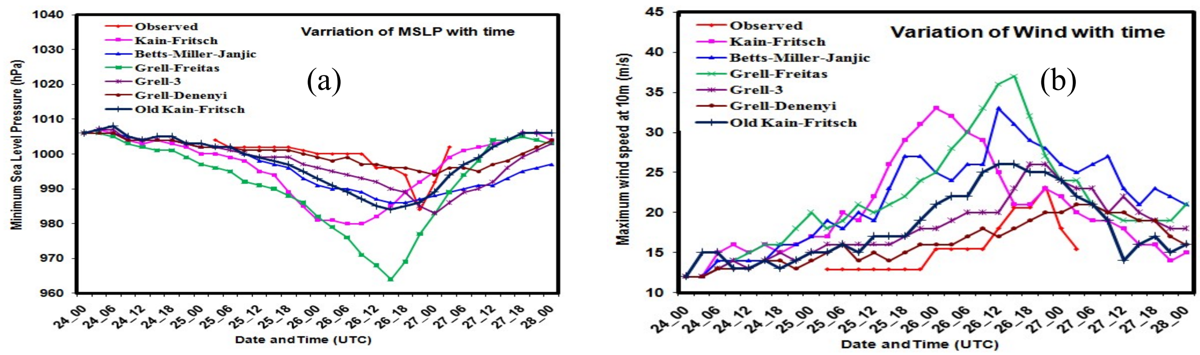

Figure 1: Model simulated and observed (a) MSLP and (b) MWS at 10m level using six different cumulus parameterization schemes of TC Rashmi with the initial condition of 0000 UTC of 24 October 2008.

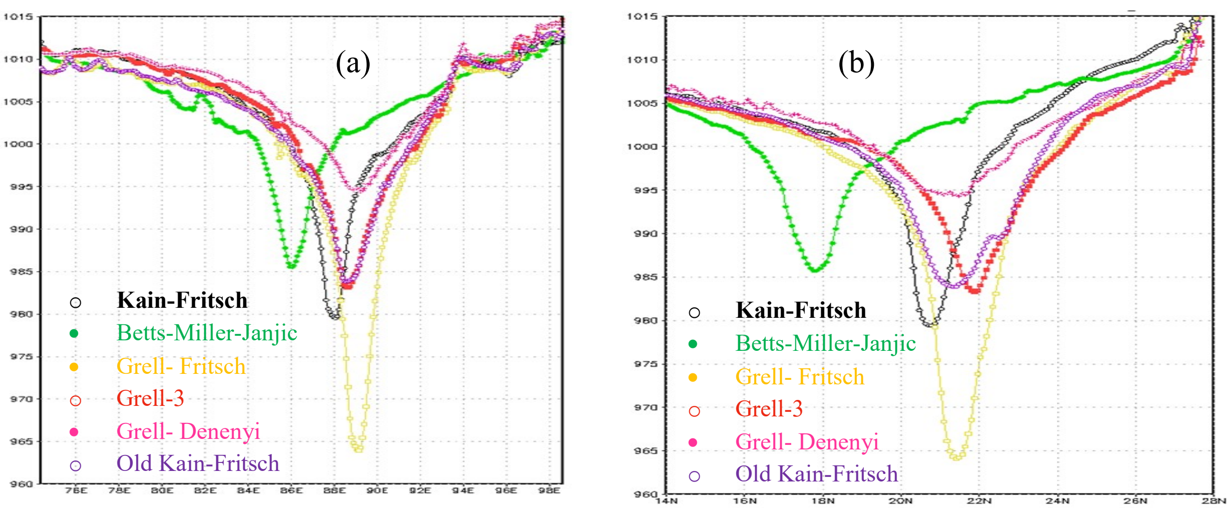

Figure 2: Model simulated (a) E-W and (b) N-S cross sectional view of MSLP of TC Rashmi at different cumulus schemes with the initial condition at 0000 UTC of 24 October.

Table 2: Observed and WRF Model simulated Landfall time, Track error, MSLP and MWS at 10m level for different cumulus schemes.

Cumulus schemes	MSLP (hPa)	MWS (m/s)	(%) of MWS	Time of landfall	Landfall Track error km	RMSE	Time error (hours)
KF	980	33	143	1000 UTC of 26 Oct	112	451	11E*
BMJ	986	33	143	0900 UTC of 27 Oct	97	1082	12 D*
GF	964	37	161	1500 UTC of 26 Oct	335	154	6 E*
G3	983	26	113	2300 UTC of 26 Oct	98	140	2 D*
GD	994	21	91	0000 UTC of 27 Oct	60	172	3 D*
OKF	984	26	113	1600 UTC of 26 Oct	100	127	5 E*
Observed	984	23		2100 UTC of 26 Oct			

E*=Earlier than observed of landfall; D*=Delayed of landfall

The E-W and N-S cross section wind at 10m level passing through its center at mature stage using different cumulus schemes is shown in Figures 4(a-b). The maximum wind of 30, 27, 34, 26, 24 and 17 m/s and the minimum wind of 3, 2, 7, 5, 2 and 3 m/s are being simulated in the E-W direction at 0000, 1200, 1500, 1800 and 1500 UTC of 26, and 0000 UTC of 27 October 2008 for KF, BMJ, GF, OKF, G3 and GD schemes respectively (Figure 4a). From figure 4(a), it is seen that the center of the eye is relaxed in the E-W direction and maximum wind speed is found in the eastern boundary of the eye of TC Rashmi. The maximum wind of 27, 31, 36, 22, 22 and 14 m/s and the minimum wind of 8, 1, 7, 5, 2 and 3 m/s are simulated in the N-S direction using KF, BMJ, GF, OKF, G3 and GD schemes respectively and are found at 0000, 1200, 1500, 1800 and 1500 UTC of 26, and 0000 UTC of 27 October 2008 respectively (Figure 4b).

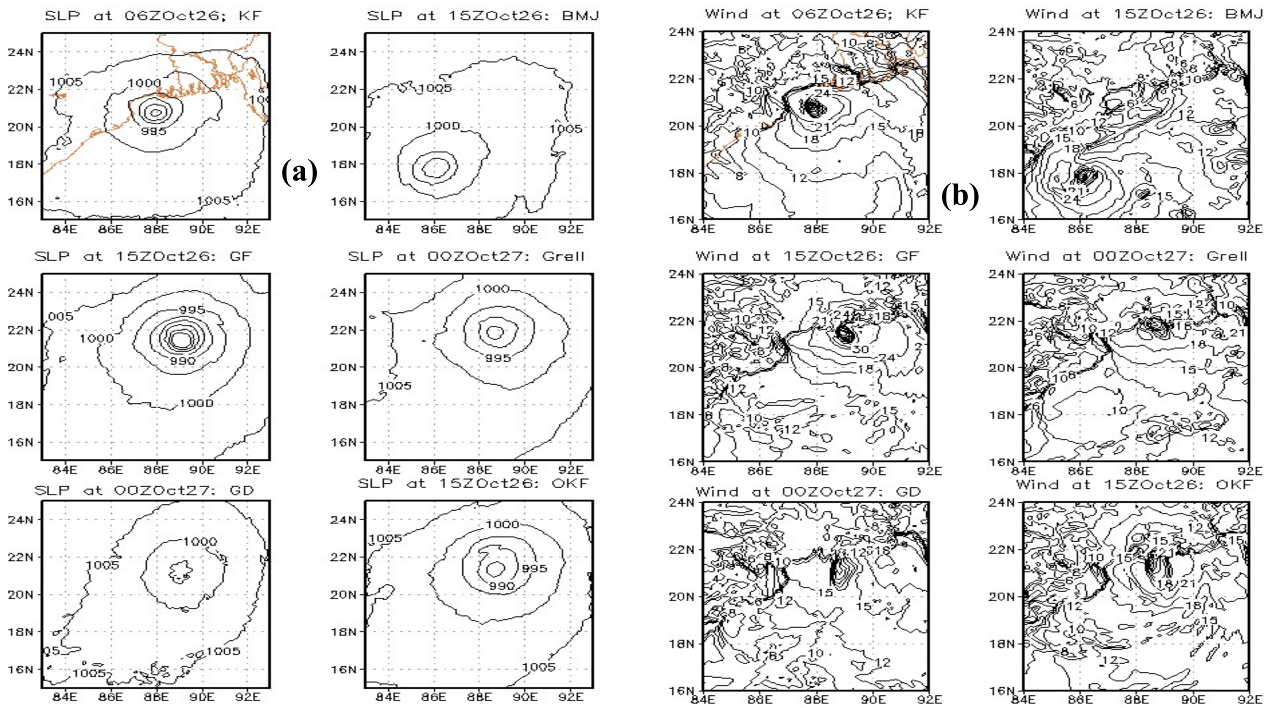

Figure 3: Model simulated (a) SLP and (b) MWS at 10m level of TC Rashmi for different six cumulus schemes.

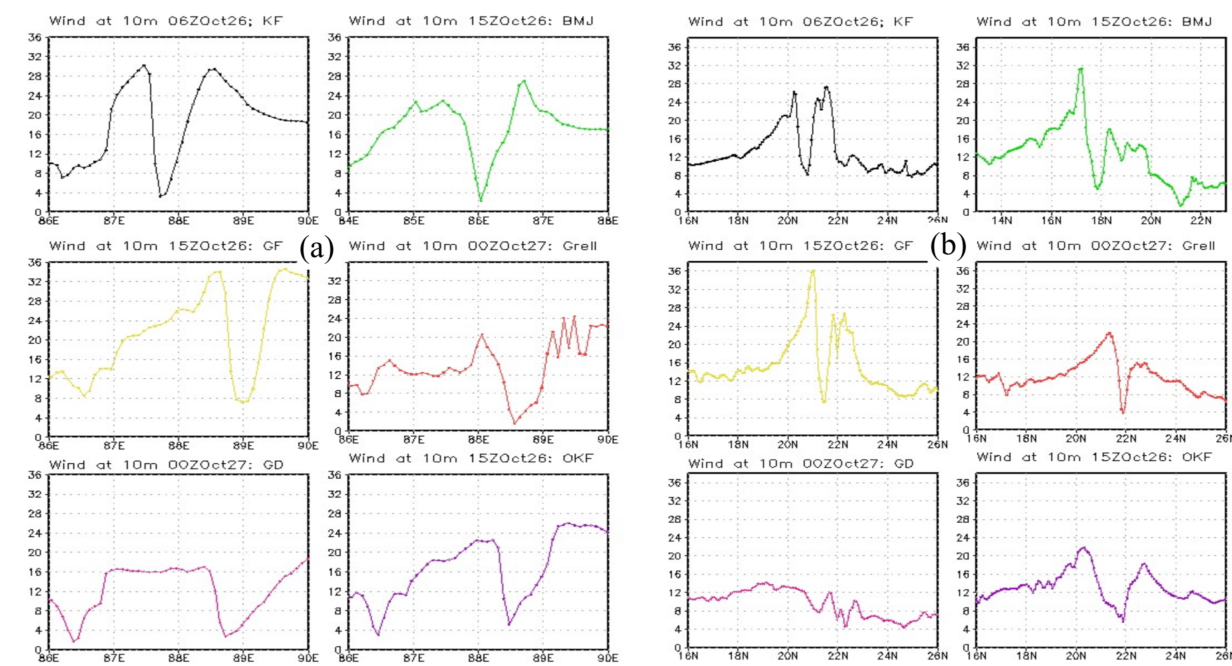

Figure 4: Model simulated (a) E-W and (b) N-S cross sectional view of 10m level wind speed of TC Rashmi at different cumulus schemes.

From figure 4(b), it is seen that the center of the eye is flattened in the N-S direction and maximum wind speed is found in the southern boundary of the eye of TC Rashmi. This suggests that the wind speed is higher in the south-east region of the eye of TC Rashmi. The vertical profile of zonal and meridional wind fields at its mature stages for KF, BMJ, GF, OKF, G3 and GD schemes are simulated at 0600, 1500, 1500 and 1500 UTC of 26, and 0000 and 0000 UTC of 27 October 2008 respectively and are shown in Figure 5(a-b). The maximum zonal wind of 12, 15, 35, 18, 15 and 12 m/s (Figure 5a) and meridional winds 32, 30, 52, 32, 27 and 38 m/s are simulated using KF, BMJ, GF, G3, GD and OKF schemes respectively (Figure 5b) at different levels.

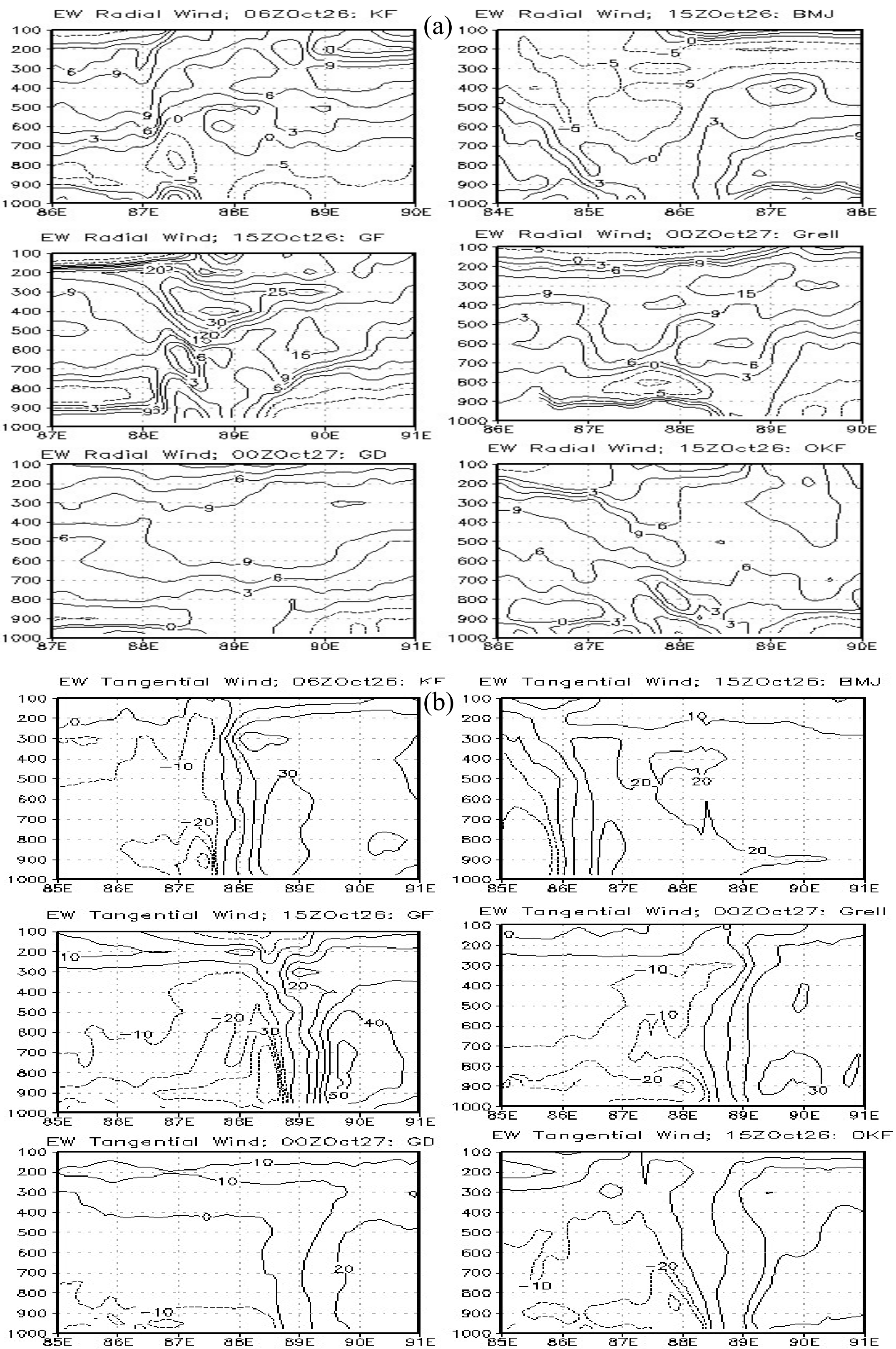

Figure 5: Model simulated vertical variation of (a) Zonal and (b) Meridional components of wind (m/s) for different cumulus schemes along the center of TC Rashmi.

4.2 Track

The model simulated 96 hours track forecast of TC Rashmi for different cumulus schemes along with observed track with the initial fields of 0000 UTC of 24 October is plotted in Figure 6. The simulated track for 96 hours is parallel to observed track but it is deviated towards west of the observed track. The landfall position for GD scheme is much closer to the observed landfall position. The track error is found minimum (60 km) for GD scheme at the time of landfall and time delayed for 3 hours. The track error is also found minimum 97, 98 and 100 km and time error 12(D), 2(D) and 5(E) hour for BMJ, G3 and OKF schemes respectively. The RMSE is smaller for OKF and G3 schemes and larger for BMJ scheme. The landfall time for G3 and GD schemes are much closer to the observed landfall time and BMJ gives the worst result than all other cumulus schemes.

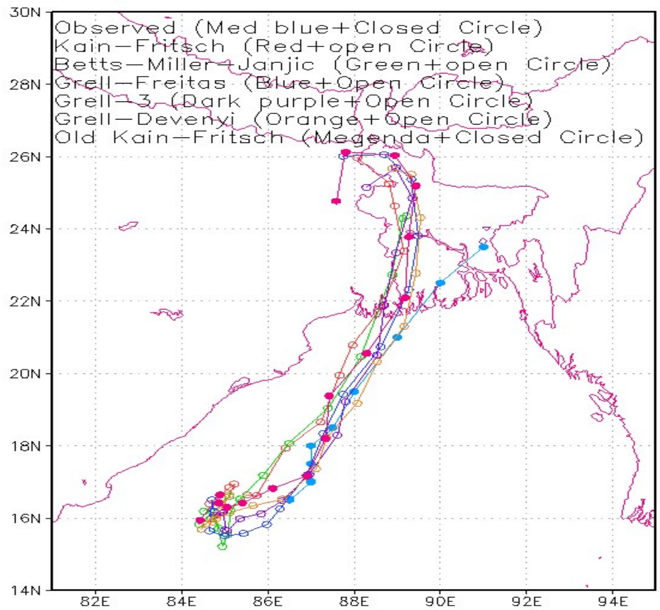

Figure 6: Observed and WRF model simulated track for different cumulus schemes of TC Rashmi with the initial condition of 0000 UTC of 24 October 2008.

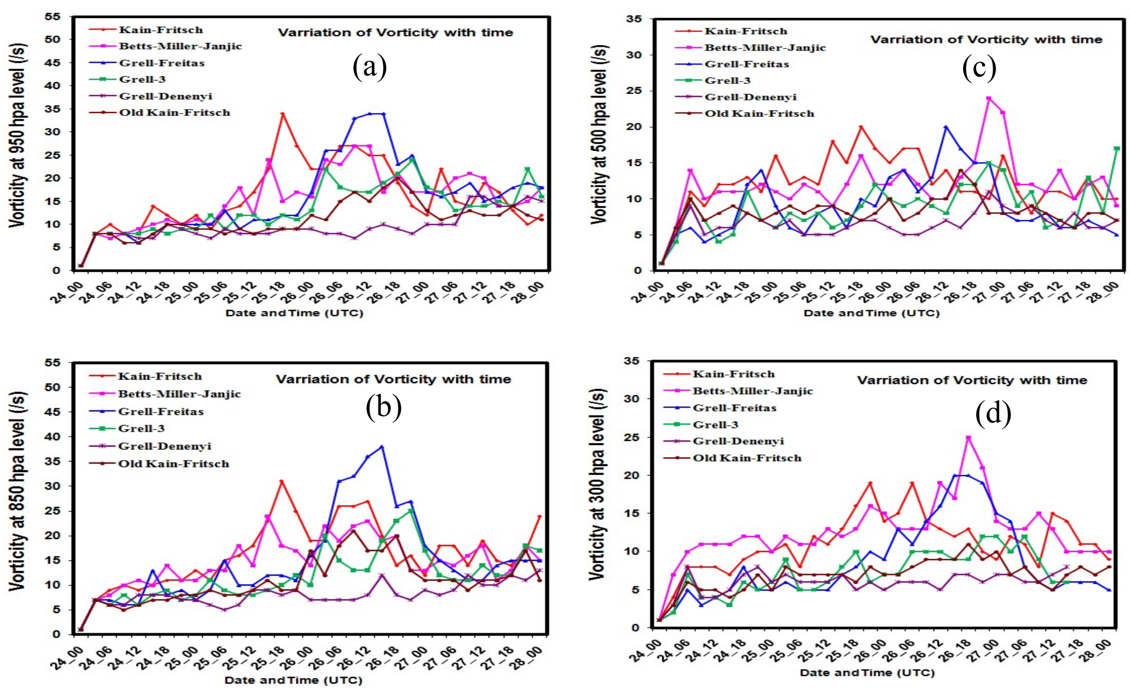

Figure 7: Time variation of model simulated vorticity for different cumulus schemes at 950, 850, 500 and 300 hPa level of TC Rashmi.

4.3 Relative Vorticity

Model simulated relative vorticity at 950, 850, 500 and 300 hPa for KF, BMJ, GF, G3, GD and OKF schemes for 96 hours (every 3 hourly) model run is presented in Figure 7(a-d). The relative vorticity has increased with the intensification of TC at all levels for all the cumulus schemes. After that the vorticity has decreased. The vorticity is found maximum at 500 and 300 hPa (Figure 7(c & d)) for BMJ scheme, 950 hPa (Figure 7a) for KF scheme and 950 & 850 hPa (Figure 7(a & b)) for GF scheme. The vorticity is found greater than zero for all levels using all cumulus parameterization schemes. The maximum vorticity at different pressure levels for different schemes are presented in Table 3.

Vertical distribution of vorticity along E-W direction and along N-S direction at 0600, 1500, 1500 and 1500 UTC of 26 Octobar and 0000 and 0000 UTC of 27 October 2008 for KF, BMJ, GF, OKF, G3 and GD schemes is shown in Figure 8(a-b). In this figure the system has the positive vorticity along the center up to 100 hPa level. The highest values are found in the E-W direction at 300, 900, 600, 850, 900 and 850 hPa levels for KF, BMJ, GF, G3, GD and OKF schemes (Figure 8a) and the values are 15, 12, 15, 12, 9 and 10 $\times 10^{-5}$/sec respectively. The highest values are also found in the N-S direction at 750, 750, 650, 950, 950 and 900 hPa levels for KF, BMJ, GF, G3, GD and OKF schemes (Figure 8b) and the values are 16, 10, 18, 9, 5 and 8 $\times 10^{-5}$/sec respectively.

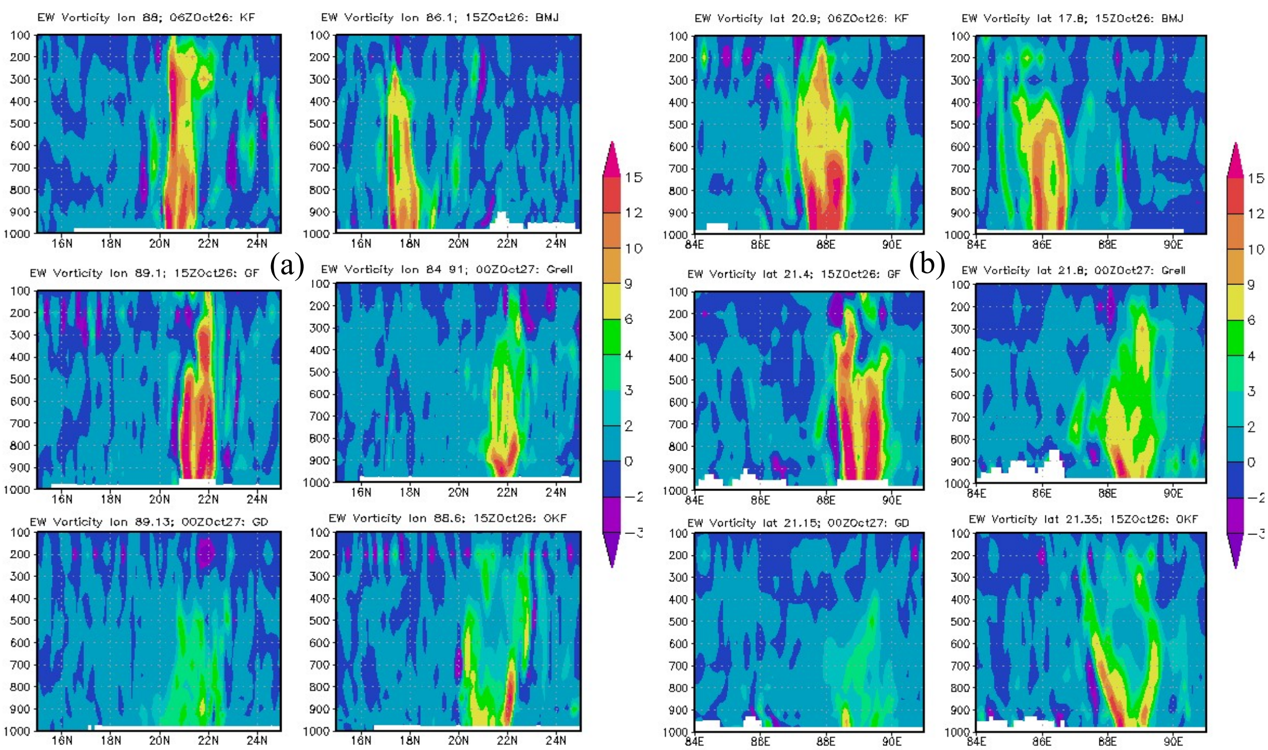

Figure 8: WRF model simulated vertical distribution of vorticity along the center of TC Rashmi at fixed (a) longitude and (b) latitude of different cumulus schemes for the time of maximum intensity.

Table 3: Model simulated maximum vorticity at different pressure levels for different cumulus schemes.

CPs/ levels	Maximum vorticity (x10^{-5} s^{-1}) at different levels and times			
	950	850	500	300
KF	35 at 18 UTC 25 Oct	31 at 18 UTC 25 Oct	20 at 18 UTC 25 Oct	19 at 21 UTC 25 Oct
BMJ	27 at 09 UTC 26 Oct	23 at 12 UTC 26 Oct	24 at 21 UTC 26 Oct	25 at 15 UTC 26 Oct
GF	34 at 12 UTC 26 Oct	38 at 15 UTC 26 Oct	20 at 12 UTC 26 Oct	20 at 12 UTC 26 Oct
G3	24 at 21 UTC 26 Oct	25 at 21 UTC 26 Oct	15 at 21 UTC 26 Oct	12 at 21 UTC 26 Oct
GD	16 at 09 UTC 27 Oct	12 at 15 UTC 26 Oct	11 at 21 UTC 26 Oct	18 at 06 UTC 24 Oct
OKF	20 at 18 UTC 26 Oct	21 at 09 UTC 26 Oct	14 at 15 UTC 26 Oct	11 at 18 UTC 26 Oct

4.4 Temperature Anomaly

The simulated temperature anomaly from the starting of model run and the difference at its mature stage at 0600, 1500, 1500 and 1500 UTC of 26 October and 0000 and 0000 UTC of 27 October 2008 for KF, BMJ, GF, OKF, G3 and GD schemes is shown in Figure 9. The warm core region is expanded up to 200 hPa level all most for all cumulus schemes. The maximum temperature anomaly has simulated 6, 5, 10, 6, 4 and 5°C for KF, BMJ, GF, G3, GD and OKF schemes and it observed 250, 600, 450, 400, 400 and 400 hPa levels respectively. The maximum temperature anomaly has simulated at 400-500 hPa level and also the MWS and MSLP are found for GF scheme, which suggest that the middle to upper level temperature anomaly are related with the intensity of TC. Since GF scheme has simulated much higher temperature in the middle to upper troposphere the intensity in terms of pressure fall and MWS at 10m level are much higher than that of other cumulus parameterization schemes. The simulated temperature anomaly demonstrates that the warm core is visible in the middle troposphere for all cumulus schemes with little exception. Negative temperature anomalies are seen at the upper levels and lower levels also.

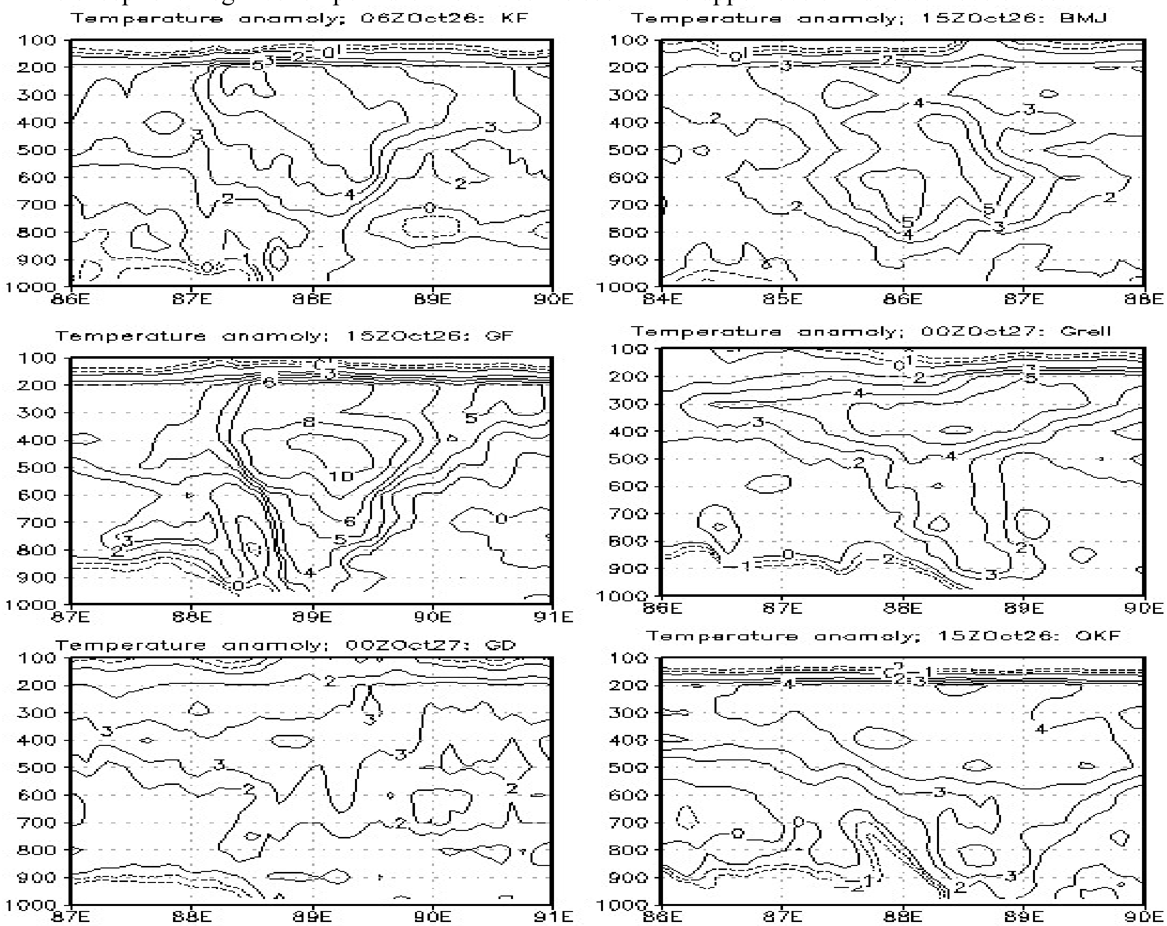

Figure 9: WRF model simulated vertical distribution of temperature difference from the beginning of model run and at its mature stage for different cumulus schemes along the longitude of TC Rashmi.

4.5 Water vapor mixing ratio (WVMR)

The vertical distribution of WVMR along the E-W cross section of the center of TC and horizontal distribution at 950 hPa of different cumulus schemes for the mature stage at 0600, 1500, 1500 and 1500 UTC of 26 and 0000 and 0000 UTC of 27 October 2008 is shown in Figure 10(a-b). Figure 10(a) shows that the highest moisture content 22 g/kg or more is found at the center of the system at 950 hPa level and it decreases upwards to 400 hPa levels or more. At the mature stage these upward levels shift up to 350 hPa level. The maximum value of WVMR is found 22 g/kg for GF scheme and 20 g/kg is found other cumulus schemes. The WVMR shows a highly asymmetric character in the horizontal distribution. In Figure 10(b), maximum WVMR of 22 g/kg is found for GF scheme and 20 g/kg is found for KF, BMJ, G3, GD and OKF schemes. It is noted that the highest WVMR is obtained at 950 hPa level near Bangladesh coast for all cumulus schemes except BMJ. Maximum value of WVMR is 22 g/kg and it is situated mainly at and around the center of the cyclone. The value of high WVMR increases slightly with the development of the system.

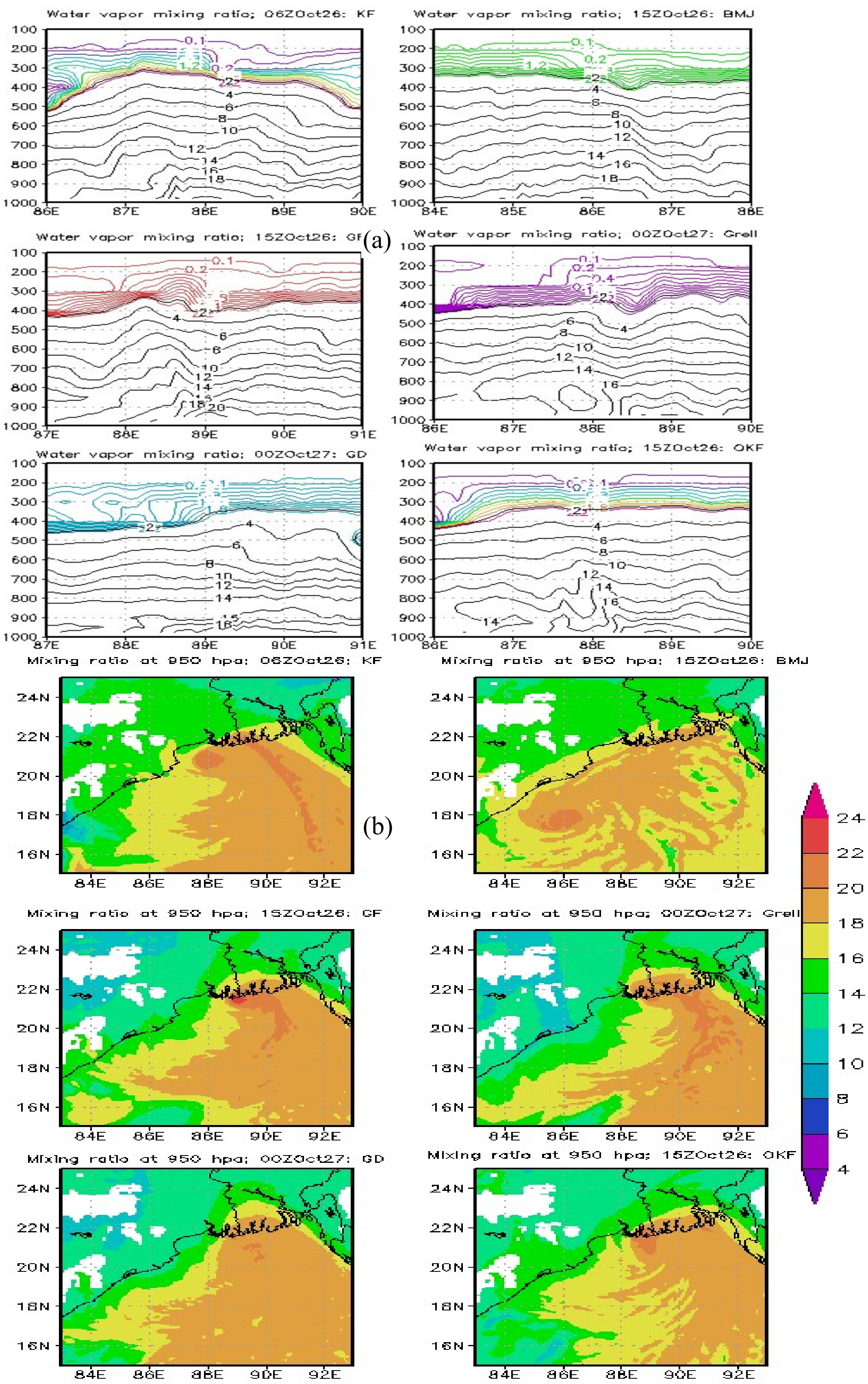

Figure 10: Model simulated (a) vertical distribution of WVMR along the east-west cross section of the center and at 950 hPa of TC Rashmi for six different cumulus schemes.

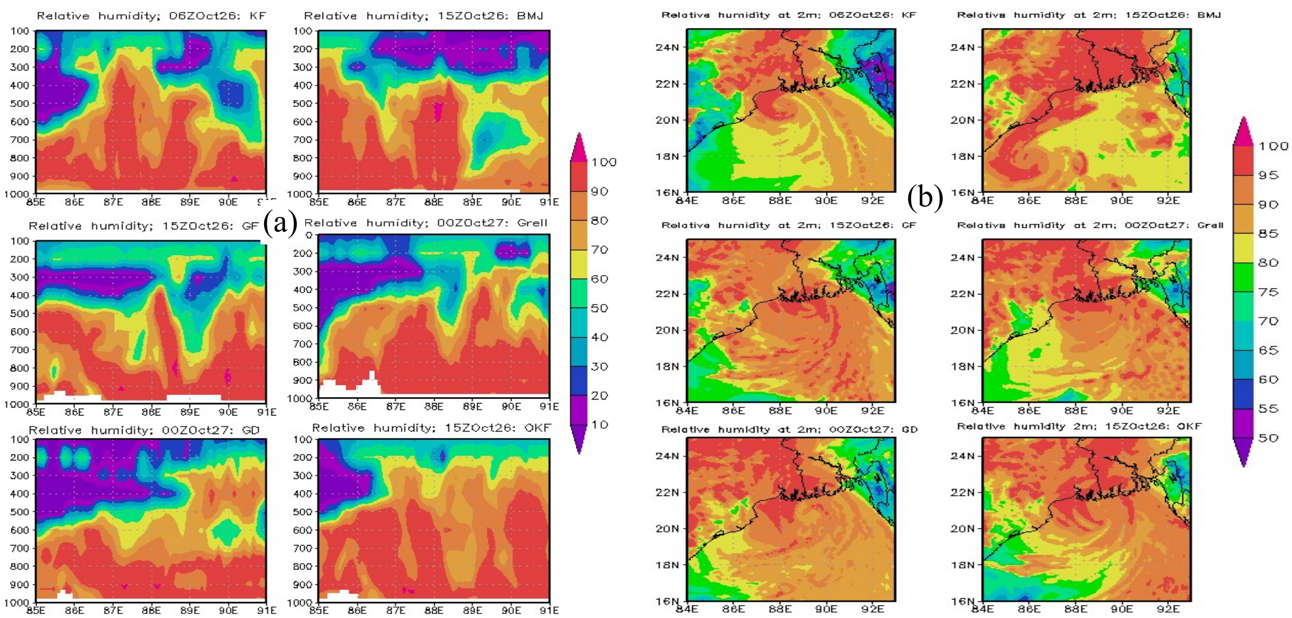

Figure 11: Model simulated (a) vertical distribution of RH in the east-west direction and (b) horizontal distribution of RH at 2m of TC Rashmi for different cumulus schemes.

4.6 Relative Humidity

The vertical cross section and horizontal distribution of RH (at 2m level) at 0600, 1500, 1500 and 1500 UTC of 26 and 0000 and 0000 UTC of 27 October 2008 (i.e. its mature stage) for KF, BMJ, GF, OKF, G3 and GD schemes are shown in Figure 11(a-b). It is noted that more than 90% RH spreads in outer range of eye wall up to 350, 550, 400, 500, 600 and 450 hPa levels for KF, BMJ, GF, G3, GD and OKF schemes respectively. High RH is also found up to 500 hPa level. The horizontal distribution of RH pattern (Figure 11b) has shown that the moisture circulation exist for all cumulus schemes except BMJ scheme. The model simulated 95% or more RH around the center of circulation.

5. CONCLUSIONS

- Simulated MSLP for Rashmi using OKF, G3 and BMJ match well with the observed than the other cumulus parameterization schemes. Variation of E-W elongated SLP and 10m wind at the center of TC Rashmi are clearly observed for six different cumulus schemes.
- The center of the eye is flattened in the N-S direction and relaxed in the E-W direction and maximum wind speed is found in the southern and eastern boundary of the eye of TC Rashmi. This suggests that the wind speed is higher in the south-east region of the eye of TC Rashmi.
- The maximum winds at 10m level are closer with the observed for GD (91%), G3 (113%) and OKF (113%) cumulus schemes. The zonal and meridional wind is found maximum for GF scheme and minimum for KF, OKF and GD schemes respectively.
- The track errors at the time of landfall are found minimum 60, 97, 98 and 110 km and time error 3(D), 12(D), 2(D) and 5(E) hour for GD, BMJ, G3 and OKF schemes respectively during 96 hours model run. The RMSE is smaller for OKF and G3 schemes and larger for BMJ scheme.
- The intensity in terms of pressure fall and MWS at 10m level are much higher for GF scheme than that of observed and other cumulus parameterization schemes due to the simulation of much higher temperature in the middle to upper troposphere. This suggests that the intensity of TC depends on temperature anomaly in the middle to upper troposphere.
- Maximum value of water vapor mixing ratio is 22 gm/kg simulated for GF scheme.

G3 and OKF scheme gives the better results among all the used cumulus parameterization schemes in terms of MWS at 10m level, MSLP, landfall track and time error of TC Rashmi.

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