Iranian Journal of Geophysics, Vol 17 No 6, 2024, Page 25 – 36 (Research Article)
DOI: 10.30499/IJG.2023.383632.1489

Evaluation of different WRF-Urban Canopy Models performance in city-scale numerical simulations in Tehran Metropolis

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(Received: 25 April 2023, Accepted: 29 January 2023)

Abstract
Simulation of near-surface weather parameters is a challenging process, especially in urban areas, because it is difficult to precisely identify surface characteristics in urban micro-scales. Different urban parameterizations for the representation of urban structure are coupled with numerical weather or climate models to improve the accuracy of the micro-scale simulations. In this study, the numerical results of the Weather Research and Forecasting model (WRF) with three different urban configurations, namely no urban canopy or the SLAB scheme, Single-Layer Urban Canopy Model (SLUCM) and Multi-Layer UCM or the Building Effect Parameterization (BEP) in the simulation of near-surface air temperature, relative humidity and wind speed are evaluated against the observations in Tehran Metropolis, during 15 to 29 June 2016. Overall, results show that SLUCM and BEP predict meteorological parameters more accurately than SLAB scheme. Although the performance of the model is not the same in different weather stations, comparing SLUCM and BEP results, on average, over four stations of Tehran shows that BEP results in minimum errors and the maximum Pearson coefficients. In addition, the more intense night-time urban heat island is also simulated in BEP (over 2.5°C) in comparison to SLUCM (1.5°C) and SLAB (0.5°C). However, the daytime UHI intensity is approximately simulated with the same intensity in the three mentioned simulations. Since high-resolution numerical simulations are time-consuming and expensive, current results can be used in other related studies to avoid extra costs.

Keywords: Microclimate simulations, WRF, urban Canopy Models, Tehran Metropolis

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1 Introduction

The WRF model is widely used in climatic and weather numerical studies in both regional meso-scale and urban micro-scale. Three different urban canopy parameterizations are introduced for the representation of the urban structure, namely the SLAB scheme, the Single-Layer Urban Canopy Model (SLUCM), and the Multi-Layer UCM (MLUCM) or the Building Effect Parameterization (BEP) (Figure 1).

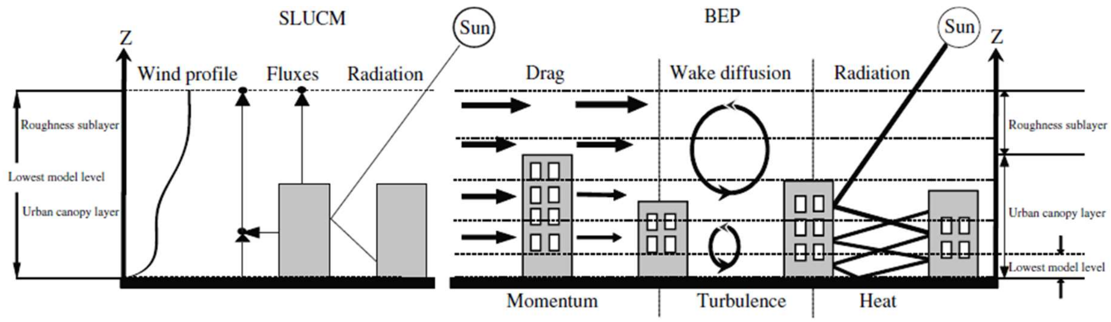

Figure 1. A schematic of SLUCM (left) and multi multi-layer BEP models (right) (Chen et al., 2011).

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SLAB scheme is the default in the WRF model which uses the 5-layer thermal diffusion model as the land surface model. This is a one-dimensional scheme that considers buildings in urban areas as increased roughness elements of the surface (roughness length equal to 0.8 m to represent turbulence caused by roughness elements as well as drag generated by buildings). In this scheme, urban canopy parameters and morphological properties over the city are not included (Liu et al., 2006). Some field observations indicate that this approach is unable to reproduce vertical turbulent fluxes in the urban roughness sub-layer (Rotach, 1993) since it does not take into consideration the surface energy balance from the shadowing and radiation trapping effects. Also, the ground is considered as the only momentum sink and is not distributed up to the building heights. Anthropogenic heat flux and fraction of vegetation are also ignored in this scheme.

The single-layer urban canopy model has been coupled with WRF to represent the simplified urban geometry by considering street canyons and urban surfaces such as roofs and walls (Kusaka et al., 2001; Kusaka and Kimura, 2004). The shadowing, reflections and trapping of radiation effects in urban canyons and a fixed temporal profile of anthropogenic heat are also considered.

The third urban canopy layer model (BEP) considers direct interaction between the buildings and the urban boundary layer, and the three-dimensional urban structure (Martilli et al., 2002). Effects of the vertical and horizontal urban surfaces on momentum, potential temperature and turbulent kinetic energy are included. BEP estimates heat emissions from the canopy by considering the drag force, diffusion factor, and radiation properties. In this model, urban structure is considered at different levels (different buildings height). Similar to SLUCM, the shadowing, radiation trapping, and reflection effects are also estimated. Unlike SLUCM, it divides the canopy into many sub-layers down to the surface. Such representation better simulates the mechanical and thermodynamic structure of the urban roughness sub-layer, hence the urban boundary layer.

The accuracy of different urban canopy simulations is investigated in different urban sites. For example, Liao et al. (2014) explored the impacts of three different urban canopy parameterizations, namely SLAB, SLUCM, BEP and BEP+BEM (Building Energy Model), in WRF/Chem on regional climate and air quality in Yangtze River

Delta, China. The results showed that compared with the SLAB scheme, BEP caused an increase of temperature (0.5°C), while SLUCM simulated lower temperature (0.7°C) in January. But in July, both the UCMs experiments calculated lower air temperatures with a reduction of 0.5°C to 1.6°C relative to the SLAB. Authors suggested that the SLAB scheme is suitable for real-time weather forecast, while multiple urban canopy scheme is necessary for quantification of the urbanization impacts on regional climate (Liao et al., 2014). Similarly, numerical simulations using WRF model coupled with different UCMs were applied to characterize the urban heat island (UHI) in Toronto. Results indicated that the SLAB is reliable for climate simulations, but for the evaluation of the UHI magnitude and to analyze more sophisticated structures, BEP has to be applied as it is critical to account for the air turbulences and multi-reflections in the urban canopy (Jandaghian and Berardi, 2020). Results of a sensitivity study to evaluate different UCMs existing within the WRF model in the urban area of Lisbon, Portugal also showed significant differences in the characteristics of the urban boundary layer between BEP and SLUCM, manifested through changes in turbulent kinetic energy (TKE) and urban boundary layer height over the city center. Compared to ground observations and radiosonde data retrieved within the core urban area, studied variables are better represented by BEP compared to SLUCM (Teixeira et al., 2019). Simulations of meteorological and air quality variables during a pollution episode in Megacity Shanghai using WRF/CMAQ model with the BULK scheme and SLUCM also demonstrate that the accuracy of results has improved in SLUCM. SLUCM predicts variables such as boundary layer height, wind speed, temperature and relative humidity but BULK scheme better simulates wind direction. It is also demonstrated that simulated concentrations at sites with high urbanization were significantly improved by considering urban parameterization (Wang et al., 2019).

The ongoing rate of urbanization in metropolitan areas such as Tehran Metropolis (TM), the capital of Iran, is an unfavorable phenomenon. Since this city suffers from an increasing population and therefore demand for residential areas has elevated in recent decades, many sub-urban regions have been converted to residential areas to respond to the demand for accommodation, and the density and population of the city center have increased, remarkably. In addition, many industrial areas are developed especially in the west and south of the city (Figure 3-b). Therefore, TM experiences environmental problems such as the intensified rate of the UHI (Alizadeh-Choobari et al., 2016; Bokaie et al., 2019; Rousta et al., 2018), low thermal comfort (Hejazi zadeh and Karbalaee, 2015) and high level of air pollution (Ali Akbar Bidokhti et al., 2016) because of heavy traffics and intense usage of fossil fuels in both industrial and domestic sections. Previous studies have proved that the complex geographical situation of TM, including the Alborz mountain range in the north and desert in the south and west (Figure 4-b), and low local wind speed (daytime anabatic and night-time katabatic) and natural ventilation over the city deteriorate mentioned environmental problems (Ali Akbar Bidokhti et al., 2016). Considering the importance of accurate and reliable simulations of near-surface parameters in the urban area of Tehran, which helps to predict future regional meteorological and environmental conditions, the suggestion of the most precise urban canopy model will be the main objective of the current study. Besides, the estimated diurnal UHL intensity over this city will be studied. To access this goal, high-resolution numerical simulations are performed by the WRF model with three different urban parameterizations (SLAB scheme, SLUCM and BEP), and numerical results are compared with observations.

2 Methodology

2-1 Modification of Landuse/Landcover

The Landuse/Landcover (LULC) information is adopted from USGS 24-category data. For a better presentation of LULC properties of the study area, free SENTINEL-2A images (https://earthexplorer.usgs.gov/) for summer 2016 have been applied and processed (Arghavani et al., 2020). In the following, in the case of BEP simulation, the urban expansion, LU_INDEX and urban fraction data of three urban and built-up areas, namely Low Residential (LR), High Residential (HR) and Commercial/Industrial (C/I) are estimated and introduced to the model in separate additional land-use categories of 31, 32 and 33, respectively. Indeed, LULC data in the SLAB and SLUCM include 24 classes of land cover (one class for the urban and build-up areas which indicates the single-layer structure of the city, Figure 2-a), while in BEP simulation, LULC data includes 33 classes of land cover (three classes of 31, 32 and 33 present the multi-layer structure of the urban canopy, Figure 2-b). Considering the mosaic approach in WRF numerical model, each grid point includes three urban classes, and the index of land-use (LU_INDEX) of each grid will be determined according to the maximum fraction between HR, LR, or C/I classes (Figure 3).

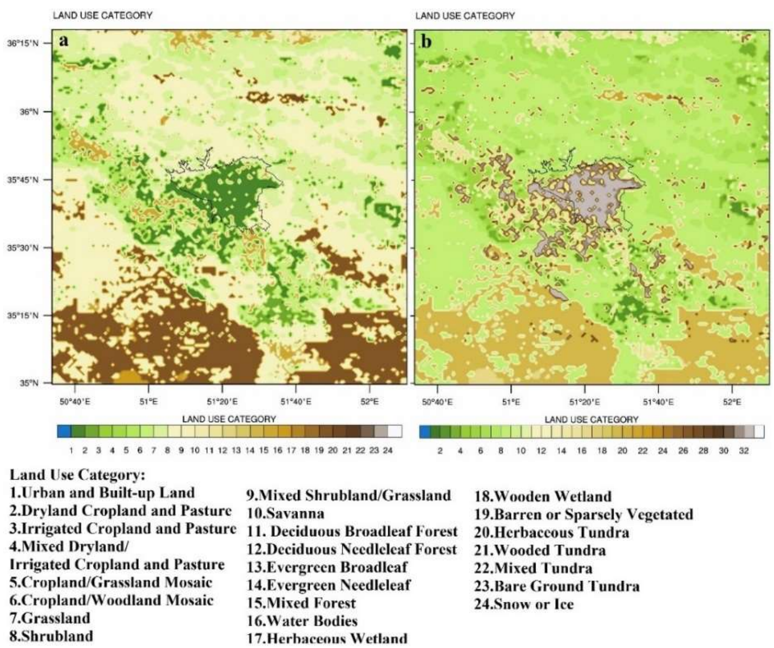

Figure 2. USGS land-use categories over the 4th domain of simulations. (a) SLAB scheme and Single-Layer UCM with 24 classes of LULC include one class of Urban and Built-up land. (b) Multi-Layer UCM (BEP) with 33 classes of LULC including 31 (Low Residential area), 32 (High Residential area) and 33 (Commercial/Industrial area) for Urban and Built-up land.

2-2 Model configuration and numerical simulations

WRF model version 3.8 (Skamarock and Klemp, 2008) coupled with Noah land surface model (Chen and Dudhia, 2001) is used for conducting simulations over four domains with resolutions of 27, 9, 3 and 1 km (Figure 4-a). Details of the model configuration are presented in Table 1. Initial and the boundary conditions are from the six-hourly National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) reanalysis data on a 1°×1° grid at 30 vertical pressure levels.

The maximum intensity of Tehran UHI occurs in the warm months (Jahangir and Moghim, 2019). So, a typical summer-time period of 15 to 29 June 2016 is selected for three simulations to ignore special weather situations (such as rainfall, cloudiness, or heat waves) impacts on results. The first

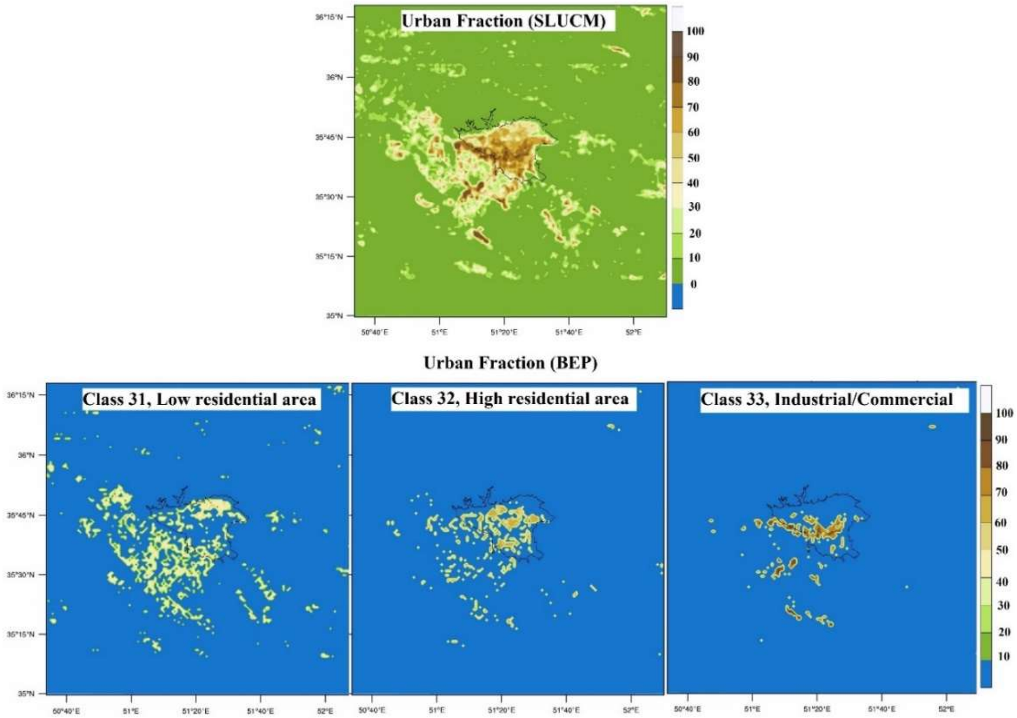

Figure 3. Fraction of Urban and Built up category over the 4th domain (SLUCM and BEP).

day of simulations is considered as the model spin-up and not included in final analysis. As mentioned in previous sections, three different simulations are performed with different urban canopy configurations. WRF urban parameters (URBPARM.TBL) for simulations are presented in Table 2. It should be noticed that according to the results found in section 2-1, the parameter FRC_URB (fraction of the urban landscape which does not have natural vegetation) in the high residential area (HR) is modified.

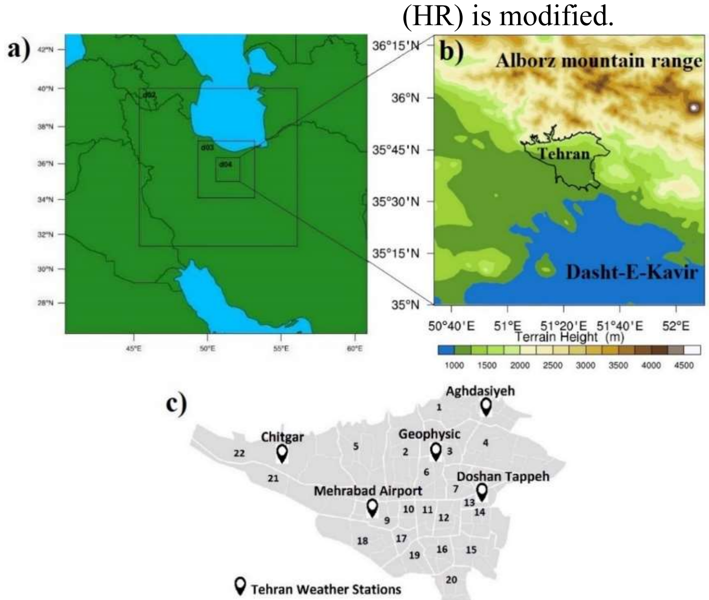

Figure 4. (a) Four simulation domains (27, 9, 3 and 1 km). (b) The extent of the 4th domain. (c) Location of weather stations over 22 regions of Tehran.

Table 1. Model configuration

Simulations Period	2016-06-15_00:00 to 2016-06-29_00:00
Microphysics	WRF Single-Moment 6-class scheme (Hong and Lim, 2006)
Radiation	Long Wave: RRTM (Mlawer et al., 1997) Short Wave: Dudhia (Dudhia, 1989)
Planetary Boundary Layer	Mellor-Yamada-Janjic scheme (Janjic, 1994)
Land Surface Model	Noah Land Surface Model
Surface Layer	Eta similarity (Janjic, 2002)
Urban Physics: **sf_urban_physics = 0** **sf_urban_physics = 1** **sf_urban_physics = 2**	Simulation 1: No urban canopy (the SLAB scheme) Simulation 2: Single-Layer Urban Canopy Model (SLUCM) Simulation 3: Multi-Layer Urban Canopy Model (BEP)
Cumulus Parameterization	Kain-Fritsch scheme (Kain, 2004)
Horizontal spacing (grid points)	d01: 27km (70 × 70), d02: 9km (109 × 109) d03: 3km (118 × 118), d04: 1km (149 × 149)
Vertical spacing	30 full sigma levels / Model top level: 50 mb
Time Step	d01: 180s, d02: 60s, d03: 20s, d04: 6s
Objective Analysis Data	GFS (ftp://nomads.ncdc.noaa.gov/GFS/)
Observation Data	Iran Meteorological Organization/synoptic stations in Tehran

Table 2. WRF model predefined urban parameters for three urban areas: Low Residential (LR), High Residential (HR) and Industrial/Commercial (C/I)

Urban Parameters	LR	HR	C/I
FRC_URB -Fraction (*modified*)	0.5	0.9 (*0.85*)	0.95
Roof level (building height) [m]	5.0	7.5	10.0
Anthropogenic heat [W/m^2]	20.0	50.0	90.0
Anthropogenic latent heat [W/m^2]	20.0	25.0	40.0
Surface albedo of roof [fraction]	0.20	0.20	0.20
Surface albedo of building wall [fraction]	0.20	0.20	0.20
Surface albedo of ground (road) [fraction]	0.20	0.20	0.20

2-3 Model Validation

Model performance in simulation of near-surface air temperature, relative humidity and wind speed is evaluated by comparing the numerical results with observation data provided by Iran Meteorological Organization (http://irimo.ir/) in four weather stations over TM, namely Tehran Shomal (S1), Geophysic (S2), Mehrabad Airport (S3) and Chitgar (S4) (Figure 4-c, Table 3). Statistical analyses are performed by Pearson coefficient (R), Mean bias error (MBE), mean absolute error (MAE), and root mean square error (RMSE):

$$\text{Mean Bias Error (MBE)} = \frac{1}{n}\sum_1^n (x_s - x_o) \quad (1)$$

$$\text{Mean Absolute Error (MAE)} = \frac{1}{n}\sum_1^n |x_s - x_o| \quad (2)$$

$$\text{Root Mean Square Error (RMSE)} = \left(\frac{1}{n}\sum_1^n (x_s - x_o)^2\right)^{\frac{1}{2}} \quad (3)$$

where x_s and x_o represent simulation and observation values, respectively.

Table 3. Characteristics of Tehran weather stations

Station	Geographical coordinates	Elevation from sea level
Tehran Shomal – S1	51˚29′E, 35˚48′N	1548 m
Geophysic – S2	51˚23′E, 35˚45′N	1415 m
Mehrabad Airport – S3	51˚19′E, 35˚41′N	1190 m
Chitgar – S4	51˚10′E, 35˚44′N	1305 m

3 Results

3-1 Near-surface air temperature

The hourly comparison of the near-surface air temperature of simulations with three urban canopy settings vs. observation for selected stations (Table 3) is shown in Figure 5. Pearson coefficients and statistical errors including MBE, MAE and RMSE are summarized in Table 4. Clearly, results are improved in simulations including urban canopy settings, especially BEP. Minimum errors and higher Pearson coefficients are simulated in UCMs in all stations, indicating that UCMs better predict the diurnal trend of near-surface air temperature in comparison to the SLAB scheme. Comparing SLUCM and BEP numerical results in four stations shows that BEP leads to the minimum errors in all stations, except for Tehran Shomal (S1) (MBE_{SLUCM} = -1.14˚C; MBE_{BEP} = -1.42˚C). Comparison of Pearson coefficients shows that SLUCM has better performance in S1 (R = 0.93) and Geophysic (S2) (R = 0.96), while in Mehrabad (S3) (R = 0.94) and Chitgar (S4) (R = 0.95), BEP results in higher values. The anthropogenic heat (in SLUCM) and also the reflection of radiations in a street canyon in UCMs settings cause these differences. Indeed, the SLAB scheme simulates cooler cities since anthropogenic heat and also the reflection of radiations in a street canyon from roofs, building walls and ground are ignored in this scheme.

3-2 Near-surface relative humidity

Similar to section 3-1, statistical evaluation for 2-m relative humidity simulations is performed by the same method, and results are summarized in Table 4. The minimum errors are observed in SLUCM in S2 (MBE = 0.45%) and S3 (MBE = 0.82%). The maximum errors are calculated in S4 in the SLAB (MBE = -5.7%) and SLUCM (MBE = -2.94%), following by BEP in S2 (MBE = 2.65%). Pearson coefficients are improved in both UCMs in comparison to the SLAB in all stations. Overall, UCMs improve the accuracy of relative humidity predictions relative to the SLAB. Comparing SLUCM and BEP shows that, although BEP better captured the diurnal variation of this parameter than SLUCM in all stations, unlike the near-surface air temperature, BEP shows higher errors relative to SLUCM in S1, S2 and S3.

3-3 Near-surface wind speed

The statistical evaluation for 10-m wind speed simulations is performed by the same method, and results are summarized in Table 4. The Pearson coefficients are clearly improved in all stations in BEP simulations. In all simulations and stations, the model overestimates wind speeds, except for S3. The maximum errors are simulated in S2 (MBE_{SLAB} = 1.44 m/s; MBE_{SLUCM} = 1.25 m/s), and the best performance of the model is observed in S1 (MBE_{SLAB} = 0.31 m/s; MBE_{SLUCM} =0.37 m/s; MBE_{BEP} = 0.27 m/s).

Since the complicated urban morphology (buildings with different heights which reduce local wind speeds) is not considered in the SLAB scheme, higher wind speeds are simulated in this scheme relative to SLUCM and BEP. Besides, in the SLAB simulation, low Pearson coefficients are calculated in four stations, proving the inefficiency of this scheme in the prediction of the wind speed diurnal trend.

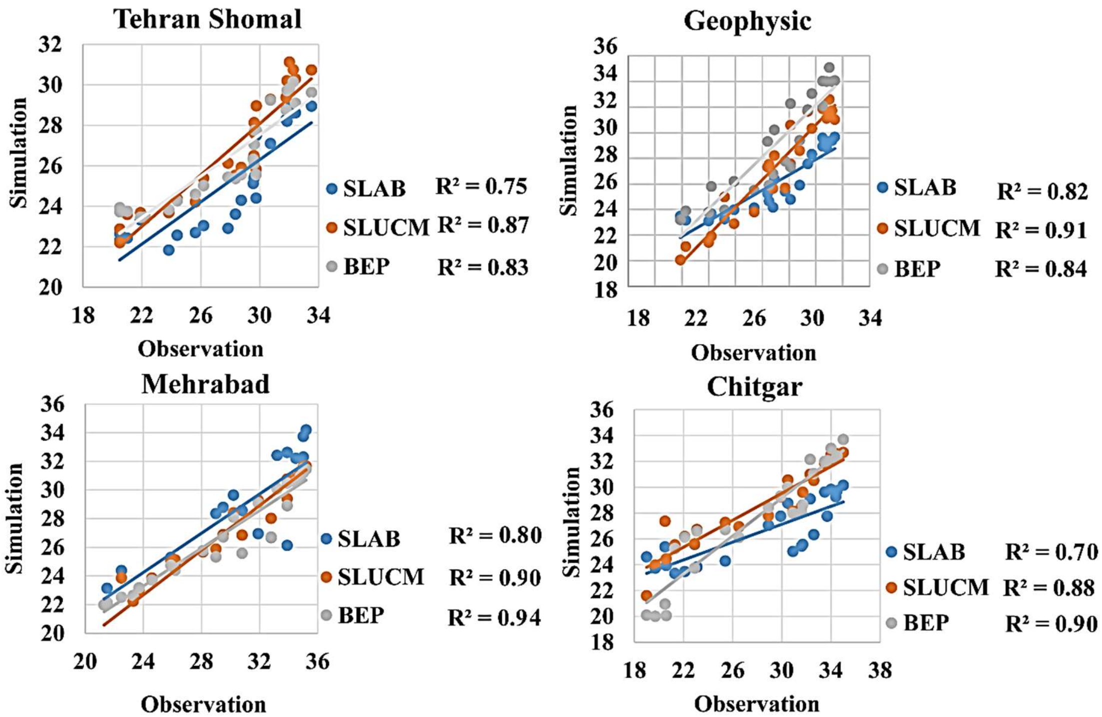

Figure 5. Example of comparison of averaged (16-29 June 2016) simulated vs. observations values (2-m air temperature) in Tehran weather stations (Tehran Shomal, Geophysic, Mehrabad Airport and Chitgar).

3-4 Urban Heat Island

The UHI is a city that is significantly warmer than its surrounding rural areas caused by LULC changes and human activities (Landsberg, 1981). The LULC change leads to variations in the physical properties of land including albedo, surface roughness, thermal inertia, and evapotranspiration, which finally result in local climate alterations (Oke et al., 1989). Therefore, for the simulation of the UHI and any other city-scale phenomenon, it is necessary to introduce the correct LULC data and proper urbanized settings to the model.

In this section, the performances of three urban canopy configurations in the simulation of UHI intensity over Tehran are evaluated. Because of the lack of observational data in sub-urban areas, only the numerical results are compared. Comparisons of night-time (00:00 local time) and daytime (12:00 local time) near-surface UHI intensity between two samples urban area of Tehran and sub-urban regions in three simulations (SLAB, SLUCM and BEP) are shown in Figure 6.

Overall, the nightly urban heat island phenomenon is predicted in all simulations but with different intensities. The difference of 2-m air temperature between points A (urban city center) and B (sub-urban) at night reaches 1˚C, 2˚C and close to 3˚C in SLAB, SLUCM and BEP simulations, respectively. As mentioned before, additional sources of heating such as the anthropogenic heat and release of stored solar heat from buildings materials in urban areas relative to sub-urban regions at night are the main causes of a warmer city in UCMs simulations. The lower wind speeds simulated in SLUCM and BEP simulations (see section 3-3) reduce the natural heat ventilation over the city and trap heat inside the urban canopy, which leads to more intense UHI than the SLAB simulation, especially in HR and C/I regions. On the other hand, 2-m air temperature difference reaches more than 3˚C relative to the east sub-urban areas and only 0.5˚C in the west, south and west-east rural areas in all simulations, in the daytime. This shows that warm local winds originating from the desert in the south and

Table 4. Statistical comparison of averaged (16-29 June 2016) simulated 2-m air temperature (˚C), 2-m relative humidity (%) and 10-m wind speed (m/s) with observations using MBE, MBA, RMSE, and R in Tehran weather stations: Tehran Shomal (S1), Geophysic (S2), Mehrabad Airport (S3) and Chitgar (S4)

		MBE			**MAE**			**RMSE**			**R**		
	Station	**SLAB**	**SLUCM**	**BEP**	**SLAB**	**SLUCM**	**BEP**	**SLAB**	**SLUCM**	**BEP**	**SLAB**	**SLUCM**	**BEP**
T2m (˚C)	S1	-2.72	-1.14	-1.42	3.39	2.44	1.94	3.54	2.63	2.13	0.86	0.93	0.91
	S2	-2.67	-1.61	0.15	3.04	1.67	1.35	3.29	1.99	1.52	0.89	0.96	0.92
	S3	-2.55	-2.31	-1.99	2.55	2.47	2.01	3.18	2.98	2.33	0.89	0.90	0.94
	S4	-1.62	0.42	-0.33	3.68	2.45	1.62	4.13	2.85	2.02	0.83	0.94	0.95
RH2m (%)	S1	1.30	1.12	-1.79	4.40	2.58	2.82	4.67	3.36	3.47	0.52	0.85	0.87
	S2	2.00	0.45	2.65	4.66	4.04	3.18	6.23	5.78	4.05	0.53	0.70	0.89
	S3	-1.92	0.82	-1.02	4.20	4.00	1.71	6.23	4.58	2.38	0.83	0.94	0.98
	S4	-5.7	-2.94	-2.04	8.04	5.07	3.17	10.43	6.29	4.05	0.88	0.90	0.96
10-m Wind Speed (m/s)	S1	0.31	0.37	0.27	0.86	0.83	0.71	1.26	1.05	0.96	0.32	0.62	0.80
	S2	1.44	1.25	1.06	1.73	1.69	1.19	2.26	1.96	1.53	0.50	0.42	0.53
	S3	-0.35	-0.45	-0.75	1.00	1.30	1.30	1.48	1.56	1.75	0.41	0.45	0.57
	S4	1.34	0.49	0.4	1.76	1.31	1.06	2.14	1.71	1.52	0.32	0.68	0.71

south-west of Tehran play a significant role in the determination of daytime UHI in this area. The most severe UHIs during the night and early morning in TM are also simulated in a previous study, and the city center is found as the night-time UHI core (Jahangir and Moghim, 2019).

4 Conclusion

In this study, numerical simulations of the WRF model with three different urban canopy configurations, namely no-canopy or the SLAB scheme, single-layer (SLUCM) and multi-layer BEP are used to suggest the most appropriate and precise urban canopy model for the prediction of near-surface meteorological variables in Tehran Metropolis. Results show that SLUCM and BEP can predict near-surface variables, including temperature, relative humidity, and wind speed more accurately than the SLAB scheme. The accuracy of numerical results is different over four weather stations indicating that model predefined settings may better match with the real structure of the city in some weather stations. This result is in agreement with the previous studies such as Wang et al. (2019), which showed more significant improvement in final simulations in HR areas than the LR areas after using SLUCM instead of the BULK scheme. Comparison of the single-layer and multi-layer urban canopies also shows that the minimum averaged errors and maximum Pearson coefficients are estimated in BEP.

On average, in all simulations, the model underestimates 2-m air temperature (probably due to the underestimation of predefined anthropogenic heat) and 2-m relative humidity but overestimates 10-m wind speed. In the case of urban heat island intensity, BEP simulates warmer city and more intense UHI relative to other simulations, especially at night.

Overall, both SLUCM and BEP lead to acceptable results in city-scale simulations, but BEP simulates the meteorological variables (near-surface air temperature and wind speed) more precisely than SLUCM and SLAB because it considers the three-dimensional structure of the city with three low residential, high residential and industrial/commercial categories in each grid points. It also considers the heterogeneity in urban structure (various bu-

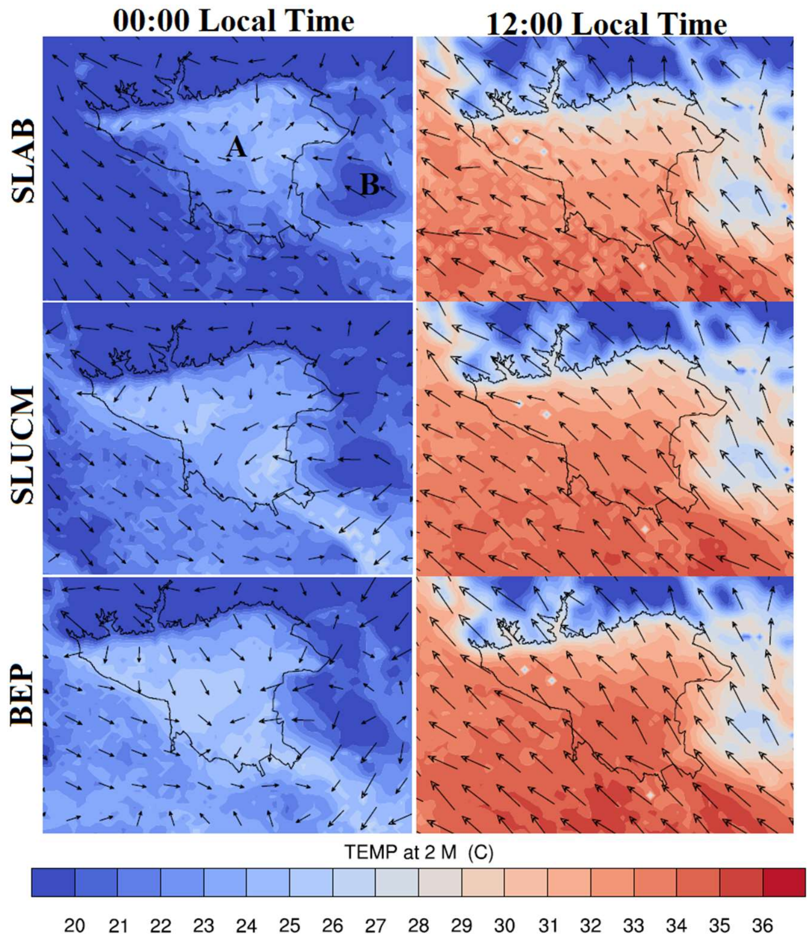

Figure 6. Comparison of night-time (00:00 local time) and daytime (12:00 local time) near-surface UHI intensity between urban area of Tehran and sub-urban areas in three simulations (SLAB, SLUCM and BEP).

ilding heights and urban fractions over the city), the effects of shadowing, radiation trapping and reflections, vertical and horizontal exchanges of momentum as well as heat and moisture in the street canopy. However, these simulations are more time taking and need additional costs and computing resources. Therefore, the selection of each urban parameterization depends on the availability of Land-use/Land-cover data (to modify land-use categories from 24 to 33) and extra computational resources. As explained in section 2-1, in this work, free satellite images are used to achieve this purpose which is a new approach in this field. Besides, high resolution simulations (four domains and 1 km resolution in the 4^{th} domain) are performed on the HPC (High Performance Computing) cluster in the case of BEP for the first time.

It should be mentioned here that these results cannot be generalized to other metropolitan areas. Authors admit the necessity of similar studies for different seasons, especially winter with intense night-time urban heat island. Finally, the authors suggest the correction of WRF predefined urban parameters such as roof and building walls albedo, anthropogenic heat and latent heat fluxes, building heights, and heat capacity of roofs and building walls according to observations and local data in Tehran, which directly influence the accuracy of the results.

Acknowledgments

Authors acknowledge the United States Geological Survey (USGS) and National Centers for Environmental Prediction

(NCEP) for providing satellite images and global model data, and Iran Meteorological Organization (IRIMO) for providing observational data.

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