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Review Article

NUMERICAL SIMULATION OF BOUNDARY LAYER FLOW PARAMETERS BY USING WRF-ARW MODEL OVER A TROPICAL REGION

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ABSTRACT

Planetary boundary layer (PBL), the lower few kilometers of the atmosphere over the surface of the earth plays an important role in the transportation of energy such as momentum, heat and moisture into the upper layers of the atmosphere. PBL flow is in general highly turbulent and showing distinct diurnal as well as seasonal variations. The simulation of boundary layer flow field parameters are very much important in various aspects of science and engineering and also plays an important role in the feed-back mechanisms of various scales of atmospheric motions from micro-scale turbulence to large-scale atmospheric mechanisms such as monsoons. Hence, in the present study an attempt has been made to evaluate the performance of five different PBL schemes [Yonsei University (YSU), Mellor-Yamada-Nakanishi-Niino (MYNN2), Mellor Yamada-Janjic (MYJ), Quasi Normal Scale Elimination (QNSE) and Asymmetric Convective Model (ACM2)] of Weather Research and Forecast (WRF-ARW) mesoscale model in simulating boundary layer flow parameters over Nagpur (21.15° N, 79.09° E) in Maharashtra. High resolution simulations (27, 9, and 3 with 27 vertical levels) are conducted with triple nested domains by using 1 × 1 degree NCEP Final Analysis meteorological fields for initial and boundary conditions. In the study, five fair weather days in winter (January 2009) with no significant synoptic activity are chosen. The present study conclude that the non-local PBL scheme YSU and local scheme MYJ could capture the characteristic variations of surface meteorological variables, vertical structure of atmospheric as seen in observations over the study region. This study advocates that YSU and MYJ schemes are very useful for the air pollution studies over the study region.

INTRODUCTION

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 wind circulation. PBL is the lowest 1–3 km region of the atmosphere within the troposphere characterized with friction and turbulent mixing (Stull, 1988). The deepness and the configuration of the atmospheric boundary layer are indomitable by thermal and physical properties of the principal surface along in the company of the thermodynamics and dynamics of lower atmosphere. Mesoscale models include complete convection of physics, turbulence

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of boundary layer, radiation, and processes of land surface which participate significant role in simulations of the atmosphere and short-range weather predictions.

In numerical models various approaches are used to parameterize the vertical turbulent mixing in the PBL. Turbulence diffusion of PBL schemes, in particular plays significant role in the evolution of lower atmospheric phenomena such as development of convective thunderstorm, diffusion of pollution and transport etc. The schemes of PBL parameterization are substance for accurate representation of turbulence simulations, wind, and air quality in the lower atmosphere thus play an significant role for a number of applications (e.g. Steeneveld et al., 2008; Storm et al., 2009; Hu et al., 2012; López-Espinoza and Zavala-Hidalgo, 2012; García-Díez et al., 2013). A number of current studies emphasized the character of PBL parameterization in atmospheric simulations with mesoscale models (e.g. Hu et al., 2010; Gilliam and Pleim, 2010; Shin and Hong, 2011; Floors et al., 2013; Yang et al., 2013). Over tropical region of Indian quite few studies are available on the performance of PBL schemes of WRF model (e.g. Srinivas et al., 2007; Sanjay et al., 2008). The assessment of air quality requires the exact predictions of boundary layer mixed layer depth, humidity, winds, and temperature. The YSU non-local diffusion scheme or the MYNN2 local diffusion scheme has construct better structures of PBL over the tropical coastal station Kalpakkam for the duration of fair weather environment (Hariprasad et al., 2014). PBL schemes play most important role for the dispersion of air pollutants (Boadh et al., 2014, 2015, 2016). In the present study, the flow and parameters of atmospheric over Nagpur region is simulated using WRF-ARW mesoscale model. The present study aims to estimate performance of WRF model for lower part of atmospheric meteorological fields by conducting sensitivity experiments with a variety of theoretically dissimilar PBL schemes.

Study region

Nagpur (21.15° N, 79.09° E) is the major city in Maharashtra state and central part of India. Nagpur is a rapid rising metropolitan area and is the third heavily populated city in Maharashtra state after Mumbai and Pune, and is the centre for industrialization, urbanization, commercial activity and development. On the other hand, the labors to improve the green envelop of the Nagpur city that has scrubbing outcome on air pollutants are inadequate. Nagpur has dry environment established for the largest part of the year with tropical wet and dry climate (Köppen climate classification). Nagpur is situated at a height of 312.42 meters above sea level. Summers are tremendously hot, enduring from March to June, by means of May mortal the hottest month. Winter lasts from November to January, during which temperatures can drop below 10°C. The lowly temperature recorded was 3.9°C in Nagpur city and maximum recorded temperature was 47.9°C on May 22, 2013.

DATA AND METHODOLOGY

Data and simulation period

The initial condition for the WRF model domains are derived from 6 h global final meteorological analysis (FNL) available at 1.0°×1.0° grids generated by the National Center for Environmental Prediction (NCEP) global forecast system (GFS). The available wind direction (degrees), wind speed (ms^{-1}), relative humidity (%), temperature (oC) and upper air Radiosonde observations consists of pressure (hPa), at Nagpur obtained from Department of Atmospheric Science, University of Wyoming (http://weather.uywo.edu/upperair/sounding.html) are used. In this study the 3B42V7 product of TRMM is used. This is a rainfall product spanning global belt from 50° N to 50° S with spatial resolution of 0.25° × 0.25°, with 3 h interval data resolution. In this study justification of the WRF-ARW model available meteorological observations such as relative humidity at 2 m height, wind direction at 10 m height, temperature and wind speed at 2 m height used from the airport of Nagpur during study duration.

In this study, to analysis the model understanding of five parameterizations PBL schemes are estimate in 2009 month of January for winter period. In January 2009, the simulations are conducted for five days (no synoptic activity days). In this study, consequently the selected dates for simulations the WRF model was integrated for a period of 48 h, starting from of 00 UTC on 10, 11, 12, 13 and 14 respectively in the month of January 2019.

Model description – Mesoscale model

In the present study, 3-D non-hydrostatic atmospheric model namely the Advanced Research Weather Research and Forecasting (ARW-WRF Version 3.6) used for simulating PBL characteristics and flow of local scale. The model consists of Eulerian mass solver with terrain following vertical coordinate, totally compressible non-hydrostatic equations, the prognostic variables include the three-dimensional wind, staggered horizontal grid with complete Coriolis and curvature terms, potential temperature and scalars (water vapour mixing ratio, cloud water etc), perturbation quantities of pressure, surface pressure, turbulent kinetic energy and geopotential. A comprehensive explanation of dynamics, equations and the model physics, is presented by Skamarock et al., 2008 and Boadh et al., 2016.

Model configuration and initialization

Horizontal and vertical resolutions are one of the factors in modeling of small scale atmospheric phenomena. However high resolution outcome in more accurate, better resolved, small-scale processes it increases the model numerical expenses (Mass et al., 2002; Gego et al., 2005; Chou, 2011). For this intention the WRF model is premeditated with three nested domain (27 km, 9 km and 3 km) and 27 vertical sigma level shown in Fig. 1. The outer domain (d01) covers a larger region with 27 km resolution and 60 × 60 grids. The second inner domain (d02) has 9-km resolution with 91 × 91 grids and innermost domain (d03) has 3 km resolution with 112 × 112 grids. The last two nested domains (2nd and 3rd) are two-way interactive domains. The model is run using required data (mention above section 3.1) for the initial and boundary conditions.

The model physics options used are Kain-Fritsch scheme (Kain and Fritsch 2004) for convective parameterization, Dudhia scheme for short wave radiation (Dudhia, 1989), Rapid Radiative Transfer Model (Mlawer et al., 1997) for long-wave radiation processes, NOAH land surface model (Chen and Dudia, 2001) for surface physics and WRF Single Moment Class 6 (WSM6) (Hong et al., 2006) for cloud microphysics.

Experiments of sensitivity

The parameterizations of PBL schemes, winds and land surface manipulate the simulation of turbulence and other state variables in the subordinate atmosphere. In this study for testing the model sensitivity five PBL schemes namely three local turbulence kinetic energy (TKE) closure [Mellor- Yamada Nakanishi and Niino Level 2.5 PBL (MYNN2) (Nakanishi and Niino, 2004),

Mellor-Yamada-Janjic (MYJ) (Janjic, 2002), quasi-normal scale elimination (QNSE) Sukoriansky et al., 2005] and two non-local schemes [Yonsei University (YSU) (Hong et al., 2006), Asymmetric Convective Model version 2 (ACM2) (Pleim, 2007)] are selected. The details of the PBL schemes are well described in [e.g. Skamarock et al., 2008; Shin and Hong, 2011].

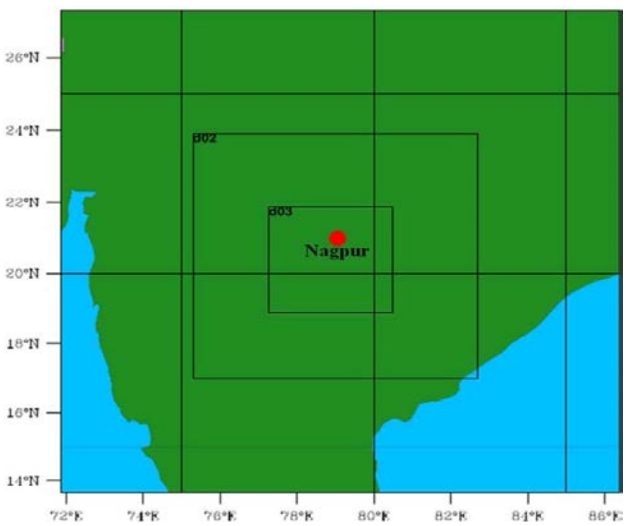

Fig. 1 Domains used in the WRF-ARW model.

RESULTS AND DISCUSSION

Surface meteorological parameters

In this section an inter-comparison of presentation of assorted PBL parameterization schemes for simulations of the diurnal deviation of surface meteorological variables such as WS (ms^{-1}), AT (°C), WD (degree) and RH (%), alongside with the *in situ* interpretation at hourly intervals at the Nagpur airport station are presented.

In general, solitary can observe that all five PBL schemes integrating the diurnal variant of AT reasonably well as seen in the observations during the study period shown in Fig. 2. Though, all the schemes closely simulated the temperature during daytime, a slight warm mean bias (i.e., observation – model<0) is noted in night-time temperatures by most schemes for both winter and summer seasons. Garcia-Diez et al., 2013; reported that the WRF model mean bias significantly depends on the season, and warm bias in winter and cold bias in summer were simulated over Europe. Close examination reveals that the local scheme MYJ and non local scheme YSU both are reasonably will with observations compare to rest of schemes.

Relative humidity is underestimated during daytime and better simulated during night time in January has shown in Fig. 3 over Nagpur. Underestimation of humidity by MYJ and YSU schemes was also reported by Misenis and Zhang 2010; over the coastal Mississippi. During the study period ACM2, YSU (non local) and MYNN2 (local) PBL schemes better simulate the relative humidity (RH) compare to the rest of the PBL schemes and diurnal variation of RH is reasonable well captured. Similar types of results are found by Garcia-Diez et al., 2013; over Europe and Hu et al., 2010; in Texas, USA.

The wind roses simulated from all five PBL schemes

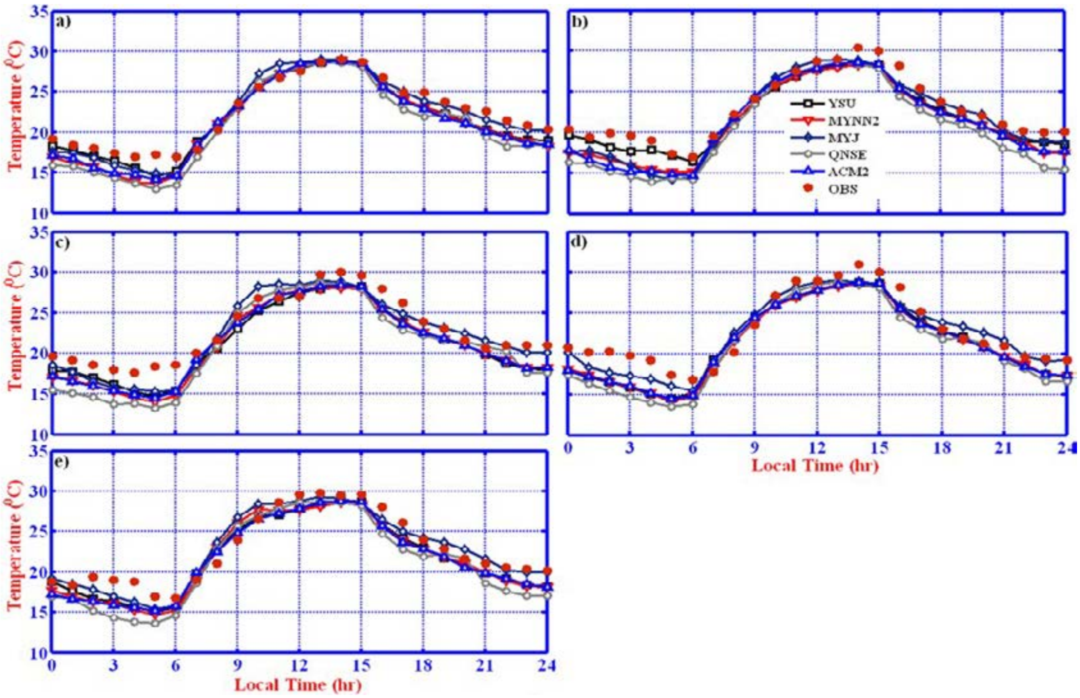

Fig. 2 Validation of model simulation of surface temperature (ºC) during 11 to 15 January 2009 over Nagpur.

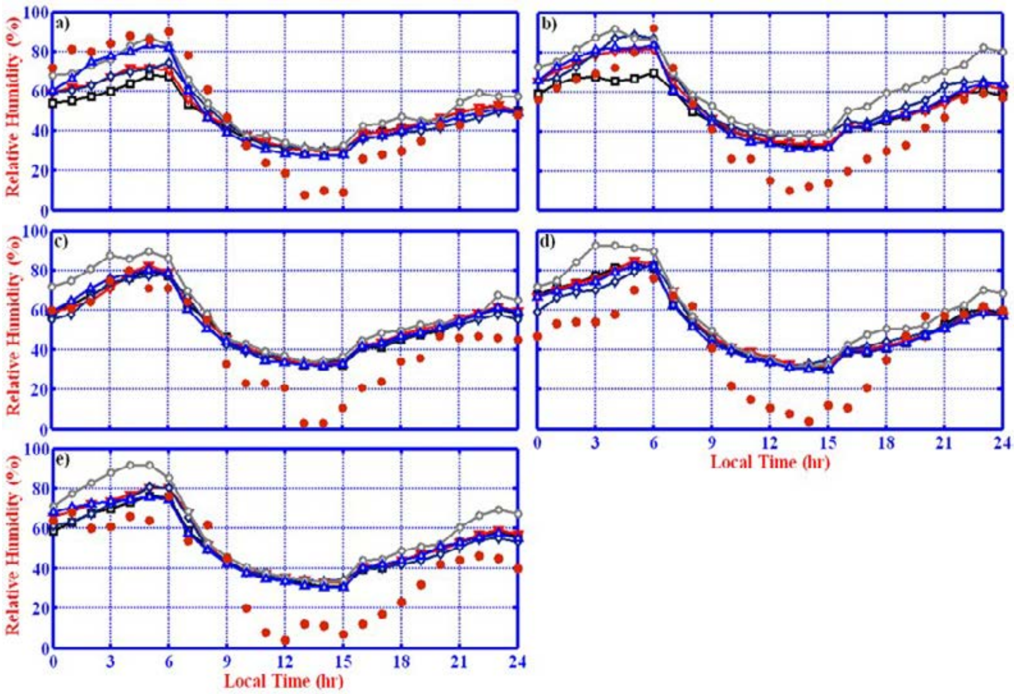

Fig. 3 Validation of model simulation of relative humidity (%) during 11 to 15 January 2009 over Nagpur.

along with observation over Nagpur station on 13 January 2009 shown in Fig. 4. From the observations one can see that wind mostly blowing from E and SE direction and similar patterns shown by non local schemes YSU and ACM2 with more variance. MYJ (local scheme) simulations reveal that winds are from EES, SSE and E i.e., the other schemes, namely, MYNN2 and QNSE having shown different wind patterns. YSU (non-local) and MYJ (local) schemes could capable to detain the conditions of low wind well compare to other schemes as seen in the observations.

Thermo-dynamical structure the atmosphere

In the present section have been discussed about the model simulations of vertical profiles of meridional and zonal wind mechanism, equivalent potential temperature and relative humidity using different PBL schemes along with the presented observations obtained from radiosonde ascents are taken from Atmospheric Science department, Wyoming University. (http://weather.uywo.edu/upperair/sounding.html). We analysis for 5 days in January 2009 for representation winter seasons respectively but here we have to discuss only one day 13 January 2009 (Fig. 5). After vigilant examination of simulations, it's found that YSU and MYNN2 schemes are reasonably well compare to other scheme. The simulated profiles by model of (a) zonal wind (ms^{-1}) (b) meridional wind (ms^{-1}) (c) relative humidity (%) (d) equivalent potential temperature (θe) (K) with observations of radiosonde over study region on 13 January 2009 at 0530 LT (Fig. 5). It's noticed that the YSU and MYNN2 simulations flow of Equivalent potential temperature, RH and wind components are in good comparison with the observed variation in addition to scale compare to remaining schemes.

These distinctiveness are simulated well by most of PBL schemes over Nagpur region, despite the fact that with a small amount of differences. The YSU and MYNN2 show relatively deeper PBLs relative to other schemes. By qualitative analysis one can see that the performance of MYNN2 followed by YSU for better simulation of the structure of thermo-dynamical of atmosphere over the study region.

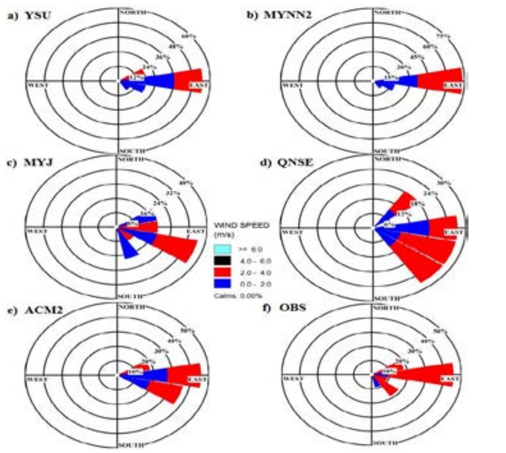

Fig. 4 Wind roses over Nagpur station on 13 January 2009.

The simulated flow field by local scheme MYJ at 850 hPa from the fine nested domain is analyzed during 00 UTC, 06 UTC, 12 UTC and 18 UTC on 13 January 2009 shown in Fig. 6. In the early morning time at 00 UTC (Fig. 6a) the wind flow is north westerly with a magnitude of 10 ms^{-1} and the temperature gradient (~ 1-2°C) over the inner-most domain is noticed. At 06 UTC large variations were found in the simulated temperature gradient (~2-3°C) and the wind flow is north westerly and the magnitude of the wind is 8 ms^{-1}.

The temperature gradient is very less at 12 UTC and wind flow of 7 ms^{-1} mostly westerly and slightly north westerly is noticed. At 18 UTC wind flow of 9 ms^{-1} mostly westerly and slightly south westerly over the domain with a high temperature gradient.

CONCLUSION

The main aspire of this study is that estimate the performance of different type of PBL schemes form ARW-WRF model for simulating the distinguishing features of mesoscale meteorological parameters over multifaceted topography region Nagpur in Maharashtra state of India. The present results specify that the model possibly will detain the flow field of local scale and the spot explicit meteorological parameters at Nagpur region. The model Simulations demonstrate broadly varying flows, air temperatures for the duration of the study episode would brunt the trajectory of plume from pollutant sources in the region of Nagpur. Analysis of dissimilar meteorological parameters shows that

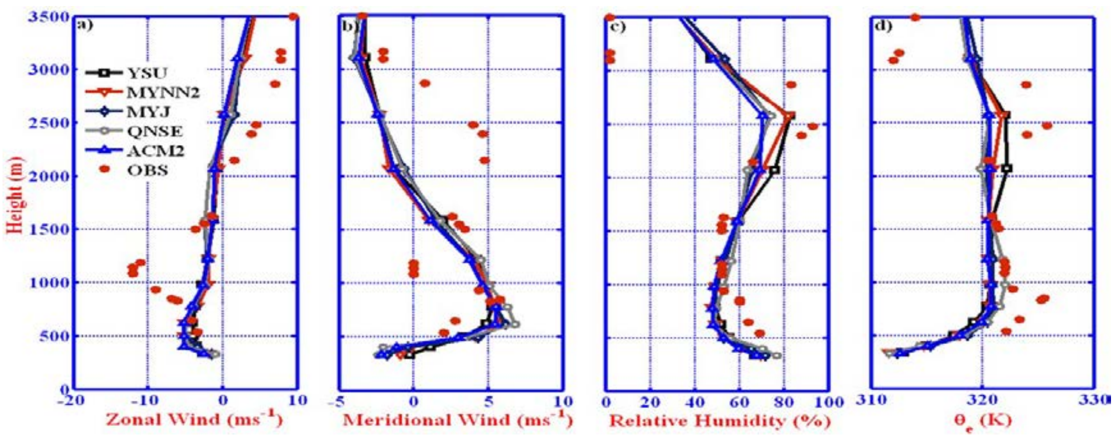

Fig. 5 Model simulated validation profiles of (a) zonal wind (ms-1) (b) meridional wind (ms-1) (c) relative humidity (%) (d) Equivalent potential temperature (θe) (K) with radiosonde observations over Nagpur lying on 13 January 2009 at 0530 LT.

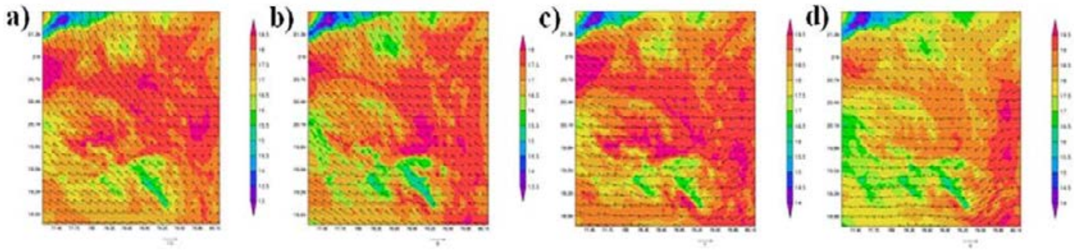

Fig. 6 Simulated flow-field for inner most domain (d3) at 850 hpa on 13 January 2009 from simulations with MYJ PBL scheme at a) 00 UTC, b) 06 UTC, c) 12 UTC and d) 18 UTC.

they are susceptible to the parameterization of PBL engaged in the model. It has been established that for the majority parameters the non-local diffusion schemes MYJ followed by YSU and MYNN2 (level 2.5 TKE) scheme formed enhanced comparisons with observations quantitatively and qualitatively. Due to the absence of meso-net meteorological observations, truthful estimation of the presentation of the PBL schemes could not be undertaken. Within the limitations, the study advocates that the non-local YSU followed by MYJ and the TKE closure ACM2 PBL turbulent diffusion parameterizations of WRF-ARW model are suitable over Nagpur. It's also advocates that YSU and MYJ schemes are very useful PBL schemes for the air pollution studies over the study region.

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