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Impacts of different urban canopy schemes in WRF/Chem on regional climate and air quality in Yangtze River Delta, China

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A B S T R A C T

Yangtze River Delta (YRD) region has experienced a remarkable urbanization during the past 30 years, and regional climate change and air pollution are becoming more and more evident due to urbanization. Impacts of urban canopy on regional climate and air quality in dry- and wet-season are investigated in this paper, utilizing the Weather Research and Forecasting/Chemistry (WRF/Chem) model. Four regimes of urban canopy schemes with updated USGS land-use data in actual state of 2004 base on MODIS observations are examined: (1) SLAB scheme that does not consider urban canopy parameters (the control experiment in this paper); (2) a single-layer urban model with a fixed diurnal profile for anthropogenic heat (UCM); (3) multilayer urban canopy model (BEP-Building effect parameterization); (4) multilayer urban models with a building energy model including anthropogenic heat due to air conditioning (BEP + BEM). Results show that, compared with observations, the best 2-m temperature estimates with minimum bias are obtained with SLAB and BEP + BEM schemes, while the best 10-m wind speed predictions are obtained with BEP and BEP + BEM scheme. For PM_{10} and ozone predictions, BEP + BEM scheme predicted PM_{10} well during January, while the best estimate of PM_{10} is obtained with UCM scheme during July, BEP + BEM and SLAB schemes best estimated ozone concentrations for both the two months. Spatial differences of meteorological factors between canopy schemes and control scheme show that compared with SLAB scheme, BEP and BEP + BEM schemes cause an increase of temperature with differences of 0.5 °C and 0.3 °C, respectively, UCM scheme simulates lower temperature with decrease of 0.7 °C during January. In July, all the canopy experiments calculates lower air temperature with reduction of 0.5 °C–1.6 °C. All the canopy experiments compute lower 10-m wind speed for both January and July. Decreases were 0.7 m/s (0.8 m/s) with UCM, 1.7 m/s (2.6 m/s) with BEP, and 1.8 m/s (2.3 m/s) with BEP + BEM schemes in January (July), respectively. For chemical field distributions, results show that, compared with SLAB scheme, UCM scheme calculates higher PM_{10} concentration in both January and July, with the differences of 22.3% (or 24.4 μg/m^3) in January, and 31.4% (or 17.4 μg/m^3) in July, respectively. As large as 32.7% (or 18.3 μg/m^3) of PM_{10} increase is found over Hangzhou city during July. While 18.6% (or 22.1 μg/m^3) and 16.7% (or 24.6 μg/m^3) of PM_{10} decreases are fund in BEP and BEP + BEM schemes during January. Compared with control experiment during January, 6.5% (or 2.6 ppb) to 10.4% (4.2 ppb) increases of ozone are computed over mage-cities by canopy experiments. All the three canopy schemes predict lower ozone concentrations and as large as 30.2% (or 11.2 ppb) decrease is obtained with UCM scheme, and

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16.5% (6.2 ppb) decrease with BEP scheme during July. The SLAB scheme is suitable for real-time weather forecast while multiple urban canopy scheme is necessary when quantify the urbanization impacts on regional climate.

1. Introduction

Urbanization causes changes of the land-use over the urban area and form the urban canopy. High building clusters in mega cities form the urban canopy layers and modify the surface energy budgets and surface roughness, and therefore change thermal and dynamic characteristics of the surface layer. These changes will significantly influence the surface heat balance (Arnfield, 2003; Rizwan et al., 2009; Zhang et al., 2010), exchange of water vapor and momentum between the atmosphere and the surface layer (Zhang et al., 2008; Lin et al., 2008; Miao et al., 2009a,b.), influence urban precipitation (Miao et al., 2009a; Assela et al., 2014; Wan et al., 2013) and change local and regional weather, climate, and affect the transport and dispersion of pollutants and air quality (Wang et al., 2007b, 2009a,b).

Recently, mesoscale models coupling the urban canopy schemes have been increasingly used to study the dynamic and thermal properties of the urban boundary layer (UBL), especially after the wildly use of the community mesoscale Advanced Research Weather Research and Forecasting (ARW-WRF) model. Lots of scientists investigate the urban climate change and elevate the ability of model prediction (Chen et al., 2004, 2011a). To represent the thermal and dynamic effects of the urban areas, the first urban scheme is developed. It uses greater heat capacity and energy conductivity to reproduce the heat storage in urban surface (Liu et al., 2006), meanwhile, the roughness parameters are considered to represent momentum sink and turbulence generation (Salamanca et al., 2011). The shortcoming of these methods is that they cannot include the heterogeneities present due to a variability of urban morphology between different neighborhoods (Salamanca et al., 2011). Thus, the more complicated urban canopy model, the single-layer urban canopy model (UCM), is developed by Kusaka et al. (2001), Kusaka and Kimura (2004). UCM represents the urban geometry by assuming infinitely-long street canyons and also considers the 3-D urban surface such as walls, roofs and roads. These improvements can be important, for example, shadowing, reflections and trapping of radiation are considered, besides, skin temperature at the roof, wall and road (calculated from the surface energy budget) and temperature profiles within the street canyon (calculated from the thermal conduction equation) are included as well. Furthermore, the sensible heat fluxes from the surface are calculated with Monin-Obukhov similarity theory and Jurges formula. The important factor anthropogenic heat (AH) and its diurnal profiles are included and added to the sensible heat flux from the street canyon (Chen et al., 2011a). Taha and Ching (2007) and Miao et al. (2009a) demonstrated that the urban heat island (UHI) intensity is greatly influenced by the conduction of AH.

The third urban canopy layer model is the multilayer canopy layer model (BEP) developed by Martilli et al. (2002). BEP allows a direct interaction between the building and the planetary boundary layer (PBL). BEP considers the 3-D urban surface and the vertical distribute source of buildings and momentum sinks throughout the whole canopy layer. The effects of vertical and horizontal surface on momentum, turbulent kinetic energy (TKE) and potential temperature are included. Like the UCM, the effect, caused by the building walls and roads, of shadowing, reflection and radiation trapping are also involved in the BEP scheme. The newly developed version of urban parameterization is an extension of BEP scheme, which is developed by Salamanca and Martilli (2010).

A simple building model (BEM) is coupled to BEP scheme that improves the results simulated by the old canopy version of BEP. This new BEP + BEM parameterization has been added in WRF V3.2 version that is released on April 2010. These newly developed WRF/urban modeling systems are evaluated and applied by many scientists to investigate the regional climate change and air quality and that demonstrate its appropriate utility. Studies (Chen et al., 2004; Ezber et al., 2007; Lin et al., 2008; Wang et al., 2009b; Miao et al., 2009a,b; Flagg and Taylor, 2011) were conducted to investigate the impacts of urbanization on surface meteorological conditions and planetary boundary layer structures. Results show that the WRF/urban model is able to capture the features of the atmospheric meteorological conditions and PBL structures. The model systems were also utilized to get further study on regional climate and air quality recently (Martilli and Schmitz, 2007; Jiang et al., 2008; Wang et al., 2009b; Misenis and Zhang, 2010). The studies demonstrated that these models are able to predict the urban and canopy effects on the regional climate change and air quality.

The Yangtze River Delta (YRD) region, located in the coastal region at the eastern part of China, has experienced a remarkable economic development and urbanization during the last 30 years. YRD region is a highly urbanized area and air pollution issues are evident. High levels of urbanization, industrialization and high population density induce sever environmental problems. Wang et al. (2007a) investigated the air pollutants trend in YRD during 1996–2003, results showed that the trends of the primary air pollutants, NO_2 and PM_{10}, in the target areas were different, surface NO_2 level was increased by 13% while PM_{10} level was decreased by 57% in the past 8 years. Deng et al. (2011) demonstrated that the visibility in Nanjing is rather poor due to its urban development and air pollutions. Zhou (2004) and Du et al. (2007) demonstrated that with the urban land/use area continuously developing, regional UHI problems in YRD region are becoming more and more serious. Cui et al. (2008) analyzed the temperature series based on observation to investigate the urbanization evident on temperature change in YRD region, the results showed that the urbanization had an obvious impact on the local climate and environment in this area. He et al. (2009) made sensitive experiments to study the impacts of urban canopy on energy balance in YRD region by developing a single-layer urban canopy model and demonstrated that coupling the canopy scheme in numerical simulation improve the ability to reproduce the meteorological performance. The canopy parameterization has an obvious influence on urban micrometeorology and atmospheric boundary layer structure (Chen et al., 2009). Zhang et al. (2010) used WRF model coupling different land/cover and urban canopy scheme to study the urbanization and canopy impacts on climate change, which demonstrate that the mean near-surface temperature in urbanized areas increases on average by 0.45 $\pm$ 0.43 °C in winter and 1.9 $\pm$0.55 °C in summer, the temperature, wind speed and precipitation do significantly influenced by urbanization. Li et al. (2011) employed the WRF/CMAQ model to study the air quality and emission in YRD region, the results show with the urban land/use increasing, ozone and haze problem have become extremely important issues in the regional air quality.

However, those studies mainly focused on the impacts of land/use change on climate, weather or air pollution events during special short-term simulations (i.e. one-week simulation), and only used one urban canopy scheme for the simulation in their investigations, furthermore, impacts of urban canopy schemes on climate and air pollution in YRD region have not been quantified. It is therefore necessary to systematically study the impacts of urban parameterizations on the seasonal variability of meteorological conditions and its impacts on air quality. In this study, the Advanced Research Weather Research and Forecast/Chemistry (WRF/Chem) model version 3.2.1 coupling with UCM, BEP, and BEP + BEM models is utilized to investigate the impacts of the urban canopy on the regional climate change and air quality. These models are able to capture impacts of urbanization on near-surface meteorological conditions and on the evolution of atmospheric boundary-layer structures in cities such as Beijing and Guangzhou (Miao et al., 2009a,b; Wang et al., 2009a; Chen et al., 2011a,b), and thus influence the air quality (Wang et al., 2012). Furthermore, high-resolution land use data is also added to allow more realistic simulation of the underlying surface properties and the evolution of the boundary layer. This paper including five sections, the remaining are: (2) Model description and experiment design; (3) Impacts on regional climate; (4) Impacts on air quality; (5) Conclusion.

2. Model description and Experiment design

2.1. WRF/Chem model description

The investigation of the impacts of the urban canopy on regional climate and air quality requires accurate models that the feedbacks between the air pollutants and meteorological conditions are included. The newly Advanced Research Weather Research and Forecast (ARW-WRF) model and air quality model-chemistry component (Chem) are fully coupled "online", which is so-called the next generation mesoscale air quality model WRF/Chem (Grell et al., 2005). The meteorological and chemical components have the same horizontal and vertical coordinates and same physical parameterizations, furthermore, feedbacks between meteorological and chemical processes are included. Similar as other advanced air quality models, WRF/Chem model provided several parameterizations for each process. In WRF/Chem version 3.2.1, the urban model BEP + BEM is included, and the model couple with different biogenic emissions schemes, such as online calculation according to the scheme of Guenther et al. (1994) and Simpson et al. (1995), modification of user specified biogenic emissions and coupling calculation with MEGAN model (Guenther et al., 2006). It also considers dry deposition

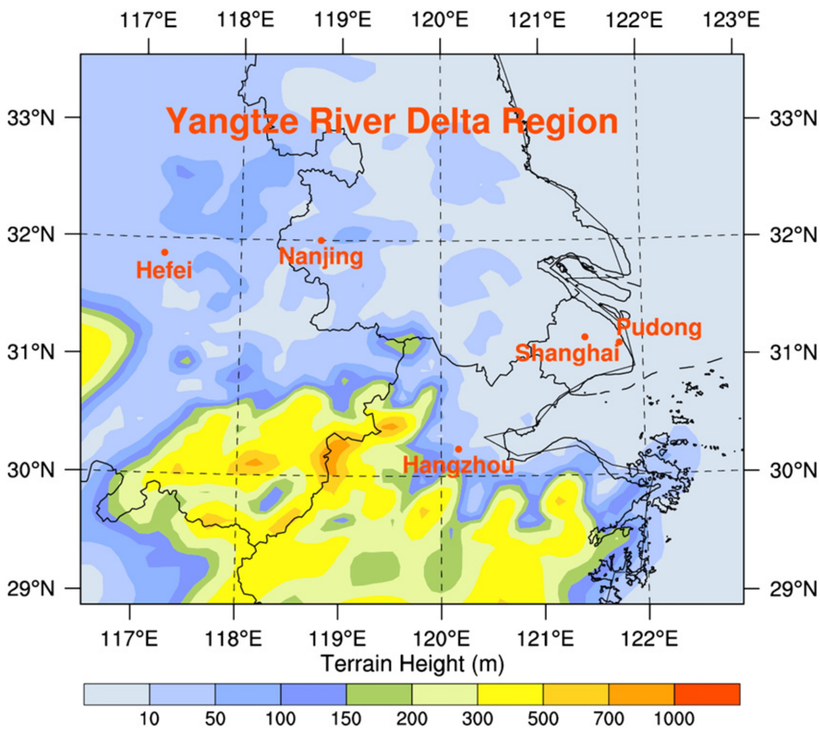

Fig. 1. The Yangtze River Delta terrain height and locations of observation sites.

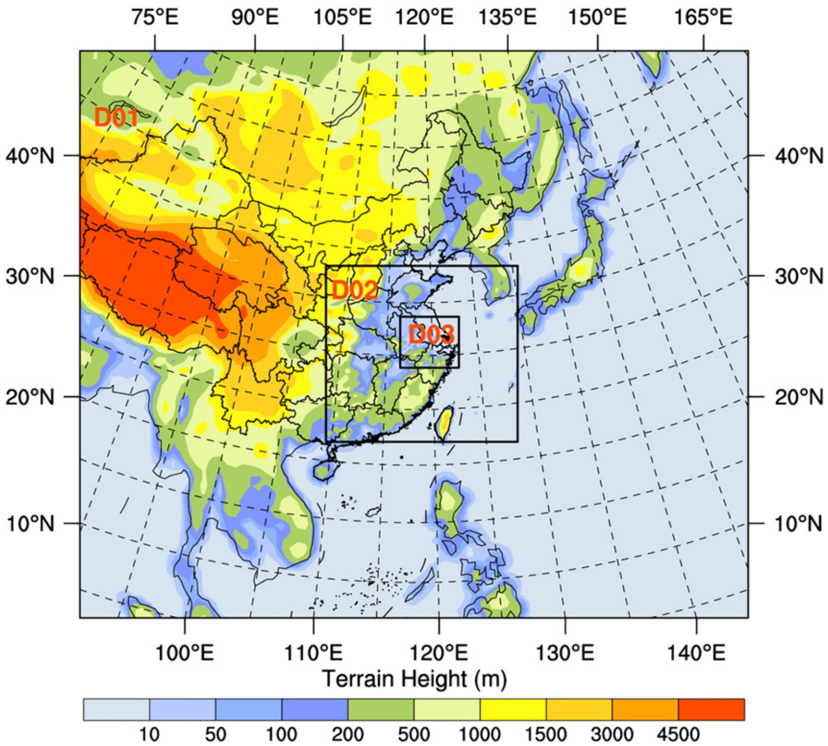

Fig. 2. Three nested domains for sensitivity simulations.

that coupling with soil/vegetation scheme; several choices for gas-phase chemical mechanisms including RADM2, RACM, CB-4 and CBM-Z chemical mechanisms; three choices for photolysis schemes, i.e., Madronich scheme coupled with hydrometeors, aerosols and convective parameterizations, Fast-J and F-TUV photolysis scheme; three options for aerosol mechanisms schemes, i.e., MADE/SORGAM, MOSAIC and a total mass aerosol module GOCART, aerosol direct and indirect effect through interaction with atmospheric radiation, photolysis, and micro-physics routines are included for MOSAIC and MADE/SORGAM options.

2.2. Description of study areas

The Yangtze River Delta (YRD) area, as illustrated in Fig. 1, is located in the middle-east coastline of China, comprises

Table 1
Details of the different urban canopy schemes in sensitivity simulation.

	SLAB	UCM	BEP	BEP + BEM
Canopy layer description	No canopy layer	Single-layer	Multilayer	Multilayer
Anthropogenic heat	No	Fixed temporal profiles	No	From a building energy model
Fraction of vegetation	No	Yes	Yes	Yes
PBL scheme coupling	MYJ	MYJ	MYJ	MYJ

Table 2
Urban parameters for UCM and BEP schemes and their usage in the different canopy schemes.

Parameters	Unit	Value	UCM*	BEP (BEM)*
Building height	m	20	YES	NO
Building width	m	15	YES	NO
Width of the road	m	10	YES	NO
Urban fraction	Fraction	0.95	YES	YES
Roof albedo	Fraction	0.2	YES	YES
Wall albedo	Fraction	0.2	YES	YES
Pavement albedo	Fraction	0.2	YES	YES
Roof roughness length	m	0.15	YES	YES
Wall roughness length	m	0.05	YES	NO
Pavement roughness length	m	0.05	YES	YES

* Yes and No represent for whether parameters used in the scheme or not.

Table 3
Parameters used in BEP and BEP + BEM only.

Street direction (°)	Width of the road (m)	Building width (m)
0.0	15.0	15.0
90.0	15.0	15.0

Building height (m)	Percentage (%)
15.0	10
20.0	25
25.0	40

southern Jiangsu province and northern Zhejiang province, and contains 15 cities that Shanghai, Nanjing and Hangzhou are the center of the economic belt and urban cluster. The YRD area is the most urbanized and industrial area in China and still keeps a rapid-growth ratio. It covers 1/10 of the area of China and holds 1/5 of the total Chinese population (the urban residence population account for approximately 62.5% of the total population over the YRD build-up area) and contributes 1/5 of the GDP of China (Zhang et al., 2010). Larges amount of cropland and forest in this area have been changed to urban build-up areas during the past decades. The fast-growth urban build-up in the area has led to one of the largest density of adjacent metropolitan areas in the world.

The climate in YRD area is mainly influenced by the East-Asia monsoon. The averaged-annual temperature is about 14.0–18.0 °C, specifically, the mean temperature in coldest season is about 0.0–5.5 °C and in warmest season is about 27.0–28.0 °C. The mean annual precipitation in YRD area are about 1000–1400 mm, most of which occurs during spring and summer. Generally, the weather in YRD is warm and wet in summer and cold and dry in winter.

2.3. Description of observation data

Observation data are used in this paper to evaluate the model performance, including meteorological and air pollutant data. The meteorological factor such as hourly 2-m temperature and 10-m wind speed are selected, which are obtained from University of Wyoming (UWMO) dataset. The selected observation sites are Hefei (HF), Nanjing (NJ), Hangzhou (HZ) and Shanghai (SH), as illustrated in Fig. 1. The air pollutant data of hourly PM_{10} and ozone are from Caochangmen (CCM) environmental monitoring site that locates in Nanjing urban (118.75°E, 32.05°N).

2.4. Model configuration and experiment design

In this study, the WRF/Chem model is configured with three nested domains (shown in Fig. 2), with gird resolution of 81 km × 81 km in domain 1, 27 km × 27 km in domain 2, and 9 km × 9 km in domain 3, the grid point dimensions for each domain is 85 × 75, 76 × 70, and 70 × 61 respectively. The coarse outer domain, named D01, comprises the whole East-Asia region and part of south-east Asia. The second domain, named D02, covers a large portion of East-China region, and the third domain, named D03, comprise the whole YRD region, with the YRD region located in the center. Two months simulations have been designed: January and July of 2010. The details of the sensitivity experiments of urban canopy schemes are summarized in Table 1. The control experiment is the SLAB case that does not consider

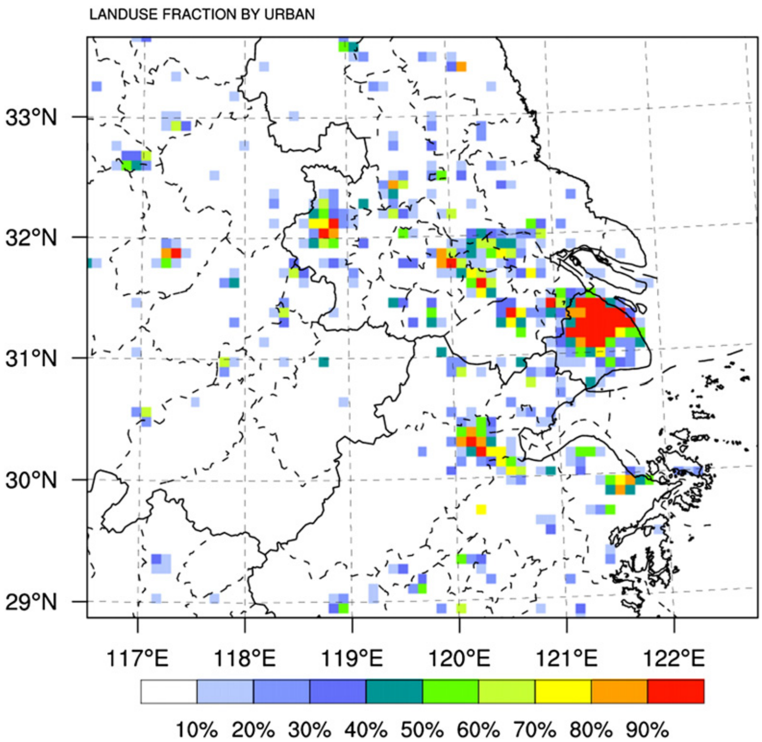

Fig. 3. Land use fraction by urban in YRD region.

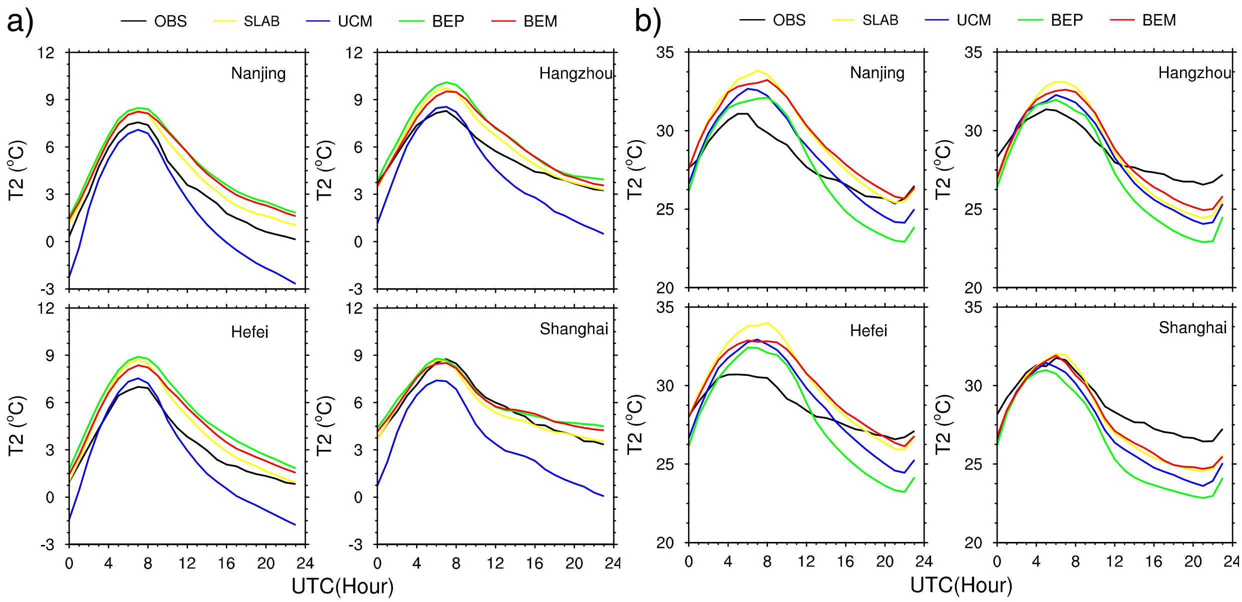

Fig. 4. Time series of 2-m temperature for different stations for (a) January and (b) July obtained with the four urban schemes against observations.

the canopy parameters, the UCM, BEP and BEP + BEM (marked with BEM in the figures hereafter) schemes are designed as canopy experiments. The anthropogenic heat is included in UCM scheme with fixed default diurnal variation due to anthropogenic heat increases air temperature. To better characterization of the actual urban canopy environment, the specific parameters used in UCM, BEP and BEP + BEM schemes are modified (as listed in Tables 2 and 3.) according to the measurement in YRD (He et al., 2009). All the experiments utilize the same physical and chemical options except for the canopy schemes. To better represent the real land use in YRD region, the urban land use in the third domain is updated base on MODIS data (shown in Fig. 3). Fig. 3 shows that YRD region is a highly urbanized area with the Shanghai, Nanjing and Hangzhou city as representative mega city. The land/use fraction by urban is event as high as 90% or above in these mega cities. The initial and boundary conditions are interpolated from 1-degree resolution global reanalysis data from National Center for Environmental Prediction (NCEP, Kalnay et al., 1996), and there are 31 eta levels with the pressure of 50 hpa at the top of the model. The height of the lowest level is about 25 m above the ground surface.

The major selected physical options are Goddard shortwave radiation scheme, the Rapid Radiation Transfer Model (RRTM) longwave radiation scheme (Mlawer et al., 1997), Noah land-surface module (Chen and Dudhia, 2001), the Mellor-Yamada-Janjic (MYJ) PBL scheme (Janjic, 1994) And the modified Purdue Lin microphysical scheme (Lin et al., 1983; Chen and Sun, 2002) and the Kain-Fritsch (new Eta, KF) cumulus parameterizations (only used in D01 and D02) are selected as well. For major chemical options, the gas-phase chemistry module CBM-Z (Zaveri and Peters, 1999) and the aerosol module MOSAIC (Zaveri et al., 2008) are used in these simulations, the feedback between the meteorology and aerosol is not included in this study Emission inventories with horizontal resolution of 0.5°by 0.5°from Zhang et al. (2009) were applied for the regions outside of Shanghai, while additional 1 km × 1 km source emission compiled by Shanghai Environmental Monitoring Center was used for Shanghai area.

Table 4
Statistical comparison of the simulated and observed 2-m temperature (°C) for January.

Site	January	SLAB	UCM	BEP	BEP + BEM
NJ	MB	0.79	−0.58	1.41	1.19
	RMSE	2.16	2.59	2.08	2.42
	CORR*	0.90	0.90	0.90	0.88
HZ	MB	0.41	−0.31	0.91	0.61
	RMSE	1.97	2.43	1.80	2.08
	CORR*	0.91	0.91	0.92	0.90
HF	MB	0.84	−0.69	1.58	1.12
	RMSE	2.38	2.89	2.07	2.57
	CORR*	0.87	0.87	0.90	0.86
SH	MB	0.08	−1.69	0.57	0.42
	RMSE	1.92	2.40	1.94	2.14
	CORR*	0.91	0.90	0.91	0.89

* Statistically significant at 95% confident level for CORR.

Table 5
The same as Table 4 but for July.

Site	July	SLAB	UCM	BEP	BEP + BEM
NJ	MB	1.89	2.46	0.08	2.02
	RMSE	2.43	2.45	2.57	2.23
	CORR*	0.75	0.77	0.76	0.74
HZ	MB	−0.31	0.33	−0.78	0.26
	RMSE	2.91	2.64	2.45	2.31
	CORR	0.61	0.69	0.77	0.74
HF	MB	1.61	2.08	−0.40	1.53
	RMSE	2.43	2.75	2.71	2.48
	CORR*	0.72	0.68	0.69	0.63
SH	MB	−0.72	−0.48	−1.95	−0.63
	RMSE	2.97	2.70	2.14	2.24
	CORR*	0.54	0.62	0.79	0.71

* Statistically significant at 95% confident level for CORR.

3. Impacts on regional climate

3.1. Diurnal variations of 2-m Temperature

Results from all the four experiments in January and July are compared with the observation data to evaluate the model performance, meanwhile, impacts on simulating diurnal variation of 2-m temperature with different urban parameters over urban areas also can be analyzed. Four urban sites (locations are shown in Fig. 1.) such as Nanjing (NJ), Hangzhou (HZ), Hefei (HF) and Shanghai (SH) are selected for evaluation of the four urban models for both January and July due to these sites are locate on urban areas with high urban fraction (see Fig. 3). Time series of 2-m temperature between modeling results and observations are shown in Fig. 4. The performance statistics are calculated in terms of mean bias (MB), Root mean squared error (RMSE) and Correlative coefficient (CORR), shown in Tables 4 and 5. Compared with observation (Fig. 4), UCM

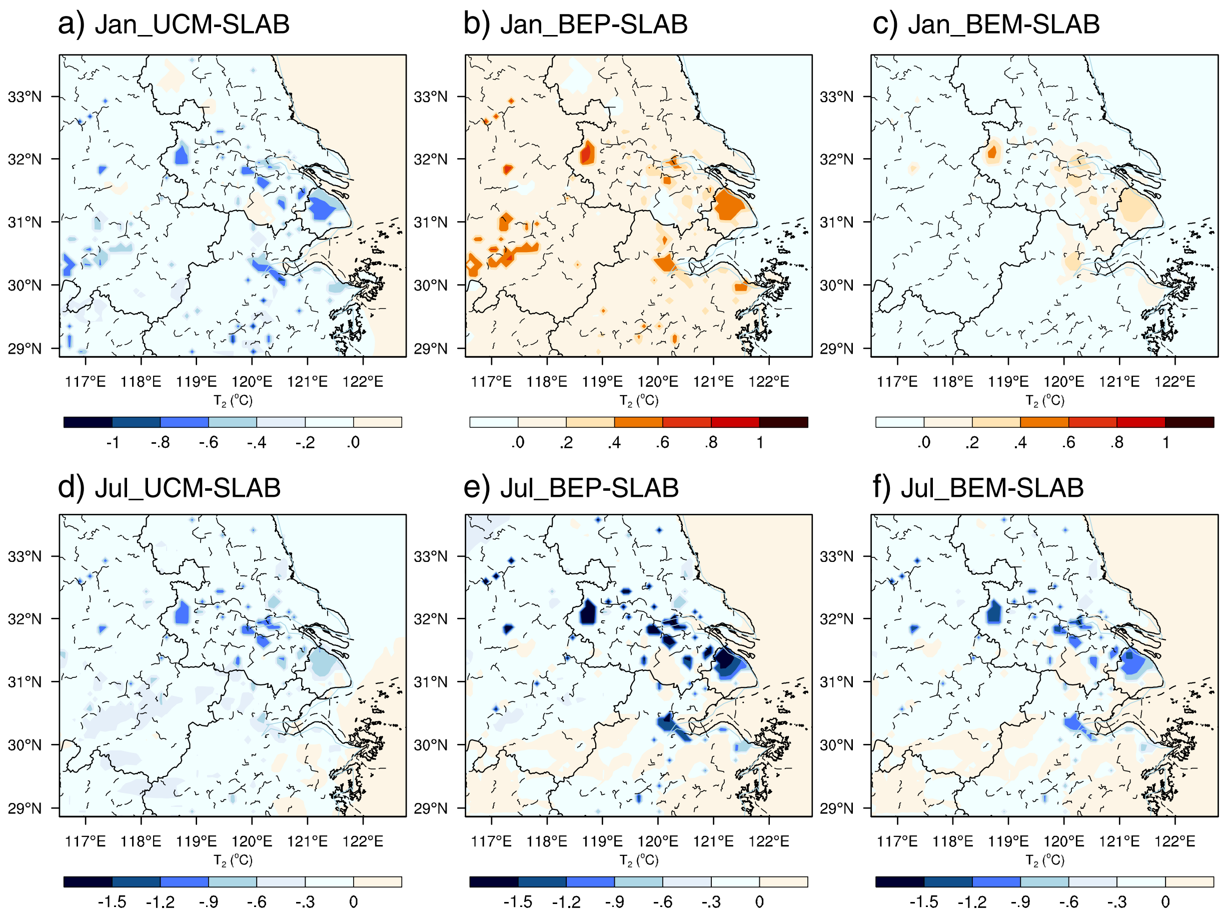

Fig. 5. The differences of the monthly-averaged 2-m temperature between canopy schemes and control schemes: a,b,c for January; d, e, f for July.

scheme tended to simulate higher 2-m temperature during 4:00 am–9:00 am UTC, while simulated lower 2-m temperature during 15:00 pm–23:00 pm UTC during January. BEP and BEP calculated higher 2-m temperature both at daytime and nighttime during January, the models simulated best 2-m temperature at SH site. For July, all the schemes calculated higher 2-m temperature during 4:00 am–12:00 am UTC while lower air temperature during 12:00 pm–24:00 pm UTC. Statistics shows that the four urban schemes reproduced the 2-m temperature accurately enough (MBs < 2.0 °C, Miao et al., 2009a) for both January and July. The UCM parameterization tends to underestimate the 2-m temperature with MB of −1.69 to −0.31 °C in January, while the BEP scheme overestimate 2-m temperature with MB of 0.57–1.58 °C. The best results were obtained with SLAB and BEP + BEM schemes for January with MBs of 0.08–0.84 °C and 0.42–1.19 °C, respectively. For July, however, the best results were obtained with SLAB and BEP scheme, MBs of 2-m temperature from which were −0.72 to 1.89 °C and −1.95 to 0.08 °C, respectively. Simulations of UCM and BEP + BEM schemes meet larger MB with magnitude of −0.48 to 2.46 °C and −0.63 to 2.02 °C. It is possible to say that the worse 2-m temperature both in January and July were obtained which UCM scheme. It indicates that more realistic urban morphology and parameters are needed to improve the model performance, because parameters used in the urban canopy schemes (i.e. building height, albedo, heat capacity and roughness length) largely influence the surface energy balance and heat absorption.

3.2. Spatial influence on 2-m temperature and PBLH

Fig. 5 shows the differences of 2-m temperature distributions between canopy experiments and control experiments. The results show that, compared with SLAB scheme, 2-m temperature from UCM scheme were about 0.7 °C lower in January and 0.5 °C lower in July over the mega cities (e.g. Nanjing and Shanghai). But for BEP and BEP + BEM schemes, these schemes seemed to simulate higher temperature during January, the differences were about 0.5 °C and 0.3 °C, respectively. While during July, both the BEP and BEP + BEM schemes simulated lower 2-m temperature over the urban areas, the differences were about 1.6 °C and 1.4 °C, respectively. The patterns of the PBLH differences between canopy schemes and control scheme are similar to 2-m temperature that influence atmospheric stability and affect PBLH, as illustrated in Fig. 6. Being different with the control scheme, results from UCM calculated lower PBLH in both January and July due to UCM scheme simulated lower air temperature, the differences were about −120 m and −75 m, respectively. Both the BEP and BEP + BEM schemes simulated higher PBLH during January,

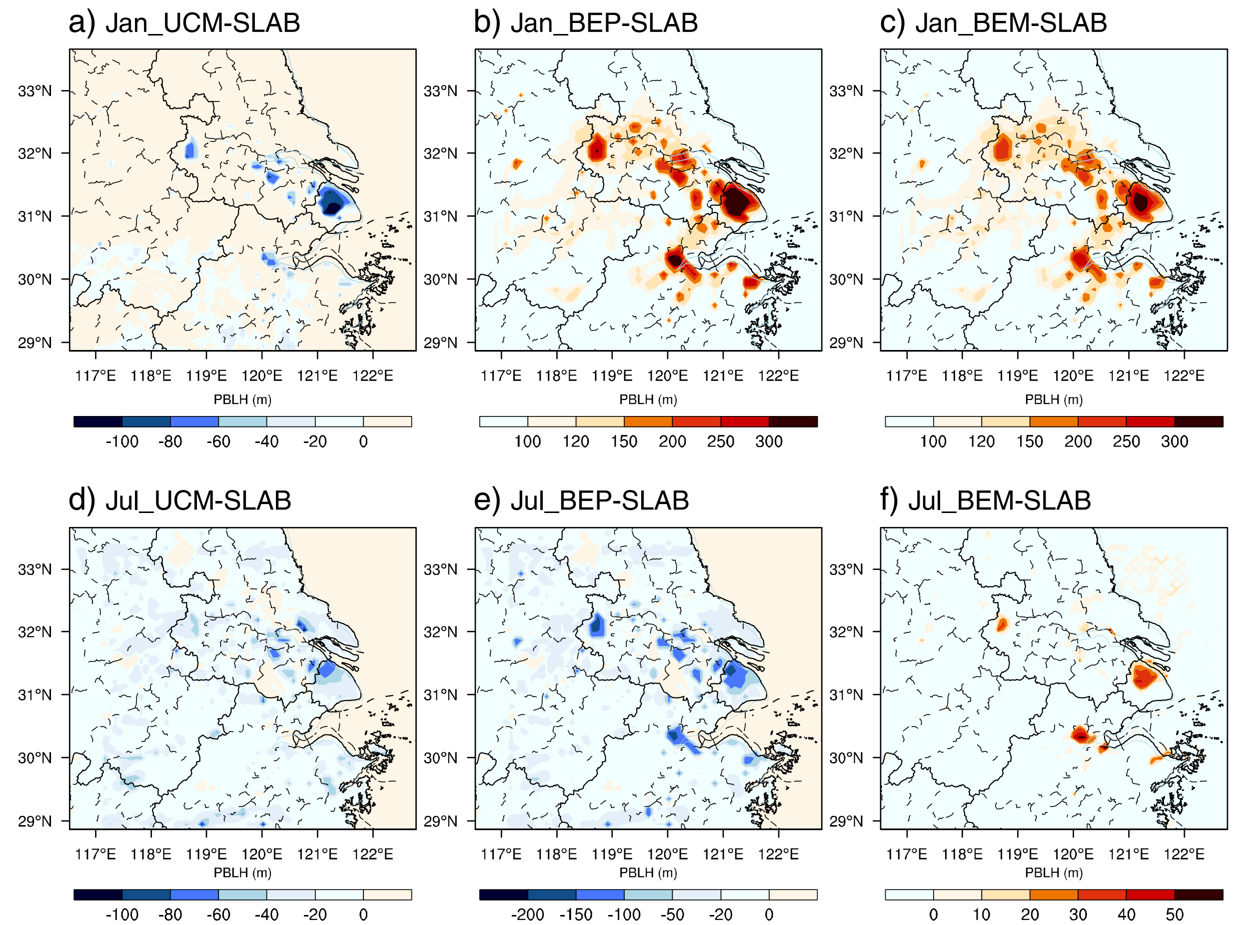

Fig. 6. The differences of the monthly-averaged PBLH between canopy schemes and control scheme: a, b, c for January; d, e, f for July.

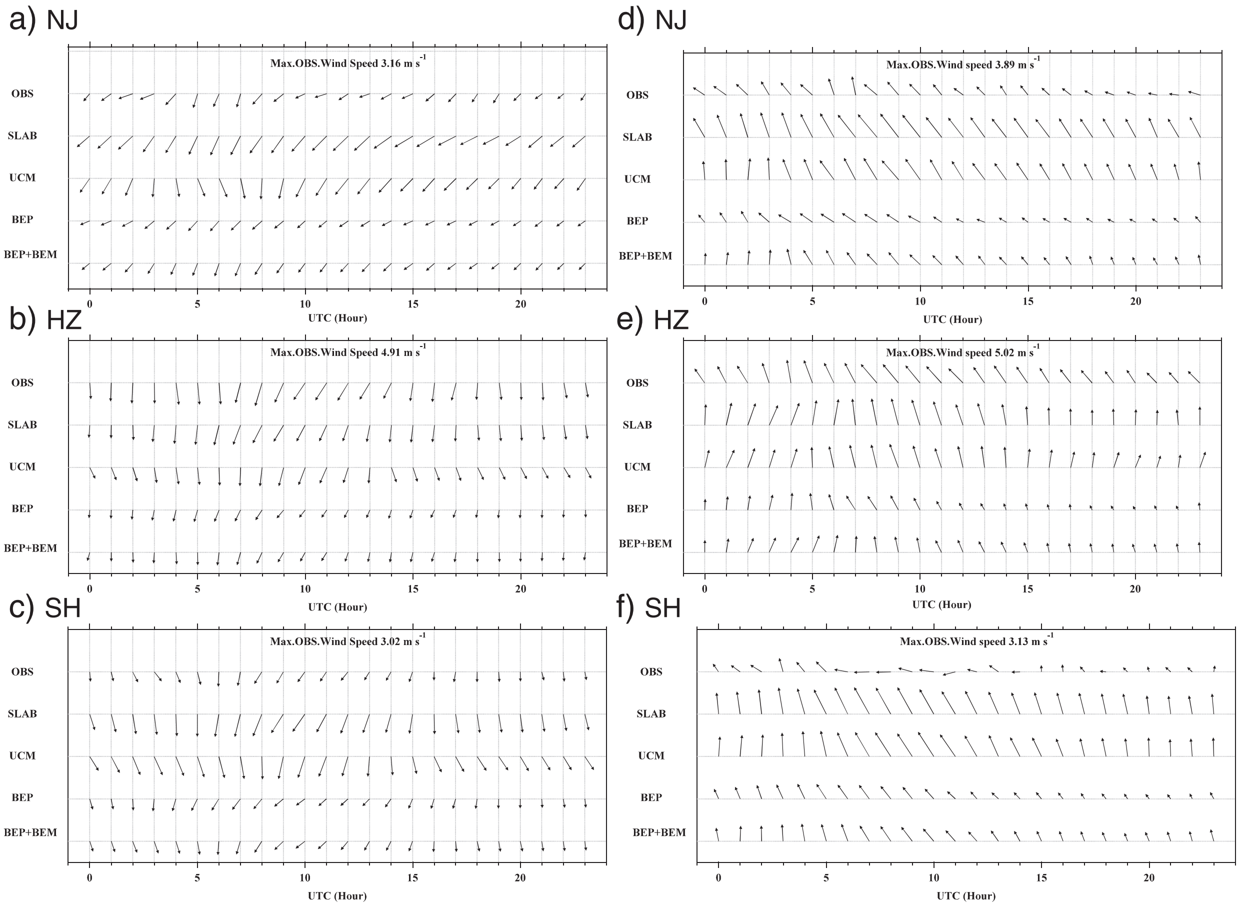

Fig. 7. Diurnal series of observed and simulated 10-m wind speed at 3 sites for January and July: a, b, c for January, d, e, f for July; NJ-Nanjing, HZ-Hangzhou, and SH-Shanghai.

with the magnitudes of 325 m and 306 m, respectively. Fig. 6 reveals that the impacts of BEP and BEP + BEM schemes on PBLH in July are not as significant as that in January. Lower PBLH was obtained with BEP scheme in July with the difference about −116 m. BEP + BEM scheme, however, simulated about 46 m higher PBLH in July.

The multiple canopy schemes have different influences on the 2-m temperature during different seasons. The reasons for the differences could be variety. It must be mentioned that the solar elevation angle is lower during winter, less amount of solar radiations reach the ground, and less radiation is shaded by the buildings, causing the difference of air temperature is more evident in July than in January. For BEP and BEP + BEM schemes, the heat exchange between the buildings involved in the canyon is considered, the heat storage in multiple canopy schemes and added AH in BEP + BEM scheme somehow offset the shade effect during the January. But for summer, the solar elevation angle is higher, solar radiation is the main source that heats the surface. Larges of radiation are shaded by buildings which results in urban cooling, the urban surface are not directly exposed to the sunlight during the daytime, thus causes the air temperature lower. For BEP + BEM scheme, the

Table 6
Statistical comparison of the simulated and observed 10-m wind speed (m s^{-1}) for January.

Site	January	SLAB	UCM	BEP	BEP + BEM
NJ	MB	1.13	0.99	−0.50	−0.42
	RMSE	1.56	1.55	1.09	1.17
	CORR*	0.44	0.45	0.54	0.46
HZ	MB	1.12	0.79	−0.45	−0.29
	RMSE	1.39	1.35	0.99	1.05
	CORR*	0.67	0.65	0.66	0.62
SH	MB	0.08	−0.08	−1.77	−1.68
	RMSE	1.48	1.56	1.51	1.57
	CORR*	0.66	0.63	0.67	0.60

* Statistically significant at 95% confident level for CORR.

Table 7
The same as Table 6 but for July.

Site	July	SLAB	UCM	BEP	BEP + BEM
NJ	MB	2.08	1.47	−0.67	−0.30
	RMSE	2.20	2.01	1.29	1.51
	CORR*	0.04	0.05	0.40	0.13
HZ	MB	2.23	1.60	0.13	0.46
	RMSE	1.75	1.79	1.42	1.43
	CORR*	0.32	0.22	0.27	0.22
SH	MB	0.78	0.37	−1.82	−1.38
	RMSE	2.16	1.91	1.46	1.67
	CORR*	0.18	0.29	0.49	0.27

* Statistically significant at 95% confident level for CORR.

inner building heat flux is transport to outside by air conditioning, and heats the out-door air temperature, these heat will also offset the shaded effect, and cause higher temperature (compared with BEP scheme). UCM scheme also calculated lower air temperature thought the AH is added, the results imply that the default AH settings are underestimated, we are aware that UCM scheme has been widely tested and validated in different situations (i.e. Wang et al., 2009a; Kusaka and Kimura, 2004; Miao et al., 2009a,b), the low urban fraction and lack of high resolution of AH emission inventory may be the main factors that influence the simulation results and the anthropogenic heat fluxes are important in the formation of the nocturnal heat island.

3.3. Diurnal variations of 10-m wind speed

In Fig. 7, the time evolution of 10-m wind speed (WS_{10}) is compared with the observation for both January and July. Three monitoring sites such as NJ, HZ and SH are shown due to HF site does not present remarkable difference. The statistics for 10-m wind speeds are computed in Tables 6 and 7. All the four experiments were able to simulate satisfactorily the rotation of

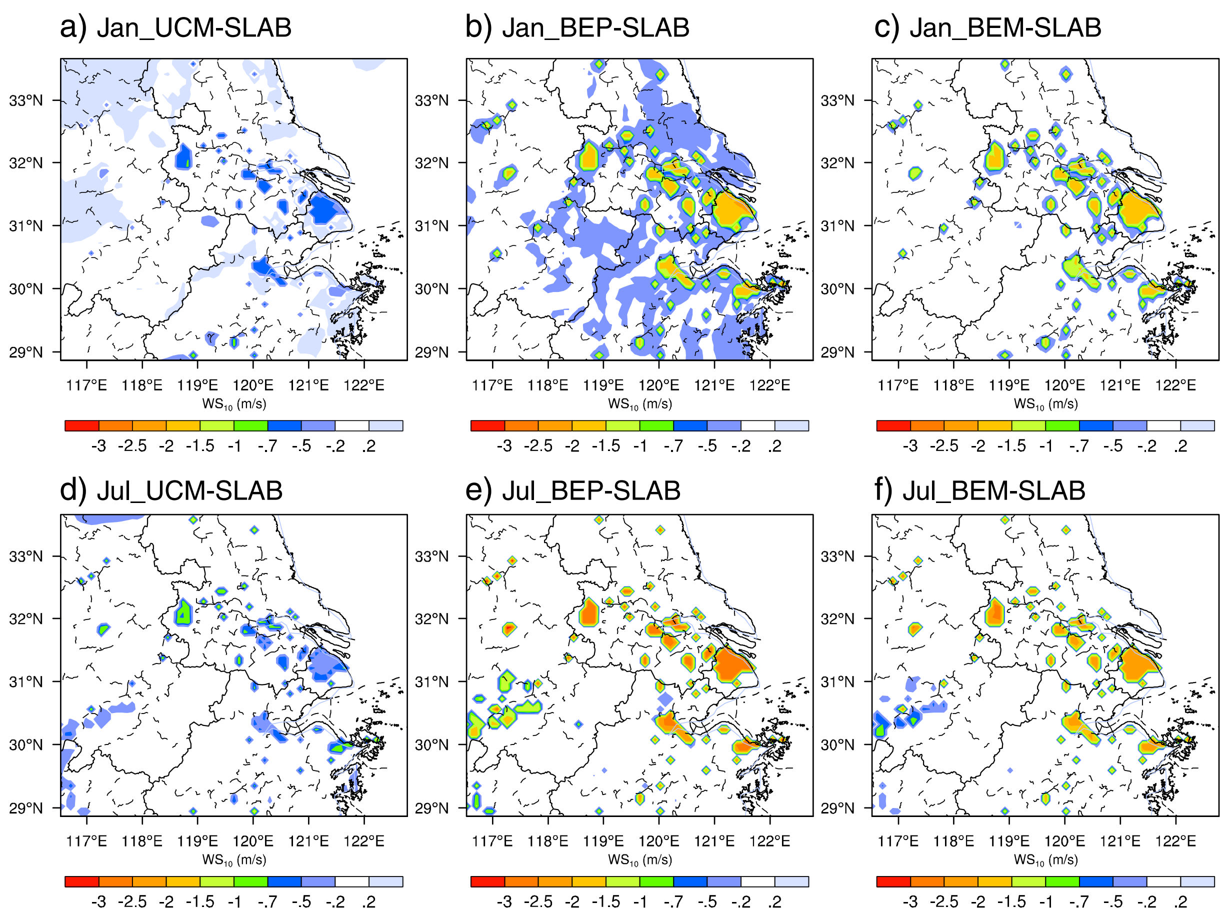

Fig. 8. Differences of Monthly averaged 10-m wind speed between canopy schemes and control scheme for a, b, c January and d, e, f July.

the wind speed at 10-m from around 9:00 am–10:00 am UTC to dawn (around 21:00–22:00 UTC). During the 2:00 am–8:00 am UTC approximately, the schemes were not able to simulate the wind direction well, the wind directions were somehow not consistent with observed wind. The reasons for this behavior may due to the solar heating and scattered clouds modeled by canopy experiments over the cities (Salamanca et al., 2011). During the study periods (in January and July), the SLAB and UCM schemes slightly overestimate the wind speed compared with observed wind (MBs are almost positive), however, multiply-canopy schemes, BEP and BEP + BEM schemes, underestimate it. The best predictions were obtained with BEP scheme and BEP + BEM scheme for both January and July, MBs were −1.82 to 0.13 m s^{-1} for BEP scheme and −1.68 to 0.46 m s^{-1} for BEP + BEM scheme, respectively. It should be aware that roughness length, which is used in numerical models to express the roughness of the surface, is not directly dependent on urban morphology for SLAB and UCM schemes, while momentum sink and drag force estimated by BEP and BEP + BEM schemes depend on urban morphology (Salamanca et al., 2011), the calculation of wind speed in BEP and BEP + BEM seem more reasonable in this study. This different estimate could explain why BEP and BEP + BEM schemes largely underestimate the 10-m wind speed at SH site (see Tables 6 and 7), which locates in highly urbanized area with high urban fraction.

3.4. Impacts on spatial distribution of 10-m wind speed

Canopy schemes significantly change the surface roughness and influence the dynamic process over the urban areas. 10-m Wind speed obviously decreases when urban canopy layer is added (Wang et al., 2009a; Kusaka and Kimura, 2004; Miao et al., 2009a,b). The impacts on wind are different according to the different canopy schemes and during different seasons (see Fig. 8). Compared with the results from SLAB scheme, the simulated 10-m wind speed from UCM scheme was 0.7 m/s lower in January and 0.8 m/s lower in July over the mega cities (i.e. Nanjing, Hangzhou, and Shanghai). For BEP and BEP + BEM schemes, the 10-m wind speeds were much lower, the difference over mega cities was −1.7 m/s for BEP and −1.8 m/s for BEP + BEM in January,

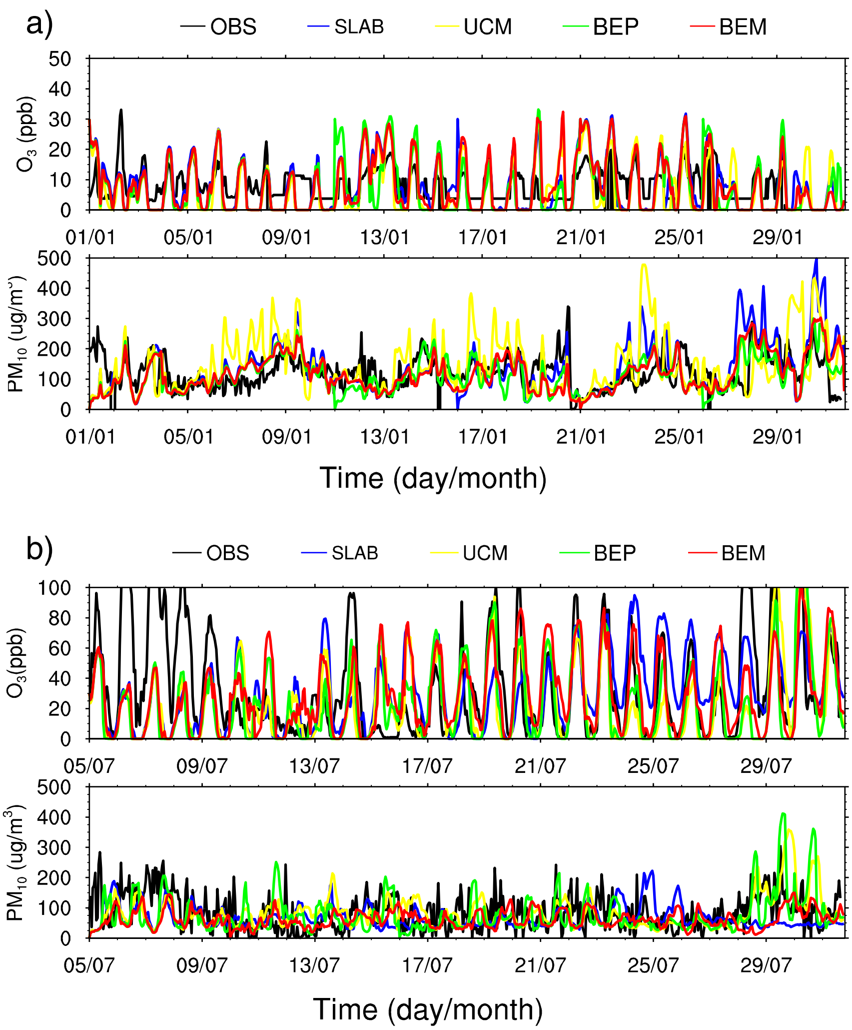

Fig. 9. Comparisons between chemical outputs from all experiments and the observations: a for January, b for July.

Table 8
The same as Table 4, but for chemical predictions.

	JAN				JUL			
Var	EXP	MB	RMSE	Corr*	EXP	MB	RMSE	Corr*
PM_{10}(μg/m^3)	SLAB	12.1	81.9	0.32	SLAB	−15.7	71.6	0.21
	UCM	23.7	96.2	0.19	UCM	−0.9	75.4	0.33
	BEP	−11.6	61.1	0.39	BEP	−7.5	75.9	0.24
	BEM	−4.5	66.0	0.33	BEM	−21.0	65.1	0.22
O_3(ppb)	SLAB	−0.3	6.9	0.58	SLAB	−3.2	33.0	0.36
	UCM	−2.3	7.1	0.52	UCM	−11.6	31.4	0.44
	BEP	−1.2	7.5	0.55	BEP	−11.0	29.8	0.52
	BEM	−0.6	7.2	0.56	BEM	−5.4	30.8	0.46

* Statistically significant at 95% confident level.

and was −2.6 m/s for BEP and −2.3 m/s for BEP + BEM in July, respectively. The impacts were more significant in July than January. Decreases of wind speed from BEP and BEP + BEM schemes may cause accumulation of air pollutants and influence air quality.

4. Impacts on air quality

4.1. Chemical predication validation

The impacts of the canopy schemes on air quality are analyzed, remember that the urban thermal and dynamic characteristics is change when urban canopy is added, it is necessary to investigate how the urban canopy influences the air quality. The observed chemical data are obtained from Caochangmen (CCM) site monitored by the environmental protection agency. Air pollutants of PM_{10} and ozone (O_3) are selected to validate the canopy impacts on air quality in this paper. Fig. 9 shows the time series of the chemical predictions from all experiments compared with observations, and statistics are summarized in Table 8. It shows that BEP and BEP + BEM schemes underestimated PM_{10} concentration but SLAB and UCM schemes overestimated it in January, the best estimate was obtained from BEP + BEM

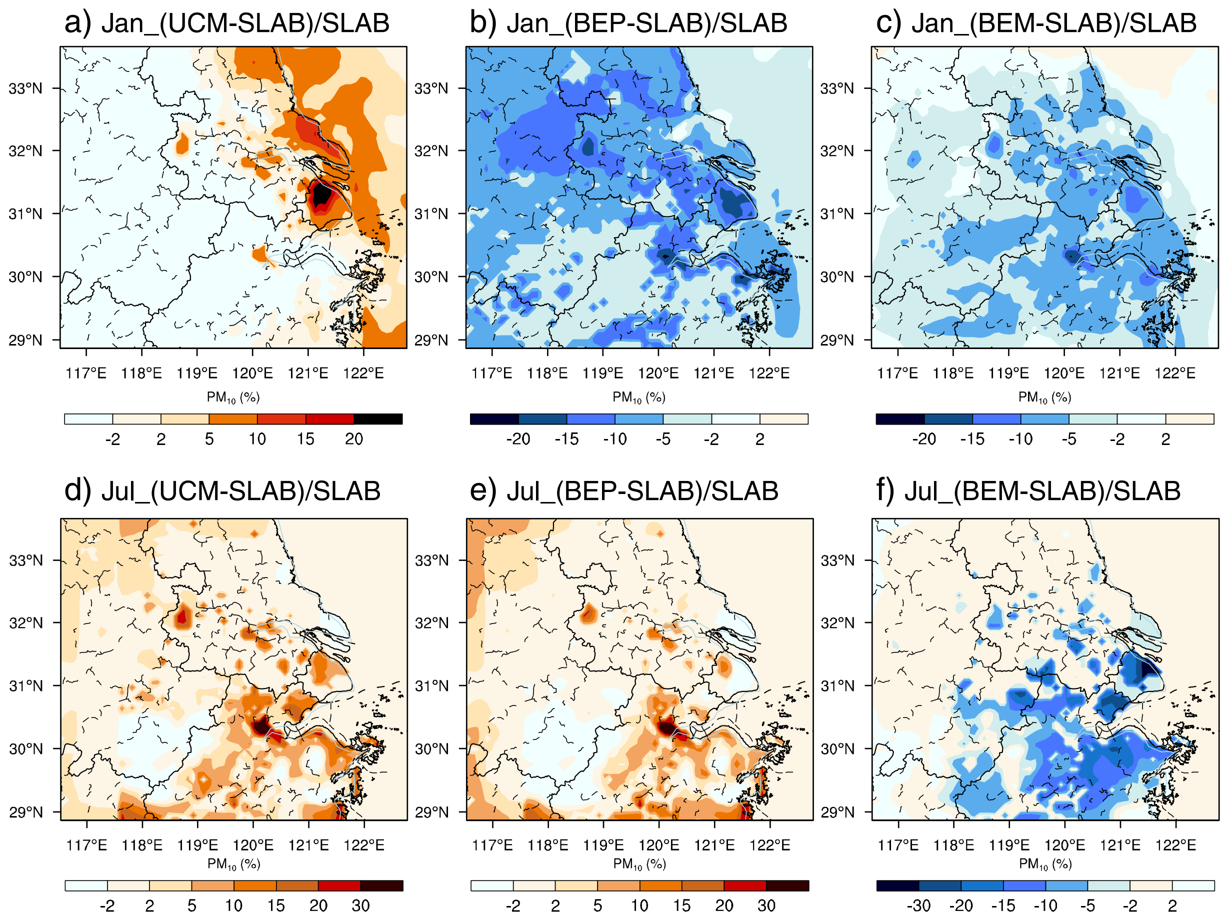

Fig. 10. Relative differences of the PM_{10} concentration between canopy schemes and control schemes: a,b,c for January; d, e, f for July.

scheme with the MB of −4.52 μg/m^3, RMSE of 66.0 μg/m^3, while the worse estimate was from UCM scheme with the of MB 23.7 μg/m^3. For July, the worse estimate was obtained from BEP + BEM scheme with MB of −21.0 μg/m^3 and RMSE of 65.1 μg/m^3, while the best estimate was from UCM scheme, the MB was only −0.9 μg/m^3 and RMSE 75.4 μg/m^3.

All the experiments well captured the variations of the ozone concentrations in January, the MB was from −1.2 ppb (BEP scheme) to −2.3 ppb (UCM scheme). For July, SLAB and BEP + BEM schemes had the best performance with MB −3.2 ppb and −5.4 ppb, RMSE 33.0 ppb and 30.8, respectively. The maximum MB (−11.6 ppb) was obtained from UCM scheme, meanwhile, BEP scheme also simulated lower ozone concentration with MB of −11.0 ppb. Generally, all the experiments capture well the variations of the chemical fields. SLAB scheme and BEP + BEM scheme have the best performance while simulating the PM_{10} and ozone concentrations.

4.2. Impacts on spatial and vertical distributions of PM_{10}

PM_{10} is chosen to be an indicator for primary pollutant transport. The relative differences of the PM_{10} concentration are shown in Fig. 10. Compared with SLAB schemes, UCM scheme saw higher PM_{10} concentration in both January and July, the high value center located in Shanghai urban area, with the magnitude of 22.3% (or 24.4 μg/m^3) in January, and locates in Hangzhou city with the magnitude of 31.4% (or 17.4 μg/m^3) in July. Both the BEP and BEP + BEM schemes simulated lower PM_{10} concentration during January, with the decrease of 18.6% (or 22.1 μg/m^3) and 16.7% (or 24.6 μg/m^3), respectively. In July, the results from BEP scheme are higher over the Hangzhou city with the increase of 32.7% (or 18.3 μg/m^3), but BEP + BEM scheme predicted lower PM_{10} concentration over the urban area with 30.8% (or 16.5 μg/m^3) decrease. The wind speed and the diffusion condition are the main factors that influence the PM_{10} spatial distributions. Compared with the SLAB scheme, the PBLHs from UCM are about 100 m lower both in January and July, and the wind speed is also lower, causing PM_{10} tend to accumulated and is difficult to diffuse over urban areas. The simulated PBLH from both BEP and BEP + BEM scheme are higher during July, the diffusion conditions for BEP and BEP + BEM schemes are better and conductive to dispersal of pollutants.

In order to study changes in vertical profile of pollutants due to different canopy schemes, PM_{10} diurnal variations within 850 hpa at urban site (CCM) in Nanjing are analyzed

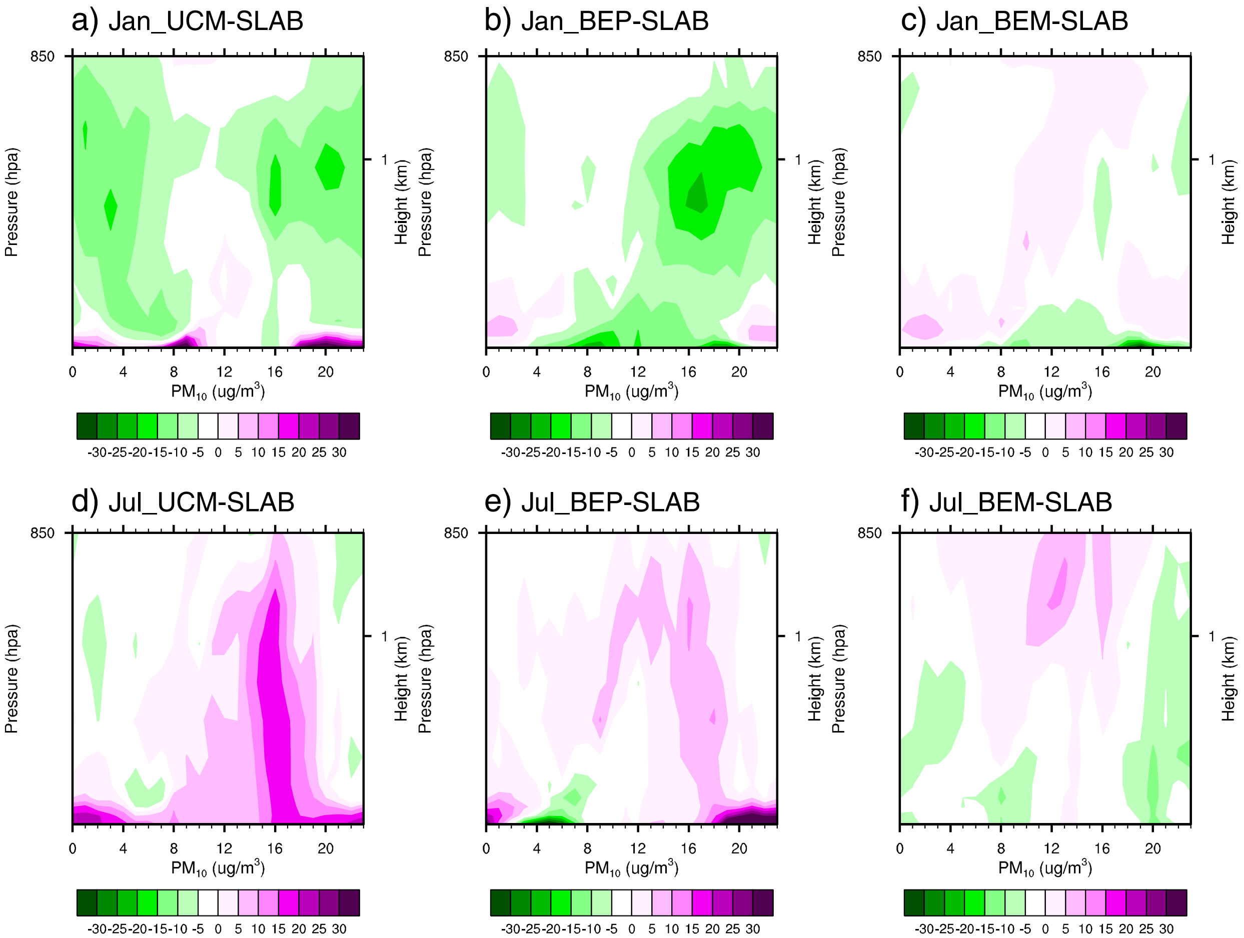

Fig. 11. Differences of PM_{10} vertical concentration between canopy schemes and control scheme at CCM site: a,b,c for January; d, e, f for July.

(shown in Fig. 11). Fig. 11 shows that, for January, UCM simulated 31.5 μg/m^3 (or 18.4%) higher PM_{10} concentration near the surface during nighttime and 7:00–10:00 LST due to lower PBLH, while BEP and BEP + BEM predicted lower PM_{10} concentration near the surface, with decrease of 18.3 μg/m^3 (or 14.5%) and 21.4 μg/m^3 (or 15.8%), respectively. Results show a large decrease in PM_{10} at upper layers of the model such as 1 km approximately above the surface (i.e. differences from UCM and BEP schemes), but in BEP + BEM scheme, the difference are smaller. For July, UCM and BEP schemes simulated higher (lower) PM_{10} concentrations during nighttime (daytime), while results from BEP + BEM scheme did not present obvious differences (~5 μg/m^3). The PM_{10} within 850 hpa layer decrease in January and increase in July, this behavior may also due to the model simulated stronger downdraft in July (see Fig. 14) which induce poorer diffusion conditions. PBLH and vertical velocity are the main factors that affect vertical PM_{10} distributions.

4.3. Impacts on spatial and vertical distributions of ozone

The influences of different canopy schemes on ozone are analyzed (Fig. 12). The ozone concentrations predicted by canopy schemes, compared with the SLAB schemes, increase over the urban areas such as Nanjing, Hangzhou cities during January, with the magnitude of 6.5% (or 2.6 ppb) in UCM scheme, 10.4% (4.2 ppb) in BEP scheme, and 7.3% (or 2.9 ppb) in BEP + BEM scheme, respectively. Yet 6.8% (or 2.7 ppb) to 10.6% (or 4.4 ppb) decrease of the ozone are also found over the sub-urban areas for the three canopy schemes. For July over the YRD region, all the three canopy schemes simulated lower ozone concentration, compared with SLAB scheme, as large as 30.2% (or 11.2 ppb) decrease in UCM scheme, 16.5% (6.2 ppb) decrease in BEP scheme, and 26.5 % (or 9.3 ppb) decrease in BEP + BEM scheme respectively. Lower PBLH and wind speed reduced the transport of ozone while higher temperature enhanced ozone generation, it seemed that horizontal transport was possibly the main factor affecting the ozone concentration distributions. It must be also mentioned that it is difficult to decide which is the major factor affecting the ozone generation and transport. For one hand, cloud position and formation, ozone precursors are also influence the ozone generation but there are no measurements over YRD region. For another hand, the changes of the canopy parameters involves in analysis of behaviors of the PBL and cloud schemes. At this stage, the influenced of canopy schemes on ozone formation and transport still contains uncertainty. Further studies are needed to investigate the influence on the ozone

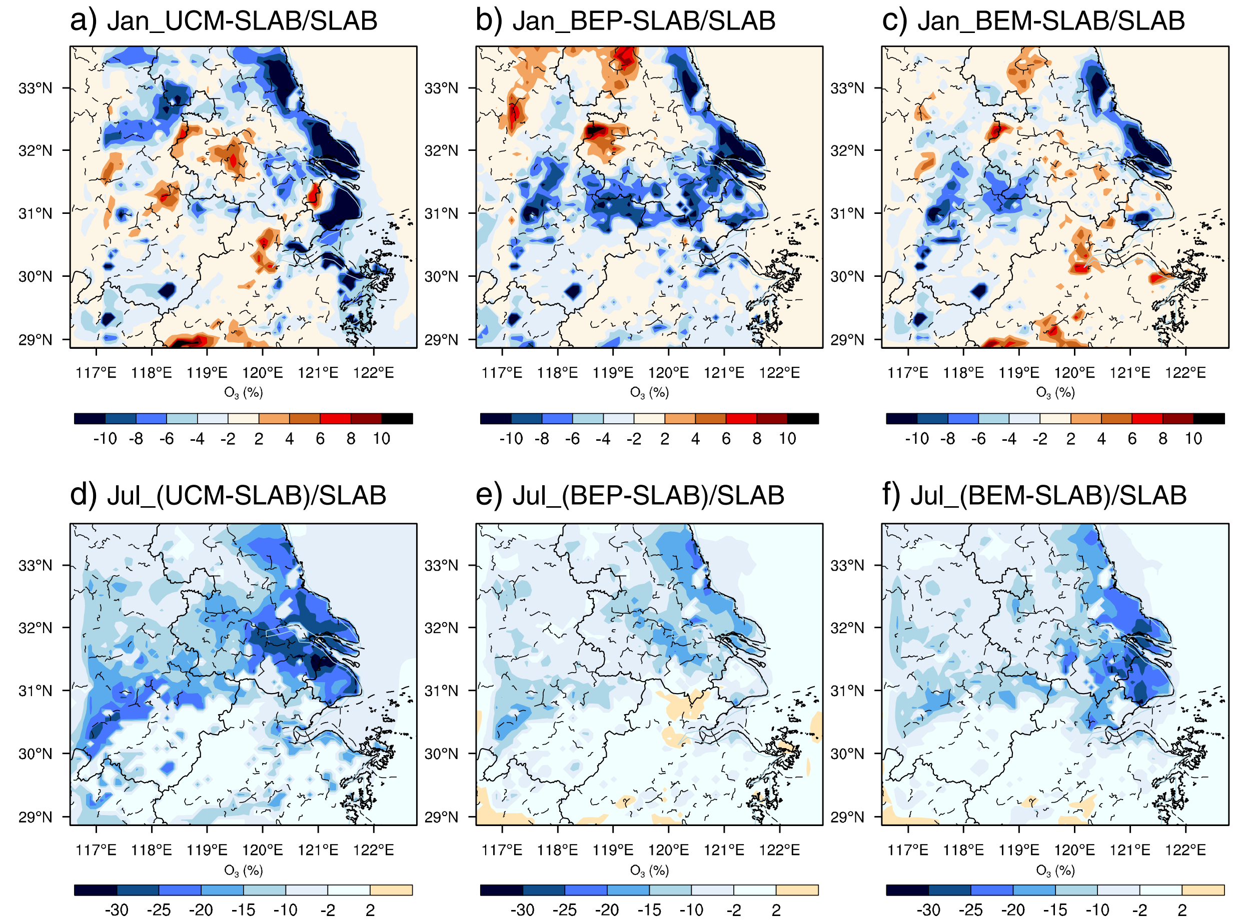

Fig. 12. Relative differences of ozone concentration between canopy schemes and control scheme: a,b,c for January; d, e, f for July.

formations due to chemical reactions, factors such as wind fields, long-term transport and biomass burning are sensitive to ozone concentration (Tang et al., 2013).

Vertical ozone and velocity (W) diurnal variations within 850 hpa over CCM site are investigated in Figs. 13 and 14. Compared with SLAB scheme, lower ozone concentration was fund during the nighttime for all the three canopy models due to SLAB scheme simulated higher air temperature. While at upper layers (~1 km above the surface), the ozone difference distributions are similar to the distributions of vertical velocity differences (Fig. 14). Higher ozone concentrations are simulated, compared with SLAB scheme, due to stronger downdraft. It indicates that the differences of ozone concentration within 850 hpa are transport from upper layers and forms a high value during nighttime.

5. Conclusions

The Weather Research and Forecasting/Chemistry (WRF/Chem) model coupled with different urban canopy models are conducted to investigate the impacts of urban canopy on urban climate and air quality in this study. Four urban canopy schemes are examined: (1) SLAB scheme that does not consider urban canopy parameters; (2) a single-layer urban model with a fixed diurnal profile for anthropogenic heat (UCM); (3) multilayer urban model (BEP); (4) multilayer urban models with a building energy model including anthropogenic heat due to air conditioning (BEP + BEM). To better represent the urban land category, updated USGS land-use data in actual state of 2004 base on MODIS observations was used, and parameters used in the schemes were also updated to better representative the local urban conditions. All the four urban models could reproduce 2-m temperature and 10-m wind speed well, and have different influences. For instance, compared with observation, 2-m temperature from UCM scheme produces maximum mean bias while the other three schemes give lower bias. UCM scheme tends to underestimate 2-m temperature in January but overestimate it in July. The multilayer canopy schemes, BEP and BEP + BEM, tend to overestimate 2-m temperature with MBs almost positive. The best 2-m temperature estimates are obtained with SLAB and BEP + BEM schemes. For 10-m wind speed, SLAB and UCM schemes tend to overestimate the wind speed whereas BEP and BEP + BEM scheme underestimate it. Compared with observations, BEP and BEP + BEM schemes calculate best 10-m wind speed predictions. But all the schemes were not able to simulate wind direction well during 2:00 am–8:00 am UTC. More specific urban parameters such as urban fraction, heat capacity and high-resolution gridded UCP data (NUDAPT) are needed to better improve model performance. The NUDAPT data are

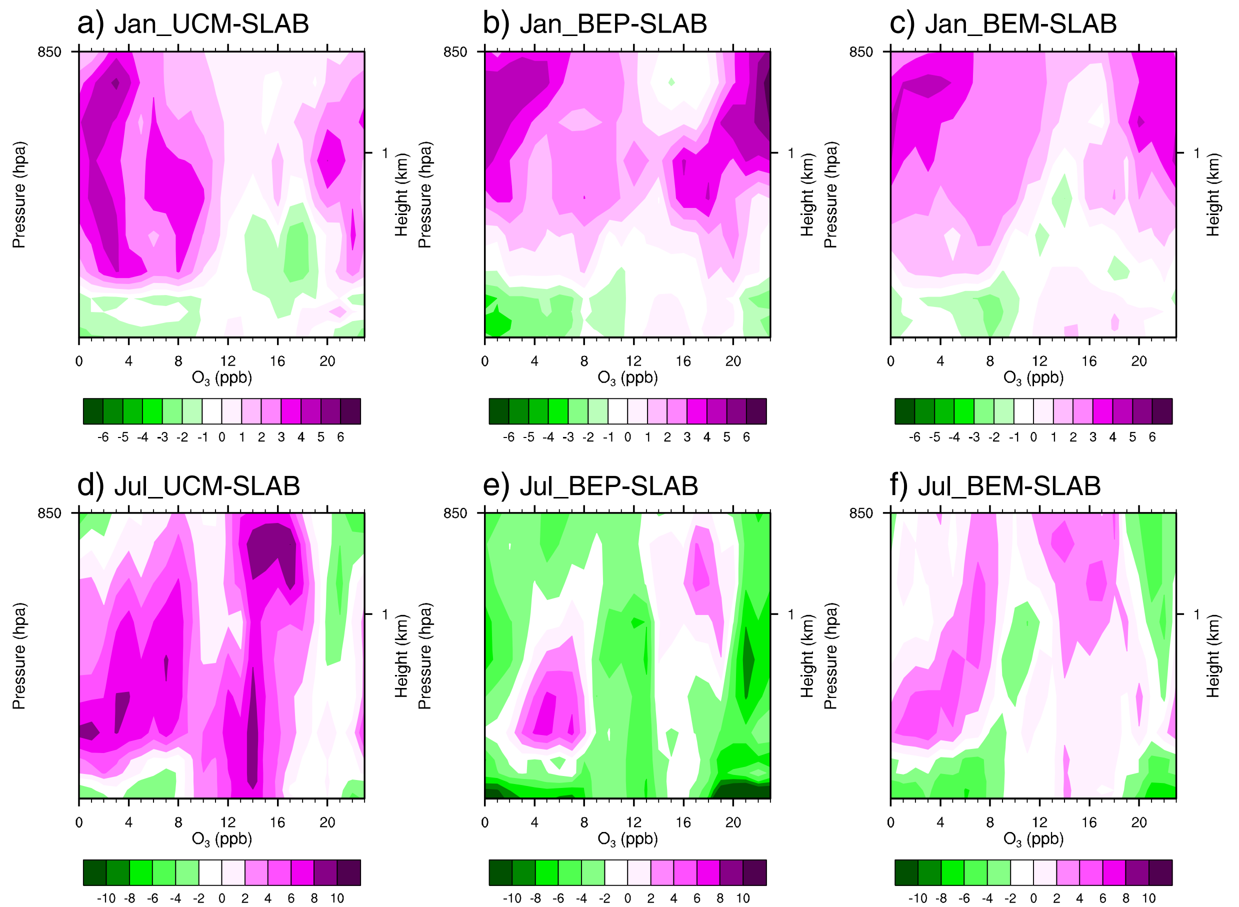

Fig. 13. Differences of vertical ozone concentration between canopy schemes and control scheme at CCM site: a,b,c for January; d, e, f for July.

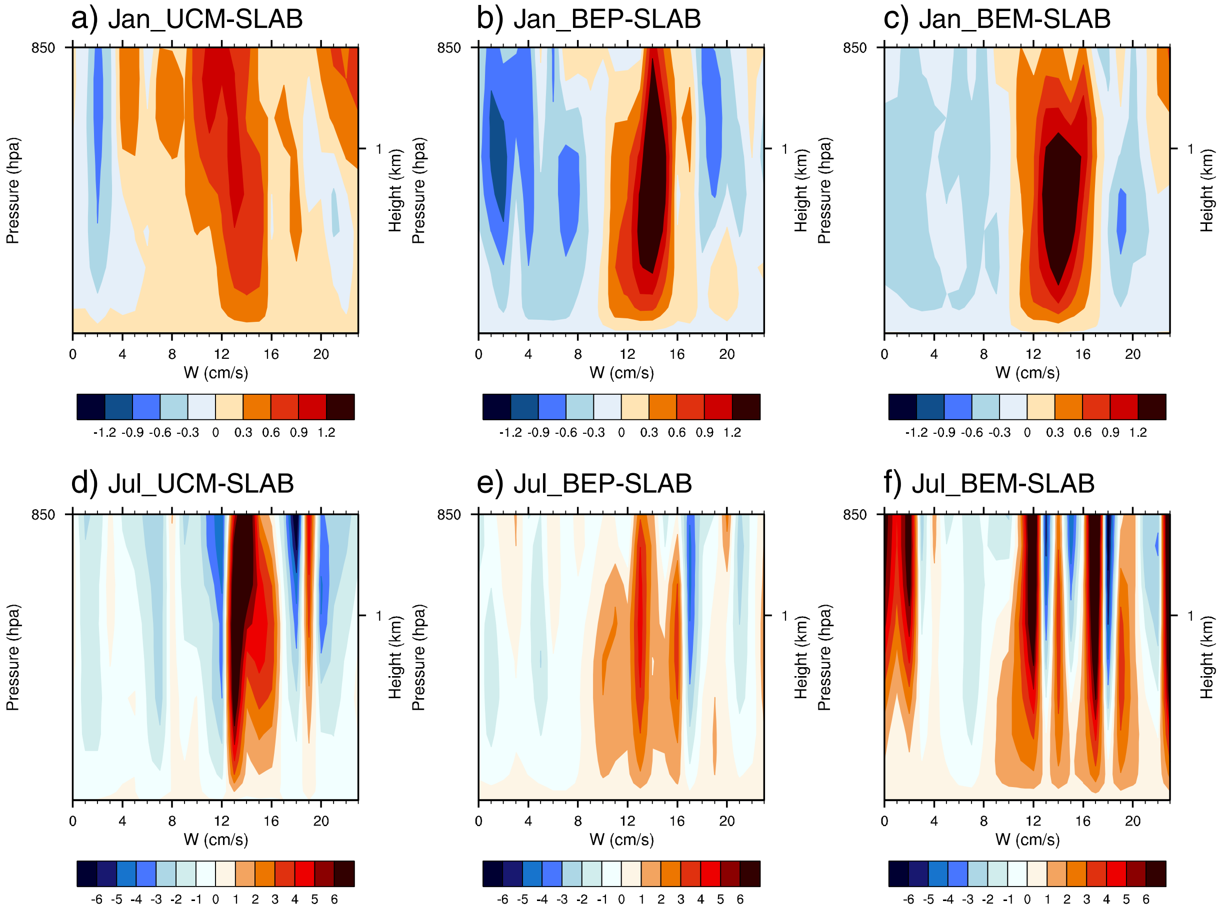

Fig. 14. Differences of vertical velocity between canopy schemes and control scheme at CCM site: a,b,c for January; d, e, f for July.

already available in newly WRF/Chem version 3.5, but these data are only for 44 cities of U.S.A., not yet available for Chinese city.

From the results, we also find that in January, 2-m temperature from BEP and BEP + BEM schemes, compared with SLAB scheme, increased with maximum value of 0.5 °C and 0.3 °C, while UCM scheme simulated lower temperature with decrease of 0.7 °C. In July, all the canopy experiments calculated lower air temperature with reduction of 0.5 °C in UCM, 1.6 °C in BEP and 1.4 °C in BEM, respectively. The patterns of PBLH differences between canopy experiments and control experiments are similar to 2-m temperature. UCM scheme predicted 120 m and 75 m lower PBLH both in January and July. BEP scheme, however, simulated 325 m higher PBLH in July while in January, simulated lower PBLH, with decrease of 116 m, BEP + BEM schemes calculated higher PBLH in both January (306 m) and July (46 m). Wind speed at 10 m significantly decreased when canopy schemes were coupled to the model. Compared with SLAB scheme, all the canopy experiments simulated lower wind velocity, for instants, 0.7 m s^{-1} (0.8 m s^{-1}) decrease with UCM, 1.7 m/s (2.6 m s^{-1}) decrease with BEP and 1.8 m s^{-1} (2.3 m s^{-1}) decrease with BEP + BEM schemes in January (July), respectively.

With the same emission inventory, compared with the observations, BEP + BEM and SLAB schemes best estimated ozone concentrations for both January and July, BEP + BEM scheme also predicted PM_{10} well during January, while the best estimate was obtained with UCM scheme during July. For chemical field distributions, compared with SLAB schemes, UCM scheme calculated higher PM_{10} concentration in both January and July, with the differences of 22.3% (or 24.4 μg/m^3) in January, and 31.4% (or 17.4 μg/m^3) in July, respectively. The multiple canopy schemes, BEP and BEP + BEM schemes, simulated lower PM_{10} concentration during January, with the decrease of 18.6% (or 22.1 μg/m^3) and 16.7% (or 24.6 μg/m^3), respectively. In July, BEP scheme predicated higher PM10 concentration, with the increase of 32.7% (or 18.3 μg/m^3), while BEP + BEM scheme predicted lower PM_{10} concentration with 30.8% (or 16.5 μg/m^3) decrease. BEP + BEM scheme simulated higher PBLH and conduct better diffusion conditions.

6.5% (or 2.6 ppb) to 10.4% (4.2 ppb) increase of ozone were computed over mage-cities by canopy experiments compared with control experiment during January. While during July, all the three canopy schemes predicted lower ozone concentrations and as large as 30.2% (or 11.2 ppb) decrease was obtained with UCM scheme, 16.5% (6.2 ppb) decrease with BEP scheme. In addition to the impacts discussed in this article, anthropogenic heat flux resulted from urbanization is an important factor affecting the PBL structure, more realistic AH inventory is needed to quantify the impacts by AH. Further study is also under-going to investigate the impacts of urban canopy on regional climate changes and air quality, for example, the use of high-resolution urban canopy parameters and NUDAPT data is of great help. Generally, the SLAB scheme is suitable for real-time weather forecast while BEP + BEM scheme is necessary when quantify the urbanization impacts on regional climate.

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