ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 26, NO. 6, 2009, 1115–1124

Building Morphological Characteristics and Their Effect on the Wind in Beijing

MIAO Shiguang*[1] (苗世光), LI Pingyang[2] (李萍阳), and WANG Xiaoyun[3] (王晓云)

[1] *Institute of Urban Meteorology, China Meteorological Administration, Beijing* 100089

[2] *National Meteorological Center, China Meteorological Administration, Beijing* 100081

[3] *Department of Integrated Observations, China Meteorological Administration, Beijing* 100081

(Received 17 May 2008; revised 9 February 2009)

ABSTRACT

An urban boundary layer model (UBLM) is improved by incorporating the effect of buildings with a sectional drag coefficient and a height-distributed canopy drag length scale. The improved UBLM is applied to simulate the wind fields over three typical urban blocks over the Beijing area with different height-to-width ratios. For comparisons, the wind fields over the same blocks are simulated by an urban sub-domain scale model resolving the buildings explicitly. The wind fields simulated from the two different methods are in good agreement. Then, two-dimensional building morphological characteristics and urban canopy parameters for Beijing are derived from detailed building height data. Finally, experiements are conducted to investigate the effect of buildings on the wind field in Beijing using the improved UBLM.

Key words: building morphological characteristics, urban boundary layer model, urban canopy model

Citation: Miao, S. G., P. Y. Li, and X. Y. Wang, 2009: Building morphological characteristics and their effect on the wind in Beijing. *Adv. Atmos. Sci.*, **26**(6), 1115–1124, doi: 10.1007/s00376-009-7223-7.

1. Introduction

Urban areas can significantly affect local and regional meteorological conditions and air quality. For example, wind speed is less in downtown areas than in suburban areas, which affects the transport and diffusion of pollutants and may lead to serious air pollution in urban areas. The effect of urbanization on local wind fields has been paid increasing attention by investigators. Recently, Grimmond (2006) and Souch and Grimmond (2006) reviewed observational studies on urban climate. Examples include the Beijing City Air Pollution Observation Experiment (BECAPEX) (Xu et al., 2004), UBL/CLU (urban boundary layer/couche limite urbaine)-ESCOMPTE (ESCOMPTE is the French acronym for a field experiment to constrain the models of pollution emission transport) (Mestayer et al., 2005), the Basel Urban Boundary Layer Experiment (BUBBLE) (Rotach et al., 2005), and the Joint Urban 2003 campaign (Allwine and Flaherty, 2006). These field experiments have significantly advanced the recognition of spatial differences both within and between cities as a result of differences in urban fabric (materials, morphology), emissions, and prevailing meteorological and climatic conditions.

In addition to observations, numerical simulation is a widely-used approach for urban boundary layer (UBL) studies (Gao and Bian, 2004; Jiang et al., 2007; Liu and Zhou, 2007; Wang, 2009). To conduct numerical simulations for multi-scale heterogeneous UBLs, an urban canopy model (UCM) is usually used to parameterize the effect of sub-grid urban buildings in the UBL. Macdonald (2000) applied the canopy approach to extensive regular arrays of urban-like cubical obstacles, showing that the predicted exponential velocity profile matched well the spatially averaged velocity profiles computed from measurements. "Distributed drag" models of urban areas have also been proposed in the literature to parameterize the effects of urban areas within mesoscale meteorological models (Brown, 2000; Martilli et al., 2002). Coceal and Belcher (2004) developed an UCM for spatially averaged mean winds within and above urban areas by introducing

*Corresponding author: MIAO Shiguang, sgmiao@ium.cn

a mean sectional drag coefficient and a canopy drag length scale. Coceal and Belcher (2005) further applied the UCM by explicitly taking into account one-dimensional variation in morphological characteristics from one neighborhood to another. Miao and Chen (2008) and Miao et al. (2008) used Weather Research and Forecasting (WRF) simulations and wind-profiler observations to show that daytime convection in urban areas is mainly in the form of convective rolls, and the WRF/Noah/UCM (Noah is the acronym for National Centers for Environmental Prediction-Oregon State University-Air Force-Hydrologie Research Laboratory land surface model) modeling system can capably capture boundary-layer convective rolls and cells.

Masson (2006) classified the UCMs developed in this community into five main categories. He pointed out that "there is need to validate further the different urban models available". However, the validation of the simulation results from UCMs is very difficult, because the simulation results are the mean value of a model grid at the scale of kilometers, while the observations in urban areas are local values that only represent a small area. It is both costly and difficult to observe a regional mean value of a physical variable in urban areas, such as for wind speed and air temperature.

Furthermore, urban building morphological characteristics/parameters are essential to UCMs. Burian et al. (2001) calculated the building morphological characteristics for a 12.0 km^2 area centered around downtown Los Angeles, California. The requirement for this kind of applied research is especially urgent for the rapidly-urbanizing megacity of Beijing.

In this paper, an UBL model is improved by introducing the UCM, and this is evaluated with a building-aware model. Building morphological characteristics are determined over the Beijing area. Experiments are conducted to investigate the effect of buildings on the wind field in Beijing. The paper is organized as follows. Section 2 describes the improvement of an urban boundary layer model (UBLM). In Section 3, two-dimensional building morphological characteristics and urban canopy parameters of Beijing are derived. Section 4 investigates the effect of buildings on the wind field in Beijing with the aid of the UBLM. Finally, Section 5 gives the conclusions and discussion.

2. The improvement of UBLM

2.1 *The primary modifications*

In order to simulate the effect of buildings, the building canopy parameterization (also called the UCM) is introduced into a regional scale boundary layer model (Wang and Jiang, 1998; Xu et al., 2002; Jiang et al., 2002), which is a 3-dimensional model solving the non-hydrostatic primitive equations of atmospheric motion in the terrain-following coordinate system with the turbulence kinetic energy (TKE) closure scheme. The primary modifications are in four aspects:

(1) A new term representing the building canopy element drag is added to the momentum equations, which is expressed as (Coceal and Belcher, 2004, 2005)

$$D_x = -\frac{|U|\,u}{L_c(z)}\,, \qquad D_y = -\frac{|U|\,v}{L_c(z)}\,, \tag{1}$$

where U is the horizontal wind speed, u and v are the x and y components of horizontal wind velocity respectively. Because in a real city, buildings are raggedly distributed with different heights even within a mesoscale gridbox, a height-distributed canopy drag length scale, $L_c(z)$, is used which can only "feel" the influence of taller buildings, and is defined as

$$L_c(z) = \frac{2h(z)}{C_D(z)}\frac{(1-\beta(z))}{\lambda_f(z)}\,, \tag{2}$$

where $h(z)$ is the plan-area-weighted average building height, $(1-\beta(z))$ is the fractional volume occupied by air in the canopy, $C_D(z)$ is the sectional drag coefficient (Macdonald, 2000), and $\lambda_f(z)$ is the frontal area per unit ground area.

(2) A new term representing the source of TKE generated by the interactions between the buildings and the airflow is added to the TKE equation (Brown, 2000), i.e,

$$D_E = \frac{(|u|^3 + |v|^3)}{L_c(\mathrm{z})}\,, \tag{3}$$

(3) The length scale, l, used in the TKE closure ($K_m = C_0 l E^{1/2}$), is modified as,

$$\frac{1}{l} = \frac{1}{l_{old}} + \frac{1}{l_b}\,, \qquad \frac{1}{l_b} = \sum_{h_i > z_k} \frac{1}{h_i}\,, \tag{4}$$

where K_m is the turbulent mixing coefficient for momentum, C_0 is a constant, E is TKE, l_{old} is the traditional length scale calculated with the formula over natural surfaces, l_b is the length scale reflecting the building effect, and h_i is the building height. It is assumed that lower levels "feel" the influence of higher and smaller buildings, while at higher levels only vortices induced by higher buildings are important (Martilli et al., 2002).

(4) The sectional drag coefficient, $C_D(z)$, varies with canopy density from 1.2 for an isolated cube to 2.6 for a relatively dense array (Coceal and Belcher, 2004). In order to apply the UCM to the two-dimensional

Table 1. The main characteristics of UBLM and USSM.

	UBLM	USSM
Dynamics	Three-dimensional Non-hydrostatic	Three-dimensional Non-hydrostatic
Scale	Urban scale ~50 km	Neighborhood scale ~1 km
Horizontal grid spacing	~1 km	~10 m
Building effect	Implicitly parameterized	Explicitly resolved
Building shading	No	Yes
Terrain effect	Yes	No
Turbulence closure scheme	TKE closure	E-ε closure
Lateral boundary condition	Zero gradient, Radiation, Nested	Zero gradient, Inflow
Vertical grid spacing	2.5–100 m	2.5–100 m
Top height	~300 m	~1500 m
Time step	0.25–3 s	~0.05 s

model, we define $C_D(z)$ to vary with building plan area density as

$$C_{\rm D}(z) = 1.2 + 1.4\frac{\lambda_{\rm p}(z)}{\lambda_{\rm pmax}}\,, \quad (5)$$

where $\lambda_{\rm pmax}$ is the maximum of building plan area density, $\lambda_{\rm p}(z)$.

2.2 *Validation*

In order to validate the performance of the UBLM on the simulation of the airflow in the building canopy and UBL, comparisons are made between the simulation results from the UBLM and from an Urban Sub-domain Scale meteorology and pollutant diffusion Model (USSM). USSM has been verified with field observational data and wind tunnel experimental data (Miao et al., 2006), and it has been shown that USSM can simulate the main characteristics of the flow in an urban sub-domain. The main characteristics of these two models are listed in Table 1. We can see that UBLM is designed for urban scale with the resolution of about 1 km, while USSM is for the neighborhood scale with the resolution of about 10 m. Also, the building effects are implicitly parameterized in UBLM, while they are explicitly resolved in USSM.

Firstly, a benchmark experiment is carried out in which results from these two models over a flat grass area are compared. In order to clearly and easily compare the results from these two different models, the initial meteorological conditions are set such that the geostrophic wind is 5 m s^{-1} from the west, the potential temperature is 300 K under 800 m with an increasing lapse rate of 0.006 K m^{-1} above 800 m under adiabatic conditions.

Figure 1 shows that the profiles of horizontal wind speed from two models match very well. Although there are big differences in TKE values from two models, the shape of TKE profiles are similar, i.e., there are large TKE values near the ground followed with rapid decreases with height. This discrepancy of TKE presumably partly results from the different turbulence closure schemes used in the two models. As shown in Table 1, UBLM uses a TKE closure scheme, while

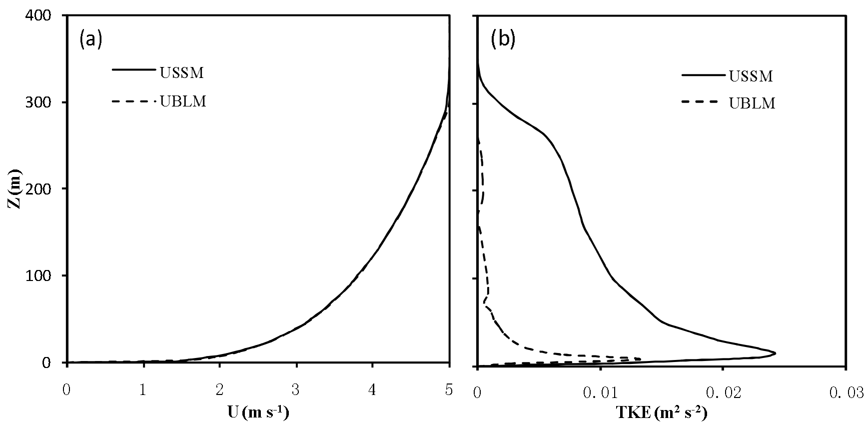

Fig. 1. The profiles of (a) horizontal wind speed (units: m s^{-1}), and (b) TKE (units: m^{2}s^{-2}) for the benchmark experiment. Solid and dashed lines are from USSM and UBLM, respectively.

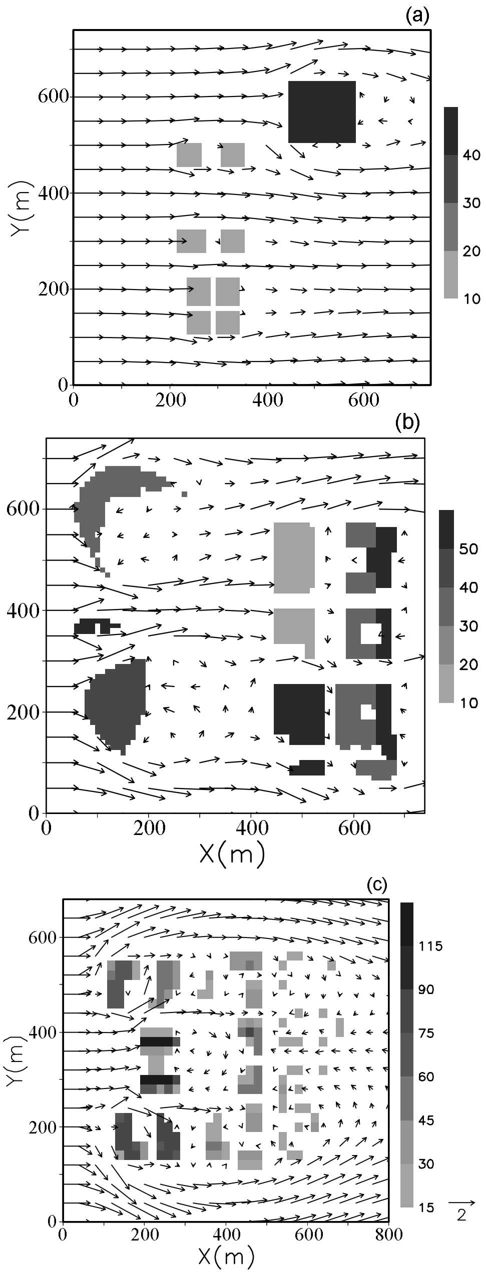

Fig. 2. The wind fields of three blocks approximately correspond to three flow regimes (vector: wind, units: m s^{-1}, the sample arrow beside panel c represents a wind speed of 2 m s^{-1}; shaded: building height, units: m): (a) Isolated roughness flow, Block: WKS1; (b) Wake interference flow, Block: WKS2; and (c) Skimming flow, Block: JRJ.

USSM employs an E-ε closure scheme. There are some systematic errors in the simulation of TKE between these two turbulence closure schemes. Castelli et al. (2001) validated these two closure schemes in the Regional Atmospheric Modeling System (RAMS) and showed that both of them performed well on the mean wind and temperature fields, while the TKE closure scheme underestimated the TKE, and the E-ε closure scheme significantly improved the simulation results when considering the turbulence field. The main contribution to the different performances is related to the boundary layer assumptions; that is, neglecting the horizontal diffusion terms and retaining only the vertical gradients will change the results. However, these horizontal terms can be important contributions under non-homogeneous conditions. Further improvement of the turbulence modeling in UBLM is needed.

Oke (1987) classified three flow regimes based on the building height H and the street canyon width W. When the buildings are relatively widely spaced (H/W <0.4 for cubic and H/W <0.3 for row buildings), the flow pattern appears almost the same as if they were isolated. At closer spacing (H/W up to about 0.7 for cubes and 0.65 for rows), the wake of any building interferes with that of the next downstream leading to a complicated pattern. At spacing closer than this, the main flow starts to skim over the building tops and drives a lee vortex in the cavity (often a street). So, we select three blocks WKS1, WKS2 and JRJ (the building heights are shown in Fig. 2, and the parameters are listed in Table 2), approximately corresponding to the three flow regimes, to simulate the turbulent flow with UBLM and USSM simultaneously. These three blocks are not absolutely subject to the three flow regimes, but they are generally suitable and realistic in urban areas. The initial meteorological conditions are the same as the benchmark experiment. The terrain is flat and the radiation process is shut down. The lateral boundary condition is a zero gradient for UBLM and inflow for USSM. Based on previous tests (Miao et al., 2006), the horizontal grid spacing of the USSM run is set to 10 m, and the vertical grid spacing increases from 2.5 m near the ground to 100 m progressively, with the top at 1500 m. The horizontal grid spacing of UBLM run equals the corresponding length of three blocks, and the vertical grid spacing increases from 2.5 m near the ground to 100 m progressively, with the top at 3000 m. With time steps of 0.25 s (UBLM) and 0.05 s (USSM), approximately 1 h of real time is integrated to reach steady-state solutions.

Figure 2 shows the wind fields of three blocks. The flow is reasonably distributed around the buildings with a displacement zone, cavity zone, and wake zone. In Fig. 2a, the main flow characteristic is isolated roughness flow although there are some very tightly packed small buildings, the same features are evident in Fig. 2b, with dominant wake interference flow and some skimming flow. In Fig. 2c, the buildings are very close to each other, which form skimming flow. These

Table 2. The parameters of the three blocks.

Name	Area (m × m)	Maximum building height (m)	λ_p	h (m)
WKS1	650×650	45	0.11	23.96
WKS2	650×650	50	0.23	36.43
JRJ	620×500	116	0.33	33.56

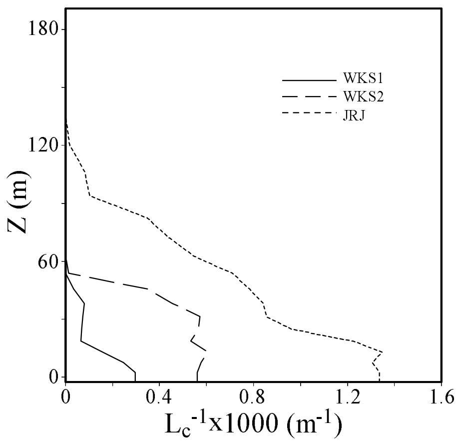

Fig. 3. Profiles of the reciprocal of height-distributed canopy drag length scale, $1/L_c$, for the three blocks (units: m^{-1}) (solid line WKS1, dashed line WKS2, short dashed line JRJ).

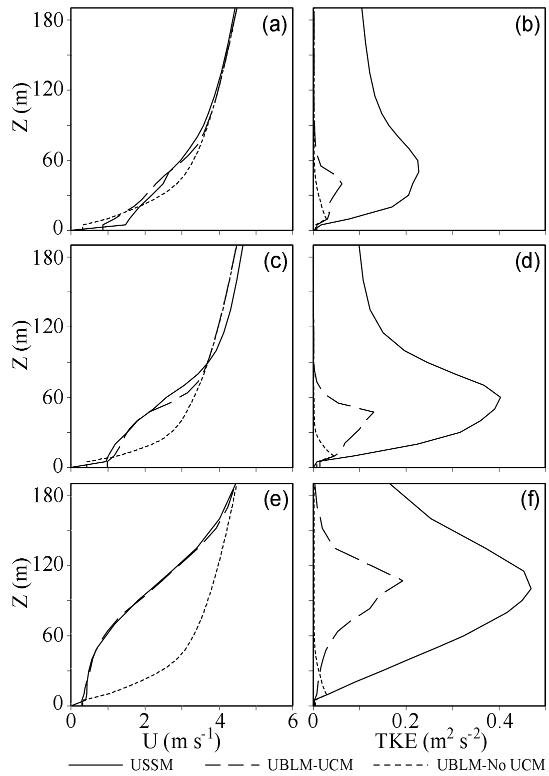

Fig. 4. The profiles of horizontal wind speed (left panels, units: m s^{-1}), and TKE (right panels, units: m^2 s^{-2}) for three blocks: WKS1 (a, b), WKS2 (c, d) and JRJ (e, f). Solid line is from USSM, and dashed and short dashed lines are from UBLM with and without UCM being used, respectively.

characteristics are consistent with previous studies (Oke, 1987).

The profiles of $1/L_c$ for the three blocks are drawn in Fig. 3, which is used in UBLM to represent the building effect. It is found that the shapes of the vertical distributions for the three blocks are different from each other. WKS1 decreases from the ground as height increases, and then is kept as a constant and finally decreases to zero. WKS2 is nearly a constant from the ground, but then sharply decreases to zero, while the profile of JRJ slowly decreases to zero.

The profiles of the horizontal wind speed and TKE from USSM and UBLM for these three blocks are shown in Fig. 4. We can see that, the profiles of wind speed for the three blocks from UBLM without UCM being used but using the traditional roughness (1.0 m) approach for the urban building effects (short dashed lines) are dramatically discrepant with those from USSM (solid lines), especially for blocks WKS2 and JRJ. Meanwhile, the profiles using UCM instead of using the traditional roughness approach (dashed lines) are very consistent on the shape and the values with those from USSM. So, after inclusion of the UCM the wind simulation of UBLM is greatly improved compared to the traditional roughness approach, especially for highly urbanized areas. Simultaneously, the simulation of TKE from UBLM with UCM is also better than that with the traditional approach, especially on the heights of maximum TKE. However, there is a big difference in the values of maximum TKE between the two models, which presumably partly results from the different turbulence closure scheme used in two models, as described for the benchmark experiment.

3. Building morphological characteristics and urban canopy parameters

3.1 *Building morphological characteristics*

Beijing is located in the northern part of the North China Plain and on the west coast of the Pacific Ocean. Tian'an Men, in the center of Beijing, is surrounded by 5 Rings (major roads for traffic). Greater Beijing has an area of 16 808 km^2, and a population of 17 million.

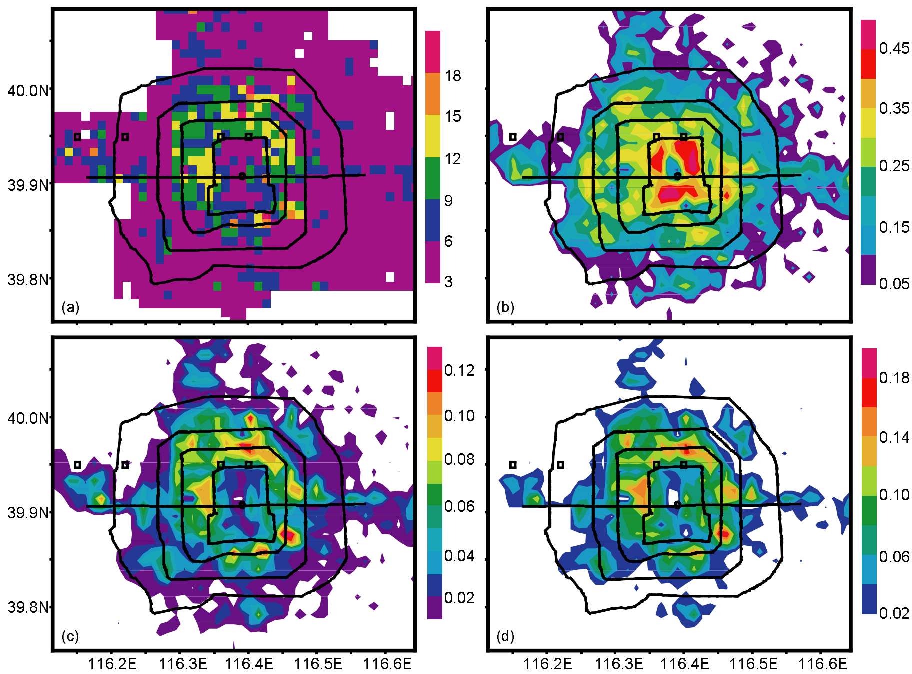

Fig. 5. Building morphological characteristics and urban canopy parameters at 1-km grid resolution for Beijing: (a) The plan-area-weighted average building height, h (units: m); (b) Building plan area fraction, $\lambda_{\rm p}$; (c) Building frontal area fraction, $\lambda_{\rm f}$, for a northerly wind direction; (d) The building canopy "density", $h/L_{\rm c}$. The rings from inner to outer are the 2nd, 3rd, 4th and 5th Rings, the transverse line is Chang'an Street, and the symbol "o" represents the position of Tian'an Men, the four squares denote the positions of the dashed lines in Fig. 8.

Beijing enjoys a moderate continental climate.

Building morphological characteristics at 1-km grid resolution for the Beijing area are determined from detailed building height data, including plan-area-weighted average building height (h), plan area fraction ($\lambda_{\rm p}$), frontal area fraction ($\lambda_{\rm f}$), complete aspect ratio, building surface area to plan area ratio, roughness length, displacement height, etc. (Grimmond and Oke, 1999; Burian et al., 2001).

It can be seen from Fig. 5 that, due to the urban layout of Beijing (old town is surrounded by new town), the building morphological parameters have a special distribution. There are many ancient low buildings in the Second Ring of Beijing, e.g. the Forbidden City, while new high-rise buildings are usually distributed outside of the Second Ring. Hence, the maximum of h and $\lambda_{\rm f}$ is between the Second Ring and the Fourth Ring, while the maximum of $\lambda_{\rm p}$ appears in the range of the Second Ring.

3.2 *Urban canopy parameters*

Based on the detailed building height data, urban canopy parameters including building canopy drag length scale ($L_{\rm c}$), wind adjustment length scale (x_0), building canopy "density" ($h/L_{\rm c}$, which "feels" the influence of all buildings in a grid) (Coceal and Belcher, 2005) are derived (shown in Fig. 5d), which is used directly in the urban canopy model. It can be seen that the "densest" building canopy is between the Second Ring and the Fourth Ring, corresponding to the distribution of high-rise buildings.

4. The effect of buildings on the wind field

In order to easily and clearly investigate the effect of buildings on the wind field, this question is here investigated under adiabatic condition and strong wind (Coceal and Belcher, 2005). We run two cases (urban case and non-urban case) using UBLM initialized with geostrophic wind speed $u_{\rm g}$=12 m s^{-1}. The horizontal grid spacing is 1 km, and the horizontal simulation domain is 45 km $\times$ 36 km. Other conditions are the same as the cases in section 2.2.

Figure 6 shows the horizontal distribution of $1/L_{\rm c}$ and wind velocity u of UBLM results at z=2.5 m, 10 m, and 50 m. We can see from the figures that due to the building element drag, the wind in the urban area is weaker than that in suburban and rural

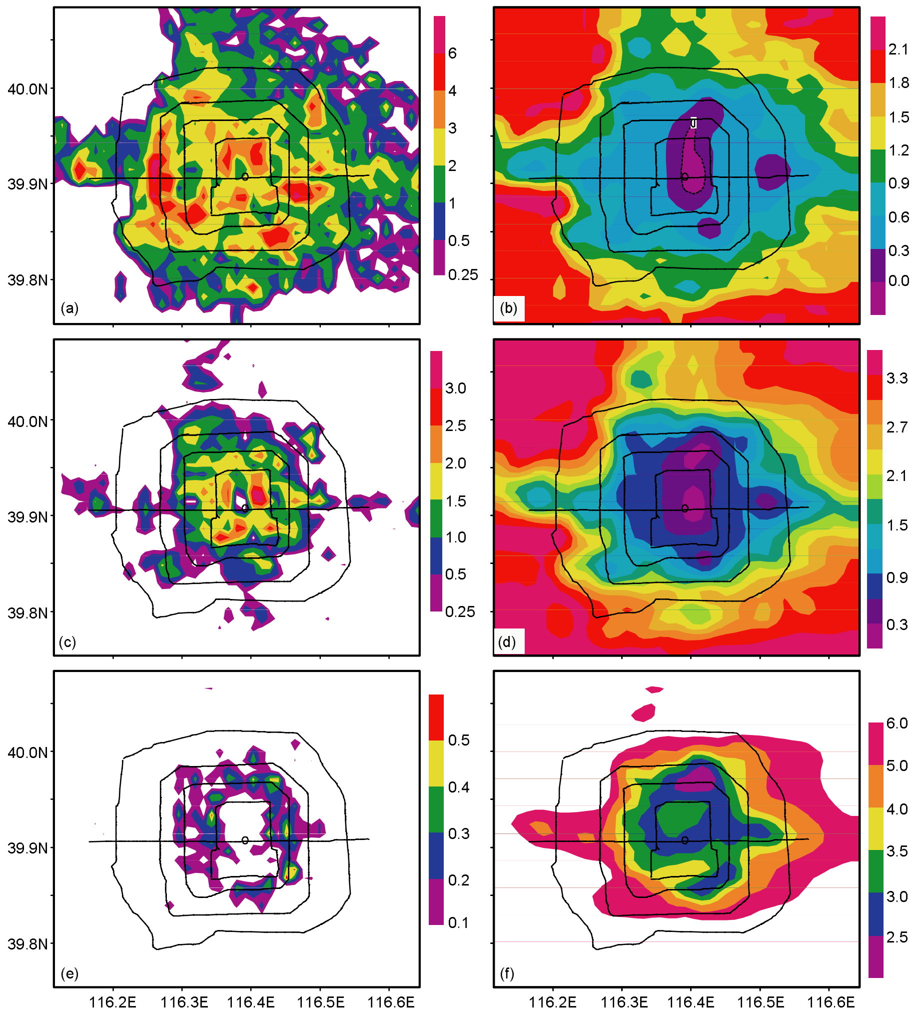

Fig. 6. The distributions of the reciprocal of height-distributed canopy drag length scale, $1/L_c \times 1000$, (left panels, units: m^{-1}), and wind velocity u of UBLM results (right panels, units: $m\ s^{-1}$) at (a), (b), z=2.5 m, (c), (d), z=10 m, and (e), (f), z=50 m.

areas, and moreover the distribution of wind velocity is opposite to the distribution of the building canopy drag coefficient. Further analysis indicates that, at the height of 2.5 m, there is a sharp variation of $1/L_c$ in the city center, and the wind velocity u is negative in this region (the flow direction is reversed), for the spatially averaged flow close to the ground. The city center lies between two tall buildings, so the wind flow is similar to that in a street canyon. The mechanism of the reversal flow near ground is essentially the same as the one responsible for the circulation observed in a street canyon, an effect that has been amply documented in the wind engineering literature. These observations offer indirect, qualitative support for the results obtained in the present building canopy simulations. At the height of 10 m, the wind velocity is very small in the city center. At z= 50 m there is a ring region with weak wind associated with enhanced drag offered by tall buildings.

The sectional figures of u, (u, w), and TKE are shown in Fig. 7. When the flow encounters the upwind edge of the urban high-rise buildings, there is updraft flow. Relative to the surroundings, lower buildings are located at the city center, so downdrafts and some reversal flows are observed near the ground. There are updrafts and distinct downdrafts at the downwind edges of urban high-rise buildings. The maximum of TKE can be found around buildings associated with the interactions between the buildings and the airflow.

Figure 8 shows the profiles of u from the non-urban case and at different locations over the urban area in the urban case. Compared with the wind velocity profile of the non-urban case, the wind velocity is reduced due to building drag effects. Further analysis shows that the wind velocity profile in the area with sparse buildings is approximately distributed according to a

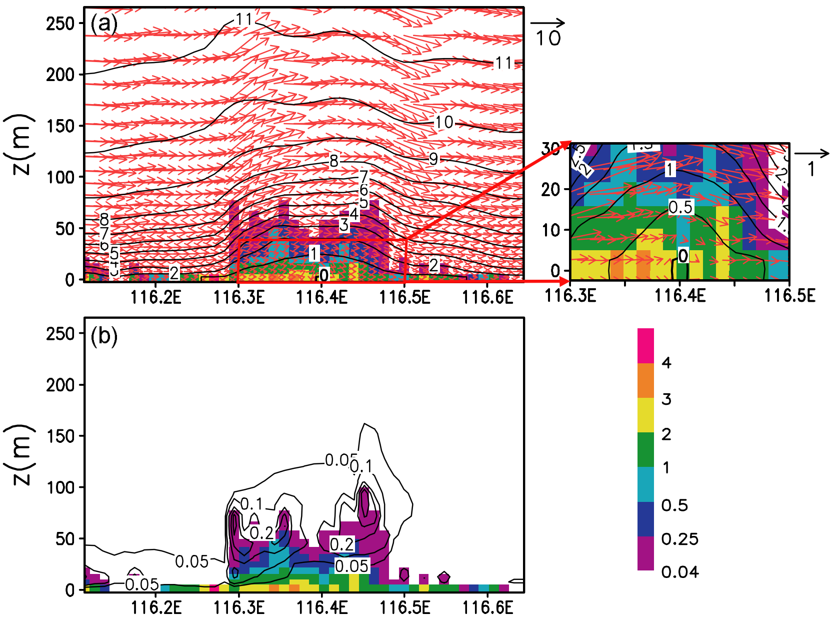

Fig. 7. The sectional figures at lat=39.95°N: (a) the reciprocal of height-distributed canopy drag length scale, $1/L_c \times 1000$, (shaded, units: m^{-1}), u (contour, units: m s^{-1}), and (u; $w \times 100$) (vector, units: m s^{-1}); (b) the reciprocal of height-distributed canopy drag length scale, $1/L_c \times 1000$, (shaded, units: m^{-1}), and TKE (contour, units: m^2 s^{-2}).

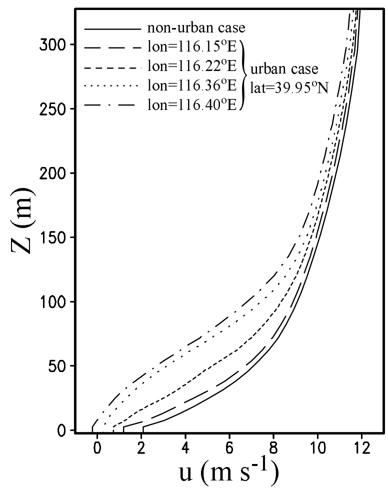

Fig. 8. The profiles of wind velocity u (units: m s^{-1}), the four dashed lines denoted with four squares in Fig. 5 respectively.

logarithm-law, which is not suitable for use in the area with dense buildings.

5. Conclusions and discussion

A regional scale boundary layer model, UBLM, is improved by introducing the UCM. The modified model is evaluated with the aid of USSM. Then the model is applied to the Beijing area. The building morphological characteristics of the Beijing area are determined from the detailed building height data, and urban canopy parameters are derived. The main conclusions are summarized as follows.

(1) The modified UBLM can reasonably simulate wind fields in urban areas for three flow regimes (isolated roughness flow, wake interference flow, and skimming flow). After the inclusion of UCM, the performance of UBLM in urban areas is significantly improved compared to the traditional roughness approach, especially for the simulation of wind. Furthermore, the best agreements are found for skimming flow (high-density urban areas); hence dramatic urban characteristics appear to be relatively easier to be modeled by using the UCM.

(2) Due to the particular urban layout (the old town is surrounded by the new town), building parameters for the Beijing area have a special distribution. The maximum of λ_p appears in the range of the Second Ring, while the maximum of h, λ_f, and the "densest" building canopy lies between the Second Ring and the Fourth Ring. These parameters are crucial for the UCM to be used appropriately in mesoscale meteorological models in order to well capture the structures and characteristics of the urban atmosphere.

(3) In Beijing, the buildings have a marked and distinct effect on the wind and TKE fields. In the

city center where the building canopy "density" varies sharply, the direction of the flow is opposite to that of the spatially averaged flow close to the ground. These characteristics presumably lead to important impacts on meteorological conditions and pollutant transport and dispersion.

The simulation results of the building effects for the Beijing area should be further validated with observations. The automatic weather station (AWS) data in the area cannot represent the real wind. The upscaling of the urban area AWS data can be done with the aid of building-aware models (e.g., USSM) to validate mesoscale models, and the horizontal observation data from lidar are also appropriate. The effects of urbanization on temperature, precipitation, and air quality in Beijing need to be systematically investigated in depth in the future.

Acknowledgements. The authors wish to thank two anonymous journal reviewers for their valuable comments. The first author would like to acknowledge the World Meteorological Organization, the International Association for Urban Climate (IAUC), the San José State University Foundation, and the local organizing committee of the 6th International Conference on Urban Climate (ICUC6) for financial support for the attendance at ICUC6, and the authors also appreciate the IAUC Awards Committee for the Japan Prize. This work was funded by National Natural Science Foundation of China (Grants Nos. 40505002, 40652001, and 40775015), Beijing Natural Science Foundation (Grant No. 8051002), Beijing New Star Project of Science and Technology (Grant No. 2005A03), and the Ministry of Science and Technology of China (Grant Nos. 2008BAC37B04, 2006BAJ02A01, and GYHY200906035).

REFERENCES

Allwine, K. J., and J. E. Flaherty, 2006: Joint Urban 2003: Study overview and instrument locations. PNNL-15967, Pacific Northwest National Laboratory, Richland, WA. [Available online from http://www.pnl.gov/main/publications/external/technical_reports/PNNL-15967.pdf].

Brown, M. J., 2000: Urban parameterizations for mesoscale meteorological models. *Mesoscale Atmospheric Dispersion*, Z. Boybeyi, Ed., WIT Press, Boston, 193–255.

Burian, S. J., M. J. Brown, and S. P. Linger, 2002: Morphological analysis using 3D building databases: Los Angeles, California. Los Alamos National Laboratory, LA-UR-02-0781, 73pp.

Castelli, S. T., E. Ferrero, and D. Anfossi, 2001: Turbulence closures in neutral boundary layer over complex terrain, *Bound.-Layer Meteor.*, **100**, 405–419.

Coceal, O., and S. E. Belcher, 2004: A canopy model of mean winds through urban areas. *Quart. J. Roy. Meteor. Soc.*, **130**, 1349–1372.

Coceal, O., and S. E. Belcher, 2005: Mean wind through an inhomogeneous urban canopy. *Bound.-Layer Meteor.*, **115**, 47–68.

Gao, Z., and L. Bian, 2004: Estimation of aerodynamic roughness length and displacement height of an urban surface from single-level sonic anemometer data. *Aust. Meteor. Mag.*, **53**, 21–28.

Grimmond, C. S. B., 2006: Progress in measuring and observing the urban atmosphere. *Theor. Appl. Climatol.*, **84**, 3–22.

Grimmond, C. S. B., and T. R. Oke, 1999: Aerodynamic properties of urban areas derived from analysis of surface form. *J. Appl. Meteor.*, **38**, 1262–1292.

Jiang, W., M. Zhou, M. Xu, and W. Wang, 2002: Study on development and application of a regional PBL numerical model. *Bound.-Layer Meteor.*, **104**, 491–503.

Jiang, W., Y. Wang, G. Liu, H. Liu, R. Zhou, Y. Ouyang, and X. Wang, 2007: Multi-scale urban boundary layer modeling system. *Journal of Nanjing University* (*Natural Sciences*), **43**, 221–237. (in Chinese)

Liu, S., and B. Zhou, 2007: Simulation of wind, temperature and humidity fields over Beijing area in summer using an improved model. *Acta Scientiarum Naturalium Universitatis Pekinensis*, **43**, 42–47. (in Chinese)

Macdonald, R. W., 2000: Modelling the mean velocity profile in the urban canopy layer. *Bound.-Layer Meteor.*, **97**, 25–45.

Martilli, A., A. Clappier, and M. W. Rotach, 2002: An urban surface exchange parameterization for mesoscale models. *Bound.-Layer Meteor.*, **104**, 261–304.

Masson, V., 2006: Urban surface modeling and the mesoscale impact of cities. *Theor. Appl. Climatol.*, **84**, 35–45.

Mestayer, P. G., and Coauthors, 2005: The urban boundary-layer field campaign in Marseille (UBL/CLU-ESCOMPTE): Set-up and first results. *Bound.-Layer Meteor.*, **114**, 315–365.

Miao, S., and F. Chen, 2008: Formation of horizontal convective rolls in urban areas. *Atmospheric Research*, **89**, 298–304.

Miao, S., F. Chen, M. A. LeMone, M. Tewari, Q. Li, and Y. Wang, 2008: An observational and modeling study of characteristics of urban heat island and boundary layer structures in Beijing. *J. Appl. Meteor. Climatol.*, **48**, 484–501.

Miao, S., W. Jiang, X. Wang, and W. Guo, 2006: Impact assessment of urban meteorology and the atmospheric environment using urban sub-domain planning. *Bound.-Layer Meteor.*, **118**, 133–150.

Oke, T. R., 1987: *Boundary Layer Climates.* 2nd ed., Methuen CO. Ltd, London and New York, 405pp.

Rotach, M. W., and Coauthors, 2005: BUBBLE – an urban boundary layer project. *Theor. Appl. Climatol.*, **81**, 231–261.

Souch, C., and S. Grimmond, 2006: Applied climatology: Urban climate. *Progress in Physical Geography*, **30**, 270–279.

Wang, W., 2009: The influence of thermally-induced mesoscale circulations on turbulence statistics over an idealized urban area under a zero background wind. *Bound.-Layer Meteor.*, **131**, 403–423.

Wang, W., and W. Jiang, 1998: A 3-dimensional nonhydrostatic dispersion modeling system for modelling of atmospheric transport and diffusion over coastal complex terrain in Hongkong-Shenzhen Area. *Meteor. Atmos. Phys.*, **68**, 23–33.

Xu, M., W. Jiang, C. Ji, X. Wang, H. Liu, and Y. Gao, 2002: Numerical modelling and verification of structures of the boundary layer over Beijing area. *Journal of Applied Meteorological Science*, **13**(Suppl.), 61–68. (in Chinese)

Xu, X., G. Ding, L. Bian, and L. Xie, 2004: Characteristics of atmospheric envinronment of boundary layer structure of city community in BECAPEX and integrate influence. *Acta Meteorologica Sinica*, **62**, 663–671. (in Chinese)