Numerical Simulation of Wind and Temperature Fields over Beijing Area in Summer*

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ABSTRACT

The non-hydrostatic mesoscale model MM5V3 is used to simulate the wind and temperature fields of the atmospheric boundary layer over Beijing area in summer with the mesh resolution of 1 km. The simulation results show that the numerical model can successfully simulate the urban heat island effect and the wind and temperature fields which are affected by the complicated topography and urban heat island. The results show that: (1) the west area (from Haidian to Fengtai Districts) is always the high temperature center of Beijing, where the surface temperature is about 6 K higher than the other suburbs; and (2) due to the unique topography the wind of Beijing area during the daytime is southern anabatic wind and at the night is northern katabatic wind. The results comparing well with the data from surface observation stations validate the accuracy of the simulation.

Key words: mesoscale model MM5, numerical simulation, urban heat island, wind field, temperature field, climatic effect over Beijing area

1. Introduction

The basic role of urban-rural boundary layer research is to study all kinds of physical process changes in the atmosphere boundary layer over urban and its surrounding areas. Urban heat island (UHI) is a well-known feature of urban-rural climate. Attempts to increase the understanding of the causes of the UHI and other urban-rural boundary layer phenomena have used observational, theoretical and modelling methods since long before. Seaman (1989) used a hydrostatic model, with real initial conditions, to assess the effects of urban moisture, surface radiative and thermal characteristics, urban roughness and urban growth on the magnitude of the UHI of St. Louis. Sun et al. (1994) carried out a synthetic field observation on the boundary layer and the soil layer in the Xi'an region. They also evaluated the effect due to the increase of fuel consumed in the Xi'an industrial area. Tong and Sang (2002) simulated the wind, temperature, concentration and aerosol fields of the atmospheric boundary layer over the Haidian District of Beijing using a three dimensional mesoscale numerical model of Peking Univiersity. The simulation shows that the wind field is affected by the topography and urban heat island. Yang et al. (2003) simulated the winter heat island of Beijing considering the daily changing anthropogenic heat. It is indicated that this consideration can improve the numerical simulation of the heat island. Cai et al. (2002) used wind-field diagnostic analysis and historical observation data to reveal general flow patterns of lower atmosphere over Beijing area, showing that air flows in this area could be classified into autumn-winter pattern and spring-summer pattern. The former is under the effect of more strong synoptic systems, while the latter displays more characteristics of mesoscale thermal circulation induced by topography.

Beijing is located in northern of North China Plain. It has an area of about 16800 km^2. Its urban area is flat, but its surrounding areas are very complicated. Yanshan Mountain lies north, and Taihang Mountain lies west. There is a great height difference

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between the surrounding mountain area and the center of Beijing. This unique topography has an important effect on the meteorological environment over Beijing area. Meanwhile the activity of more than 11 million population of Beijing exerts also very important effect on the environment of Beijing. These effects are concerned with the living conditions, air quality, evaluation of the rationality of the constructions etc.

In this paper the non-hydrostatic mesoscale model MM5V3 is used to simulate the wind and temperature fields of the atmospheric boundary layer over Beijing area from 10 to 11 July. The results are very important to understand the local climate over Beijing area, the feature of diffusion of pollutants and will help to make practical urban design.

2. Model description and parameters

MM5 (Version 3) mesoscale model is an atmospheric modeling system in a limited area, originally developed by PSU/NCAR on the base of MM4. The major difference between MM5 and MM4 is that MM4 is hydrostatic equilibrium while MM5 adopts the non-hydrostatic scheme. MM5 has more physical options, a four-dimensional data-assimilation capability and a multiple-nest capability. It describes the physical process finer. Now MM5 is widely used for the research of atmospheric boundary layer and real-time studies, including simulation of monsoons, hurricanes and cyclones. It can also be used for studies involving mesoscale convective systems, fronts, land-sea breezes, mountain-valley circulations and urban heat islands, etc. meso-beta and meso-gamma scale systems. Some universities and research institutes in China adopted in this model successively, and transplanted this model to run on small computers and even PC computers, in order to simulate the important weather processes to study their thermodynamics and dynamics features.

In this paper an area of 80 km by 100 km with the center of the Tian'anmen Square (located at 39°54'27"N, 116°23'17"E) is selected as the modelling domain. And the domain is divided into 8000 grids (80×100), with each grid having an interval of 1 km.

The vertical height is partitioned into 23 layers (σ coordinate). To reflect the features of the boundary layer well, the resolution in the lower layer is much finer than the above. The proportion is taken as σ=1.00, 0.995, 0.99, 0.985, 0.98, 0.97, 0.96, 0.93, 0.89, 0.85, 0.80, 0.75, 0.70, 0.65, 0.60, 0.55, 0.50, 0.45, 0.40, 0.35, 0.30, 0.20, 0.10 and 0.00. Here $\sigma = \frac{p - p_{\text{top}}}{p_{\text{bottom}} - p_{\text{top}}}$, where P_{bottom} is the surface pressure, p_{top} is a specified constant top pressure, and 100 hPa is selected. Physical options chosen in our simulation are listed below: PBL scheme is Eta M-Y (Mellor-Yamada) PBL-scheme, as used in the Eta model by Janjic (1990, MWR) and Janjic (1994, MWR). It predicts TKE and has local vertical mixing. Explicit moisture scheme is Schultz scheme, it is a highly efficient and simplified scheme (based on Schultz 1995 with some further changes), designed for running fast and being easy to tune for real-time forecast systems. It contains ice and graupel/hail processes. Atmospheric radiation scheme is the cloud-radiation scheme, it is sophisticated enough to account for longwave and shortwave interactions with explicit cloud and clear-air. As well as atmospheric temperature tendencies, this provides surface radiation fluxes. The integral interval is 5 seconds. The simulation is 24 h in duration, starting from 1400 BT 10 July to 1400 BT 11 July, which represents a typical summer day without strong synoptic system.

3. Input data

USGS's (U. S. Geological Survey) 30"×30" terrain height data are used. The 3D meteorological field from 1400 BT 10 July to 1400 BT 11 July produced from the NCEP's (National Centers for Environmental Prediction) global analysis data set is adopted as the background meteorological data fields, with a resolution of 1° × 1°.

4. Results of the numerical experiment and compared with observations

The data used for comparison are from "D file" of July 2000 at 14 surface observation stations around Beijing area. These stations include Shunyi Station, Haidian Station, Tongzhou Station, Chaoyang Station, Changping Station, Mentougou Station, Beijing Meteorological Bureau Station. Shijingshan Station, Fengtai Station, Daxing Station, and Fangshan Station.

Figure 1 illustrates the simulated changes of horizontal wind field near the surface (18 m hight) from 10 to 11 July. Listed in time order, Fig.1a shows the wind field of 1700 BT 10 July, Fig.1b shows the wind field of 0300 BT 11 July, and Fig.1c shows the wind field of 1400 BT 11 July. During the daytime represented by Fig.1a and Fig.1c, there is obviously anabatic wind blowing from the south to the northwest along the valley. This is because that south of the mountain receives strong solar radiation during the daytime, then the warm air lifts along the hillside. During the night represented by Fig.1b, there appears katabatic wind in the northwest area. This is because that the temperature in the mountain area falls sharply, then the cold air flows down the hillside and forms the northwest wind. These are all typical wind field features affected by the local geography environment. The simulation results presented in Fig.1 parallel well with the actual features of Beijing's wind fields that the wind is always south wind in daytime while the nighttime the wind turns north without the influence of strong synoptic system.

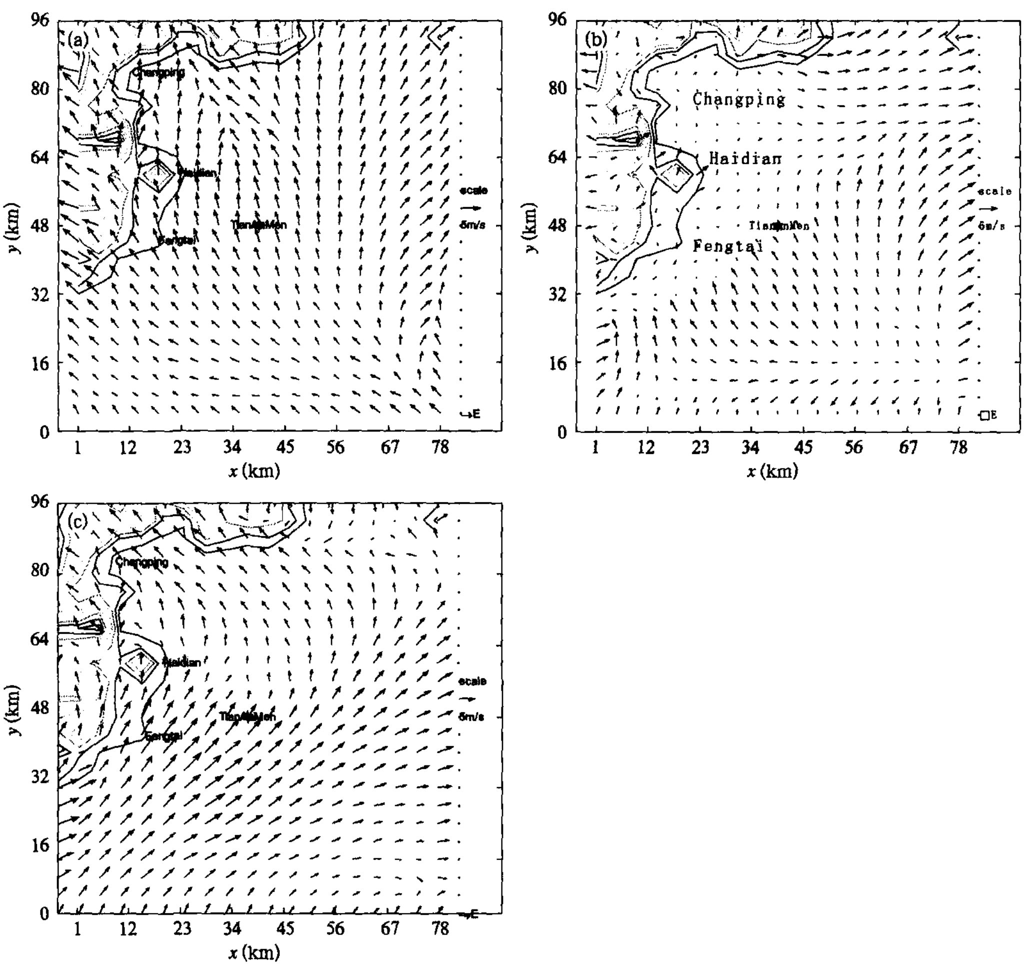

Fig.1. Wind fields from 10 to 11 July at (a) 1700 BT 10 July, (b) 0300 BT 11 July, and (c) 1400 BT 11 July.

Figure 2 is drawn based on the actual wind data provided by 'D file'. Their relationship of parallel in time with Fig.1 is Fig.2a to Fig.1a, Fig.2b to Fig.1b and Fig.2d to Fig.1c. The comparative result demonstrates that the simulation results are in good agreement with the observations. At 1700 BT 10 July in Fig.2a the nearly east wind of the several surface observation stations parallels the southeast wind in Fig.1a. As time goes to 0300 BT 11 July the katabatic wind appearing in the south of the northern mountain converges with the south wind which has no time to retreat. So in the convergence area there is almost no horizontal wind. This is well presented both in Fig.2b and Fig.1b. In Fig.2b there is almost no horizontal wind in Station Changping, Shijingshan, Mentougou and Fangshan while the katabatic wind appears in Haidian Station. That is to say the simulation is validated again the observations. In Fig.2c at 0500 BT 11 July the katabatic wind is obvious. The wind in Stations Shijingshan, Mentougou, Haidian and Beijing Meteorological Bureau Station is all northwest. As time goes on to 1400 BT 11 July the wind field turns southwest in Fig.2d. The simulation result in Fig.1c is comparative well with this.

To present the thermodynamic cause for the changes of wind fields the temperature fields are given below.

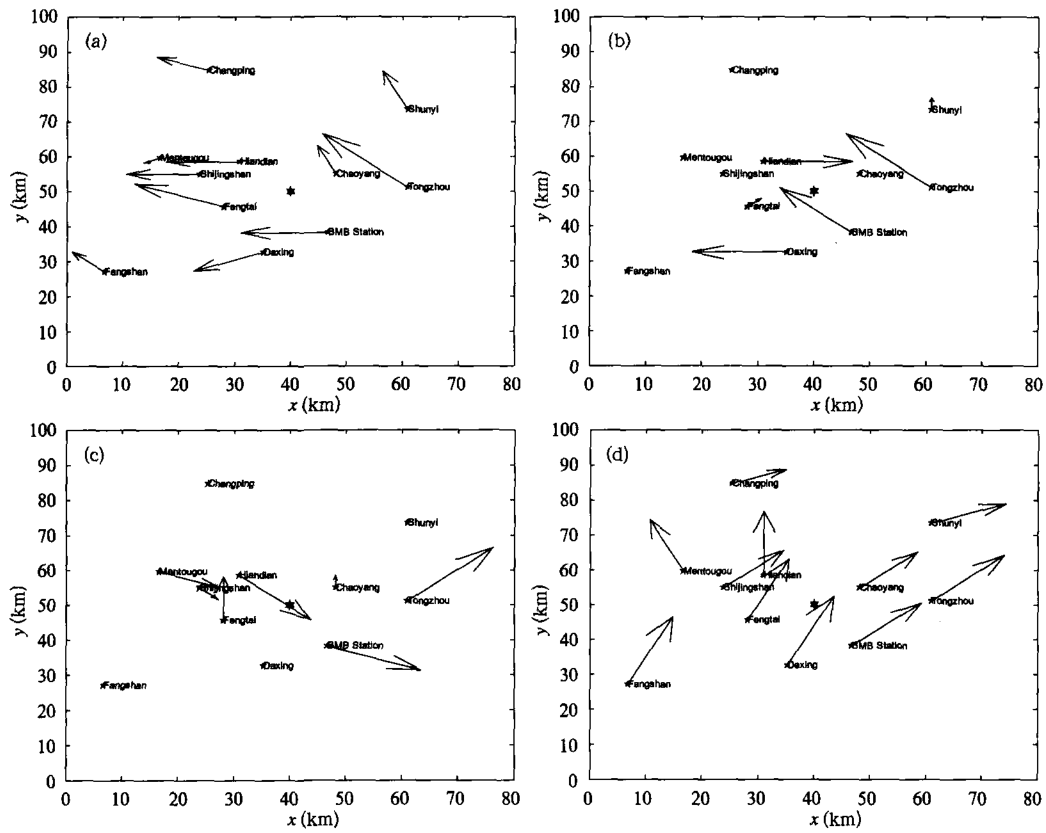

Fig.2. Observed wind fields from 10 to 11 July at (a) 1700 BT 10 July, (b) 0300 BT 11 July, (c) 0500 BT 11 July, and (d) 1400 BT 11 July.

Figure 3 presents the simulation result of horizontal structure of air temperature fields (18 m height) over Beijing area at 0200 BT 11 July and 1400 BT 11 July, showing that no matter during daytime or nighttime, the air temperature over the center area of the city is always higher than its surrounding areas. This is the evidence for obvious UHI effect in Beijing summer. Taking more attention to Fig.3b one may find that the center of the heat island departures a little north from the center of the city. More details will be shown in Fig.4. The reason for this is the wind field. The center of heat island always departures from the center of the city to the downwind area. In addition, the complicated topography in northwest area results in the complicated temperature structure over there. This will help shape the complicated local atmosphere

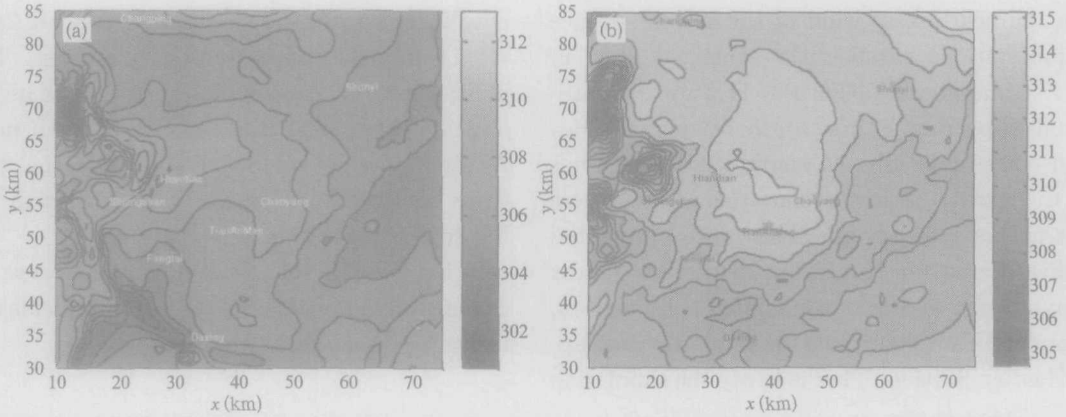

Fig.3. Horizontal structure of air temperature fields (at 18 m) at (a) 0200 BT 11 July, and (b) 1400 BT 11 July.

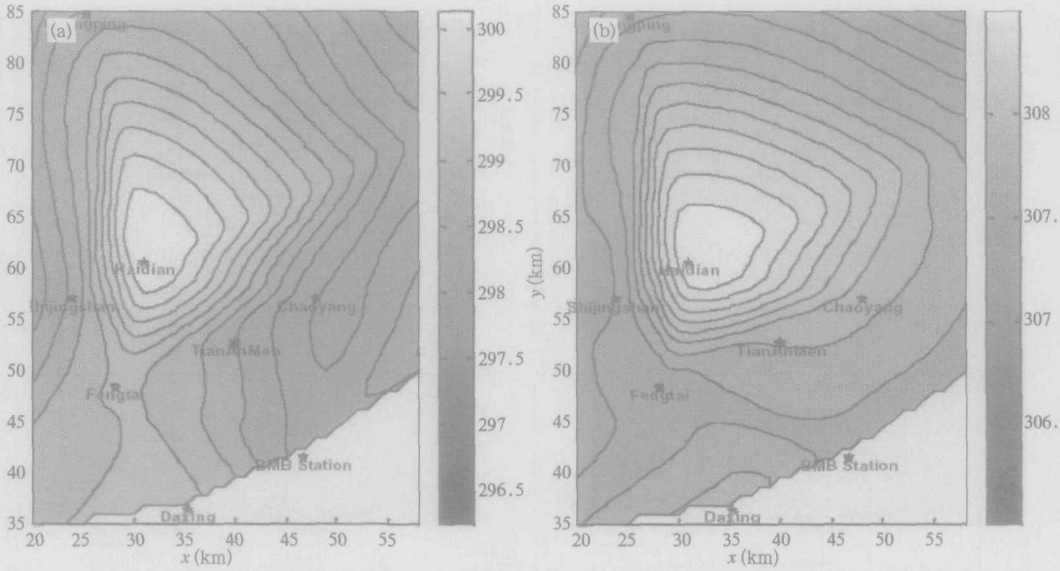

Fig.4. Observed horizontal temperature fields at (a) 0200 BT 11 July, and (b) 1400 BT 11 **July.**

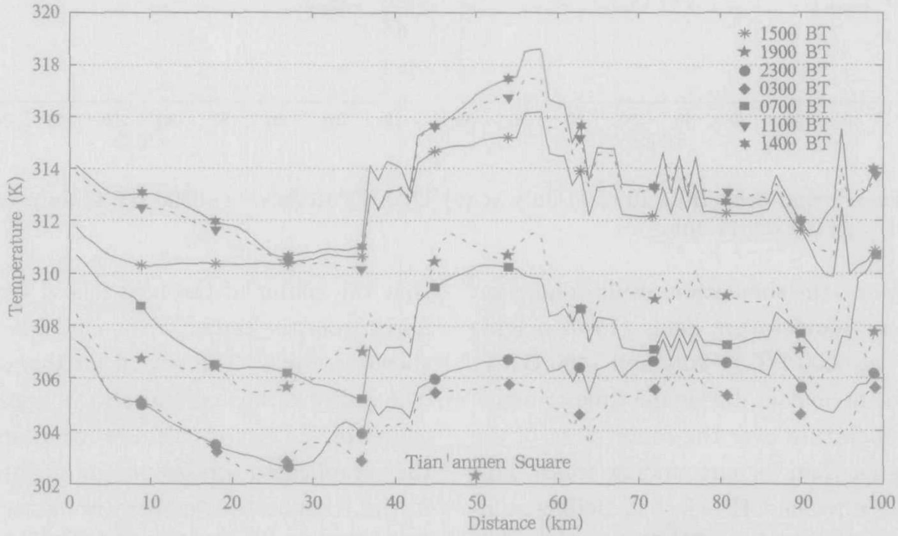

Fig.5. Diurnal change of surface temperature along the south-north axis of Beijing.

cycle over there.

Figure 4 is drawn basing on the actual temperature data provided by 'D File'. It illustrates observed horizontal air temperature fields. Before drawing the contours, the area except the stations are given interpolated value by the 'cubic' method. Because lack of the observations of Hebei Province, the area southeast to Beijing Meteorological Bureau Station (54511) is blank in each figure. From Fig.4 it can be seen that the observed air temperature fields compare well with the simulation fields seen in Fig.3. In Fig.4a the area around Haidian lies in a high temperature center, it is alike with Fig.3a. In Fig.4b the large area north to the Tian'anmen Square lies in a high temperature center, it is alike with Fig.3b. Therefore this proves that the simulation compares well with the fact.

Figure 5 presents the simulation result of diurnal change of surface temperature along the axis across Tian'anmen Square. The center of the abscissa represents the position of the Tian'anmen Square. We can see that the UHI effects exist all the time. A maximum urban-rural surface temperature departure of 6-8 K has been obtained. This simulation result is much the same as that by Xu et al. (2002). The maximum departure appeared in afternoon, at 1400 BT 11 July the center of the UHI located at the area 10 km north of the Tian'anmen Square. The surface temperature reached 318.5 K. At that time the minimum temperature appeared in the area 20 km south of the Tian'anmen Square, which located in the upwind direction of the Tian'anmen Square, the surface temperature was only 310.5 K. That is to say the temperature of the north area of the city is higher than the south area of the city.

Figure 6 shows the simulation result for diurnal changes of surface temperature along the transmeridional axis across Tian'anmen Square from 10 to 11 July, spanning a distance of 40 km, showing that there is obvious urban heat island phenomenon in the city of Beijing in summer. At 1400 BT 11 July the highest surface temperature in the heat island is higher than the temperature in the area 20 km east of Tian'anmen Square by 6 K. Another obvious feature is that the surface temperature in western area is always higher than that in eastern area.

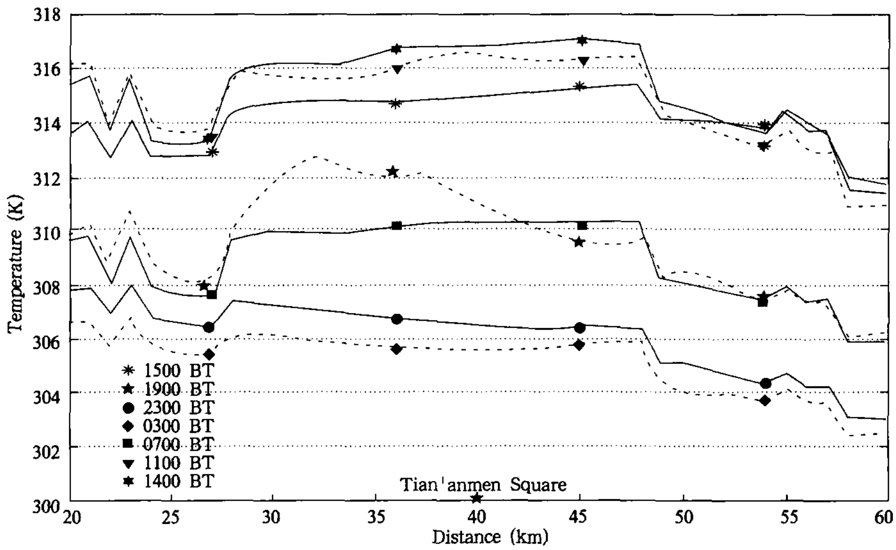

Fig.6. Diurnal change of surface temperature along the transmeridional axis.

Figure 7 shows the observed diurnal change of near-surface air temperature along the transmeridional axis. The data used here are obtained from the observed horizontal temperature fields as shown in Fig.4. Although it does not illustrate the surface temperature as in Fig.6, we can see some common points comparing these two figures. The area 10 km west of the Tian'anmen Square is always the center of high temperature. The observation results illustrated in Fig.7 show that it is 1.6 K higher than the 'low temperature center' which is 12 km east of the Tian'anmen Square at 0200 BT 11 July. This value of the intensity of the UHI is similar to that obtained by Shi and Gu (2001) when they studied the heat island of Kunming.

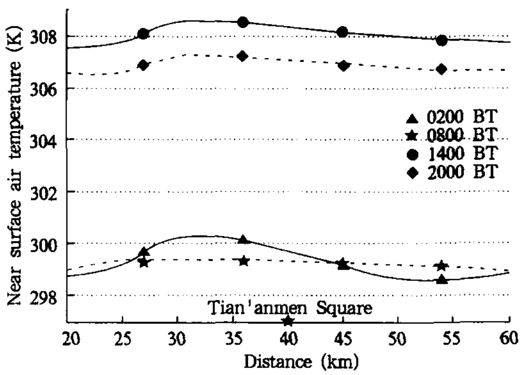

Fig.7. Observed diurnal change of air temperature along the transmeridional axis of 11 July.

The feature that the west area is hotter than the east area also shows a good agreement with the data presented in Fig.8.

Figure 8 illustrates observed air mean temperature fields of 10 and 11 July. The mean temperature is obtained by averaging the four times of observed temperature at 0200, 0800, 1400, and 2000 BT respectively. The data are also from 'D file'. The area chosen spans 40 km in the east and west direction, same as in Fig.5. In Fig.6 in both of these two days it can be seen that the west area represented by Haidian is warmer than the east area represented by Chaoyang. This is correlated with the air flow convergence. When the south wind in the daytime turns north, the air flow converge at Haidian area. This phenomenon is clear in both simulation results represented by Fig.lb and the observations represented by Fig.2b. That is to say, the Haidian area is both convergence area and the warm area. This coherence of the convergence center and the warm center compares well with the former observation by Garstang et al. (1975). In addition the fact that the center of the UHI lies in Haidian area is the same as the result by Zhang et al. (2002). They studied the mean air temperature in a long period in Beijing, and the results showed that Haidian, Shijingshan, Fengtai lie in a elliptical close warm area, the main area of Beijing's UHI.

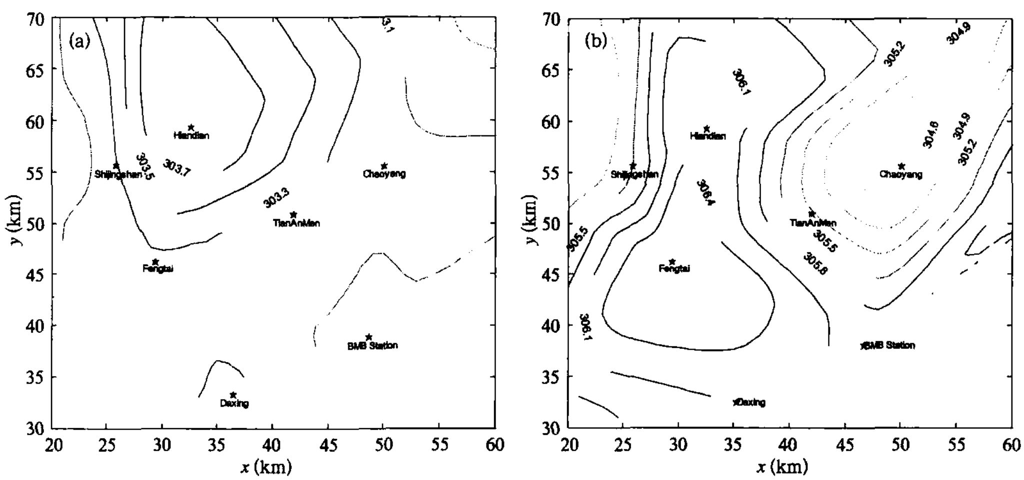

Fig.8. Horizontal structure of observed air mean temperature fields on (a) 10 July, and (b) 11 July.

To understand the effect of the topography and the UHI on the atmospheric boundary layer of the city, the temperature profiles over the center of Beijing and the area 15 km north to the center of Beijing are shown below.

Figure 9 illustrates the temperature profile over the center of Beijing and the area 15 km north to the center of Beijing. From Fig.9 it can be seen that as the radiation cools the air temperature near the surface falls in the nighttime. But the inversion over the Tian'anmen Square is not as strong as that over the area 15 km north of the Tian'anmen Square at 2300 BT 10 July and 0300 BT 11 July. This is because there is still residual layer over the center of the city due to the UHI phenomena, then the turbulence activity is still strong there. It also can be seen that the depth of the inversion layer over the Tian'anmen Square at 2300 BT 10 July and 0300 BT 11 July is lower than that over the area 15 km north of the Tian'anmen Square.

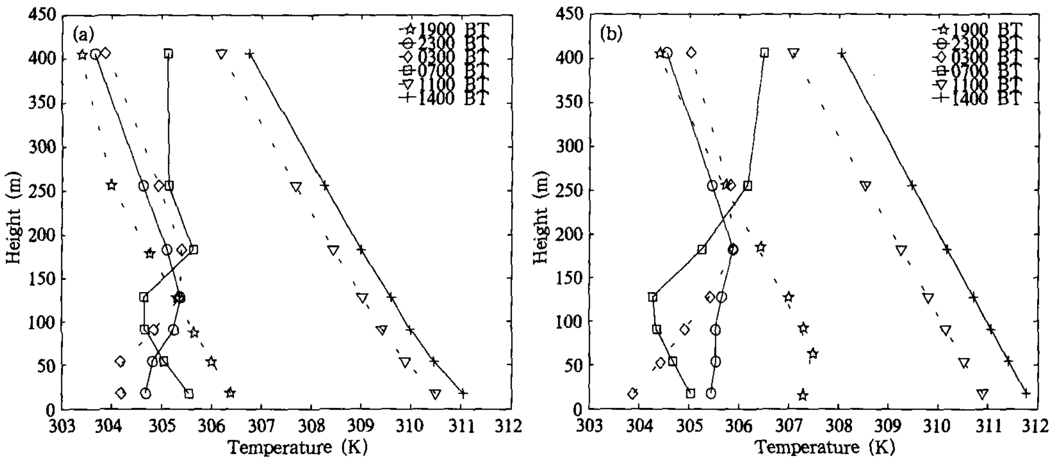

Fig.9. Temperature profile from 1900 BT 10 July to 1400 BT 11 July over (a) the Tian'anmen Square, and (b) the area 15 km north to the Tian'anmen Square.

5. Conclusion

Through the simulation and the analysis of the wind and temperature fields the primary results can be drawn as follows: The mesoscale model MM5V3 ability to simulate the wind fields affected by the complicated topography and the UHI etc. physics processes is very strong. The results of simulation over Beijing area show that: The UHI effect over Beijing's urban-rural area is obvious in summer. The maximum temperature departure arrives at 6-8 K. Haidian area is both the convergence area and the warm area. Due to the unique topography the wind of Beijing area during the daytime is southern anabatic wind and in the night is northern katabatic wind. This phenomenon is weakened by the UHI effect to certain extent. The results are very important to understand the local climate over Beijing area, the feature of diffusion of the pollutant and will help to make practical urban design. In addition the simulation results are helpful to validate the observations of interrelated studies. Because that the autumn-winter pattern of air flows over Beijing is different from the spring-summer pattern, the former is under the effect of more strong synoptic systems, while the latter shows more characteristics of mesoscale thermal circulation induced by topography, the simulation of the wind and temperature fields in autumn-winter season will be submitted in another paper.

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