Numerical Simulations of Impacts of Urbanization on Heavy Rainfall in Beijing Using Different Land-Use Data*

JIANG Xiaoyan†(江晓燕) and LIU Weidong(刘伟东)

Institute of Urban Meteorology, CMA, Beijing 100089

(Received March 26, 2007)

ABSTRACT

A summer strong convective precipitation event on 10 July 2004 over Beijing is numerically simulated in this paper, and the impact of urban heat island (UHI) on summer convective rain is investigated. The analysis reveals that a mesoscale convective cloud cluster system leads to this heavy rainfall event, suggesting the supply of moisture by the large scale circulation before the initiation of precipitation, a generally weaker UHI of 2-3°C existed in the urban area. Much like a sea breeze, the anomalously warm urban air created relatively low pressure, inducing the inflow of cooler rural air towards the urban center, which is favorable to the ascending motion and the formation of convective precipitation over the urban area. In addition, the numerical simulation of the strong convective precipitation event suggests that the simulated result of precipitation using the 2002 LANDSAT-7 land-use data with 30-m resolution is much better than that using the 1992-1993 USGS land-use data with 1-km resolution, whether in the magnitude of rainfall or in the location of precipitation. The simulation confirms to some extent that the UHI has a significant role in causing extreme rainfall event.

Key words: urban heat island (UHI), heavy rainfall, numerical simulation, land-use data

1. Introduction

In the past 30 years, Beijing has rapidly become a metropolitan city for commerce, industry, and transportation. The fraction of urban population, defined by the Chinese Census Bureau, has increased to 72% since 1990, and increased by 17% since 1978. With the development of the city, on the one hand, the economy increases tremendously; on the other hand, more and more land surface becomes urbanized. The urbanization causes unique phenomena owned by the city, such as the urban heat island (UHI). Meanwhile, the summertime convective rainfall events increase significantly. Weather anomalies in the urban area can be attributed to the change of land surface and the deforestation.

In the 1970s, a Metropolitan Meteorological Experiment (METROMEX) project was initiated in the United States, which was to investigate the urban impacts on the convective systems (Changnon et al., 1977, 1978; Huff, 1986). The results of this project indicated that the urban development had a key role in the number of convective rainfall events. The areas of increased precipitation are usually located over the urban center and downwind of the urban area. And the increased precipitation can be attributed to the UHI and the change of the urban roughness. In particular, Huff and Changnon (1973) found seven of nine local rainfall events were caused by the urbanization in the United States. The main area of increased precipitation ranged from directly over the urban center to 80-km downwind of the urban center. In more recent studies, Bornstein and LeRoy (1990) and Bornstein and Lin (1999) found that urban played an important role in the development and movement of the summertime thunderstorms. They reported three UHI events initiated precipitation in Atlanta during a 9-day period in July and August 1996 (Bornstein and Lin, 2000). These events mainly occur in the downwind of the urban area. The common characteristics of these events are the existence of UHI and weak convergence before the initiation of the precipitation. Shepherd et al. (2002) found that urbanization in Atlanta produced 19.5% increase in precipitation downwind of the

*Supported by Natural Science Foundation of Beijing (No. 8072009), Beijing Specific Project to Foster Elitist (No. 20061D0200800060), and Beijing New Star Project on Science & Technology (2004A57).

†Corresponding author: xyjiang78@gmail.com.

metropolitan area compared with an upwind control area during the warm seasons of 1998-2000. More recently, Thielen et al. (2000) studied the possible effects of urban land surfaces on rainfall development and showed that sensible heat flux affected the development of precipitation. The previous work indicates that the urban development has an obvious effect on the precipitation in summer.

In China, much work has been done to understand the physical mechanisms of local convective systems. Wang and Ding (1994) and Sun et al. (1996) did a statistical analysis about the large-scale systems in which the local heavy rainfall developed. Through the statistical analysis, a conceptual model was achieved to improve the weather forecast in the local regions. Li and Li (2000) analyzed the environment conditions and dynamic trigger mechanism of a severe convective rainfall in Beijing. Other approaches, such as the convective energy, were used to forecast the location of heavy rainfall (Li et al., 2004). Satellite data are also one of very useful methods to track the evolution of convective systems (Bai et al., 1997; Shi et al., 1996). With the development of numerical models, the mesoscale models are widely used to study the evolution of heavy rainfall (Lin and Bueh, 2003) and to understand the impacts of land surface on the convective systems (Dong et al., 1999). With the urbanization of Beijing, much effort is being made on studying the interaction between the UHI and extreme rainfall events.

On 10 July 2004, a heavy rainfall causes a serious transportation problem in the urban area of Beijing. The averaged 2-h precipitation in most urban areas is over 50 mm, and in some observation stations, the maximum rainfall can reach 100 mm. From the magnitude and persistence of precipitation aspects, it is clear that this heavy rainfall event is caused by a mesoscale convective system. This study is to investigate the impacts of urban land use on the summertime heavy rainfall. For the purpose, the role of the land use in the rainfall, the routine observations, reanalysis data, satellite data, and the numerical model are used in this study.

2. Case description

In this section, detailed precipitation analyses of observations with hourly auto weather station (AWS) data are examined. Currently, the AWSs cover most parts of the Beijing area. The hourly rainfall data are achieved by doing quality control for the AWS rainfall data. Figure 1 presents the evolution of the rainfall event occurred from 1400 to 2300 BT (Beijing Time) 10 July 2004. The amount of rainfall in some locations shows a maximum value larger than 100 mm and the averaged precipitation over the urban area was about 50 mm. It is notable that precipitation initiated in the southwest of Beijing at 1400 BT. The intensity of the rainfall was relatively small and the precipitation rate was only 2 mm h^{-1}. Then, the intensity of the rainfall gradually increased and the maximum precipitation reached 27 mm h^{-1}. The region covered by heavy rainfall expended and rainfall center moved to the urban center (39.5°N, 116.4°E). At 1800 BT 10 July, precipitation over the whole urban area increased and the scale of the rainfall system was around 100-150 km. Additionally, we found that precipitation increased significantly in the northeast of Beijing during 1800-1900 BT and the amount of precipitation continued to increase in the following several hours. It is not difficult to find that the location of the rainfall system was always in the urban center and the northeast of urban area. This heavy rainfall case ended around 2300 BT. From the evolution of rainfall as shown in Fig.1, it is very clear that this heavy rainfall event is caused by a mesoscale convective system. In the next section, we will focus on exploring the synoptic conditions under which the mesoscale convective system initiated.

3. Synoptic-scale conditions

3.1 Characters of cloud clusters

Figure 2 shows the GOES infrared weather satellite image at 1400 BT 10 July 2004, from which we can see this rainfall event occured at the end of a cloud belt, which is Bangladesh coast and South China Sea

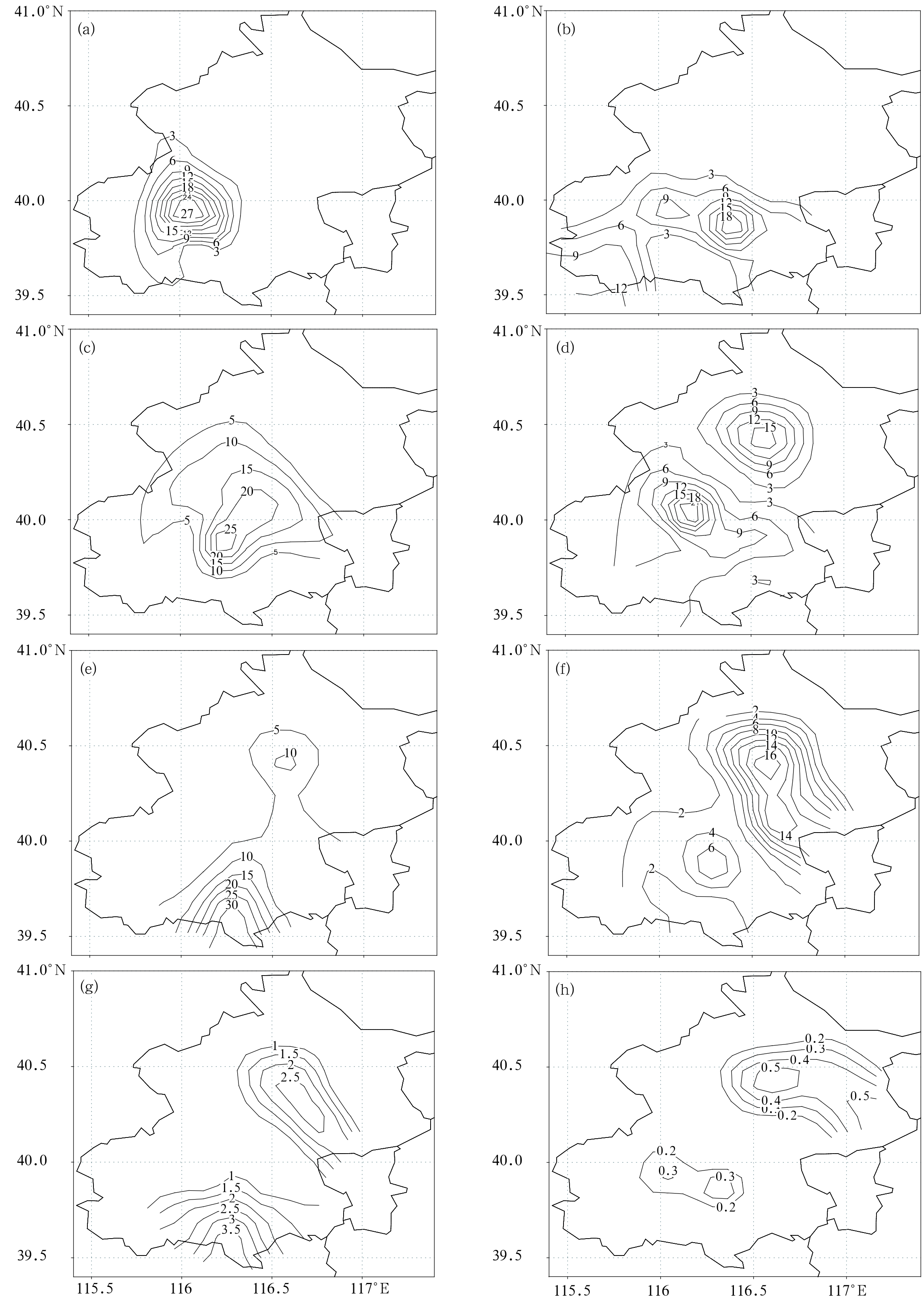

Fig.1. Observed hourly rainfall (mm) on 10 July 2004. (a) 1500-1600 BT; (b) 1600-1700 BT; (c) 1700-1800 BT; (d) 1800-1900 BT; (e) 1900-2000 BT; (f) 2000-2100 BT; (g) 2100-2200 BT; and (h) 2200-2300 BT.

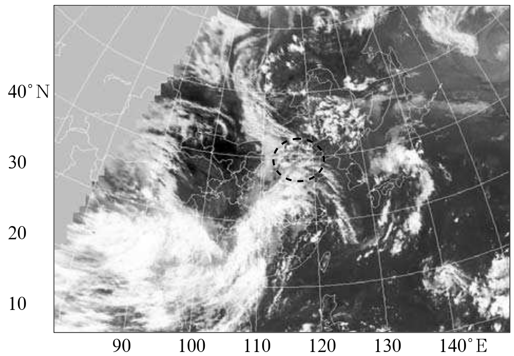

Fig.2. GOES-9 infrared image at 1400 BT 10 July 2004.

monsoon cloud belt. It is unusual that rainfall occurs at the north of monsoon cloud belt. In this case, this cloud belt brought warm and moist air to North China, which is very important for the development of local storms. This case we are studying occurred under this special condition. Warm and moist air brought by the monsoon cloud belt, combined with local meteorological conditions, initiates the local heavy rainfall.

To gain an insight of the development and evolution of this heavy rainfall case, blackbody brightness temperature (TBB) is a very useful tool in discussing the evolution of mesoscale convective systems. Previous studies have shown that TBB data can be used to identify and track the convective system movement. Figure 3 illustrates the temporal evolution of cloud clusters near Beijing area by using TBB data, which

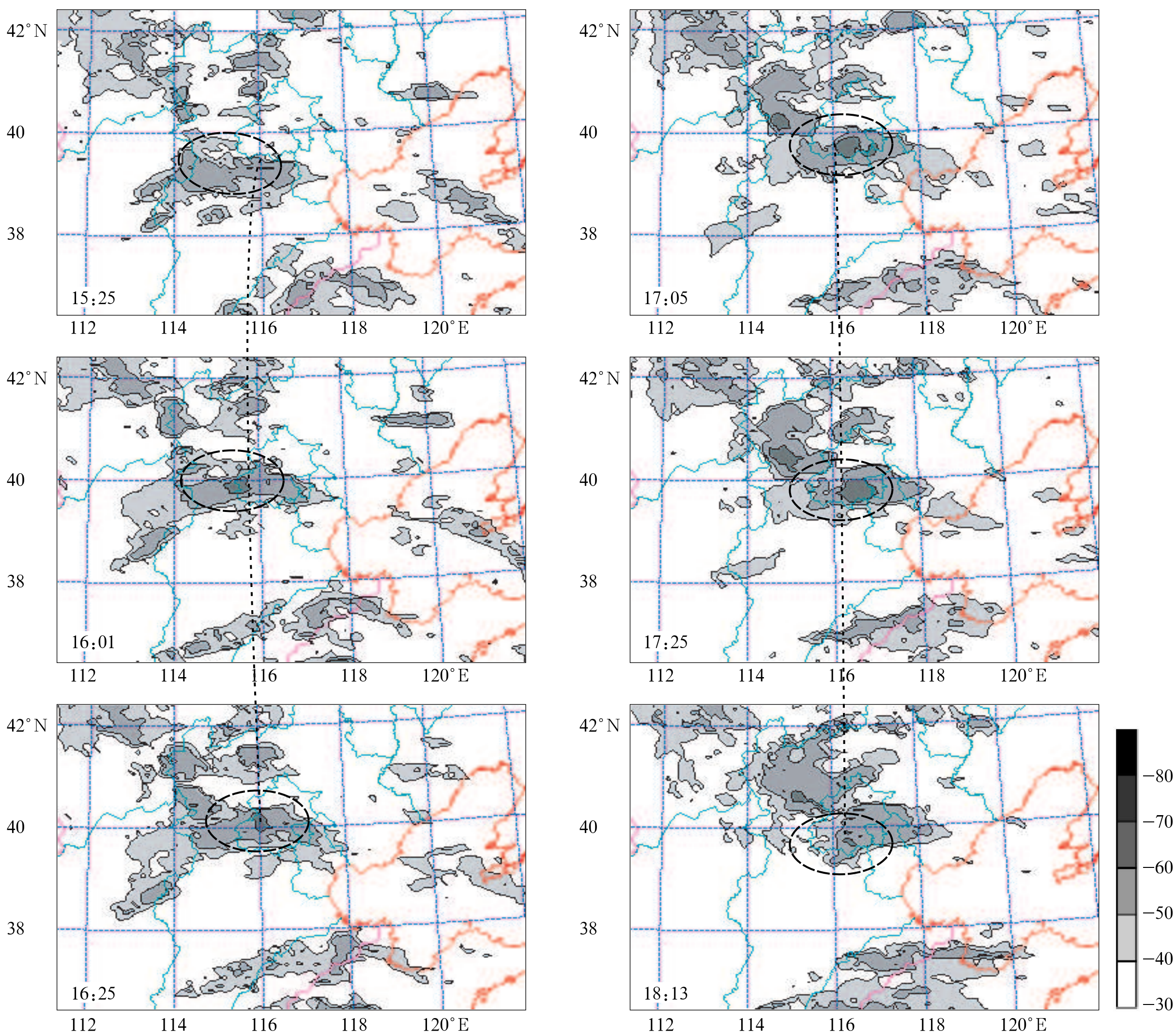

Fig.3. GOES-9-observed TBB from 1525 to 1813 BT 10 July 2004 (°C). The dashed line delineates the position of the convective cloud cluster, which caused the heavy rain in Beijing area.

was derived from GOES infrared weather satellite image. The dashed line represents the mesoscale cloud cluster causing heavy rainfall in Beijing. At 1525 BT 10 July, cloud clusters developed in the southeast of Beijing. The convective cloud cluster gradually developed and moved to the center of Beijing. By 1625 BT, the cloud cluster intensified into a well-defined mesoscale convective system and the lowest cloud top temperature was −60°C. The location of this cloud cluster was in the center of Beijing, and thus heavy rainfall occurred during this period. The mesoscale cloud cluster began to become progressively weaker, and finally dissipated as shown in Fig.3f. Zhang et al. (2003) found that precipitation can continue 1-2 h after the mature of convective cloud cluster. But the intensity decreased due to the lack of enough warm and moist air. The plots of TBB show the heavy rainfall case on 10 July was induced by the development and evolution of a mesoscale convective system. It should be paid attention that the maximum precipitation fell in the urban center in terms of the location of the minimum TBB. The shape of the cloud cluster was irregular, and the temperature gradient was not significant.

3.2 Low level and upper level circulation

Figure 4 shows the surface and upper level conditions at 1400 BT 10 July and the upper level conditions were plotted from NCEP 1° reanalysis data. The weather conditions show that Beijing was located

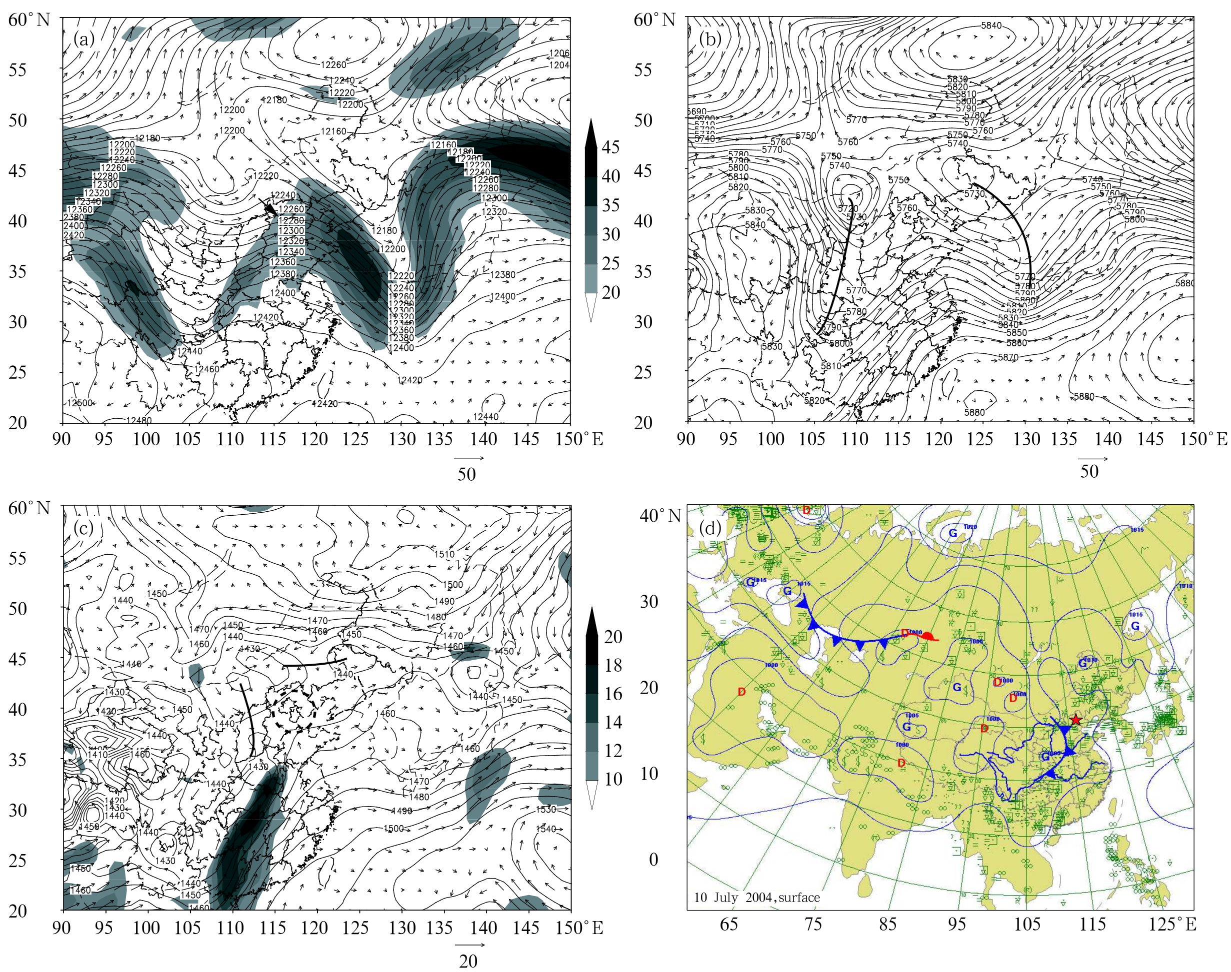

Fig.4. Synoptic situation at 1400 BT 10 July 2004 geopotential heights (solid line; units: m) and wind vectors at 200 hPa (a; the shaded areas are for horizontal wind speed greater than 20 m s^{-1}), 500 and 850 hPa (b and c; the thick solid lines represent troughs), and surface pressure (d; the thick line delineates the position of cold front, and ⋆ denotes the location of Beijing).

near a cold front, along which was warm air. When the cold air located north of the cold front met with the warmer air, the convection was produced. The stable longitude circulation benefited the development of local heavy rainfall. The large-scale cloud belt was towards South-North, the west of which was clear sky. Upper level circulation made the summer South Asian high (SAH) distinctive (Fig.4a) at 25°N and there was a high level jet at 5°N, 120°E. Beijing was located near the high level jet shown by an arrow. The circulation at 500 hPa was relatively stable, the West Pacific Ocean subtropical high pressure stabilized around 25°N, and the typical two troughs and one ridge existed. Due to standing the east of synoptic-scale ridge which was behind the long wave trough, there was cold advection in Beijing. The existence of cold advection was of benefit to the development of downward motion. In the west and north of Beijing there are two low pressure troughs at 850-hPa level (Fig.4c), and the divergence beside the two low pressures is above Beijing region (shown by dashed line). This characteristic is well represented in the corresponding downward velocity. The low level jet is clearly shown at 30°N, 112°E area accompanied by the low pressure trough. The low level jet is beneficial for the feeding of moist and warm air for the development of local storms. In Fig.4d, a cold front is situated in North China, corresponding to the low pressure trough at 850 hPa. The cold front is approaching the northwest of Beijing in the following hours. After 12 h, the cold front moves over Beijing and dissociates. The role of this cold front is obvious in the development of the heavy rainfall.

4. UHI and convective system

Much work has shown that the local heavy rainfall in the urban area is often related to the UHI. In this section, we examine the impacts of UHI on the development of the convective system. The strength of the UHI is measured by the UHI intensity, which describes the maximum difference in temperature between urban and rural locations within a given time period. Here, we simply define the UHI intensity by subtracting the near-surface temperature in the rural area from the near-surface temperature in the urban area. Figure 5a presents time series of hourly rainfall and the time series of UHI intensity, which is the difference of near-surface temperature between the rural AWS (Gongrentiyuguan) and urban AWS (Yanqing). It is obvious that the intensity of UHI is the strongest during 1200-1400 BT and the maximum value is 4°C. Then, the intensity of UHI decreased and the urban cool island appeared at 1800 BT. To be corresponding to the evolution of UHI, most precipitation in these stations started increasing in the following several hours. The hourly precipitation was above 10 mm. The relationship between the UHI and precipitation is negative; the role of UHI is evident in the occurrence of this heavy rainfall.

Figures 5b, c, and d are the plots of near-surface temperature, wind field, and the corresponding convergence. All of the data are obtained from the AWS. The wind field is observed at 10 m, the temperature field was obtained at 1.5 m, and the divergence/convergence was calculated using the wind speed. Figure 5b is the near-surface temperature field at 1400 BT 10 July in Beijing area. It shows that there was a 29.5°C high temperature center, and the temperature in the urban center was greater than the rural area. It is indicated that a generally weak daytime UHI existed. Maximum UHI intensity values ranged from 2 to 3°C, after that, clouds were initiated. Cloud formation gradually weakened the UHI intensity over the subsequent 1-2-h period, due to solar blockage. Compared with Fig.1, precipitation followed in 1 h. At the same time, the convergence that was calculated from wind speed component values observed presented in the urban center. The strongest convergence of 15×10^{-5} s^{-1} was found, causing the cooler air to converge to the urban area from the rural area. In Fig.1, the precipitation became more and more intense since 1500 BT and the maximum precipitation reached 27 mm h^{-1}. The convergence was responsible for the strong precipitation in the urban center. Since that time, at 1700 BT, southwest of Beijing was a cyclone. It showed that Beijing area was located in the strong southwesterly environment flow. From the convergence field that calculated using observed data, we can see two convergence centers

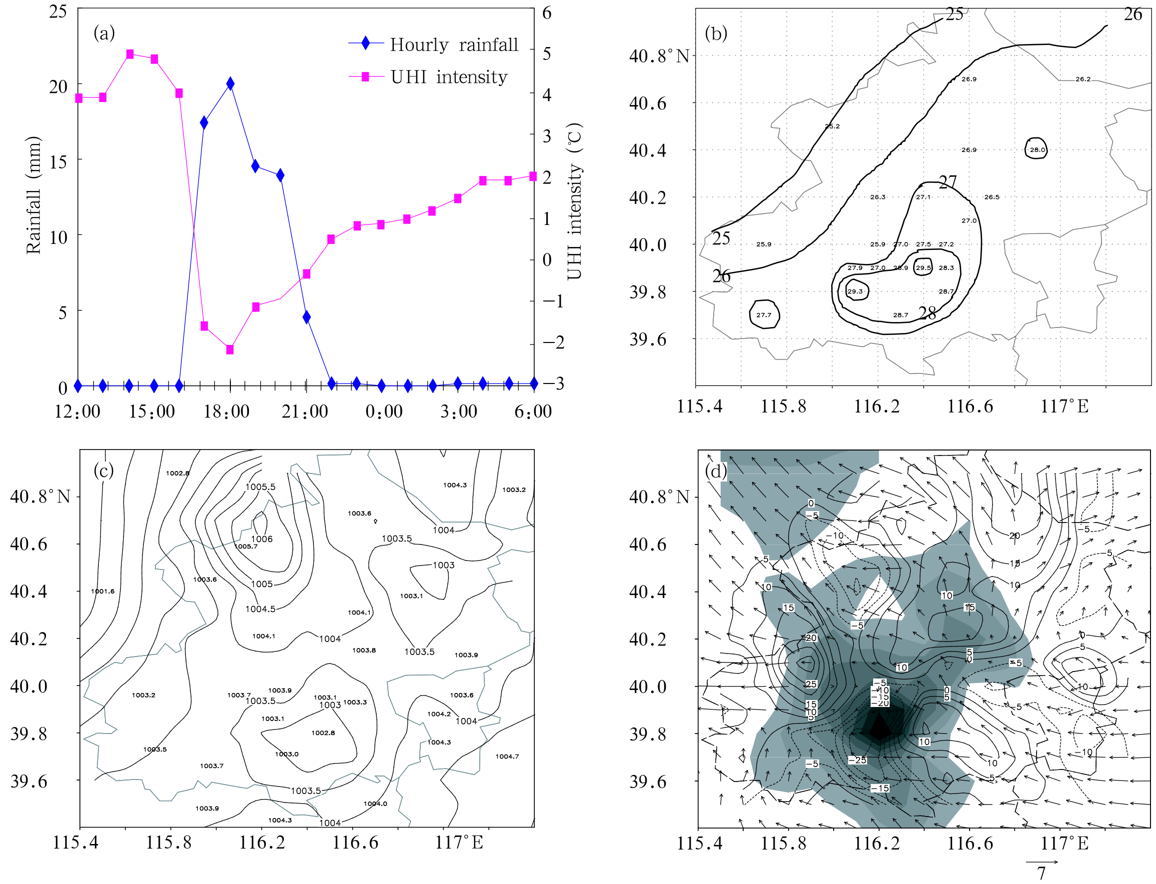

Fig.5. Hourly evolution of UHI intensity (°C) and rainfall (mm) on 10 July 2004 (a), AWS observed surface temperature (b;°C), pressure (c; hPa), and divergence (d; 10 s; shading: precipitation area; vector: surface wind) patterns at 1400 BT.

situated at (40°N, 116.2°E) and (40.2°N, 116.56°E). It was also found that one of the two convergence centers was located over the urban center; the other was 20-30-km downwind of the urban center. Correspondingly, in Fig.1, precipitation initiated at the convergence center that was located over the urban center. After 1-2 h, precipitation also produced downwind of the urban center. Precipitation continued at the two areas in the next 3 h, and the precipitation was above 10 mm h^{-1}.

According to the above analysis, the evolution and distribution of precipitation was due to the low pressure produced by the warm air at the urban center. Because of the low pressure, the cold air converged to the warmer area from the rural area. The convergence at the urban center caused the updraft which resulted in the precipitation. During the process of air rising, more air coagulated into rainwater, which brought rainfall. In addition, the results were that the precipitation was initiated in the UHI-induced convergence zones. The UHI was effective in producing vertical motions. The vertical motions were important for the convective precipitation. Simultaneously, influenced by the environment flow, the warm air moved downwind of the urban area. When the warm air met with the rural cold air, the precipitation increased downwind of the urban area. Therefore, it is clear that the UHI played a vital role in this event, and it made the precipitation take place over the urban center and 20-30-km downwind of the urban center. In order to analyze the mechanism of this event, the numerical model is used in the next section.

5. Model configuration and experimental design

The above analysis indicates that the precipitation was mainly located over the urban center and downwind of the city. Before the initiation of precipitation, the UHI phenomenon was very obvious. Because the UHI was related to the development of city, the urban may affect the convective precipitation.

The numerical model used in this study is the Weather Research and Forecast (WRF) model developeded at the national center of atmospheric research. The WRF model is a nonhydrostatic, fully compressible model with complete physical parameterizations.

The land use/cover data in the USGS high resolution dataset provided WRF a global land cover database with a 1-km spatial resolution. It was acquired from 1992-1993 Advanced Very High Resolution Radiometer (AVHRR) image. The data were classified according to the 24-category USGS land use/cover system. Urban areas were added to the dataset after being extracted from the digital chart of world. Because of the economy development, the urban area in the 1993 USGS land use data does not represent the new urban distribution any longer. Especially, in these decades, urban area in Beijing is much lager than before. Therefore we should modify the land use data in USGS data. Land cover data with 30-m spatial resolution are available for the Beijing metropolitan region for 2002. The land cover data were derived from the US LANDSAT-7 reflectance data in May 2002. The data were classified for land cover using a maximum likelihood decision rule. Then the 2002 land cover data were incorporated into WRF 30 USGS data file to modify the land use data using geographical information system techniques. Figure 6 shows the urban area in Beijing in 1993 and 2002. Significant changes can be seen in the extent of the urban area. The urban area of Beijing in 2002 grew larger than 10 years ago.

In order to illustrate the urban impacts on the precipitation, the simulated results were presented for the 1993 USGS land cover data and the 2002 LANDSAT classification data. A two-level nesting has been used with the spatial resolution of 12 and 4 km for the domains D1 and D2, respectively. The initial and boundary conditions have been obtained from the AVN model analysis for the period of 0800 BT 10 July to 0800 BT 11 July at 6-h interval. Two numerical experiments were performed to investigate the impact of urban treatment. One used the 1993 USGS land-use data, and the other used 2002 LANDSAT-7 land-use data.

6. Results

6.1 Near-surface air temperatures

Several studies on the sensitivity of thermal field to the land cover showed that urban land cover had a significant influence on the simulated near-surface

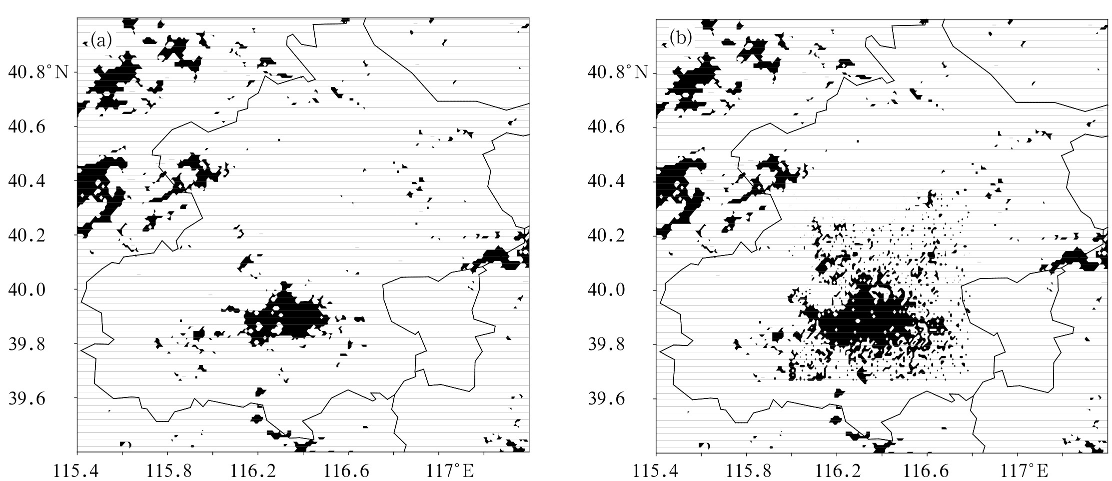

Fig.6. Beijing urban range defined by the 1-km USGS land-use map in 1993 (a) and the 30-m LANDSAT-7 land-use map in 2002 (b). Black denotes the urban area.

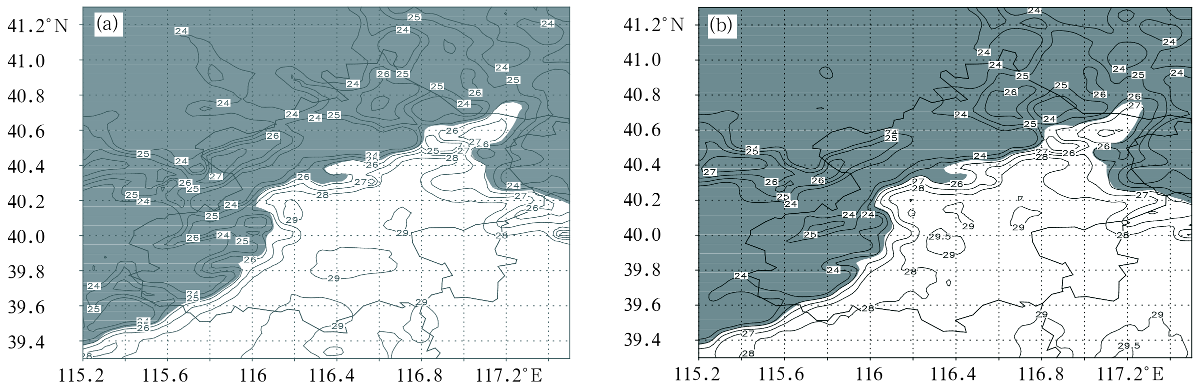

Fig.7. Surface air temperatures (°C) at 1400 BT 10 July 2004 simulated by using the 1993 USGS land-use data (a) and the 2002 LANDSAT land-use data (b).

temperature. Figure 7 illustrates the simulated and observed near surface air temperature for 1400 BT 10 July 2004. Figure 7a is the real-time near-surface temperature. In the urban center there was the 29.5°C high temperature center. The temperature of the rural area was 2-3°C lower than the urban center. A generally weak daytime UHI center existed in the urban center, after which clouds were initiated. Cloud formation gradually weakened the UHI over the subsequent 1-2-h period due to the solar blockage. Figure 7b indicates the simulated 2-m air temperature for 1400 BT 10 July using the 1993 USGS land cover data. The influence of land use on the simulations for the near-surface temperature was shown in Fig.4c using the new LANDSAT land cover data. The differences in the maximum temperature between the lands cover data used different data. There was a significant underestimation of temperature for the 1993 USGS land cover data in the urban center in Fig.7b. However, the maximum temperature using the new LANDSAT land cover data was corresponding with the real-time near-surface temperature. In addition, the location of the maximum temperature was the same as the real-time temperature. As can be seen in Fig.7, land cover changes improved the significant underestimation of the simulated daytime temperatures. Particularly, the simulated warmer center was located in the urban center, and the site which experienced the highest UHI effect. The simulated results illustrated that the UHI existed before the precipitation. The UHI was responsible for this heavy rainfall in the urban.

6.2 Simulated precipitation

For the thermal effect on the rainfall is crucial, Fig.8 shows accumulated rainfall from 1400 BT 10 July to 0000 BT 11 July 2004 for the two simulations. Care should be taken when comparing simulated rainfall with the real-time observed rainfall. First, simulated rainfall near the boundaries may be the result of spurious gradients imposed by two-way interactive grid nesting and may not be physical. Secondly, the models may underestimate the local maximum rainfall for not only normal weather but also severe weather events because the grid resolutions of mesoscale models substantially limit the predictability of fine-scale convective systems. With these considerations, the simulation with NCEP reanalysis initialization using new LANDSAT land cover data best reproduced total rainfall shown in Fig.8c. But the intensity of precipitation was still weaker than the observed total rainfall. Simulation using 1993 USGS land cover data severely underestimated total rainfall in Fig.8b. Improved simulations using new land cover data were likely caused by the influence of the land use. Furthermore, the land surface data had a major impact on the location and the intensity of precipitation. This was due to the sensitivity of turbulence flux in planetary boundary layer (PBL) and the structure of PBL to the land cover data. On the other hand, the turbulence flux in PBL and the PBL structure have an important effect the thermal and dynamic components. Therefore the simulation using the new land cover data has an

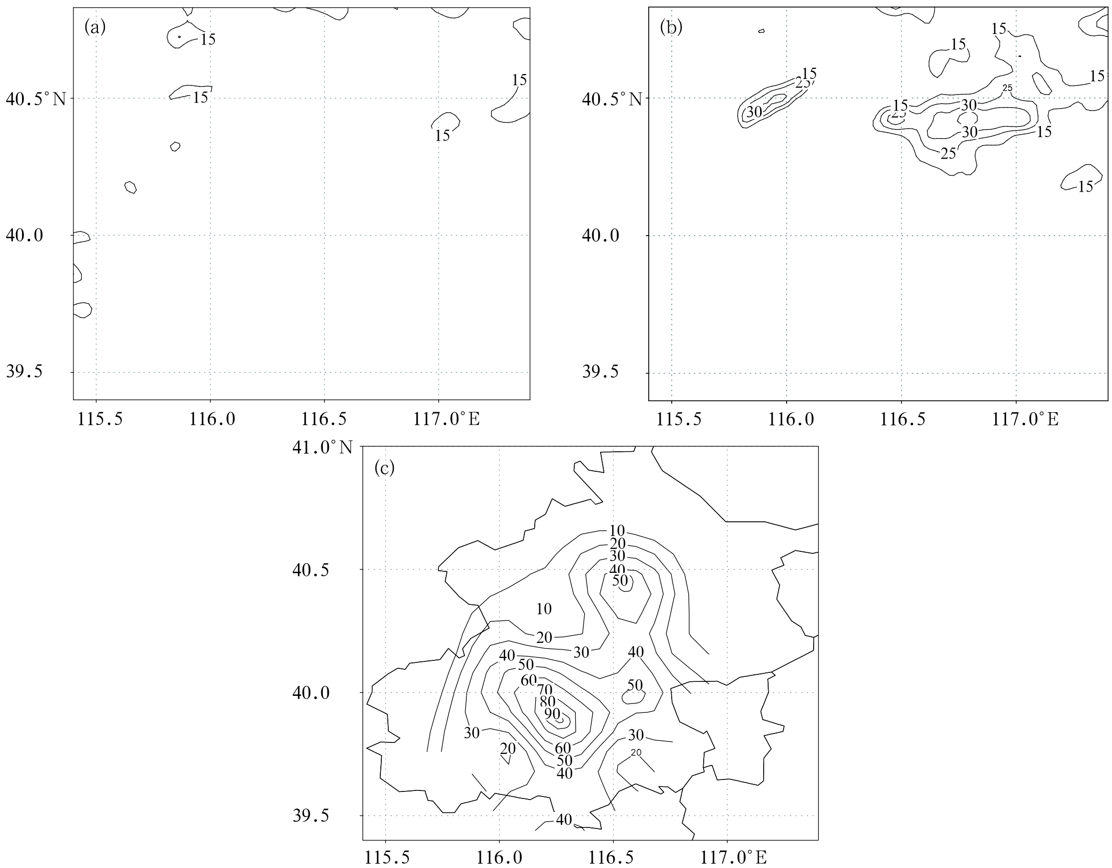

Fig.8. Rain (mm) from 1400 BT 10 to 0000 BT 11 July 2004 simulated using the USGS land-use data (a), the LANDSAT land-use data (b), and the observed (c).

improvement in the location and the intensity of heavy precipitation. In conclusion, the simulated near-surface temperature and the precipitation using the LANDSAT land cover data were better than using the USGS land cover data. In the new land cover data, the urban area has expanded largely since 1993. In some sense, it showed that the development of the city was responsible for this event.

7. Summary and conclusions

To summarize, results of this study show that the heavy rainfall in Beijing was caused by a mesoscale convective system which can be demonstrated by the TBB data. The structure of the convective cloud cluster was irregular without the strong gradient of brightness temperature. The surface temperature and wind pattern indicate that the UHI plays a significant role in producing convection over the urban center and downwind of the city. The low pressure produced by the UHI drove the surrounding cooler air to convergent to the urban center favoring the initialization of convective system. The synoptic-scale systems bring warm and moist air to the local area to enhance the development of the mesoscale convective system. Simulations using different land-use data indicate that land-use change has an impact on the thermal and dynamic fields. Using the new LANDSAT land cover data simulated the total rainfall better than using the USGS land cover data. Thus, we suggest that the effects of land-use change were significant on the location and the intensity of precipitation.

A number of important questions remain to be answered. These include the following: 1) How does the land-use data influence the location and the intensity of precipitation; and 2) Other studies should be done to provide some valuable dynamical insight for a more thorough understanding of urban-induced weather and climate in complex real situations.

REFERENCES

Bai Jie, Wang Hongqing, and Tao Zuyu, 1997: Recognition and tracing of severe convective cloud from IR images of GMS. *J. Tropical Meteor.*, **13**(2), 158-167. (in Chinese)

Bornstein, R., and M. LeRoy, 1990: Urban barrier effects on convective and frontal thunderstorms. Preprint volume, Fourth AMS Conference on Mesoscale Processes, Boulder, CO, 25-29 June.

Bornstein, R., and Q. Lin, 1999: Urban heat islands and summertime convective thunderstorms in Atlanta: Daytime case study. Proceedings of the Sixth International ASAAQ'98 Conference, Beijing, China, 11 pp.

Bornstein, R., and Q. Lin, 2000: Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies. *Atmos. Environ.*, **34**, 507-516.

Changnon, S. A., F. A. Huff, P. T. Schickedanz, et al., 1977: Weather anomalies and impacts. In: Summary of METROMEX Vol. **1**, Illinois. State Water Survey, *Bull.*, **62**, Champaign, 260 pp.

Changnon, S. A., 1978: Urban effects on severe local storms at St. Louis. *J. Appl. Meteor.*, **17**, 578-586.

Dong Peiming, Zhang Weihuan, and Shen Tongli, 1999: Numerical study on the effects of underlying surface forcing on torrential rain process over Beijing-Tianjin-Hebei region. *Quart. J. Appl. Meteor.*, **10**(4), 436-444. (in Chinese)

Huff, F. A., and S. A. Changnon, 1973: Precipitation modification of major urban areas. *Bull. Amer. Meteor. Soc.*, **54**, 1220-1232.

Huff, F. A., 1986: Urban hydrological review. *Bull. Amer. Meteor. Soc.*, **67**, 703-712.

Li Yaodong, Liu Jianwen, and Gao Shouting, 2004: On the progress of application for dynamic and energetic convective parameters associated with severe convective weather forecasting. *Acta Meteor. Sinica*, **62**(4), 401-409. (in Chinese)

Li Yaodong, Gao Shouting, and Liu Jianwen, 2004: A calculation of convective energy and the method of severe weather forecasting. *Quart. J. Appl. Meteor.*, **15**(1), 10-20. (in Chinese)

Li Zhinan and Li Tingfu, 2000: Analysis on the environment conditions and dynamic trigger mechanism of a severe convective rainstorm in Beijing. *Quart. J. Appl. Meteor.*, **11**, 304-311. (in Chinese)

Lin Yonghui and C. Bueh, 2003: Numerical simulation of mesoscale convective systems of Shanghai rainstorms in August 2001. *Acta Meteor. Sinica*, **61**(2), 196-203. (in Chinese)

Shepherd, J. M., H. Pierce, and J. NegriA, 2002: Rainfall modification by major urban areas: Observations from spaceborne rain radar on the TRMM satellite. *J. Appl. Meteor.*, **41**, 689-701.

Shi Dingpu, Zhu Wenqin, Wang Hongqing, et al., 1996: Cloud top blackbody temperature analysis of infrared satellite image for mesoscale convective system. *Acta Meteor. Sinica*, **54**(5), 600-611. (in Chinese)

Sun Mingsheng, Wang Ximing, Luo Yang, et al., 1996: A prospect forecasting method study of severe convective weather in Beijing area. *Quart. J. Appl. Meteor.*, **7**(3), 336-343. (in Chinese)

Thielen, J., W. Wobrock, A. Gadian, et al., 2000: The possible influence of urban surfaces on rainfall development: A sensitivity study in 2D in the meso-α-scale. *Atmos. Res.*, **54**, 15-39.

Wang Xiaofang and Ding Yihui, 1994: Study on method of short-range forecast of severe convective weather in Beijing area. *Scientia Atmospherica Sinica*, **18** (2), 173-183. (in Chinese)

Zhang Q., K. Lau, Y. Kuo, et al., 2003: A numerical study of a mesoscale convective system over the Taiwan Strait. *Mon. Wea. Rev.*, **131**, 1150-1170.