



## Performance Evaluation of PBL Schemes of ARW Model in Simulating Thermo-Dynamical Structure of Pre-Monsoon Convective Episodes over Kharagpur Using STORM Data Sets

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**Abstract**—In the present study, advanced research WRF (ARW) model is employed to simulate convective thunderstorm episodes over Kharagpur (22°30'N, 87°20'E) region of Gangetic West Bengal, India. High-resolution simulations are conducted using 1 × 1 degree NCEP final analysis meteorological fields for initial and boundary conditions for events. The performance of two non-local [Yonsei University (YSU), Asymmetric Convective Model version 2 (ACM2)] and two local turbulence kinetic energy closures [Mellor–Yamada–Janjic (MYJ), Bougeault–Lacarrere (BouLac)] are evaluated in simulating planetary boundary layer (PBL) parameters and thermodynamic structure of the atmosphere. The model-simulated parameters are validated with available in situ meteorological observations obtained from micro-meteorological tower as well as high-resolution DigiCORA radiosonde ascents during STORM-2007 field experiment at the study location and Doppler Weather Radar (DWR) imageries. It has been found that the PBL structure simulated with the TKE closures MYJ and BouLac are in better agreement with observations than the non-local closures. The model simulations with these schemes also captured the reflectivity, surface pressure patterns such as wake-low, meso-high, pre-squall low and the convective updrafts and downdrafts reasonably well. Qualitative and quantitative comparisons reveal that the MYJ followed by BouLac schemes better simulated various features of the thunderstorm events over Kharagpur region. The better performance of MYJ followed by BouLac is evident in the lesser mean bias, mean absolute error, root mean square error and good correlation coefficient for various surface meteorological variables as well as thermo-dynamical structure of the atmosphere relative to other PBL schemes. The better performance of the TKE closures may be attributed to their higher mixing efficiency, larger convective energy and better simulation of humidity promoting moist convection relative to non-local schemes.

**Key words:** Thunderstorm, planetary boundary layer, Doppler weather radar, ARW model.

### 1. Introduction

Thunderstorms are short-lived mesoscale deep convective weather phenomena that are manifested in the form of squally winds, thunders, lightning, hail and heavy precipitation. The severe thunderstorms cause damage to agricultural crops, damage to structures and loss of life by extreme winds, lightning and hail leading to severe socio-economic impacts in affected regions (TYAGI 2007). Thunderstorms occur in different parts of India during different seasons, but with widespread and peak activity all over the country during the hot weather period, also known as the summer or pre-monsoon season, from March to May. Severe thunderstorms form and move generally from northwest to southeast over the eastern and north-eastern states of India during the pre-monsoon season, they are locally called “Kal-baishakhi” or “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 from head Bay of Bengal (BoB) (KESSLER 1982; GHOSH *et al.* 2008; SOMESHWAR *et al.* 2014). Over the Gangetic West Bengal (GWB) region, comprehensive data sets are not available to understand the thermodynamic features of atmosphere to improve the forecasting skill of the occurrence of thunderstorm activity. Keeping this in view, the Department of Science and Technology of the Government of India launched a multi-institutional programme named “Severe Thunderstorms-Observations and Regional Modelling (STORM)” over GWB and NE parts of India (STORM Science Plan 2005).

Few observational studies have been reported on pre-monsoon thunderstorms over the GWB region in

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an attempt to understand and delineate the characteristic signatures in the development of these events (e.g. MUKHOPADHYAY *et al.* 2009; CHAUDHURI 2011; TYAGI *et al.* 2011, 2013a, b; SOMESHWAR *et al.* 2014). MUKHOPADHYAY *et al.* (2009) studied formation of severe thunderstorms over Kolkata region by using Doppler radar and satellite observations and conclude that severe thunderstorms occur mainly due to the interaction of large-scale and mesoscale environment. CHAUDHURI (2011) suggested that Convective Inhibition (CIN) ( $0\text{--}150 \text{ Jkg}^{-1}$ ) and warm air (surface temperature  $30\text{--}38 \text{ }^\circ\text{C}$ ) are the most significant parameters for the prevalence of severe thunderstorms over Kolkata region during the pre-monsoon season. TYAGI *et al.* (2011) proposed the threshold values of the thermo-dynamical indices such as convective available potential energy (CAPE), lifted index (LI), K index (KI), humidity index (HI) on the days of thunderstorm activity using larger data set over Kolkata region. Observed values of these indices revealed that occurrence of scattered, multi-cellular thunderstorms are possible over Kolkata region during pre-monsoon months. TYAGI *et al.* (2013a, b) studied thermo-dynamical structure of atmosphere and surface energy fluxes during pre-monsoon season over Kharagpur using STORM data sets. It has been concluded that significant moisture availability in the lower troposphere in the presence of convective instability conditions leads to thunderstorm development at Kharagpur during pre-monsoon season. Field experiments have been conducted (SOMESHWAR 2014) to gather comprehensive observations on severe thunderstorms over the South Asian Region for understanding their genesis and regional modelling.

Short-range prediction of severe weather such as thunderstorms is an important aspect of the regional weather in the northeastern states of India. An accurate, location specific and timely prediction is required to avoid loss of lives and properties due to strong winds and heavy precipitation associated with such weather systems. Prediction of thunderstorms is one of the most difficult tasks in weather prediction, due to rather smaller spatial, temporal scales and inherent non-linearity of their dynamics and physics and due to the problem of prescribing precise initial conditions. Few modelling studies have been reported for pre-monsoon thunderstorms analysis over the

GWB region in an attempt to predict the development of these events (LITTA *et al.* 2012a, b; SRIKANTH *et al.* 2013; DAWN and MANDAL 2014; KIRAN PRASAD *et al.* 2014; PROSENJIT *et al.* 2015; SOMESHWAR *et al.* 2015). LITTA *et al.* (2012a) used a high-resolution (3 km) WRF non-hydrostatic mesoscale model (WRF-NMM) model to simulate severe thunderstorm events over east and northeast Indian region. With physics sensitivity experiments, they concluded that NMM model with Ferrier microphysics scheme has well captured the instability of the atmosphere for the occurrence of severe thunderstorms in the above regions. LITTA *et al.* (2012b) studied the performance of WRF-NMM for a few thunderstorm cases during the STORM field experiments in 2007, 2009 and 2010 and reported that WRF-NMM with 3-km resolution predicted the events with reasonable accuracy over east and northeast Indian region. SRIKANTH *et al.* (2013) studied the performance of convective parameterization schemes (Kain–Fritsch, Grell–Devenyi and Betts–Miller–Janjic) of WRF-ARW for simulating pre-monsoon thunderstorm events around Kharagpur and showed that Grell–Devenyi performed better than the other tested schemes in representing the thermo-dynamical state of atmosphere during the thunderstorm events over Kharagpur region. KIRAN PRASAD *et al.* (2014) studied the impact of Doppler weather radar (DWR) data on thunderstorm simulation during STORM pilot phase over eastern and northeastern parts of India. They reported remarkable improvements in the mesoscale model results after assimilating DWR fields. DAWN and MANDAL (2014) studied the WRF model-simulated surface mesoscale features associated with pre-monsoon convective episodes over the GWB, India by using STORM data sets. PROSENJIT *et al.* (2015) studied the three pre-monsoon season convective episodes over the GWB, India by using mesoscale model MM5. They have shown that mesoscale models are having the capability of simulating temperature drop, rainfall and regions of pressure rise and drop that occurs during the thunderstorm period. SOMESHWAR *et al.* (2015) simulated 15 severe thunderstorms using WRF model that formed over northeast India during the pre-monsoon season of 2008. They simulated all the storms though they are slightly shifted in positions and time. Planetary

Boundary Layer (PBL) encompasses 2–3 km of the atmosphere of lower troposphere and plays an important role in the transportation of energy such as momentum, heat and moisture into the upper layers of the atmosphere (STULL 1988) and acts as a feedback mechanism in the generation and sustenance of thunderstorms. The intensity of convective thunderstorms is determined by the supply of heat and moisture from the surface. The PBL determines the amount of convectively available potential energy of the atmosphere that determines the genesis of thunderstorms. In numerical models various approaches are used to parameterize the vertical turbulent mixing in the PBL. Consequently, the characteristics of the simulated storms may depend on the specific parameterizations to some extent. Studies were reported in literature regarding the sensitivity of PBL schemes to the meteorological modelling (e.g. BRIGHT and MULLEN 2002; SRINIVAS *et al.* 2007a, b, 2013, 2015; XIE *et al.* 2012; RAMAKRISHNA *et al.* 2012; LI and PU 2008; MIAO *et al.* 2009; HU *et al.* 2010; HARIPRASAD *et al.* 2014; SRIKANTH *et al.* 2015). HU *et al.* (2010) examined the ability of three PBL schemes in WRF (MYJ, YSU and ACM2) to simulate the PBL features for fair weather conditions over Texas. With comparison of surface and boundary layer observations, they suggested that ACM2 scheme produced better simulations over the other two. SRIKANTH *et al.* (2014) studied severe thunderstorm events using WRF-ARW model over Gadanki in southern peninsular India using five PBL and three cumulus parameterization schemes. In simulating they reported that the MYJ with Grell–Devenyi ensemble (GD) combination better simulated the boundary layer parameters, thermodynamic structure and vertical velocity profiles and the characteristics of severe thunderstorm events. From the literature review, PBL parameterization studies over India are mostly limited to cyclones and fair weather conditions and relatively few studies are available on thunderstorms. In particular, studies related to PBL parameterizations for meteorological modelling of thunderstorms are limited over the GWB region. In the present study, an attempt is made to examine the performance of PBL parameterizations of ARW model in simulating the thermo-dynamical environment associated with thunderstorms during the pre-

monsoon season of 2007 at Kharagpur using STORM-2007 data sets. The model simulations are validated with the available observations and statistical analysis performed to assess the efficiency of different PBL schemes for simulating the storm events.

## 2. Study Region

The study region comprises GWB and the field meteorological data are obtained from the agriculture farm site at Indian Institute of Technology Kharagpur, Kharagpur (22°30'N, 87°20'E) region of west Midnapore, GWB, India. The mean sea level height of the station is 39 m and topographically the site is flat and grassy. 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 [STORM Science Plan (2005)]. Details of site location and the sensors used in the data acquisition during the field programme are given in Tyagi and Satyanarayana (2010).

## 3. Data and Methodology

### 3.1. Data

In the present study, the initial conditions for the model domains are derived from 6-h global final meteorological analysis (FNL) available at  $1.0^\circ \times 1.0^\circ$  grids generated by the National Center for Environmental Prediction (NCEP) (<http://rda.ucar.edu/datasets/ds083.2>). The DWR imageries are provided by cyclone detection radar (CDR), Kolkata, India Meteorological Department (IMD) and STORM Weather Summary (MOHANTY *et al.* 2006, 2007) is analysed for the qualitative assessment of the occurrence of the thunderstorm activity. The measured parameters from 50-m micro-meteorological tower are atmospheric pressure, wind speed, wind direction, temperature and relative humidity at 6 heights, 2, 4, 8, 16, 32 and 50 m (slow response data, 1 Hz), fast response turbulence measurements obtained from sonic anemometer (10 Hz) and rainfall

obtained at IIT Kharagpur campus and the upper air observations consists of pressure (hPa), temperature ( $^{\circ}\text{C}$ ), relative humidity (%), wind speed ( $\text{m s}^{-1}$ ) and wind direction ( $^{\circ}$ ) obtained from DigiCORA radiosondes obtained from Kalaikunda Air Force Station (at a spatial distance of 8 km from IIT Kharagpur) are used for the validation of model simulations. In this study, the 3B42V7 product of TRMM is used ([http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance\\_id=TRMM\\_3-Hourly](http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=TRMM_3-Hourly)). Since the rain gauge data are not available for the thunderstorm event TD2, the TRMM satellite measurements are used for rainfall comparison for this event.

### 3.2. Delineation of Thunderstorm Day

Thunderstorms over Kharagpur are classified based on time of occurrence of the event on a given day. The log-book information during the experiment, tower observations and information about thunderstorms from CDR Kolkata with verification against DWR imaging were used to finalize the time of occurrence and duration of the thunderstorm event at the field site following TYAGI *et al.* (2013a).

In the present study, three thunderstorm events occurred over Kharagpur during 26 April 2007 (henceforth referred to as TD1), 08 May 2007 (henceforth referred to as TD2) and 19 May 2007 (henceforth referred to as TD3) are chosen. TD1, TD2 and TD3 occurred during 1000–1220 UTC, 0930–1220 UTC and 1100–1220 UTC over Kharagpur.

### 3.3. Mesoscale Model

Advanced Research Weather Research and Forecasting (ARW Version 3.2) model is used in the present study. It consists of Eulerian mass solver with fully compressible non-hydrostatic equations with complete Coriolis and curvature terms, and the prognostic variables include the three-dimensional wind, perturbation quantities of pressure, potential temperature, geopotential, surface pressure, turbulent kinetic energy and scalars (water vapour mixing ratio, cloud water, etc.). A detailed description of model equations, physics and dynamics is available in SKAMAROCK *et al.* (2008).

The land surface and PBL processes influence the dynamical and thermo-dynamical state variables in the lower atmosphere. These PBL vertical transports of heat, moisture and momentum are parameterized in various ways in models. In the present work, to test the model sensitivity four PBL parameterizations schemes namely two first-order closure schemes Yonsei University (YSU), Asymmetric Convective Model version 2 (ACM2) and two turbulent kinetic energy (TKE) closure schemes Mellor–Yamada–Janjic (MYJ), Bougeault–LaCarrere (BouLac) are used. The land surface models (LSMs) influence the eddy heat and moisture transports in PBL through the surface energy fluxes. The NOAA land surface model is used for calculating the time varying surface boundary fluxes with inclusion of explicit soil and vegetation effects. For microphysics Eta scheme is used following results for thunderstorm simulations by LITTA *et al.* (2012a) over WGB. For long-wave radiation transfer Rapid Radiation Transfer Model (RRTM) model, for shortwave radiation Dudhia scheme are used. For computing the large-scale convection, the Grell–Devenyi ensemble scheme (GD) is used following our earlier results for thunderstorm simulations (SRIKANTH *et al.* 2013) over Kharagpur. Food and Agriculture Organization of the United Nations (FAO) Soils data (17 categories) with resolutions 5, 2 m and 30 s (0.925 km) and the United States Geological Survey (USGS) topography and vegetation data (25 categories) were used to define the lower boundary conditions. Model domain of study region with topography is given in Fig. 1a, b. The details of the model configuration are given in Table 1.

The ARW model is integrated for a period of 24 h, for thunderstorm events (TD) starting from 0000 UTC on 26 April 2007 (TD1), 08 May 2007 (TD2) and 19 May 2007 (TD3) as initial conditions. In each simulation the first 6-h period is considered for model-spin up. The model is configured with three nested domains of 27, 9 and 3 km grid spacing. The outer domain (d01) covers a larger region with 27 km resolution and 60x59 grids. The second inner domain (d02) has 9 km resolution with  $100 \times 100$  and innermost domain (d03) has 3 km resolution with  $151 \times 151$ . Initial conditions for the parent domain (d01) are derived from 6 h global final analysis

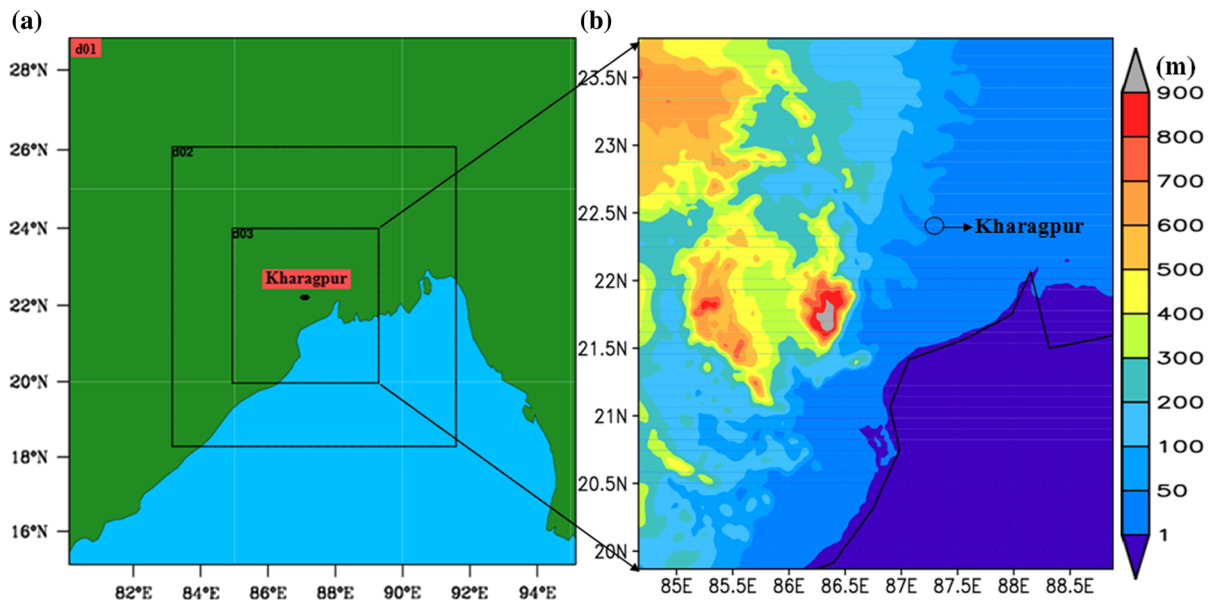


Figure 1  
Domains used in the WRF-ARW model

Table 1

*Overview of WRF model*

Dynamics	Non-hydrostatic
Initial and boundary data	NCEP FNL
Temporal interval of boundary data	6 h
Grid size	Domain1: (60 × 59) × 59 Domain2: (100 × 100) × 59 Domain3: (151 × 151) × 59
Resolution	Domain1: 27 km × 27 km Domain2: 9 km × 9 km Domain3: 3 km × 3 km
Covered area of outermost domain	15.1°–28.5°N and 80.1°–94.9°E
Map projection	Mercator
Horizontal grid system	Arakawa-C grid
Integration time step for outermost domain	90 s
Vertical coordinates	Terrain-following hydrostatic pressure vertical co-ordinate with 59 vertical levels
Time integration scheme	3rd order Runge–Kutta scheme
Spatial differencing scheme	6th order centre differencing
PBL schemes	YSU, MYJ, BOULAC and ACM2
Cumulus parameterization for domains 1 and 2	Grell–Devenyi
Surface layer parameterization	Noah land surface scheme
Microphysics	Eta microphysics
Short wave radiation	Dudhia scheme
Long-wave radiation	RRTM scheme
Terrain and land use data	USGS

(FNL) at 1.0° × 1.0° grids generated by the NCEP. Analysis fields, including temperature, moisture, geopotential height and wind, are interpolated to the

mesoscale grids by the ARW Pre-processing System (WPS). These derived fields served as initial conditions for the present experiments. The solver uses a

third-order Runge–Kutta time integration scheme and 2nd to 6th order advection option in both horizontal and vertical directions. The grid staggering is the Arakawa-C grid. The domain is configured with vertical structure of 59 unequally spaced sigma (non-dimensional pressure) levels with the top of model at 50 hPa. All the model domains are initialized at the same time.

#### 4. Results and Discussion

The performance of the PBL schemes in the WRF simulation of the thunderstorms is evaluated using temporal variation of surface meteorological parameters; thermo-dynamical structure and stability parameters and convective precipitation over Kharagpur during the study period.

##### 4.1. Variation of Surface Meteorological Parameters

Surface meteorological parameters play a significant role in the genesis of the thunderstorm (ASNANI 2005). In this section, an inter-comparison of performance of various PBL parameterization schemes in simulating the diurnal variation of surface meteorological variables such as air temperature (AT) ( $^{\circ}\text{C}$ ) and relative humidity (RH) (%) at 2 m, wind speed (WS) ( $\text{ms}^{-1}$ ) at 10 m above ground level (AGL) along with the in situ observations during three thunderstorm (TD) events over study region is depicted in Fig. 2.

##### 4.1.1 Thunderstorm Cases

**4.1.1.1 Variation of the Surface Meteorological Variables During TD1** Figure 2a shows the comparison of observed and model-simulated AT by different PBL schemes during TD1. All the schemes over-predicted AT throughout the day. The reason could be due to the initial value problem of AT (NCEP-FNL data) is about  $3.5^{\circ}\text{C}$  higher compared with the observations. During the event time (1000–1100 UTC) a sudden fall of AT from  $32.5$  to  $22.5^{\circ}\text{C}$  (drop of  $10^{\circ}\text{C}$ ) is noticed in the observations. The occurrence time and magnitude of temperature drop is simulated differently by different

PBL schemes. Among the different PBL schemes the MYJ and BouLac captured a temperature fall of  $8.5^{\circ}\text{C}$  (from  $37.5$  to  $28^{\circ}\text{C}$ ) at (0900–1000 UTC), which is found to be in reasonable agreement with observations (one hour lead). The YSU simulated a temperature drop of  $8^{\circ}\text{C}$  but with a lag of 1 h. ACM2 scheme was not able to capture the temperature drop properly both in terms of occurrence time as well as the magnitude as seen in the observations.

The comparison between observed and model-simulated RH is depicted in Fig. 2b during TD1. Observations revealed a sudden rise of RH from 1000 to 1200 UTC from around 62–82 % (rise of 20 %) during the occurrence of the thunderstorm event. This is attributed to the moist air incursion and associated rainfall during the thunderstorm. This rise in RH is reasonably captured by YSU and MYJ schemes, but with a time lag of about an hour. The MYJ and YSU schemes were able to simulate the sharp rise from around 60 % to 87 % (rise of 27 %) between 1100 UTC and 1300 UTC.

The comparison between observed and model-simulated WS at 10 m level is presented in Fig. 2c during TD1. All the schemes overestimated the surface wind speed in the pre-storm or convection development stages indicating a bias in downward momentum transfer within PBL. The simulated winds in pre-storm time are about 6–12  $\text{m s}^{-1}$  varying from different PBL schemes. Overestimation of surface winds seems to be a general problem in ARW and the present case is no exception. Previous studies with ARW over various regions have also reported overestimation of surface winds (STEENVELD *et al.* 2008; SHIMADA *et al.* 2011; HARIPRASAD *et al.* 2014; SRIKANTH *et al.* 2015). These studies suggest the overestimation of winds could be largely due to under-representation of topographic (i.e. roughness) effects on the flow. Stronger winds would influence the surface drag forces and shear energy available for turbulence generation within the PBL. This could be related to the errors in the land surface characteristics such as roughness and the surface drag parameterization.

**4.1.1.2 Variation of the Surface Meteorological Variables During TD2** The evolution of simulated and observed surface meteorological variables for the

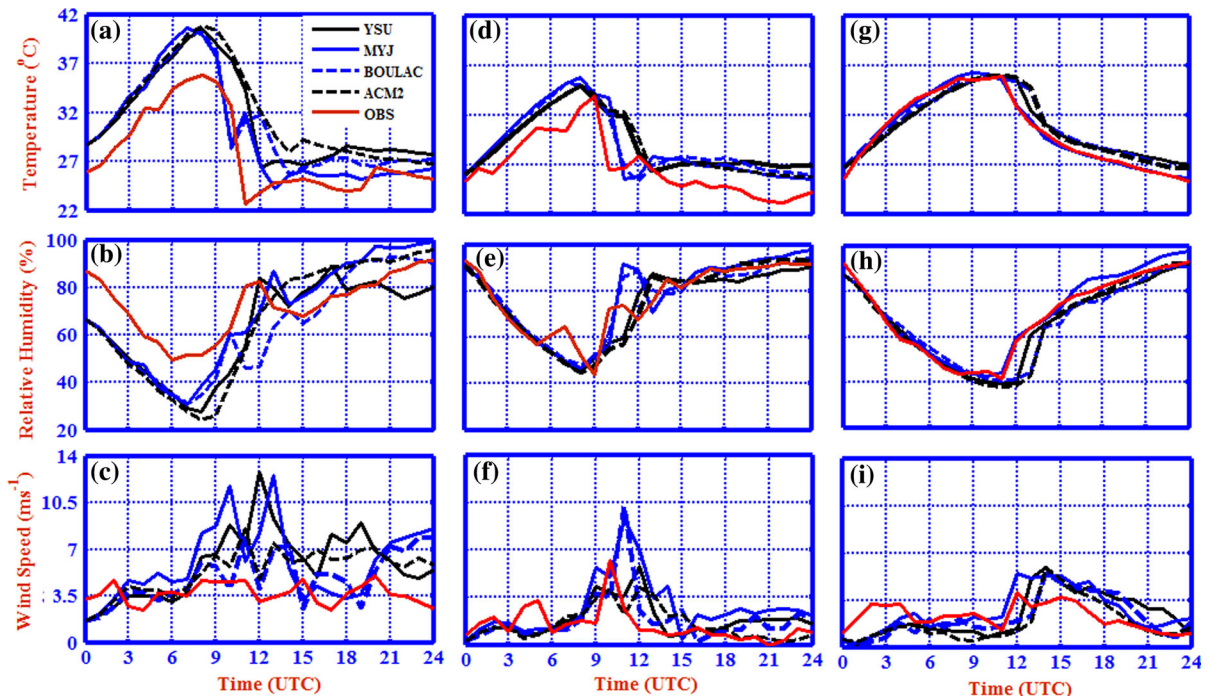


Figure 2

Validation of model simulations of surface meteorological parameters air temperature ( $^{\circ}\text{C}$ ) (a, d, g), relative humidity (b, e, h) (%) and wind speed ( $\text{ms}^{-1}$ ) (c, f, i) over Kharagpur during 26–27 April 2007, 08–09 May 2007 and 19–20 May 2007 with observations

TD2 is depicted in Fig. 2d–f. Observations during the TD2 indicate that this event occurred between 0900 and 1000 UTC and is characterized by a sudden drop in AT by  $7.5^{\circ}\text{C}$  (from  $34$  to  $26.5^{\circ}\text{C}$ ), rise in relative humidity by  $28\%$  (from  $44$  to  $72\%$ ) and sharp increase of winds by  $5\text{ ms}^{-1}$  (from  $1.5$  to  $6.5\text{ m s}^{-1}$ ). The MYJ and BouLac schemes could reasonably simulate the temperature drop of  $9^{\circ}\text{C}$  but with a 1-h time lag and YSU and ACM2 schemes show temperature drop of around  $5^{\circ}\text{C}$  but with a 2-h lag (Fig. 2d). Similarly the sharp rise in RH is reasonably captured by both MYJ and BouLac schemes, but with an overestimation by  $\sim 20\%$  and with a time lag of about an hour. MYJ and BouLac schemes show a sharp rise from around  $56$ – $91\%$  (rise of  $35\%$ ) between 1000 UTC to 1100 UTC. YSU and ACM2 schemes capture the sharp rise from around  $60$  to  $80\%$  (rise of  $20\%$ ) between 1100 UTC to 1200 UTC (2 h lag) (Fig. 2e). While observations reveal occurrence of strong winds ( $6.2\text{ ms}^{-1}$ ) at 1000 UTC (Fig. 2f), both MYJ and BouLac schemes show the peak winds of about  $9.5\text{ ms}^{-1}$  at 1100 UTC with a one hour lag. The sharp strengthening of surface

winds could be reasonably simulated by MYJ and BouLac schemes though with some overestimation, YSU scheme show the peak winds of about  $6\text{ ms}^{-1}$  at 1200 UTC with a 2-h lag and ACM2 scheme could not capture the sharp rise during event time.

#### 4.1.1.3 Variation of the Surface Meteorological Variables During TD3

The evolution of observed and simulated surface meteorological variables for the TD3 is presented in Fig. 2g–i. For this case the initial differences between first guess and observations in all the variables are negligible. Obviously the model outputs have close comparison with observations though with few differences due to application of different PBL schemes. Accordingly, all simulations overestimated the daytime air temperature and humidity, though with some differences. Compared to the first two events TD3 is relatively less intensive characterized by a small rise in humidity ( $\sim 25\%$ ) and fall in air temperature ( $\sim 5^{\circ}\text{C}$ ) between 1100 and 1200 UTC. Simulations indicate that both MYJ and BouLac simulated the fall in temperature and rise in humidity associated with the storm and in the case

of YSU and ACM2 schemes with a 2-h lag (Fig. 2g, h). The MYJ also picked up the sharp rise of winds during the storm while the other YSU with a 1-h lag to simulate the variation of winds associated with the convective event (Fig. 2i). Based on the qualitative results, one can observe that for most variables in the PBL the MYJ followed by BouLac schemes better simulated during the storm events.

**4.1.1.4 Validation of Model Simulations of Surface Layer Friction Velocity and Sensible Heat Flux During TD1** We validated the simulations of friction velocity ( $u_*$ ) and sensible heat flux ( $Q_H$ ) with the computed fluxes using eddy-correlation technique (BUSINGER *et al.* 1971) from fast response sonic anemometer at Kharagpur. The fast response data are first subjected to extensive quality checks following the procedures used in various earlier studies (FOKEN and WICHURA 1996; VISWANADHAM *et al.* 1997; ROTH *et al.* 2006; SATYANARAYANA *et al.* 2014). The model simulations of  $u_*$  and  $Q_H$  obtained from different PBL schemes along with the observations for TD1 are depicted in Fig. 3. In comparison with the available observations, it is noticed that all the PBL schemes under-predicted the  $u_*$  few hours prior to the occurrence of thunderstorm (Fig. 3a) and afterwards the magnitudes are close in the range of simulations. From Fig. 3b one can see that all the PBL schemes have reasonably simulated the  $Q_H$  in comparison with the observations. A sharp rise and sudden fall of  $Q_H$

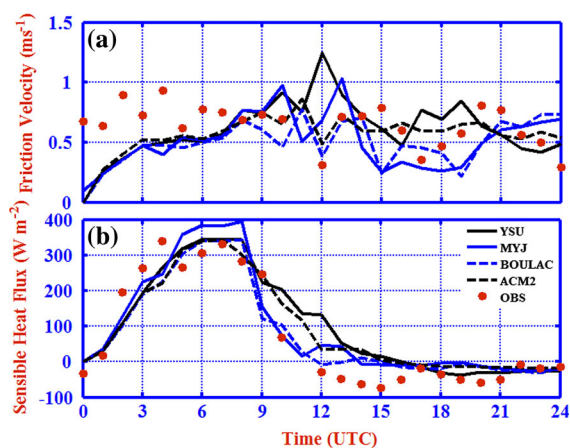


Figure 3

Validation of model simulations of **a** friction velocity ( $\text{ms}^{-1}$ ) and **b** sensible heat flux ( $\text{Wm}^{-2}$ ) over Kharagpur during 26 April 2007, 0000 UTC to 27 April 2007, 0000 UTC with observations

found in the observations and simulations during the thunderstorm events corroborate with the reported works of TYAGI *et al.* (2012, 2013b). The MYJ and BouLac schemes could capture this signature of the convection. Based on validation exercises with the observed fluxes, we notice that MYJ followed by BouLac schemes have better performed in simulating the  $u_*$  and  $Q_H$  during TD1 event compared to other PBL schemes.

#### 4.2. Vertical Profiles of Dynamical and Thermo-Dynamical Parameters

Limited vertical observations are available for the thunderstorm analysis in the study region. The radiosonde ascent is not available for the thunderstorm event TD1 and the available DigiCORA radiosonde ascents during TD2 and TD3 are used to analyse the vertical model structure for storm events. The model simulations of vertical profiles of wind speed, wind direction, RH and equivalent potential temperature ( $\theta_e$ ) using different PBL schemes along with the available upper air observations obtained from high-resolution radiosonde ascents at 0600 UTC and 1200 UTC for 08 May 2007 (TD2) and 19 May 2007 (TD3) are presented in Figs. 4 and 5, respectively. The equivalent potential temperature profiles show a neutral layer up to 1500 m above ground level (AGL), a deep unstable layer from 1.5 to 4.8 km and stable layer from 4.8 km to 10 km AGL at 0600 UTC. All schemes similarly simulated these features in good agreement with observations except for an overestimation of temperature in the lower atmosphere (below 1.5 km). The profiles just after the passage of thunderstorm (Fig. 4h) show significant modifications in the temperature structure of PBL. The vertical profiles of  $\theta_e$  reveals the presence of a shallow unstable mixed layer ( $\sim 300$  m deep) adjacent to the ground, thereupon an inversion layer up to 1 km and above that a well mixed PBL up to 5 km and stable layer form 5 km to up to 10 km AGL at 1200 UTC. This shows multiple regions of PBL mixing during the storm and these characteristics are well simulated by BouLac followed by MYJ schemes, the variations in temperature during the storm. The profiles of humidity show that the noon time humidity distribution of the vertical humidity



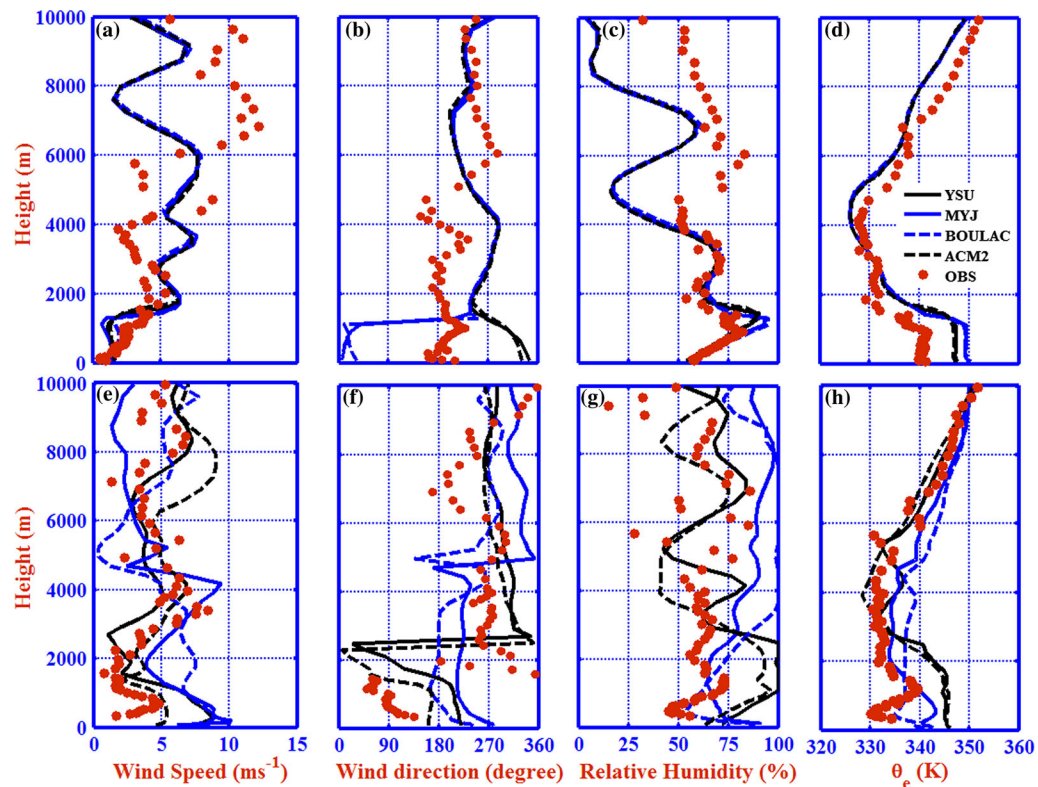


Figure 4

Validation of model-simulated profiles of **a, e** zonal wind ( $\text{ms}^{-1}$ ); **b, f** meridional wind ( $\text{ms}^{-1}$ ); **c, g** relative humidity (%); **d, h** equivalent potential temperature ( $\theta_e$ ) (K) with radiosonde observations over Kharagpur on 08 May 2007 at 0600 UTC and 12 UTC with observations

distribution within PBL is well simulated by all the schemes. At Kharagpur winds from the southeast to southwest quadrants indicate onshore winds from the BoB, while northerly and northwesterly winds are of land mass origin. The pre-storm winds (Fig. 4b) at the lower levels (below 3 km AGL) show onshore winds which bring large humidity to the station leading to moist convection in the daytime under strong heating. The humidity profiles also show high humidity (Fig. 4c) associated with the southerly winds. While all PBL schemes similarly simulated the wind speed and direction in PBL at 0600 UTC, ACM2 reasonably simulated the wind variations during the storm time. Similarly all PBL features are seen in the vertical profiles (Fig. 5) for the TD3 event also, except stronger winds and higher humidity are noticed in post-storm environment.

The  $\theta_e$  profile shows a neutral layer up to 1.8 km AGL, a deep unstable layer from 1.8 to 3.8 km at 0600 UTC (Fig. 5d). Upon comparing with the

available observations, it is seen that all employed PBL schemes have simulated these meteorological parameters reasonable well, except for an overestimation of temperature in the lower atmosphere (below 1.8 km). Northeasterly winds that are noticed in the lower atmosphere up to 300 m are seen in the observations and then the winds changed to south westerly up 0.3 to 1.8 km. Subsequently, the winds became mostly northwesterly up 1.8–6 km at 0600 UTC (Fig. 5b). After the passage of the thunderstorm, southwesterly winds are noticed in lower atmosphere up to 1.5 km and then winds changed to north–northeasterly up 1.5–2.7 km and after those winds shifted to north–northwesterly 2.7–4.1 km at 1200 UTC (Fig. 5f). In general, one can see that all the schemes are reasonably close with the observations, but on close examination, the MYJ and BouLac schemes have represented the wind speed and wind direction better than the other schemes. All the schemes simulated RH profiles before and after the

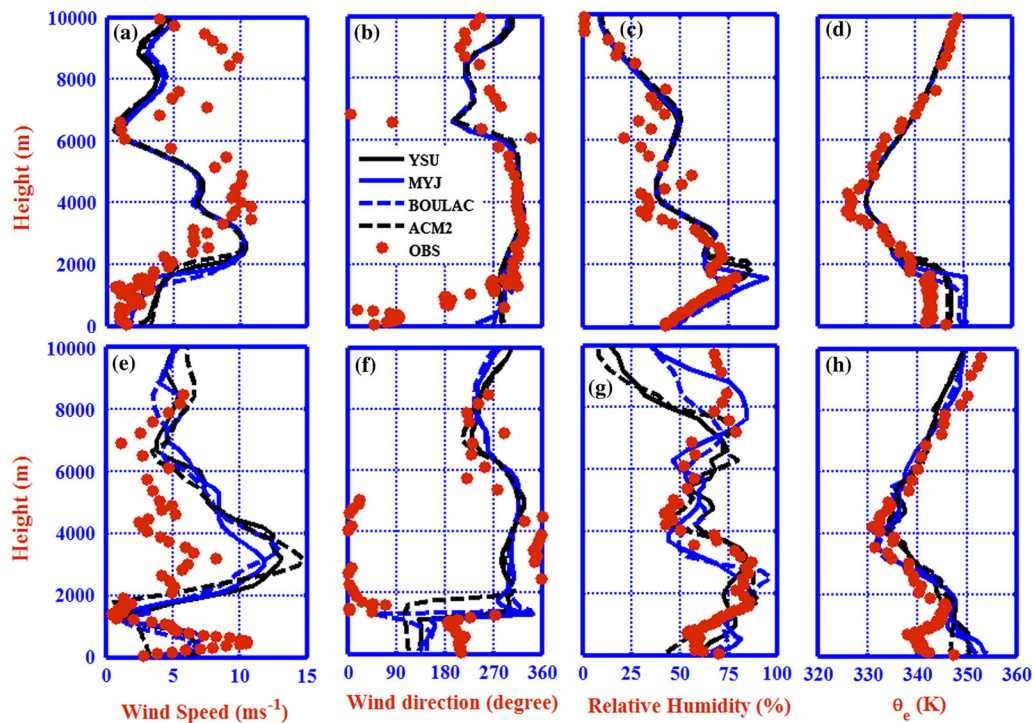


Figure 5

Validation of model-simulated profiles of **a, e** zonal wind ( $\text{ms}^{-1}$ ); **b, f** meridional wind ( $\text{ms}^{-1}$ ); **c, g** relative humidity (%); **d, h** equivalent potential temperature ( $\theta_e$ ) (K) with radiosonde observations over Kharagpur on 19 May 2007 at 0600 UTC and 12 UTC with observations

storm are found to be very close to the observations as shown in Fig. 5c, g. Upon comparing with the observations, simulated RH profiles of all the schemes are very close to the observations up to 2 km.

Based on the results, qualitatively, one can observe that the MYJ followed by BouLac schemes has reasonably simulated the PBL vertical thermodynamical structure before and after the storm events.

#### 4.3. DWR Imageries

The maximum reflectivity from simulations is analysed for each of the storm cases and compared with available DWR reflectivity imagery. Here the reflectivity comparisons for TD1 (26 April 2007) are presented. Reflectivity (dBZ) of the convective cells is considered in identifying the location and movement of thunderstorms over the study region following PRADAN *et al.* (2012). On these days, there were thunderstorm cells over Kharagpur and nearby regions. We have noticed that the convective cells are

propagating in a northeasterly direction, prior to reaching Kharagpur. Figure 6a–d depicts the movement of convective cells till they dissipated/moved away from the study region. Figure 6a shows that a well developed thunderstorm cell formed over Kharagpur site with a reflectivity value of  $\sim 52$  dBZ and with a vertical extent of  $\sim 14$  km. By 1300 UTC the convective cells have completely passed away from Kharagpur region leaving behind the stratiform clouds.

#### 4.4. Model-Simulated Reflectivity and Surface Pressure Variations During TD1

Spatial variation of the model-simulated radar reflectivity (dBZ) and surface level pressure (hPa) over the Kharagpur region from the innermost domain (d3 with 3 km resolution) with YSU, MYJ, BouLac and ACM2 schemes during 1000, 1100, 1200 and 1300 UTC for TD1 (various stages of thunderstorm activity) are depicted in Figs. 7, 8, 9 and 10, respectively.

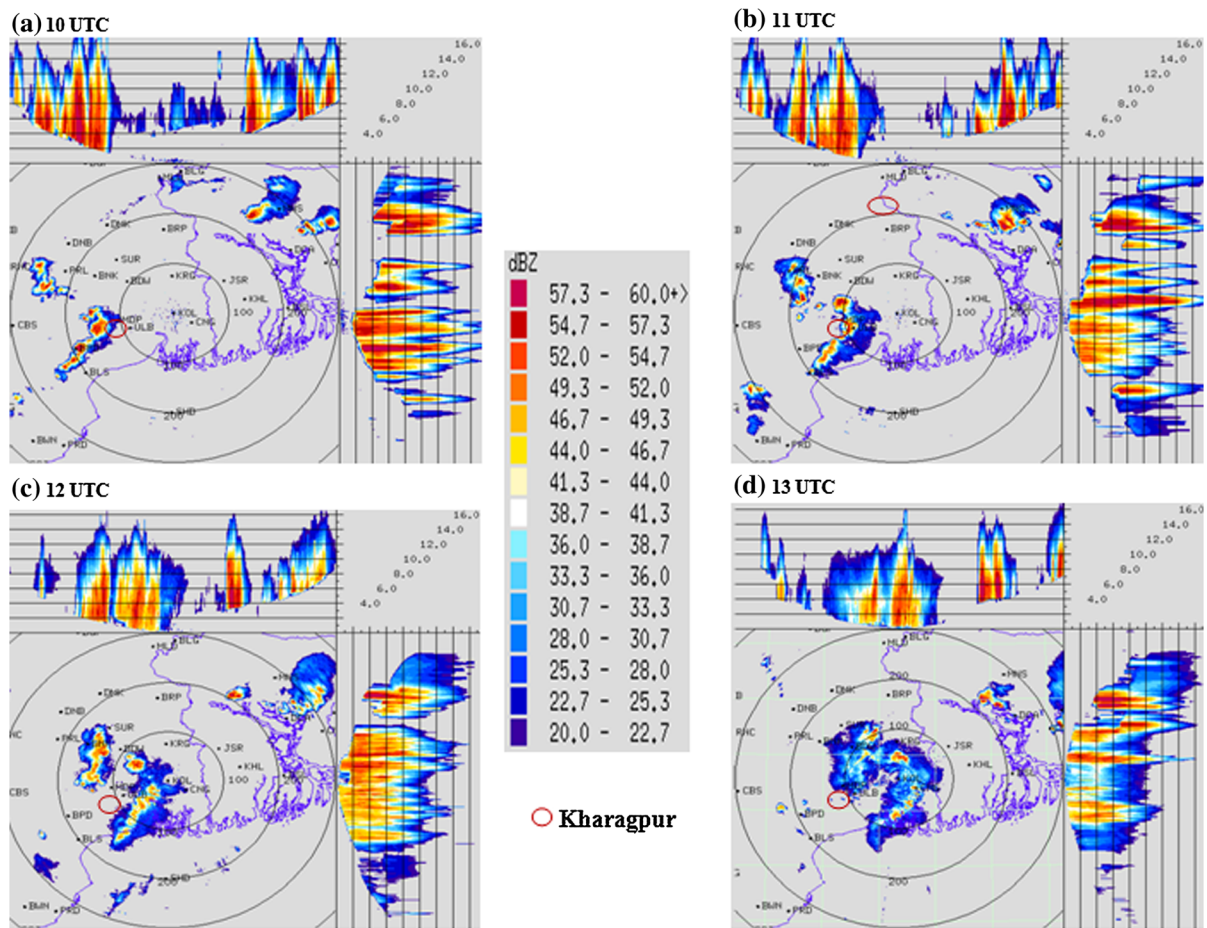


Figure 6  
Kolkata DWR radar reflectivity (dBZ) imageries during 26 April 2007: **a** 10 UTC, **b** 11 UTC, **c** 12 UTC and **d** 13 UTC

Significant variations in surface pressure related to the presence of convective intensity (in terms of reflectivity, dBZ) are noticed in the region of 21.7N–23.6N and 86.5E–88.0E (mostly covering Kharagpur and adjoining regions) during these times. The reflectivity patterns simulated with the YSU and ACM2 schemes indicate the storm was located about 50 km northwest of the observation site at 1000 UTC and dissipation after 1200 UTC (Figs. 7, 10). The reflectivity pattern after the passage of the convective cell over the observation site is well simulated with MYJ followed by BouLac schemes. Figures 8a and 9a reveal a hook-shaped ‘convective cloud band’ (connecting the higher reflectivity) towards the northeastern part of the domain. Preceding the convective line, a low

pressure region of 1004–1005 hPa, which can be recognized as wake-low can be identified in the case of MYJ and BouLac. Adjacent to this wake-low, relatively a high-pressure region (1005–1009 hPa) is noticed over the convective line. This high-pressure region can be identified as ‘meso-high’ associated with the convective storm. A region with fall in pressure ( $\sim 1004$  hPa) adjacent to meso-high is observed and can be denoted as ‘pre-squall low’.

Interestingly, the regions of wake-low, meso-high and pre-squall low (for more detailed explanation, refer TYAGI *et al.* 2012; DAWN and MANDAL 2014) are correlated well with model-simulated updrafts/down-drafts as shown in Fig. 12b, c. Similar kinds of features are seen in the remaining hours also. These

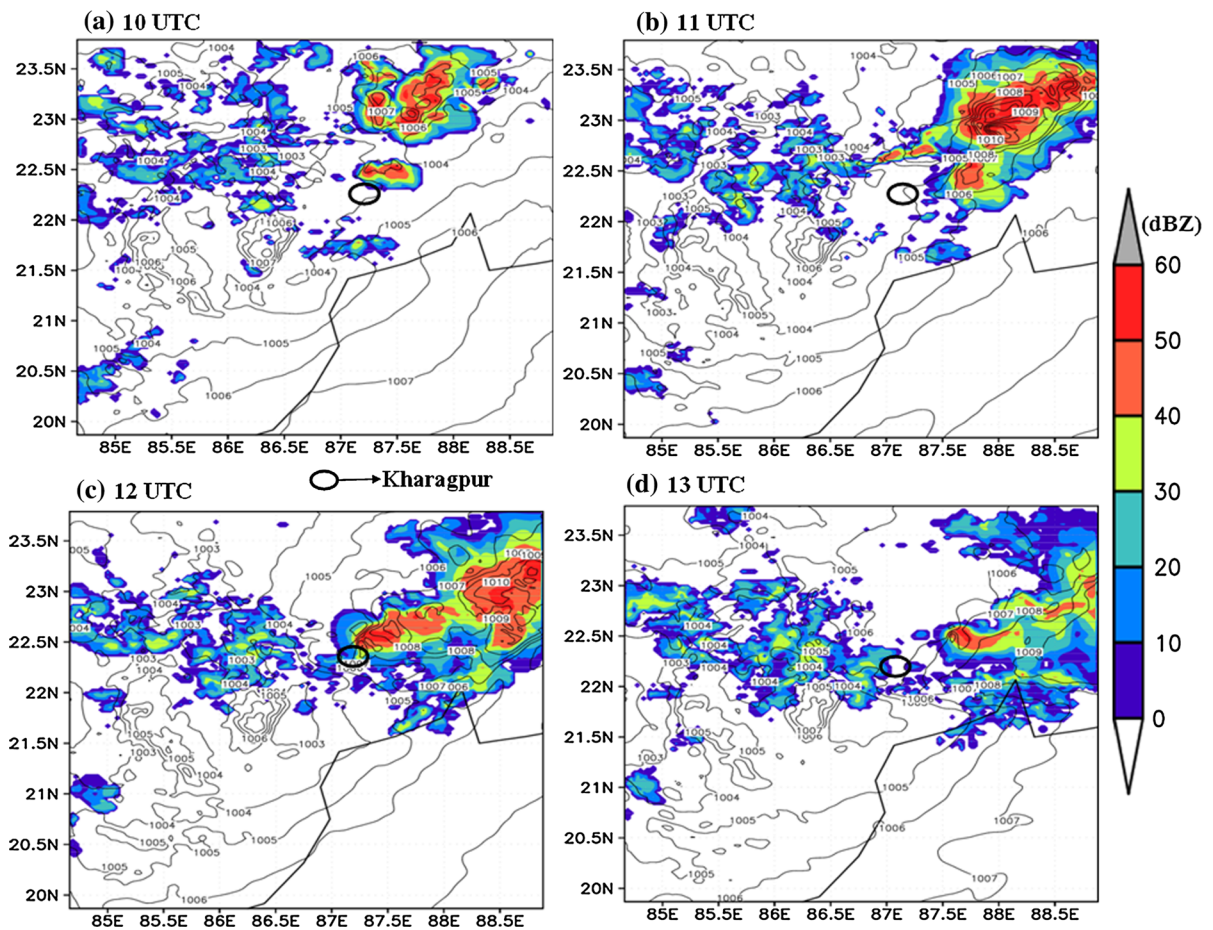


Figure 7

Model-simulated (innermost domain d3 with 3 km resolution) radar reflectivity (dBZ) and surface pressure variations (hPa) during 26 April 2007: **a** 10 UTC, **b** 11 UTC, **c** 12 UTC and **d** 13 UTC with YSU scheme

typical surface pressure variations serve to identify the signatures of the occurrence of thunderstorm activity (DALAL *et al.* 2012; TYAGI *et al.* 2012; SRIKANTH *et al.* 2014; SATYANARAYANA *et al.* 2014). The reflectivity and pressure patterns clearly show that MYJ followed by BouLac schemes alone could simulate the typical features associated with the thunderstorm. Both MYJ and BouLac clearly show the main squall to be located at about 30–50 km northeast of Kharagpur and the extension of small meso-vortices covered Kharagpur between 1000 and 1100 UTC and that the whole storm moved away from Kharagpur station by 1300 UTC towards northeast. This is also supported by the time series of DWR reflectivity pictures. Overall MYJ followed

by BouLac schemes well simulated the intensity, coverage and movement of the convective storm in good agreement with DWR data. Comparison of reflectivity outputs clearly shows that MYJ simulated the timing and intensity of the storm in good agreement with as seen in the observed DWR imageries (Fig. 6).

#### 4.5. Validation of Model-Simulated Reflectivity for TD1 over Kharagpur

Model-simulated reflectivity (dBZ) over Kharagpur during 26 April 2007, 0000 UTC to 27 April 2007, 0000 UTC are shown in Fig. 11a YSU, b MYJ, c BouLac and d ACM2. During TD1 period, a

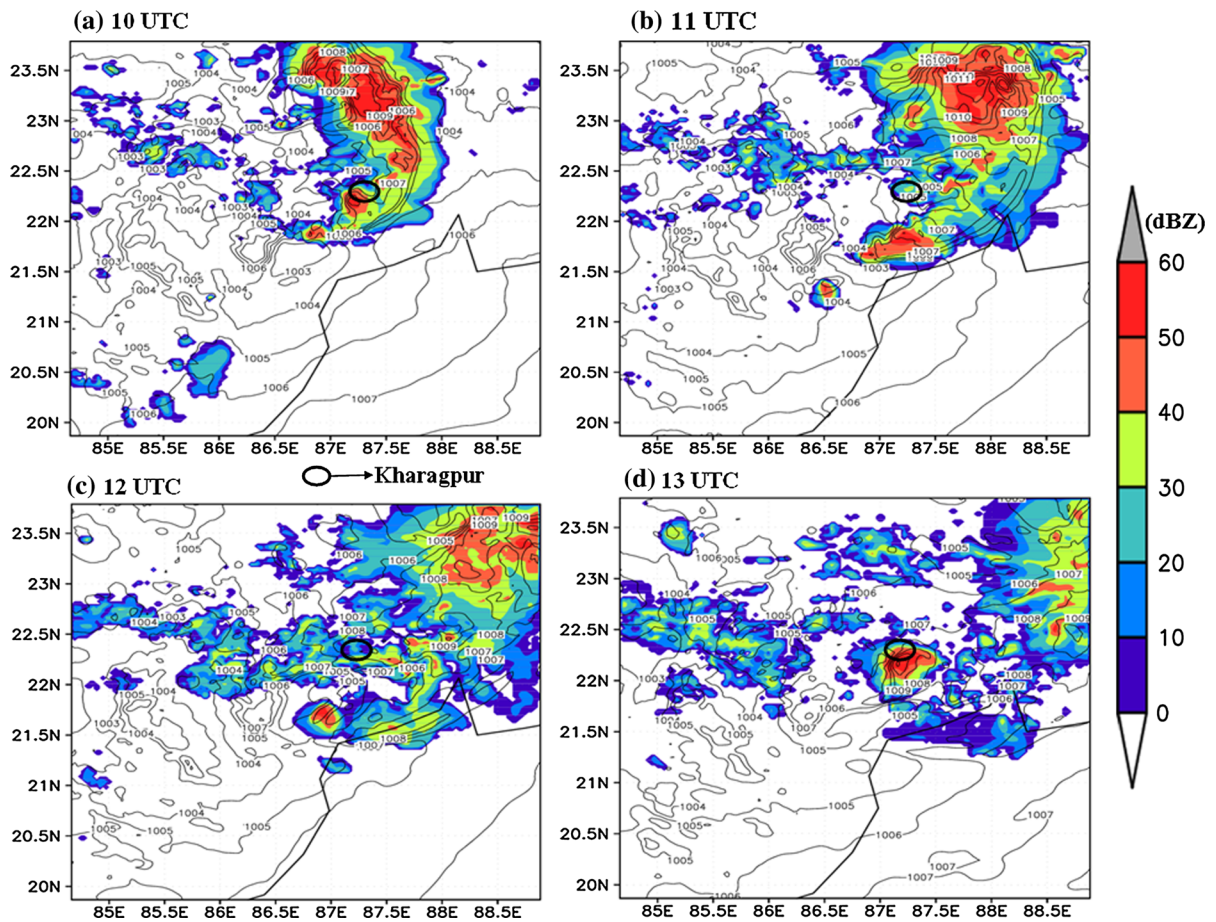


Figure 8

Model-simulated (innermost domain d3 with 3 km resolution) radar reflectivity (dBZ) and surface pressure variations (hPa) during 26 April 2007: **a** 10 UTC, **b** 11 UTC, **c** 12 UTC and **d** 13 UTC with MYJ scheme

thunderstorm activity is observed during 1000–1220 UTC over Kharagpur site with a completely developed convective cell is noticed at 1026 UTC. The maximum reflectivity for this event is noted to be  $\sim 52$  dBZ extending to  $\sim 16$  km (Fig. 6). The model simulation with MYJ scheme shows reflectivity in the range 40–50 dBZ around 9.30–12.30 UTC with vertical extent up to 10 km. Interestingly, BouLac scheme also simulated a vertical reflectivity around 1200 UTC, but with a relatively lesser intensity ( $\sim 25$  dBZ). The other two schemes YSU and ACM2 failed to capture this feature. The analysis concludes that reflectivity during the event (1000–1200 UTC) is well simulated by MYJ followed by BouLac in terms of both the intensity and time of occurrence.

#### 4.6. Model-Simulated Time–Height Cross Section of Pressure Vertical Velocity During TDI

MAY and RAJOPADHYAYA (1999) stated that the better prediction of convection depends on the accurate simulation of magnitude of vertical motion which is primarily responsible for the initiation of convection. In this section, the model simulations of convective updrafts and downdrafts quantified in terms of pressure vertical velocity parameter (LITTA *et al.* 2012b), intensity, vertical extent and time of occurrence are presented. An event of thunderstorm can be identified from co-existence of a strong updraft and downdraft without mutual interference (ASNANI 2005).

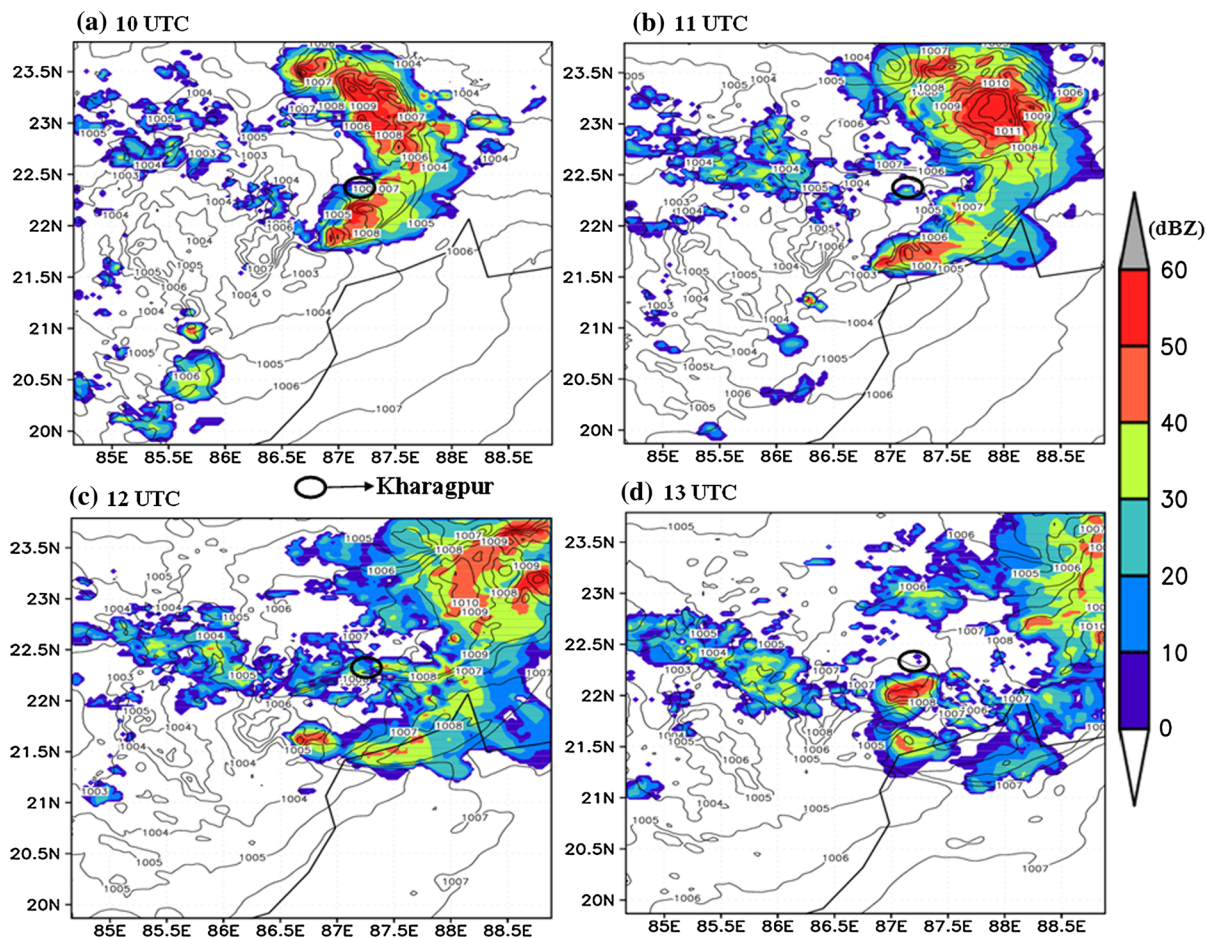


Figure 9

Model-simulated (innermost domain d3 with 3 km resolution) radar reflectivity (dBZ) and surface pressure variations (hPa) during 26 April 2007: a 10 UTC, b 11 UTC, c 12 UTC and d 13 UTC with BouLac scheme

Similar features were discussed described by various other researchers in different thunderstorm studies (RAJEEVAN *et al.* 2010; LATHA and MURTHY 2011; SRIKANTH *et al.* 2014; SATYANARAYANA *et al.* 2014). Model-simulated pressure vertical velocities ( $\text{Pa s}^{-1}$ ) over Kharagpur during 26 April 2007 0000 UTC to 27 April 2007 0000 UTC are presented in Fig. 12a YSU, b MYJ, c BouLac, d ACM2, respectively. On 26 April 2007 (TD1) cores of deep convective updrafts and downdrafts are well simulated with MYJ followed by BouLac than the YSU and ACM2 schemes. Large vertical velocities ( $>1.5 \text{ Pa s}^{-1}$ ) are simulated with MYJ and BouLac around 1100–1200 UTC. The vertical motions are propagated up to 200 hPa in MYJ,

BouLac and YSU and up to 300 hPa in ACM2. The distribution of vertical motion indicates the convective activity started around 0900 UTC and extended up to 1300 UTC in the case of MYJ, BouLac lasted from 1100 to 1200 UTC in YSU and ACM2 schemes, respectively. Similar signatures of these drafts are reported from the analysis of wind profiler data analysis during thunderstorm events over Gadanki MST radar facility (RAJEEVAN *et al.* 2010; SRIKANTH *et al.* 2014; SATYANARAYANA *et al.* 2014). Based on the intensity and time of occurrence of the event, it is noted that the MYJ brings out a better distribution of convective motions during the thunderstorm event than the PBL schemes (YSU and ACM2).

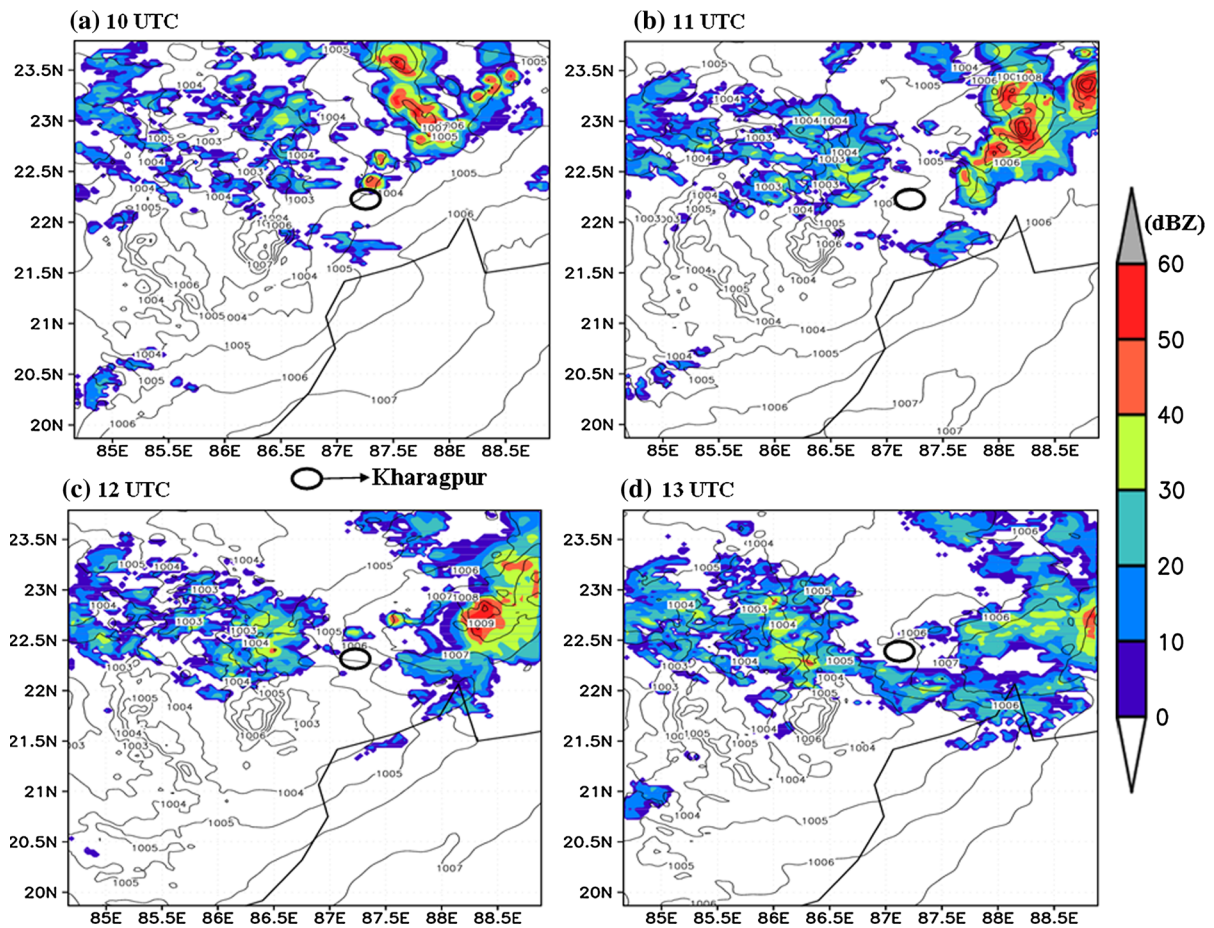


Figure 10

Model-simulated (innermost domain d3 with 3 km resolution) radar reflectivity (dBZ) and surface pressure variations (hPa) during 26 April 2007: **a** 10 UTC, **b** 11 UTC, **c** 12 UTC and **d** 13 UTC with ACM2 scheme

#### 4.7. Vertical Cross Section of Flow Field Parameters During TD1

The time–height section of model-simulated surface level wind vectors and potential temperature (in shades) at Kharagpur location are analysed for the high-resolution innermost domain (d03) (Fig. 13) for TD1. The pre-storm atmosphere is warm over a deeper atmospheric layer for the MYJ and BouLac schemes as compared to other schemes. In all the simulations, the pre-storm winds are from southwest, which changed gradually to southeast. The timing and vertical extent of these southeasterly winds and potential temperature are differently simulated by different experiments. The MYJ and BouLac schemes the transition of winds from southwesterly to southeasterly flow around 0900 UTC indicating the

onset of the storm as per the observations. Both winds and temperature in the PBL indicate the MYJ and BouLac well simulated the progression of the storm compared to the other two schemes.

#### 4.8. Validation of Model-Simulated Rainfall for TD1

Spatial distributions of simulated 24-h cumulative rainfall over Kharagpur region from the innermost domain with different PBL schemes along with corresponding TRMM rainfall data for 26 April 2007 (TD1) are presented in Fig. 14. Rainfall prediction is one of the most difficult parameters in numerical weather prediction (NWP) in spite of the fact that the skill of numerical models has been improving during the past several decades (WANG and

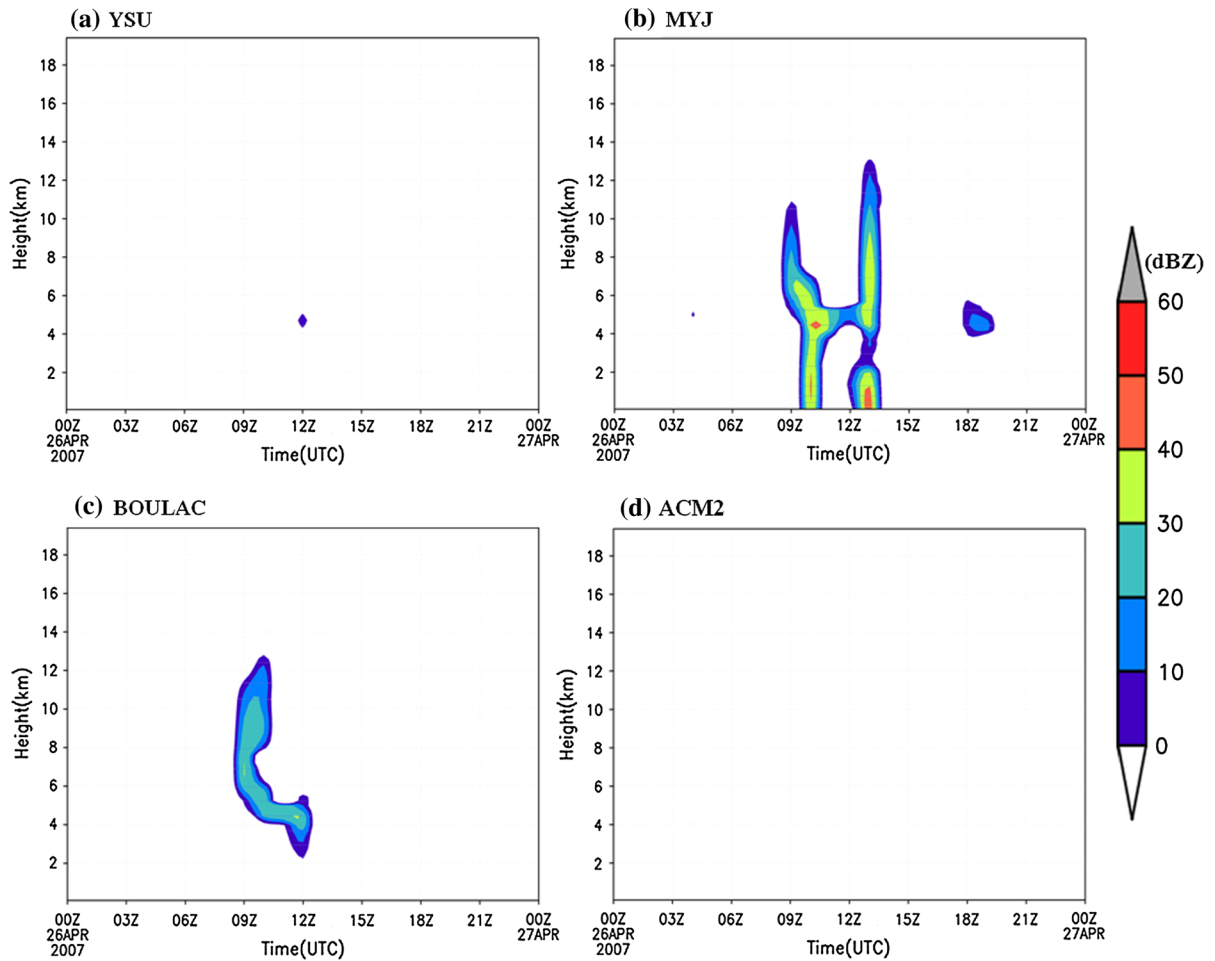


Figure 11

Time–height cross section of model-simulated radar reflectivity ( $dBZ$ ) over Kharagpur during 26 April 2007, 0000 UTC to 27 April 2007, 0000 UTC with **a** YSU, **b** MYJ, **c** BouLac and **d** ACM2

SEAMAN 1997). In all the simulations, rainfall is overestimated and the peak rainfall is located towards the northwest of Kharagpur in agreement with the major cluster of the storm. While the TRMM data show a comma cloud band structure, the rain bands from all the simulations are spread from southwest to northeast, i.e. more in the West Bengal region as compared to the TRMM rainfall. Overall the location and distribution of rainfall associated the storm are well simulated by both BouLac and MYJ schemes.

#### 4.9. Thermo-Dynamical Stability Indices

Convection in the atmosphere strongly depends on its thermodynamic stability characteristics.

Various stability indices namely Convective Available Potential Energy (CAPE), Humidity Index (HI), K Index (KI), Total Totals Index (TTI) obtained from ARW model simulations with different PBL schemes on TD1, TD2 and TD3 for 0900 UTC, 1000 UTC, 1100 UTC and 1200 UTC (average of value during these hours) over Kharagpur are analysed. Limited radiosonde observations are available for the thunderstorm analysis in the study region. We compared over model-derived thermodynamic indices values with that of proposed threshold values of various thermodynamic indices by TYAGI *et al.* (2011) based on large number of thunderstorm cases which are to forecast the occurrence of thunderstorm events over Kolkata. In the subsequent studies, TYAGI *et al.*



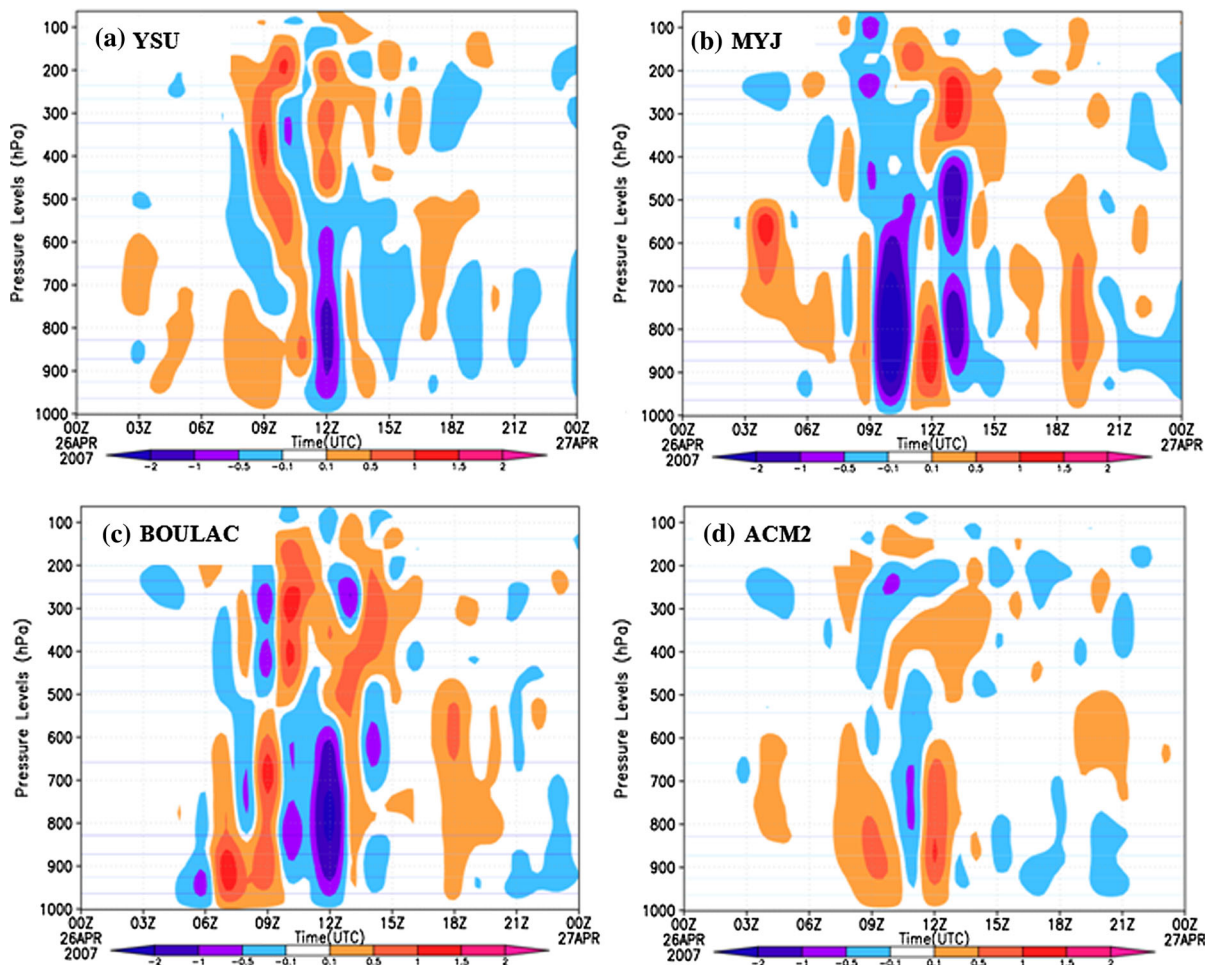


Figure 12

Time–height cross section of model-simulated pressure vertical velocity ( $\text{Pa s}^{-1}$ ) over Kharagpur during 26 April 2007, 0000 UTC to 27 April 2007, 0000 UTC with **a** YSU, **b** MYJ, **c** BouLac and **d** ACM2

(2013b) reported that these threshold values hold good for Kharagpur as well. The CAPE represents the amount of buoyant energy available to accelerate a parcel vertically. The HI gives a combination of the measure of humidity saturation in the atmospheric layer 850–500 hPa which is very important in the thunderstorm generation and intensification. The 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. The TTI is useful to assess the storm strength but fails to consider the latent instability below 850 hPa and it is a combination dry bulb temperature difference between 850 and 500 hPa and difference between dew point temperature at 850 and

dry bulb temperature at 500 hPa. The threshold values of the indices:  $\text{CAPE} > 1000 \text{ J kg}^{-1}$ ,  $\text{HI} \leq 45$ ,  $\text{KI} (\text{°C}) \geq 24$  and  $\text{TTI} \geq 46$  suggested by TYAGI *et al.* (2011) for the occurrence of severe thunderstorms in the study region are used in the present analysis. The model time evolution of CAPE using different PBL parameterizations schemes for the thunderstorm events on TD1, respectively (Fig. 15). As already mentioned, the thunderstorm occurred at around 1000–1200 UTC on TD1. A progressive rise in CAPE before the storms and an abrupt fall after the storms are well simulated with MYJ and BouLac schemes. These time variations of CAPE indicate generation of instability in the model is highly influenced by the turbulence diffusion and

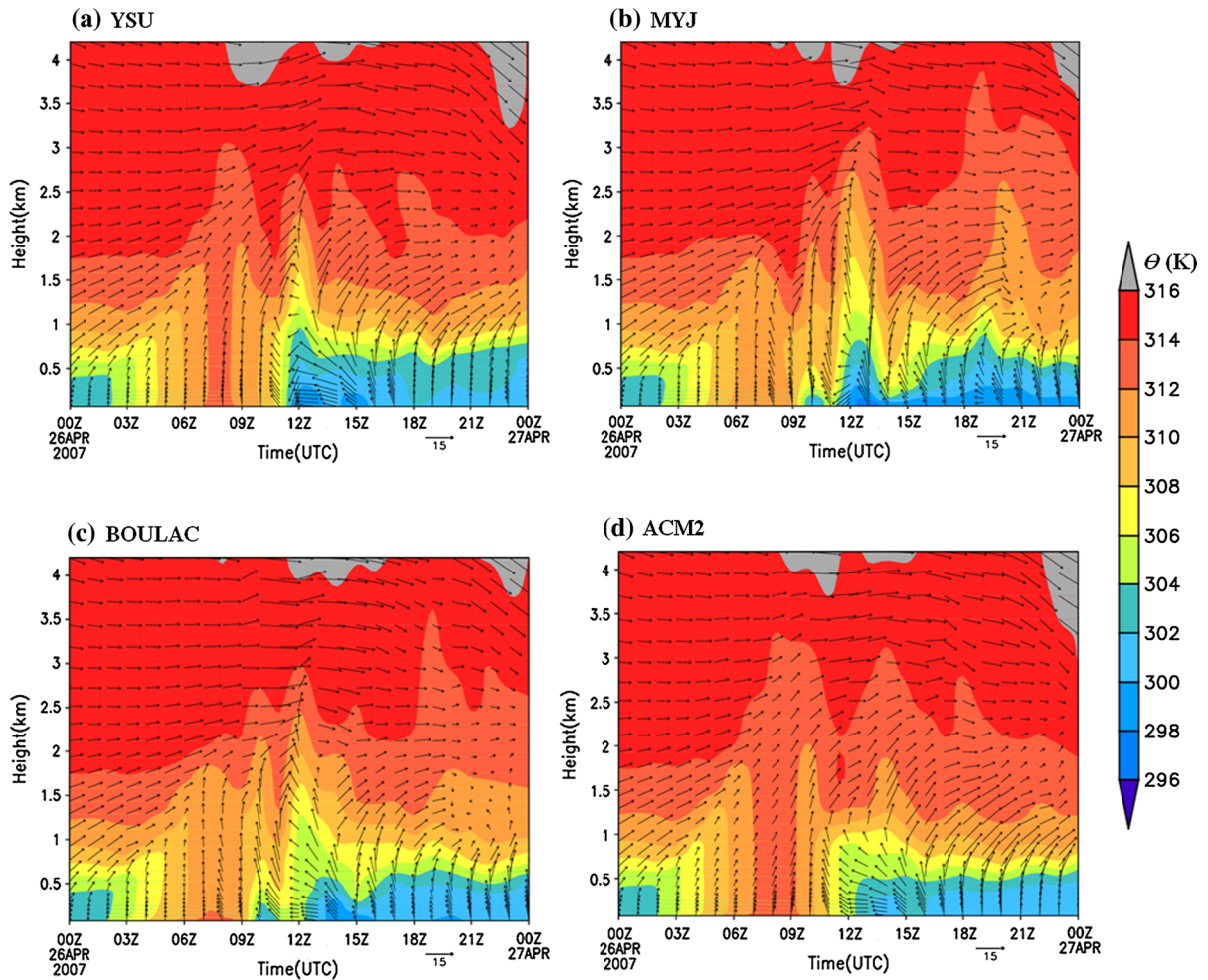


Figure 13

Time–height cross section of model-simulated surface level wind vectors and potential temperature over Kharagpur during 26 April 2007, 0000 UTC to 27 April 2007, 0000 UTC with **a** YSU, **b** MYJ, **c** BouLac and **d** ACM2

that the local-TKE closures better represent the development of convection compare to non-local closures. The values of simulated thermo-dynamical parameters (CAPE, HI, KI and TTI) obtained using different PBL schemes with the TYAGI *et al.* (2011) proposed threshold values presented in Table 2. Though there are differences in the values of thermo-dynamical parameters simulated with different PBL schemes, it is noted that during the study period most of the above parameters are well simulated. For CAPE on most days all the PBL schemes simulated the threshold minimum except on

TD3 where YSU and ACM2 simulated very low CAPE (<950). Similarly, the TTI is simulated to be below the threshold minimum of 46 by all the PBL schemes on TD2 and TD3. Leaving these few exceptional cases a general comparison with threshold values for all the thunderstorm events shows that MYJ-simulated values for CAPE, HI, KI and TTI followed by BouLac, YSU and ACM2 schemes. This indicates that the MYJ followed by BouLac schemes quite reasonably captured the instability of the atmosphere during the thunderstorms on the above events.

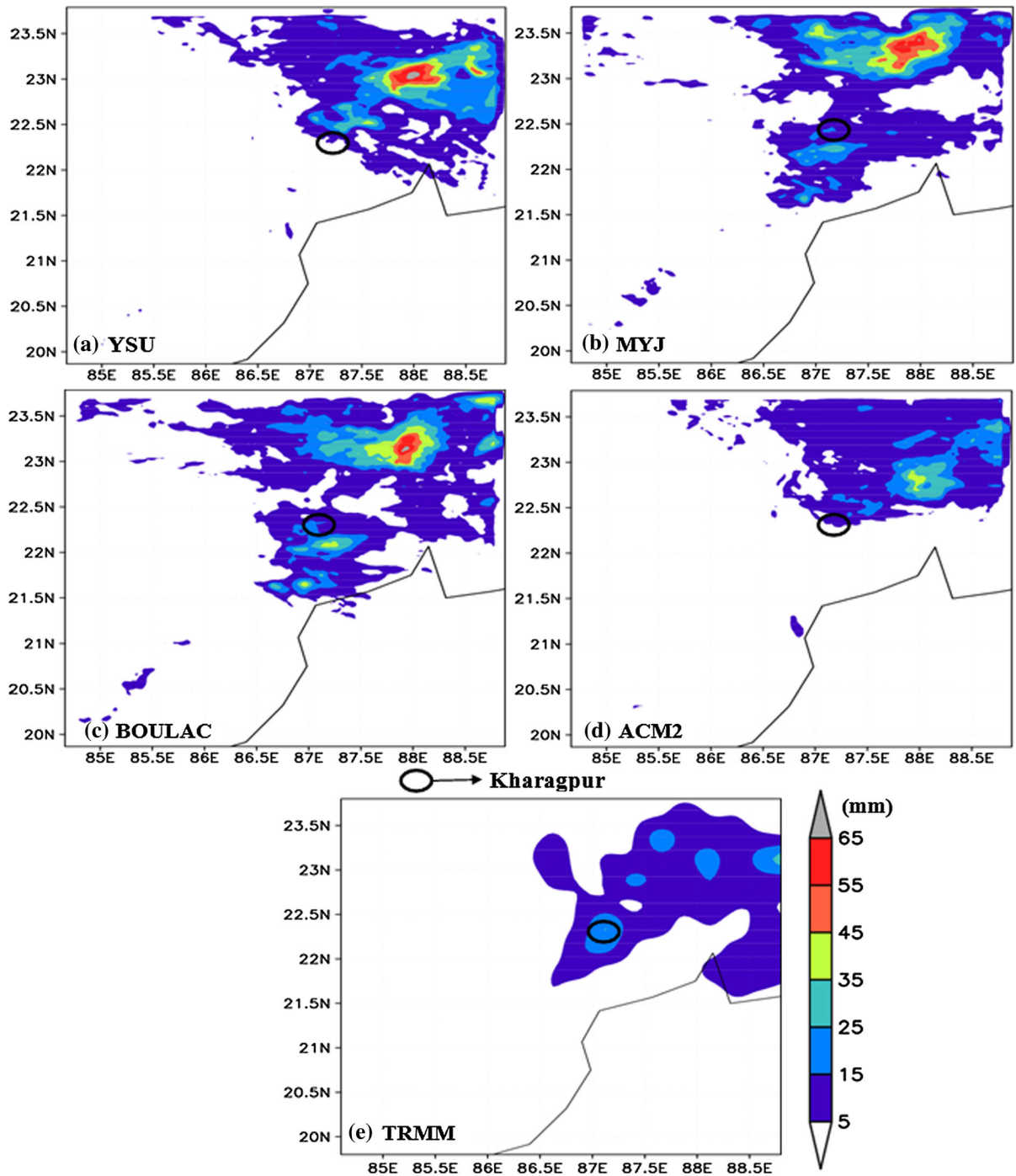


Figure 14

Model-simulated 24-h accumulated rainfall for innermost domain (d03) during 26 April 2007, 0000 UTC to 27 April 2007, 0000 UTC with a YSU, b MYJ, c BouLac, d ACM2 and (e) TRMM

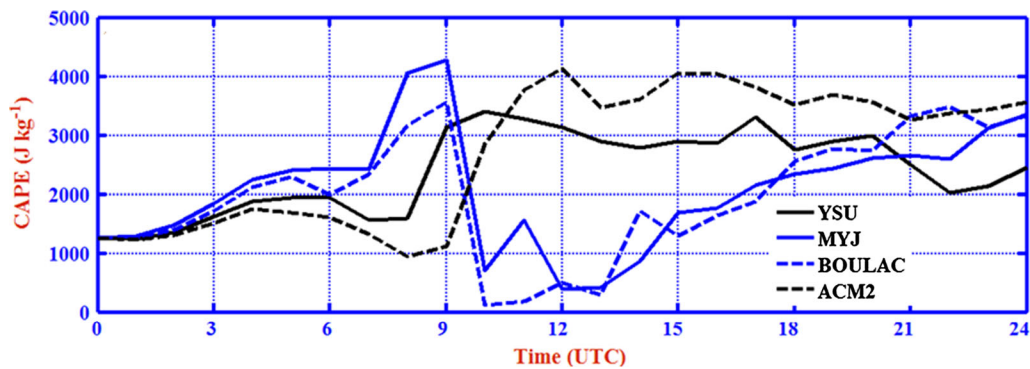


Figure 15

Model-simulated diurnal variation of convective available potential energy for thunderstorm events during **a** 26 April 2007, 0000 UTC to 27 April 2007, 0000 UTC; **b** 27 April 2007, 0000 UTC to 28 April 2007, 0000 UTC

Table 2

The inter-comparison of model-simulated stability indices with different PBL schemes average value between 0900 and 1200 UTC during 3 thunderstorm events over Kharagpur

Date	Stability indices	YSU	MYJ	BOULAC	ACM2	(TYAGI <i>et al.</i> 2011, threshold values)
26 April 2007 (TD1)	CAPE	3238.4	1733.6	1084.8	2966.9	$>1000 \text{ J kg}^{-1}$
	HI	17.2	21.7	21.9	19.1	$\leq 45$
	KI	40.5	35.1	34.5	41.4	$\geq 24 \text{ (}^\circ\text{C)}$
	TTI	53.0	49.2	48.6	51.8	$\geq 46$
08 May 2007 (TD2)	CAPE	1021.0	1203.7	996.5	839.9	$>1000 \text{ J kg}^{-1}$
	HI	19.7	16.6	14.7	19.2	$\leq 45$
	KI	33.2	36.4	37.1	35.2	$\geq 24 \text{ (}^\circ\text{C)}$
	TTI	44.1	44.2	43.9	45.3	$\geq 46$
19 May 2007 (TD3)	CAPE	969.8	1880.3	1488.8	706.5	$>1000 \text{ J kg}^{-1}$
	HI	14.8	22.4	18.9	15.2	$\leq 45$
	KI	38.8	34.4	36.0	39.6	$\geq 24 \text{ (}^\circ\text{C)}$
	TTI	43.7	44.1	44.3	44.3	$\geq 46$

#### 4.10. Accumulated Rainfall

In this section, the model with four different PBL schemes such as YSU-, MYJ-, BOULAC- and ACM2-simulated rainfall estimates are compared with surface rain gauge observations near the 50 m tower over Kharagpur. The model-simulated 24-h accumulated rainfall by four PBL schemes along with the rain gauge measurements for TD1, TD3 and TRMM satellite rainfall measurements for TD2 are shown in Fig. 16a–c, respectively. As the onsite rain gauge data are absent during TD2, the TRMM satellite data-derived rainfall data are used for the validation of model-derived rainfall. The model significantly underestimated the rainfall with YSU and ACM2 for TD1 over the study region. In general

it is noticed that observational comparisons in all three cases indicate the numerical experiment with MYJ simulated the rainfall in better agreement with observations than the other schemes.

#### 4.11. Statistical Analysis of Surface Meteorological Variables and Thermo-Dynamical Structure of the Atmosphere

A statistical analysis based on mean bias (MB), mean absolute error (MAE), root mean square error (RMSE) and correlation coefficient (CC) (DROULIA *et al.* 2008; WILKS 2011) between the simulated and observed surface meteorological variables such as AT, RH, and WS with 4 PBL schemes for the 3 TD

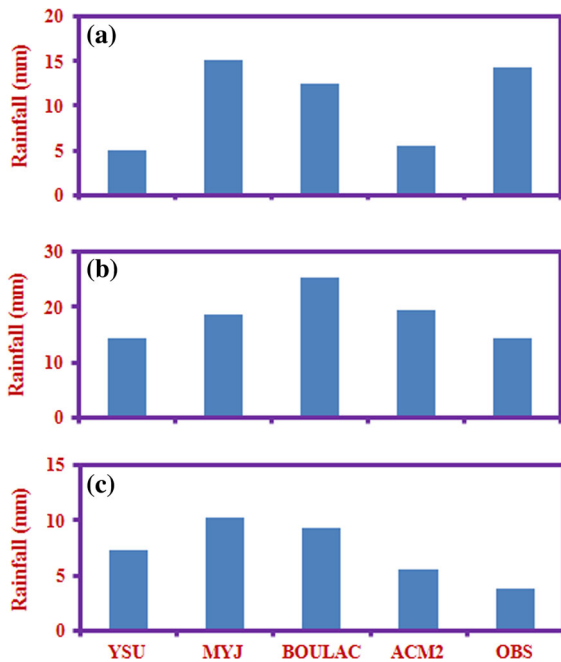


Figure 16

Validation of model simulations of accumulated rainfall with observed rainfall during **a** 26–27 April 2007, **b** 8–9 May 2007, **c** 19–20 May 2007 at Kharagpur with observations

cases are given in Table 3. The mean statistics for all the 3 days show that all schemes for TD cases give mostly warm mean bias (i.e. observation—model <0) in temperature, dry bias in humidity, higher momentum in the lower atmosphere relative to the observations and overestimation of surface winds. The MYJ scheme produced least error statistics followed by BouLac, YSU and ACM2 schemes for the simulation of various parameters in the PBL except wind speed. The warm and dry biases indicate generation of more convective turbulence with most schemes. The relatively lesser humidity errors obtained with MYJ scheme support the results of good thunderstorm simulations. A statistical analysis MB, MAE, RMSE and CC between the simulated and observed vertical profiles ascents at 0600 UTC and 1200 UTC for 08 May 2007 (TD2) and 19 May 2007 (TD3) of wind speed ( $\text{ms}^{-1}$ ), wind direction ( $^{\circ}$ ), relative humidity (%) and equivalent potential temperature ( $K$ ) with different PBL schemes are given in Table 4. All the PBL schemes reasonably captured the thermo-dynamical structure of the atmosphere.

The mean statistics show that all PBL schemes mostly show overestimation of strength of winds, shift in the wind direction, less cold bias in humidity expect ACM2 and warm mean bias (i.e. observation—model <0) in equivalent potential temperature.

In general, all the employed PBL schemes reasonably simulated the meteorological parameters such as wind speed, wind direction, relative humidity; overall statistical analysis reveals better performance of MYJ and BouLac schemes.

### 5. Summary and Conclusions

The main aim of the present study is to evaluate the performance of various PBL schemes of the mesoscale model ARW in simulating the major characteristics of a few pre-monsoon thunderstorm events over Kharagpur. For this purpose, model-simulated thermo-dynamical structure of the atmosphere, surface meteorological variables and rainfall are compared with the available observations during the study period over Kharagpur. Various features of thunderstorm activity such as sudden fall of air temperature, rise in relative humidity, variations in winds during the thunderstorm events are found to be reasonably captured by MYJ followed by BouLac schemes but with 1 h lag. The efficiency of turbulent mixing using the TKE local closures in led to a realistic representation of the development of instability of the pre-storm atmosphere and a better simulation of various thunderstorm environments on various events under study. The thermal structure, wind components and RH with height are well captured by the MYJ followed by BouLac schemes. It could capture the presence of neutral and convective instability in lower layers of the atmosphere during the pre-storm stages. Higher moisture content available in the atmosphere leading to moist convection and thunderstorm as seen in the observational reports are better represented in the model simulations with MYJ followed by BouLac schemes. These two schemes also captured the reflectivity, surface pressure patterns such as meso-high, wake-low, pre-squall low and the convective updrafts and downdrafts reasonably well. These schemes quite

Table 3

*Statistical analysis of simulated surface air temperature ( $^{\circ}\text{C}$ ), surface relative humidity (%) and surface wind speed ( $\text{m s}^{-1}$ ) with different PBL schemes*

Parameter	Errors	YSU	MYJ	BOULAC	ACM2
Air temperature ( $^{\circ}\text{C}$ )	MB	3.07	2.55	2.91	3.33
	MAE	3.08	2.78	3.09	3.33
	RMSE	3.56	3.23	3.51	3.96
	CC	0.88	0.89	0.87	0.85
Relative humidity (%)	MB	-6.84	-2.45	-5.08	-6.27
	MAE	9.57	8.84	8.42	11.03
	RMSE	11.89	10.69	11.34	14.10
	CC	0.86	0.87	0.85	0.83
Wind speed ( $\text{ms}^{-1}$ )	MB	1.10	1.55	0.86	0.90
	MAE	1.69	2.01	1.57	1.56
	RMSE	2.36	2.69	2.07	1.98
	CC	0.57	0.57	0.54	0.58

Table 4

*Statistical analysis-simulated vertical profiles of wind speed ( $\text{m s}^{-1}$ ), wind direction ( $^{\circ}$ ), relative humidity (%) and equivalent potential temperature (K) with different PBL schemes*

Parameter	Errors	YSU	MYJ	BOULAC	ACM2
Wind speed ( $\text{m s}^{-1}$ )	MB	0.56	0.60	0.57	0.51
	MAE	2.66	2.64	2.80	2.61
	RMSE	3.37	3.26	3.42	3.35
	CC	0.31	0.33	0.28	0.29
Wind direction ( $^{\circ}$ )	MB	27.51	-6.23	-7.40	21.59
	MAE	69.94	63.07	64.41	72.61
	RMSE	94.70	83.67	85.69	97.40
	CC	0.07	0.50	0.48	0.07
Relative humidity (%)	MB	1.78	3.60	4.28	-0.93
	MAE	14.14	14.44	15.23	13.41
	RMSE	20.06	20.31	21.27	18.87
	CC	0.48	0.49	0.48	0.52
Equivalent potential temperature (K)	MB	2.70	2.86	2.61	1.46
	MAE	3.96	4.15	4.01	3.78
	RMSE	5.14	5.34	4.98	4.76
	CC	0.77	0.79	0.80	0.75

reasonably captured the thermo-dynamical stability indices of the atmosphere during the thunderstorm events. It also simulated the 24-h accumulated rainfall in better agreement with rainfall measurements at the study area. A statistical analysis based on mean bias, mean absolute error, root mean square error and correlation coefficient revealed better performance of MYJ followed by BouLac schemes in simulating various surface meteorological variables and the thermo-dynamical structure of the atmosphere associated with the thunderstorm events over the study

region. The important conditions for the development of thunderstorms are large-scale heating, convective instability and sufficient moisture leading to thunderstorm cells. The MYJ and BouLac schemes with TKE-based local-closure seems to sustain these pre-storm convective conditions better than the non-local YSU and ACM2 schemes parameterizations. However, to advocate the application of the MYJ followed by BouLac schemes for thunderstorm forecasting in the GWB region it is required to simulate and analyse more number of cases for arriving at definite

conclusions. A major limitation for such comprehensive evaluation is the lack of observations for assimilation and validation. This study highlights the importance of proper turbulence diffusion parameterization in simulating the convective thunderstorms in mesoscale models based on results for a few thunderstorm events using the STORM data sets in the GWB region.

### Acknowledgments

The authors are thankful to Doppler Weather Radar Division, India Meteorological Department Kolkata, for providing Doppler weather radar imageries. We gratefully acknowledge the Department of Science & Technology, Govt. of India, New Delhi, for providing funding in conducting experiment under the STORM programme during pre-monsoon months at Kharagpur. We acknowledge with thanks to STORM Advisory Committee and its Chairman, Prof. U.C. Mohanty, for STORM weather summaries and academic advice. Thanks are due to Dr. M. Mandal for providing the tower data. Mr Srikanth extends his thanks to Dr. B. Venkatraman (Division Head & Associate Director, RSEG/IGCAR) and Dr. R. Baskaran (Head, RIAS) for providing the computational facilities at IGCAR. Mr. Srikanth Madala would like to gratefully acknowledge Indian Institute of Technology Kharagpur for providing research fellowship and necessary facilities to conduct PhD work.

### REFERENCES

- ASNANI, G.C. (2005), *Tropical Meteorology* (Revised Edition). Indian Institute of Tropical Meteorology, Pune, 2.
- BRIGHT, D.R., MULLEN, S.L. (2002), *The sensitivity of the numerical simulation of the southwest monsoon boundary layer to the choice of PBL turbulence parameterization in MM5*. *Weather and Forecasting*, 17, 99–114.
- BUSINGER, J.A., WYNGAARD, J.C., IZUMI, Y., BRADLEY, E.F. (1971), *Flux-profile relationships in the atmospheric surface layer*. *J. Atmos. Sci*, 28, 181–189.
- CHAUDHURI, S. (2011), *A probe for consistency in CAPE and CINE during the prevalence of severe thunderstorms: statistical-fuzzy coupled approach*. *Atmos Clim Sci*, 4(1), 197–205.
- DALAL, S., LOHAR, D., SARKAR, S., SADHUKHAN, I., DEBNATH, G.C. (2012), *Organizational modes of squall-type mesoscale convective systems during pre-monsoon season over eastern India*. *Atmos. Res*, 106, 120–138.
- DAWN, S., and MANDAL, M. (2014), *Surface mesoscale features associated with leading convective line-trailing stratiform squall lines over the Gangetic West Bengal*. *Meteorology and Atmos. Phys.*, 125, 119–133. <http://dx.doi.org/10.1007/s00703-014-0323-7>.
- DROULIA, F., LYKOUDES, S., TSIROS, I., ALVERTOS, N., AKYLAS, E., GAROFALAKIS, I. (2008), *Ground temperature estimations using simplified analytical and semi-empirical approaches*. *Solar Energy*, 83, 211–219.
- FOKEN, T., and WICHURA, B. (1996), *Tools for quality assessment of surface-based flux measurements*. *Agric. For. Meteorol*, 78, 83–105.
- GHOSH, A., LOHAR, D., DAS, J. (2008), *Initiation of Nor'wester in relation to mid-upper and low-level water vapor patterns on METEOSAT-5 images*. *Atmospheric Research*, 87, 116–135.
- HARIPRASAD, K.B.R.R., SRINIVAS, C.V., BAGAVATH SINGH, A., VIJAYA BHASKARA RAO, S., BASKARAN, R., VENKATRAMAN, B. (2014), *Numerical simulation and intercomparison of boundary layer structure with different PBL schemes in WRF using experimental observations at a tropical site*. *Atmospheric Research*, 145, 27–44.
- HU, XIAO-MING., NIELSEN-GAMMON, J.W., ZHANG, F. (2010), *Evaluation of three planetary boundary layer schemes in the WRF model*. *Journal of Applied Meteorology and Climatology*, 49, 1831–1844.
- KESSLER, E. (1982), *Thunderstorm morphology and dynamics*, US Department of commerce, National Oceanic and Atmospheric Administration. Environmental Research Laboratories, 2.
- KIRAN PRASAD, S., MOHANTY, U.C., ROUTHAY, A., KRISHNA K.O., RAMAKRISHNA, S.S.V.S., NIYOGI, D. (2014), *Impact of Doppler weather radar data on thunderstorm simulation during STORM pilot phase-2009*. *Natural Hazards*, 74(3), 1403–1427.
- LATHA, R., and MURTHY, B.S. (2011), *Boundary layer signatures of consecutive thunderstorms as observed by Doppler sodar over western India*. *Atmospheric Research*, 99, 230–240.
- LI, X., and PU, Z. (2008), *Sensitivity of numerical simulation of early rapid intensification of Hurricane Emily (2005) to cloud microphysical and planetary boundary layer parameterizations*. *Monthly Weather Review*, 136, 4819–4838.
- LITTA, A.J., MOHANTY, U.C., and IDICULA, S.M. (2012a), *The diagnosis of severe thunderstorms with high-resolution WRF model*. *Journal of Earth System Science*, 121(2), 297–316.
- LITTA, A.J., MOHANTY, U.C., SOMESHWAR, D., IDICULA, S.M. (2012b), *Numerical simulation of severe local storms over east India using WRF NMM mesoscale model*. *Atmos. Res*, 116, 161–184.
- MAY, P.T., and RAJOPADHYAYA, D.K. (1999), *Vertical velocity characteristics of deep convection over Darwin, Australia*. *Mon. Weather Rev*, 127, 1056.
- MIAO, J.F., WYSER, K., CHEN, D., RITCHIE, H. (2009), *Impacts of boundary layer turbulence and land surface process parameterizations on simulated sea breeze characteristics*. *Annales Geophysicae*, 27, 2303–2320.
- MOHANTY, U. C., et al. (2006), *Weather summary during pilot experiment of severe thunderstorms—observations and regional modeling (STORM) programme-2006 (13 April to 31 May, 2006)*. Department of Science & Technology, Government of India, Technology Bhawan, New Delhi.

- MOHANTY, U. C., *et al.* (2007), Weather summary during pilot experiment of severe thunderstorms—observations and regional modeling (STORM) programme-2007 (15 April to 31 May, 2007). Department of Science & Technology, Government of India, Technology Bhawan, New Delhi.
- MUKHOPADHYAY, P., MAHAKUR, M., SINGH, H.A.K. (2009), *The interaction of large scale and mesoscale environment leading to formation of intense thunderstorms over Kolkata Part I: Doppler radar and satellite observations*. *J. Earth Syst. Sci.*, *118* (5), 441–466.
- PRADAN, D., DE, U.K., SINGH, U.V. (2012), *Development of now-casting technique and evaluation of convective indices for thunderstorm prediction in Gangetic West Bengal (India) using Doppler Weather Radar and upper air data*. *Mausam*, *63* (2), 299–318.
- PROSENJIT, C., UTPAL KUMAR, De., and DEVENDRA, P. (2015), Simulation of Severe Local Storm by Mesoscale Model MM5 and Validation Using Data from Different Platforms. *International Journal of Atmospheric Sciences*, Article ID 198704, 23 pages, <http://dx.doi.org/10.1155/2015/198704>.
- RAJEEVAN, M., KESARKAR A., THAMPI, S.B., RAO K.N., RADHAKRISHNA, B., and RAJSEKHAR, M. (2010), Sensitivity of WRF cloud microphysics to simulations of a severe thunderstorm event over Southeast India. *Annales Geophysicae*, *28*, 603–619.
- RAMAKRISHNA, S.S.V.S., VIJAYA SARADHI, N., SRINIVAS, C.V. (2012), *On the role of Planetary Boundary Layer in the numerical simulation of Severe Cyclonic Storm Nargis with a Mesoscale Model*. *Nat. Hazards*, *63* (3), 1471–1496.
- ROTH, M., SALMOND, J.A., and SATYANARAYANA, A.N.V. (2006), *Methodological Considerations Regarding the Measurement of Turbulent Fluxes in the Urban Roughness Sublayer: The Role of Scintillometry*. *Boundary Layer Meteorology*, *121*, 351–375.
- SATYANARAYANA, A.N.V., SABIHA SULTANA, NARAYANA RAO, T., SATHEESH KUMAR, S. (2014), *Evaluation of atmospheric turbulence, energy exchanges and structure of convective cores during the occurrence of mesoscale convective systems using MST radar facility at Gadanki*. *Atmospheric Research*, *143*, 198–215.
- SHIMADA, S., OHSAWA, T., CHIKAOKA, S., KOZAI, K. (2011), *Accuracy of the wind speed profile in the lower PBL as simulated by the WRF model*. *Sola*, *7*, 109–112.
- SKAMAROCK, W.C., KLEMP, J.B., DUDHIA, J., GILL, D.O., BARKER, D.M., DUDHA, M.G., HUANG, X., WANG, W., POWERS, Y. (2008), A Description of the Advanced Research WRF Ver. 30. In: NCAR Technical Note. NCAR/TN-475STR. Meso-scale and Micro-scale Meteorology Davison, National Centre for Atmospheric Research, Boulder Colorado, USA, 113 p.
- SOMESHWAR, D., and Co-authors. (2014), *The SAARC STORM: A Coordinated Field Experiment on Severe Thunderstorm Observations and Regional Modeling over the South Asian Region*. *Bull. Amer. Meteor. Soc.*, *95*, 603–617.
- SOMESHWAR, D., ABHIJIT, S., MOHAN, K.D., Md. MIZANUR, RAHMAN., Md. NAZRUL, ISLAM. (2015), *Composite characteristics of Nor'westers based on observations and simulations*. *Atmospheric Research*, *159*, 158–178.
- SRIKANTH, M., SATYANARAYANA, A.N.V., SRINIVAS, C.V., and KUMAR, M. (2015), *Mesoscale atmospheric flow-field simulations for air quality modelling over complex terrain region of Ranchi in eastern India using WRF*. *Atmospheric Environment*, Vol. 107, pp. 315–328.
- SRIKANTH, M., SATYANARAYANA, A.N.V., BHISHMA, TYAGI. (2013), *Performance Evaluation of Convective Parameterization Schemes of WRF-ARW Model in the Simulation of Pre-monsoon Thunderstorm Events over Kharagpur using STORM Data Sets*. *International Journal of Computer Applications*, *71*(15), 43–50.
- SRIKANTH, M., SATYANARAYANA, A.N.V., NARAYANA RAO, T. (2014), *Performance evaluation of PBL and cumulus parameterization schemes of WRF ARW model in simulating severe thunderstorm events over Gadanki MST radar facility-Case study*. *Atmospheric Research*, *139*, –17.
- SRINIVAS, C.V., HARIPRASAD, K.B.R.R., NAIDU, C.V., BASKARAN, R., and VENKATRAMAN, B. (2015), *Sensitivity Analysis of Atmospheric Dispersion Simulations by FLEXPART to the WRF Simulated Meteorological Predictions in a Coastal Environment*. *Pure and Applied Geophysics*, doi:[10.1007/s00024-015-1104-z](https://doi.org/10.1007/s00024-015-1104-z).
- SRINIVAS, C.V., VENKATESAN, R., BAGAVATH SINGH, A. (2007a), *Sensitivity of mesoscale simulations of land-sea breeze to boundary layer turbulence parameterization*. *Atmospheric Environment*, *41*, 2534–2548.
- SRINIVAS, C.V., VENKATESAN, R., BHASKAR RAO, D.V., HARI PRASAD, D. (2007b), *Numerical Simulation of Andhra Severe Cyclone (2003): Model Sensitivity to the Boundary Layer Turbulence and Convective Parameterization*. *Pure Appl. Geophys.*, *164*, 1465–1487.
- SRINIVAS, C.V., YESUBABU, V., BHASKAR RAO, D.V., BASKARAN, R., and VENKATRAMAN, B. (2013), *Tropical Cyclone Predictions over the Bay of Bengal using high resolution Advanced Research Weather Research and Forecasting Model (ARW)*. *Q. J. R. Meteorol. Soc.*, *139*, 1810–1825.
- STEENEVELD, G.J., MAURITSEN, T., de BRUIJN, E.I.F., VILÀ-GUERAU DE ARELLANO, J., SVENSSON, G., HOLTSLAG, A.A.M. (2008), *Evaluation of limited area models for the representation of the diurnal cycle and contrasting nights in CASES99*, *Journal of Applied Meteorology and Climatology* *47*, 869–887.
- STORM SCIENCE PLAN, 2005. Severe Thunderstorms-Observations & Regional Modeling (STROM) Programme, Department of Science & Technology, Government of India, New Delhi, December 2005.
- STULL, R.B. (1988), *Introduction to boundary layer meteorology*, xiii + 666 pp. Dordrecht, Boston, London. Kluwer Academic Publishers.
- TYAGI, A. (2007), *Thunderstorm climatology over Indian region*. *Mausam*, *58*(2), 189–212.
- TYAGI, B., NARESH KRISHNA, V., SATYANARAYANA, A.N.V. (2011), *Skill of Thermodynamic indices for forecasting pre-monsoon thunderstorms over Kolkata during STORM pilot phase 2006–2008*. *Natural Hazards*, *56*, 681–698.
- TYAGI, B., SATYANARAYANA, A.N.V. (2010), *Modeling of Soil Surface Temperature and Heat Flux during Pre-monsoon season at two Tropical Stations*. *Journal of Atmospheric and Solar-Terrestrial Physics*, *72* (2–3), 224–233.
- TYAGI, B., SATYANARAYANA, A.N.V., and NARESH KRISHNA, V. (2013a), *Thermodynamical structure of atmosphere during pre-monsoon thunderstorm season over Kharagpur as revealed by STORM data*. *Pure and Applied Geophysics*, *170*(4), 675–687.
- TYAGI, B., SATYANARAYANA, A.N.V., RAJVANSHI R.K., MANDAL, M.M. (2013b), *Surface Energy Exchanges during Pre-monsoon Thunderstorm Activity over a Tropical Station Kharagpur*. *Pure and Applied Geophysics*, doi:[10.1007/s00024-013-0682-x](https://doi.org/10.1007/s00024-013-0682-x).
- TYAGI, B., SATYANARAYANA, A.N.V., KUMAR, M., MAHANTI, N.C. (2012), *Surface energy and radiation budget over a tropical station: an observational study*. *Asia Pac. J. Atmos. Sci.*, *48* (4), 411–421.



- VISWANADHAM, D.V., SATYANARAYANA, A.N.V., SRIVASTAVA, M.K., MISHRA, STUTI, (1997), *Surface layer turbulent kinetic energy budget over Kharagpur*. J. Sci. Res, 47, 11–20.
- WANG, W., and SEAMAN, N.L. (1997), *A comparison study of convective parameterization schemes in a mesoscale model*. Mon. Weather Rev, 125, 252–278.
- WILKS, D.S. (2011), *Statistical Methods in the Atmospheric Science*, third ed. Elsevier Academic Press, U.S.A. 704.
- XIE, B., FUNG, J.C.H., CHAN, A., and LAU, A. (2012), *Evaluation of nonlocal and local planetary boundary layer schemes in the WRF model*. J. Geophys. Res., 117, D12103, doi:[10.1029/2011JD017080](https://doi.org/10.1029/2011JD017080).

(Received August 16, 2015, revised November 4, 2015, accepted November 8, 2015, Published online November 20, 2015)