Performance Evaluation of Convective Parameterization Schemes of WRF-ARW Model in the Simulation of Pre-monsoon Thunderstorm Events over Kharagpur using STORM Data Sets

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ABSTRACT
Thunderstorms associated with severe gusty winds and lightening cause loss of life and property even though they last for an hour or so. Forecasting of these severe weather events is highly essential due to their impact on socio-economic conditions of affected regions. Kharagpur (22°30′ N, 87°20′ E) is in the region of Gangetic West Bengal (GWB) affected by high frequency of occurrence of thunderstorms during pre-monsoon months. In the present study an attempt has been made to understand the performance of convective parameterization schemes (e.g. Kain-Fritsch, Grell-Devenyi ensemble and Betts-Miller-Janjic) of a meso-scale model WRF-ARW version 3.2 in simulating pre-monsoon thunderstorm events that occurred during 12 May 2009 and 5 May 2010 over Kharagpur. Numerical experiments are carried out by considering convection explicitly. The model simulations are compared with the available observations. Statistical evaluation of simulated parameters along with the observations revealed Grell-Devenyi ensemble and Kain-Fritsch schemes performed reasonably well in representing the thermo- dynamical state of atmosphere during the thunderstorm events.

General Terms
Mesoscale model, Statistical evaluation, Simulation.

Keywords
Numerical Experiments, Convection parameterization, Thunderstorm

1. INTRODUCTION
During pre-monsoon months (March to May), occurrence of thunderstorms are quite frequent over Eastern, North Eastern India and GWB regions which are locally known as *'Kalbaishakhi'* or *Nor'westers*. Pre-monsoon season is the transition period from winter monsoon to summer monsoon circulations. Two different air masses, west to northwesterly winds of land origin and moist winds from the Bay, co-exist over West Bengal region [1]. There exists a low pressure system over Chota Nagpur Plateau, West Bengal, Assam, Bangladesh and the adjoining regions and a seasonal high over the Bay of Bengal during this time [2,3]. Climatologically, thunderstorms generate over Chota Nagpur region and moved over to GWB region in SE direction [4]. Forecasting of thunderstorms is one of the most difficult tasks in weather prediction due to their small spatial and temporal scales. Meteorological conditions, the inherent non-linearity of their dynamics and physics associated with the days of thunderstorm and no thunderstorm give a clear idea of atmospheric variation and primary factors in triggering of thunderstorm [5].

Even though the life time of the thunderstorms are of few hours, they cause huge damage to the life and property thereby result in severe socio-economic impact in the affected regions [6,7]. Forecasting of thunderstorms is essential in order to safeguard the casualties and loss of property. Various thermodynamic parameters and stability indices are being used to predict the possibility of thunderstorm occurrence over different parts of the globe [8,9,10,11,12,13,14,15,16,17,18]. Few observational studies have been reported for pre-monsoon thunderstorms analysis over the GWB region in attempt to predict the development of these events [e.g. 18, 19, 20].

Simulation of these thunderstorms with the help of mesoscale models is one of the ways to understand the physics and dynamics of these severe thunderstorms and attempted by various researchers for the Indian region [e.g. 15,17,21,22,23,24,25,26,27]. These studies are using non-hydrostatic meso-scale models like the PSU/NCAR community model (MM5), Advanced Regional Prediction System (ARPS), Regional Atmospheric Modeling System (RAMS), Weather Research and Forecasting model (WRF) with two options: WRF-ARW (WRF Advanced Research) and WRF-NMM (Nonhydrostatic Mesoscale Model). These models are having different physics and dynamics options compare to each other.

Present study focuses on simulation of two thunderstorm events occurred on 12 May 2009, and 5 May 2010 over Kharagpur (22°30′ N, 87°20′ E) region of GWB. GWB affected by high frequency of occurrence of thunderstorms during pre-monsoon months. To improve the forecasting capability of these storms Department of Science & Technology (DST), New Delhi, Government of India had initiated multi-institutional field experiment, Severe Thunderstorm – Observations and Regional Modeling (STORM) spanning over GWB and Northeastern states of India. Present study utilizes the STORM data. The mesoscale model used for thunderstorm simulation in the present study is Weather Research Forecasting (WRF ARW Version 3.2) with triple nested domain: outermost domain (d1) with 27 km resolution, second domain (d2) with 9 km resolution and the inner most domain (d3) with 3 km grid resolution. The main focus of the present study is to examine the performance of different Convective Parameterization Schemes (CPSs) in simulating thermodynamical structure of the atmosphere, variations in surface layer meteorological variables and rainfall during the thunderstorm events.

2. STUDY SITE

The site for the present study is Kharagpur region of west Midnapore, GWB, India. The study area is in agriculture farms at Indian Institute of Technology Kharagpur. A 50-m instrumented micrometeorological tower and upper atmospheric sounding system (DigiCORA radiosondes) has been established at this site as part of research projects sponsored by DST, Government of India under STORM programme [28]. Details of site map and the sensors used for taking the observations are given in [19, 29]. This site consists of sandy loam soil, which is amixture of sand (64.1 %), silt (20.1 %), and clay (15.8 %) [30,31]. Topographically the site is flat and grassy.

3. DATA USED

Two thunderstorm events (12 May 2009 and 5 May 2010) occurred over Kharagpur are considered for the present study. The thunderstorm event occurred during 0642-0751 UTC on 12 May 2009 with a rainfall of 25.1 mm during thunderstorm hour and a total of 35.4 mm rainfall during the day. On 5 May 2010, thunderstorm event occurs during 0937-1042 UTC with a rainfall of 19.6 mm during thunderstorm hour and a total of 23.8 mm rainfall during the day. The following data sets have been used for the present study:

1. Upper air Radiosonde observations consists of pressure (hPa), temperature (^{o}C), relative humidity (%), wind speed (ms^{-1}) and wind direction (degrees).
2. 50 m micro-meteorological tower observations (From Slow sensors: atmospheric pressure, wind speed, wind direction, temperature and relative humidity at 6 heights, 2 m, 4 m, 8 m, 16 m, 32 m and 50 m., and Rainfall)
3. FNL data 1.0°×1.0°
4. TRMM 3B42V7 accumulated rainfall
5. Doppler Weather Radar (DWR) imageries obtained from Cyclone Detection Radar centre, India Meteorological Department, Kolkata.
6. Synoptic weather information was provided by STORM advisory group over the region for the Intensive Observation Period (IOP) days

4. DESCRIPTION OF NUMERICAL MODEL

The Advanced Research Weather Research and Forecast (ARW) version 3.2 mesoscale model developed by the National Center for Atmospheric Research (NCAR) [32] is used in this study. The model consists of fully compressible non-hydrostatic equations and the prognostic variables include the three-dimensional wind, perturbation quantities of pressure, potential temperature, geo-potential, surface pressure, turbulent kinetic energy and scalars (water vapor mixing ratio, cloud water etc.) [33,34]. Terrain following vertical coordinate system and Arakawa C-grid staggering in the horizontal is used in the present study. Third-order Runge–Kutta time integration is employed in the model. For the present study the model is configured with three interactive nested domains. Model specifications used in the present study are provided in (Table 1).

The model was integrated for a period of 24 h, starting from of 0000 UTC on 12 May 2009 and 5 May 2010. Initial conditions for the parent domain (d01) are derived from 6 h global final analysis (FNL) at 1.0°×1.0° grids generated by the National Center for Environmental Prediction (NCEP)'s global forecast system (GFS). Analysis fields, including temperature, moisture, geopotential height and wind, are interpolated to the mesoscale grids by the WRF Pre-processing System (WPS). These derived fields served as initial conditions for the present experiments. The domain is configured with vertical structure of 59 unequally spaced sigma (non-dimensional pressure) levels with the top of model at 50 hPa. The outer domain (d01) covers a larger region with 27-km resolution and 40*49 grids. The second inner domain (d02) has 9-km resolution with 73*91 and innermost domain (d03) has 3-km resolution with 109*121. These three domains used in present study are shown in Figure 1.

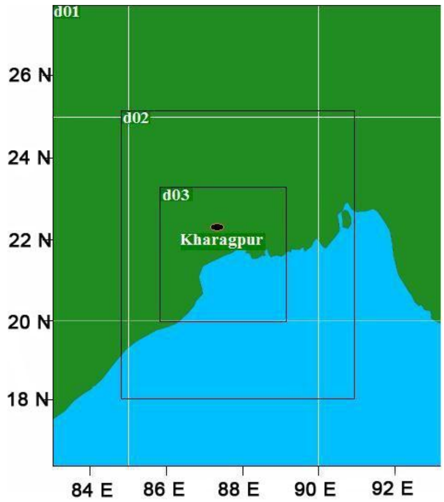

Fig 1: WRF-ARW Domain

The physics schemes used in the present study are the Mellor-Yamada-Janjic (MYJ) [35,36] for PBL processes, Kain–Fritsch (KF) [37,38], Grell-Devenyi ensemble scheme(GD) [39] and Betts-Miller-Janjic (BMJ) scheme [40,41,42] for cumulus convection. In addition, a simulation without a convective scheme in third domain: (KF-NO) and (GD-NO) is performed for each case to determine if the model could simulate the convection explicitly. Noah land Surface Scheme [43], Eta microphysics [44] for Microphysics options, Rapid Radiation Transfer Model (RRTM) for long-wave radiation [45] and Dudhia scheme [46] for shortwave radiation are opted for the study.

5. RESULTS AND DISCUSSION

This section presents model simulation with different CPSs and analysis of resulted meteorological variables, thermodynamic indices and their variations during thunderstorm events compared with the available *in-situ* observations. Statistical analysis is also done to identify the most significant CPS for thunderstorm modeling studies over the study region.

Table1. Overview of WRF model

Dynamics	Non hydrostatic
Data	NCEP FNL
Interval	6 hrs
Grid size	Domain1: (40× 49) × 59 Domain2: (73× 91) × 59 Domain3: (109× 121) × 59
Resolution	Domain1: 27km × 27km Domain2: 9km × 9km Domain3: 3km × 3km
Covered area	16.3º-27.4º N and 83.1º-92.8º E
Map Projection	Mercator
Horizontal grid system	Arakawa-C grid
Integration time step	60 sec
Vertical coordinates	Terrain-following hydrostatic pressure vertical co-ordinate with 59 vertical levels
Time integration scheme	3^{rd} order Runga-Kutta Scheme
Spatial differencing scheme	6^{th} order center differencing
PBL Scheme	MYJ
Surface layer Parameterization	Noah land Surface Scheme
Microphysics	Eta microphysics
Short wave radiation	Dudhia scheme
Long wave radiation	RRTM scheme
Cumulus Parameterization	1) Kain-Fritsch scheme 2) Grell-Devenyi ensemble scheme 3) Betts-Miller-Janjic scheme

5.1 Variation of surface meteorological variables

The diurnal variation of surface meteorological variables such as air temperature (AT), relative humidity (RH), wind speed (WS) and surface level pressure (SLP) simulated by different CPSs along with the available observations during 12 May 2009 (12 May 0000 UTC to 13 May 0000 UTC) and 5 May 2010 (5 May 0000 UTC to 6 May 0000 UTC) are depicted in Figures 2 and 3, respectively.

Case 1 (*12 May 2009*):

Observations revealed a sudden rise of RH during 0700 to 0900 UTC from around 70% to 92% (Figure 2a) which is the period of the thunderstorm event. This is attributed to the moist air incursion and associated rainfall during the thunderstorm at site. This sudden rise is not captured well by any schemes but to some small rise in RH is seen in GD-NO. It is also noticed that the magnitudes of CPSs are less than the observations. But on close examination of the results, one can see that KF and GD only exhibit rise in RH during the time of the event and afterwards as seen in the observations. During the event, a sudden fall of 8 ^{o}C is seen in the observed AT (see Figure 2b). No scheme has captured this feature except GD-NO, which shows a marginal fall in AT. It is seen that all the schemes are producing too warm atmosphere and close to each other. Figure 2c depicts the typical diurnal variation of SLP. The pre-squall low at 1000 UTC, meso-high at 1400 UTC and wake low at 1600 UTC is showing the typical thunderstorm feature in SLP observations [19]. This feature is not captured by any of CPSs. But the semi-diurnal variation of SLP as expected and noticed in the observations was reasonably captured by all the schemes.

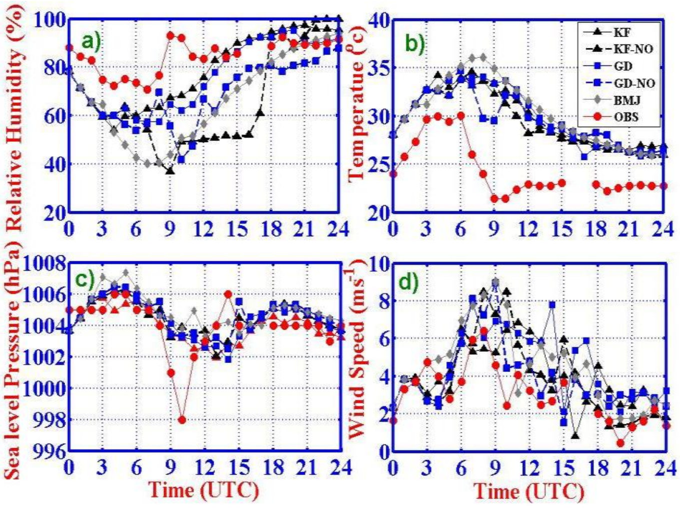

Fig 2: The inter-comparison of different CPSs simulations with the observations of the surface meteorological variables (a) relative humidity (%) (b) temperature (º C) (c) sea level pressure (hPa) (d) wind speed (ms^{-1}) over Kharagpur during 12 May 2009 0000 UTC to 13 May 2009 0000 UTC

As seen in Figure 2d, all the schemes in general over-estimated WS for most of the day. On the close examination, we noticed that KF winds are close to observations till 0700 UTC where as GD-NO could able to reproduce the WS variations with subtle differences in the magnitude.

Case 2 (*5 May 2010*):

As seen in Case 1, a sudden rise of RH (48% to 95% during 0900-1100 UTC) is noticed in the observations depicted in Figure 3a. The KF, GD and KF-NO are able to capture the increase of RH after 0900 UTC but not able to capture the sharp rise. Among these three CPSs, GD scheme seems to be closely agreeing with the observations. Figure 3b delineates the typical variation of AT noticed in the observations and the model simulations with different cumulus schemes. AT with magnitude of 25^{o}C at 0000 UTC reached to a maximum value of 34.9^{o}C at 0800 UTC. But a sharp decrease of AT of the order of around 13°C can be seen in observations during 0900 to 1000 UTC, which was the thunderstorm period. The magnitude of AT simulated by various schemes is higher than observations at 0000 UTC (29°C) as seen in CASE 1. However, GD-NO and KF-NO schemes are able to capture the sharp decrease during thunderstorm event. In general one can conclude that GD-NO values are better than KF-NO. As noticed in CASE 1, AT obtained from KF are close to observations after 1500 UTC. The SLP inter-comparisons are portrayed in Figure 3c. As seen in the observations, KF-NO and GD-NO schemes could able to capture the pre-squall low, meso high and wake-low features approximately one hour before the occurrence of the event. The observed and model simulated WS are compared in Figure 3d. As seen in CASE 1, the model simulations over-estimated for most of the day. WS simulations by various schemes are close to observed winds up to 0700 UTC. From close examination of results, it is seen that KF, GD and GD-NO could able to capture the observed variations with reasonable degree of accuracy in magnitude.

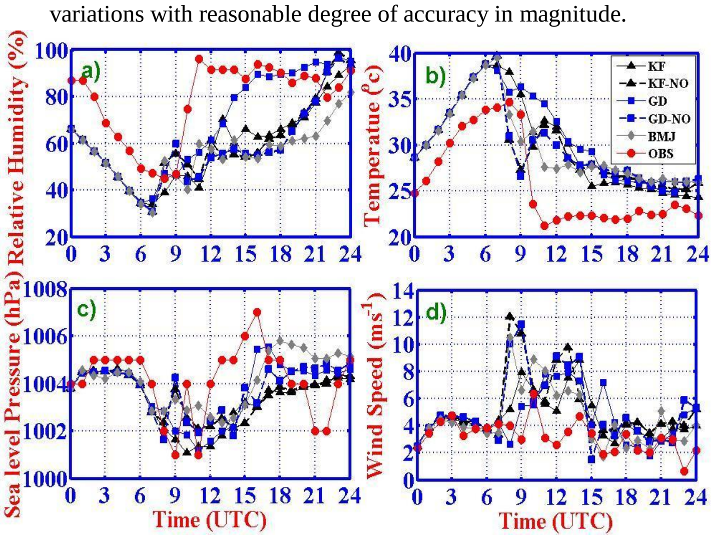

Fig 3: The inter-comparison of different CPSs simulations with the observations of the surface meteorological variables (a) relative humidity (%) (b) temperature (°C) (c) sea level pressure (hPa) (d) wind speed (ms^{-1}) over Kharagpur during 5 May 2010 0000 UTC to 6 May 2010 0000 UTC.

5.2 Vertical Profiles of zonal and meridional wind components, equivalent potential temperature and relative humidity

The model simulations using different CSPs of vertical profiles of zonal and meridional wind components, RH and equivalent potential temperature along with the available observations obtained from high resolution radiosonde ascents are presented in Figures 4 and 5, respectively at 0600 UTC of Case 1 and Case 2. After careful examination of the simulations, it is found that KF and GD schemes are reasonably good and hence analysis using these two only has been presented.

Case 1: During this day, the wind data is not available hence only the model simulations of vertical profiles of zonal and meridional wind obtained from KF and GD are only analyzed (Figs.4a and 4b). Interestingly both the schemes almost exhibited identical wind variation with height. In the layer from surface to 1000 m winds are north-easterly; above this layer up to 2000 m winds are south-easterly. Change of wind direction (smaller magnitude of wind speeds) noticed and winds are found to be south-westerly in the layer from 2000 to 4000 m and above this layer north-westerly winds are noticed. The site geography indicates that winds from the southeast to southwest come from the Bay of Bengal (BoB), while northerly and north-westerly winds are of land mass origin. KF and GD simulations along with the observed RH profiles are shown in Figure 4c. Upon comparing with the observations, KF simulations are close to the observations in the lower layers approximately up to 1500 m, above that GD performance is improved. But qualitatively both the schemed could able to capture the observed variation of the humidity. We noticed that the layer from surface to 2000 m is highly humid and above that up to around 4500 m moderately humid layer and above that humidity decreased drastically.

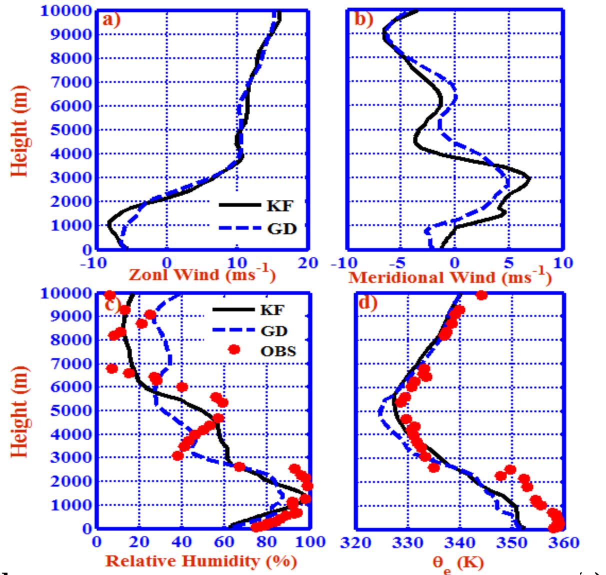

Fig 4: Validation of KF and GD simulated profiles of (a) relative humidity (%), (b) equivalent potential temperature (θ_e) (K) with available observations at Kharagpur at 12 May 2009, 0600 UTC

More humidity in the lower layers are brought by the winds blowing from BoB and the supply of moisture seized in the higher levels as the winds are land origin as reported by [19]. The observed vertical variation of equivalent potential temperature was captured by KF and GD schemes except less in magnitude of around 5 K up to 2500 m (Fig.4d). From the observations, we can see the existence of convective instability up to the layer 2500 m having super-adiabatic and neutral layer in the lower levels near to the surface. Above this layer up to around 5000 m very less gradient of temperature is noticed indicating the existence of potential instability. Above this height atmosphere tend to become stable.

Case 2: From Figures 5a and 5b, it is noticed that the KF and GD simulations of wind components are in good comparison with the observed variation as well as magnitude. Mostly south-westerly winds are noticed in the entire vertical column of the atmosphere except at little variation near the surface level.

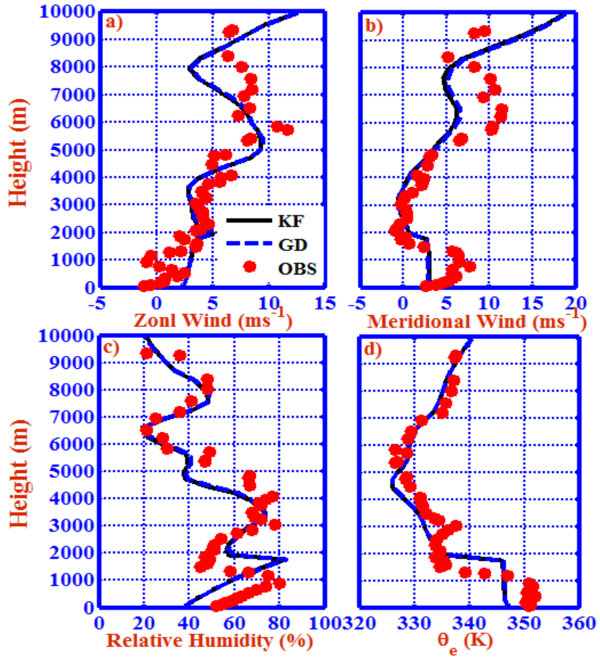

Fig 5: Validation of KF and GD simulated profiles of (a) zonal wind (ms^{-1}) , (b) meridional wind (ms^{-1}), (c) relative humidity (%), (d) equivalent potential temperature (θ_e) (K) with available observations at Kharagpur at 5 May 2010 0600 UTC

Highly humid layer up to around 4000 m is seen in the observations as well as simulations as depicted in Figure 5c. Above this layer also reasonable magnitudes of humidity are noticed than in Case 1. This clearly establishes the fact that the moisture laden winds from BOB are responsible for bringing moisture into the study area. As noticed in Case 1, it is noticed convective instability in the layer up to 4500 m and above that potential instability from the observations of equivalent potential temperature profile shown in Figure 5d. KF and GD could able to capture the thermal structure of the atmosphere as explained above.

5.3 Accumulated rainfall

Every three hourly accumulated rainfall obtained from observations, TRMM, and simulations from different CPSs for Case 1 and Case 2 are presented in Figure 6a and Figure 6b respectively. In Case 1, KF and GD simulated 24 hour accumulated rainfall is 59 mm and 15 mm, where as observations and TRMM reported 35.4 mm and 30.5 mm respectively. Remaining schemes failed to capture rainfall magnitude. In this event, KF simulations are better than GD. In Case 2, KF and GD simulated 24 hour accumulated rainfall is 17 mm and 22 mm, where as observations and TRMM reported 23.8 mm and 16 mm respectively. Based on these results, it is seen that KF and GD simulations are close to TRMM and observed rainfall, respectively. In both the cases, these schemes have shown the rainfall three hours before the surface rainfall observations and TRMM.

5.4 Simulation of Thermodynamical Stability Indices

Convection in the atmosphere is strongly depended on its thermodynamic state. In the present study, an attempt is made to examine different stability indices obtained from simulations with different CPSs on 12 May 2009 at 0600 UTC and 5 May 2010 at 0600 UTC over Kharagpur.

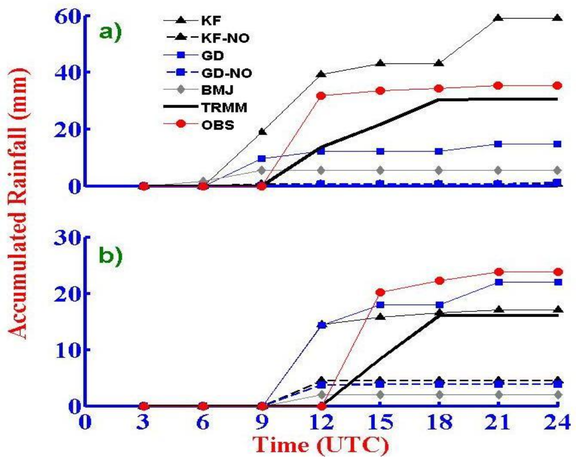

Fig 6: Validation of different CPSs simulated accumulated rainfall with TRMM and observed rainfall during (a) 12 May 2009 0000 UTC to 13 May 2009 0000 UTC and b) 5 May 2010 0000 UTC to 6 May 2010 0000 UTC at Kharagpur

Observed radiosonde profile data obtained over the study area using DigiCORA system has been used to validate the model simulated stability indices. [18] proposed threshold values of various thermodynamic indices to forecast the occurrence of thunderstorms over Kolkata. In the subsequent studies [47] reported that these threshold values hold good for Kharagpur as well. Convective Available Potential Energy (CAPE) represents the amount of buoyant energy available to accelerate a parcel vertically. Total totals index (TTI) is useful to assess the storm strength. KI index is used for determining the air mass thunderstorm and it is a combination of moisture at 850 and 700 hPa and temperature difference between 850 and 500 hPa. Humidity Index (HI) gives a combination of the measure of saturation at 850, 700 and 500 hPa which is very important in the thunderstorm generation and intensification. The threshold values of the indices: CAPE > 1000 J kg^{-1}, TTI $\geq$ 46, KI (°C) $\geq$ 24 and HI $\leq$ 45 is suggested by [18] is necessary for severe thunderstorms to occur. Table 2 shows the inter-comparison of observations and model simulated stability indices with different CPSs over Kharagpur valid for 12 May 2009 and 5 May 2010 at 0600 UTC. The thermodynamic indices during the two cases both simulated as well as observed followed the threshold values as referred above and observed that thunderstorms occurred over the study area.

5.5 Statistical Evaluation of surface meteorological variables

A statistical analysis based on mean absolute error (MAE), root mean square error (RMSE) and correlation coefficient (CC) is performed for comparisons between the simulated and observed surface meteorological variables such as RH, AT, SLP and WS with different CPSs for two thunderstorm cases considered in the present study are given in (Tables 3, 4, 5 and 6). From the (Table 3), we can clearly see that, RH simulated by GD scheme has less MAE and RMSE and good CC, followed by KF scheme compared to all other schemes. In the case of AT (Table 4), in general all the schemes have shown similar error and CC. But on close examination, statistically KF performance is better followed by GD, KF-NO.

Table 2. The inter comparison of Observation and model simulated stability indices with different CPSs over Kharagpur for 12 May 2009 (CASE 1) and 5 May 2010 (CASE 2) at 0060 UTC

Stability Index	CASES	KF	KF-NO	GD	GD-NO	BMJ	OBS
CAPE	CASE 1	3959	4067	3753	3516	1416	2853
	CASE 2	2526	2532	2530	2552	2415	2245
	CASE 2	53	53	53	53	54	50
HI	CASE 1	24	32	30	22	22	21
	CASE 2	24	24	23	23	17	45
KI	CASE 1	40	38	34	38	32	37
	CASE 2	41	41	41	42	42	39

Table 3. Statistical analysis of surface relative humidity (%) with different CPSs over Kharagpur for 12 May 2009 (CASE 1) and 5 May 2010 (CASE 2)

	CASES	KF	KF-NO	GD	GD-NO	BMJ
MAE	CASE 1	11.88	19.21	11.67	15.75	17.77
	CASE 2	19.69	22.01	13.41	22.78	22.99
RMSE	CASE 1	14.10	24.00	14.91	19.35	22.28
	CASE 2	22.99	24.74	16.77	25.80	25.40
CC	CASE 1	0.42	0.44	0.36	0.2	0.41
	CASE 2	0.67	0.51	0.76	0.49	0.69

Table 5 revealed the SLP simulated by GD is good followed by KF scheme. In the case of WS, KF scheme followed by BMJ has shown better statistical performance based on the results given in (Table 6).

6. CONCLUSIONS

The preset paper mainly focus on the performance of various convection parameterization schemes of WRF-ARW version 3.2 in simulating thunderstorms that occurred over Kharagpur on 12 May 2009 and 5 May 2010 using STORM data sets. In this study the model simulated thermodynamical structure of the atmosphere, variation of surface meteorological variables and rainfall variations are validated with the available observations to evaluate the capability of the model for forecasting the thunderstorms. Except the use of different convection parameterization schemes, the rest of the model setup were the same in all the numerical experiments conducted.

Table 4. Statistical analysis of Air temperature (^{0} C) with different CPSs over Kharagpur for 12 May 2009 (CASE 1) and 5 May 2010 (CASE 2)

	CASES	KF	KF-NO	GD	GD-NO	BMJ
MAE	CASE 1	5.21	4.86	5.24	5.06	5.79
	CASE 2	4.26	4.72	5.02	4.75	4.34
RMSE	CASE 1	5.82	5.53	6.12	5.52	6.71
	CASE 2	4.94	5.14	5.83	5.10	4.56
CC	CASE 1	0.56	0.55	0.39	0.65	0.38
	CASE 2	0.87	0.73	0.79	0.74	0.89

Table 5. Statistical analysis of surface pressure (hPa) with different CPSs over Kharagpur valid for 12 May 2009 (CASE 1) and 5 May 2010 (CASE 2)

	CASES	KF	KF-NO	GD	GD-NO	BMJ
MAE	CASE 1	1.05	1.17	1.19	1.24	1.36
	CASE 2	1.27	1.34	1.16	1.31	1.43
RMSE	CASE 1	1.54	1.67	1.721	1.66	1.82
	CASE 2	1.68	1.72	1.51	1.69	1.71
CC	CASE 1	0.46	0.42	0.39	0.49	0.45
	CASE 2	0.36	0.10	0.43	0.14	0.10

Table 6. Statistical analysis of surface wind speed (ms^{-1}) with different CPSs over Kharagpur for 12 May 2009 (CASE 1) and 5 May 2010 (CASE 2)

	CASES	KF	KF-NO	GD	GD-NO	BMJ
MAE	CASE 1	1.50	1.20	1.85	1.37	1.56
	CASE 2	1.41	2.12	1.67	2.25	1.57
RMSE	CASE 1	1.95	1.75	2.22	1.63	2.05
	CASE 2	1.97	3.17	2.41	3.25	2.28
CC	CASE 1	0.35	0.67	0.48	0.64	0.70
	CASE 2	0.52	0.23	0.13	0.16	0.52

Hence the variations in the simulated parameters can be attributed to the sensitivity of the convective schemes. Sudden rise in RH, fall of AT, variations in WS during the thunderstorm events are reasonably captured by GD and KF schemes with one hour lead and/or lag. But the schemes are failed capture the typical variation of SLP (pre squall low, meso high and wake low as seen in the observations. The thermal structure, wind components and RH with height are well captured by GD and KF schemes. These schemes could able to capture the presence of convective instability in lower layers and potential instability in upper layers with sufficient moisture which is a necessary and sufficient condition for the occurrence of the thunderstorm. GD and KF schemes simulated the accumulated rainfall with reasonable accuracy and are validated with TRMM as well as rainfall measurements at the study area. All the schemes could able to simulate the thermo dynamical indices reasonably well and the values are in accordance with the tested threshold values in identifying the occurrence of thunderstorms over the study area. A statistical analysis based on mean absolute error, root mean square error and correlation coefficient revealed good performance of GD scheme followed by KF scheme on simulating various parameters associated with the thunderstorms over the study region. This work advocates the usefulness of this model and identified GD (first option) and KF (second option) convection parameterization schemes efficiency in forecasting the thunderstorms over Gangetic West Bengal region.

7. ACKNOWLEDGMENTS

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