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Performance evaluation of PBL and cumulus parameterization schemes of WRF ARW model in simulating severe thunderstorm events over Gadanki MST radar facility — Case study

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ABSTRACT

In the present study, an attempt has been made to simulate three severe thunderstorm events that occurred over Gadanki (13.5° N, 79.2° E) region of the Mesosphere–Stratosphere–Troposphere (MST) Radar facility using Weather Research Forecasting (WRF ARW version 3.2) model. We examined the performance of five planetary boundary layer (PBL) parameterization schemes namely, the Yonsei University (YSU), Mellor–Yamada–Janjic (MYJ), Mellor–Yamada Nakanishi and Niino Level 2.5 PBL (MYNN2), and Medium-Range Forecast (MRF) and Asymmetric Convective Model version 2 (ACM2) and three cumulus parameterization schemes Kain–Fritisch (KF), Betts–Miller–Janjic (BMJ) and Grell–Devenyi ensemble scheme (GD) in simulating boundary layer parameters, thermodynamic structure and vertical velocity profiles on the days of the thunderstorm events. Triple nested domain having the inner-most domain of 3 km grid resolution over the study area is considered. The model simulated parameters are validated with the available *in situ* meteorological observations obtained from micro-meteorological tower, radiosonde, MST radar wind profiler and observed rainfall along with the surface fluxes at Gadanki. After validating the model simulations with the available PBL observations and the statistical assessment reveal that the MYJ scheme could be able to capture the characteristic variations of surface meteorological variables such as air temperature, relative humidity, wind component, vertical profiles of wind, relative humidity and equivalent potential temperature and surface layer fluxes during the study period. Cores of strong convective updrafts with a time lag and lead of one and half hour are better represented by the model with MYJ scheme with GD as seen in the vertical velocity profiles obtained from MST radar observations. The present study advocates that the MYJ–GD combination is suitable for the simulation of thunderstorm events over the study region.

1. Introduction

Thunderstorms are intense mesoscale convective systems associated with gusty winds, heavy precipitation and hailstorm that cause loss of life and property in many parts of India, thereby necessitating their accurate forecasting with reasonable lead time. The physics and the dynamics of severe thunderstorms can be understood by simulating these systems with the help of mesoscale models. Accurate prediction requires knowledge about the necessary and sufficient atmospheric and topographic conditions for their development and evolution. Planetary boundary layer (PBL) plays an important role in the transportation of energy such as momentum, heat and moisture into the upper layers of the atmosphere and acts as a feedback mechanism in the generation and sustenance of thunderstorms. PBL is the region of the lowest 1–3 km of the lower atmosphere

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or the troposphere (Stull, 1988). The depth and the structure of the atmospheric boundary layer are determined by the physical and thermal properties of the underlying surface along with the dynamics and thermodynamics of the lower atmosphere.

Some attempts in simulating thunderstorm events using WRF mesoscale modeling system (e.g., Litta and Mohanty, 2008; Litta et al., 2009, 2012a; Srikanth et al., 2013) were reported over the Gangetic West Bengal (GWB) region using data generated by the STORM (Severe Thunderstorm Observations and Regional Modeling) program sponsored by the Department of Science & Technology (DST), Government of India (STORM Science Plan, 2005; Mohanty et al., 2006, 2007). In these above studies the model results are not validated with the *in situ* surface fluxes and vertical velocity profiles obtained from MST Radar wind profilers to ascertain the performance of the mesoscale models in simulating the thunderstorm events. Mukhopadhyay et al. (2003, 2009) reported the objective forecast using conventional indices as well as the interaction of large scale fields with the mesoscale environment in the formation of thunderstorms using Doppler radar and satellite observations.

Observational studies in identifying the characteristic signatures of variation of atmospheric boundary layer parameters, surface energy exchanges and thermodynamical structure of the atmosphere during different epochs of thunderstorms over the GWB region using STORM experimental data sets are reported in the literature (e.g. Tyagi et al., 2011, 2012, 2013a, 2013b).

Based on these data sets few observational studies (e.g. Tyagi et al., 2011, 2012, 2013a, 2013b) are also reported in explaining the characteristic signatures of variation of atmospheric boundary layer parameters, surface energy exchanges and thermodynamical structure of the atmosphere during different epochs of thunderstorms over the GWB region using STORM experimental data sets. Latha and Murthy (2011) reported boundary layer signatures in terms of wind variations using SODAR data over Pune, India. Vaidya (2007) applied two mesoscale models such as WRF and ARPS to simulate a thunderstorm as well as cyclonic circulation systems over the east coast of India and concluded that ARPS could be able to capture the rainfall events better than WRF. Chatterjee et al. (2008) simulated a hail storm case that occurred in the pre-monsoon month of April 2006 by employing MM5 model to test the performance of cloud microphysics parameterization schemes. Litta et al. (2012b) simulated a tornado event that occurred over Ludhiana, India. In mesoscale meteorological modeling, various models (e.g. MM5, ARPS, and WRF) consist of various types of PBL schemes in order to characterize the boundary layer structure in the lower atmosphere. PBL parameterization utilizes different assumptions to describe the turbulence or eddy activities under stable, neutral or convective conditions. Studies were reported in literature regarding the sensitivity of PBL schemes to the meteorological modeling (e.g. Bright and Mullen, 2002; Misenis et al., 2006; Zhong et al., 2007; Srinivas et al., 2007; Li and Pu, 2008; Miao et al., 2009; Hu et al., 2010).

Southern Peninsular India is prone to the occurrence of thunderstorms during pre-monsoon as well as monsoon seasons. To monitor and study various convective systems (e.g. monsoon depressions, cyclones, and thunderstorms), a MST Radar facility was established at Gadanki (13.5° N, 79.2° E). Very few modeling studies are reported in simulating thunderstorms over this region (e.g. Rajeevan et al., 2010) other than some observational reports (e.g. Venkat Ratnam et al., 2001; Uma and Rao, 2008; Venkat Ratnam et al., 2013; Madhulatha et al., 2013). Hence, the present case study is mainly focused on evaluating the performance of PBL and cumulus parameterization schemes of WRF ARW mesoscale model in simulating three severe thunderstorm events that occurred over the MST Radar facility of Gadanki. The model simulations are validated with the available observations and were assessed with statistical skill to understand the performance of these schemes of the model.

2. Data and methodology

2.1. Data

The Indian Mesosphere–Stratosphere–Troposphere Radar (IMSTR) is located at Gadanki (13.5° N, 79.2° E), situated about 80 km from the coast of the Bay of Bengal in southern peninsular India. The MST radar is a high-power, mono-static, coherent-pulsed Doppler radar. For more details of the MST Radar please refer to Rao et al. (1995, 1999). In the present study the data generated by the MST radar consisting of derived vertical profiles for three severe thunderstorm days (25 April, 4 May and 6 June of 2011) were used.

The MST radar facility also consists of an upper air radiosonde observational system and a 50-m micro-meteorological tower instrumentation and the data from these experimental platforms are also used in the present work. The radiosonde data consisting of temperature (K), wind speed (ms^{-1}), wind direction (°), and relative humidity (%) at various pressure (hPa) levels are used. The micro-meteorological tower consists of slow response (1 Hz) consisting of air temperature (AT), relative humidity (RH), wind speed (WS) and wind direction (WD) at 6 different heights viz. 2, 4, 8, 16, 32 and 50 m and surface air pressure (SLP) and rainfall (mm) are utilized. Fast response data (20 Hz) consists of 3-dimensional wind and temperature obtained from sonic anemometer at 4 m height has been utilized to compute frictional velocity as well as sensible heat flux for validating the model results. In the present study, FNL data 1.0° × 1.0° resolution during 25–26 April, 4–5 May, and 6–7 June 2011 is used. The Doppler Weather Radar (DWR) imageries obtained from the Doppler Weather Radar Division, India Meteorological Department at Chennai are analyzed for the qualitative assessment of the occurrence of the thunderstorm activity.

2.2. DWR imagery analysis during the thunderstorm events

Three thunderstorm events that occurred over the Gadanki region are considered in the present study and details of the identification of the convective cells based on DWR imageries (figures not shown) are given hereunder.

Case 1. 25 April 2011

On 25 April 2011 at 1200 UTC a convective cell is observed near the Gadanki region in DWR imageries. At 1200 UTC its intensity of reflectivity was measured to be 28 dBZ. The intensity of reflectivity increases gradually to 49.3 dBZ at 1230 UTC. During 1310 UTC the intensity of reflectivity was at the maximum of 53.4 dBZ. Afterwards the intensity of