4.9 INFLUENCES OF URBANIZATION ON PRECIPITATION AND WATER RESOURCES IN THE METROPOLITAN BEIJING AREA

Chao-lin Zhang[1] *, Fei Chen[2], Shi-guang Miao[1], Qing-chun Li[1], and Chun-yi Xuan[3]

[1] Institute of Urban Meteorology, China Meteorological Administration, Beijing 100089, China
[2] National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO, 80307-3000, U.S.A.
[3] Beijing Meteorological Bureau, Beijing 100089, China

ABSTRACT

In this study, the analysis of long-term rainfall data collected in the metropolitan Beijing area reveals that the summer rainfall reduction in the northeast areas of Beijing, where the major reservoirs are located, from 1980-2003 is statistically correlated with rapidly urban development in Beijing since 1980. This may be the leading factor for the shortage of water resources in the Beijing area, which has increasingly become a serious factor constraining sustainable economic development. To understand the effects of urbanization on summer rainfall and the potential measures to mitigate such effects, a mesoscale weather/land-surface/urban coupled model and different urban land-use scenarios are used to conduct numerical simulations for a selected heavy summer rainfall event. Results show that urbanization produces less evaporation, higher surface temperatures, larger sensible heat fluxes, and a deeper boundary layer. These modified atmospheric conditions lead to less water vapor, more water-vapor mixing in the boundary layer and hence less convective available potential energy for triggering initiation of convection and rainfall formation. The combination of these factors induced by expanding urban surfaces, results in reduced precipitation for the Beijing area, in general, and for the Miyun reservoir area (the major source for the local water supply), in particular. Increasing the green vegetation coverage in the Beijing area would produce more rainfall, and model results show that planting grass is more effective than planting trees, in this regard. For the same vegetation planted, the rainfall difference from simulations using two green-planting layouts (annular and cuneiform) is small.

1. Introduction

The Greater Beijing metropolitan area, is one of the ten largest megacities in the world with a population of more than 10 million, and has experienced a rapid urbanization in the last twenty years. Such urban expansion, with increasing built-up areas and human activities, results in significant modifications in the underlying surface properties and atmospheric circulations. One alarming sign is that aridity and water shortage has become an increasingly serious problem – potentially a man-made disaster for Beijing in the future, if not mitigated. According to statistics, China's total water resources ranks sixth of the world, however, the average amount per person is only 1/4 of the world's per person average, and the average amount in Beijing is only 1/25 of the world's per person average. Observations show that heavy summer rainfall in the Miyun reservoir area, a major source for Beijing's water supply, has decreased in recent years. The shortage of water resources is a key factor limiting sustainable economic development in the Beijing area, which obviously has a direct impact of the quality of life for the citizens.

In this study, we explore the relationship between urbanization and the evolution of summer rain in Beijing using climatologic data from 1981 to 2003. We also investigate the possible causes for summer rainfall change due to urban expansion, using mesoscale weather/land-surface models and high-resolution urban land-use data.

In urban areas, natural surfaces (grass and soil) are replaced by man-made surfaces (concrete and pavement) with thermal properties (albedo, thermal conductivity, emissivity) different from non-urban areas. It is has long been known that under clear skies and light wind conditions, cities are warmer than surrounding rural environments. These areas are called urban heat islands (UHIs) and up to 10oC can form due to urban-rural differences (Bornstein, 1987). These urban-rural

*Corresponding author address: Chao-lin ZHANG, Institute of Urban Meteorology, China Meteorological Administration, No.55 Beiwaxili Road, Haidian District, Beijing, China, 100089,Voice: 86-010-68400743, Fax: 86-010-68475440, Email: clzhang@ium.cn and c_lzhang@yahoo.com

differences profoundly affect the surface energy budgets. For instance, evaporation in urban areas is reduced by impervious surfaces, and the storage of solar energy within urban structures reduces nocturnal loss of ground-level long-wave radiation by canyon-wall absorption. These modifications in the underlying urban surfaces change the wind velocity, mixing layer depth and thermal structures in the boundary layer, and the local and regional atmospheric circulations (Bornstein and Johnson, 1977; Liu et al., 2006; Lo et al., 2006).

Furthermore, urban areas can alter precipitation patterns (Changnon and Huff, 1986). For instance, based on synoptic analyses, Huff et al. (1978) and Vogel et al. (1978) showed that in St. Louis, MO, USA, the urban surface is the main factor affecting the spatial and temporal distributions and the intensity of short-term rainfall. Rosenfeld (2000) and Givati et al. (2004) indicated that rain and snow are suppressed by urban air pollution. Shepherd (2005) reviews the progress of urban-induced rainfall from 1990, and shows impacts of urbanization on rainfall has attracted more attention recently. The analysis and numerical study of impacts of land-use change on the climate in North China was conducted, and was summarized by Li et al. (2004). Nevertheless, these studies are mostly focused on chronological effects of the thermodynamic and dynamic forces on the atmospheric process caused by land-use and aerosol changes and on studying the effect of the development and change of the underlying surface on rainfall using the statistical method and sensitivity simulations by coarse-resolution climate models.

Wu et al. (2000) show that the characteristics (frequency and intensity) of heavy summer rainfall determine the annual rainfall and its spatial distribution in Beijing, and hence the water budgets in the reservoir areas. Li et al. (2005) analyzed the statistical relationship between land-use change and the spatiotemporal distribution of rainfall, and showed that since the 1960s significant changes in the distribution of rainfall has taken place in the Beijing area. Currently, the physical processes through which local and regional urbanization impact summer short-term heavy rainfall are still poorly understood.

Recent progress in developing advanced land surface models (LSMs) coupled with mesoscale atmospheric models (Chen et al.. 2001a,b) have permitted examination of interactions among land surface processes, boundary layer structures, and convective precipitation in increasingly complex and realistic regional-scale environments (Chen et al. 2001c; Trier et al. 2004; Holt et al. 2006). Recent mesoscale model studies by Zhang et al. (2005a, b) are successful in revealing the effects of Beijing's U-shaped topography on the climatic distribution of heavy rainfall. Therefore, in this study, we investigate the influences of rapid urbanization in the Beijing area on heavy summer precipitation and local water resources through the use of climatologic data and a high-resolution weather/LSM coupled modeling system. The main objectives are: 1) to explore the relationship between summer rainfall pattern and urban development in the Greater Beijing area using long-term data, and 2) to understand the effects of urbanization and future green planting on summer convection through a numerical study of a typical, climatologically representative, heavy summer rainfall-event in Beijing. We hope to reveal potential impacts of human activities on megacity water resources and methods for mitigating the water-supply shortage, information valuable for planning future urban development and for water resource usage in Beijing.

In Section 2, we investigate the correlationship between precipitaiton and water resource within Beijing. In Section 3, we examine the long-term distribution of rainfall in Beijing and its relation to urban development. In Section 4, we discuss the case selected for this study, characteristics of the numerical model and high-resolution urban land-use data, and the design of numerical simulations. Our results are discussed in Section 5, and a summary and concluding remarks are presented in Section 6.

2. Relationship of precipitation with water resource within Beijing

Table 1 gives the correlation coefficients

Table 1. The correlation coefficients between precipitation (mm) and water resource ($10^8 m^3$) within Beijing according to the 15-year-averaged observations 1986-2000.

precipitation (mm)	water resource （$10^8 m^3$）		
	total	surface water	ground water
annual	0.898	0.874	0.915
summer (Jun.-Aug.)	0.926	0.920	0.926

between precipitation and water resource according to the averaged observations from 1986-2000. Obviously, all of the correlation coefficients between annual precipitation and water resources of total, surface and ground exceed 0.87, respectively. Furthermore, there are the closer relationships between summer precipitation and each component of water resource. (each correlation coefficient high up over 0.92). Above facts indicate that to investigate urbanization impacts on precipitation, especially on summer precipitation, cloud give the extensive equivalent clue to understand its impacts on water resources.

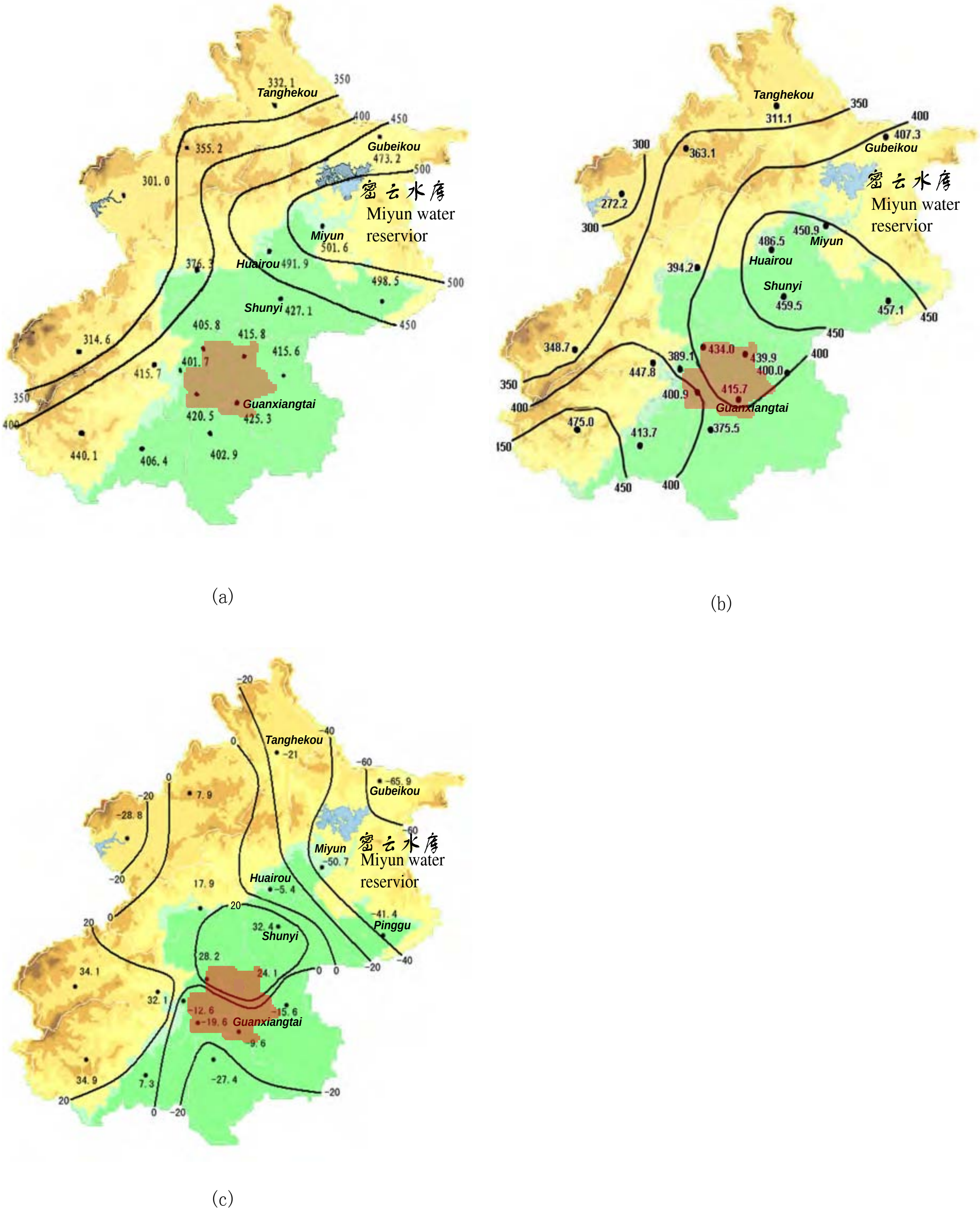
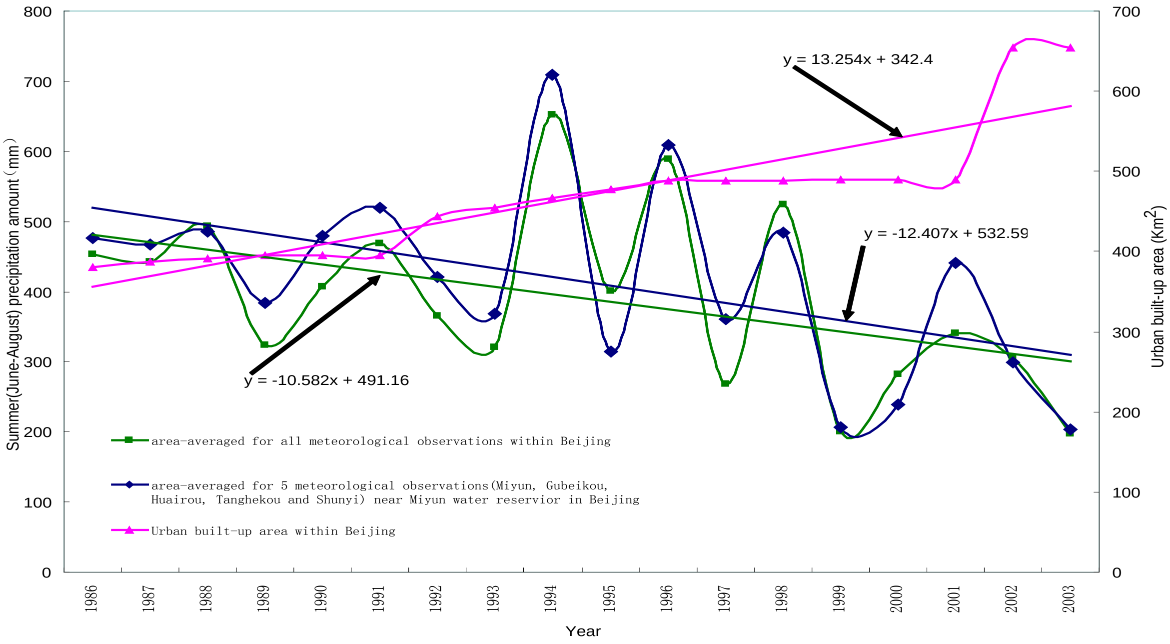
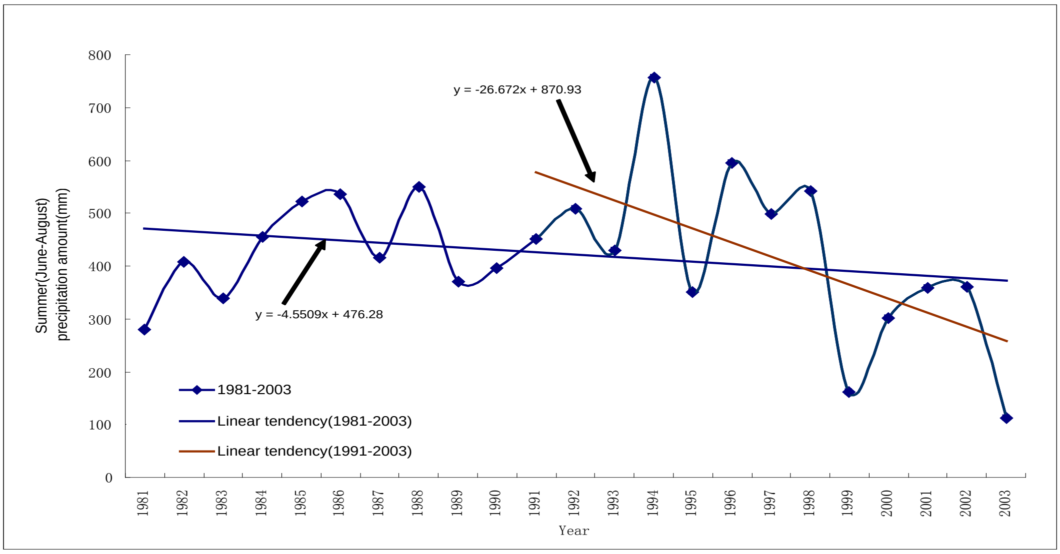


Figure 1. Distribution of decadal-averaged summer (June-August) precipitation (mm) in the Beijing area: (a) for 1981-1990, (b) for 1991-2000, and (c) difference of precipitation (mm) between (a) and (b). The names of the observation stations are also shown. The yellow shades represent high elevations and green for low elevations, and light-red areas represent Beijing city downtown areas.



(a)



(b)

Figure 2. (a) The annual summer (June-August) precipitation (mm) and urban built-up area (km2) for the Beijing city area and in the vicinity of the Miyun reservoir (Miyun, Gubeikou, Huairou, Tanghekou and Shunyi); (b) annual summer (June-August) precipitation (mm) obtained from the Shunyi site. Urban built-up data are obtained from "Beijing Statistical Annals (1985-2003)", which is released by the Beijing Statistical Bureau and published yearly by the China Statistical Press, Beijing. The meaning of the lines with symbols is illustrated in the lower-left part of each plot, and the lines without symbols are their corresponding linear tendency change (see linear-fitted equations in this figure).

Table 2. The correlation coefficient between built-up area (km^2) and summer (Jun.-Aug.) precipitation, annual precipitation of observatories in Beijing

Built-up area (km^2)	Miyun	Huairou	Gubeikou	Tanghekou	Shunyi
Summer precipitation (mm)	**-0.45**	-0.41	**-0.54**	**-0.45**	**-0.44**
annual precipitation (mm)	-0.42	**-0.48**	**-0.56**	-0.42	**-0.44**

3. Characteristics of spatiotemporal distribution of rainfall and its relationship to urbanization in Beijing

Figs. 1a and 1b show the spatial distributions of decadal-average summer (June to August) rainfall in Beijing. For the period of 1981-1990, the maximum summer rainfall is centered in the eastern part of Beijing with a maximum value of 500 mm located in the vicinity of the Miyun reservoir in the northeast of Beijing (Fig. 1a). For the period of 1991-2000, the center of maximum summer rainfall moves to the southern part of the city (Huairou, Shunyi, and Pingu) and the maximum rainfall decreases to 450 mm (Fig. 1b). It is clear from Fig. 1c that the summer rainfall in Beijing has been declining since 1981, with the largest decrease (by more than 40 mm) in the northeast area (around the Miyun reservoir). Note that the percentage of summer rainfall (June to August) to yearly rainfall, based on data from the Beijing Observatory, is 71.19% as averaged for the period of 1971-2003, with a maximum of more than 85% (91.23% in 1975 and 87.39% in 1982) and a minimum of 40-50% for 1999 and 2003. Because the Miyun reservoir is the most important reservoir for public life in Beijing, and the reduction of summer rainfall in the vicinity of the Miyun area, shown in this twenty-year trend, obviously contributes to the recent water shortage in Beijing, makes this an issue of major importance.

As shown in Fig. 2a, urban development in Beijing increases at an annual increment of 13.254 km^2, but the increase rate is more substantial after 2000, indicating a rapid urbanization of Beijing in the last few years. Also evident is the decreasing trend of summer (June-August) rainfall over the whole Beijing area, fluctuating with an increment of -10.582 mm per year. The decreasing rainfall trend is more pronounced, fluctuating with a linear variation of -12.407 mm per year, in the vicinity of the Miyun reservoir, in the towns and villages of Miyun, Gubeikou, Huairou, Tanghekou and Shunyi. Fig. 2b shows that for the Shunyi area the rainfall change rate is -4.55 mm per year from 1981 to 2003, but increases to -26.67 mm per year from 1991-2003, a much higher rate than that averaged for 1981-2003. These results show that there has been less available water resources in Beijing since 1999. As shown in Fig. 1c, while there is a tendency for maximum summer rainfall moving southward to the Shunyi area, the precipitation amount clearly decreases in recent years following the general climate trend of the whole region.

The correlation coefficients between the developed areas, summer rainfall in Beijing, and the annual rainfall in Miyun and its surrounding areas are documented in Table 2, and they are all negative. The negative correlation coefficients for Miyun and surrounding areas (Miyun, Gubeikou, Huairou, Tanghekou, and Shunyi) are especially large. The correlation coefficients between urban development and observed annual rainfall in Gubeikou, Huairou and Shunyi are -0.56, -0.48, and -0.44, respectively; the correlation coefficients between the development in Beijing and heavy summer rainfall in Miyun, Shunyi, Gubeikou and Tanghekou are -0.45, -0.54, -0.45 and -0.44, respectively. Therefore, based on the analysis of the 20-year data, statistics clearly show that the summer and annual precipitation in the Greater Beijing area, particularly in the vicinity of the Miyun reservoir, decreases with urban expansion.

4. Numerical model and experiment design used to investigate a heavy rainfall case of 18 August 2002

4.1 Case description

After having analyzed several major heavy-rainfall events during the summers of 2000-2004, we selected a heavy-rainfall event occurring from 18-19 August 2002 in the Miyun reservoir area for a detailed modeling study. We chose this data set because it represents typical summer convection in Beijing and main rainfall-change characteristics in the Shunyi area after the 1980s. This rainfall event mainly occurred from 1200 UTC (2000 LST) 18th to 0000 UTC□0800 LST□ 19th with four locations with heavy precipitation. The maximum 12-hour-accumulated rainfall reached 81.4 mm in Shunyi in the southeast of the Miyun reservoir. The other three rainfall centers were located in Changpin, Tanghekou and Zhaitang with the rainfall amount of 53.9, 62.9, and 22.3 mm, respectively (see Fig. 3a). The characteristic of its spatial distribution is similar to that of typical summer rainfalls in the last ten years in Beijing (see Fig. 1b) in that the maximum rainfall is located southeast of the Miyun reservoir; therefore the location and intensity of rain bands have important impacts on the water resource budget in the Miyun reservoir. As shown in Fig. 3b, the Beijing area has high temperature and high humidity immediately before the main convection event while in northeast of Beijing there is a large-scale, cold high-pressure system. At the same time, in southwest of Beijing (40N, 115E), there is a

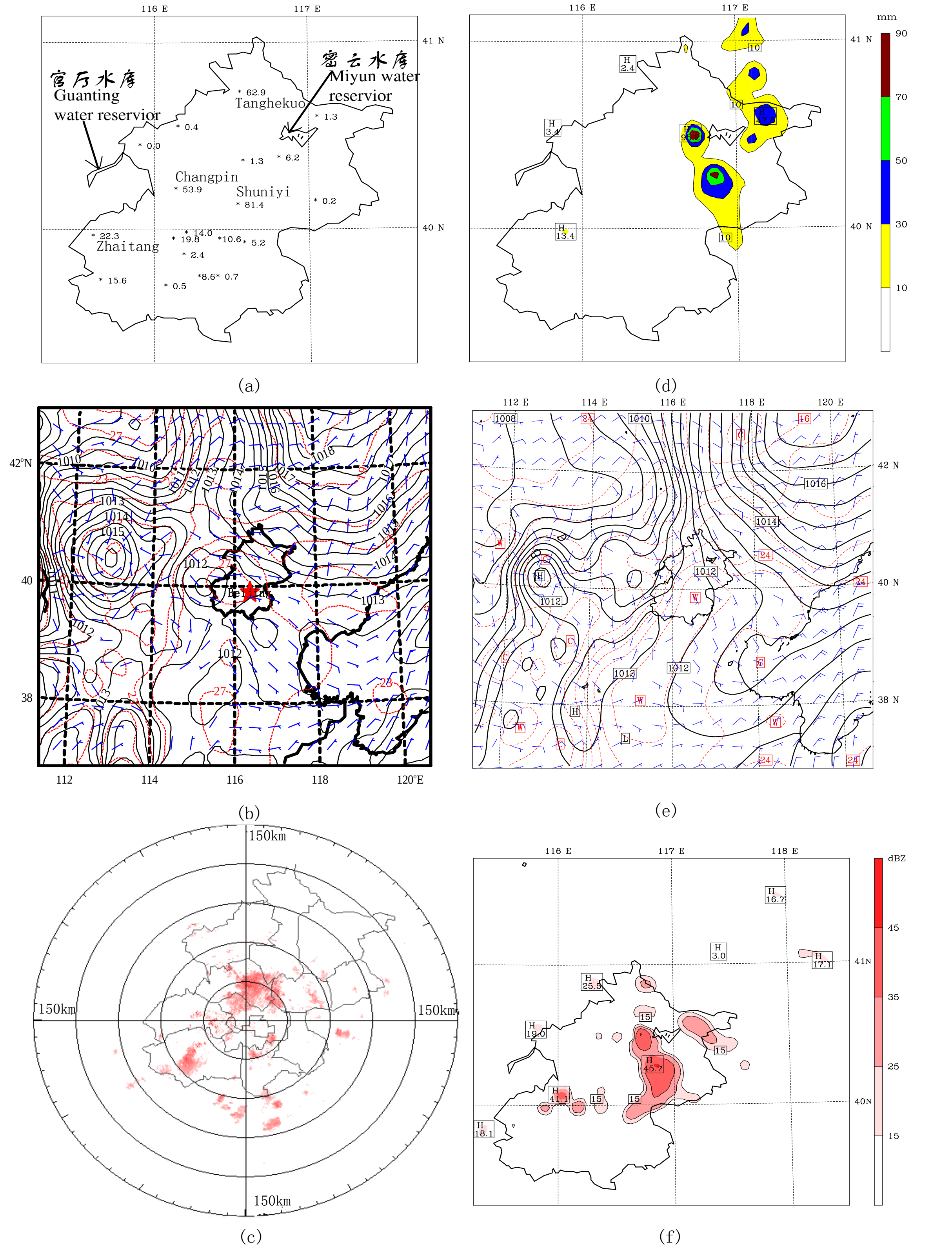


Fig3. The observed and simulated fields of the control experiment Exp2000. (a) Observed 12-h precipitation (mm) for 1200 UTC 18 - 0000 UTC 19 August 2002; (b) surface weather map at 1200 UTC 18 August 2002. Black line: sea level pressure (hPa), temperature in red dash line (^{O}C), and wind vector (blue arrow) at 1200 UTC 18 August 2002; (c) Beijing c-band radar reflectivity (dbz) at 1805 UTC 18 August 2002 at an elevation of 1.5 degree; (d) same as (a), but for Exp2000; (e) same as (b) but for Exp2000; and (f) same as (c) but for Exp2000 at the σ = 0.815.

meso-β scale warm low-pressure system. At the bottom of the northeast high-pressure system the strong eastern circumfluence draws in a cold, humid air mass from the western Pacific, which meets the warm, humid convergent stream of the southwestern micro-scale ground low-pressure system in middle-eastern Beijing. The 500-hPa and 700-hPa synoptic maps (not shown here) show that the upper air of Beijing is dominated by a warm, high-pressure ridge, with the eastern cold, humid flow of the lower high-pressure and the strong convergent updraft in the middle-eastern part; the synoptic system with large temperature differences between surface and upper air is formed, which is conducive to accumulating unstable energy and creating heavy nocturnal rainfall on 18 August 2002. The Beijing c-band radar reflectivity observed at 1805 UTC 18 August (0205 LST 19th, Fig. 3c) show that the development of this rainfall event in Beijing is mainly affected by the meso- and micro-scale system split from the eastern circumfluence at the bottom of the northeast high-pressure and local thermodynamic and dynamic conditions, rather than being forced by large-scale synoptic systems. Because this rainfall event is mainly forced by meso- and micro-scale circulations and sensitive to surface conditions, this investigation is expected to illustrate effects of the underlying surface characteristics on this rainfall event, especially to understand how the daytime exchange between the boundary layer and urban surfaces influences the atmospheric thermodynamic structures preceding the main rainfall event.

4.2 Models used

The coupled fifth-generation Pennsylvania State University–National Center for Atmospheric Research nonhydrostatic Mesoscale Model (MM5, Grell et al. 1994)–land surface modeling system (version 3.6) is used in this study. The MM5 incorporates a complex, thermodynamic and dynamic interaction between land surface characteristics (e.g. topography, soil moisture, and vegetation) and atmospheric processes, and is widely used to study the mutual effects between land surface characteristics and synoptic processes. The model is configured for the current study with two two-way interactive grids, centered at 40N and 116E (see Fig. 4), and has horizontal grid spacings of 10, and 3.33 km and grid point dimensions of 81x 67 and 133x115 for Domain 1 (D1) and Domain 2 (D2), respectively. The same 34 sigma levels are specified for all simulations. Pressure at the top of the model, where a radiative boundary condition is used, is 100 hPa. The initial and boundary conditions are from the National Centers for Environmental Prediction's (NCEP) global 1-degree reanalysis data (Kistler, et al. 2001). While the lateral boundary condition is updated every 6 hours, surface and upper-air

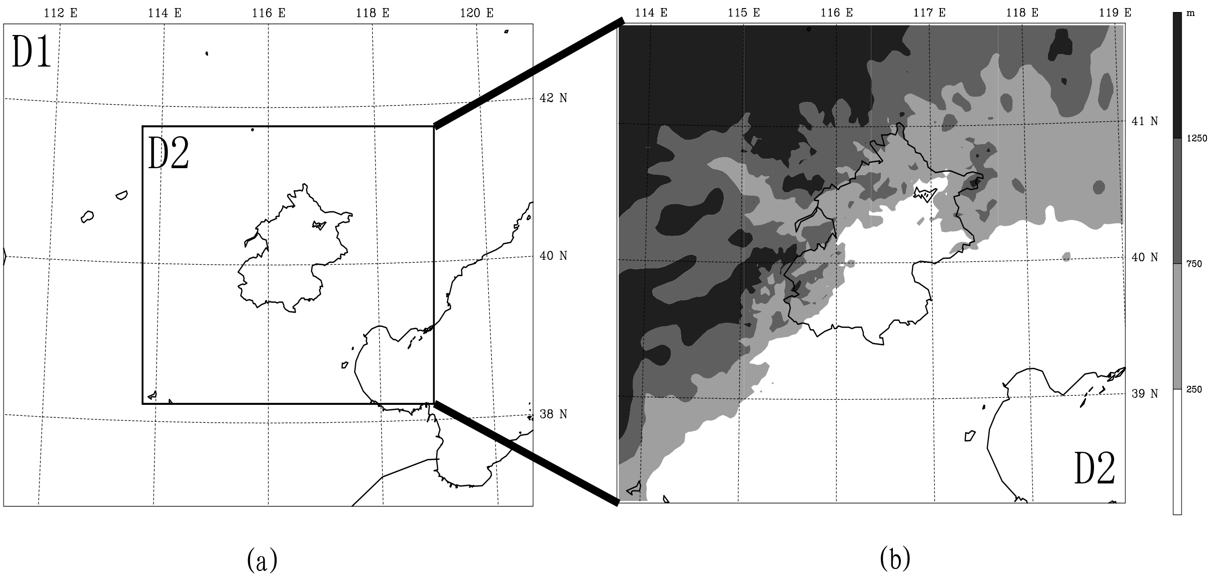


Figure 4. (a) MM5 modeling domains; and (b) terrain height in D2. The grey-filled areas denote the elevation with 500-m interval..

conventional observational data are incorporated into the initial analysis using a Cressman-type analysis scheme. MM5 runs for a 24-h simulation and is integrated from 0000 UTC (0800 LST) 18 to 0000 UTC (0800 LST) 19 August 2002.

The main physics schemes are: the MRF PBL scheme (Hong and Pan, 1996) modified by Liu et al. (2006), Dudhia's cloud radiation scheme and

Table 3. Design of numerical experiments

Numerical Experiment		Land Use Data Used	
Control experiment	Exp2000	The USGS used in MM5 is replaced by 2001 500-m resolution land-data for the Greater Beijing area	See Figure 5(b)
Sensitivity experiments on urbanization	Exp1980	Same as Exp2000, except for using 1993 USGS land-use data	See Figure 5(c)
	Exp00eu	Same as Exp2000, but assuming that the plain area surrounding Beijing downtown is replaced by urban as well, the western and northern mountainous area remain natural (dominant grass cover)	See Figure 5(d)
	Exp00nu	Same as Exp2000, but the urban areas in downtown Beijing are replaced by grassland	See Figure 5(e)
Sensitivity experiments on future green planting scenarios	Exp10hg	Same as Exp2000, except that the urban in major five beltway areas are replaced by grassland according to the annular green planning of Beijing for 2010	See Figure 5(f)
	Exp10ht	Same as Exp10hg, except that ring roads are planted with tree (instead of grass)	See Figure 5(g)
	Exp10xg	Same as Exp10hg, except for planting cuneiform grass (instead of grass belts)	See Figure 5(h)
	Exp10xt	Same as Exp10xg, except for planting cuneiform tress (instead of grass)	See Figure 5(i)

simple ice explicit microphysics scheme for both D1 and D2 (Dudhia 1989), and the Grell (Grell, 1994) cumulus parameterization only used for the 10-km D1. The Noah land surface model (LSM) coupled to the MM5 (Chen and Dudhia 2001, Ek et al. 2003; Chen 2005) has a single canopy layer and predicts volumetric soil moisture and temperature in four soil layers. The depths of the individual soil layers from top to bottom are 0.1, 0.3, 0.6, and 1.0 m. The root zone is contained in the upper 1 m (top three layers). The Noah LSM urban enhancements by Liu et al. (2006) included: 1) increasing the roughness length to 0.8 m to better account for the drag due to buildings; 2) reducing the surface albedo to 0.15, where this reduction accounts for the shortwave radiation trapping in the urban canyons; 3) increasing the volumetric heat capacity to 3.0 x 106 J m-3 K-1 and the soil thermal conductivity to 3.24 W m-1 K-1 to be more consistent with the prevailing concrete or asphalt materials; and 4) reducing the green vegetation fraction to reduce evaporation. The performance of the MM5 modeling system coupled to this simple urban treatment was verified with surface and wind profiler data for the Oklahoma City area (Liu et al. 2006) and for the PRD region and (Lo et al. 2006).

4.3 Land-use change scenarios used in sensitivity experiments

Our main objective is to explore the effects of urbanization on summer precipitation and the potential measures to mitigate these effects, so

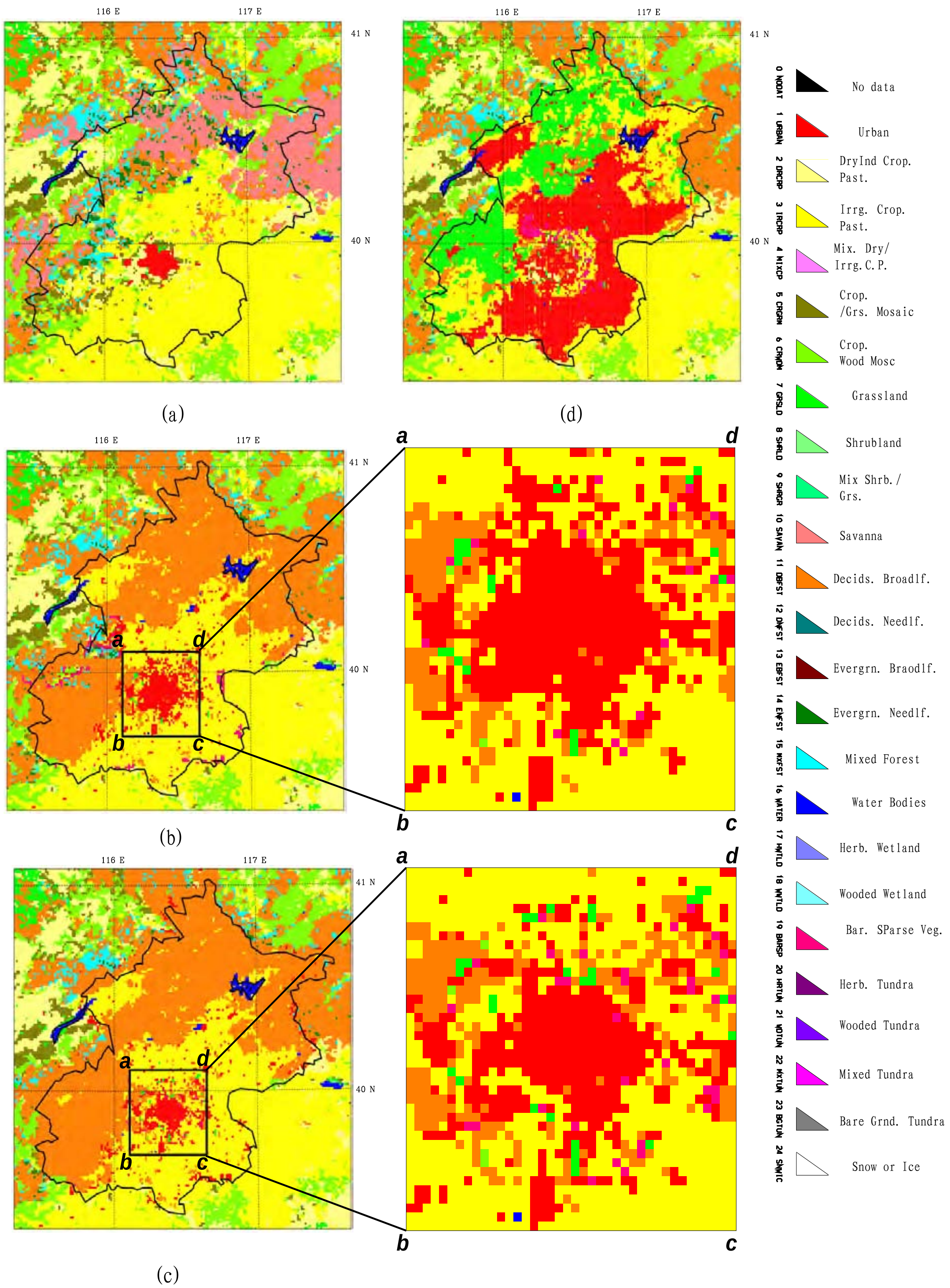

116 E
117 E
41 N
40 N
(a)
(d)
a
d
b
c
(b)
(c)
No data
Urban
Drylnd Crop. Past.
Irrg. Crop. Past.
Mix. Dry/ Irrg. C. P.
Crop. /Grs. Mosaic
Crop. Wood Mosc
Grassland
Shrubland
Mix Shrb. / Grs.
Savanna
Decids. Broadlf.
Decids. Needlf.
Evergrn. Braodlf.
Evergrn. Needlf.
Mixed Forest
Water Bodies
Herb. Wetland
Wooded Wetland
Bar. SParse Veg.
Herb. Tundra
Wooded Tundra
Mixed Tundra
Bare Grnd. Tundra
Snow or Ice

Fig. 5 a - 5d

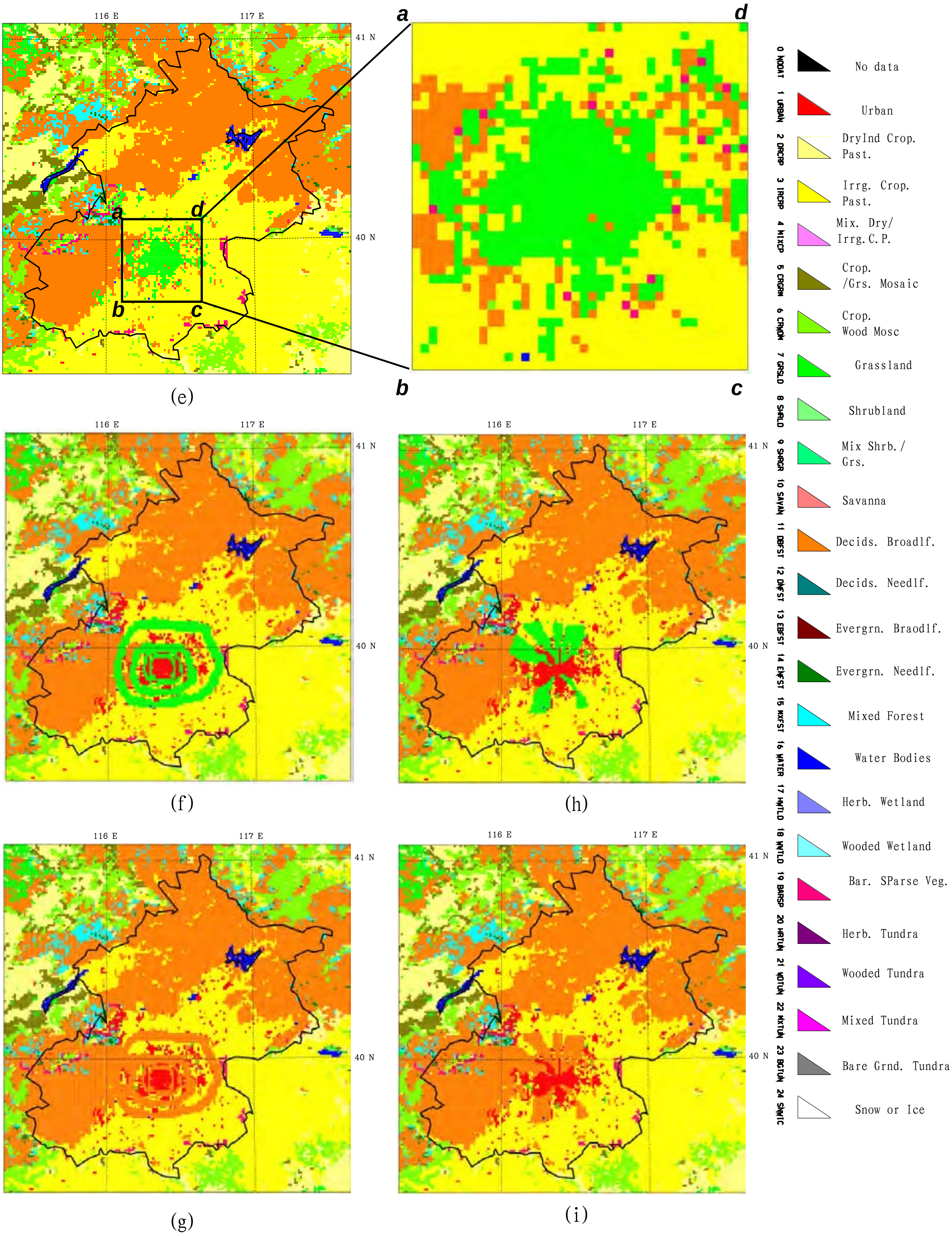


Figure 5. 30-second (~1 km resolution) surface characteristics in the Beijing area used in various MM5 simulaitons. (a) USGS data; (b) Exp2000; (c) Exp1980; (d) Exp00eu; (e) Exp00nu; (f) Exp10hg; (g) Exp10ht; (h) Exp10xg; (i) Exp10xt.

we use three different land-use change scenarios in MM5 sensitivity tests: 1) the original United States Geological Survey (USGS) global land-use map in MM5, based on the 1992-1993 1-km Advanced Very High Resolution Radiometer (AVHRR) and reflects, to a large degree, Beijing's urban surfaces in late 1980; 2) recent land-use data based on the 500-m resolution 2001 Geographical Information System (GIS) data for Beijing, reflecting Beijing's current urban distribution; and 3) future land-use distribution scenarios based on the current plan for 2010 green planting for Beijing. These land-use change scenarios are summarized in Table 3. All MM5 experiments employ the same initial and lateral boundary conditions, the same physics packages, and the same model configurations. The only difference between them is the specification of land-use distribution in the Beijing area.

Different scenarios of land-use change are shown in Fig. 5. Compared to the 1993 USGS land-use distribution (Fig. 5a), the 2001 GIS-based land-use (Fig. 5b) has two important improvements: 1) the rapid urban expansion is more realistically represented; 2) the type of Savanna in the middle-latitudes of Asia in USGS data is corrected to deciduous broadleaf. The assessing experiments of the two improvementon was investigated on a severe

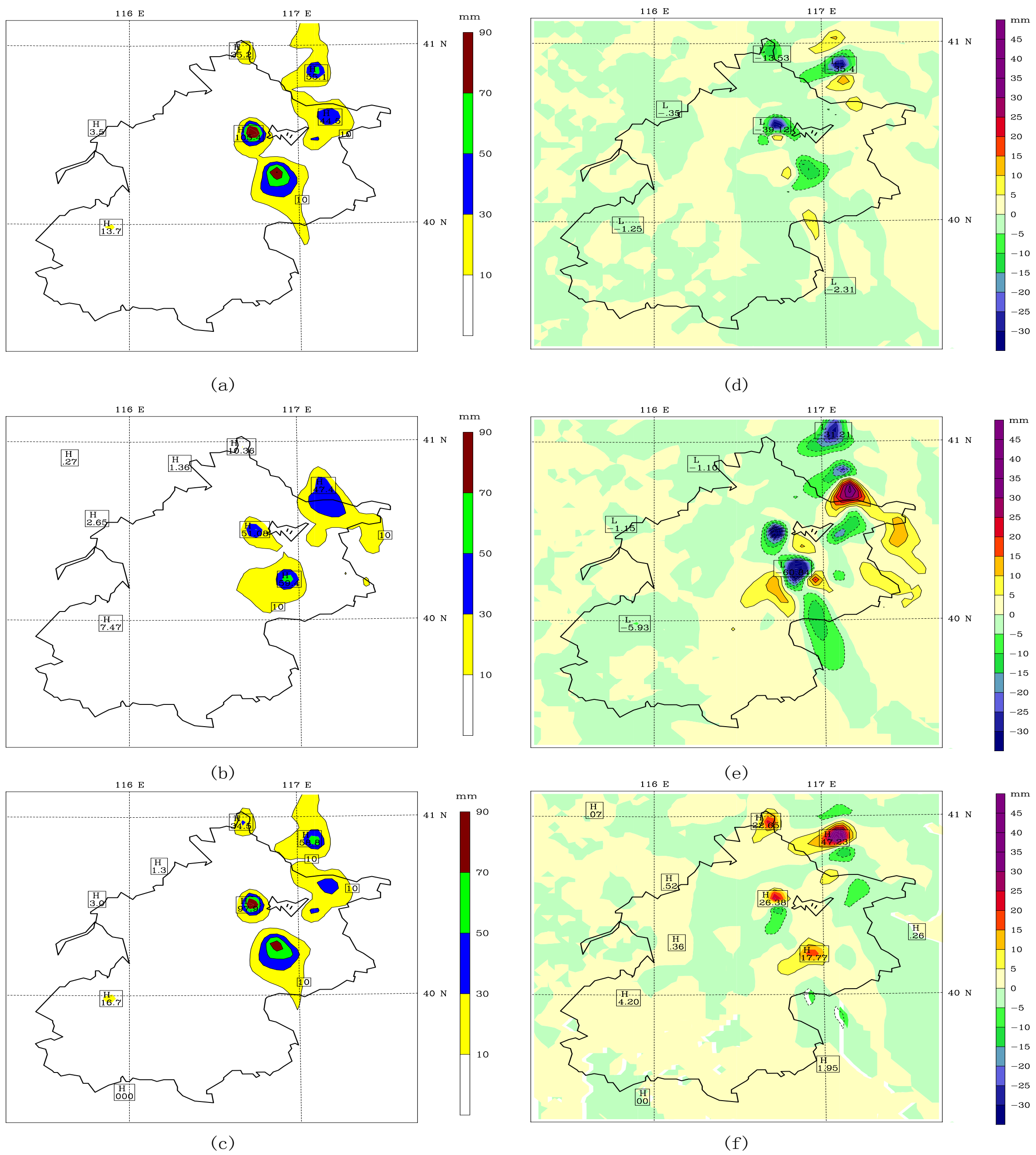


Figure 6. Simulated 12-h accumulated precipitation (mm) from 1200 UTC 18 to 0000 UTC 19 August 2002 (Unit in: mm). (a) Exp1980; (b) Exp00eu; (c) Exp00nu; (d) Exp2000-Exp1980; (e) Exp00eu-Exp2000; and (f) Exp00nu-Exp2000.

severe rainfall event (Zhang et al. 2006).

5. Results and discussions

5.1 Control simulation (EXP2000)

In the control simulation, the 12-h (1200 UTC 18 Aug–0000 UTC 19 Aug) rainfall in the Miyun reservoir area (northeast of Beijing, Fig. 3d) has a maximum value of 95.2 mm, and exceeds 70 mm in Shunyi; the location and intensity of simulated rainfall compare with observations reasonably well. Nevertheless, for the southwest area of Beijing, the maximum rainfall has a smaller amount and area coverage than observations. A comparison of Fig. 3e and Fig. 3b shows that the control simulation successfully captured the three observed surface weather features preceding the heavy rainfall: 1) a strong eastern circumfluence at the bottom of a macro-scale cold, high-pressure system at the northeast of Beijing, 2) a meso-β scale warm, low-pressure system near the location (40^{o}N, 115^{o}E) southwest of Beijing, and 3) a high-pressure system near the location (40oN, 113oE). The simulated radar reflectivity (Fig. 3f) captured well the main observed precipitation cells (Fig. 3c). In short, the control experiment reasonably simulates the development and evolution of this

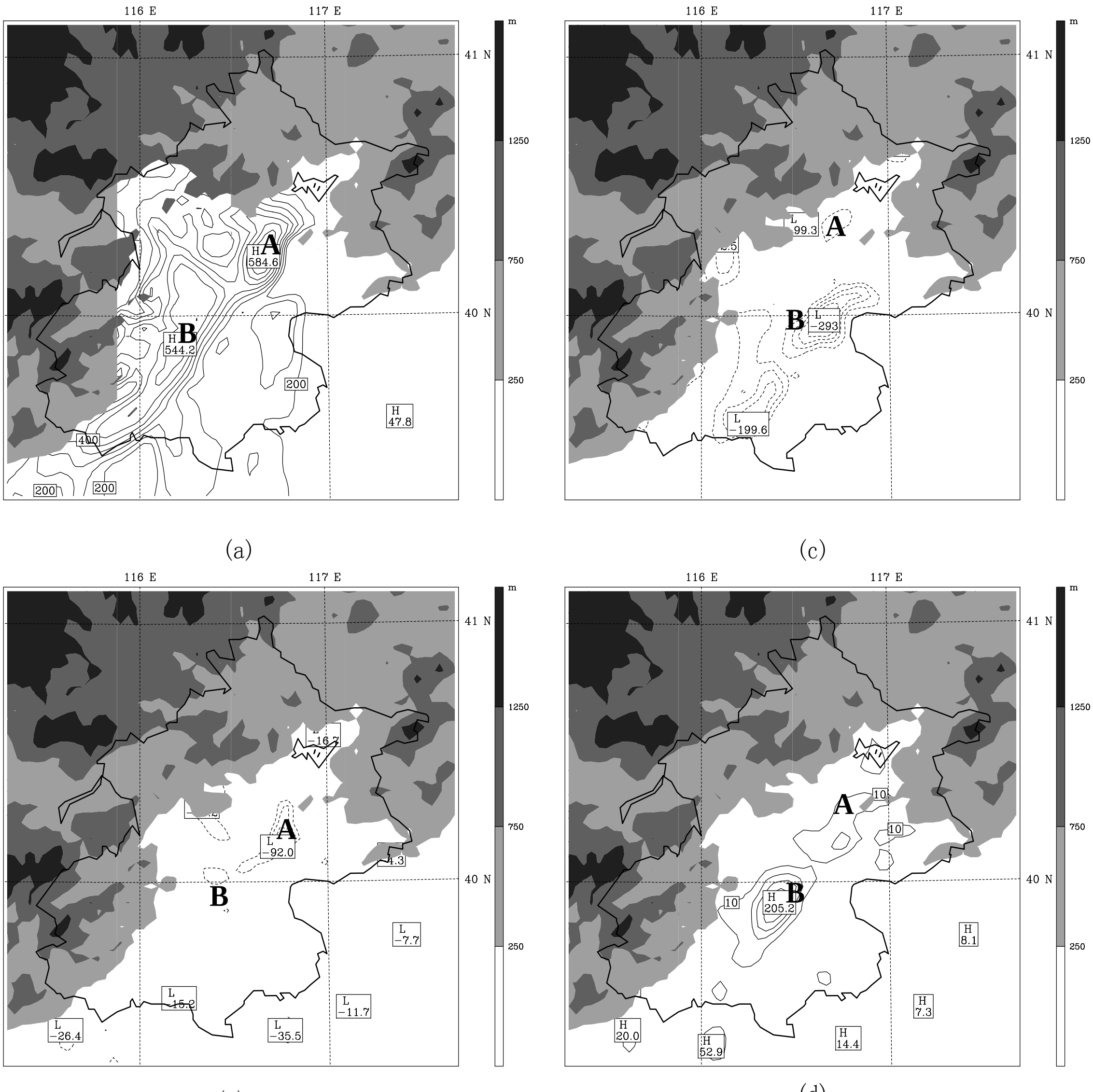


Figure 7. The maximum convective available potential energy (MCAP in J kg-1) and its difference at 1700 UTC 18 Aug. 2002. (a) MCAP for Exp2000; (b). MCAP difference for Exp2000-Exp1980; (c) MCAP difference for Exp00eu-Exp2000; and (d) MCAP difference for Exp00nu-Exp2000. In Fig. 7a and 7d, the contours of MCAP field are drawn with an interval of 50. In Fig. 7b and 7c the contour interval are -25 and -50, respectively. The grey-filled areas denote the elevation with 500-m interval.

locally forced heavy rainfall event.

5.2 Effects of urbanization on rainfall

1) Effects on the distribution and intensity of rainfall

Comparing Fig. 6a (Exp1980), Fig. 6b (Exp00eu), and Fig. 3d (Exp2000) reveals that although the general characteristics of the spatial distribution of rainfall bands are similar among these three simulations, the intensity and the location of maximum rainfall are different. For instance, the 12-hour maximum rainfall is 105.4 in Exp1980, 59.4 in Exp00eu, and 95.2 mm in Exp2000. Compared to Exp2000, Exp1980 (with less built-up area) produces more rainfall, while Exp00eu (with more built-up area) dramatically decreases rainfall. For Exp00eu, the area-average rainfall in two maximum rain centers is about 50 mm, much less than 70 mm for Exp2000.

The areas with rainfall differences between Exp1980, Exp00eu, and Exp2000 are confined approximately in the range of 50 km from the original location of rainfall bands (Fig. 6d and 6e). The difference is mainly negative in the Miyun reservoir and its surrounding areas, with a maximum value of about -30 mm. These results indicate that the urban land-use change in Beijing has important effects on the intensity and location of rainfall. The relative difference of the maximum rainfall can reach 30-40%, and the impact areas can extend to 50 km. Reduction of rainfall amount in simulations with more built-up areas (especially the difference between Exp2000 and Exp1980) is consistent with the statistical analysis in Section 2 and with the spatiotemporal-distribution variations of water resources in the Miyun reservoir from 1980. Therefore, the urban expansion in the Greater Beijing area is an important factor for decreasing summer rainfall in the Miyun reservoir and contributing to the shortage of water resource in Beijing.

An additional no-city sensitivity experiment (Exp00nu) is conducted, in which the Beijing urban area is replaced with grassland. Its rainfall distribution (Fig. 6c) is generally similar to that of Exp2000, and the rain belt range of maximum center is relatively larger with the maximum of 97.9 mm, which is higher than 95.2 mm of the control experiment. The difference of rainfall simulation (Exp00nu-Exp2000 in Fig. 6f) shows the opposite characteristics of the urbanization impact (Fig. 6d and 6e). Note that the positive difference appears in the Miyun reservoir and its surrounding areas, with the maximum value larger than 15 mm, indicating that green replanting in downtown Beijing would increase rainfall in the Miyun reservoir area and could mitigate the water shortage problem.

2) Effects of urbanization on thermodynamic and dynamic structures in the atmosphere

(a) The maximum convective available potential energy

Hourly rainfall data show that heavy rainfall occurred at 1700 UTC 18 August 2002 (0100 LST 19 August 2002) in Beijing. Figs. 7a-7c show the maximum convective available potential energy (MCAP)[1] calculated for various simulations at 1700 UTC 18 August 2002. Exp2000 has two areas of maximum MCAP in low elevations with 584.8 and 544.2 J kg-1 located at points A and B in Fig. 7a, which directly contributes to triggering a deep convection near the Miyun reservoir at the northeast of Beijing and Zhaitang, at the southwest of Beijing (see Figs. 3a and 3d). Simulations with more urban areas (Exp2000 and Exp00eu) produce less MCAP (by about 100 J kg-1, Figs. 7b, 7c). Conversely, the simulation without urban areas (Exp00nu, Fig.7d) produces the largest MCAP. Therefore, the urbanization of Beijing tends to reduce the instability energy in the corresponding areas prior to the development of convection, leading to a reduced rainfall amount.

---

[1] Convective available potential energy (***CAPE***) denotes the energy obtained by air mass from the power of atmospheric positive buoyancy under the condition of humid convection above the height of free convection height. It is translated into the kinetic energy of air mass possibly, and is conducive to convection. The formula is $CAPE = g\int_{Z_{LFC}}^{z_{EL}} \left(\frac{T_{vp} - T_{ve}}{T_{ve}} \right) dz$. Here, T_v represents virtual potential temperature, subscript ***e,p*** denote variables relative to environment and air mass respectively; z_{LFC} is free convection height; z_{EL} is balance height. Other symbols are in common use. The maximum convective available potential energy(***MCAP***) is the CAPE for the parcel in each column with maximum equivalent potential temperature below 3000m above ground level.

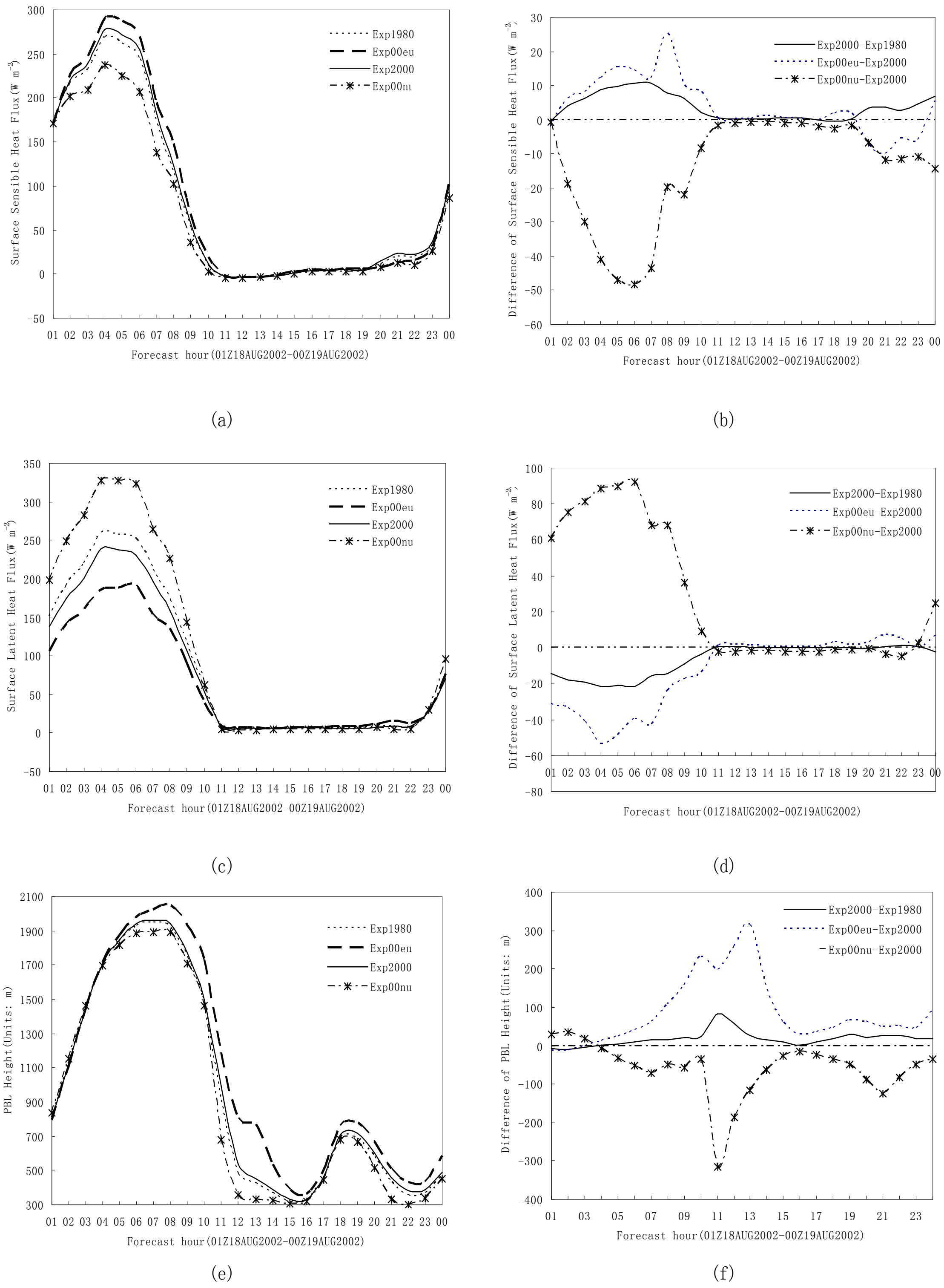


Figure 8. Hourly area-averaged PBL height, surface sensible heat flux and surface latent heat flux and their experimental differences for the square abcd illustrated in Fig. 5. (a) surface sensible heat flux (w m^{-2}). Solid line is Exp2000, dotted line Exp00eu, dashed line Exp1980, star-dashed line Exp00nu; (b) Differences of surface sensible heat flux (solid line is Exp2000-Exp1980, dotted line Exp00eu-Exp2000, star-dashed line Exp00nu-Exp2000; (c) surface latent heat flux (w m-2). Line denotations are same as (a); (d) Difference of surface latent heat flux. Line denotations are same as (b); (e) PBL Height (m). Line denotations are same; and (f) Difference of PBL height (m). Line denotations are same as (b).

(b) The surface heat transfer and the PBL depth over urban areas

The effects of urbanization on convective available potential energy are a reflection of the profound changes in the PBL thermodynamic and dynamic structures. Fig. 8 shows the diurnal cycle of the PBL height, surface sensible heat flux and surface latent heat flux as an area-average for the urban core (marked by the square area abcd in Figs. 5b-5d). The difference of surface sensible and latent heat fluxes between these urbanization sensitivity experiments mainly appears in daytime due to different responses of underlying urban surfaces to downward solar-radiation forcing, especially at local noon when the downward solar radiation reaches its maximum. During daytime, before rainfall events, the surface sensible heat flux (Fig. 8a) is the highest in Exp00eu (with the largest urban areas) and lowest in Exp00nu (without urban areas).

When the vegetated surface in areas surrounding downtown Beijing is urbanized, the enhancement of surface sensible heat flux becomes more evident as shown in the difference between Exp00eu-Exp2000 and Exp2000-Exp1980 (Fig. 8b). However, due to replanting in Exp00nu, the surface sensible flux decreases significantly, resulting in a difference (Exp00nu-Exp2000) of -49 W m-2 at local noon. Compared to vegetated surfaces, urban surfaces (with less available water for evaporation) produce lower latent heat fluxes (Fig. 8c), higher surface temperature, and larger sensible heat fluxes, which can considerably modify the PBL structures over urban areas, as we will discuss later.

Additionally, the comparison between the difference of sensible and latent heat fluxes between experiments (Figs. 8b, 8d) shows that urbanization affects latent heat flux more than sensible heat flux. For example, the difference of latent heat flux (Exp00nu-Exp2000, about 100 W m-2) is twice as much as that of sensible heat flux (-50 W m-2). Similar features can be found in other sensitivity experiments (e.g., Exp2000-Exp1980 and Exp00eu-Exp2000).

The impact of urbanization on the PBL depth is also prominent. Fig. 8e shows two peaks at 0600 UTC and 1800 UTC 18 August 2002 (1400 LST 18 August and 0200 LST 19 August) in the diurnal variation of the PBL height in all four urbanization-sensitivity experiments. The first peak (~1900 m at 1400 LST) is a direct response to the daytime maximum of sensible heat fluxes resulting from a strong exchange between the urban surface and the PBL. The second peak (~700 m at 0200 LST) appears during the nocturnal rainfall event, which, at first glance, cannot be related to the diurnal variation of surface sensible heat fluxes. However, note that the nocturnal sensible heat fluxes from urban surfaces are positive (i.e., heat transferring from the surface to the atmosphere). This situation, despite the relatively smaller amount compared to the daytime values, can reduce the stability in the nocturnal PBL and sometimes even turn it slightly unstable. Therefore, the combination of this nocturnal positive sensible heat flux and other convergence caused by meso- and micro-scale circulations helps reduce the stability and subsidence in the nocturnal PBL and create this second peak. The positive differences in the PBL depth (Exp2000-Exp1980 and Exp00eu-Exp2000) and negative differences (Exp00nu-Exp2000) shown in Fig. 8f indicate that besides enhancing surface sensible heat fluxes, the urbanization can deepen the PBL depth and strengthen the mixing of water vapor in the lower atmosphere. This, in conjunction with low evaporation from urban areas, prevents the accumulation of water vapor in the PBL, decreases the convective available potential energy, and hence reduces the chances for deep convection to develop.

(c) The flow and vertical structure of the lower atmosphere

In the lower atmosphere (σ=0.815, at the height of 1000-1500 m), a convergence zone is located near point A in the south of the Miyun reservoir in Exp2000 (Fig. 9a) and contributes to the development of deep convection in the corresponding area. The differences of the flow field of Exp2000-Exp1980 (Fig. 9b) and Exp00eu-Exp2000 (not shown) show a weaker convergence zone near point A in Exp2000 and Exp00eu, while the differences of Exp00nu-Exp2000 (Fig. 9c) show a stronger convergence zone near point A. Therefore, the urbanization of Beijing tends to weaken the convergence zone in the area of rainfall. Fig. 9d shows the vertical structure of differences of temperature and vertical velocity between Exp2000 and Exp1980 along line B1-A-B2 in Fig. 9b (i.e. 42.50 N). In the area near A, difference fields of temperature and vertical velocity can reach above 700 hPa, indicating a rather vigorous exchange between the nocturnal PBL and the atmosphere above. Modification in underlying urban surfaces in Beijing can change temperature by more than 1 K at 1700 UTC (0100 LST) and vertical velocity by 40 cm s-1. More importantly, in area A, the more developed areas produce weaker updraft (a negative differences with a maximum -42.3 cm s-1 between 1000 and 850 hPa),

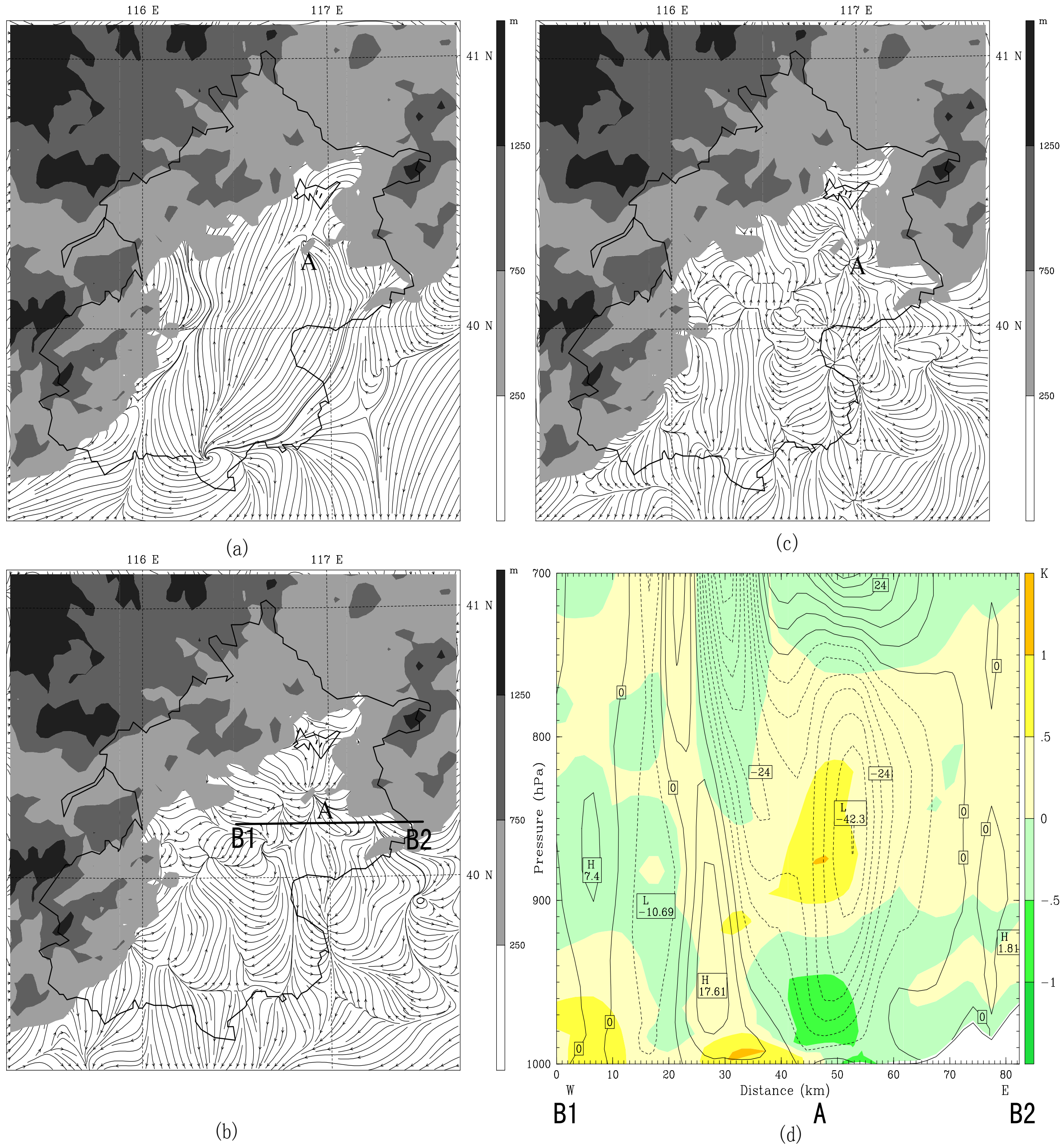


Figure 9. The streamline, temperature fields and their differences in the lower atmosphere (at the vertical level σ=0.815 of the numerical model) at 1700 UTC 18 August 2002. (a) streamline in Exp2000; (b) difference of wind stream field between Exp2000 and Exp1980 (Exp2000-Exp1980); (c) difference of wind stream field between Exp00nu and Exp2000 (Exp00nu-Exp2000); and (d) The vertical cross-section of differences in temperature and vertical wind velocity along 42.5 N latitude (Exp2000-Exp1980). In Figure 9a, 9b and 9c, the grey-filled contours denote the elevation with 500-m interval. In Figure 9b and Figure 9c, the wind stream field is compounded by differences of the horizontal wind components. In Figure 9d the left coordinate axis denotes atmospheric pressure with unit hPa, and the color-filled contours denote the temperature difference fields with the interval of 0.5 K.

lower temperature below 900 hPa, and higher temperature between 900-800 hPa. Compared to Exp1980, Exp2000 and Exp00ue form a more stable atmospheric condition throughout the PBL above the area near A. Therefore, changing the characteristics in the underlying surface in Beijing can, through atmospheric-land surface interactions, exert a significant non-linear effect on the PBL structures and suppress the onset (or reduce the strength) of deep convection in the Miyuan and its surrounding areas northeast of Beijing.

5.3 Influences of urban green-planting on rainfall

The analysis of the sensitivity experiment with no-urban indicates that increasing green coverage has the potential to enhance rainfall in the reservoir areas of Beijing and to mitigate the city water shortage. To further investigate the role of green planting in Beijing, we conduct four additional sensitivity experiments (Table 2: Exp10hg, Exp10ht, Exp10xg, Exp10xt) according to the Beijing greening plan for 2010. Analysis of the 12-hour rainfall simulation (1200 UTC 18 – 0000 UTC 19 August) obtained from these four experiments and their differences relative to the control experiment shows that with both annular and cuneiform green layouts, increasing green coverage in the future (planting grass or trees) results in rain in the main rainfall locations in Beijing and in its surrounding areas and larger rainfall coverage in Beijing overall. The rainfall bands of Exp10hg and Exp10xg with grass planting are very similar, so are Exp10ht and Exp10xt with tree planting. Thus, there are similar distribution characteristics of the rainfall positive and negative difference in the figures of the 12-hour rainfall difference between green planting sensitivity experiments and control experiments (figures omitted). With planting the same vegetation type, the rainfall differences between annular and cuneiform plantings are small. In the Beijing area, the maximum 12-hour rainfall in simulations with grassland (113.0 mm for Exp10hg, and111.5 mm for Exp10xg) is larger than that in simulations with the same green layout but with trees (92.31 mm for Exp10ht and 79.66 mm for Exp10xt). The positive (negative) difference of Exp10hg-Exp2000 (Exp10xg-Exp2000) is bigger (smaller) than that of Exp10ht-Exp2000 (Exp10xt-Exp2000). Therefore, with the same layout, planting different vegetation types can affect the intensity and location of rainfall in Beijing. Enlarging grass coverage is more conducive to the enhancement of rainfall than enlarging tree coverage.

6 Summary and conclusion

In this study, we investigate influences of rapid urbanization in the Beijing area on summer heavy precipitation and local water resources through the use of climatologic data and simulations of a selected case using the MM5/Noah/urban coupled modeling system with high-resolution land-use data. In particular, we focus on rainfall change in the Miyun reservoir area, a major source for Beijing's local water supply. The main results are summarized as:

• Based on the analysis of 20-year rainfall and urban development data, it is clear that summer and annual precipitation in the Greater Beijing area has decreased with urban expansion since 1981 with largest reduction (by more than 40 mm per year) around the Miyun reservoir. The center of maximum summer rainfall moves to the southern part of the city for this period.

• Numerical simulations show that urbanization with larger heat capacity and less available water for evaporation produces smaller latent heat flux, higher surface temperature, larger sensible heat fluxes, and a deeper boundary layer. These results indicate less water vapor but more (water vapor) mixing in the PBL, hence less convective available potential energy, and a reduction of rainfall for the Beijing area, in general and for the Miyun reservoir area, in particular. These simulation results are consistent with the above statistical analysis.

• Increasing green coverage in the Beijing area can produce more rainfall, and planting grass seems more effective to increase rain than planting trees. For the same vegetation planted, the rainfall difference from simulations using two green-planting layouts (annular and cuneiform) is small.

The response of global climate changes and local extreme weather events to human activities (including urbanization) is a very complex and challenging problem. For instance, this study demonstrates that the urban land-use change and green planting have important effects on the intensity and location of summer rainfall in Beijing. The relative difference of maximum rainfall can reach 30-40%, and the impact range for modifying rainfall bands can extend to 50 km, as a result of complex interactions between land surface and urban processes (such as topography, soil, vegetation, urban heat island), boundary layer processes, and precipitation processes. The method combining case studies and long-term statistical analysis used in this investigation can shed light on how to better plan urban development and green planting to mitigate the shortage of water resource in mega cities, which is valuable information for the local and regional policy makers.

Urbanization and green planting have important impacts on summer rainfall in mega cities. This study reveals some preliminary results using a simple urban treatment. Given the complex interactions between urban surfaces and the atmosphere, more sophisticated urban models (e.g. urban canopy models by Kusaka et al. 2001, and Martilli et al. 2002) are needed in the future to discern, for instance, building geometry (height, widths, etc) and to more realistically simulate urban effects .

Acknowledgements

This study was supported by the project of the Beijing New Star (No. H013610330119), Ministry of Science and Technology of the People's Republic of China (No. 2005DIB3J098), Beijing Municipal Science & Technology Commission (No. H020620250330), the National Natural Science Foundation of China (No. 40505002) and Beijing Natural Science Foundation (No. 8051002). Fei Chen's work was supported by U.S. NASA–THP Grant NNG04GI84G.

References

Bornstein, R.D., and D.S. Johnson, 1977: Urban-rural wind velocity differences. Atmospheric Environment, 11, 597-604.

Bornstein, R. 1987: Urban climate models: nature, limitations, and applications. Meteorol. and Atmos. Physics, 38, 185-194.

Changnon S.A., and F.A. Huff, 1986: The urban-related nocturnal rainfall anomaly at St. Louis. Jnl.Clim.Appl.Met., 25, 1985-1995.

Chen, F., and J. Dudhia, 2001a: Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity. Mon. Wea. Rev., 129, 569-585.

Chen, F., and J. Dudhia, 2001b: Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part II: Preliminary model validation. Mon. Wea. Rev., 129, 587-604.

Chen, F. T. Warner, and K. Manning, 2001c: Sensitivity of orographic moist convection to landscape variability: A Study of the Buffalo Creek, Colorado, flash-flood case of 1996. J. Atmos. Sci., 58, 3204-3223.

Chen, F. 2005: Variability in global land surface energy budgets during 1987-1988 simulated by an offline land surface model. Climate Dynamics, doi: 10.1007/s00382-004-0439-4.

Dudhia, J., 1989: Numerical study of convection observed during winter monsoon experiment using a mesoscale two-dimensional model. J. Atmos. Sci., 46, 3077-3107.

Dudhia, J., 1993: A nonhydrostatic version of the Penn State/NCAR mesoscale model: Validation tests and simulation of an Atlantic cyclone and cold front. Mon. Wea. Rev., 121, 1493-1513.

Ek, M.B., Mitchell, K.E., Lin,Y., Rogers, E., Grunmann, P., Koren, V., Gayno, G. and Tarpley, J.D., 2003: Implementation of Noah land-surface model advances in the NCEP operational mesoscale Eta mode. J. Geophys. Res., 108 (D22): No. 8851, 10.1029/2002JD003296.

Givati, A., D. Rosenfeld, 2004: Quantifying Precipitation Suppression Due to Air Pollution, 43, 1038-1056.

Grell, G.A., Dudhia, J. and Stauffer, D. R. 1994: A description of the fifth-generation Penn State/NCAR mesoscale model (MM5). NCAR Technical Note, NCAR/TN-398+STR, National Center for Atmospheric Research, Boulder, CO, pp.117.

Holt, T., D. Niyogi, F. Chen, K. Manning, M. A. LeMone, A. Qureshi, 2006: Effect of Land - Atmosphere Interactions on the IHOP 24-25 May 2002 Convection Case. Mon. Wea. Rev., 134, 113-133.

Hong, S.-Y., and H.-L. Pan, 1996: Non local boundary layer vertical diffusion in a medium-range forecast model. Mon. Wea. Rev., 124, 2322-2339.

Huff, F.A., and J.L. Vogel, 1978: Urban, Topographic and diurnal effects on rainfall in the St. Louis Region. J. Appl. Meteor., 17, 565-577.

Kistler, R., Kalnay,E., Collins,W., Saha,S. and co-author. 2001: The NCEP-NCAR 50-Year Reanalysis: Monthly Means CD-ROM and Documentation. Bull. Amer. Meteor. Soc., 82, 247-268.

Kusaka , H., H. Kondo, Y. Kikegawa and F. Kimura, 2001: A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. Bound.-Layer Meteor., 101, 329-358.

Li, Q., and Y. Ding, 2004: The progress in the impact study of vegetation coverage change on Chinese regional climate, J. Nanjing Meteor. Inst., 27, 131-140. (in Chinese with English abstract)

Li, Q., C. Zhang, S. Miao, 2005: The distribution characteristics of rainfall and the effect of land use in Beijing area, J. Desert Research, 25(Supp.), 60-65. (in Chinese with English abstract)

Liu, Y., Chen,F., Warner ,T. ,and J. Basara, 2006: Verification of a Mesoscale Data Assimilation and Forecasting System for the Oklahoma City Area during the Joint Urban 2003 Field Project. J. of Appl. Meteor. In press.

Lo, J., A. Lau, F. Chen, and J. Fung, 2006: Implication of rapid urban growth on the meteorological conditions in the Pearl River Delta Region. J. Appli. Meteorol, accepted.

Martilli, A., A. Clappier, and M. W. Rotach, 2002: An Urban Surface Exchange Parameterization for Mesoscale Models. Bound.-Layer Meteor., 104, 261-304.

Rosenfeld, D. 2000: Suppression of rain and snow by urban air pollution. Science, 287, 1793–1796.

Shepherd, J.M, 2005: A Review of Current Investigations of urban-induced rainfall and recommendations for the future, Earth Interactions, 9, 1-27.

Trier, S., F. Chen, and K. Manning, 2004: A Study of convection initiation in a mesoscale model using high-resolution land surface initiation conditions. Mon. Wea. Rev., 132, 2954-2976.

Vogel, J. L., and F.A. Huff, 1978: Relation between the St. Louis Urban rainfall anomaly and synoptic weather factors, J. Appl. Meteor., 17, 1141-1152.

Wu Z., S. Chu, and H. Li, 2000: Climatological features of the number of the equivalent torrential rain days in Beijing, Chinese J. Atmos. Sci., 24, 58-66 (in Chinese with English abstract).

Zhang C.L, C. Ji, and Y.-H. Kuo, S. Fan, C. Xuan, and M. Chen, 2005a: Numerical simulations of topography impacts on "00.7" heavy rainfall in Beijing, Progress in Nature Sciences, 15, 818-826.

Zhang C., M. Chen, Y.-H. Kuo, S. Fan, and J. Zhong, 2005b: Numerical assessing experiments on the individual components impact of the meteorological observation network on the "00.7" sever rainfall in Beijing, Acta Meteorologica Sinica, 63,922-932(in Chinese with English abstract); aslo accepted and to be published by its english vesion.

Zhang C., S. Miao., C. Li, F. Chen. 2006: Incorporation of fine-resolution land use information of Beijing into numerical weather model and its assessing experiments on a summer severe rainfall. Chinese J . Geophys. , accepted.