## Numerical Study of Winter Urban Boundary Layer Structure over Beijing Area<sup>\*</sup>

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#### ABSTRACT

Based on the successful simulation of a typical winter urban boundary layer (UBL) process over Beijing area during the Beijing City Air Pollution Experiment (BECAPEX) in 2001 by the use of MM5 coupled with urban canopy parameterization, a series of simulation experiments are performed to investigate the effects of urban influence, surrounding terrain, and different extent of urbanization on urban boundary layer structures over Beijing area. The results of factor separation experiments of urban influence indicate that the total effect of urban influence, which is the synthetic effect of urban infrastructure on thermal and dynamic structures of atmosphere, is responsible for the formation of main UBL features over Beijing area. Meanwhile, the relative importance of thermal and mechanical factors of urban infrastructure and interaction between thermal and mechanical factors for the formation and evolution of UBL over the Beijing area are also explored. The results show that, during nighttime, mechanical factors are responsible for main characteristics of nocturnal urban boundary layer such as elevated inversion layer over downtown area, smaller wind speed and stronger turbulent kinetic energy (TKE) and its behavior with peak at the top of canopy layer, whereas in the daytime, thermal factors play dominant role in the structure of UBL, such as the intensity of mixed layer and temperature in the lower atmosphere in urban area. The interaction between mechanical and thermal factors plays an important role in the formation and evolution of UBL, but its specific characteristics of mechanisms are complex. The results of surrounding terrain experiment show that terrain surrounding Beijing area not only determines the characteristic of prevailing airflow over Beijing area, but also has obvious effect on thermal structure of UBL, such as the distribution of elevated inversion and urban heat island, and makes them with special localization feature. The results of different extent urbanization experiment show that with the increase in the density and height of buildings in Beijing area, wind speed would decrease and TKE increase. Meanwhile, the bottom of nocturnal elevated inversion would increase in downtown area, and the intensity of urban heat island would strengthen, and even probably is obvious in the daytime.

Key words: urban boundary layer (UBL), urban canopy parameterization, simulation experiments

#### 1. Introduction

The urban canopy layer (UCL) (Roth, 2000) is defined as a layer in the vertical structure of urban boundary layer (UBL) ranging from the surface to the top of buildings. The urban infrastructures within UCL, such as buildings with different heights, the heterogeneity of urban land cover and the anthropogenic activity, all directly influence the thermal and dynamical structures of atmosphere and net radiation budget at the surface, meanwhile, affect the structure of urban sub-roughness layer or even higher layer through turbulent diffusion and local circulation, thus eventually result in some key features of UBL, such as urban heat island, nocturnal elevated inversion layer over downtown area, smaller wind speed and stronger turbulent kinetic energy (TKE) relative to those in rural and suburb areas. In the past few years, the influences of increasing urbanization in Beijing area on atmospheric structure and air pollution have been paid more attentions. With respect to the researches of UBL on Beijing area, observational studies (Xie and Cao, 1996; Yin and Hong, 1999; Bian et al., 2002; Bi et al., 2003; Li et al., 2004) and numerical researches (Xu et al., 2002; Yang and Xu, 2003) have obtained many meaningful results. However, there are still some issues needed to be further investigated about the formation and evolution of UBL over Beijing area

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due to the constraints of observation data and the parameterization of urban underlying surface in the models, these issues are related to the mechanism of the formation of nocturnal elevated inversion layer over downtown area, the formation and evolution of turbulent characteristics of UBL, and the impacts of surrounding terrain on UBL in Beijing area.

The impacts of complex urban infrastructures on the structure of UBL can be mainly measured in terms of their effect on mechanical and thermal factors. The effects of mechanical factors are mainly caused by the drag and friction of buildings to the airflow, and effects of thermal factors are characterised by the impacts of building structures on energy budget at urban surface, and the emission of anthropogenic heat toward atmosphere. Several field experiments and numerical researches have shown that these two factors both affect the formation of UBL characteristics. In addition, the effect of non-linear interaction between mechanical and thermal factors cannot be neglected. The numerical models coupled with detailed urban parameterization scheme would be important tools and prerequisite conditions to study the effects of the above urban factors on the structure of winter UBL over Beijing area.

Li et al. (2003) developed an urban canopy parameterization (UCP) scheme and coupled it with MM5 (hereinafter MM5-UCP), and successfully simulated a typical winter UBL case in BECAPEX (Xu et al., 2003) periods by the use of MM5-UCP. Therefore, we will continue to study the impacts of different factors of urban infrastructure on the formation and evolution of main winter UBL characteristics in Beijing area based on MM5-UCP by means of a factor separation technique, which can effectively separate the effects of different factors on atmospheric fields. In addition, in order to further understand the mechanism of the formation and evolution of UBL in Beijing, the effect of specific terrain surrounding Beijing area on the structure of UBL is investigated by MM5-UCP. At last, the impacts of urbanization progress of Beijing are explored by sensitivity experiments with changing the urbanization morphology.

### 2. Brief description of urban canopy parameterization

The main aim of the development of urban canopy parameterization (UCP) is to represent the effects of detailed urban underlying surface in MM5 model when it is used to study the real urban atmosphere at horizontal resolution of 1-3 km. In UCP, an urban grid is described as the underlying surface with buildings at various heights and different kinds of horizontal land cover components. Compared with the original urban parameterization in MM5, which only represents the characteristics of urban underlying surface through roughness, and thermal parameters of surface, our developed UCP is characterized as follows.

(1) According to the distribution of buildings and horizontal heterogeneity of urban underlying surface, the various urban feature parameters are redefined, such as urban morphological parameters, dynamical and thermal parameters, etc., by the use of high resolution urban underlying geophysical information system (GIS) data for Beijing area.

(2) With respect to dynamical effects of urban underlying surface, the urban local friction velocity is used to describe the momentum flux dependent on heights in UCL, besides, the effects of drag force induced by the buildings at various heights on momentum and TKE are also considered.

(3) With respect to thermal effects of urban underlying surface, the variance of net radiation flux in UCL, and anthropogenic heat as function of urban surface components and with diurnal variation are considered.

(4) With respect to the treatment of urban surface energy budget, in addition to the effects of horizontal heterogeneity of urban surface, the effects of net radiation flux and anthropogenic heat are considered as well.

# 3. Experiments of factor separation of urban infrastructure

#### 3.1 Selection of the case

In this paper, the two days (27, 28 February 2001) during BECAPEX are selected as the study case. The

reason to choose these two days are twofold. Firstly, the weather condition of these two days in Beijing area was very suitable to study the structure of winter UBL. Secondly, we have used the intense UBL observation data and automatic weather station data of these two days to verify the performance of MM5-UCP, and verification results show that MM5-UCP can successfully reproduce many observed dynamic and thermal structures of winter UBL over Beijing area in these two days, such as elevated nocturnal inversion layer over downtown, urban heat island, wind field and TKE field in the lower layer of UBL. Therefore, we still use this case to study the effects of urban infrastructures on the formation and evolution of UBL structure.

#### 3.2 Set-up of experiments

Stein and Alpert (1993) proposed a factor separation technique, which can be used to effectively determine relative importance of different factors influencing atmospheric circulation, as well as non-linear interaction among various factors. Martilli (2002) used this approach to study urban impact on boundary layer structure based on the typical European urban structure, and got some innovative results about the formation of UBL. Here we also use this method to investigate the effects of mechanical and thermal factors of urban infrastructures and interaction between those two factors on the formation of UBL under the condition of the 'real' urban infrastructure in Beijing area. The methodology of factor separation technique is described as follows.

Let variable f depends on n factors  $\psi_i$  $(i=1,2,\ldots,n)$ , and every factor is multiplied by a coefficient  $c_i$ , in such a way that f can be expressed as  $f = f(c_1, c_2, \ldots, c_n)$ . The f can be decomposed in terms of Taylor series expansion into

$$f(c_1, c_2, \dots, c_n) = \hat{f}_0 + \sum_{i=1}^n \hat{f}_i(c_i) + \sum_{i,j=1,2}^{n-1,n} \hat{f}_{ij}(c_i, c_j) + \sum_{i,j,k=1,2,3}^{n-2,n-1,n} \hat{f}_{ijk}(c_i, c_j, c_k) + \dots + \hat{f}_{123\dots n}(c_1, c_2, c_3, \dots, c_n),$$
(1)

where  $\hat{f}_0$  represents the reference value of f without considering n factors,  $\hat{f}_i$  is the impact of individual factor  $c_i$ ,  $\hat{f}_{ij}$  is the contribution of mutual interaction between two factors,  $f_{ijk}$  is the mutual interaction among three factors, and the rest can be inferred by analogy. The value of coefficient  $c_i$  (i = 1, 2, ..., n) is 0 or 1, using a notation in which  $f_{ij}$  is the value of f in a simulation with  $c_i = c_j = 1$  while all the rest of the coefficient are zero. For simplicity, here f barely depends on two factors in Eq.(1) and yields

$$f_0 \equiv f(0,0) = \widehat{f}_0,\tag{2}$$

$$f_i = \hat{f}_i + \hat{f}_0$$
 (*i* = 1, 2), (3)

$$\hat{f}_{12} = \hat{f}_{12} + \hat{f}_1 + \hat{f}_2 + \hat{f}_0.$$
 (4)

Equations (2)-(4) can be solved by recursive elimination:

$$\widehat{f}_0 = f_0,\tag{5}$$

$$\widehat{f}_1 = f_1 = f_0,\tag{6}$$

$$\hat{f}_2 = f_2 - f_0, \tag{7}$$

$$\widehat{f}_{12} = f_{12} - (f_1 + f_2) + f_0. \tag{8}$$

Therefore, according to this technique, four simulation experiments based on MM5-UCP are needed to evaluate the impacts of mechanical, thermal factors of urban underlying surface and interaction between mechanical and thermal factors in UCL (see Table 1). In Table 1 the results of experiments Urban are equal to  $f_{12}$  in Eq.(8), the results of experiments  $Urb_{-}m$ ,  $Urb_{-}t$ , and Rural are corresponding to  $f_1$ ,  $f_2$ , and  $f_0$ in Eq.(8), respectively.

Three nested domains are used in the above four experiments with horizontal grid points of  $63 \times 63$ .  $79 \times 73$ , and  $79 \times 73$  at horizontal resolutions 9, 3, and 1 km, respectively, and with 31 vertical levels (21 layers below 1500 m). The simulation period ranges from 08 BT 27 February to 00 BT 1 March 2001. Analyses of T106 spectral model are used as the background field of initial conditions, and objective analysis is performed by the use of conventional sounding data and intensified surface data at every 3 hours, besides, the PBL profile data at corresponding times from BECAPEX are also used in objective analysis program to represent the local atmospheric information in Beijing area. Various urban morphological parameters and surface characteristic parameters defined in UCP are obtained by urban underlying data with 7 categories at 500 m resolution over whole Beijing domain, and building height data at 200 m resolution over downtown area.

Based on the above four experiments, the impacts of four urban factors are classified into (1) total effect of urban infrastructure, obtained by results of *Urban* experiment minus those of *Rural* experiment (hereinafter, total effect); (2) the effects of mechanical factors, computed by Eq.(6) (hereinafter, mechanical factors); the effects of thermal factors, computed by Eq.(7) (hereinafter, thermal factors); and (4) interaction between mechanical and thermal factors, computed by Eq.(8) (hereinafter, interaction).

 Table 1. Simulation schemes of factor separation experiments

Experiments	Schemes		
Urban	In MM5-UCP, the effects of urban underlying surface on temperature, momentum, TKE		
	of atmosphere and surface energy budget are all considered.		
$Urb_{-}m$	In MM5-UCP, the impacts of urban underlying surface on the momentum and TKE are considered.		
$Urb\_t$	In MM5-UCP, the impacts of urban underlying surface on atmospheric temperature and surface		
	energy budget are considered.		
Rural	In MM5 without UCP, urban grids in Beijing domain are replaced by rural grids, and parameters		
	and its values used in rural grids are in Table 2.		

Table 2. Parameters of land use in the Rural experiment

Albedo	Moisture availability	Emissivity	Thermal inertia	Roughness
(%)	(%)	(%)	$(cal \ cm^{-2} K^{-1} s^{-1/2})$	(m)
21	50	92	0.05	0.1

#### 3.3 Results

For simplicity, only the results in domain 3 (1 km resolution) at 02, 08, 14, and 20 BT 28 February are selected to analyze the impacts of urban infrastructure on the formation and evolution of UBL over Beijing area.

#### 3.3.1 Results at midnight

In a previous paper (Li et al., 2003), we successfully simulated the observed temperature profile at 02 BT 28 February. at downtown area (figure not shown), showing that there is a mixed layer structure from the surface to the height of 120 m, and inversion layer aloft up to about 300 m. Here we will investigate the mechanism of the formation of this special vertical temperature structure through factor separation. Figures 1a and 1b give the temperature profiles of the total effect, mechanical factors, thermal factors and interaction in a downtown point (39.92°N, 116.38°E) at 02 BT 28 February.

With respect to the impacts of the above four factors on temperature, the influencing range of total effect is below 360 m, wherein positive impact (value greater than zero, the same in the following) on temperature is below 120 m, and aloft negative impact (value smaller than zero, same in the following) appears and increases with the height up to 200 m, above it the intensity of the negative impact decreases with heights. The above features of total effect are basically consistent with the observed facts (mixed layer in the lower levels of UBL, and elevated inversion layer above 120 m). These results not only further show that MM5-UCP has the ability to successfully reproduce the nocturnal thermal structure of UBL, but also indicate that urban underlying surface can significantly change the thermal structure in the lower layers of PBL and thus form one of the special nocturnal temperature features, the elevated inversion layer over downtown. The impacts of other factors on formation of thermal structure of UBL are illustrated in Fig.1b. The positive impact of thermal factors reaches up to 360 m, which is in favor of the formation of mixed layer in the lower layers of UBL. The temperature profile of mechanical factors is similar to that of total effect, indicating that mechanical factors are probably dominant factors for the formation of



**Fig.1.** Vertical profiles of total effect, thermal factors, mechanical factors and interaction between thermal and mechanical factors of urban infrastructure in a downtown point of Beijing at 02 BT 28. (a), (c), and (e): Temperature, TKE, and wind speed profiles of total effect, respectively. (b), (d), and (f): Temperature, TKE, and wind speed profiles of thermal, mechanical factors and interaction, respectively, in which solid lines are for thermal factors, long dashed lines for mechanical factors, and dotted lines for interaction. Units are in °C, m<sup>2</sup> s<sup>-2</sup>, and m s<sup>-1</sup>, respectively.

nocturnal elevated inversion layer over downtown area. This conclusion is in agreement with numerical study of Uno et al. (1989) using an urban boundary layer model, in which they found that the mechanical effects produced by buildings play an important role in the formation of nocturnal elevated inversion layer over city. Besides, the importance of mechanical factors can be also verified by results of TKE profiles. It should be pointed out that positive impact of mechanical factors below 40 m is in the excess of that of thermal factors at this time, which may be attributed to the wind speed in experiment periods. Martilli (2002) found that the effect of same factors, like mechanical factors or thermal factors, on the structure of temperature near the surface is different under different wind speed. In addition, we also find that the effect of interaction on the formation of mixed layer in the lower layers and elevated inversion layer is notable.

The vertical profile of total effect for TKE (Fig.1c) shows that total effect makes TKE strengthen up to 240 m, with a maximum at the top of urban canopy layer approximately 60 m. This vertical feature of TKE in downtown point is basically consistent with the observed result from wind tunnel experiment by Kastner and Rotach (2001), meanwhile, it also characterizes the effect of urban infrastructure on TKE in Beijing area. Figure 1d displays the effects of other factors on TKE, showing that positive impact of mechanical factors is the largest compared with those of thermal factors and interaction, and its TKE profile is very similar to that of total effect. The positive impact of interaction on TKE profile is also remarkable, especially in the height of 150 m to 200 m, it even exceeds effect of mechanical factors, indicating that the effect of interaction can help enhance the height of mixed layer. The effect of thermal factors on TKE is relatively small. This may be related to the smaller buoyant term of TKE at night. From the above results, we can conclude that the mechanical factors are probably the dominant factors to determine vertical structure in lower parts of UBL at night, and also responsible for the peak TKE value at the top of urban canopy layer. In addition, the effect of mechanical factors on TKE profile can further explain their important role on the formation of elevated inversion layer. The stronger TKE induced by mechanical factors has remarkably vertical mixing effect in the lower layers, and thus constrains the formation of ground inversion due to surface cooling. Therefore we find out that there is no impact of mechanical factors on TKE at about 200 m, and this is basically the height of the bottom of elevated inversion layer in temperature profile.

The wind profile of total effect in Fig.1e shows that the total effect makes wind speed decrease, with a minimum at the top of urban canopy layer, which is in a good agreement with the maximum TKE at same height. These results generally agree with one of main characteristics of turbulence in urban atmosphere summarized by Roth (2000), and also indicate that there is an obvious transformation process from average kinetic energy into TKE in lower layers of UBL over Beijing area. To further analyze the effects of other factors of urban infrastructure on wind field, we can find that mechanical factors and interaction both decrease the wind speed in the lower layers, of which mechanical factors are more remarkable because the wind profile of mechanical factors is very close to that of total effect. As a consequence, the effect of mechanical factors on wind speed further reveals their dominant role in the structure of UBL at night. The impact of thermal factors on wind speed is contrary to that of mechanical factors, which acts to increase wind speed in the lower layers with a maximum at the surface, the reason for this is probably due to the fact that the temperature gradient (warmer in downtown, and cooler in suburb) induced by thermal factors would increase wind speed.

#### 3.3.2 Results in the daytime

Compared with the temperature profile of total effect at night, the influencing range of total effect at 08 BT enhances up to above 700 m (Fig.2a). The height of positive impact of total effect is about 600 m, which is higher than that at 02 BT but with smaller intensity. The above temperature feature of total effect is basically similar to the observed vertical temperature difference between downtown point and suburban point at the same time [see Fig.5 in Bian et al. (2002)]



Fig.2. As in Fig.1, but for profiles of temperature and TKE at 08 BT 28 February.

and with closer intensity in the lower layers of PBL. Meanwhile, there is a similar elevated inversion layer (above 200 m) in observed temperature difference between downtown and suburb grid, but its intensity and height are different from those of total effect. The above elevated inversion layer difference between the observed and the simulated by total effect can be understood from the calculation of the total effect, which is obtained by the results of Urban experiment (considering both thermal and dynamical effects of urban infrastructure) minus the results of Rural experiment (without considering any urban impact), and is to certain extent different from the observed temperature difference between urban and suburb. In general, the temperature simulation in the lower layers of UBL from MM5-UCP at 08 BT is reasonable.

Figure 2b shows the effects of other urban factors on temperature structure. The positive effect of thermal factors is the strongest compared with other two factors. This is different from the effect of thermal factors at night. The more emission of anthropogenic heat in the daytime than at night and radiation characteristics of urban underlying surface may be responsible for this behavior of thermal factors on temperature in the daytime. Comparing with the temperature profile calculated by total effect, we can find that the interaction plays an important role in the maintenance of elevated inversion layer over downtown and temperature characteristic of the whole UBL. The effect of mechanical factors on temperature at this time is relatively weak, probably due to smaller wind speed at this time (observed wind speed is about  $0.4 \text{ m s}^{-1}$ , and simulated  $0.8 \text{ m s}^{-1}$ ).

The positive impact of total effect on TKE at 08 BT (Fig.2d) is stronger than that at 02 BT, reaching

up to 600 m. This is also the height of bottom of elevated inversion layer in Fig.2a. Among the effects of other factors, positive effect of thermal factor is the



Fig.3. As in Fig.1, but at 14 BT 28 February.

largest, and also closest to the impact of total effect, indicating that thermal factors may be the dominant role in determining TKE structure in the lower layers of UBL. This can be further explained from the impact of thermal factors on temperature: thermal factors at this time can make temperature increase and strengthen the buoyant term in TKE equation, thus increase the intensity of TKE. The effect of interaction on TKE at this time is complicated, showing that there is a weak negative effect below 240 m with the trend to offset the positive effects of thermal and mechanical factors, thus resulting in the positive effect above that height and negative effect again at higher levels.

At 14 BT, the impacts of total effect on temperature and TKE can reach the height of about 1000 m (Fig.3a). The impact of thermal factors at 14 BT, similar to the results at 08 BT, is still dominant. This can be easily understood by the thermal feature of urban infrastructure and higher anthropogenic heat emission in the daytime. However, the interaction has obvious negative effect on temperature and TKE, and to certain extent mitigates the positive effects of thermal and mechanical factors. We think that one of the main reasons for this strong negative impact of interaction at this time is probably due to relatively larger wind speed compared with at other times (the observed average wind speed in a layer near ground is  $3.2 \text{ m s}^{-1}$ and the simulated is  $2.5 \text{ m s}^{-1}$ ), because the non-linear temperature advection produced by larger wind speed is disadvantageous to the heat accumulation in downtown. The impact of total effect on wind speed at lower levels at 14 BT is similar to that at night, representing that total effect decreases the wind speed, of which mechanical factors and interaction are main factors to reduce wind speed, but thermal factors make positive contribution to wind speed in the lower layers. 3.3.3*Results in the evening* 

The temperature and TKE profiles of total effect and other factors at 20 BT are presented in Fig.4. From the temperature profile of total effect, we can find that its positive effect on temperature significantly decreases compared with that in the daytime, only reaching up to 240 m, and it even has small negative effect from 240 m to 650 m, of which a small similar elevated inversion structure exists at the height of above 480 m. This feature is similar to the impact of total effect on nocturnal elevated inversion layer above 200 m at 02 BT previously discussed. This further reveals the effect pattern of urban infrastructure on the formation of nocturnal thermal structure of UBL.

Comparing the impacts of various factors, we can find that the effect of thermal factors remarkably decreases now compared to those in the daytime, but its value seems to be too small. This phenomenon may result from the inadequacy of the description of heat storage for urban underlying surface in UCP. At this time the mechanical factors play an important role in the formation of inversion layer above 480 m compared with result of total effect, and this is similar to the effect of mechanical factors at midnight. The similar behavior for mechanical factors in the evening and midnight can further indicate the importance of mechanical factors on the formation of nocturnal elevated inversion layer over downtown. It should be noted that at this time the contribution of interaction has turned into positive effect from strong negative effect in the daytime, especially within scores of meters near the surface. The positive effect of interaction can also be represented in TKE profile. Concerning with the effect of interaction at midnight and in the daytime, we can conclude that the interaction plays an important role in the formation and evolution of UBL, but its feature is complicated, sometimes with strengthening effect and sometimes with decreasing one. This feature of interaction is probably related to the relative intensity of the effects of thermal and mechanical factors, and wind speed, but the concrete reasons need further to be investigated through more typical cases. The TKE structure of total effect in the evening is basically the same as that at midnight 02 BT, both with maximum at the top of canopy layer. This further reveals the basic feature of the effect of urban infrastructure on nocturnal TKE in Beijing area.

#### 4. Experiments of terrain surrounding

There is a special topography around Beijing area, with higher elevation mountain areas in both the north



Fig.4. As in Fig.1, but for profiles of temperature and TKE at 14 BT 28 February.

and west areas, whereas flat terrain in downtown. This special topography would affect to certain extent the meteorological condition of Beijing area. Some researches about the flow features in Beijing area have been made in recent years, but numerical studies, considering both the terrain and urban effects at the same time, to investigate the effect of terrain on the structure of UBL are still rare. Therefore, in this paper we try to explore the mechanism of terrain effect on the formation of winter UBL structure by the use of MM5-UCP. The simulation case will still focus on the case in Section 3 (27 to 28 February 2001). Two experiments are designed: One is *Urban* experiment in Table 1, which includes the urban effect and real terrain elevation; the other is Urban - flat exper-

iment, which includes the urban effect and the terrain elevation being reduced to 1/2. The simulation results in temperature and wind in the above two experiments are mainly compared as follows.

#### 4.1 Temperature results

From the comparison of horizontal structure of temperature between two experiments at a layer near the surface (figure not shown), obvious difference can be found not only in the northern and western suburb near mountains, but also in the downtown area and the eastern and southern suburb far away from mountains. As for downtown area, although the temperature values of Urban-flat experiment in this area are basically the same as those of Urban experiment,

the distribution of urban heat island and the scope of higher temperature in downtown area in these two experiments are different, showing that the terrain surrounding Beijing area affects the formation of thermal structure in the lower parts of PBL in downtown area. In addition, the impact of terrain on temperature can be illustrated in vertical structures, for example, at midnight 02 BT, the intensity and depth of elevated inversion layer over downtown calculated by Urban-flat experiment are both smaller than those by Urban experiment (figure not shown), and at 08 BT, the difference in vertical structures of temperature between two experiments is more remarkable (Figs.5a and 5b). Compared with the vertical temperature structure of Urban experiment, the thermal plum over downtown in Urban-flat experiment tilts towards south. This is probably related to the wind direction differences simulated by two experiments (details in the comparison of wind results).

The above results show that though the urban-

ization is the most important factor to determine the thermal structure of UBL, the terrain surrounding Beijing area still plays an obvious role in the formation and distribution of main thermal feature of PBL over downtown, such as urban heat island, elevated inversion layer.

#### 4.2 Wind results

The horizontal wind fields in the layer near the surface simulated by two experiments can be used to evaluate the effect of terrain on the flow structure in the lower parts of UBL. For simplicity, we just display the results at 08 BT (Figs.5c and 5d). These figures show that the wind fields in two experiments exhibit obvious difference in the western and northern part of Beijing area. The airflow over these areas in *Urban* experiment is southerly, except for downslope wind in the northwest corner of simulation domain, which is also the typical feature of mountain-valley wind observed often in Beijing area. However, the airflow



**Fig.5.** The vertical cross-sections of temperature (°C) and horizontal wind (m s<sup>-1</sup>) fields at a layer near the surface of *Urban* and *Urban-flat* experiments at 08 BT 28. (a), (c) For *Urban* experiment; and (b), (d) for *Urban-flat* experiment.

in Urban-flat experiment is strong northerly, almost contrary to that in Urban experiment. This northerly in Urban-flat experiment may be responsible for the thermal plume tilting towards south mentioned in temperature results. Meanwhile, the difference of the airflow between two experiments over downtown area far from mountain is obvious, such as the direction and intensity of airflow in Chaoyang District. This difference can also be found at other times. In conclusion, the special local terrain surrounding Beijing area not only determines the directions of prevailing airflow in the lower layers over Beijing area, but also significantly affects the flow directions over downtown area.

From the comparisons of diurnal variation of average wind speed in a layer near the surface simulated by two experiments (figure not shown), we can discover that the wind speed over downtown and suburb area in Urban-flat experiment is more even during the whole simulation period compared with that in Urban experiment, indicating that the terrain surrounding Beijing has a forcing effect on the formation of the wind speed feature in the lower layers of UBL.

#### 5. The experiments of urbanization progress

The urban development of Beijing has experienced great changes in the past ten years. Many lower buildings in downtown are replaced by higher buildings, and original farms are also covered by new road (cement or asphalt) and buildings. This increasing urbanization progress in Beijing will be continuous with the economical development and urban construction enlargement. In order to objectively evaluate and reveal the effects of this increasing urbanization on UBL structure in Beijing area, based on the case in Sections 3 and 4, three sensitivity experiments with different urbanization level, characterized by the change in urban morphology and building density in MM5-UCP, are performed.

#### 5.1 Simulation schemes

Table 3 gives three experiments to study urbanization progress. It should be noted that the height of urban canopy layer in *Urban-large* and *Urban* experiments are assumed to be the same, in the light of real constraint on the building height in Beijing urban plan.

#### 5.2 Simulation results

The simulation results of three experiments at 02 BT and 14BT are selected to represent the results in nighttime and daytime, respectively. From the comparison of temperature profiles calculated by three experiments at 02 BT (Fig.6a), we can find that temperature in the lower layers of UBL (below 150 m) will increase with the enhancement of urbanization level, and the amplitude of enhancement is about 1°C. Meanwhile, the bottom of the elevated inversion layer also increases with the enhancement of urbanization level. These results indicate that the change in building construction in UCL will significantly affect the vertical thermal structure of lower UBL. From the horizontal temperature in a layer near the surface calculated by three experiments (figure not shown), it the can be found that the temperature in downtown and the intensity of urban heat island also increase about 1°C with enhancement of urbanization level. This result is basically identical to the statistic feature of increasing heat island in the past ten years in Beijing area (Zhang et al., 2002). In summary, without consideration of

Experiments	Schemes	Objective
Urban	Current urbanization level in Beijing, same as	The reference status for urbanization progress
	Urban experiment in Table 1	
Urban-large	Increase the building cover fraction and area	To study the effects of further urbanization
	density of urban canopy on current urbanization	level on the structure of UBL in Beijing
	level	area
Urban-small	Contrary to $Urban-large$ experiment, decrease	To study the effects of past urbanization level
	the building cover fraction and area density of	on the structure of UBL in Beijing area
	urban canopy on current urbanization level	

Table 3. Sensitivity experiments of different urbanization level in Beijing area



**Fig.6.** The profiles of temperature (a, in °C), TKE (b, in m<sup>2</sup> s<sup>-2</sup>), and horizontal wind (c, in m s<sup>-1</sup>) for various urbanization level experiments in urban grid at 02 BT, and same for (d), (e), (f) but at 14 BT, in which solid lines are for *Urban* experiment, dotted lines for *Urban-large* experiment, and long-dashed lines for *Urban-small* experiment.

other factors, the urbanization development in Beijing area will further strengthen the main features of thermal structure of nocturnal UBL, such as enhancement in the intensity of urban heat island, and increase in the bottom of the nocturnal elevated inversion layer.

From the comparison of wind speed at night, we can discover that wind speed in the lower layers of UBL calculated by Urban-large experiment with highest urbanization level is the smallest, and that by Urban-small is the largest. These results agree with the wind observation fact that the occurrence frequency of weather with small and zero wind speed has been increasing in recent years in Beijing area. Furthermore, it also indicates that the increase in the density and height of buildings may be the main reason for small wind speed over downtown in Beijing area. The TKE results of three experiments are totally opposite to the wind speed results, indicating that enlarging building cover and density would strengthen TKE in the lower parts of UBL at night, especially at the top of urban canopy layer.

The effects of different urbanization level on structure of UBL in the daytime are similar to those at night, with the largest temperature and TKE values and the smallest wind speed calculated by experiment with the highest urbanization level (Urban-large). It should be noted that the heat island with the intensity of more than 2°C is found in Urban-large experiment in the daytime, indicating that with enhancement of urbanization level in Beijing area, the temperature will increase, wind speed will decrease, and stronger heat island will also probably appear in the daytime.

#### 6. Conclusions and discussions

Based on the successful simulation of thermal and dynamical structures of a typical winter UBL process in Beijing area by the use of MM5-UCP, a factor separation technique is introduced to investigate the impacts of total effect, mechanical factors and thermal factors of urban infrastructure, and interaction between mechanical and thermal factors as well, on the formation and evolution of main characteristics of UBL. In addition, the experiments to study the impacts of the terrain surrounding Beijing area on the formation of structure of UBL are also performed. The impacts of urbanization progress in Beijing on UBL structure are investigated by changing the urban morphology and building density in MM5-UCP. The results of the above experiments are summarized as follows:

(1) The total effect of urban infrastructure, that is the synthetic effect of urban infrastructure on the thermal and dynamical structure of atmosphere, greatly changes the structure of PBL over the original nature surface, and thus forms the main features of winter UBL in Beijing. With respect to thermal structure of atmosphere, the total effect results in the nocturnal elevated inversion layer over downtown and heat island with weaker effect in the daytime and stronger one in the nighttime. With respect to dynamical structure of atmosphere, the total effect makes wind speed decrease, TKE increase with its maximum at the top of canopy layer, and kinetic energy being transformed into TKE in the lower parts of UBL.

(2) The effects of various factors of urban infrastructure on the formation and evolution of winter UBL over Beijing area are different. At night, the mechanical factors play dominant roles in determining the nocturnal elevated inversion layer over downtown, small wind speed and large TKE with its maximum at the top of urban canopy layer in the lower parts of UBL. In the daytime, the thermal factors are more important to the formation of the structure of UBL, such as the height of mixed layer and temperature distribution in the lower layers over downtown area. The interaction between thermal and mechanical factors also plays an important role in the formation and evolution of UBL, but the specific mechanisms of the interaction are complicated and further investigations are still needed.

(3) Although urbanization plays a leading role in the formation of UBL in Beijing area, the special terrain surrounding Beijing area also has obvious impacts on the formation of thermal structures, such as the structure and distribution of elevated inversion layer and urban heat island with localization features. Furthermore, the terrain is also the main forcing source for the airflow feature in the lower layers in Beijing area. (4) The results of sensitivity experiments of different urbanization level show that the urbanization development in Beijing would significantly influence the UBL structure, representing that with the increase in the density and height of urban buildings, the wind speed in downtown will decrease and TKE will increase, the bottom of the nocturnal elevated inversion layer and intensity of urban heat island will enhance. The stronger heat island will also probably appear in the daytime.

It must be pointed out that the above conclusions are just made based on a single typical winter UBL process in Beijing, and some of them are probably needed to be verified through more case studies. Meanwhile, it is important to realize that it is a big challenge for the researches of UBL just from observation perspective due to the complexity of urban underlying surface. Therefore, as for the studies about urban parameterization scheme for numerical models based on observation, our developed urban canopy parameterization is still quite preliminary, and more work is needed to further improve it.

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