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Evaluating Land Surface Models in WRF Simulations over DMIC Region

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Abstract

Objectives: To evaluate the four land-surface parameterizations viz. Thermal, Noah, RUC and Pleim-Xiu embedded within Weather Research and Forecasting (WRF) model over Delhi-Mumbai Industrial Corridor (DMIC). **Methods:** WRF model simulations are carried out for five different cases over DMIC region by considering a nested configuration with outer and inner domain horizontal resolutions 30 km and 10km respectively. The performance of the considered land-surface parameterizations or LSMs are compared with the real time observations and statistical analysis is evaluated using probability density function, cumulative density function as well as the root mean square error. **Findings:** The analysis of results indicates that the LSMs are quite sensitive to the forecasting of the near surface and boundary layer characteristics. Performance of all land-surface schemes is reasonably good for the prediction of near surface temperature and 10 m wind speed for the five cases. However, the errors are found to be significant for Relative Humidity (RH). On the other hand, sensitiveness of different land-surface parameterizations appears to be less important when there are extreme weather events. It is realized that the model error increases with increase in intensity of rainfall and extremity of the events for prediction of precipitation. Pleim-Xiu scheme is found to be performing better in dry case as well as moderately heavy rainfall case, whereas Noah scheme performs efficiently during hotter and colder scenarios. Additional monthly simulations agreed with these findings reasonably well. Thus, it is inferred that Noah and Pleim-Xiu land-surface parameterizations may be used for WRF simulations over DMIC region as per the requirements in view of the consideration of urban or non-urban aspects. **Application/Improvements:** The present study would be helpful for understanding the behavior of WRF model in view of improving the forecasting of different meteorological parameters over DMIC region.

Keywords: DMIC, Noah, Pleim-Xiu, RUC, Thermal, WRF

1. Introduction

The recent developments in numerical modelling of weather and climate, especially during the last decade have gained significant amount of attention of researchers working on the land-surface characteristics and associated processes[1–11]. There is a growing interest in understanding the interactions between atmosphere and the underlying land-surface. Over the tropics, particularly in the Indian subcontinent, land-surface processes constitute an important driver for weather[2,12–14] and climate[15] system. Land Use and Land Cover (LULC) changes due to anthropogenic activities as well as natural processes impact the regional or mesoscale weather[6,16] and climate[17–18]. In view of this, a robust numerical model is required for taking into account the changes related to LULC over a particular region through appropriate parameterizations.

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In mesoscale or regional scale numerical models like MM5 or Weather Research and Forecasting (WRF), land-use and land-cover changes and the associated characteristic features or processes are usually parameterized by considering a Land Surface Model (LSM). The appropriate input from LSMs to the Planetary Boundary Layer (PBL) is quite significant to define the land-atmospheric interaction within the considered numerical modelling framework. Of the various atmospheric processes, the PBL and land-surface ones are quite interactive and play important roles in the simulation of the lower atmospheric characteristics. The LSMs usually compute heat and moisture fluxes over land and sea-ice points and provide these inputs to the considered PBL schemes[19]. And, the growth and development of PBL depends upon these surface fluxes and their upward movement through the turbulent transport and subsidence. In view of these, the available land-surface parameterizations like Noah, Rapid Update Cycle (RUC), Pleim-Xiu and Thermal diffusion scheme within WRF model[19] may be considered for relevant simulations. The Noah and RUC LSMs are at the moderately complex, though RUC has a relatively complicated snow scheme than Noah Table 1. Pleim-Xiu comprises a 2-layer force-restore soil temperature and moisture parameterization with three pathways for moisture fluxes from wet canopies. On the other hand, the Thermal diffusion scheme is relatively simple and is based on the MM5 5-layer soil parameterization. These LSMs can provide a better understanding of the impact of land surface processes on regional WRF simulated weather and climate. Further, they can also provide an insight on how the level of their complexity has impacts on the accuracy of numerical simulations.

Although several researchers have used the available LSMs within MM5 or WRF model in order to study the associated processes and consequent impact on regional scale weather and climate[1-8,10-11] very few studies are carried out over Indian region. In Indian context, a fewstudies[18,20] have considered the role of underlying land-surface characteristics in order to understand the consequent impact on simulation of summer monsoon. Thus, the importance of underlying land surface is quite significant in view of the regional scale weather and climate studies over India. It is because the relevant input to the LSMs within a numerical modelling framework determines the near surface atmospheric characteristics including the regional scale circulation patterns within the atmospheric boundary layer[13-14]. Further, studies in other parts of the world[3,8,10-11] suggest that LSMs are quite sensitive to short, medium and long-term forecasting of near surface temperature distribution, precipitation over a particular region and water budget. These sensitivities are primarily caused due to LSM-induced differences in surface sensible heat flux and initial soil moisture consideration. However, it is difficult to infer from these studies whether the performance of the LSMs would be similar irrespective of geographical region and different weather and climatic conditions. Therefore, the present analysis bears its importance.

The primary objective of the present study is to understand the significance of land surface parameterizations using advanced research WRF model for five different cases. For this purpose, four LSMs having different levels of complexity (Thermal, Noah, RUC, and Pleim-Xiu) are used Table 1. In order to quantify their role, some of the relevant statistical parameters are analyzed considering the computed values of temperature, wind and relative humidity etc., depending upon the availability of data.

2. Model and Data Used

2.1 Numerical Model and Configuration

The present study uses Advanced Research WRF or ARW (version 3.2.1) regional (or mesoscale) model that is widely used for research and forecasting purposes. The technical details about the model can be found in Skamarock et al.[19].The ARW adopted for this study uses 28 vertical levels (generic levels supplied with WRF name list options) with considered model top as 50 hPa. The horizontal resolutions for the considered domains (Figure 1a) are 30 km and 10 km respectively in 3:1 parent to nested grid ratio. One-way nesting option is used for defining the model configuration.WRF version 3 (and higher ones) provides a choice of four LSMs differing in the number of prognostic variables, accounted processes and complexity of their representation. The considered four land surface schemes include Thermal diffusion (here after Thermal) scheme, Noah scheme[21], RUC[22-24] scheme and Pleim-Xiu scheme[24-27]. A brief comparison between these parameterizations is presented in Table 1. The land-surface related parameters are considered in each of these schemes in accordance to the hypothesis adopted. Therefore, the performance of the schemes would purely be dependent upon the physical concepts

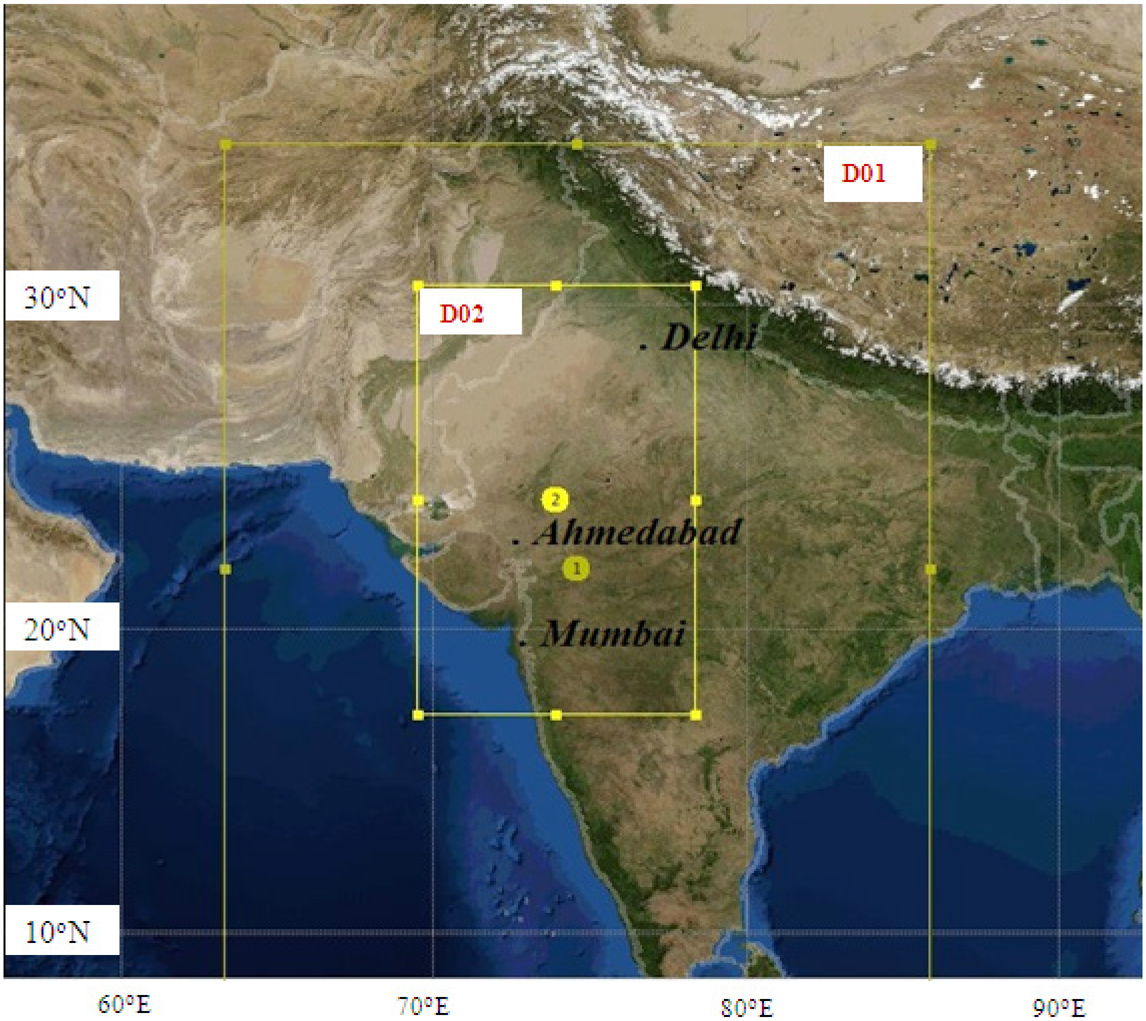


Figure 1 (a). Considered domains of study. The rectangular boundaries signify the domains 1 and 2. D01 is the outer or parent domain whereas D02 is the nested one with resolutions 30 and 10 km respectively.

or the way the land-surface features are parameterized. In view of this, four experiments are carried out using the discussed land-surface schemes in each of the five considered cases within the computational framework.

Besides considering the desired LSMs, the other physics requirements in this study include consideration of surface layer and boundary layer parameterizations, short wave and long-wave (LW) radiation schemes, cumulus convection as well as microphysics. The Kain-Fritsch scheme is chosen to parameterize cumulus convection[28]. The Mellor-Yamada-Janjic (MYJ) PBL scheme[29–30] is adopted along with Eta Similarity in order to deal with the surface layer and boundary layer processes. The microphysics scheme selected for the present study is the WRF Single-Moment 3-class (WSM3) scheme[31]. The Rapid Radiative Transfer Model (RRTM)[32], is considered for taking into account Long-Wave (LW) radiation and the Dudhia Short-Wave (SW) scheme[33] is chosen for the consideration of SW radiation in ARW modelling framework.

2.2 Geographical Area, Case Studies and Data Used

The main emphasis for this study is Delhi-Mumbai Industrial Corridor (DMIC) region. In order to address existing system related challenges and encourage a broad-based, multi-stakeholder development model for infrastructure creation, the Government of India has envisaged the DMIC (Figure 1b) project, spanning over 1,483 km between the political (Delhi) and the finan-

Table 1. Basic features of considered four land surface parameterizations available in advanced research WRF modelling system.

Scheme	Vegetation Process	Soil Variables (Layers)	Snow Scheme	Soil Moisture
Thermal	No	Temperature (5)	None	Soil moisture is fixed within a land-use and season dependent constant value
Noah	Yes (only one vegetation type in one grid cell, no dynamic vegetation and carbon budget	Temperature, Water plus Ice,(4)	1 layer, fractional, fixed snow density	Calculate soil moisture at 4 layers
RUC	Yes (one vegetation in one grid cell, sub- Grid width up to 10 Vegetation type in 1 cell. No dynamic Vegetation	Temperature, Ice ,water plus ice (6)	More complex and multi-layer, changing snow density	Calculate soil moisture at 6 layers
Pleim-Xiu	Yes	Temperature (2)	Input only	Soil moisture at 2 layers.

cial (Mumbai) capitals of the country. Over this DMIC region Figure 1b, five events are considered for this study in different time periods and at different places. The first event is considered at Delhi during 15–31 May 2009. This time period is chosen in view of hot and dry weather in Delhi under normal climatic conditions when no rainfall occurred. However, two wet cases (with rainfall) are considered over Mumbai and Ahmedabad. Over Mumbai, the well-studied heavy rainfall event in the year 2005 is considered during 26-28 July. Over Ahmedabad, the considered period is also in Monsoon season of the year 2006 during 8-12 August. In addition, one hotter (May 3, 2008) and one colder (January 22, 2008) event is considered primarily taking into account heat or cold wave conditions over north Indian region. These cases are simulated using ARW for the specified domain configuration shown in Figure 1a. FNL global data set (http://rda.ucar.edu/datasets/ds083.2/)[34] is used for providing the desired initial and periodic boundary conditions to the model that include initial soil temperature and moisture input to Noah, RUC, and Pleim-Xiu land surface schemes. In Thermal scheme, only soil temperature is used for initialization and no soil moisture computation is carried out. For proper representation of the underlying land surface in the considered region of interest Figure 1, geographical data sets from USGS are used.

For validating the near surface variables from 20 simulations carried out in this study, meteorological observations are collected from the weather stations located in the considered region. In order to quantify the performance of land-surface schemes, three meteorological parameters such as temperature, wind speed and relative humidity are primarily taken from Weather Underground. The obtained results are discussed briefly in the following section.

3. Results and Discussion

In order to quantify the performance of the land-surface schemes available in WRF modelling system over DMIC region, the near surface variables are obviously significant and need to be compared with the observations during the considered five events. For this purpose, the statistical analysis is performed over important cities such as Delhi, Jaipur (only for hotter and colder scenarios), Ahmedabad and Mumbai depending upon the availability of observational data. The quantitative analysis of results in this study includes Probability Density Function (PDF) and Cumulative Density Function (CDF) in the sidelines of discussion regarding the simulated and observed near surface meteorological parameters viz. temperature, relative humidity (RH) and wind speed. Not to mention that the WRF model performance can always be evaluated through statistical analysis and comparing with the actual observations for real time simulations[9,14,35-38]. However, using PDF and CDF in this context is quite distinctive though the present study also uses basic statistical parameters including maximum, minimum and root mean square error (RMSE) for discussing the results as per the requirement.

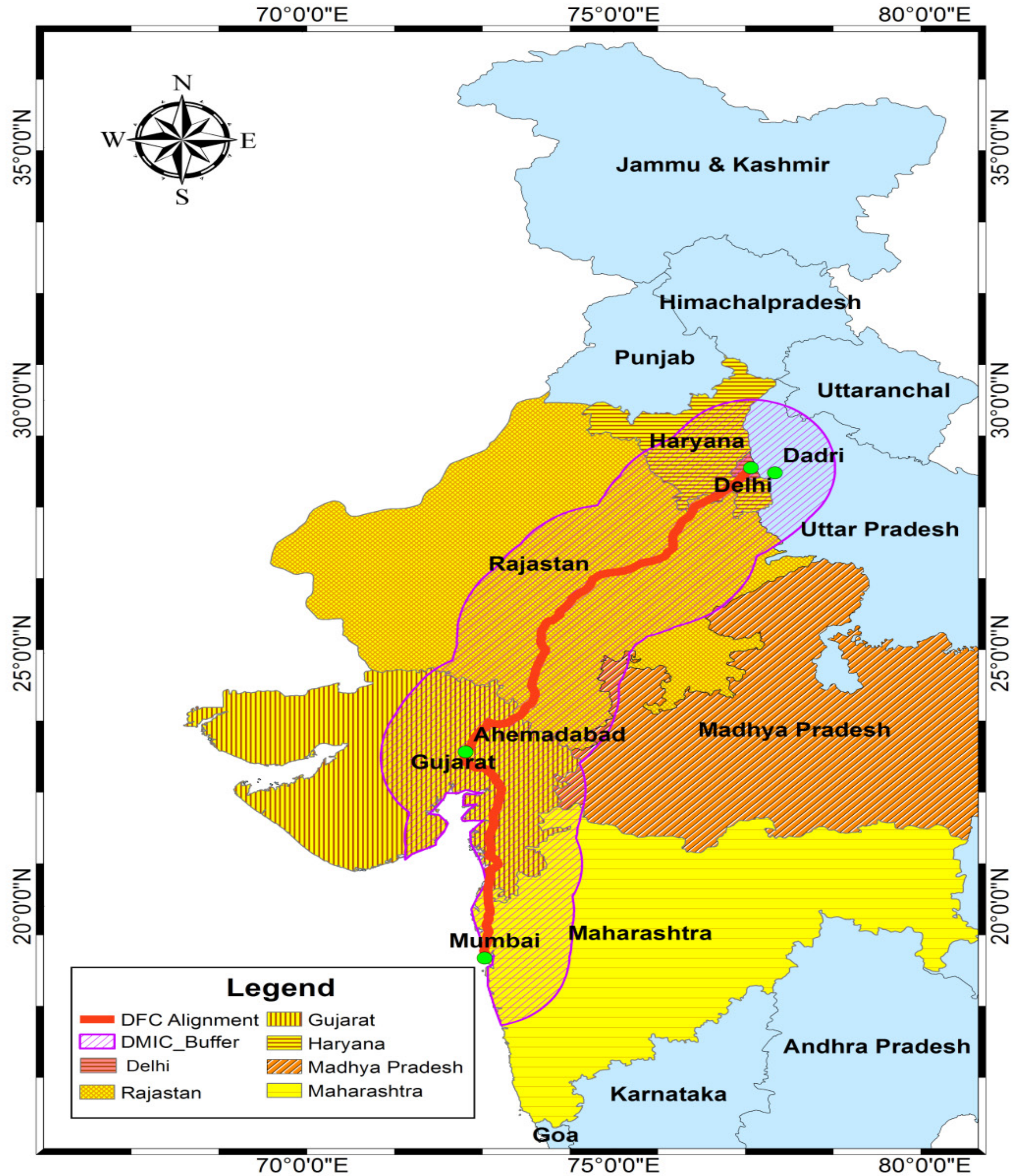


Figure 1(b). Delhi-Mumbai Industrial Corridor (DMIC) region planned by Government of India (indicated within the buffer area in part of India's map).

3.1 Dry Case for Delhi

For evaluating WRF model and quantify the performance of considered land-surface parameterizations during the simulated dry case (15 – 31 May 2009), the comparison of model output with observations is done over Delhi. Consideration of Delhi for the performance evaluation is primarily due to its significance as a mega city, geographical location, prevailing meteorological conditions and availability of data. The direct comparison between the observed and simulated near surface temperature is shown in Figure 2a. The general trend of the temporal variation of temperature for all the four land-surface parameterizations is found to be similar to the observed one. However, the difference between the simulated and

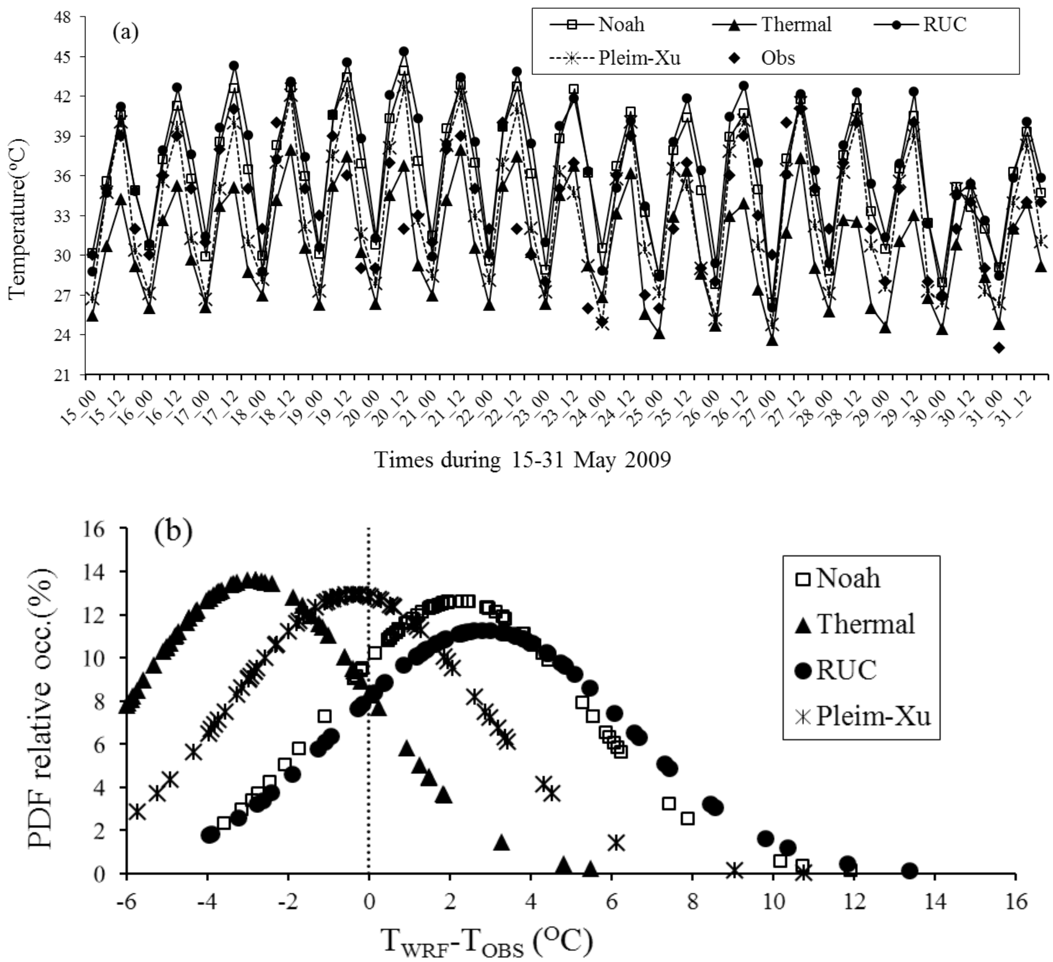


Figure 2 (a). Time series of temperature for all the four land surface schemes and observed temperature for Delhi and (b) probability density function of relative occurrence of error.

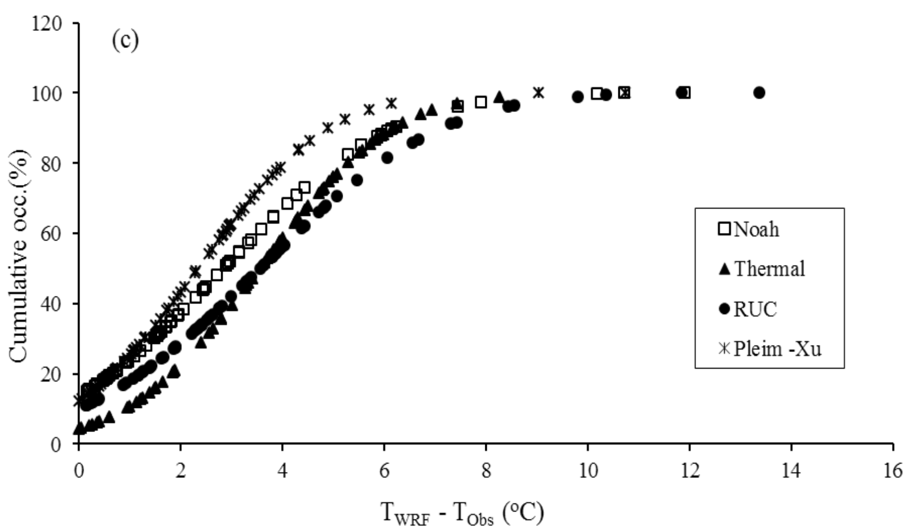


Figure 2 (c). Cumulative density functions of error for comparison of simulated and observed temperature distribution over Delhi.

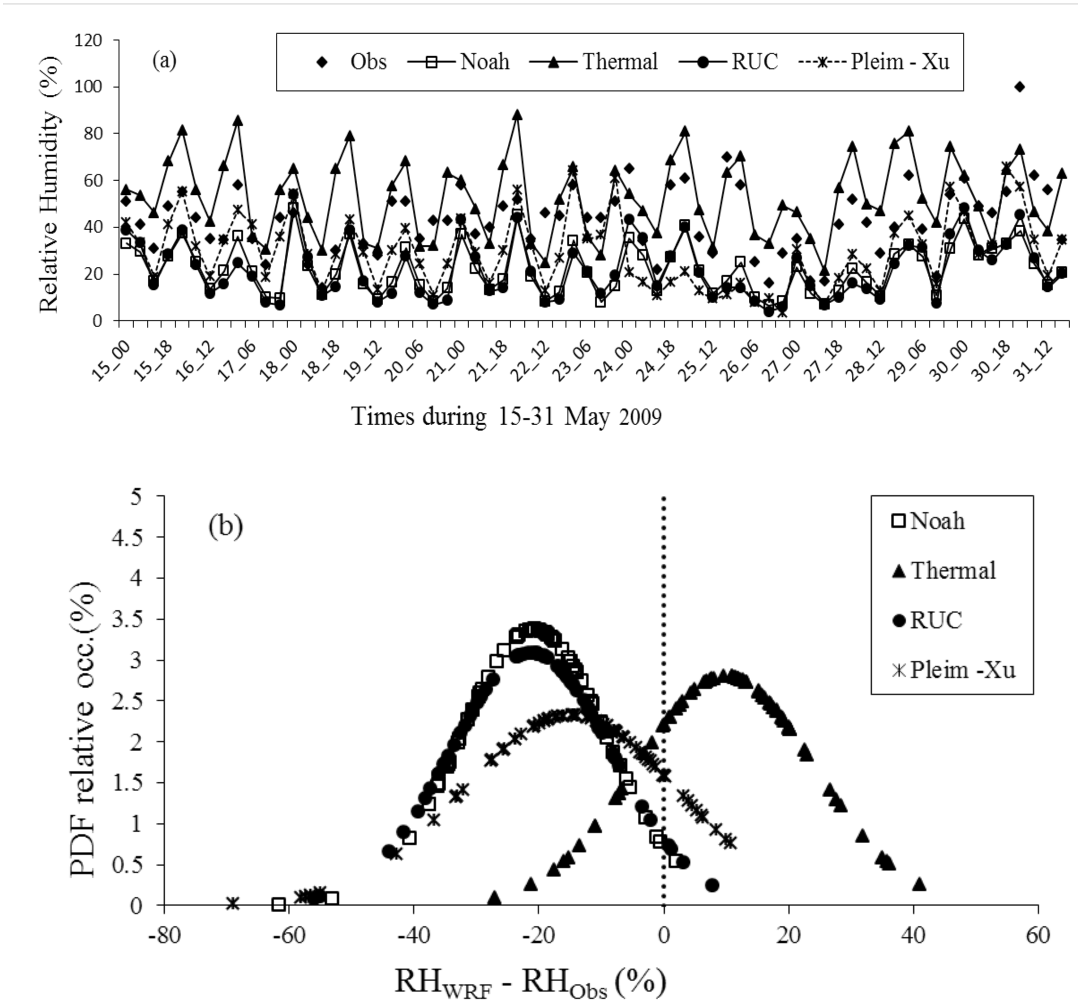


Figure 3(a). Time series of Relative Humidity (RH) for all the four land surface schemes and observed RH for Delhi and (b) Probability density function (PDF) of relative occurrence of error (i. e. difference between model and observed RH).

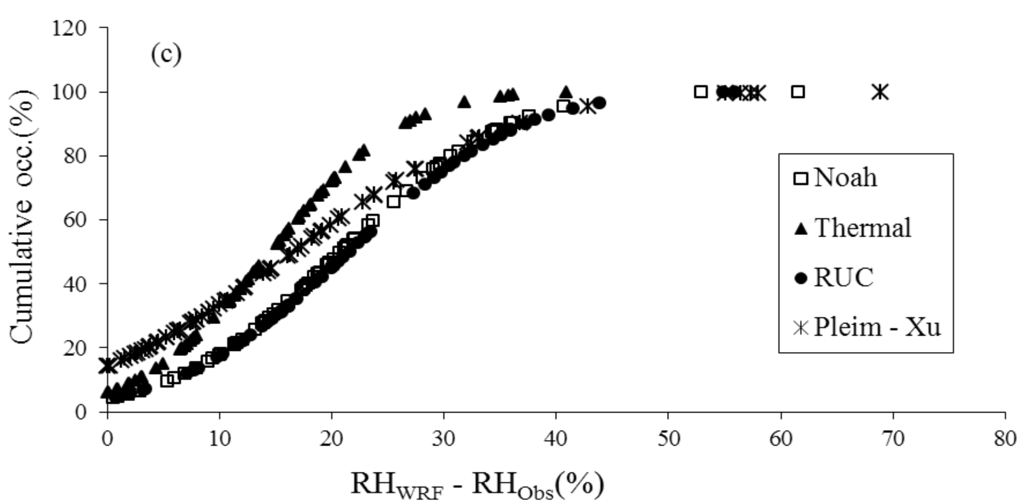


Figure 3(c). Cumulative density function of error for comparison of simulated and observed near surface relative humidity over Delhi.

observed value (i. e. $T_{WRF} - T_{Obs}$) can be properly realized through the analysis of PDF shown in Figure 2b. It shows that the Pleim-Xiu scheme performs relatively better as compared to other schemes being slightly closer to the observations. RUC and Noah schemes have a warm bias whereas Thermal shows slightly cold bias. The same is confirmed from the CDF values shown in Figure 2c, where it indicates that most values (~90%) remain in lower side of the difference T_{WRF}-$T_{Obs(in\ the\ range\ 0\text{-}6oC)}$.

The temporal variation of RH is shown in Figure 3a, while PDF and CDF of relative occurrence of error (i. e. the difference RH_{WRF}-RH_{Obs}) are shown in Figures 3b and 3c respectively. From the temporal variation of near surface RH Figure 3a it is difficult to infer which scheme performs better as when compared with the observations though it indicates that besides Thermal scheme all the other land-surface parameterizations behave in a similar manner and the Thermal scheme appears to show over prediction most of times. This is also evident in the variation of CDF of relative occurrence of error Figure 3c. However, the Figure 3b indicates that the Thermal scheme has a wet bias (about 2%) and the other three schemes are found to yield similar results showing mostly dry bias.

The direct comparison of 10 m wind speed during dry case over Delhi is presented in Figure 4a. The PDF and CDF of relative occurrence (%) of error (i. e. the difference between model and observed 10 m wind speed) are shown in Figures 4b and 4c.It is realized that WRF simulates relatively stronger winds as compared to observations for all the four LSMs in during the considered case over Delhi. However, RUC scheme gives the largest

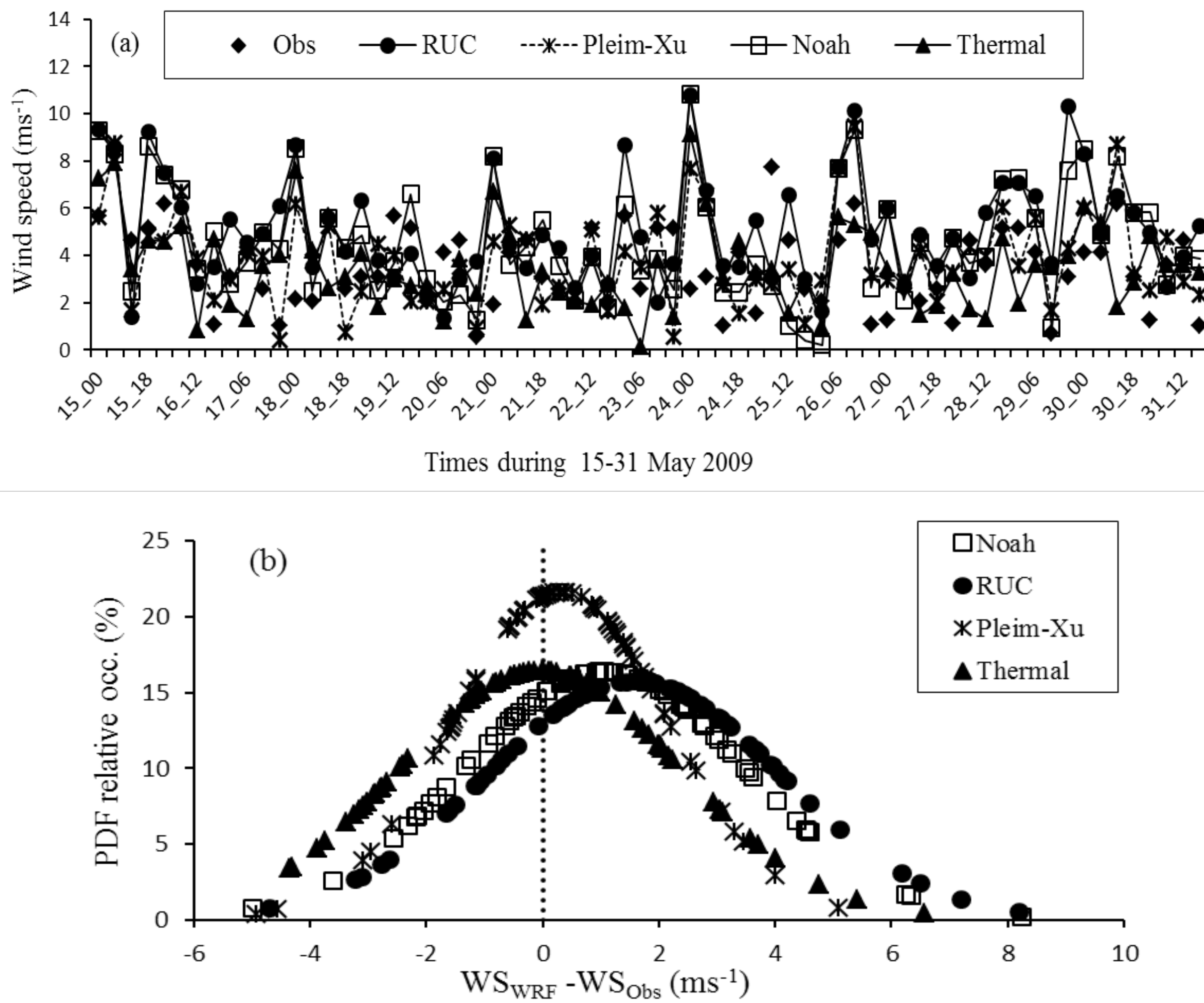


Figure 4(a). Time series of observed and computed wind speed for the entire four land surface for dry case over Delhi and (b) PDF of relative occurrence of error (i. e. difference between model and observed wind speed) during 15-31 May 2009.

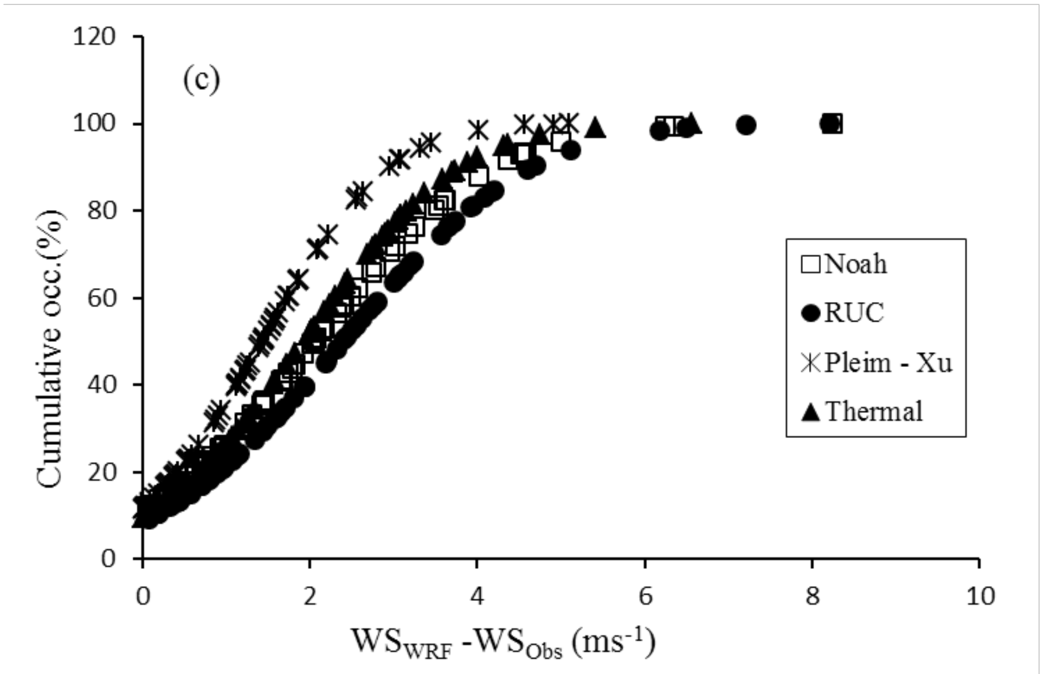


Figure 4(c). Cumulative density function of error (i. e. difference between model and observed wind speed) for comparison of simulated and observed near surface wind speed for dry case over Delhi during 15-31 May 2009.

cumulative error and Pleim-Xiu is slightly less biased as compared to land-surface parameterizations.

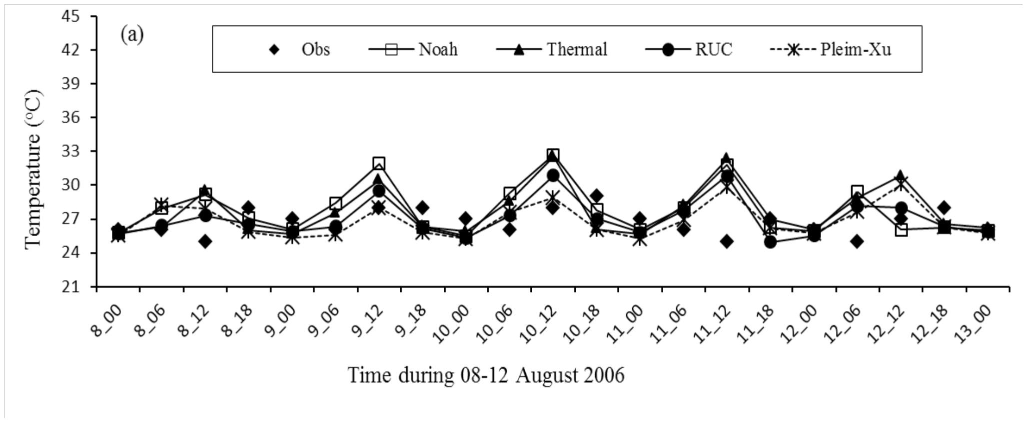
The above discussed aspects can be further justified through more statistical analysis by comparing the Root Mean Square Error (RMSE) values (Table 2). The comparison indicates that Pleim-Xiu is performing better in predicting near surface temperature and wind speed for the dry case over Delhi as when compared to other three land-surface schemes with an exception for RH, where the RMSE values are found to be smaller in case of Thermal land-surface scheme. Some of the earlier studies[13,14] suggested that Noah scheme performs reasonably well as compared to Thermal and RUC schemes when used along with MYJ PBL during dry conditions. They used relatively older version of advanced research WRF which did not have Pleim-Xiu in a relatively coarser model domain configuration and did not consider near surface RH as well. It may be noted that one of the roles of LSMs is to redistribute the incoming solar radiation between latent and sensible heat fluxes. Therefore, a better parameterization is always needed for improving the performance of a mesoscale model like WRF. Therefore, this study helps in advancing the knowledge in this direction as far as the performance of land-surface parameterizations in predicting the near surface variable in dry conditions over Delhi is concerned.

Table 2. Root Mean Square Error (RMSE) for different parameters derived from the considered land-surface parameterizations (or LSMs) in WRF for dry case over Delhi.

RMSE for considered meteorological variables			
LSM	**Temperature (°C)**	**Relative humidity (%)**	**Wind speed (ms^{-1}) at 10 m**
Noah	3.85	23.88	2.64
Thermal	4.09	17.25	2.41
RUC	4.52	24.75	2.97
Pleim-Xu	3.08	19.68	1.86

3.2 Moderately Heavy Rainfall Case over Ahmedabad

The second scenario considered for this study under DMIC region is a moderately heavy rainfall event (8-12 August 2006) over Ahmedabad. It is observed from the actual rainfall recorded by rain-gauges at the Indian Air Force stations during 7–8 August 2006, Ahmedabad (23.04°N,72.38°E), Gandhinagar (23.12°N, 72.39°E) and



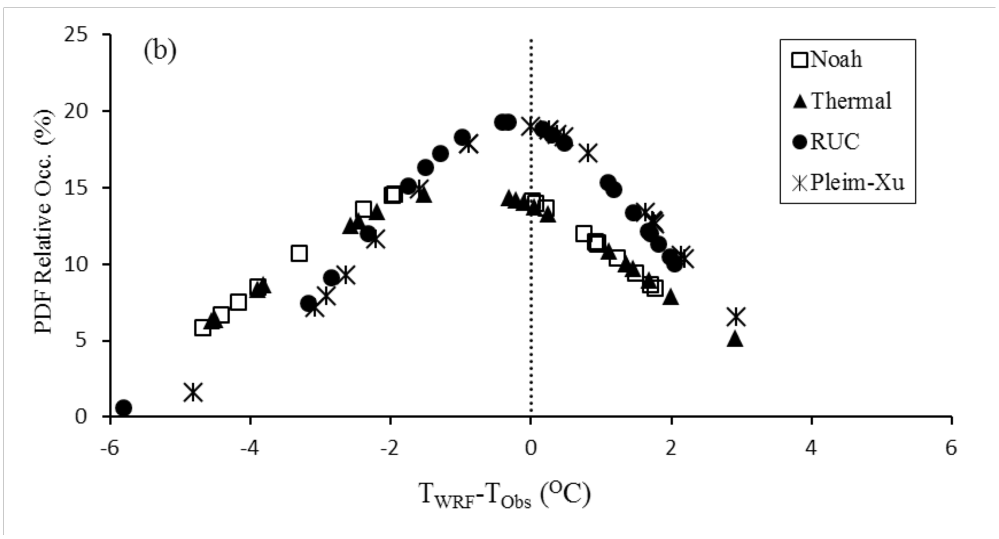


Figure 5(a). Time series of observed and computed near surface temperature for considered four land surface parameterizations in moderately heavy rainfall case over Ahmedabad and (b) corresponding PDF of relative occurrence of error (i. e. difference between model and observed temperature) during 8-12 August 2006.

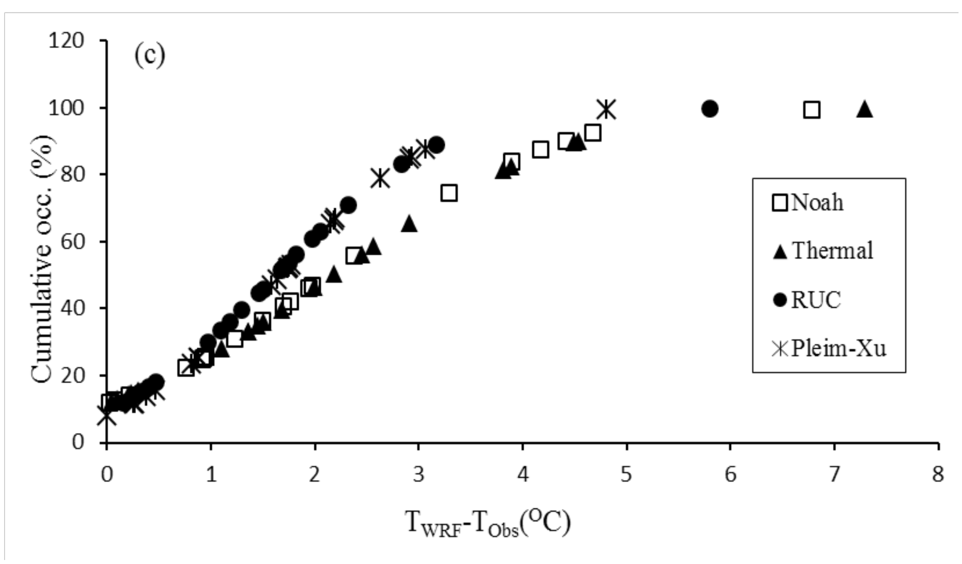


Figure 5(c). Cumulative density function of error (i. e. difference between model and observation) for comparison of simulated and observed near surface temperature for moderately heavy rainfall case over Ahmedabad during 8-12 August 2006.

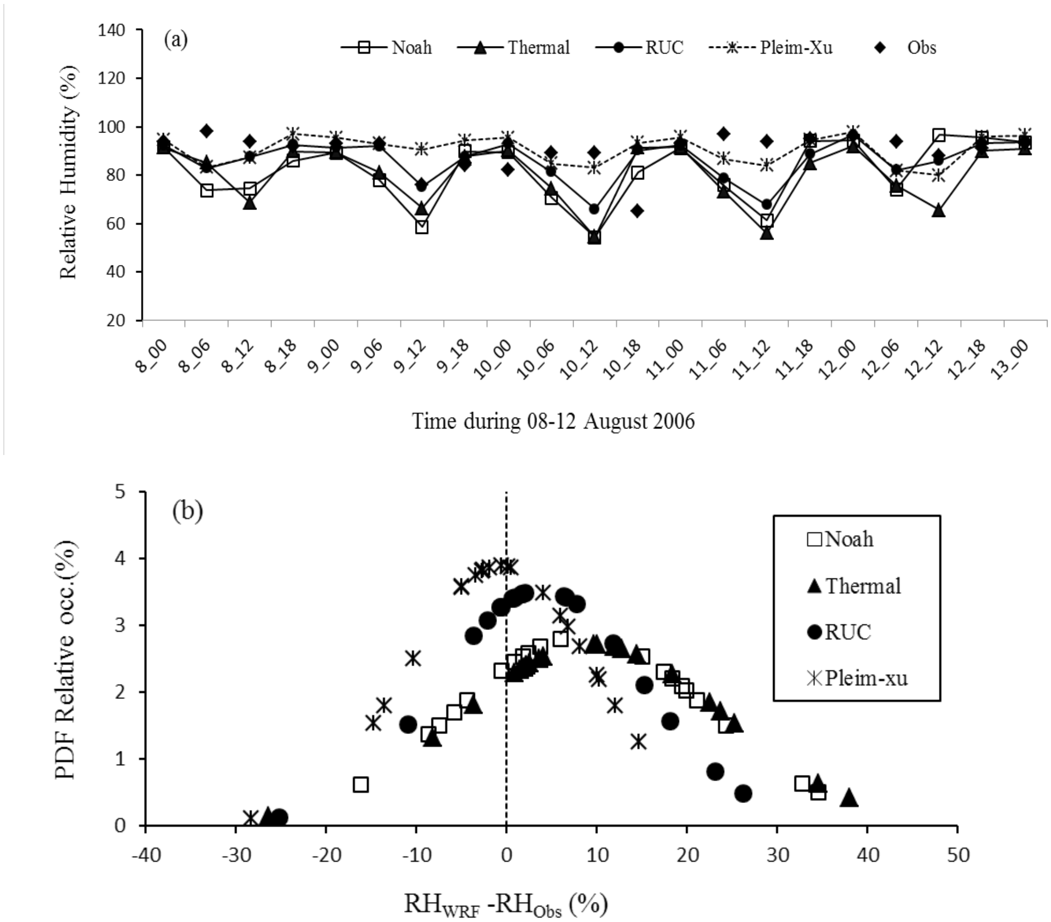


Figure 6(a). Time series of observed and computed near surface RH for considered four land surface parameterizations in moderately heavy rainfall case over Ahmedabad and (b) corresponding PDF of relative occurrence of error (i. e. difference between model and observed RH) during 8-12 August 2006.

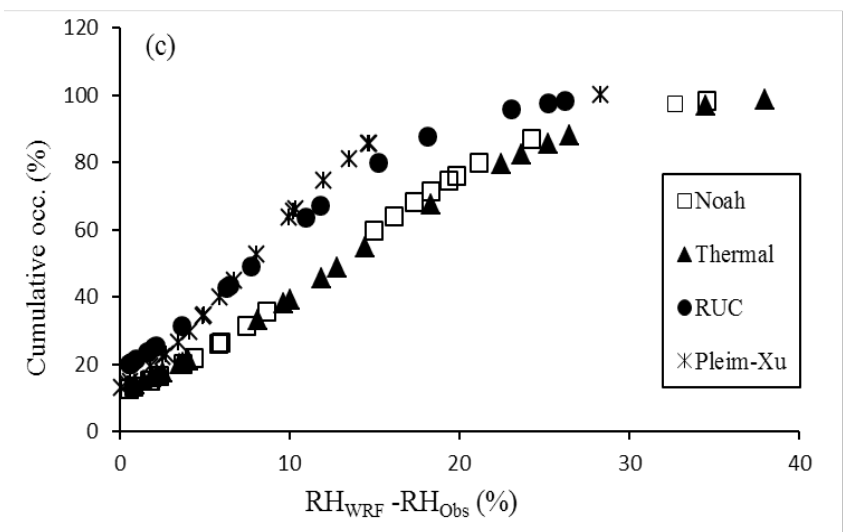


Figure 6 (c). Cumulative density function of error (i. e. difference between model and observation) for comparison of simulated and observed near surface RH for moderately heavy rainfall case over Ahmedabad during 8-12 August 2006.

Vadodara (22.20°N, 73.13°E) received 108.8mm,102.2mm and 172.0mm of rainfall respectively. Another spell of rainfall was also observed during 11–13 August 2006 over the central part of Gujarat. During this period, observed rainfall over Ahmedabad was recorded to be 97.7 mm on 12 August 2006. In view of this, the considered period for simulation purpose is from 8th to 12th August 2006 and this period is selected due to the occurrence of heavy rainfall event and availability of data. The WRF model has been evaluated for this event, especially the cumulus convection schemes[39]. According to this, study Kain-Fritsch scheme performs relatively better though the rainfall amount is underestimated by this cumulus parameterization. However, the model could capture the large-scale circulation pattern and moisture fields reasonably well. This study uses the said cumulus parameterization since the primary purpose of the present study is to evaluate the performance of different land-surface parameterizations during the wet case i.e. when there is occurrence of rainfall.

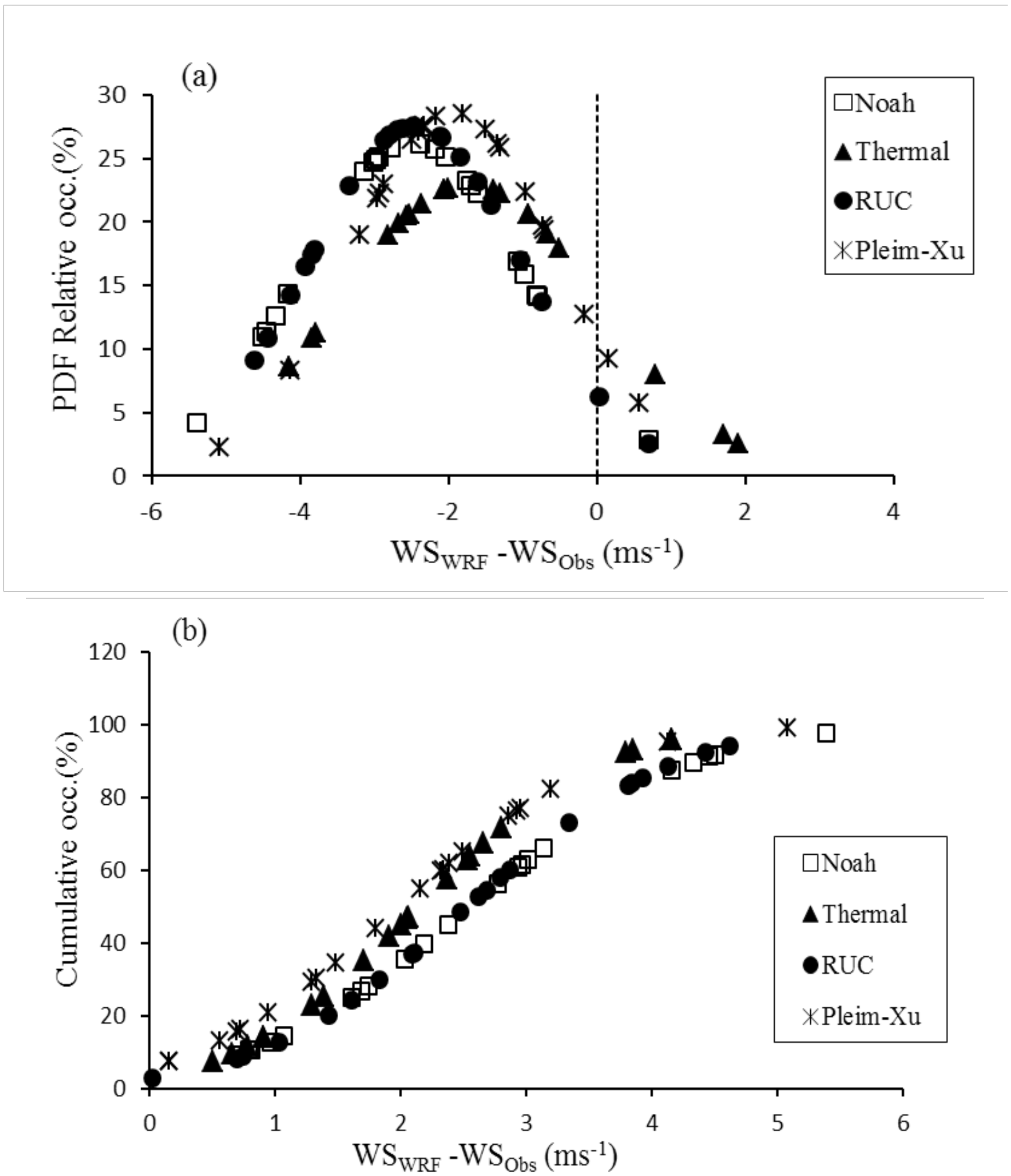


Figure 7(a). PDF of relative occurrence of error (i. e. difference between model and observed 10 m wind speed) and (b) Cumulative density function of error for comparison of simulated and observed near surface wind speed for moderately heavy rainfall case over Ahmedabad during 8-12 August 2006.

The comparison of the simulated near surface temperature with observation indicates that there is a shift (towards left) in predicting the maximum temperature (Figure 5a). On the other hand, the overall comparison indicates that the RMSE is minimum (2.04°C) for RUC and Pleim-Xiu schemes (Table 3). The corresponding PDF (Figure 5b) and CDF (Figure 5c) shows similar results. The comparison of observed RH with the computed values from considered four land-surface schemes indicates that results from the experiment considering Pleim-Xiu parameterization are relatively closer to observations (Figure 6a). The comparison of computed RMSE values confirms the same Table 3 as well. Further analysis using PDF and CDF values (Figures 6b-c) indicates that the behavior of them also found to be realistic since the shifts in maximum PDF values are observed towards right in all other schemes except Pleim-Xiu and most of the PDF values remain within 80%. However, none of the schemes behave well for the prediction of wind speed (figure not shown for brevity) and this is confirmed from the analysis of PDF as well as CDF values (Figure 7). On the other hand, the simulation considering Pleim-Xiu scheme is found to perform fairly well as compared to other schemes when the RMSE values are compared to each other Table 3. As far as the model performance for predicting precipitation in the four experiments considering various land-surface parameterizations are concerned, it is realized that the RMSE values are in higher side even as compared to those for RH Table 3. However, the simulation considering Pleim-Xiu scheme performs fairly well as compared to other experiments though the RMSE values are reasonable for the prediction of near surface temperature and 10 m wind speed Table 3 like that of the dry case over Delhi Table 2. Thus, consideration of Pleim-Xiu land-surface parameterization for a dry case as discussed earlier in sub-section 3.1 and a wet case (moderately heavy rainfall case) like the one over Ahmedabad is found to be a better choice as compared to other schemes available in advanced research WRF model. On the other hand, this may not be true always and can be case sensitive. Therefore, another wet case is considered over Mumbai region. The considered second wet case is an extremely heavy rainfall event and it would be definitely an interesting scenario to test the model performance in general as considered by several researchers[40-43] and especially the consideration of land-surface characteristic features[2,12,43] for simulation of such types of cases.

3.3 Extremely Heavy Rainfall Scenario over Mumbai

The third scenario considered in this study is an extremely heavy rainfall event that occurred during 26-28 July, 2005. On July 26, India Meteorological Department (IMD) rain-gauge at Santacruz International Airport (19.11°N, 72.85°E) on the north side of Mumbai (18°56N, 72°51°E) metropolis located in west coast of India, recorded 944mm of 24 h accumulated rainfall (0300 UTC 26 July to 0300 UTC 27 July). Mumbai usually receives heavy rainfall during the south-west monsoon season being influenced by the Western Ghats. However, several features make the 26 July 2005 event unique including the rainfall amount of 944mm, which is an extremely high value recorded for a single-day rain event over a megacity (population> 10million) such as Mumbai. Several studies have been carried out by considering this extreme rain event. Some of the studies conducted observational analysis[44-45] using observations from satellites, radar and/or ground stations. These studies suggest that the formation of mesoscale convective systems containing super thunderstorm cells and their interaction with the prevailing synoptic conditions over the adjoining Sea gave rise to the concentrated extremely heavy rainfall. Most of the studies analysed the extreme weather event by using results from numerical model simulations[40-43]. These studies demonstrated the dynamical and thermo-dynamical features including moisture transport, the vertical cloud distribution and associated precipitation. They specify that the large-scale rising motion over Mumbai is synoptically forced. Further, some of the studies suggest a significant role of land-surface processes[2,12,43] as well. They suggest that mesoscale land-surface feedback played a vital role in modulating the location and intensity of the rain due to changes in the winds and regional moisture convergences. Therefore, the role of urbanization cannot be discarded as evidenced from the climatological analysis[46]. However, an urban model embedded within a mesoscale modelling system by itself is not capable of playing a dominant role in governing the enhancement in rainfall though such type of model is helpful in determining the energy budget and to study the role of land-atmospheric interactions during this extreme event[12]. On the other hand, the land-surface parameterizations may have a notable role in determining the near surface atmospheric characteristics and possibly impact the rainfall prediction[2].

In view of the consideration of LSMs in numerical simulations using WRF model, the present study performs a statistical analysis for this case like that of the moderately heavy rainfall event over Ahmedabad (sub section 3.2). It is realized that the performance of the model in predicting near surface temperature is similar as when compared to the moderately heavy rain event over Ahmedabad since the RMSE values are < 3 in all of the four simulations (Tables 3-4). However, the RMSE values are appreciably higher for Pleim-Xiu and RUC schemes while predicting near surface RH though this is contrasting in case of Noah and Thermal schemes Tables 3-4. For 10 m wind speed, the RMSE values are between 5 to 7 for all the four simulations Table 4 and thus, the ability to predict in such a scenario reduces as when compared to the dry case over Delhi (sub-section 3.1; Table 2) and moderately heavy case over Ahmedabad (sub-section 3.2; Table 3). Similar is the situation for rainfall prediction by the model, where it is realized that the RMSE values are quite high (>71) showing weaker predictive capability of the model Table 4 compared to the moderately heavy rainfall scenario over Ahmedabad, where the RMSE values were also significant Table 3. When the PDF and CDF values are analyzed against the difference between model predicted and observed values of near surface temperature, RH and 10 m wind speed, it is realized that none of the simulations could predict them reasonably well (Figures 8-10) even though in some of the variables (viz. 10 m wind speed), it is seen that most of the CDF values lie within 80%. Thus, it is found that the performance of none of the land-surface schemes is appreciable for the extreme rainfall event case over Mumbai except for the prediction of near surface temperature. However, it may be noted that this event was dynamically stronger where super thunderstorm cells embedded within the mesoscale convective system interacted with the prevailing synoptic system[43,45]. Further, a land-surface parameterization does not play the only role in predicting accurate values of the near-surface variables and rainfall. In order to improve the predictability while considering the land-atmospheric interaction[43], appropriate representation of underlying land-use pattern in the urban setting is also required[2,6,12] besides using other observations for performing data assimilation[38,42]. On the other hand, Chang et al.[2] shows that Thermal scheme could reproduce the appropriate mesoscale features including moisture convergence zones for predicting a better rainfall over Mumbai while considering an explicit convection though it is well understood that regional scale precipitation prediction is quite sensitive to cumulus convection when such types of activities interact with synoptic features.

Table 3. Root Mean Square Error (RMSE) for different parameters derived from the considered land-surface parameterizations (or LSMs) in WRF for moderately heavy rainfall case over Ahmedabad.

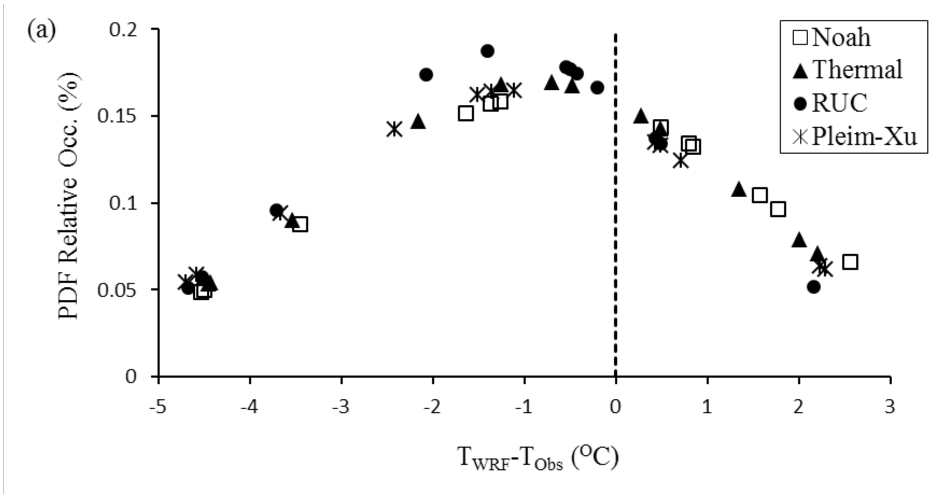
RMSE for meteorological parameters considered				
LSM	**Temperature (°C)**	**Relative humidity (%)**	**10 m wind speed (ms^{-1})**	**Precipitation (mm)**
Noah	2.74	16.09	2.89	23.83
Thermal	2.81	17.19	2.42	19.55
RUC	2.04	11.65	2.83	19.08
Pleim-Xu	2.04	10.04	2.36	18.54

Table 4. Root Mean Square Error (RMSE) for different parameters derived from the considered land-surface parameterizations (or LSMs) in WRF for extremely heavy rainfall case over Mumbai.

RMSE for meteorological parameters considered				
LSM	**Temperature (°C)**	**Relative humidity (%)**	**10 m wind speed (ms^{-1})**	**Precipitation (mm)**
Noah	2.46	15.61	5.56	76.38
Thermal	2.41	14.46	6.46	74.17
RUC	2.38	15.98	6.00	72.45
Pleim-Xu	2.56	16.25	6.22	71.08

3.4 Hotter and Colder Environmental Conditions in DMIC Region

In addition to the previously discussed three types of scenarios, it is also important to understand how the model behaves in hotter and colder environmental conditions. In view of this, two cases are considered one being a hotter case on May 3, 2008 and other being a colder case on January 22, 2008. The consideration of these days is based on the prevailing heat wave conditions over north India (basically during 11am – 6pm local time) including Delhi and Jaipur in the hotter case. Similarly, the consideration of the colder case i. e. January 22, 2008 is based on the prevailing cold wave conditions over north Indian region. The model simulations are performed for 24 hours in



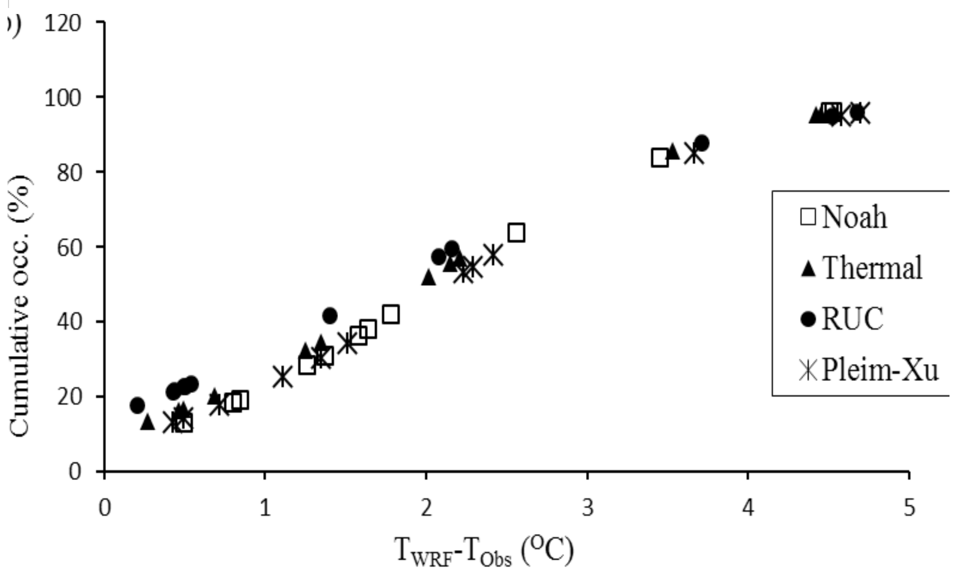
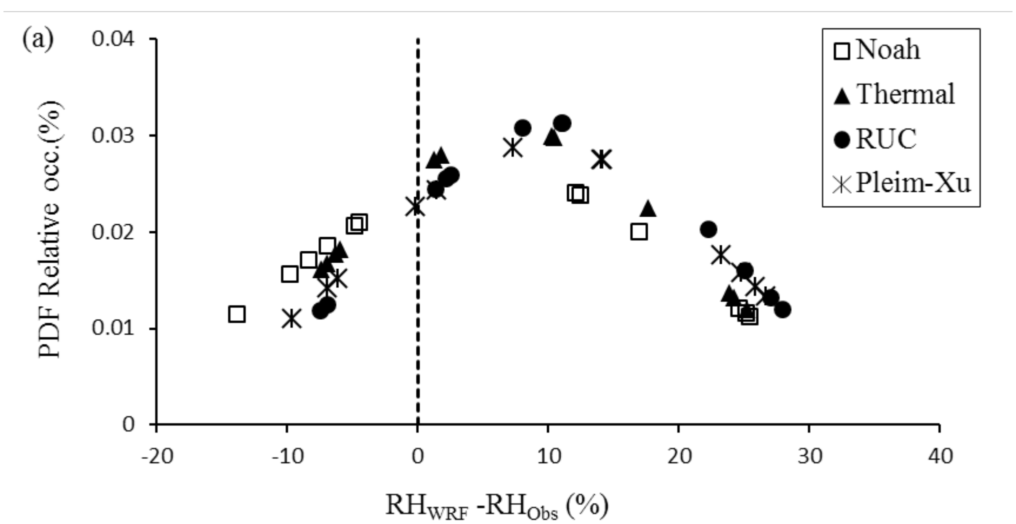


Figure 8(a). PDF of relative occurrence of error (i. e. difference between model and observed near surface temperature) and (b) cumulative density function of error for comparison of simulated and observed near surface temperature for extremely heavy rainfall case over Mumbai during 26-28 July 2005.



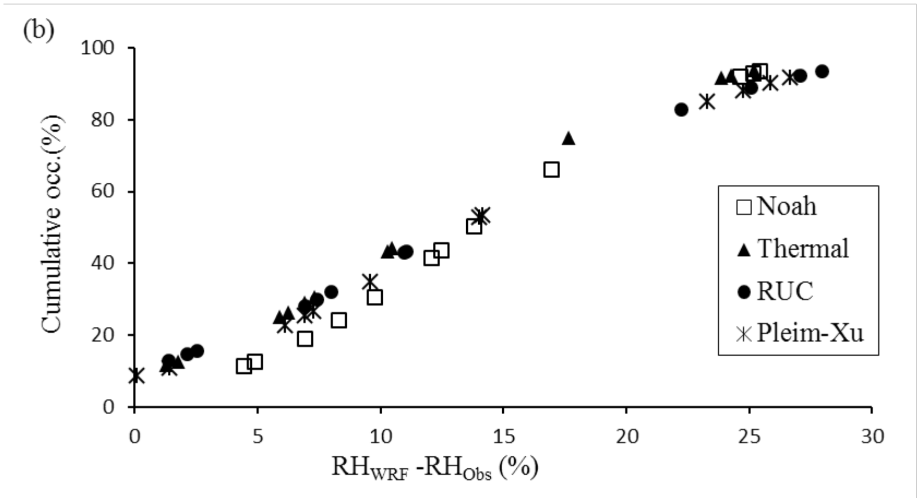
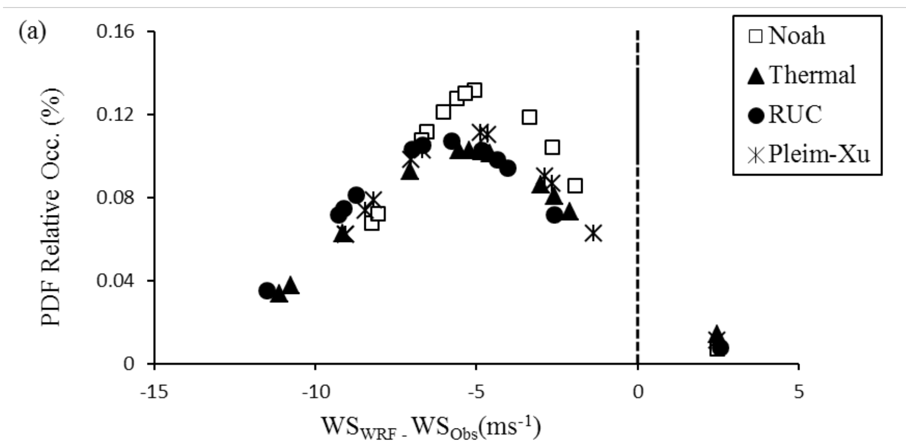


Figure 9(a). PDF of relative occurrence of error (i. e. difference between model and observed near surface RH) and (b) cumulative density function of error for comparison of simulated and observed near surface RH for extremely heavy rainfall case over Mumbai during 26-28 July 2005.



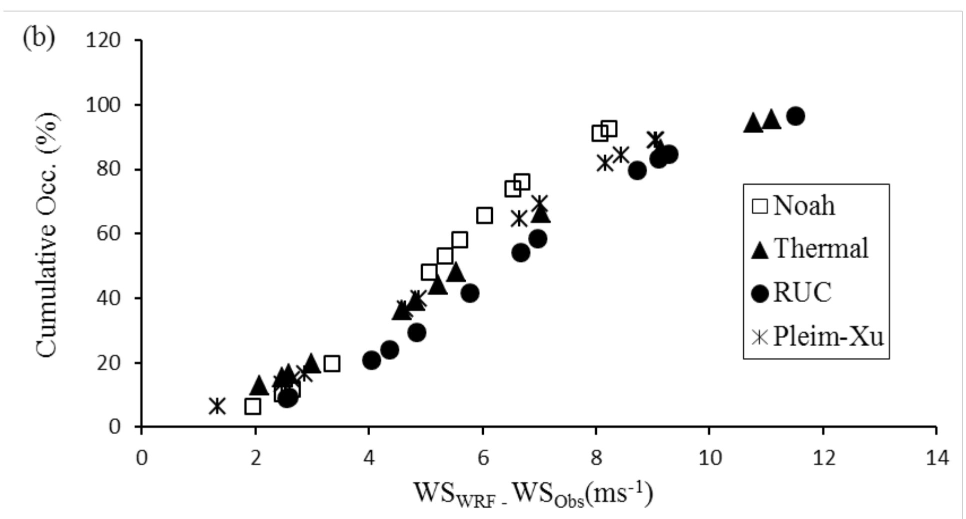


Figure 10(a). PDF of relative occurrence of error (i. e. difference between model and observed 10 m wind speed) and (b) cumulative density function of error for comparison of simulated and observed 10 m wind speed for extremely heavy rainfall case over Mumbai during 26-28 July 2005.

these two cases starting from 00 UTC on the said days using the previously mentioned four land-surface parameterizations.

The model performance is evaluated by comparing the actual observations with the simulated results for near surface temperature and RH as well as 10 m wind

Table 5. RMSE for different parameters derived from the considered land-surface parameterizations (or LSMs) in WRF for hotter temperature scenario in the DMIC region.

City Name	Land-surface schemes/ Simulations/ Experiments	Temperature	Relative Humidity (RH)	Wind Speed (WS)
Delhi	Noah	2.11	10.45	1.06
	Thermal	6.62	46.05	1.74
	RUC	2.23	7.15	0.98
	Pleim-Xu	2.88	8.23	1.01
Mumbai	Noah	2.37	13.43	1.40
	Thermal	2.80	21.34	1.10
	RUC	2.91	15.37	1.42
	Pleim-Xu	2.75	17.67	1.19
Ahmedabad	Noah	1.45	8.40	2.19
	Thermal	3.88	35.54	1.32
	RUC	2.38	11.95	2.12
	Pleim-Xu	2.15	16.79	1.44
Jaipur	Noah	2.84	9.64	2.31
	Thermal	7.62	56.24	3.11
	RUC	3.17	8.74	2.45
	Pleim-Xu	3.69	12.92	2.53

Table 6. RMSE for different parameters derived from the considered land-surface parameterizations (or LSMs) in WRF for colder temperature scenario in the DMIC region.

City Name	Land-surface schemes/ Simulations/ Experiments	Temperature	Relative Humidity (RH)	Wind Speed (WS)
Delhi	Noah	0.97	14.22	1.34
	Thermal	1.26	27.45	1.25
	RUC	1.21	11.52	1.33
	Pleim-Xu	2.81	14.97	1.06
Mumbai	Noah	2.12	22.64	0.95
	Thermal	2.44	19.12	0.64
	RUC	2.19	22.68	0.88
	Pleim-Xu	2.27	18.42	0.67
Ahmedabad	Noah	1.73	24.79	0.87
	Thermal	1.85	26.99	0.70
	RUC	2.08	24.29	0.98
	Pleim-Xu	1.82	16.51	0.81
Jaipur	Noah	0.85	12.48	Observations not available
	Thermal	1.76	34.85	
	RUC	1.03	14.90	
	Pleim-Xu	2.75	14.42	

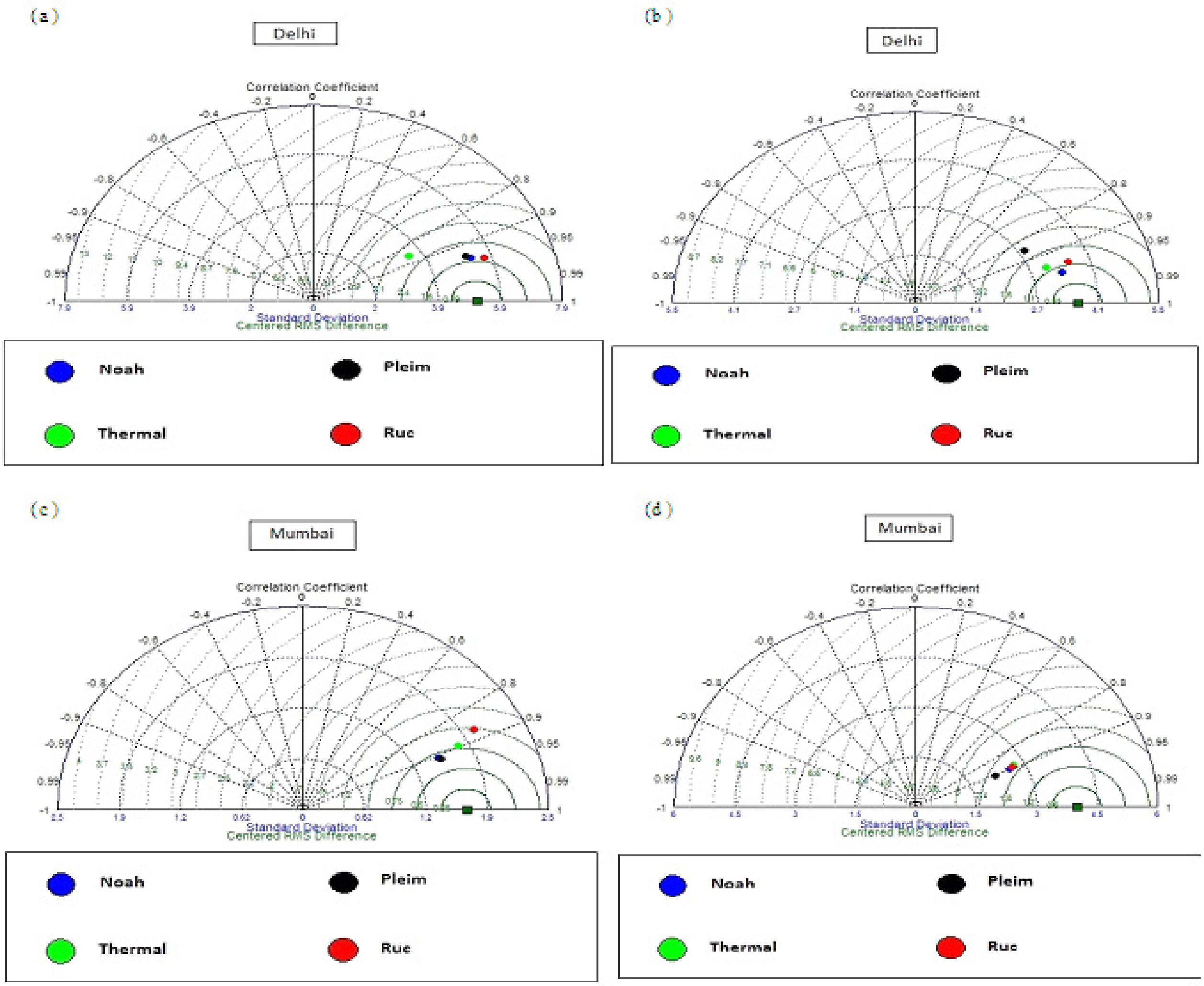


Figure 11. Taylor diagrams representing co-relation coefficients, standard deviation and RMSE for near surface temperature during hotter (a, c) and colder (b, d) scenarios over Delhi and Mumbai for evaluating the performance for four LSMs considered in the study. The top panel is for Delhi and the bottom one is for Mumbai.

speed. Quantitative evaluation of the model performance is done using RMSE values shown in Tables 5 and 6 besides standard deviation and correlation coefficient (Figures 11-12). The analysis of RMSE values indicates that the performance of Noah land-surface scheme is better as compared to the other three parameterizations for predicting the near-surface temperature over four cities Delhi, Jaipur, Ahmedabad and Mumbai within DMIC region Tables 5-6. This result agrees with the findings of Panda et al. (2009) and Panda and Sharan et. al. (2012). However, the performance of the model in predicting other two meteorological variables such as near surface RH and 10m wind speed is ambiguous. Comparison of RMSE values reveals that the performance of Thermal scheme is poor in both hotter and colder cases over all the cities (except Mumbai in colder case) as when compared to other schemes for prediction of near surface RH Tables 5-6. As far as the prediction of 10 m wind speed is concerned, the RMSE values in colder case are found to be ~ 1 ms^{-1} for all the experiments over Delhi, Mumbai and Ahmedabad. However, the observational data is not available for Jaipur for computation of RMSE values. The probable reason could be because of the prevailing stable environment during winter and the model is able to capture the low to moderate wind scenario in a better manner[13]in all the four experiments. In the hotter case,

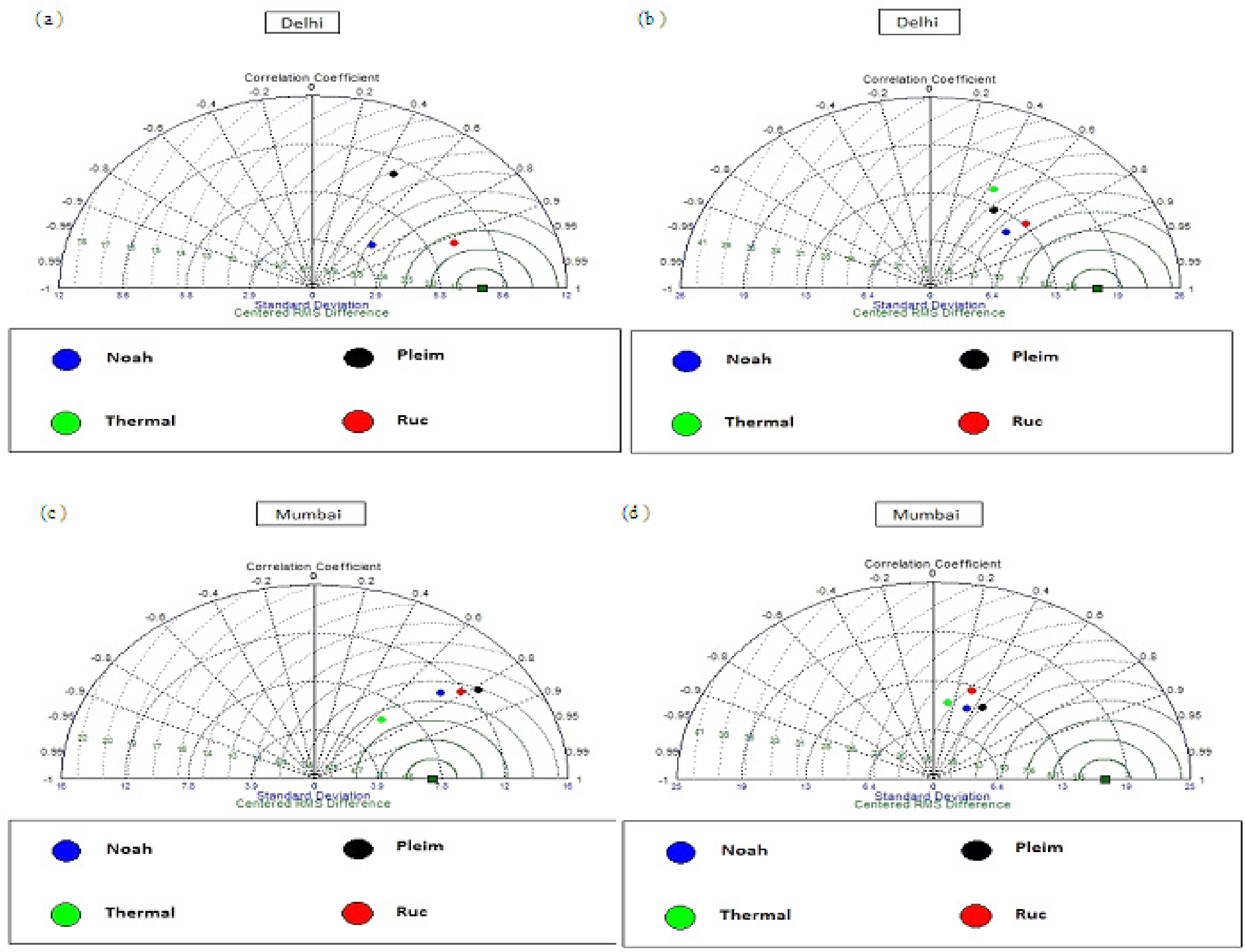


Figure 12. Same as figure 11 but for near surface relative humidity.

the RMSE values are comparatively higher though most of them are < 2.2 as seen in case of Delhi, Mumbai and Ahmedabad Table 5 whereas the corresponding values over Jaipur are between 2.3 and 3.2. The probable reason could be the prevailing localized unstable environment over Jaipur and the consequent local flow is not captured by the model in an appropriate manner.

However, the analysis may be extended by considering the standard deviations and correlation coefficients besides RMSE in the form of Taylor diagrams. Accordingly, the results are analyzed over Delhi, Jaipur, Ahmedabad and Mumbai. For representation purpose, the Taylor diagrams for the said statistical parameters for near surface temperature and RH are shown in Figures 11 and 12 respectively over Delhi and Mumbai. The collective analysis of the said statistical parameters suggest that Noah and Pleim-Xiu are performing better in most of the cases irrespective of hotter or colder environmental conditions. However, the moist variable RH is found to be predicted well in several instances when RUC LSM is considered.

Table 7. Overall RMSE values for near surface minimum and maximum temperatures and relative humidity for the month of May 2008 and 2009 taken together.

Variables	Thermal LSM	Noah LSM	RUC LSM	Pleim-Xiu LSM
Maximum temperature	7.71054	2.436	2.526	2.208
Minimum temperature	7.23284	3.37	6.51	6.54
RH	32.2809	16	17.41	17.39

Based on the analysis of various statistical parameters over Delhi, Mumbai, Jaipur and Ahmedabad in the present study within the considered modelling framework, it is realized that the overall performance of the model for prediction of the near surface variables during hotter and colder scenarios is found to be reasonably good when modestly complex land-surface parameterizations (viz. Noah, RUC and Pleim-Xiu) are considered instead of the simple Thermal scheme (popularly known as Slab model). On the other hand, the performance of the relatively simpler Thermal LSM is found to be sporadically good in few occasions.

3.5 Additional Simulations for May 2008 and 2009 using a Recent Version of WRF

Since the simulations carried out in this study primarily used a relatively older version of WRF and considers five cases for model evaluation over designated cities, it is important to update the results using a relatively recent version of the model. Therefore, WRF version 3.6 is considered in order to perform simulations for the whole month of May 2008 and 2009, which are relatively recent considerations as well. This has been done for a different perspective by considering a nested configuration with horizontal resolutions of 60 and 20 km for parent and nested domain respectively. All of the other configurations remain same as considered for previously discussed five cases. Model evaluations are performed over 10 stations in the DMIC region viz. Palam (New Delhi), Ahmedabad, Jaipur, Dhar (Madhya Pradesh), Jawai Bandh (Pali district of Rajasthan), Surat (Gujarat), Mumbai, Pune, Nimach (Madhya Pradesh) and Dabok (Udaipur, Rajasthan) by considering IMD observations for maximum and minimum near surface temperature and relative humidity depending upon the availability of data. For model performance evaluation purpose, RMSE values are computed for the said parameters by taking into account the simulated values from the nested domain. They are presented in the Table 7. Accordingly, it is found that the performance of Pleim-Xiu LSM is relatively better as compared to other schemes for predicting the maximum near surface temperature over the considered stations. However, the RMSE values for RUC and Noah LSM are not significantly different from that of the Pleim-Xiu for the maximum near surface temperature prediction. On the other hand, the model performs better for prediction of minimum temperature and relative humidity near the surface, when Noah LSM is considered as compared to RUC and Pleim-Xiu parameterizations. The performance of Thermal scheme is considerably poor. The reasons could be similar as stated earlier in previous sub-sections. In view of this result and previously case studies, it may be inferred that Noah LSM is probably a better choice for WRF simulations over the DMIC region.

4. Conclusions and Future Scope

Looking into the urbanization perspectives over DMIC region and Government of India's proposed projects in this context, it is important to understand how the near surface atmospheric variables would behave while numerical modelling is performed. In view of this, the first important parameterization that would play vital role in governing the near surface atmospheric characteristic features is the land-surface scheme. Thus, the present study uses the state of the art numerical mesoscale modelling system ARW. The newer versions (version 3 onward) of ARW contain four land-surface models including relatively simpler 5-layer thermal diffusion scheme or slab model or Thermal scheme and moderately advanced land-surface parameterizations such as Noah, RUC and Pleim-Xiu. In this study, these four land-surface schemes are considered for simulations at a regional scale for five cases including a dry case during summer 2009 over Delhi, a moderately heavy rainfall case during Aug 2006 over Ahmadabad, an extremely heavy rainfall case during July 2005 over Mumbai, a hotter case during May 2008 in which heat wave conditions were prevailing over northern parts of India and a colder case during January 2008 in which cold wave conditions were prevalent over the north Indian region. These time periods were chosen on the basis of prevailing environmental conditions and in view of testing the model performance in these scenarios.

Land surface processes are quite useful for determining the near surface temperature, humidity and wind speed. In case of clear sky when there are no clouds or fog in the atmosphere as considered in the dry case over Delhi, Pleim-Xiu is found to be performing better for predicting the near surface temperature and 10 m wind speed as compared to the other three land-surface schemes with an exception for RH, where the RMSE values are found to be smaller in case of Thermal scheme. In a moderately heavy rainfall case over Ahmedabad, Pleim-Xiu scheme also performs fairly well. In the extremely heavy rainfall case, the performances of all the three land-surface parameterizations are reasonably good for the prediction of near surface temperature. However, the performance of the model in predicting the near surface RH and 10 m wind speed is poor. And, it is also noticed that the errors are significantly high for the prediction of RH and precipitation in both moderately and extremely heavy rainfall cases. The error increased with the increase in extremity of the rainfall event and with the intensity of the rainfall while predicting the precipitation. It may be noted that the heavy rainfall events are usually associated with a dynamically unstable atmosphere and intensive thunderstorms. Further, the events if interact with the prevailing synoptic features, it is important that one should consider an appropriate cumulus convection parameterization during such extreme weather scenarios[2,35-36,47-49] for efficient prediction of regional scale precipitation. For, the predictability of the WRF model in the land-atmospheric interaction studies[6,43] appropriate representation of underlying land-use pattern in the urban setting is essential[2,6,12] besides using other observations for performing data assimilation[38,42].

In very few situations, it is observed that relatively simpler Thermal land-surface scheme performs reasonably well as compared to the moderately complex and advanced schemes like Noah, RUC and Pleim-Xiu. This is also noticed by Chang et al[2] during Mumbai rainfall event. However, this is not true in all the cases considered in this study. And, over northern Indian region Noah land-surface parameterization performs better in dry, hotter and colder scenarios[13,14] for prediction of near surface variables. Therefore, conclusion drawn is probably case and region specific as far as the performance of Thermal scheme is concerned. And, the performance of the moderately complex schemes is supposed to be better while predicting the near surface meteorological variables in WRF model simulations in most of the cases including the hotter and colder temperature scenarios as perceived in this study. The overall analysis of five events suggests that predictability of near surface atmospheric parameters is quite sensitive to the consideration of land-surface parameterizations in WRF model simulations. Having noticed that, it is also realized that the consideration of Noah and Pleim-Xiu for land-atmospheric interaction studies may be on the basis of the requirement in view of urban or non-urban aspects, geographical location and meteorological scales since their performances are found to be superior in several instances including the present study. On the other hand, it is difficult to conclude the sensitivity regarding the prediction of precipitation while analyzing the simulated results from the designed experiments considering land surface parameterizations only[3].

Further, the present study is carried out using ARW model version 3.2.1 in view of the available limited computational resources in the early stage of research. However, the more recent versions of the model (e.g. version 3.6) consider mosaic approach to Noah that has some similarity to the considerations in Pleim-Xiu scheme. Using these advanced features incorporated in the recent versions of the model may help improve the performance of Noah land-surface parameterization in WRF simulations especially when the grid cells are relatively larger. In view of this, the additional simulations are carried out with an updated version of the model (i.e. version 3.6). And, the results are found to be similar over the Indian region for the month of May 2008 and 2009 taken together. The future studies would consider other aspects including land use and land cover changes as per the feasibility and test WRF performance using newer versions of the model. Few studies emphasize upon utilization of soil moisture nudging or appropriate soil moisture initialization for proper use of LSMs including Pleim[1,11]. It is because, with growing sophistication, LSMs produce larger wet bias due to overestimation of moisture flux convergence that is attributed to the overestimated surface evapotranspiration[10]. However, the scope of this study is limited to the evaluation of the available schemes rather than considering nudging aspect since it may dilute the primary objective. In addition, thermal land-surface or SLAB scheme has a limitation of not taking into account the temporal variation of land-surface characteristics[14] including soil moisture and thus, may not be a state of art scheme even if it can produce reasonable results occasionally!

In order to better represent the underlying land-surface characteristics, a well-defined high resolution LULC data set is required. Such data sets are quite useful for high resolution model simulations of mesoscale weather[6,16] or regional climate studies[18]. Therefore, future studies would consider the updated high resolution LULC data sets for WRF simulations.

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