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ORIGINAL ARTICLE

Sensitivity Study with Physical Parameterization Schemes for Simulation of Mesoscale Convective Systems Associated with Squall Events

Mohan K. Das[a,b*], Md. A. M. Chowdhury[b] and Someshwar Das[c]

[a]SAARC Meteorological Research Centre, Dhaka, Bangladesh, [b]Jahangirnagar University, Savar, Bangladesh, [c]*India Meteorological Department*, New Delhi, India

*Corresponding Author :

Mohan K Das

Email: mohan28feb@yahoo.com; mkdas@smrc.org.bd

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Abstract

Improving the simulation of the Pre-monsoon squall events is important as such events routinely result in strong gusty wind, hails, rain and significant loss of life and property over Bangladesh, Indian eastern, northeastern region and neighborhood. Performance of the mesoscale models is sensitive to the physical parameterizations schemes. This study deals the improvement of numerical simulation of squall events during pre-monsoon season through parameterizations. Advanced Research Weather Research and Forecasting model (WRF ARW) is used to improve the simulation of squall events. Several sensitivity experiments were conducted with different combinations of cloud microphysics schemes (MPSs) (namely; Lin, WSM3, WSM6 and Milbrandt), planetary boundary layer (PBL) schemes (namely; YSU, MYJ and ACM2) and cumulus (CU) parameterization schemes (namely; Kain-Fritsch, Betts-Miller-Janjić, Grell-Devenyi and no-cumulus), to examine the root mean square errors (RMSE) of rainfall, wind speed at 10 m and forecast time. In particular, the combination of Milbrandt and WSM6 microphysics scheme with Yonsei University (YSU) PBL scheme and no CU scheme provides optimal combination of physical parameterization schemes in simulation of the squall events.

Keywords*:* Squall, Parameterization, WRF ARW, MPS, PBL.

1. Introduction

Severe thunderstorms have significant socio-economic impact in most parts of Bangladesh. 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 severe weather systems. Accurate simulation requires knowledge about “where” and “when” storms will develop and how they will evolve (Weiss *et al.*, 2006; Das *et al.*, 2015). Wind speed and precipitation associated with thunderstorms are recognized as the most difficult parameters to forecast/simulate with numerical weather prediction (NWP) models (Das *et al.*, 2006, 2015). There have been considerable improvements in the field of mesoscale prediction over past few decades using high resolution state-of-art mesoscale models and these models are recently proved to be more successful for the prediction of convective heavy rainfall events and wind speed (Kumar *et al.*, 2008; Rao and Prasad, 2005; Routray *et al.*, 2005). Most of the improvements are due to increase in computing resources, developments in numerical techniques, improved understanding of physical processes and improvements in observing systems, objective analysis and advanced data assimilation techniques.

However, these modeling systems need to be customized and tuned suitably for the prediction of different weather events separately over the region. It is well accepted that the physical processes such as microphysics (MP), cumulus (CU) and Planetary Boundary Layer (PBL) play dominant role in the initiation and development of tropical weather systems unlike in the mid-latitude, where dynamical forcing are dominant. A large number of parameterization schemes (18 MP options, 12 CU options and 16 PBL options and many others related schemes are available in the WRF model latest version) for the important physical processes have been developed over the years. As the performance of these schemes depends on the resolution of the host model and on the scale of the weather system, one has to test the suitability of these schemes for specific applications. In the present study, the focus will be on the physical processes that are expected to modulate the performance of the mesoscale models towards simulation of squall events due to the presence of Mesoscale Convective System (MCS).

Convection has long been recognized as a process of central importance in the development of numerous weather events. The performance of a mesoscale model in forecasting wind speed and precipitation depends upon how good the convection is parameterized in the model. Thus, parameterization of CU convection got immense importance and a wide variety of cumulus parameterization schemes (CPSs) are developed (viz., Kuo, 1974; Arakawa and Schubert, 1974; Anthes, 1977; Betts, 1986; Frank and Cohen, 1987; Tremback, 1990; Emanuel, 1991; Kain and Fritsch, 1993; Grell, 1993; Arakawa, 2004). But, almost all of these schemes are formulated for a specific convective regime and there is no universal conceptual framework for CU parameterization (Arakawa, 1993). Thus, it is important to test the suitability of a convection scheme for its use in a region other than those tested by the developers. Wang and Seaman (1997) conducted a comparison study of four convection schemes in simulating six precipitation events over continental United States. Lee *et al.* (2001) compared four CPSs in different horizontal resolutions with four heavy rainfall cases over Korea in the monsoon season.

It has been illustrated that the PBL is a critical factor in producing mesoscale weather systems such as convective rainfall events and storms, land-sea breezes, thermal boundaries and mountain valley circulations (Pilke and Mahrer, 1975). Due to the large fluxes of heat, moisture and momentum that take place in PBL, there has been much interest in the incorporation of high resolution PBL parameterizations into three dimensional mesoscale models (Mandal *et al.*, 2004; Zhang and Anthes, 1982). The performances of these parameterization schemes also vary with specific events and regime. Thus, it is important to find the suitability of CPSs and PBL parameterization schemes and their combination in simulating the convective events over Bangladesh region during pre-monsoon season. Varble *et al.* (2011) found a notable impact of microphysics on the hydrometeor distribution, but the more complex models that include more prognostic moments of the size distributions were not superior to the simpler models in terms of cloud top height and radar reflectivity. Similarly, Wang *et al.* (2009) found that a more complex microphysics scheme (MPS) overestimated cirrus clouds during dry periods compared to more simple schemes, while it produced more realistic mixed phase clouds during convection. Rao *et al.* (2014), Manish *et al.* (2014) and many others have recently addressed the issue of sensitivity studies using WRF model for short scale simulations. Some sensitivity studies carried out over the Indian region for thunderstorm (Das *et al.*, 2007; Litta *et al.*, 2011), tropical cyclones (Panda and Giri, 2012; Raju *et al.*, 2011; Rao and Prasad, 2006), and heavy rainfall events (Alam, 2014; Kumar *et al.*, 2014) with physical parameterization schemes available in numerical modeling system. Das *et al.*, (2007) examined the sensitivity to different physical parameterization schemes for simulation of intense organized convective precipitation observed during the Arabian Sea Monsoon Experiment (ARMEX) along the west coast of India. The simulation of the convective event has been improved with certain combinations of physical parameterization schemes. Rao and Prasad (2006), Mandal *et al.* (2004) and Trivedi *et al.* (2006) studied the sensitivity of different physical processes on the simulation of track and intensity of the tropical cyclone over the east coast of India using the MM5 model.

This study is the first sensitivity study of study of squall events over Bangladesh with the combination of MPSs, CPSs and PBL Schemes (PBLSs). The purpose of this study is to determine how the available MPSs, CPSs and PBLSs in the WRF ARW model simulate squall events over Bangladesh. The essential features of the mesoscale model WRF ARW used in the present study are described in the sections 2, 3 and 4. These include basic equations of the model and some important components of Model Physics and Parameterizations. Experimental Design and study domain is presented in the section 5. Realized weather and satellite features of the selected events for the parameterization study are provided in section 6. The results of the numerical experiments and related discussions are presented in section 7. Finally, the broad conclusions are provided in the section 8.

2. Weather Research and Forecasting (WRF) Model

The Weather Research and Forecasting (WRF) model version 3.5.1 has been used for simulation of the MCSs associated with squalls in this study. The WRF Model is a new generation mesocale NWP system designed to serve both operational forecasting and atmospheric research needs (NCAR. 2009). It features multiple dynamical cores, a 3DVAR data assimilation system, and a software architecture allowing for computational parallelism and system extensibility.

The model physics options and parameterization details are presented in Skamarock *et al.* (2008). WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. Applications of WRF include research and operational NWP, data assimilation and parameterized physics research, downscaling climate simulations, driving air quality models, atmosphere-ocean coupling, and idealized simulations (i.e., boundary layer eddies, convection, baroclinic waves).

3. Model Physics

The WRF modeling system has a sophisticate physical package. This includes MP, CU parameterization, PBL, land surface model, radiation and diffusion. The detail description of these physical processes is very much lengthy and it can be found in NCAR technical documents of ARW by Skamaraock *et al.* (2008). The physical processes on which sensitivity experiments are conducted in the present study are described in brief in the subsequent sections. Primitive equations using sigma coordinate system, polar stereographic projection. According to the National Weather Service Handbook No. 1- Facsimile Products, the primitive equations can be simplified into the following equations:

Zonal wind:

$$\frac{\partial u}{\partial t} = \eta v - \frac{\partial \Phi}{\partial x} - c_p\theta\frac{\partial \pi}{\partial x} - z\frac{\partial u}{\partial \sigma} - \frac{\partial(\frac{u^2+v^2}{2})}{\partial x}$$

Meridional wind:

$$\frac{\partial v}{\partial t} = -\eta\frac{u}{v} - \frac{\partial \Phi}{\partial y} - c_p\theta\frac{\partial \pi}{\partial y} - z\frac{\partial v}{\partial \sigma} - \frac{\partial(\frac{u^2+v^2}{2})}{\partial y}$$

Temperature:

$$\frac{\delta T}{\partial t} = \frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}$$

The first term is equal to the change in temperature due to incoming solar radiation and outgoing longwave radiation, which changes with time throughout the day. The second, third, and fourth terms are due to advection. Additionally, the variable *T* with subscript is the change in temperature on that plane. Each *T* is actually different and related to its respective plane. This is divided by the distance between grid points to get the change in temperature with the change in distance. When multiplied by the wind velocity on that plane, the units kelvins per meter and meters per second give kelvins per second. The sum of all the changes in temperature due to motions in the *x*, *y*, and *z* directions give the total change in temperature with time.

Perceptible water:

$$\frac{\delta W}{\partial t} = u\frac{\partial W}{\partial x} + v\frac{\partial W}{\partial y} + w\frac{\partial W}{\partial z}$$

This equation and notation works in much the same way as the temperature equation. This equation describes the motion of water from one place to another at a point without taking into account water that changes form. Inside a given system, the total change in water with time is zero. However, concentrations are allowed to move with the wind.

Pressure thickness:

$$\frac{\partial}{\partial t}\frac{\partial p}{\partial \sigma} = u\frac{\partial}{\partial x}x\frac{\partial p}{\partial \sigma} + v\frac{\partial}{\partial y}y\frac{\partial p}{\partial \sigma} + w\frac{\partial}{\partial z}z\frac{\partial p}{\partial \sigma}$$

These simplifications make it much easier to understand what is happening in the model. Things like the temperature (potential temperature), precipitable water, and to an extent the pressure thickness simply move from one spot on the grid to another with the wind. The wind is forecast slightly differently. It uses geopotential, specific heat, the exner function *π*, and change in sigma coordinate. Solution to the linearized primitive equations

The analytic solution to the linearized primitive equations involves a sinusoidal oscillation in time and longitude, modulated by coefficients related to height and latitude.

$$\{u, v, \phi\} = \{\hat{u}, \hat{v}, \hat{\phi}\}e^{i(s\lambda+\sigma t)}$$

where *s* and **σ** are the zonal wavenumber and angular frequency, respectively. The solution represents atmospheric waves and tides.

When the coefficients are separated into their height and latitude components, the height dependence takes the form of propagating or evanescent waves (depending on conditions), while the latitude dependence is given by the Hough functions.

This analytic solution is only possible when the primitive equations are linearized and simplified. Unfortunately many of these simplifications (i.e. no dissipation, isothermal atmosphere) do not correspond to conditions in the actual atmosphere. As a result, a numerical solution which takes these factors into account is often calculated using general circulation models and climate models.

4. Parameterization

Some meteorological processes are too small-scale or too complex to be explicitly included in NWP models. Parameterization is a procedure for representing these processes by relating them to variables on the scales that the model resolves. For example, the grid boxes in weather and climate models have sides that are between 5 kilometers (3 mi) and 300 kilometers (200 mi) in length. A typical cumulus cloud has a scale of less than 1 kilometer (0.6 mi), and would require a grid even finer than this to be represented physically by the equations of fluid motion. Therefore the processes that such clouds represent are parameterized, by processes of various sophistication. In the earliest models, if a column of air in a model grid box was conditionally unstable (essentially, the bottom was warmer and moister than the top) and the water vapor content at any point within the column became saturated then it would be overturned (the warm, moist air would begin rising), and the air in that vertical column mixed. More sophisticated schemes recognize that only some portions of the box might convect and that entrainment and other processes occur. Weather models that have grid boxes with sides between 5 and 25 kilometers (3 and 16 mi) can explicitly represent convective clouds, although they need to parameterize cloud microphysics which occur at a smaller scale (Narita and Shiro, 2007). The formation of large-scale (stratus-type) clouds is more physically based; they form when the relative humidity reaches some prescribed value. Sub-grid scale processes need to be taken into account. Rather than assuming that clouds form at 100% relative humidity, the cloud fraction can be related a critical value of relative humidity less than 100%, (Frierson, 2000) reflecting the sub grid scale variation that occurs in the real world.

The amount of solar radiation reaching the ground, as well as the formation of cloud droplets occur on the molecular scale, and so they must be parameterized before they can be included in the model. Atmospheric drag produced by mountains must also be parameterized, as the limitations in the resolution of elevation contours produce significant underestimates of the drag (Stensrud, 2007). This method of parameterization is also done for the surface flux of energy between the ocean and the atmosphere, in order to determine realistic sea surface temperatures and type of sea ice found near the ocean's surface (McGuffie and Henderson-Sellers, 2005). Sun angle as well as the impact of multiple cloud layers is taken into account (Mel′nikova and Vasilyev, 2005). Soil type, vegetation type, and soil moisture all determine how much radiation goes into warming and how much moisture is drawn up into the adjacent atmosphere, and thus it is important to parameterize their contribution to these processes (Stensrud, 2007). Within air quality models, parameterizations take into account atmospheric emissions from multiple relatively tiny sources (e.g. roads, fields, factories) within specific grid boxes (Baklanov *et al.*, 2009).

4.1 Microphysics

Microphysics provides atmospheric heat and moisture tendencies, Microphysical rates and surface rainfall. The simulations from numerical models are known to be sensitive to the representation of the physical processes. The MP schemes vary in complexity from relatively simple single-moment schemes that explicitly predict the mixing ratio of each hydrometeor species to a more sophisticated double-moment scheme that predicts both the mixing ratio and number concentration. Each MPS contains prognostic equations describing the evolution of six hydrometeor species (water vapour, cloud water, rainwater, ice, snow and graupel) (Otkin and Greenwald, 2008). Sensitivity experiments have been conducted for the event on 5 and 17 May 2008 with the four MPS namely Lin Scheme (Lin *et al.*, 1983), WRF Single–moment 3–class Schemes (Hong *et al.*, 2004), WRF Single–moment 6–class Scheme (Hong *et al.*, 2006) and Milbrandt–Yau Double Moment Scheme (Milbrandt and Yau, 2005a, b).

The sensitivity of cloud microphysics in predicting convective storms and precipitation has been addressed by many researchers (e.g., Liu and Moncrieff, 2007; Rao *et al.*, 2007; Chatterjee *et al.*, 2008; Rajeevan *et al.*, 2010). The choice of schemes was based on a prior experiment for which the results were reported elsewhere. In all experiments, the model setups were identical except for the use of different MPSs. The model results are analyzed and compared to the available surface observations and satellite derived data in order to identify the parameterizations that provide the best representation of the spatio-temporal variability of thunderstorm affected parameters.

4.2 Cumulus Convection

Cumulus convection schemes are responsible for the sub-grid-scale effects of convective and/or shallow clouds. The schemes are intended to represent vertical fluxes due to unresolved updrafts and downdrafts and compensating motion outside the clouds. They operate only on individual columns where the scheme is triggered which provide vertical heating and moistening profiles. In the WRF model, as many as twelve CPSs are included and each of them is based on some assumptions which make them suitable for certain weather systems and horizontal resolutions. In the present study, three CU convection schemes are examined towards simulation. These include Kain-

Fritsch scheme (Kain and Fritsch, 1993; Kain, 2004), Betts-Miller-Janjić scheme (Janjić, 1994, 2000; Betts, 1986), and Grell-Devenyi ensemble scheme (Grell and Devenyi, 2002; Grell and Freitsas, 2014). Additionally one experiment conducted without CU scheme.

4.3 Planetary Boundary Layer

Surface fluxes of momentum, latent and sensible heat plays important role in the development and modulation of significant weather events. These fluxes are estimated through planetary boundary layer (PBL) parameterization scheme. In this study, three PBL schemes are used for the study namely Yonsei University (YSU) Scheme (Hong *et al.*, 2006), Mellor–Yamada–Janjić (MYJ) Scheme (Janjić, 1990, 1994, 2002) and Asymmetric Convection Model 2 (ACM2) Scheme (Pleim, 2007a, b).

5. Experimental Design and Study Domain

The Advanced Research Weather Research and Forecasting model (ARW), version 3.5.1 (Skamarock *et al.*, 2008) used in this study, which is a three-dimensional, fully compressible, nonhydrostatic model. The vertical coordinate is a terrain-following hydrostatic pressure coordinate and the model uses the Runge–Kutta third-order integration scheme.

A single domain with 4 km horizontal spatial resolution was configured (Fig 1), which is reasonable in capturing the mesoscale cloud clusters. Data from the National Centers for Environmental Prediction (NCEP) 6 h FNL (Final) Global Analyses (FNL) at 1.0° × 1.0° grids were used as initial and lateral boundary conditions (LBC) for the domain. Main features of the model employed for this study are summarized in Table 1. In the present simulation, the model was integrated for a period of 24 h, starting at 0000 UTC of the occurrence day, as initial values.

The design of WRF model is suitable for investigating severe weather systems and is used by many authors to simulate the thunderstorms over the Indian region (Litta and Mohanty, 2008, 2012; Dawn and Mandal, 2014; Chevuturi *et al*., 2014).

Many numerical sensitivity experiments are also conducted on triple nested domains (27, 9 and 3 km resolutions) using different combinations of physical parameterization schemes. The data and diagrams are not shown here for brevity. Results of the nested domains showed that while the intensity of the storm was similar, but the storms moved very fast compared to observations from the Radar. Interestingly, the relatively 4 km resolution simulation shows the squall line closer to the observed time and location. While it is expected that the higher resolutions from nested domain should simulate the convective storms better, but in this case the results are not as expected. The success of model simulation is relative to input data, experiment design, situation dependent, physics dependent, and diffusion dependent. The effect of the higher resolution in simulation of high intensity rainfall events using a regional climate model reported the similar results (Almazroui, 2011) and concluded that the influence of boundary forcing plays important role in producing the rainfall system. They also emphasized that the use of high resolution does not systematically improve the simulation of such rainfall event. In our case, this may be due to several reasons; (1) though individual thunderstorm cells may have the horizontal scale of 1-10 km, the squall lines have typical length of about 200 km, (2) the simulations are carried out using the initial and boundary conditions from the NCEP global model at about 1° resolution, (3) no additional observations are assimilated in the model at higher resolutions.

Several sensitivity experiments were conducted with different combinations of CPSs (namely; Kain-Fritsch, Betts-Miller-Janjić, Grell-Devenyi) and no-CU, cloud MPSs (namely; Lin, WSM3, WSM6 and Milbrandt), and PBLs (namely; YSU, MYJ and ACM2) to examine the root mean square errors (RMSE) of forecasts. The NOAH scheme was used for land surface processes in all the experiments.

Table 1 gives a brief illustration on the model configuration of the present study. Nine sensitivity experiments were conducted with four MP, 3 CU and no CU and 3 PBL parameterizations schemes. The design of the experiment is presented in the Table 2.

6. Realized Weather and Satellite Features of the Events

The realized weather of the squall events are given below:

- Trough of low persisted over the North Bay of Bengal.
- There were strong southerly and southwesterly wind flows in the lower levels over the region of squall events.
- The upper air cyclonic circulation was over north Chhattisgarh, Assam and nearby regions in lower levels.
- A north-south oriented trough persisted from sub-Himalayan West Bengal (SHWB) to the North Bay of Bengal in the middle of troposphere.
- A well marked convergence line in the lower levels extending from the east coast of India to northeast India across Bangladesh, and
- Intrusion of a plume of high CAPE and low CINE from the Bay of Bengal into Bangladesh

Table 1: WRF model configurations

Model Features		Configurations
Horizontal Resolution		4 km
Vertical Levels		40
Topography		USGS
Dynamics		
Time Integration		Semi Implicit
Time Steps		20 s
Vertical Differencing		Arakawa’s Energy Conserving Scheme
Time Filtering		Robert’s Method
Horizontal Diffusion		2nd order over Quasi-pressure, surface, scale selective
Physics		
Convection	Parameterizations	KF, BMJ, GDE and No CU
PBL		YSU, MYJ, ACM2
Cloud Microphysics		Lin, WSM3, WSM6 and Milbrandt
Surface Layer		Monin-Obukhov
Radiation		RRTM (LW), Mlawer *et al.* (1997) SW (Dudhia, 1989)
Gravity Wave Drag		No
Land Surface Processes		Unified NOAH Land Surface Model

Table 2: Sensitivity experiments using different combinations of physical parameterizations

S.N.	Parameterizations schemes	Options
Expt. 1	Lin, KF, YSU	m2c1p1
Expt. 2	WSM3, KF, YSU	m3c1p1
Expt. 3	WSM6, KF, YSU	m6c1p1
Expt. 4	Milbrandt, KF, YSU	m9c1p1
Expt. 5	Milbrandt, BMJ, YSU	m9c2p1
Expt. 6	Milbrandt, GDE, YSU	m9c3p1
Expt. 7	Milbrandt, GDE, MYJ	m9c3p2
Expt. 8	Milbrandt, GDE, ACM2	m9c3p7
Expt. 9	Milbrandt, No-CU, YSU	m9c0p1

Table 3: Selected squall events for the parameterization study

Date	Reported Stations	Reported Time (UTC)	Wind Speed ($m\ s^{-1}$)	Wind direction
5 May 2008	Rangpur	1730	12.86	NW
	Khulna	1730	12.86	NW
	Dhaka	1810	21.09	NW
	Chittagong	2333	12.34	SE
17 May 2008	Rangpur	0530	14.40	W
	Satkhira	0900	16.46	NW
	Khulna	0930	20.57	NW

Observed feature of the squall events of 5 May 2008 and 17 May 2008 are presented in the Table 3. Dundee satellite observed IR imageries are shown for the events which indicate that intense convection persisted over northwest of Bangladesh on 5 May 2008 and south of Bangladesh on 17 May 2008 (Fig 2).

7. Results and Discussion

Now-a-days 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 (1992) and McNulty (1995) have reviewed severe thunderstorms and tornado forecasting in detail. According to them, three of the most important factors to examine in determining occurrence of squall 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 squall events are explored in the following section. Analysis of the results of these experiments is helpful to understand the impact of parameterization schemes (MPSs, CPSs and PBLs) on the simulation of 5 May 2008 and 17 May 2008 squall events and assist in the customization of model for future squall events simulation over Bangladesh region.

Simulation of rainfall using a mesoscale model is more challenging task compared to simulation of temperature. The success of model simulation is relative to input data, experiment design, situation dependent, physics dependent, and diffusion dependent. The structure of the thunderstorms are diagnosed by the model, and compared with available products derived from TRMM and ground based radar.

7.1 Station Averaged of 24 Hours Accumulated Rainfall

Bangladesh Meteorological department has 35 synoptic observatories of which data are available for study. In this study meteorological parameters and station averaged value have been calculated by considering all 35 stations observations of Bangladesh Meteorological Department.

Milbrandt-No CU-YSU scheme is able to simulate station averaged rainfall of 6.7 mm (Fig 3), which is lower compared to actual station averaged observation (8.9 mm) of 5 May 2008. The combination of Milbrandt-No CU-YSU scheme has simulated the rainfall at 0900 to 2100 UTC, which is the 2 h earlier as the actual rainfall occurrence at 1100 to 2100 UTC. All other combination of schemes has failed to simulate the intensity and time of occurrence of rainfall of this squall event.

For the event 17 May 2008 the combination of Milbrandt-No CU-YSU scheme is able to simulate 8.1 mm of rainfall (Fig 4), which is overestimated compared to actual observation (5.48 mm). Milbrandt-No CU-YSU scheme has simulated the rainfall at 0600 to 1200 UTC, which is the closer to the actual squall occurrence (0530 to 0930 UTC) time. All other combination of schemes has failed to simulate the intensity and time of this squall event. The combination Milbrandt-BMJ-YSU has simulated highest amount of rainfall (Fig 4) at 1501 to 1800 UTC, which is delayed by 9 h compared to actual observation.

7.2 Station Averaged of Wind Speed at 10 Meter

Milbrandt-No CU-YSU scheme is able to simulate 6.67 m s^{-1} of wind speed, which is overestimated compared to actual observation (5.42 m s^{-1}) at 2100 UTC of 5 May 2008. Milbrandt-No CU-YSU scheme has predicted the wind speed 2.6 to 6.67 m s^{-1} almost whole day. All the experiments overestimated the wind speed as compared to observation. At the time of squall occurrence (1730 to 2333 UTC) the combination Milbrandt-No CU-YSU has given the best result (Fig 5). All other combination of schemes has failed to capture the intensity and time of this squall event.

Milbrandt-No CU-YSU scheme is able to simulate 3.9 m s^{-1} of wind speed (Fig 6), which is the nearest as compared to actual observation (3.45 m s^{-1}) of 17 May 2008. Other experiments have overestimated the wind speed; especially the Milbrandt-GDE-MYJ combination has simulated 6.35 to 6.98 m s^{-1} (0600 to 0900 UTC) station average wind speed which is almost twice of actual observation.

7.3 Station Averaged of Temperature at 2 Meter

For the event of 5 May 2008, the Milbrandt-No CU-YSU scheme is able to simulate 35.8 °C of maximum temperature (Fig 7), which is overestimate as compared to actual observation (33.89 °C). For the minimum temperature, the same combination has simulated 26.5 °C and actual observation 23.57 °C which is the closest in comparison to other experiments.

For the event of 17 May 2008, the Milbrandt-No CU-YSU scheme is able to simulate 33.01 °C of maximum temperature (Fig 8), which is overestimate as compared to actual observation (31.00 °C). Milbrandt-No CU-YSU scheme has simulated minimum temperature of 27.21 °C and actual observation is 25.48 °C.

Model simulated station averaged temperature at 2 m reveals that all the experiment results are closer and difference with the actual observation is almost similar (Figs 7-8).

7.4 Comparison of Hourly Rain Rate

Precipitation has been simulated by the model for the observed events 5 and 17 May 2008 and is -

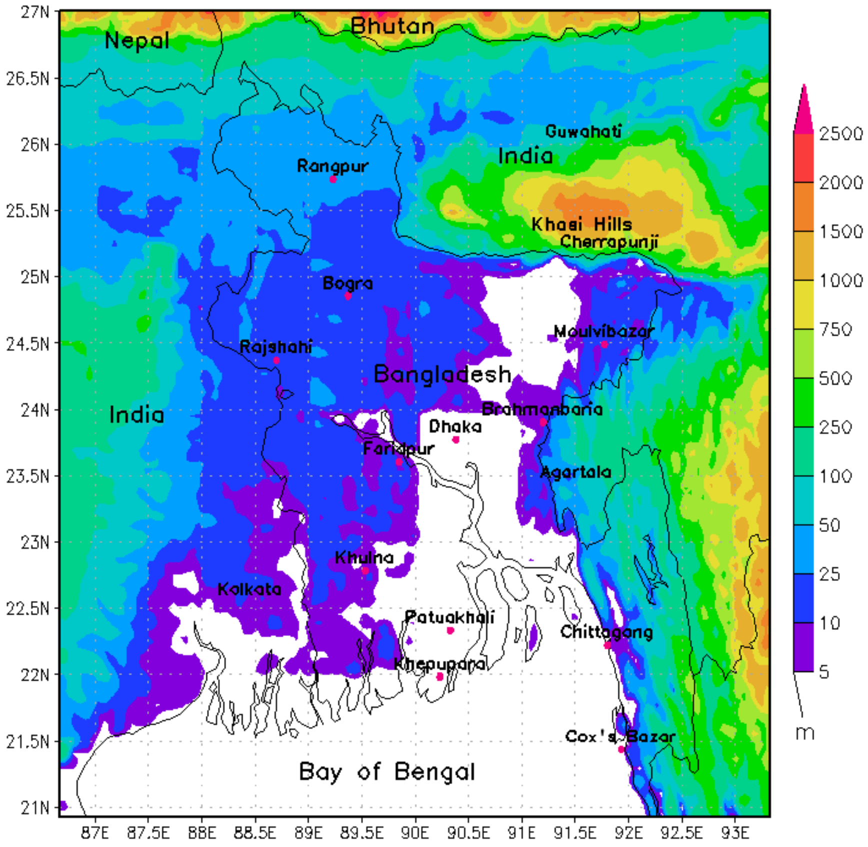

Fig 1: WRF model domain used for simulations and topography (shaded).

Table 4: RMSE of rainfall, wind speed at 10 m and forecast time. The values in the parenthesis indicate the positions of the RMSE. In the comments column, the values in the parenthesis indicate sum of 3 RMSE positions value.

S.N.	Name of experiment	RMSE			Comments
		Rainfall	Wind Speed	Forecast	
	MPSs				
Expt. 1	Lin, KF, YSU	15.77 (2)	9.47 (1)	132.04 (3)	(6)
Expt. 2	WSM3, KF, YSU	22.96 (4)	9.72 (3)	47.43 (1)	(8)
Expt. 3	WSM6, KF, YSU	16.55 (3)	9.98 (4)	174.33 (4)	(11)
Expt. 4	Milbrandt, KF, YSU	13.02 (1)	9.62 (2)	63.64 (2)	(5)
	CPSs				
Expt. 4	Milbrandt, KF, YSU	13.02 (1)	9.62 (3)	63.64 (1)	(5)
Expt. 5	Milbrandt, BMJ, YSU	23.16 (3)	6.85 (1)	171.18 (3)	(7)
Expt. 6	Milbrandt, GDE, YSU	19.35 (2)	6.75 (1)	60.47 (1)	(4)
	PBLSs				
Expt. 6	Milbrandt, GDE, YSU	19.35 (2)	6.75 (1)	60.47 (1)	(4)
Expt. 7	Milbrandt, GDE, MYJ	26.97 (3)	8.44 (2)	135.83 (2)	(7)
Expt. 8	Milbrandt, GDE, ACM2	17.69 (1)	9.98 (3)	141.88 (3)	(7)
	No CPSs				
Expt. 9	Milbrandt, No CU, YSU	12.91 (1)	6.21 (1)	41.49 (1)	(3)

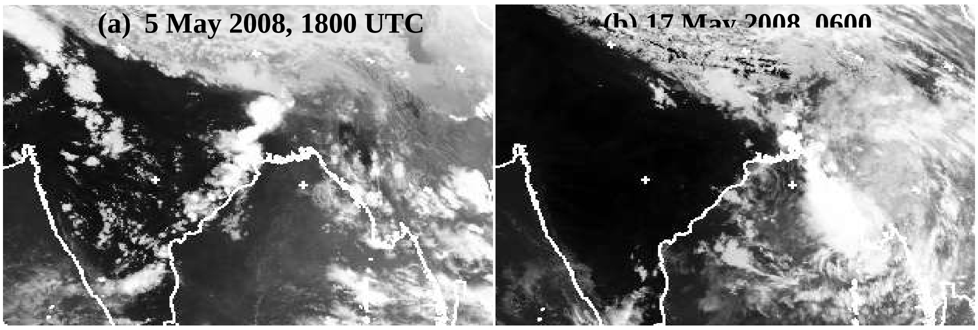

Fig 2: Dundee satellite derived IR imageries for the event of a) 5 May 2008 and b) 17 May 2008.

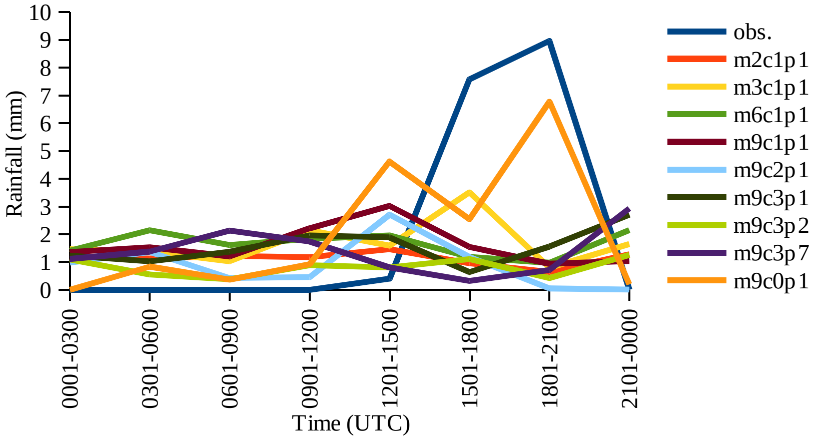

Fig 3: The inter-comparison of station averaged observed and model simulated accumulated rainfall (mm) with different parameterization schemes (MPS, CPS and PBLSs) over Bangladesh valid from 5 May 2008 at 0000 UTC to 6 May 2008 at 0000 UTC.

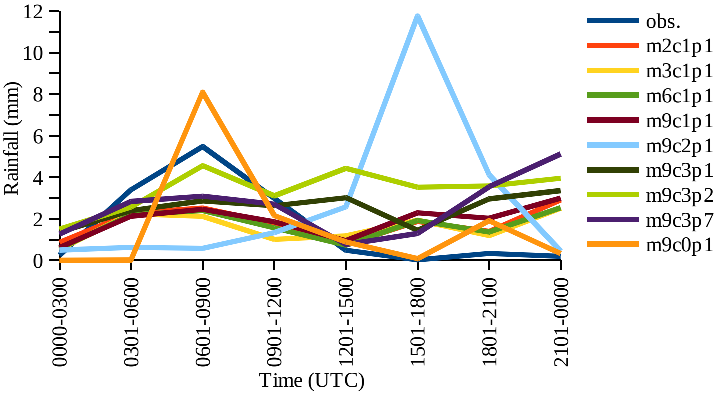

Fig 4: The inter-comparison of station averaged observed and model simulated accumulated rainfall (mm) with different parameterization schemes (MPS, CPS and PBLSs) over Bangladesh valid from 17 May 2008 at 0000 UTC to 18 May 2008 at 0000 UTC.

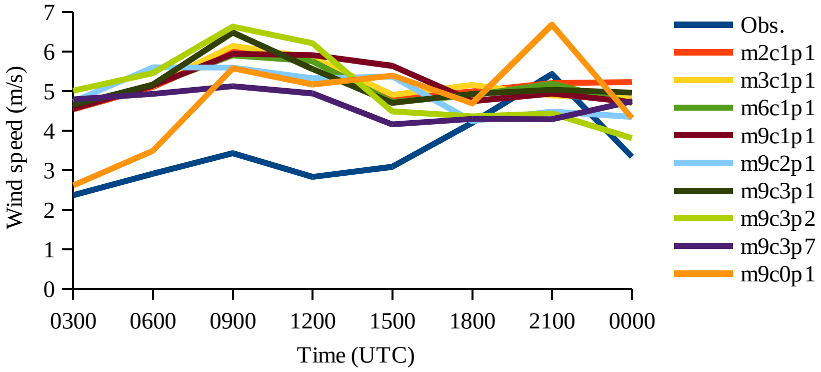

Fig 5: 5 May 2008 station averaged wind speed.

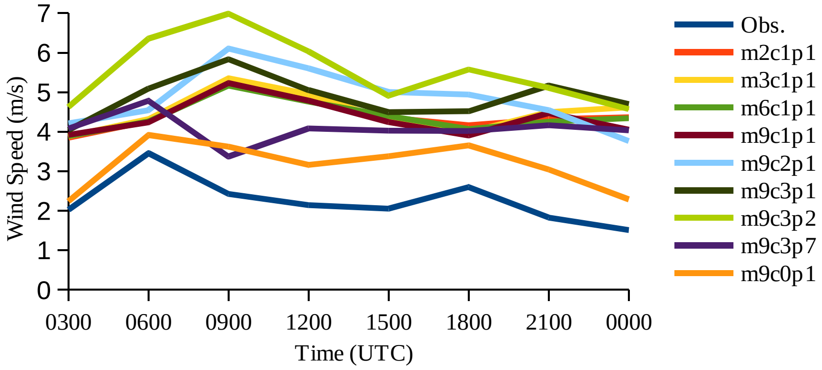

Fig 6: 17 May 2008 station averaged wind speed.

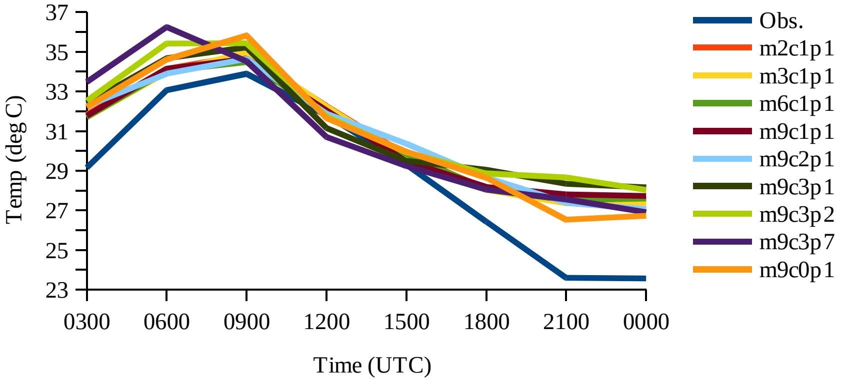

Fig 7: 5 May 2008 station averaged temperature at 2 m.

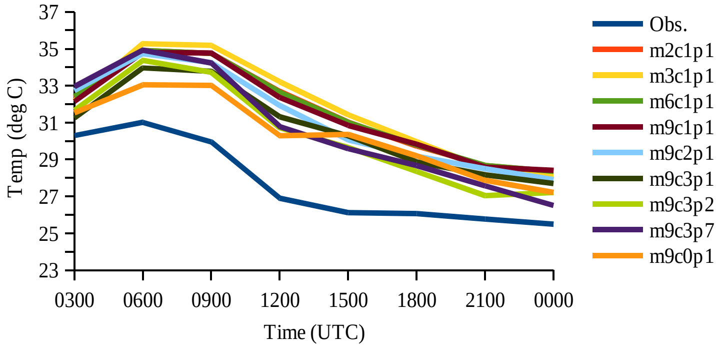

Fig 8: 17 May 2008 station averaged temperature at 2 m.

Table 5: Coefficient correlation of rainfall, wind speed at 10 m

S.N.	CC of rainfall		CC of wind speed at 10 m	
	5 May 2008	17 May 2008	5 May 2008	17 May 2008
Expt. 1	-0.85	0.44	0.12	0.04
Expt. 2	0.26	0.29	-0.06	-0.10
Expt. 3	-0.82	0.47	0.10	0.02
Expt. 4	-0.32	0.26	-0.19	0.53
Expt. 5	-0.20	-0.43	-0.50	0.27
Expt. 6	-0.39	0.22	0.01	0.25
Expt. 7	-0.14	0.19	-0.35	0.67
Expt. 8	-0.64	0.18	-0.54	0.52
Expt. 9	0.72	0.76	0.73	0.79

presented in Figs 9-10. The model result shows shifted location of precipitation. But the intensities of the precipitation rates are simulated well compared to the rain rate of Dhaka radar. For the event of 5 May 2008, Milbrandt-KF-YSU combination (Fig 9d) and Milbrandt-No CU-YSU combination (Fig 9i) clearly show double line squall pattern which is absent in the other experiments. Lin-KF-YSU, WSM3-KF-YSU and WSM6-KF-YSU combinations (Fig 9a-c) show almost similar pattern of rain rate and the intensity similar to the observation but location is fully difference.

For the event 17 May 2008, the Milbrandt-No CU-YSU combination has simulated location and intensity specific rain rate (Fig10 i). Milbrandt-BMJ-YSU (Fig10 e) and the rain rate pattern simulated by Milbrandt-BMJ-YSU (Fig 10 f) combination is similar to observation but with location shifted towards north. In the experiment, Milbrandt-GDE-MYJ (Fig 10 e) has simulated rain nearer to the observed location but in other area rain is higher, which are absent in the rain rate derived by Dhaka radar.

7.5 Rain Water Mixing Ratio

Fig 11 illustrates the vertical profiles of rainwater mixing ratio obtained by the WRF model on the days of squalls. The values are converted to mm h^{-1} from kg kg^{-1} for comparison with the TRMM profiles. The instantaneous vertical profile of rainfall rate is designated as 2A25 in the TRMM products. The 2A25 data with 5 km horizontal and 250 m vertical sampling from surface to 20 km altitude is used in this study. The spatial distribution and vertical variation of rain intensities are analyzed similar to Islam and Uyeda (2008) and Das *et al.* (2015) that occurred between April to May 2008. The left Panel of Figs 11 and 12 presents vertical profiles of rain rate retrieved from TRMM from surface to 20 km altitude. The satellite passes over Bangladesh approximately once in a day.

The values present below the freezing level may be the rainwater, while those above the freezing level may be interpreted as snow. The model shows multi-cellular structure of the squalls as observed by TRMM.

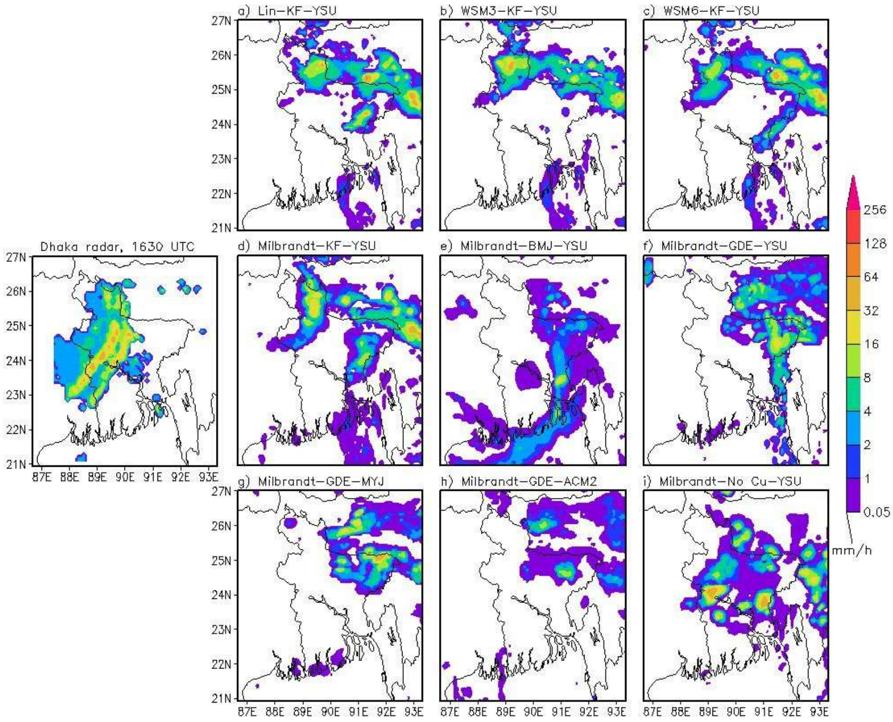

Fig 9: The spatial distribution of hourly rain rate (mm h^{-1}) at 1700 UTC with different parameterization schemes (MPS, CPS and PBLSs) on 5 May 2008 in comparison with Radar.

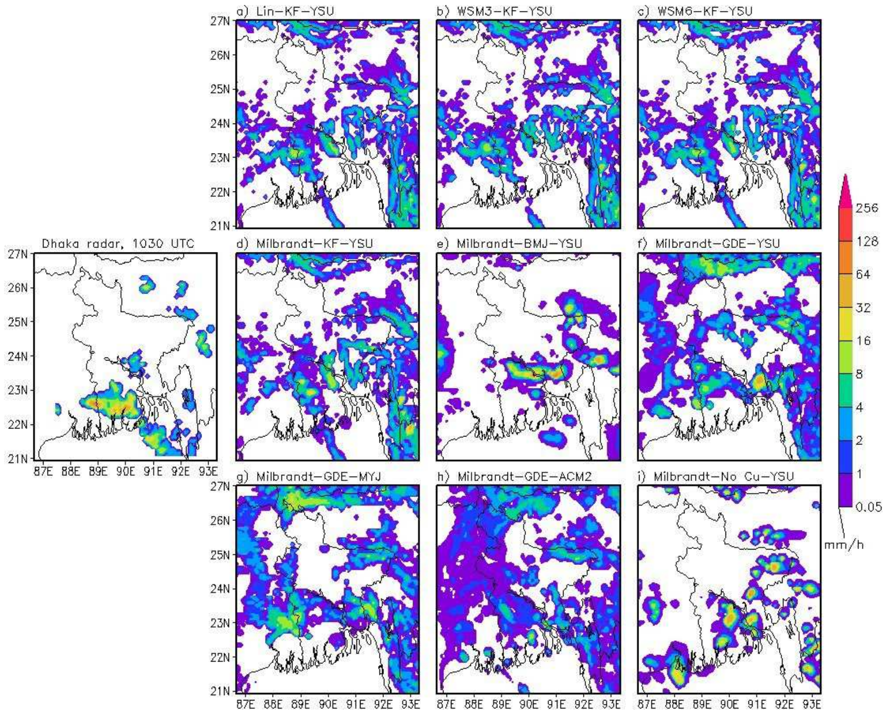

Fig 10: The spatial distribution of hourly rain rate (mm h^{-1}) at 1100 UTC with different parameterization schemes (MPS, CPS and PBLSs) on 17 May 2008 in comparison with Radar.

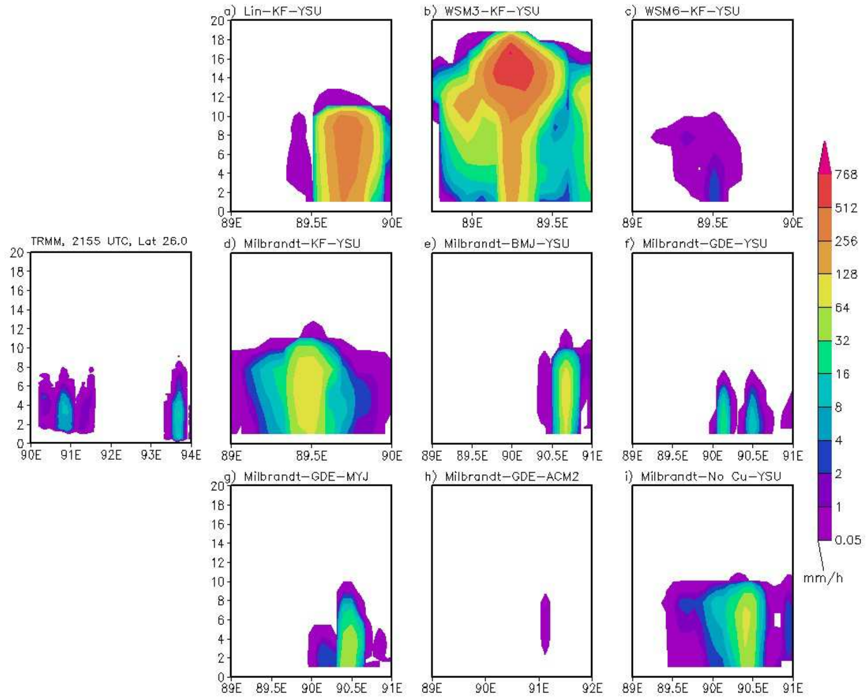

Fig 11: Rain water mixing ratio on 5 May 2008 in comparison with TRMM.

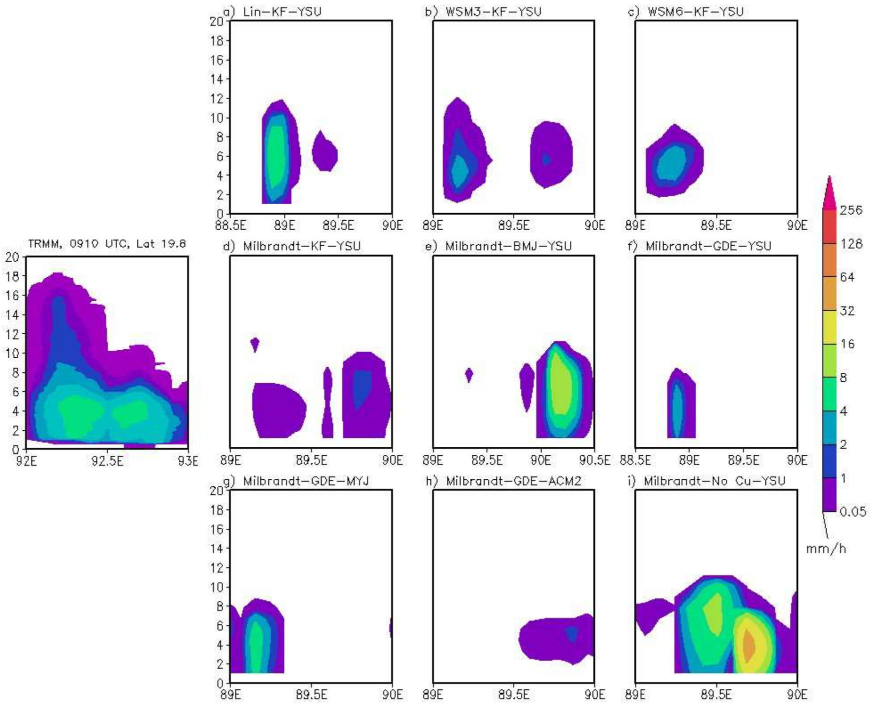

Fig 12: Rain water mixing ratio on 17 May 2008 in comparison with TRMM.

The simulated profiles indicate that the core of maximum precipitation ranges from 1 to 18 km of altitudes. The maximum intensities are more than twice the rate observed by TRMM. Also, the altitudes of maximum intensity simulated by the model are higher than the TRMM values.

For the event of 5 May 2008, WSM3-KF-YSU combination (Fig 11b) has simulated extreme rainwater mixing ratio (> 512 mm h^{-1}) and cloud has been found to extend up to altitude of 18 km but for all other combinations the cloud has been found to reach up to altitude of 12 km. Milbrandt-No CU-YSU combination (Fig 11 i) has simulated pattern and intensity of rainwater mixing ratio (> 64 mm h^{-1}) almost matching with the TRMM and the cloud has reached up to 11 km. The combination of WSM6-KF-YSU (Fig 11c) Milbrandt-GDE-ACM2 (Fig 11 h) has simulated very less amount of rain water mixing ratio.

For the event of 17 May 2008, Milbrandt-No CU-YSU combination has simulated almost similar pattern of rainwater mixing ratio as compared to TRMM and altitude of cloud top has reached up to 11 km but for all other combinations patterns are not found to match with the TRMM. The combination Milbrandt-GDE-ACM2 (Fig 11 h) has simulated rain water mixing ratio amount, which is very less (1-2 mm h^{-1}) compared to other experiments.

7.6 Statistical Analysis of Different Experiments

The statistical analysis of rainfall with different combinations of MPSs, CPSs and PBLSs from Table 4 shows Milbrandt-KF-YSU scheme has less error (RMSE) as compared to all other combinations. From the RMSE of wind speed and forecast it is evident that the results of Milbrandt, YSU and No CU combination are comparatively better than other experiments.

The statistical analysis of wind speed (m s^{-1}) with different combination (Table 4) shows the RMSE for Milbrandt-No CU-YSU scheme is less as compared to all other combinations of schemes. Overall, Milbrandt-No CU-YSU scheme has well simulated the meteorological parameters associated the thunderstorms as compared to all other combinations of schemes for the occurrence of squall events on 5 and 17 May 2008, although 30 minutes to two hour time lag exist. RMSEs for rainfall (mm) and wind speed at 10 m (m s^{-1}) calculated for the all the 7 squall events are presented in the Table 3. Forecast error (minutes) has been calculated only for the events on 5 May 2008 at Rangpur and 17 May 2008 at Satkhira.

Another verification method used for this study is correlation coefficient. From the Table 5 we can clearly see that, Expt. 9 (Milbrandt, No-CU, YSU) positively correlated and has the highest correlation coefficient (>0.7) as compared to all other experiments.

8. Conclusions

In this study, sensitivity experiments have been conducted with the WRF ARW model to test the impact of parameterization schemes (MPS, CPS, PBLSs) on simulating squall events that occurred over Bangladesh on 5 and 17 May 2008 and the model results have been validated with observations. A statistical analysis based on RMSE is performed for comparison among simulated and observed data with different parameterization schemes (MPS, CPS, PBLSs) and explicit scheme. In all experiments, the setups have been identical except for the use of different parameterization schemes (MPS, CPS, PBLSs). Hence differences in the simulation results may be attributed to the sensitivity of the parameterization schemes (MPS, CPS and PBLSs). This study shows that the prediction of parameters associated with squalls are sensitive to parameterization schemes of Milbrandt, YSU, Kain-Fritsch and Grell-Devenyi ensemble scheme. It is clearly demonstrated that the performance of Milbrandt, No CU, YSU (m9c0p1) parameterization scheme is significantly better than other parameterization schemes including explicit scheme.

By comparing both the squall events, all the experiments have well simulated the station averaged wind speed at 10 m and temperature at 2 m. The combination of Milbrandt, No CU, YSU (m9c0p1) schemes provides the best results as compared to all other combinations of parameterization schemes.

The temporal and spatial distribution patterns of precipitation simulated by Milbrandt, No CU, YSU (m9c0p1) schemes are in good agreement with the observation. But all other schemes have failed to simulate the intensity and time of occurrence for both the squall events. The time-series plot and statistical analysis of station averaged rainfall have revealed that Milbrandt, No CU, YSU (m9c0p1) schemes have well captured the sufficient deep humid layer for the occurrence of squalls on 5 May 2008 and 17 May 2008 as in the observation.

After analyzing the aforementioned datasets, it can be concluded that the WRF ARW model with Milbrandt, No CU, YSU (m9c0p1) parameterization schemes has well simulated the squall 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 have demonstrated the capability of high resolution WRF ARW model in simulation of squall events and found out the suitable parameterization schemes (MPS, CPS and PBLSs) for Bangladesh region.

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