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# A Comparative Study of Convective Parameterization Schemes in WRF-NMM Model

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## ABSTRACT
Severe local storms, including tornadoes, damaging hail and wind gusts, frequently occur over the eastern and northeastern states of India during the pre-monsoon season (March-May). Forecasting thunderstorms is one of the most difficult tasks in weather prediction, due to their rather small spatial and temporal extension and the inherent non-linearity of their dynamics and physics. In this paper, sensitivity experiments are conducted with the WRF-NMM model to test the impact of convective parameterization schemes on simulating severe thunderstorms that occurred over Kolkata on 20 May 2006 and 21 May 2007 and validated the model results with observation. In addition, a simulation without convective parameterization scheme was performed for each case to determine if the model could simulate the convection explicitly. A statistical analysis based on mean absolute error, root mean square error and correlation coefficient is performed for comparisons between the simulated and observed data with different convective schemes. This study shows that the prediction of thunderstorm affected parameters is sensitive to convective schemes. The Grell-Devenyi cloud ensemble convective scheme is well simulated the thunderstorm activities in terms of time, intensity and the region of occurrence of the events as compared to other convective schemes and also explicit scheme.

## General Terms
Modeling, Simulation, Statistical Analysis

## Keywords
Thunderstorm, computational model, simulation, precipitation, statistical analysis, convective parameterization scheme.

## 1. INTRODUCTION
Thunderstorms, resulting from vigorous convective activity, are one of the most spectacular weather phenomena in the atmosphere. The severe thunderstorms form and move from northwest to southeast over the eastern and northeastern states of India (i.e., Gangetic West Bengal, Jharkhand, Orissa, Assam and parts of Bihar) during the pre-monsoon season (March-May). They are locally called "Nor'westers". Strong heating of landmass during mid-day initiates convection over Chhotanagpur Plateau, which moves southeast and gets intensified by mixing with warm moist air mass. These severe thunderstorms produce heavy rain showers, lightning, thunder, hail-storms, dust-storms, surface wind squalls, down-bursts and tornadoes. The strong wind produced by the thunderstorm is a real threat to aviation. The highest numbers of aviation hazards are reported during occurrence of these thunderstorms. In India, 72% of tornadoes are associated with these thunderstorms. These severe thunderstorms have significant socio-economic impact in the eastern and northeastern parts of the country. An accurate location specific and timely prediction is required to avoid loss of lives and property due to strong winds and heavy precipitation associated with these sever weather system. Accurate simulation requires knowledge about "where" and "when" storms will develop and how they will evolve [1].

The use of Numerical Weather Prediction (NWP) output to complement the interpretation of conventional observations can add great value to the forecast process. The higher time and space resolution of the model data enables a forecaster to view the evolution of the weather situation in much greater detail and can provide an insightful framework within which actual observations can be interpreted. The convective processes are implemented in NWP models through parameterizations because they are not resolved in the grid systems of most large scale and mesoscale models. The convective parameterization schemes (CPSs) are procedures that attempt to account for the collective influence of small-scale convective processes on large-scale model variables. They are representing thermodynamic and dynamic processes of moist convection occurring at sub-grid scales. No universal framework exists for CPSs, which led to the development of numerous different schemes. Properly parameterizing the effects of convection is still a challenging problem for NWP [2]. Most CPSs are developed in specific convective environments, and are evaluated in a limited number of cases [3]. Several studies have demonstrated that differences in convective parameterizations can have substantial impacts on simulated convective activity and precipitation [4, 5].

In this paper, sensitivity experiments are carried out for studying the impact of CPSs on simulating severe thunderstorm events that occurred over Kolkata ($22.52^0$ N, $88.37^0$ E) on 20 May 2006 and 21 May 2007 using WRF-NMM model. In addition, a simulation without CPS was performed for each case to determine if the model could simulate the convection explicitly. The purpose of this study is to determine how the available CPSs in the WRF-NMM model simulated severe thunderstorm events over east region of India. The outline of the paper is as follows: Section 2 gives a brief description of the severe thunderstorm events. Section 3 presents the description of numerical model and configurations. The results and discussion are described in section 4 and the conclusions in section 5.

## 2. CASE DESCRIPTION

The occurrence of pre and post monsoon thunderstorms over Indian continent is a special feature. Thunderstorms are associated with heavy rainfall during short duration of 2–3 hours. Following are the details of the severe thunderstorm cases studied in the present paper.

### 2.1 CASE 1-20 May 2006

A severe thunderstorm, which was reported on 20 May 2006 at 1200 UTC over Kolkata (see Figure 1), is taken here for the present study. This intense convective event produced 52 mm rainfall over Kolkata. The weather situation started with a squall passing Kolkata airport on 20 May 2006 at 1100 UTC with a maximum speed of 19 $ms^{-1}$ lasting for a few minutes. A few places recorded moderate rainfall over Gangetic West Bengal (GWB) and isolated rainfall over Orissa, Chattisgarh and Bihar. Dum Dum recorded 50 mm and Alipore 40 mm of rainfall. By analyzing Kolkata Doppler Weather Radar (DWR) imageries, scattered echoes developed north-east of Kolkata at 0900 UTC. This echo gradually moved towards Kolkata at 1000 UTC and intensified at 1100 UTC. This echo disappeared at 1300 UTC [6].

### 2.2 CASE 2- 21 May 2007

Another severe thunderstorm occurred over Kolkata on 21 May 2007 at 1100 UTC is taken here for the present study. A squall was reported over Kolkata at 1100 UTC from northwesterly direction with max speed of 19$ms^{-1}$ lasted for 1 minute. This convective event produced 20 mm rainfall over Kolkata. A few places recorded moderate rainfall over GWB and isolated rainfall over Orissa, Bihar and Jharkhand. By analyzing Kolkata DWR imageries, scattered echoes were developed near Dumka (DMK) at 0800 UTC and moving south eastwards at 0900 UTC. This echo is intensified into a squall (30 km north of Kolkata) at 1000 UTC. This squall moved further and over Kolkata at 1100 UTC [7].


**Fig 1: The geophysical location of experiment domain (region of study).**

## 3. WRF-NMM MODEL

The Non-hydrostatic Mesoscale Model (NMM) is a next-generation mesoscale forecast model that can be used to advance the understanding and the prediction of mesoscale convective systems. The WRF-NMM model was developed by the National Oceanic and Atmospheric Administration (NOAA)/ National Centers for Environment Prediction (NCEP). The WRF-NMM is designed to be a flexible, state-of-the-art atmospheric simulation system that is portable and efficient on available parallel computing platforms. The WRF-NMM is suitable for use in a broad range of applications across scales ranging from meters to thousands of kilometers.

The WRF-NMM is a fully compressible, non-hydrostatic model with a hydrostatic option. The WRF-NMM modeling system, illustrated in Figure 2, consists of three major components: WRF Preprocessing System (WPS), WRF-NMM solver, Postprocessor utilities and graphics tools including WRF Postprocessor (WPP). WPS is used for real-data simulations. Its functions include defining the simulation domain, interpolating terrestrial data (such as terrain, land-use, and soil types) to the simulation domain, degribbing and interpolating meteorological data from another model to the simulation domain and the model coordinate. The model uses a terrain following hybrid sigma-pressure vertical coordinate denoted by $\sigma$ and defined as

$$\sigma = \frac{\pi - \pi_t}{\mu} \quad \text{where} \quad \mu = \pi_s - \pi_t \tag{1}$$

where $\pi$ is the hydrostatic component of the pressure, $\pi_s$ and $\pi_t$ refer to the values along the surface and top boundaries, respectively and $\mu$ is the hydrostatic pressure difference between the surface and top of the model. The grid staggering is the Arakawa E-grid. The model uses a forward-backward scheme for horizontally propagating fast waves, implicit scheme for vertically propagating sound waves, Adams-Bashforth scheme for horizontal advection, and Crank-Nicholson scheme for vertical advection. The same time step is used for all terms. The dynamics conserve a number of first and second order quantities including energy and enstrophy [8]. WPP can be used to post-process WRF-NMM forecasts and was designed to interpolate the forecasts from the model's native vertical coordinate to National Weather Service (NWS) standard output levels.

The WRF-NMM model software is organized functionally as a three-level hierarchy (see Figure 2) superimposed over the model subroutine call tree. The highest levels of the call tree correspond to the *driver layer* and the lowest levels correspond to the *model layer*. A *mediation layer* provides the interface between the driver and model layers. The driver is responsible for top-level control of initialization, time-stepping, I/O, instantiating domains, maintaining the nesting hierarchy between domain type instances, and setting up and managing domain decomposition, processor topologies, and other aspects of parallelism. The model layer comprises the subroutines that perform actual model computations. Model subroutines are written to be callable over an arbitrarily shaped piece of the three-dimensional model domain. The mediation layer provides the glue between the model and driver layers. The mediation layer contains information pertaining to both the model layer and the driver layer: model-specific information such as the flow of control to compute a time step on a domain and driver-specific mechanisms such as tiling and communication.

Several studies related to the simulation of severe thunderstorm events using WRF-NMM model have been performed recently [1, 9, 10, 11]. Numerical simulations by means of WRF-NMM (V3) model with different convective parameterization schemes have been carried out for the present study. The model was integrated for a period of 24 hours, starting at 0000 UTC of 20 May 2006 as initial time for the first case and starting at 0000 UTC of 21 May 2007 as initial time for the second case. A single domain with 3-km horizontal spatial resolution is configured as shown in Figure 3, which is reasonable in capturing the mesoscale cloud clusters. Initial conditions (IC) for the 3-km domain are derived from 6-h global final analysis (FNL) data at $1^0$ x $1^0$ grids generated by NCEP's global forecast system (GFS). Analysis fields, including temperature, moisture, geopotential height and wind, are interpolated to the mesoscale grids by WPS (V3). These derived fields served as initial conditions for the present experiments. The domain covers 86.0$^o$ E to 90.0$^o$ E and 21.0$^o$ N to 24.0$^o$ N. The grids are centered at 88.0$^o$ E, 22.5$^o$ N with 167 X 165 grid points. The domain is configured with vertical structure of 38 unequally spaced sigma (non-dimensional pressure) levels.

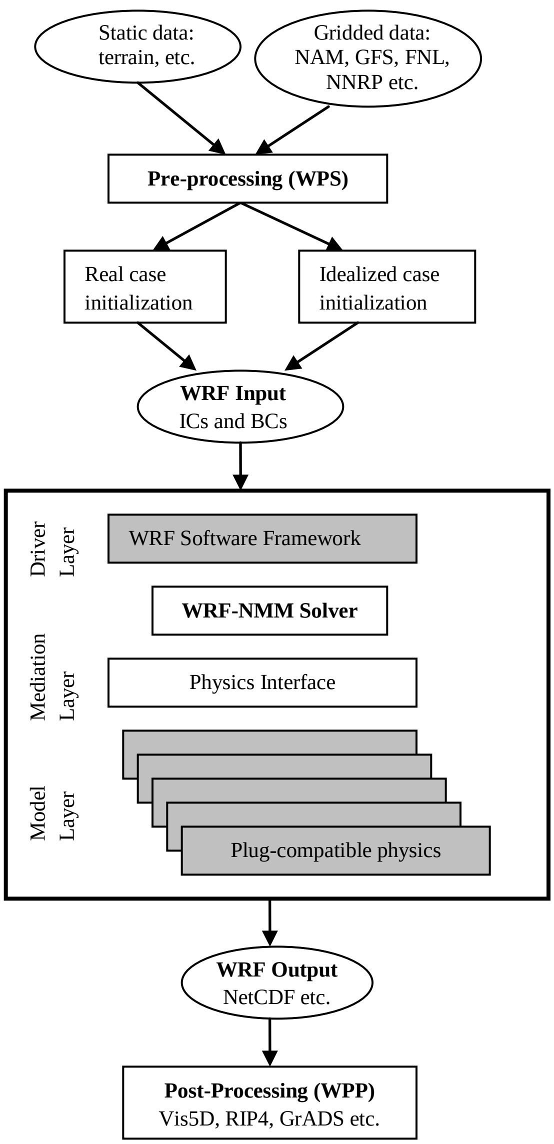


**Fig 2: Schematic of WRF-NMM modeling**

The simulations from numerical models are known to be sensitive to the representation of the physical processes. In order to obtain realistic results it is necessary to incorporate appropriate physics into the model. It is believed that physics errors become more important as model resolution increases [12], such that numerical prediction of precipitation and associated convective processes remain a key challenge. In the present study, we did four simulations for each case by changing the CPSs of the WRF-NMM regional model. The first simulation used the Kain-Fritsch scheme (KF), based on Kain [13] and Kain and Fritsch [14]. The second simulation used Betts-Miller-Janjic (BMJ) parameterization, which is based on Janjic [15] and Janjic [16]. The third one used Grell-Devenyi ensemble (GD) parameterization, based on Grell and Devenyi [2]. Finally, the simulation used simplified Arakawa-Schubert scheme (AS), based on Arakawa and Schubert [17] as simplified by Grell [18]. In addition, a simulation without a convective scheme (NO) is performed for each case to determine if the model could simulate the convection explicitly. Wang and Seaman [19] investigated these schemes for various mid-latitude convective environments and concluded that the KF scheme tended to perform better. Another earlier study by Kuo et al. [20] found that the KF scheme performed best for the simulation of an ERICA IOP 5 storm. On the other hand, Kerkhoven et al. [21] suggested that both the GD and BMJ schemes performed better at simulating a summer monsoon rainfall event over the east China regions. These studies suggest that a particular convective scheme may work for a particular event or convective environment, but may not work in others. The effectiveness of a particular scheme to simulate the convection depends on the design aspects of the scheme that include its triggering function, closure assumption, and precipitation scheme [20, 21]. However, the assumption and simplification of a particular convective scheme has basically limited its effectiveness.

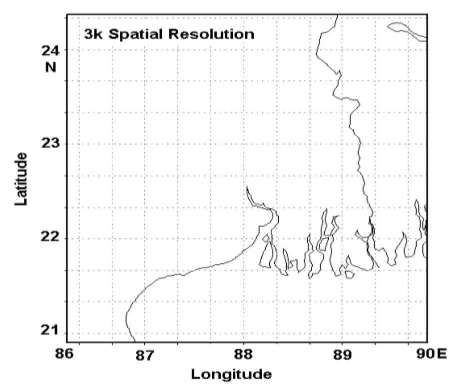


**Fig 3: WRF-NMM model domain**

The other physical parameterizations used in this study are Geophysical Fluid Dynamics Laboratory (GFDL) for longwave and shortwave radiation [22, 23], NMM Land surface scheme for land surface [24], Mellor Yamada Janjic (MYJ) scheme for planetary boundary layer [25], Ferrier scheme for microphysics [26] and Janjic similarity scheme for surface layer [27]. The choice of schemes was based on a prior experiment for which the results were reported elsewhere. To compare the differences among the CPSs, simulations are performed for a particular time period utilizing the same initial and boundary conditions (BC) and other physical parameterizations for each CPSs and then the model outputs are compared with observation. 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 data with different CPSs.The hourly observation of Automatic Weather Stations (AWS) at Kolkata is used as observed data.

# 4. RESULTS AND DISCUSSION

Today there are a number of parameters available that may be used to characterize pre-convective conditions and predict the beginning of convection. Johns and Doswell [28] and McNulty [29] have reviewed severe thunderstorms and tornado forecasting in detail. According to them, three of the most important factors to examine in determining occurrence of severe thunderstorm events are intense instability, a sufficiently deep humid layer in the lower and middle troposphere and an updraft to initiate convection. The formation of thunderstorms is an interaction between these conditions on different scales. The model simulated results of these severe thunderstorm cases are explored in the following section. Analysis of the results of these experiments is helpful to understand the impact of CPSs on the simulation of 20 May 2006 and 21 May 2007 severe thunderstorm events and assist in the customization of model for future severe thunderstorm simulations over east Indian region.

## 4.1 Instability indicators from the model

### *4.1.1 CASE 1- 20 May 2006*

Variation of convection in the atmosphere depends upon dynamics as well as thermodynamic instability indices. A number of stability indices are devised in order to detect the likely occurrence of thunderstorms. An attempt is made to examine different stability indices obtained from simulations with different CPSs on 20 May 2006 at 1200 UTC over Kolkata ($22.52^0$ N, $88.37^0$ E). FNL data is used for the validation of model simulated stability indices. Convective Available Potential Energy (CAPE) represents the amount of buoyant energy available to accelerate a parcel vertically and a CAPE value greater than 1500 $Jkg^{-1}$ is suggested by Johns and Doswell [28] as being necessary for severe thunderstorms to form. Table 1 shows the inter-comparison of FNL and model simulated stability indices with different CPSs over Kolkata valid for 20 May 2006 at 1200 UTC. It can be seen that only GD scheme is able to simulate a high value (1909 $Jkg^{-1}$) during the thunderstorm hour, which is a favorable condition for severe thunderstorms. The CAPE value of NO scheme (1433 $Jkg^{-1}$) is also close to the critical level. But all other CPSs and also including FNL analyzed value (965 $Jkg^{-1}$) are less than the critical level during thunderstorm hour. The BMJ simulated CAPE is very less (983 $Jkg^{-1}$) as compared to all other CPSs, but close to FNL analyzed data (Table 1).

**Table 1. The inter-comparison of FNL and model simulated stability indices with different CPSs over Kolkata valid for 20 May 2006 at 1200 UTC.**

| Stability Index | FNL | KF | BMJ | GD | AS | NO |
|---|---|---|---|---|---|---|
| CAPE | 965 | 1215 | 983 | 1909 | 1244 | 1433 |
| LI | -4 | -3 | -2 | -5 | -3 | -4 |
| TTI | 45 | 46 | 44 | 46 | 44 | 45 |

The Lifted Index (LI) measures the difference between a parcel's temperatures compared with the environmental temperature at 500 hPa, after the parcel has been lifted from the Lifting Condensation Level [30]. LI has proved useful for indicating the likelihood of severe thunderstorms. The chances of occurrence of a severe thunderstorm are high when LI is less than or equal to -3. This is because air rising in these situations is much warmer than its surroundings and can accelerate rapidly and create tall and violent thunderstorms. The GD scheme captured the lowest value (-5) compared to all other CPSs as in CAPE. The NO scheme simulated LI is -4, which is equal to the FNL analyzed data (-4). The AS and KF simulated LI (-3) is close to the FNL and equal to the critical level. The BMJ simulated LI is -2, which is higher than the critical value and not favorable for thunderstorm occurrences (Table 1).

Miller [31] introduced the Total Totals Index (TTI) for identifying areas of potential thunderstorm development. It accounts for both static stability and the presence of 850 hPa moisture. A TTI of greater than 44 indicates favorable conditions for development of severe thunderstorms [30]. All the CPSs are able to capture a TTI of greater than or equal to 44, which is a favorable condition for severe thunderstorms. The GD and KF simulated TTI is 46. The NO scheme simulated TTI is equal to FNL data (45). The BMJ and AS are captured the least value (44) compared to other CPSs (Table 1) and equal to the critical level. By comparing all the stability indices of CPSs with FNL data, we can conclude that all the CPSs are well simulated the overall pattern except BMJ scheme. The GD scheme simulated stability indices are well shown the instability of the atmosphere at 1200 UTC for the occurrence of a severe thunderstorm.

### *4.1.2 CASE 2- 21 May 2007*

An attempt is made to examine different stability indices obtained from simulations with different CPSs on 21 May 2007 at 1100 UTC over Kolkata ($22.52^0$ N, $88.37^0$ E). Table 2 shows the inter-comparison of model simulated stability indices with different CPSs over Kolkata valid for 21 May 2007 at 1100 UTC. It can be seen that GD, AS and BMJ schemes are able to capture a high value (4413, 3742, 2128 $Jkg^{-1}$ respectively) during the thunderstorm hour, which is a favorable condition for severe thunderstorms. The other schemes namely KF and NO (1071, 1034 $Jkg^{-1}$ respectively) are not able to capture a value greater than the critical level (1500 $Jkg^{-1}$). The GD simulated LI is -8, which is the lowest value among all other CPSs. The AS and BMJ schemes are also able to capture a low value (-7 and -5) during the thunderstorm hour. The NO scheme simulated LI is -4. The KF simulated LI is equal to the critical level (Table 2).

**Table 2. The inter-comparison of model simulated stability indices with different CPSs over Kolkata valid for 21 May 2007 at 1100 UTC.**

| Stability Index | KF | BMJ | GD | AS | NO |
|---|---|---|---|---|---|
| CAPE | 1071 | 2128 | 4413 | 3742 | 1034 |
| LI | -3 | -5 | -8 | -7 | -4 |
| TTI | 47 | 46 | 47 | 48 | 45 |

All the CPSs are able to capture a TTI of greater than 44, which is a favorable condition for severe thunderstorms. The AS scheme simulated TTI is the highest among all other schemes (48). The GD and KF simulated TTI is 47. The BMJ scheme is also captured a high value which is equal to 46 (Table 2). By comparing all the stability indices of different CPSs, we can conclude that GD, AS, and BMJ schemes are well simulated the stability indices which is shown the instability of the atmosphere at 1100 UTC for the occurrence of a severe thunderstorm.

## 4.2 Surface pattern

### *4.2.1 CASE 1- 20 May 2006*

Precipitation is recognized as one of the most difficult parameters to forecast in NWP. Difficulties exist in at least three areas. First, our understanding of precipitation processes is still quite limited. Second, data deficiencies often limit the accuracy of a model's initial condition. The third involves the representation of both resolved and subgrid-scale precipitation processes in a mesoscale model. The latter is known as the convective parameterization problem, and its challenge and complexity have acknowledged for many years [19]. This study presents an inter-comparison of a few CPSs in WRF-NMM model with different meteorological parameters like precipitation, relative humidity and surface wind. Figure 4a shows the inter-comparison of observed and WRF-NMM model simulated diurnal variation of accumulated rainfall (mm) with different CPSs over Kolkata valid from 20 May 2006 at 0000 UTC to 21 May 2006 at 0000 UTC.

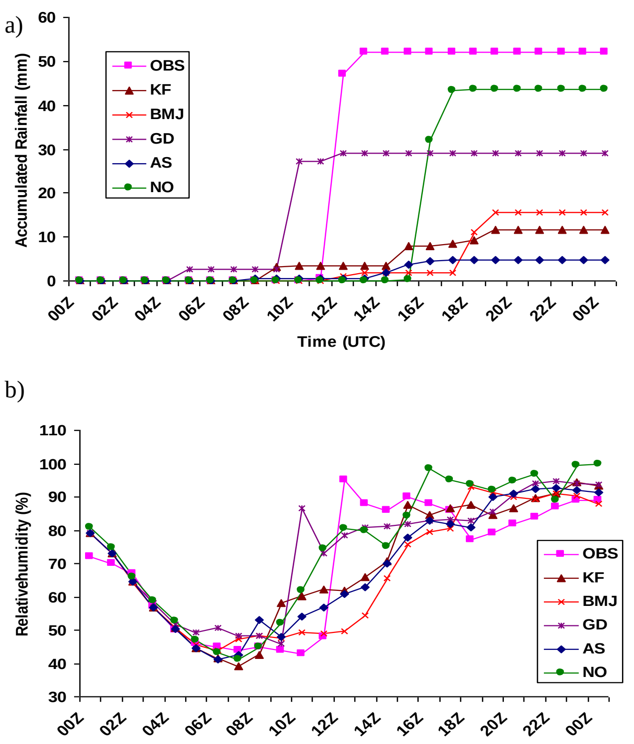


**Fig 4: The time-series plot of observed and model simulated (a) accumulated rainfall (mm) (b) relative humidity (%) with different CPSs over Kolkata valid from 20 May 2006 at 0000 UTC to 21 May 2006 at 0000 UTC.**

GD scheme is able to capture 29 mm of rainfall, which is less compared to actual observation (52 mm). GD scheme has predicted the rainfall at 1000 UTC, which is two hour prior to the actual severe thunderstorm occurrence (1200 UTC). The NO scheme is well captured the intensity (43 mm) with five hour time lag. But other schemes are failed to capture the intensity and time of occurrence. The spatial distribution of 3-hourly accumulated rainfall (mm) between 0900 and 1200 UTC with different CPSs on 20 May 2006 is shown in Figure 5. From the figures, we can see that, GD scheme is well simulated the rainfall intensity as compared to other schemes during the thunderstorm hours. NO scheme is also able to simulate the intensity, but the location is shifted to eastwards (near Bangladesh border). All other CPSs are failed to capture the intensity and time of this severe thunderstorm event.

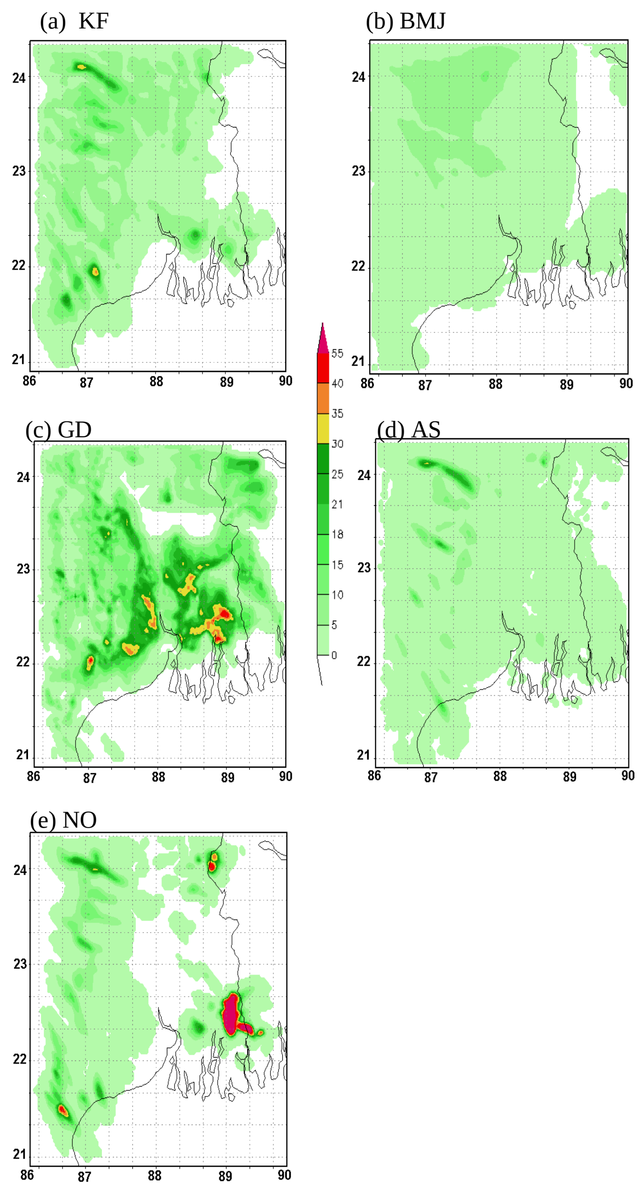


**Fig 5: The spatial distribution of 3-hourly accumulated rainfall (mm) between 0900 and 1200 UTC with different CPSs on 20 May 2006 at (a) KF (b) BMJ (c) GD (d) AS and (e) NO.**

Relative humidity at surface level has been taken into account, as it is an essential factor in intense convection. Storm days require a sufficiently humid and deep layer in the lower and middle atmosphere [28]. Figure 4b shows the inter-comparison of observed and model simulated relative humidity (%) using different CPSs over Kolkata valid from 20 May 2006 at 0000 UTC to 21 May 2006 at 0000 UTC. The observed relative humidity values are peaked from 48% to 95% (47% increase) at 1200 UTC whereas GD scheme showed a sharp rise from around 45% to 87% (40%) at 1000 UTC, which is two hour prior to the thunderstorm occurrence. But all other CPSs are failed to capture the sudden rise, which is a characteristic feature of thunderstorm.

A statistical analysis based on MAE, RMSE and CC is performed for comparisons between the simulated and observed relative humidity with different CPSs valid for 20 May 2006 (Table 3). From the table, we can clearly see that, GD scheme has less error as compared to all other schemes. There is not much variation between KF and AS scheme MAE, which is less compared to BMJ and NO schemes. In the case of RMSE, GD scheme has the least error compared to all other CPSs. The next position is for KF and AS schemes. The NO and BMJ schemes simulated results have the most error as in the case of MAE. Another verification method used for this study is correlation coefficient. From the table we can clearly see that, all the CPSs are positively correlated. The GD scheme has the highest correlation coefficient (0.87) as compared to all other CPSs. There is not much variation between the correlation coefficient of NO (0.82), AS (0.82) and KF (0.81) schemes. The BMJ scheme has the least correlation (0.73) than other CPSs in the case of relative humidity. All the schemes have strong correlation (>0.8) except BMJ scheme. The statistical analysis of wind speed ($ms^{-1}$) with different CPSs over Kolkata valid for 20 May 2006 are given in Table 4. In the case of MAE and RMSE, GD scheme has less error as compared to all other CPSs. All the parameterization schemes are weak correlated (<0.5) in wind speed simulation as compared to relative humidity. GD scheme has a good correlation as compared to all other schemes. The trends shown by various meteorological fields of NMM model with GD scheme are in good agreement with each other and very much consistent with dynamic and thermo-dynamic properties of the atmosphere for the occurrence of a severe thunderstorm on 20 May 2006 even though two hour time lead exists.

**Table 3. The statistical analysis of relative humidity (%) with different CPSs over Kolkata valid for 20 May 2006 (CASE 1) and 21 May 2007 (CASE 2).**

| | CASES | KF | BMJ | GD | AS | NO |
|---|---|---|---|---|---|---|
| MAE | CASE 1 | 7.81 | 8.36 | 7.55 | 7.68 | 8.59 |
| | CASE 2 | 9.85 | 10.52 | 9.14 | 9.56 | 13.16 |
| RMSE | CASE 1 | 10.79 | 14.11 | 10.70 | 10.87 | 11.78 |
| | CASE 2 | 16.87 | 15.25 | 11.16 | 15.12 | 20.49 |
| CC | CASE 1 | 0.81 | 0.73 | 0.87 | 0.82 | 0.82 |
| | CASE 2 | 0.69 | 0.72 | 0.78 | 0.74 | 0.55 |

### *4.2.2 CASE 2- 21 May 2007*

The initiation and intensification of this severe thunderstorm is examined by the analysis of surface parameters namely precipitation, relative humidity, and surface wind. The rainfall fields are examined by temporal and spatial pattern. Figure 6a shows the inter-comparison of observed and WRF-NMM model simulated accumulated progressive rainfall with different CPSs at Kolkata valid from 21 May 2007 at 0000 UTC to 22 May 2007 at 0000 UTC. The GD scheme is able to capture 18.5 mm of rainfall at 1000 UTC, which is very close to the actual observation (20 mm). The GD scheme has predicted the rainfall at 1000 UTC, which is one hour prior to the actual thunderstorm occurrence (1100 UTC). The GD scheme is well simulated the intensity and time of occurrence of precipitation over Kolkata on 21 May 2007. But other schemes are failed to capture the intensity and time of occurrence of precipitation as compared to GD scheme. The spatial distribution of 3-hourly accumulated rainfall (mm) between 0900 and 1200 UTC with different CPSs on 21 May 2007 is shown in Figure 7. From the figures, we can clearly see that GD scheme is well simulated the rainfall intensity as compared to other schemes during the thunderstorm hours. All other CPSs are failed to capture the intensity and time of this severe thunderstorm event.

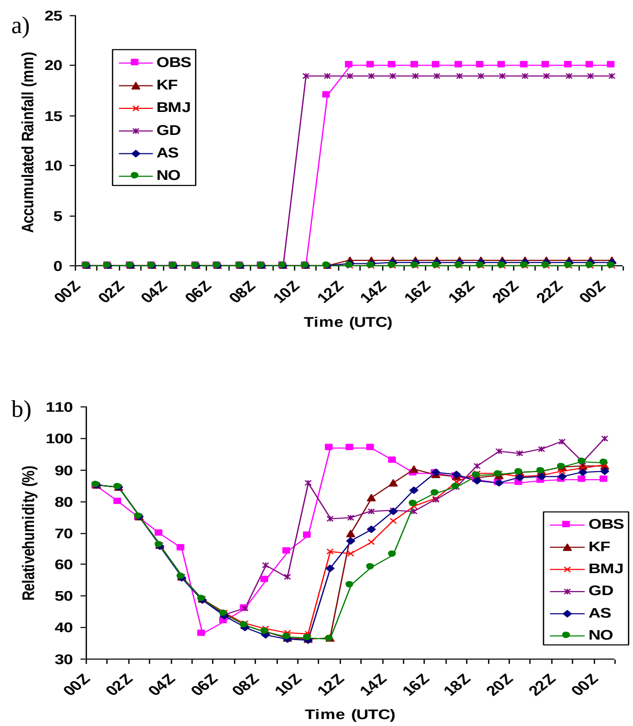


**Fig 6: The inter-comparison of observed and model simulated (a) accumulated rainfall (mm) (b) relative humidity (%) with different CPS over Kolkata valid from 21 May 2007 at 0000 UTC to 22 May 2007 at 0000 UTC.**

Figure 6b shows the inter-comparison of observed and model simulated relative humidity (%) using different CPSs over Kolkata valid from 21 May 2007 at 0000 UTC to 22 May 2007 at 0000 UTC. GD scheme has well captured the rising of relative humidity values during the model simulated thunderstorm hour as in the observation. The observed relative humidity values peaked from 69% to 97% (28% increase) at 1100 UTC whereas model showed a sharp rise from around 56% to 86% (30%) at 1000 UTC, which is one hour prior to the observed. All other parameterization schemes are failed to capture the intensity as compared to the observation and GD scheme. A statistical analysis based on MAE, RMSE and CC was performed for comparisons between the simulated and observed relative humidity with different CPSs (Table 3).

**Table 4. The statistical analysis of wind speed ($ms^{-1}$) with different CPSs over Kolkata valid for 20 May 2006 (CASE 1) and 21 May 2007 (CASE 2).**

| | CASES | KF | BMJ | GD | AS | NO |
|---|---|---|---|---|---|---|
| MAE | CASE 1 | 2.58 | 1.45 | 1.43 | 1.79 | 2.02 |
| | CASE 2 | 1.43 | 1.41 | 0.89 | 1.39 | 1.04 |
| RMSE | CASE 1 | 3.74 | 1.85 | 1.82 | 2.52 | 2.54 |
| | CASE 2 | 1.74 | 1.91 | 1.20 | 1.81 | 1.29 |
| CC | CASE 1 | 0.10 | 0.25 | 0.41 | 0.28 | 0.23 |
| | CASE 2 | 0.21 | -0.22 | 0.38 | -0.07 | 0.03 |

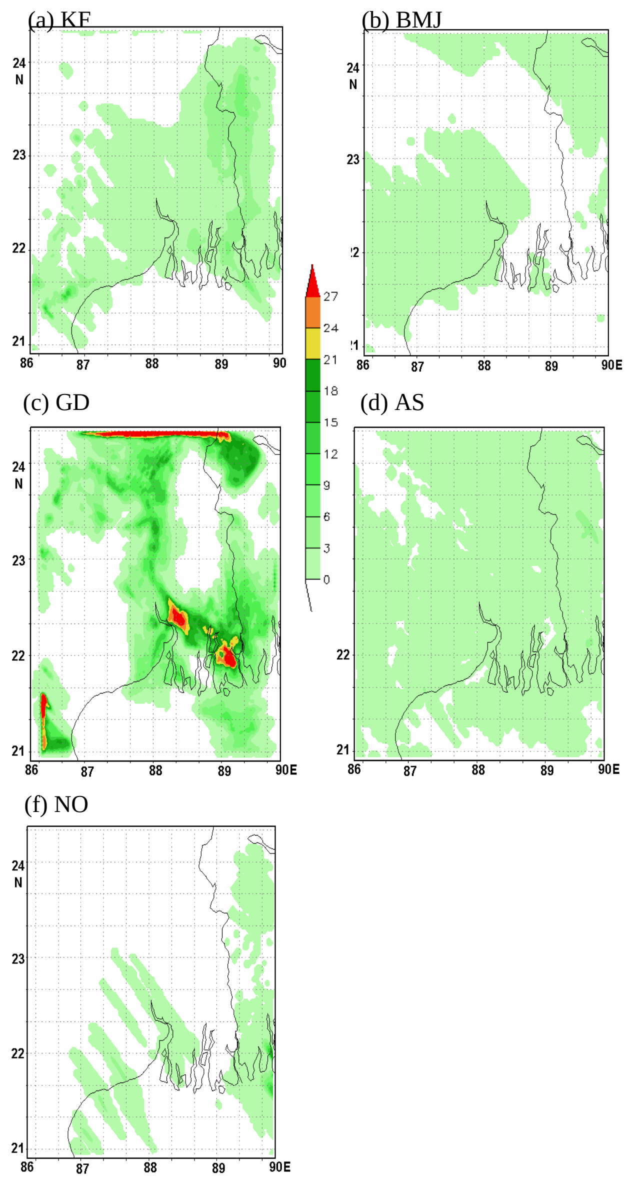


**Fig 7: The spatial distribution of 3-hourly accumulated rainfall (mm) between 0900 and 1200 UTC with different CPSs on 21 May 2007 at (a) KF (b) BMJ (c) GD (d) AS and (e) NO.**

The statistical analysis of relative humidity with different CPSs from Table 3 shows GD scheme has less error (both MAE and RMSE) as compared to all other CPSs. In the case of CC also, GD scheme is well correlated (0.78) to the observation than all other CPSs. The NO scheme has more error and also less correlation. The statistical analysis of wind speed ($ms^{-1}$) with different CPSs (Table 4) shows the MAE and RMSE for GD scheme are less as compared to all other CPSs. All the parameterization schemes are less correlated to the observation in the case of wind speed. The GD, KF and NO schemes are positively correlated. The CC of GD is better than all other schemes. Overall, GD scheme is well simulated the thunderstorm affected meteorological parameters as compared to all other CPSs for the occurrence of a severe thunderstorm on 21 May 2007 even though one hour time lead exists.

## 5. CONCLUSIONS

In this paper, sensitivity experiments have been conducted with the WRF-NMM model to test the impact of convective parameterization schemes on simulating severe thunderstorms that occurred over Kolkata on 20 May 2006 and 21 May 2007 and validated the model results with observation. A statistical analysis based on mean absolute error, root mean square error and correlation coefficient is also performed for comparison among simulated and observed data with different convective parameterization schemes and explicit scheme. In all experiments, the setups were identical except for the use of different convective schemes. Hence differences in the simulation results may be attributed to the sensitivity of the convective schemes. This study shows that the prediction of thunderstorm affected parameters is sensitive to convective parameterization schemes. It is clearly demonstrated that Grell-Devenyi cloud ensemble convective parameterization scheme performance is significantly better than other parameterization schemes including explicit scheme.

By comparing both the thunderstorm cases, GD scheme is well simulated the instability of the atmosphere in terms of CAPE, Lifted index, K index and Total Total index for the occurrence of a severe thunderstorm over Kolkata as compared to all other convective parameterization schemes. The temporal and spatial patterns of precipitation simulated by GD scheme are in good agreement with the observation. But all other schemes are failed to capture the intensity and time of occurrence for both the thunderstorm cases. The time-series plot and statistical analysis of relative humidity revealed that GD scheme is well captured the sufficient deep humid layer for the occurrence of a severe thunderstorm on 20 May 2006 and 21 May 2007 as in the observation. The statistical analysis of wind speed with different CPSs showed that only GD scheme is reasonably captured the overall squall intensity.

After analyzing the aforementioned datasets, we can conclude that the WRF-NMM model with Grell-Devenyi convective parameterization scheme is well simulated the thunderstorm activities in terms of time, intensity and the region of occurrence of the events as compared to other convective parameterization schemes. The results of these analyses demonstrated the capability of high resolution WRF-NMM model in simulation of severe thunderstorm events and found out the suitable convective parameterization scheme for the eastern Indian region.

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